# Formation of long-lived phase space structures by high frequency Alfvén Eigenmodes through the Doppler-shifted cyclotron resonance*

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*Supported by U.S. DEPARTMENT OF ENERGY Office of Science

PPPL PRINCETON PLASMA PHYSICS LABORATORY

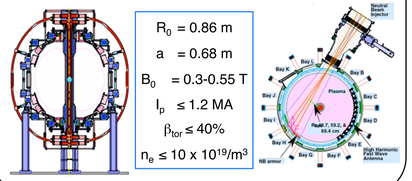
NSTX

53rd Meeting of the American Physical Society, Division of Plasma Physics, November 14 – 18, 2011, Salt Lake City, Utah



## NSTX has low field, high density and current; perfect for study of fast ion-driven modes

- Low field, high density $V_{Alfvén} \approx 0.5 - 2.7 \times 10^6$ m/s.
- Beam injection energy 60 - 100 kV, $V_{fast} \approx 2.6 - 3.1 \times 10^6$ m/s
- Reactors would have higher field, fusion $\alpha$'s and $V_{fast}/V_{Alfvén} > 1$

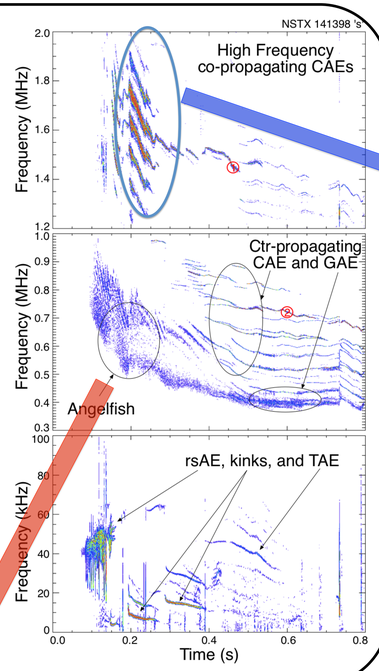


$R_0$ = 0.86 m
a = 0.68 m
$B_0$ = 0.3-0.55 T
$I_p$ ≤ 1.2 MA
$\beta_{tor}$ ≤ 40%
$n_e \leq 10 \times 10^{19}$/m$^3$




## Neutral Beams excite a broad spectrum of Alfvén waves

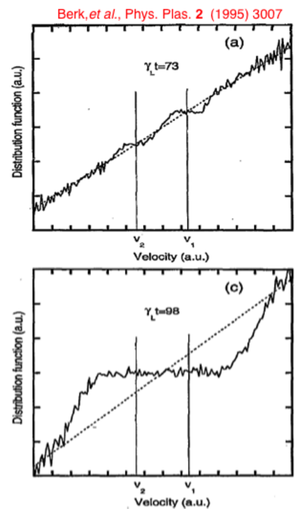
- The formation of long-lived fast-ion phase space structures can be responsible for the saturation of energetic particle driven modes, mode frequency chirping, and multi-mode avalanches.
- In 'real' systems, these long-lived particle resonances can be complicated as particle's orbits move them in three dimensions, and the parallel velocity varies due to mirroring.
- The low aspect ratio, high field mirror ratios of spherical tokamaks exacerbate those problems.
- Many fast-ion driven modes on NSTX are excited through a Doppler-shifted cyclotron resonance, which further complicates long lived resonances.
- Here we present experimental evidence for long-lived phase space structures supporting modes excited through a Doppler-shifted cyclotron resonance.




## Multiple modes can have fast ion resonances that overlap in phase space, enhancing fast ion transport

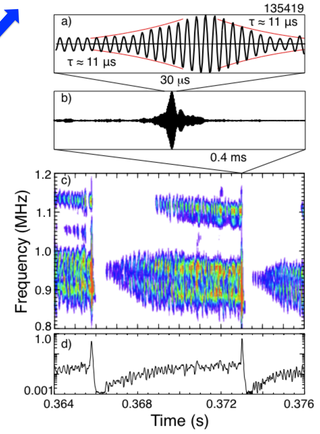
- Simulations with a simple bump-on-tail model have demonstrated principle.
- Fast ions become 'trapped' in the wave, forming the flat region in phase space.
- The flat region becomes larger as the wave amplitude increases.

