NSTX

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

# Fast Ion Transport due to TAE Avalanches

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TTF-Energetic Particles
Annapolis, Maryland, April 10-13, 2012

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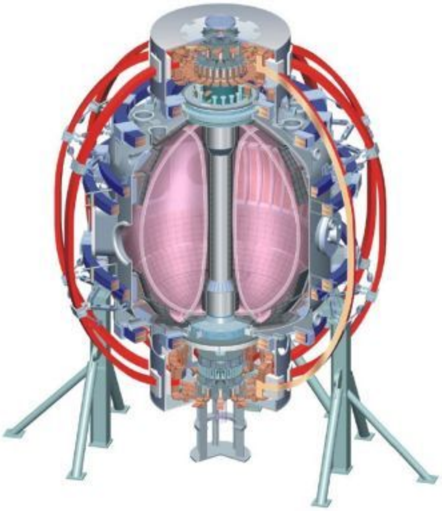

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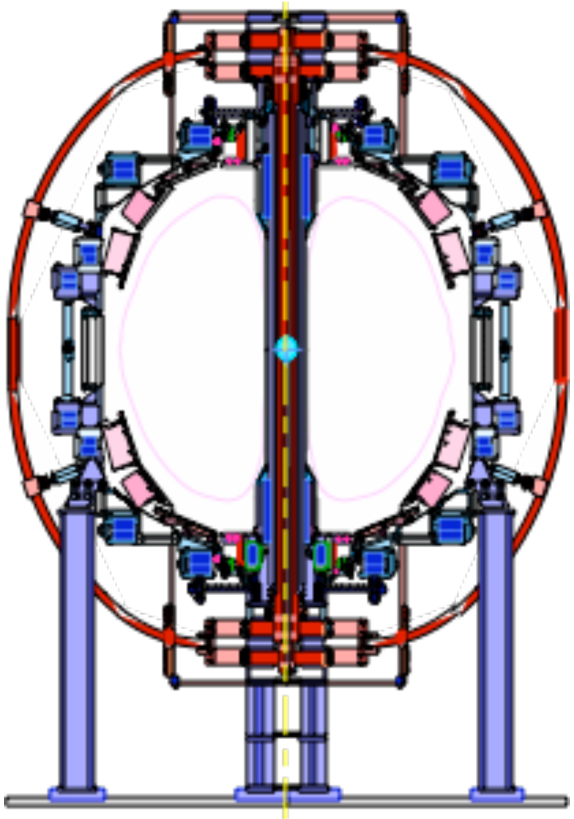
# *How far can NOVA – ORBIT modeling of fast ion transport during, e.g., TAE bursts be pushed?*

- Neutron rate drops seen with fishbone-like modes, strong TAE bursts (avalanches) on NSTX.
- An earlier study of TAE avalanches in L-mode plasmas found promising agreement, here we extend to H-modes.
- TAE structure can be modeled with NOVA code, but mode amplitude and frequency chirping are introduced empirically.
- Fast ion transport is presently modeled with the guiding center code (ORBIT), but full-orbit simulations (SPIRAL*) will be used to validate the guiding-center calculations.
- Surprising result is that a drop in fast-ion energy, rather than ion losses, is responsible for most of the neutron rate drop.

