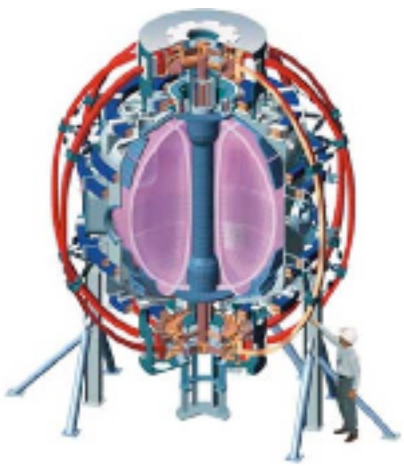


Three-wave interaction of fast-ion modes in NSTX

NA Crocker, ED Fredrickson, and many others …

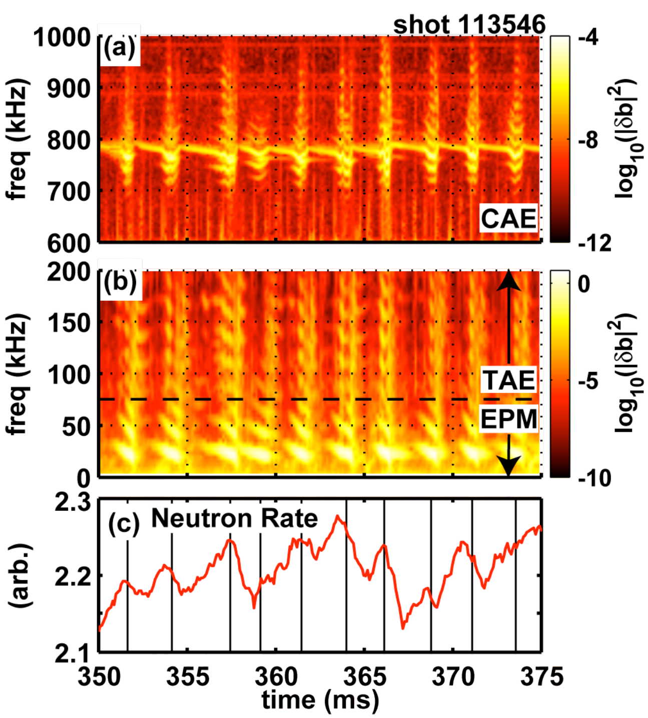
NSTX Results and Theory Review

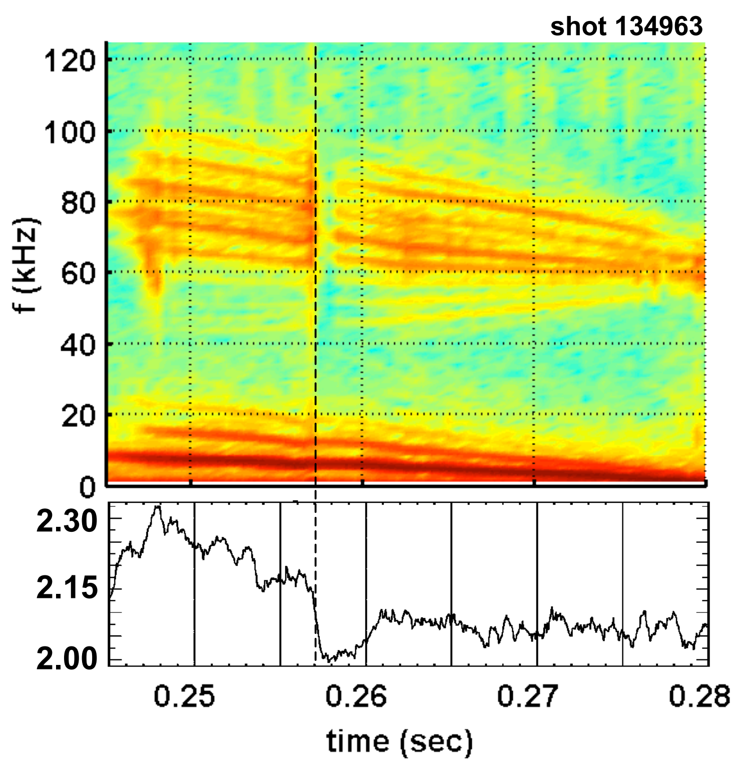
September, 2009

Three-wave interaction may play significant role in fast-ion modes dynamics and fast-ion transport

