NSTX

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

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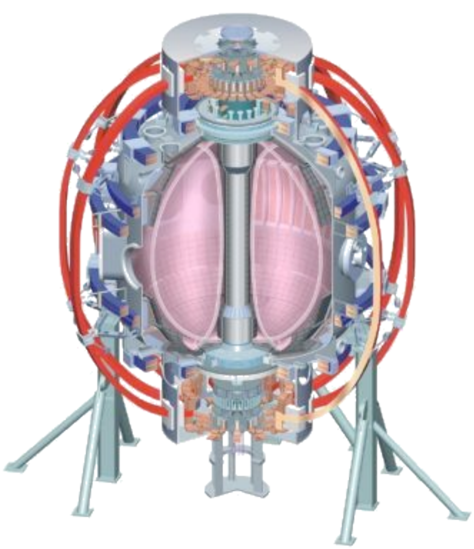

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Summary

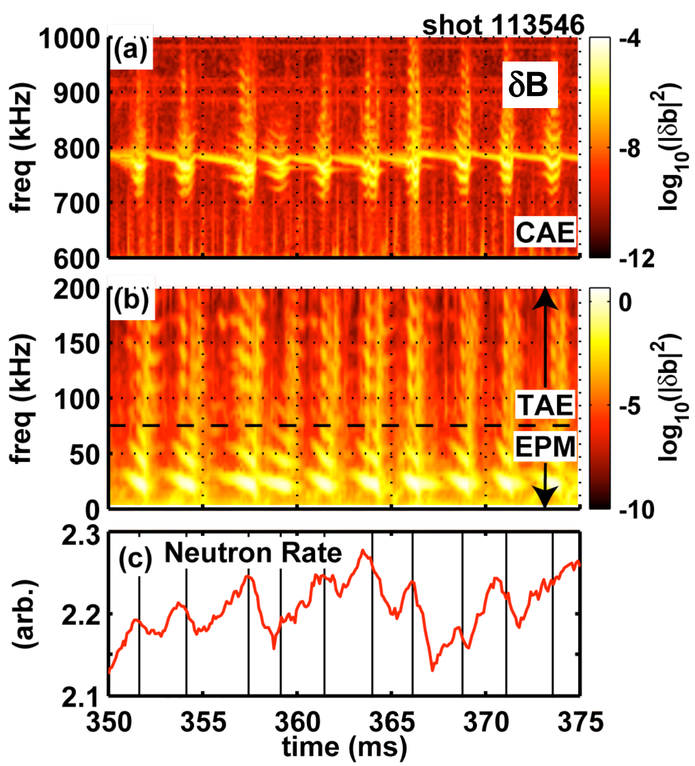
- Bursts of fluctuations observed with broad spectrum of fast-ion modes: EPM, TAE and CAE — bursts correlate with fast-ion loss
- Spacing of spectrum ($\Delta f, \Delta n$) indicates three-wave interactions between EPM, TAE and CAE
- Three-wave interactions indicated by spectrum are confirmed by high bicoherence of mode triplets
- Interaction with the EPMs toroidally localizes TAEs and CAEs into wave-packets
- CAE wave-packet subdivided by interaction with TAEs
- Orbit modification is nonlinear $\Rightarrow$ observed wave-packets may have consequence for fast-ion transport