**** G. Kramer***

# *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 and fusion* $\alpha$*'s with* $V_\alpha/V_{Alfvén} > 1$



$R_0 = 0.86$ m

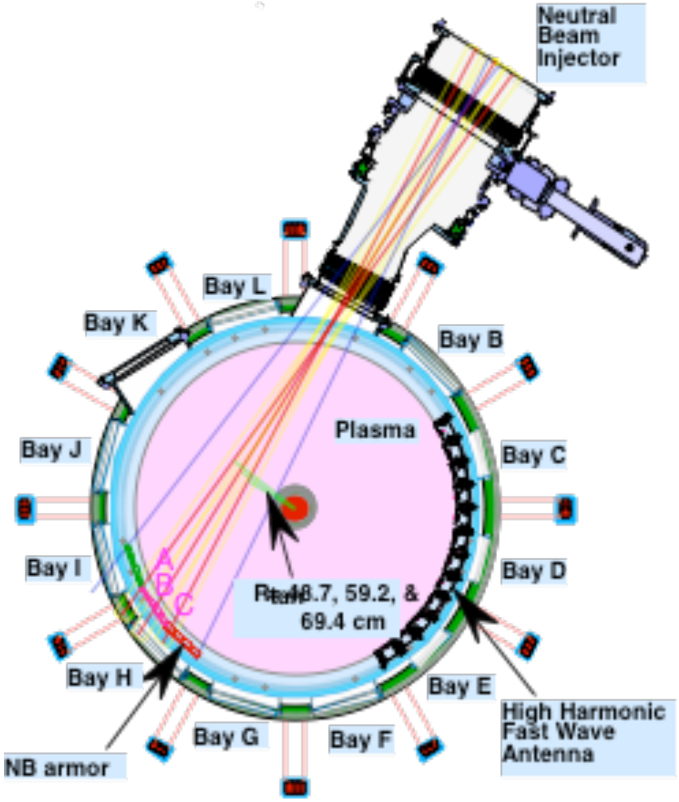
$a = 0.68$ m

$B_0 = 0.3\text{-}0.55$ T

$I_p \leq 1.2$ MA

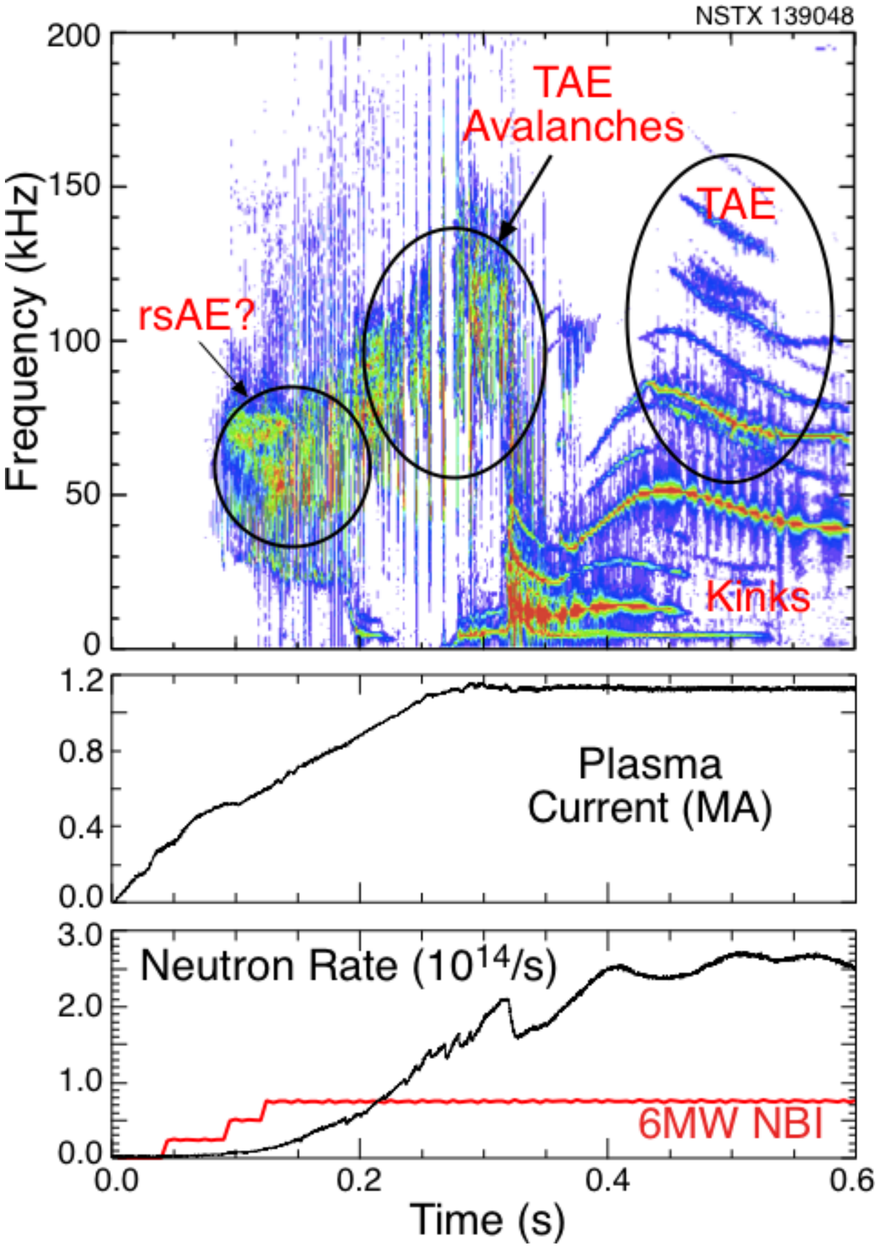
$\beta_{tor} \leq 40\%$

$n_e \leq 10 \times 10^{19}/m^3$