- Linear theory has many successes (e.g. prediction of mode structure), but may not fully explain fast-ion transport

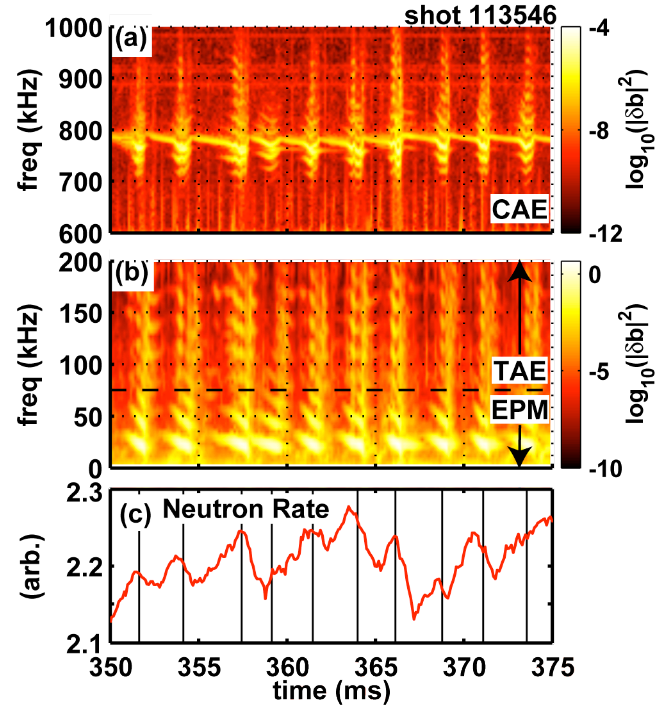
- Nonlinear three-wave interaction of fast-ion modes common in NSTX NB plasmas
  - often observed during fast-ion loss events
  - often coincident with other non-linear processes (e.g. avalanches)

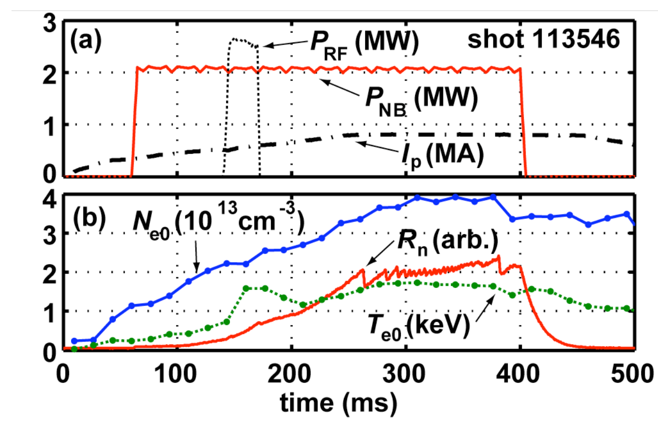




Three-wave interactions observed during fast-ion loss events

- 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
  - EPMs: f = 0 – 75 kHz, n = 1 – 3
  - TAEs: f = 75 – 200 kHz, n = 3 – 7
  - CAEs: f = 100 – 1000 kHz, n = -12 – -3
- Analysis shows three-wave interactions between EPMs and TAEs, between EPMs and CAEs and between TAEs and CAEs.





Spectrum suggests three-wave interactions occur between EPM, TAE and CAE

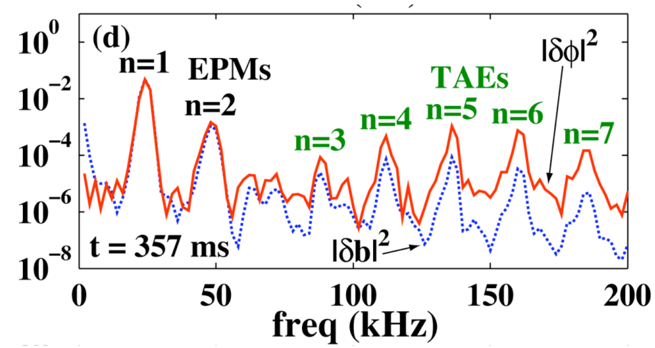
- Mode triplet can interact if:

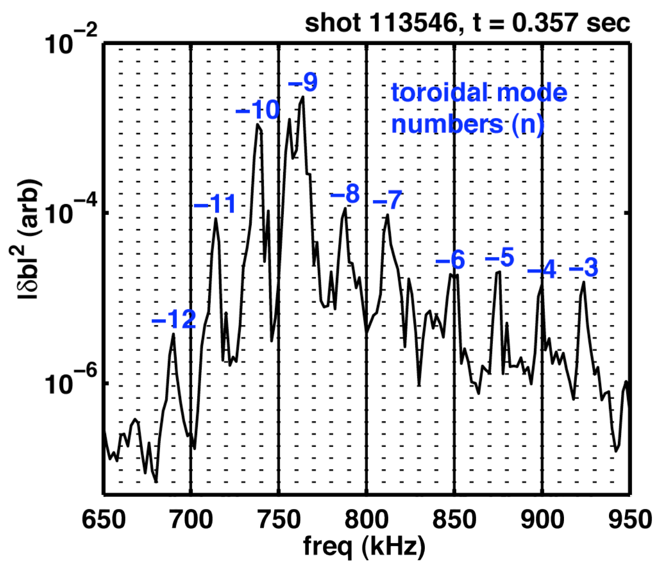
  $f_1 = f_2 + f_3$ and $n_1 = n_2 + n_3$

- Pairs of neighboring TAEs can interact with EPMs:
  - spectrum spacing matches fundamental EPM: $\Delta f_{TAE} = f_{EPM}$ = 1, $\Delta n_{TAE} = n_{EPM}$ = ~ 24 kHz
  - TAE pair (f_{TAE1}, n_{TAE1}) and (f_{TAE2}, n_{TAE2}): $f_{TAE2} = f_{TAE1} + f_{EPM}$, $n_{TAE2} = n_{TAE1} + n_{EPM}$

- Some CAE pairs can interact with EPMs, others with TAEs
  - Two groups of CAEs:
    - n = -12 – -7, f = 690 – 810 kHz;
    - n = -6 – -3, f = 850 – 925 kHz
  - Spacing within each group matches fundamental EPM
  - Spacing between groups match fundamental TAE:

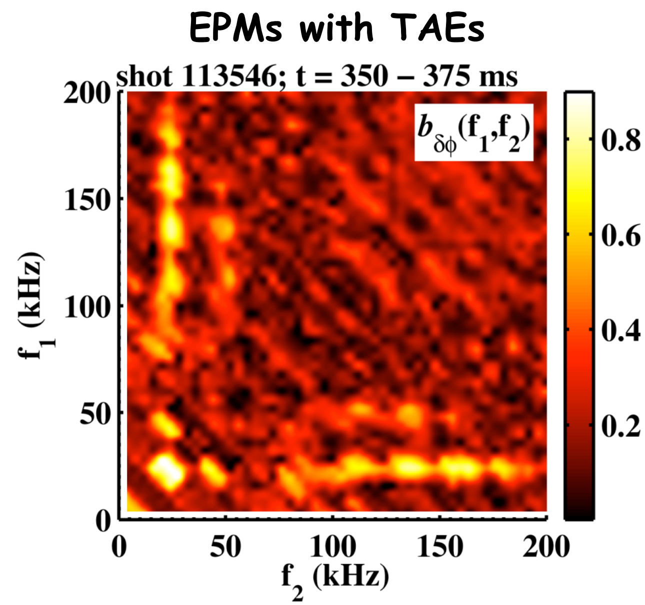
    $\Delta f = f_{TAE}$ = 5, $\Delta n = n_{TAE}$ = ~ 135 kHz