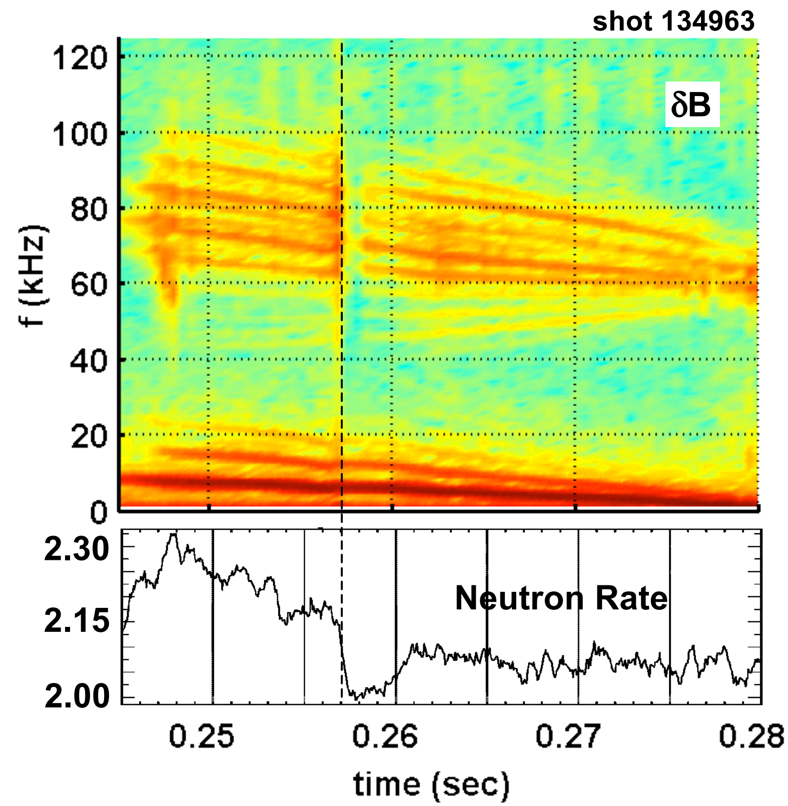
Motivation: three-wave interaction of fast-ion modes can impact plasma performance

- Plasma heated by fast-ions (*e.g.* fusion α's, neutral beam ions) — *fast-ions must be confined*
- Fast-ion modes — modes excited by fast-ions (*e.g.* Alfvén eigenmodes and energetic particle modes) — modify fast-ion orbits
  - fast-ions transported, possibly lost from plasma
- Orbit modification is *nonlinear*
  - multiple modes can cause *disproportionate* transport (*e.g.* avalanches)
  - relative *phasing* and *amplitude* of modes matters
- Three-wave interaction can impact fast-ion transport
  - can broaden fast-ion mode spectrum $\Rightarrow$ more modes
  - can change relative phases of modes $\Rightarrow$ coherent structures (e.g. wave-packets)

Three-wave interaction impacts fast-ions in neutral beam heated NSTX plasmas

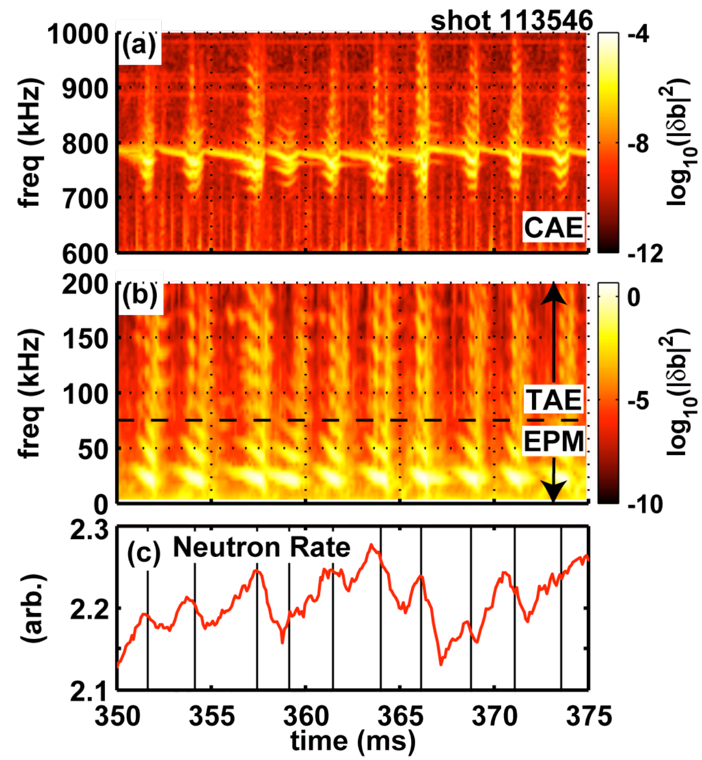
- Three-wave interaction of fast-ion modes common in NSTX neutral beam heated plasmas
- Three-wave interaction often observed during fast-ion loss events