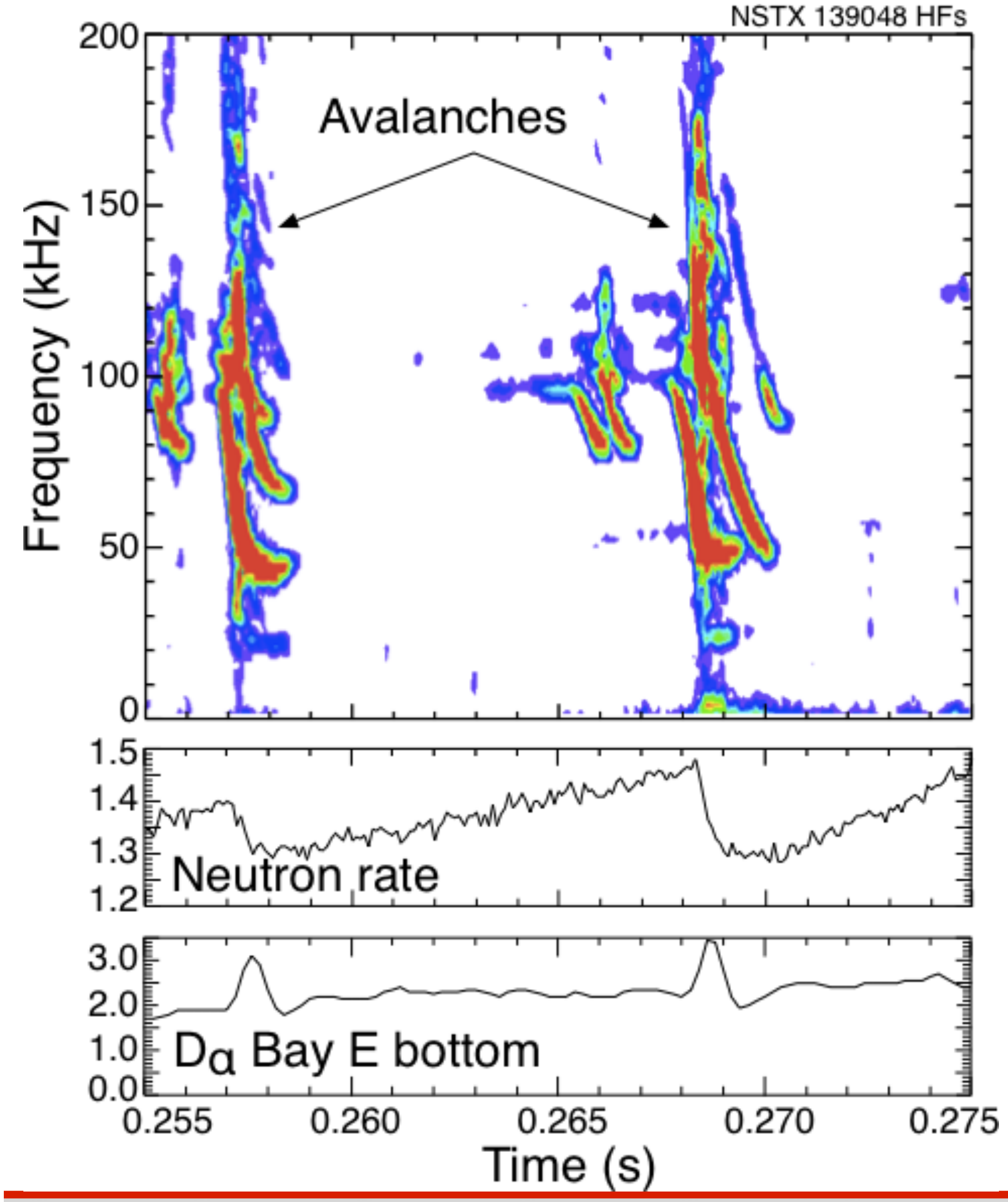


# Large $\beta_{fast}$, $V_{fast}/V_{Alvén}$ gives NSTX many energetic particle driven modes

- *Modes, possibly rsAE, typical during current ramp.*
- *TAE and/or TAE avalanches around start time of current flattop;*
  - *low density, high fast ion $\beta$.*