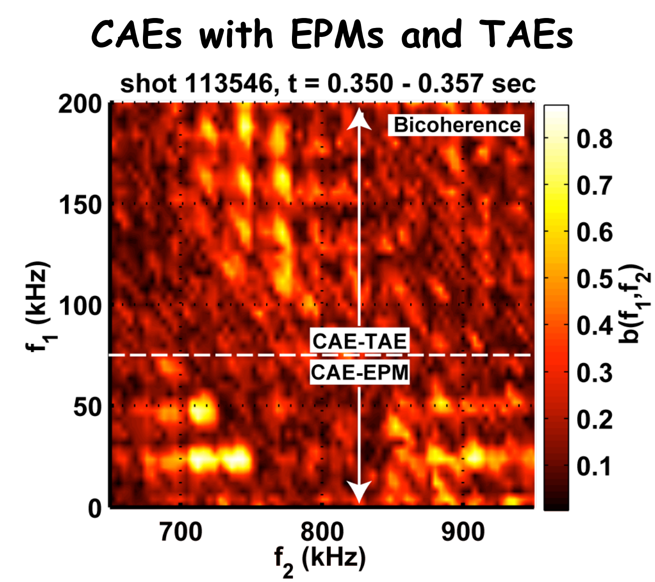




Three-wave interaction confirmed by high bicoherence of mode triplets

- Bicoherence tests for statistically significant three-wave interaction
  - bicoherence = coherence of nonlinear product of wave pair with the sum wave
- Bicoherence of TAEs with EPMs shows peaks for triplets indicated by TAE spectrum
- Bicoherence of CAEs with EPMs and with TAEs shows peaks corresponding to triplets indicted by CAE spectrum

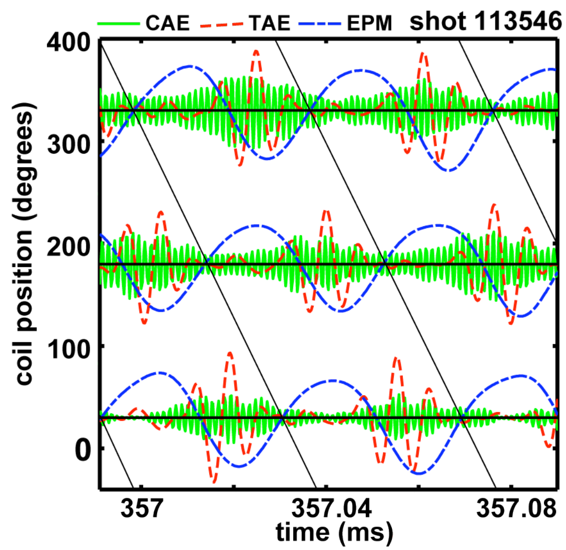




$$b_{\delta\phi}(f_1, f_2) = \frac{|\langle \delta\phi(f_1)\delta\phi(f_2)\delta\phi^*(f_1+f_2)\rangle|}{\left(\langle|\delta\phi(f_1)\delta\phi(f_2)|^2\rangle\langle|\delta\phi(f_1+f_2)|^2\rangle\right)^{1/2}}$$

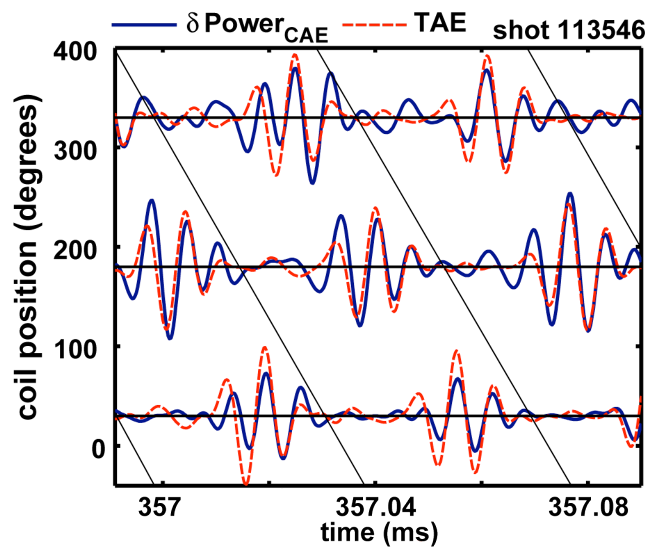
Interaction with the EPMs toroidally localizes TAEs and CAEs into wave-packets

- 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

Interaction with the TAEs subdivides CAE wave-packet



- 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 introduces TAE scale structure into EPM-induced wave-packet

Summary of Experimental Results

- Three-wave interaction may play significant role in fast-ion modes dynamics and fast-ion transport
- Bursts of fast-ion modes over broad spectrum observed — EPM, TAE and CAE; bursts correlate with fast-ion loss
- Spectrum suggests three-wave interactions occur between EPM, TAE and CAE — confirmed by high bicoherence of mode triplets
- Interaction with the EPMs toroidally localizes TAEs and CAEs into wave-packets
- Interaction with the TAEs subdivides CAE wave-packet

Questions raised and avenues for future research

Questions for the 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
  - experimental cases needed with good fast-ion population diagnosis and good three-wave statistics

Broader Questions

- Do three-wave interactions transfer energy across scales — e.g. does EPM–TAE interaction destabilize TAEs?
  - 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?
  - …?