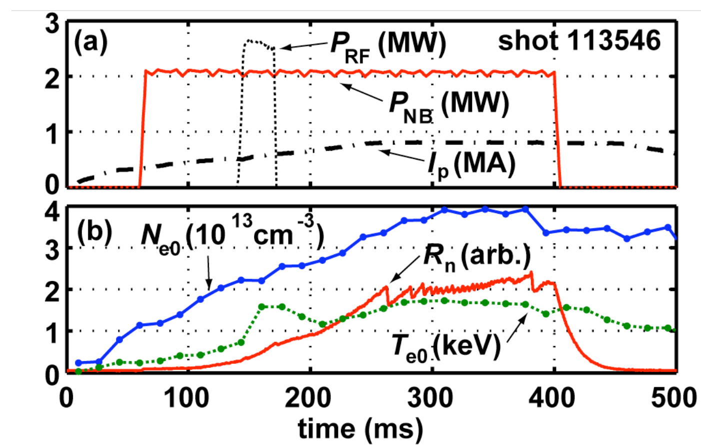




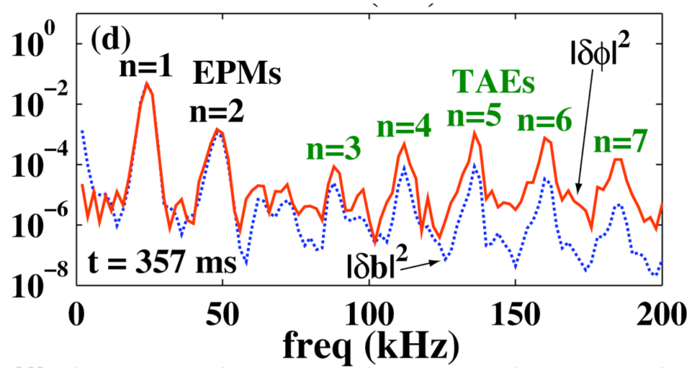
Broad spectrum of fast-ion modes observed during fast-ion loss events

- Bursts of magnetic fluctuations observed in L-mode, NB plasma
  - 2 MW NB
  - $T_e \sim 2$ keV; $n_e \sim 4 \times 10^{13}$ cm^{-3}
- Bursts correlate with neutron rate drops (~ 5%)
- Bursts exhibit broad spectrum of fast-ion modes
  - energetic particle modes (EPM): f = 0 – 75 kHz, n = 1 – 3
  - toroidicity-induced Alfvén eigenmodes (TAE): f = 75 – 200 kHz, n = 3 – 7
  - compressional Alfvén eigenmodes (CAE): f = 100 – 1000 kHz, n = -12 – -3