- *Neutron rate drops correlated with avalanches.*
- *Later, at higher density, lower amplitude TAE activity.*
- *Dominant TAE have toroidal mode numbers $2 < n < 6$.*
- *Low frequency 'kinks' may be related to "long-lived" modes.*



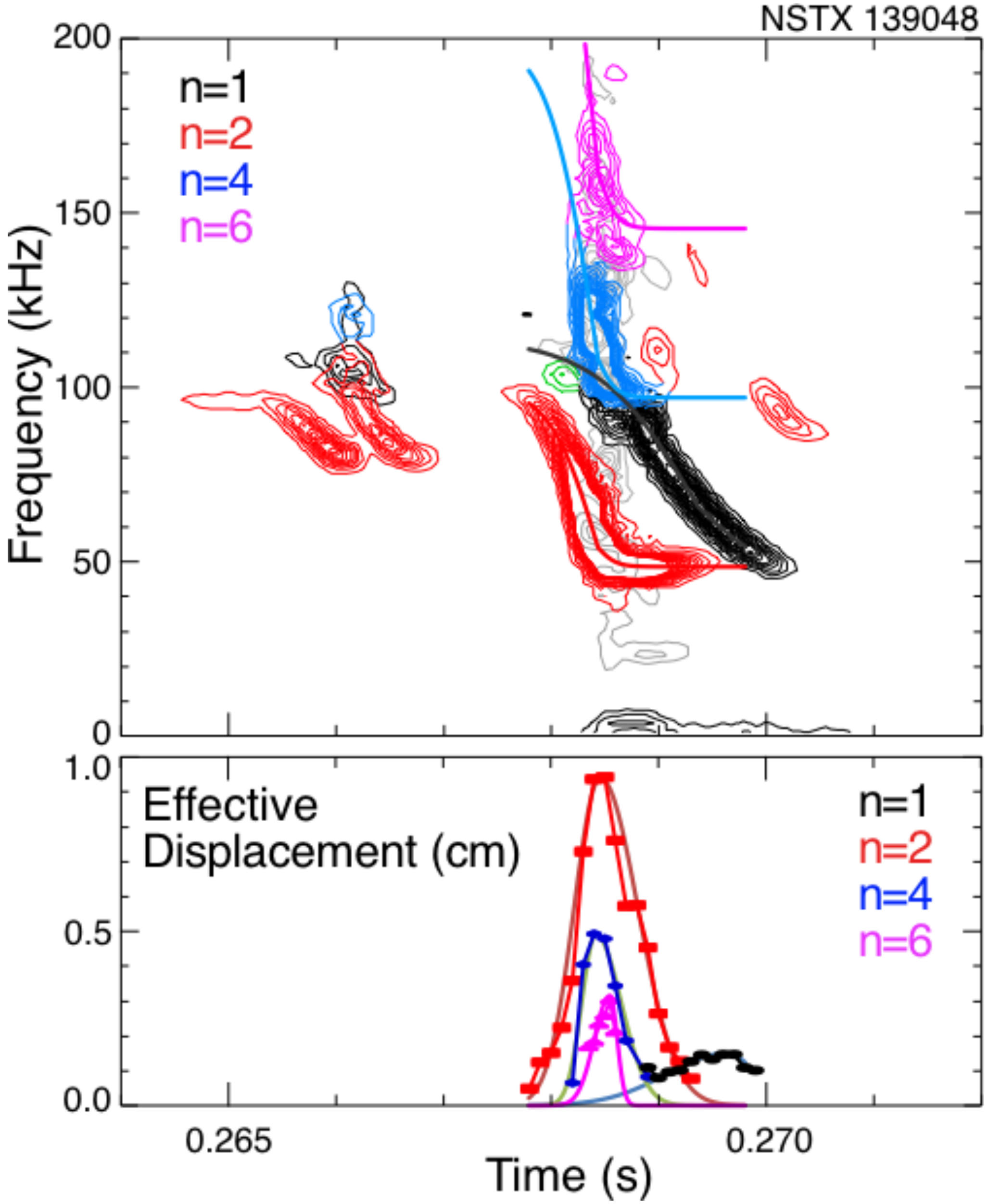
# *Expanded spectrogram shows multiple modes appear during final avalanche burst*