Berk, *et al.*, Phys. Plas. **2** (1995) 3007

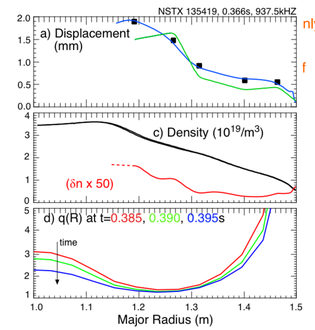



## GAE show avalanching behavior with short bursts of high amplitude, followed by quiescent period

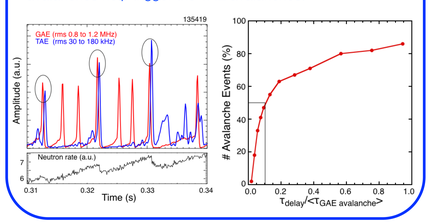
- Pre-avalanche and avalanche are from multiple, counter-propagating, Global Alfvén Eigenmodes.



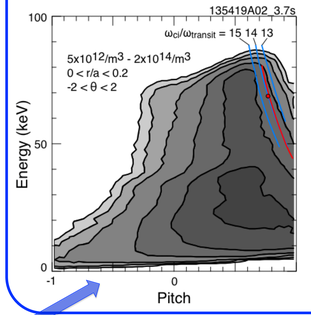

- Mode displacement profile from reflectometer array; black points are reflectometer data, green curve is effective displacement, blue curve is reflectometer response simulated with green displacement.
- Peaking towards axis consistent with identification as GAE.




- GAE redistribute fast ions, triggering marginally stable TAE avalanches.
- Statistical analysis shows strong evidence that the GAE avalanches help trigger the TAE avalanches.



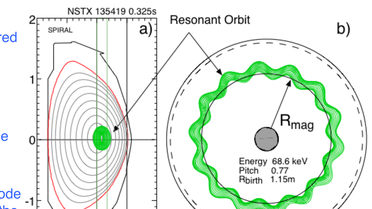

## Conditions for Doppler-shifted cyclotron resonance




- Contours of the fast ion distribution function near the magnetic axis (mode location) calculated in TRANSP are shown at right.
- The red curve indicates approximate parameters of fast ions resonant with mode.
- The blue curves indicate locations of fast ions whose toroidal transit time is resonant with the cyclotron frequency, $\omega_{ci} = N\ \omega_{transit}$.
- Low field, tight aspect ratio makes cyclotron frequency low, transit frequency higher than conventional aspect ratio tokamak.
- Better chance for fast ions to stay in resonance with mode over orbit.

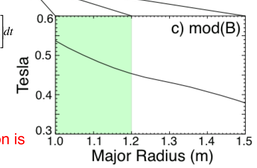
## Resonant fast ions have *relatively* low ratio of $\omega_{transit}$ to $\omega_{ci}$

- Full orbit calculation of fast ion orbit with SPIRAL code for parameters indicated by red dot in fast ion distribution shown above.
- This particular fast ion has resonance between transit and cyclotron frequencies.
- Orbit is also close to stagnation point, very little variation of mod(B) over orbit, thus little variation of cyclotron frequency.
- The approximate range of phase variation between the fast-ion resonance and the mode can be estimated from the dependence of the parallel velocity on pitch and mod(B) and the variation of the cycltron frequency with mod (B) over the fast-ion orbit:



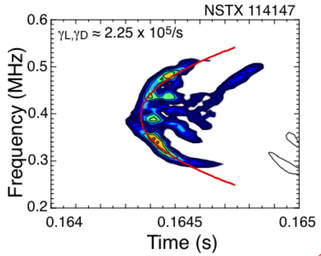

$$\delta\phi(t) \approx \int \left[\omega + < k_{\parallel} V_{B\parallel} > (1 - \frac{\varepsilon}{2}\frac{1-p^2}{p^2}\cos(\omega_T t)) - < \omega_{ci} > (1 + \varepsilon\cos(\omega_T t))\right] dt$$

$$\delta\phi(t) \approx \frac{< k_{\parallel} V_{B\parallel} >}{\omega_T}\frac{\varepsilon}{2}\frac{1-p^2}{p^2}\sin(\omega_T t) + \frac{< \omega_{ci} >}{\omega_T}\varepsilon\sin(\omega_T t)$$

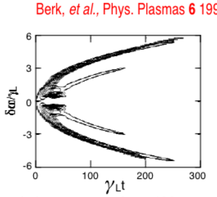



For this fast ion parameters, the phase variation is ≈ ±65° over the fast ion orbit.

## Bifurcation of mode into upward and downward frequency chirps indication of hole-clump formation



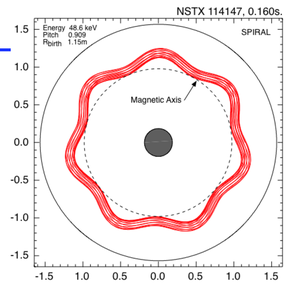

Berk, *et al.*, Phys. Plasmas **6** 1999

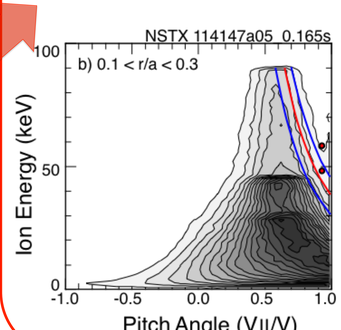



- The fast ions remain in resonance for ≈ 400 $\mu$s, or approximately 600 cyclotron periods, 70 toroidal transits.
- Some fast ions might go out of resonance where mode amplitude was weak, then come back in, conserving phase, but nearby populations would lose the phase and weaken drive.

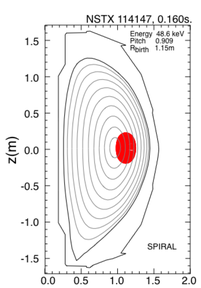
## At the very low field in this shot, ≈ 2.2 kG, stagnant' fast ions have low resonance between cyclotron and transit frequencies

- The mode is a counter-propagating CAE mode with n=5.
- Blue curves show fast ions satisfying an approximate expression for the resonance condition at the extremes of the up and down frequency chirps, the red curve at the onset frequency.
- The black dot indicates the location of the fast ion orbit calculated with the full-orbit SPIRAL code.
- The panel at right shows the 'plan' view of the fast ion orbit, parameters chosen for a resonance between the transit and cyclotron frequencies.




- "Good" Angelfish were best found at the lowest toroidal fields, consistent with ease of maintaining Doppler-shifted cycltron resonance.
- The fast ion orbit is nearly stagnant; very little variation in major radius, thus mod(B) is nearly constant.




## Long-lived fast-ion phase space structures are seen for modes excited through a Doppler-shifted cyclotron resonance in NSTX

- Global Alfvén Eigenmode avalanches lasting ≈ 100 cyclotron periods redistribute fast ions in phase space, triggering marginally stable TAE avalanches.
- Upward and downward frequency chirping Angelfish suggest the formation of hole-clump pairs lasting for ≈ 600 cyclotron periods.
- Fast ions resonant with the mode tend to be near stagnation orbits – orbits that experience relatively little field variation.
- These fast ions can apparently remain trapped in the wavefield due to modest variation in ion cyclotron frequency over ion orbit, and relatively small ratio of the ion gyrofrequency to the transit frequency:
  - $\omega_{ci}/\omega_{transit} \approx 14$ for GAE avalanches
  - $\omega_{ci}/\omega_{transit} \approx 7$ for low field Angelfish