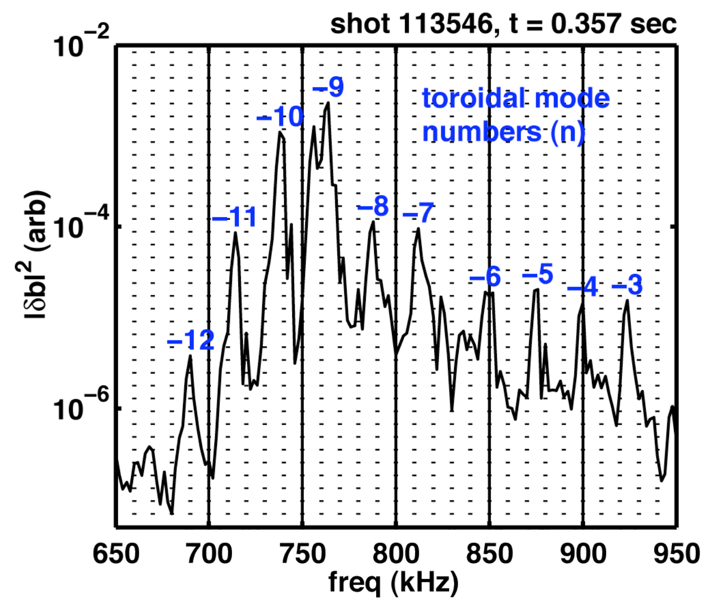


Spectrum indicates three-wave interactions of EPMs with TAEs



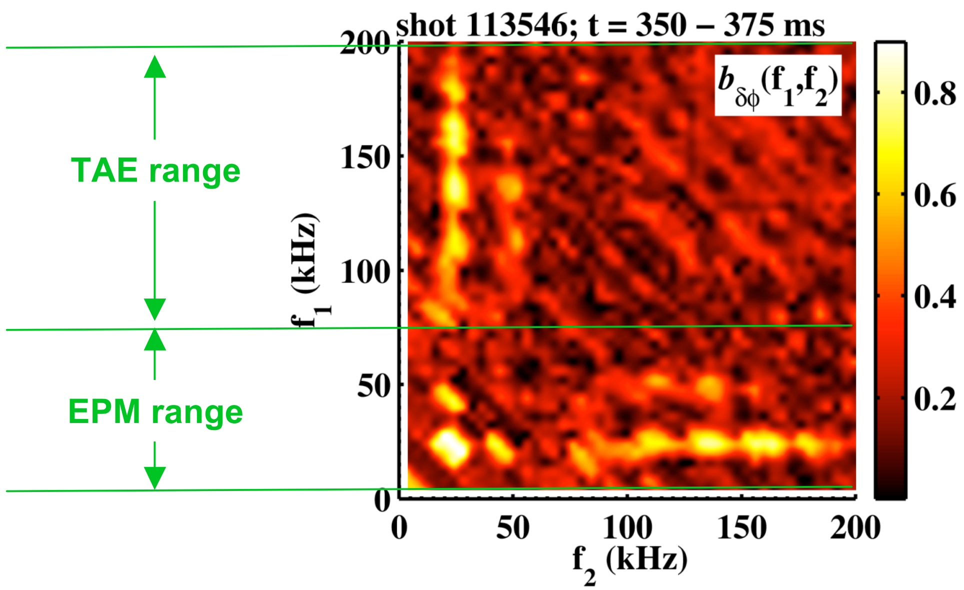
- Mode triplet interacts if $f_1 = f_2 + f_3$ and $n_1 = n_2 + n_3$
- TAE spectrum shows pairs of neighboring TAEs can interact with EPMs:
  - spectrum spacing matches fundamental EPM: $\Delta f = f_{EPM} = 1, \Delta n = n_{EPM} =$ ~ 24 kHz
  - pairs of neighboring TAEs, (f_{TAE1}, n_{TAE1}) and (f_{TAE2}, n_{TAE2}), satisfy: $f_{TAE2} = f_{TAE1} + f_{EPM}$, $n_{TAE2} = n_{TAE1} + n_{EPM}$

Spectrum indicates three-wave interactions of CAEs with EPMs *and* with TAEs



- CAE spectrum shows two groups of CAEs
  - n = -12 – -7, f = 690 – 810 kHz;
  - n = -6 – -3, f = 850 – 925 kHz
- Some CAE pairs can interact with EPMs, others with TAEs
  - spacing within each group matches fundamental EPM:
    $\Delta f = f_{EPM} = 1$, $\Delta n = n_{EPM} = \sim 24$ kHz
  - spacing between groups matches fundamental TAE:
    $\Delta f = f_{TAE} = 5$, $\Delta n = n_{TAE} = \sim 135$ kHz

High bicoherence of mode triplets confirms three-wave interaction of EPMs with TAEs