- *Drops in the neutron rate are correlated with each avalanche event.*
- *Typical drops are in the range from 5% to 15%.*
- *Avalanche bursts are characterized by larger amplitude (x10), more modes, and stronger, longer frequency chirps.*
- *Neutron drops often correlated with $D_\alpha$ bursts, consistent with lost fast ions striking limiter tiles.*

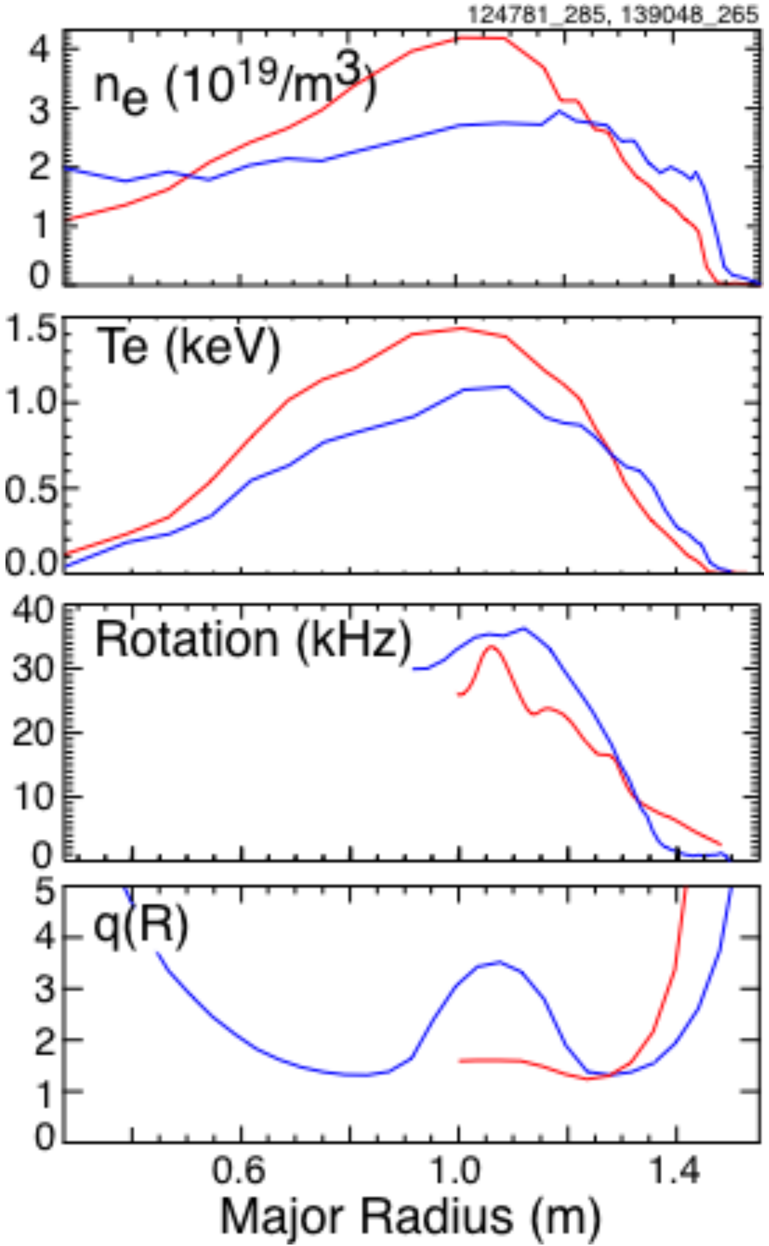
# Multiple modes appear during final, approximately 1ms long, avalanche burst

- *Mode numbers are indicated by the color of the contours.*
- *Mode amplitudes, profiles, fast ion losses are measured with reflectometer array.*
- *Avalanche bursts chirp; modeling has found only modest enhancement of losses correlated with frequency chirping.*



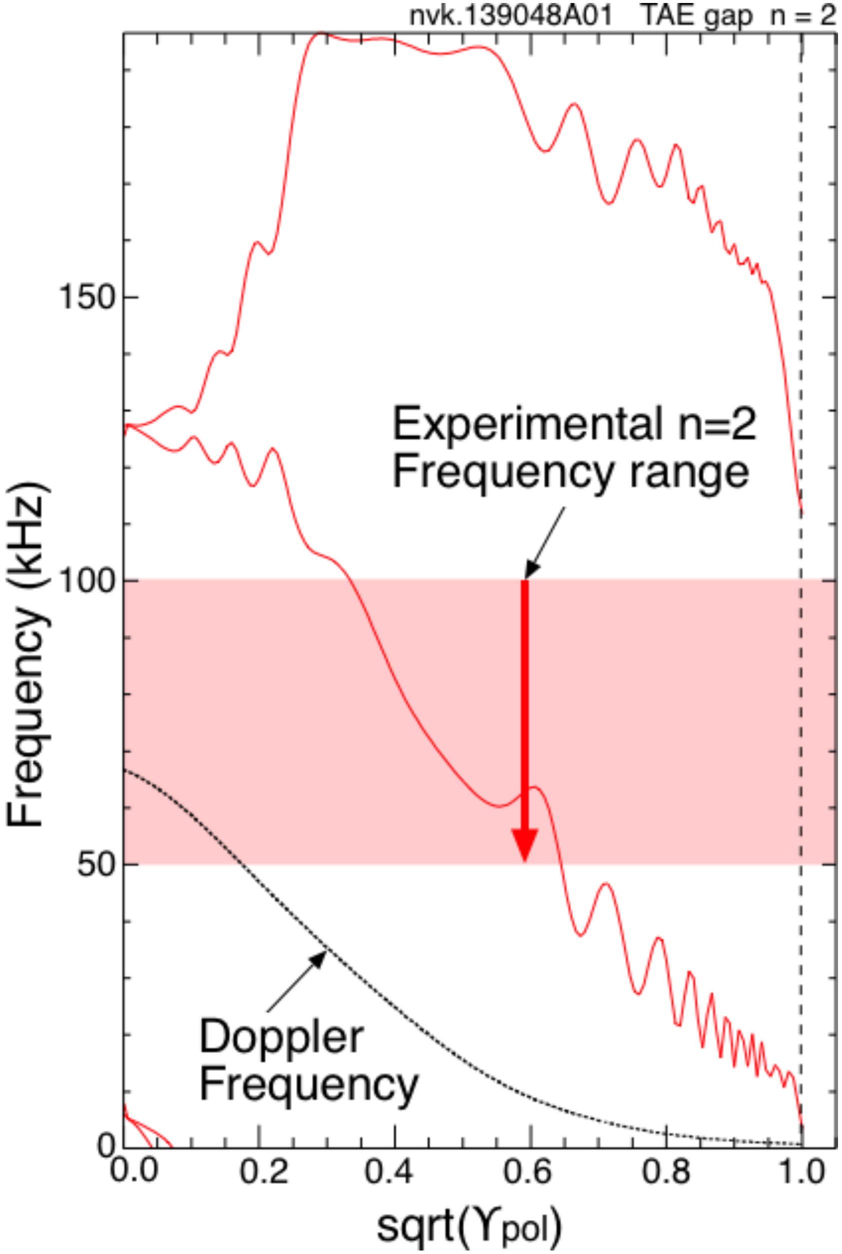
# Profiles at time of analysis for H-mode (**blue**) and L-mode (**red**) avalanches are similar