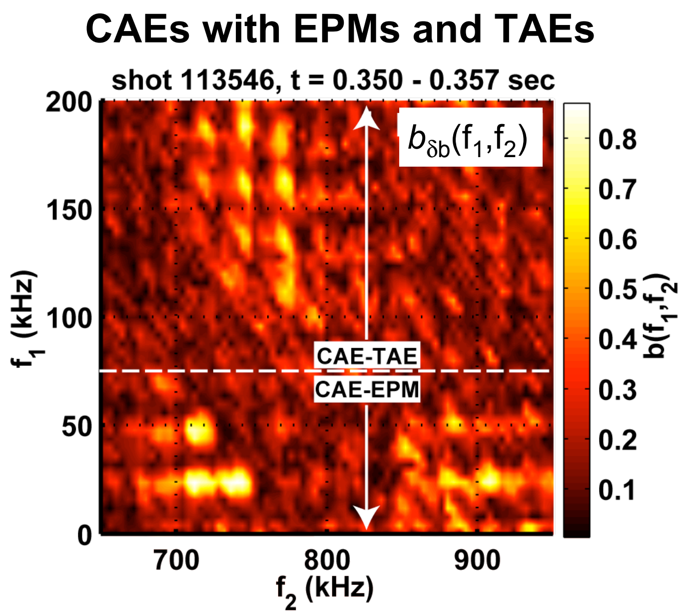


- Bicoherence tests for statistically significant three-wave interaction
  - bicoherence = coherence of *product of wave pair* $[\delta x(f_1)\delta x(f_2)]$ with *sum wave* $[\delta x(f_1+f_2)]$

$$b_{\delta x}(f_1, f_2) = \frac{|\langle \delta x(f_1)\delta x(f_2)\delta x^*(f_1+f_2)\rangle|}{\left(\langle|\delta x(f_1)\delta x(f_2)|^2\rangle\langle|\delta x(f_1+f_2)|^2\rangle\right)^{1/2}}$$

- High bicoherence peaks seen for triplets that include EPM (e.g. f ~ 24 kHz, n = 1) and pair of neighboring TAEs

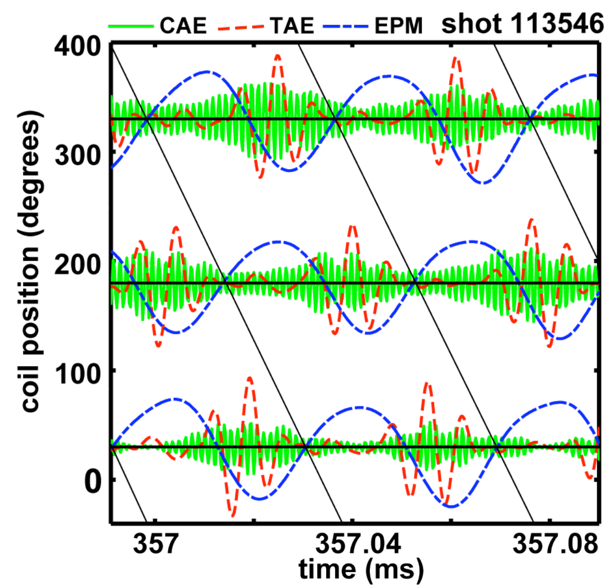
High bicoherence of mode triplets confirms three-wave interaction of CAEs with EPMs and with TAEs



- Interaction of CAEs with *EPMs*: high bicoherence peaks seen for triplets that include EPM (e.g. f ~ 24 kHz, n = 1) and pair of *neighboring* CAEs *within each group*
- Interaction of CAEs with *TAEs*: high bicoherence peaks seen for triplets that include TAE (e.g. f ~ 135 kHz, n = 5) and pair of CAEs *with one from each group*