- *H-mode with weakly peaked density profile chosen for reflectometer data.*
- *Avalanches correlated with low density; perhaps* $\beta_{fast}$ *larger.*
- *Strong rotation goes with beam heating; TAE frequency can be near zero on axis.*
- *TAE avalanches also seem correlated with reversed-shear q-profiles.*

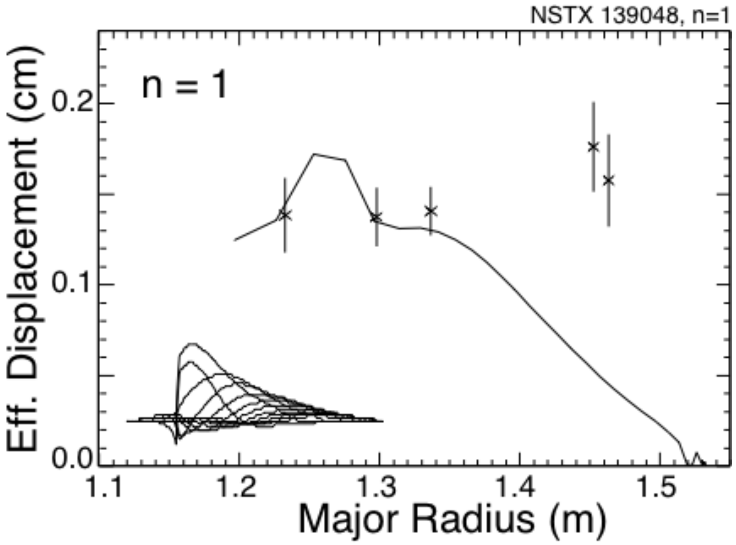


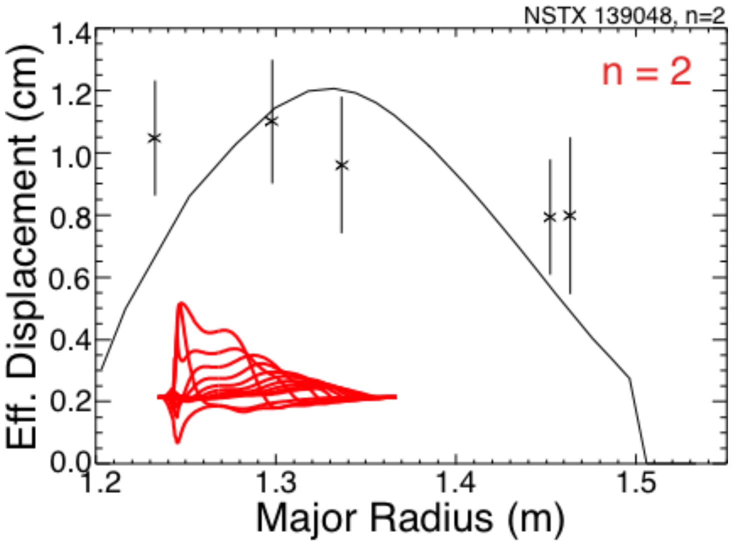
# *TAE typically intersect continuum, partly due to strong toroidal rotation*