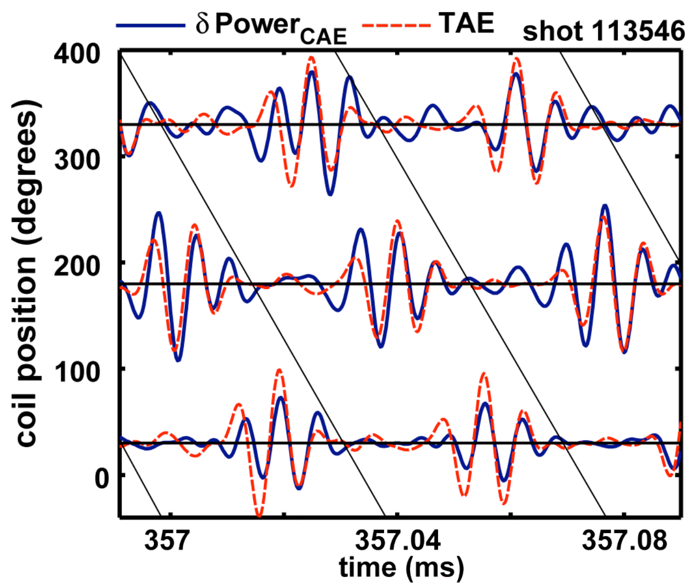
Interaction with the EPMs toroidally localizes TAEs and CAEs into wave-packets

- CAE and TAE fluctuations concentrated into toroidally propagating wave-packets
  - band-pass filtering divides magnetic fluctuation into distinct contributions of EPM, TAE and CAE
  - TAE and CAE amplitudes modulated
  - phase of amplitude modulation increases with toroidal angle



- Wave-packets phase-locked to EPM
  - amplitude modulation frequency = EPM frequency
  - phase of amplitude modulation correlates with toroidal phase of EPM
- Phase-locking of wave-packets with EPM expected from three-wave interaction
  - $\Delta f/\Delta n = f_{EPM}/n_{EPM}$ for TAE and CAE spectra $\Rightarrow$ group velocity of superposition = phase velocity of EPM

CAE wave-packet subdivided by interaction with TAEs



- CAE fluctuation power is modulated at TAE frequency
  - CAE fluctuation power obtained by low pass filtering square of CAE fluctuation
  - modulation by TAEs isolated by band-pass filtering to retain TAE frequency range
- Modulation correlates in time and space with TAE wave-packet (both envelope *and* carrier wave)
- Modulation induces TAE scale structure into EPM-induced wave-packet

Discussion: Observed wave-packets have possible consequences for fast-ion transport

- Orbit modification is *nonlinear*
  - multiple modes can cause *disproportionate* transport (*e.g.* avalanches*)*
  - relative *phasing* and *amplitude* of modes matters
  - multiple modes form beat and sum waves $\Rightarrow$ possible new resonances for fast-ion orbits
- Observed three-wave interactions form wave-packets $\Rightarrow$ relative mode phases are modified
- Wave-packet may impact transport differently from same spectrum with random mode phases
  - wave-packet formation concentrates perturbation spatially $\Rightarrow$ locally amplifies "kick" delivered to fast-ions
  - fast-ions orbits can resonate with envelope or carrier wave
  - wave-packet structure implies pondermotive force — is it significant?

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Questions raised and avenues for future research

Questions for near term

- Is spectrum of interacting TAEs (or CAEs) composed of linear eigenmodes? (i.e. is three-wave interaction weak)?
  - is spacing of linear TAE and CAE spectrum conducive to weak three-wave interaction?
  - if yes, radial/poloidal wave-packet structure may be predicted
- How does wave-packet impact on fast-ions orbits? ⇒ ORBIT calculation
  - compare wave packet to random phase fluctuations with same power
  - assumptions and/or measurement required for radial/poloidal wave-packet structure
  - need experimental cases with good fast-ion diagnosis and three-wave statistics

Broader questions

- Do three-wave interactions transfer energy across scales — e.g. does EPM–TAE interaction destabilize TAEs?
  - broader spectrum ⇒ more efficient transfer of fast-ion energy to plasma?
- What nonlinearities give rise to interaction?
  - MHD/fluid nonlinearities? (e.g. JXB — well-known to couple Alfvén to acoustic waves)
  - toroidal modulation of fast-ion pressure?
  - …?

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