- *Low aspect ratio gives broad TAE gap, but near core, aspect ratio isn't low and gaps can be closed.*
- *Strong toroidal rotation distorts continuum, closing gaps near axis.*
- *Separatrix (large $q_a$) tends to close gap at plasma edge.*
- *Frequency chirping moves modes further out of gap – no effect has been clearly seen in mode profile measurements.*
- *Experiments are looking for KAW waves with High-k, BES.*

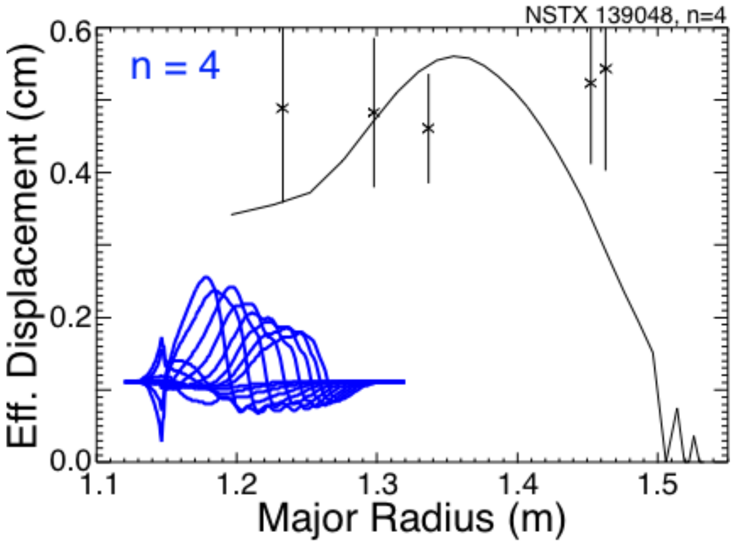


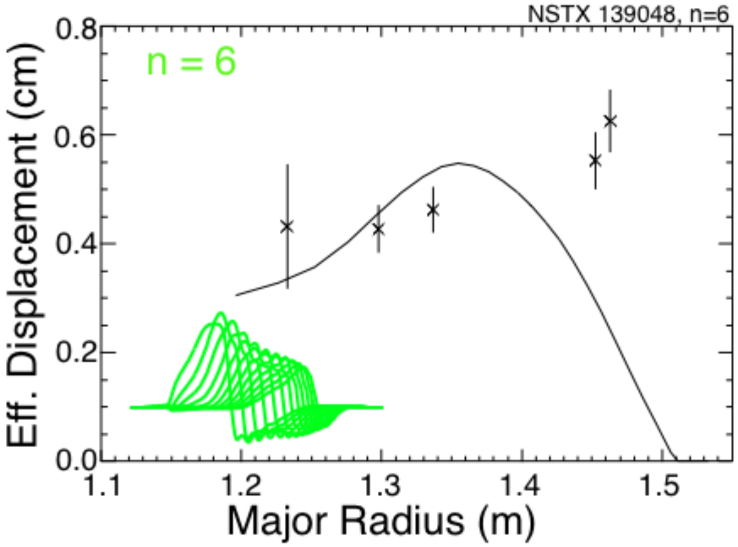
# Eigenmodes for each toroidal mode are found with NOVA, best fit to frequency, profile is chosen





- *Reasonable fits found for each observed mode.*
- *Black curves are simulated reflectometer responses for NOVA eigenmodes (insets).*
- *Compression included.*

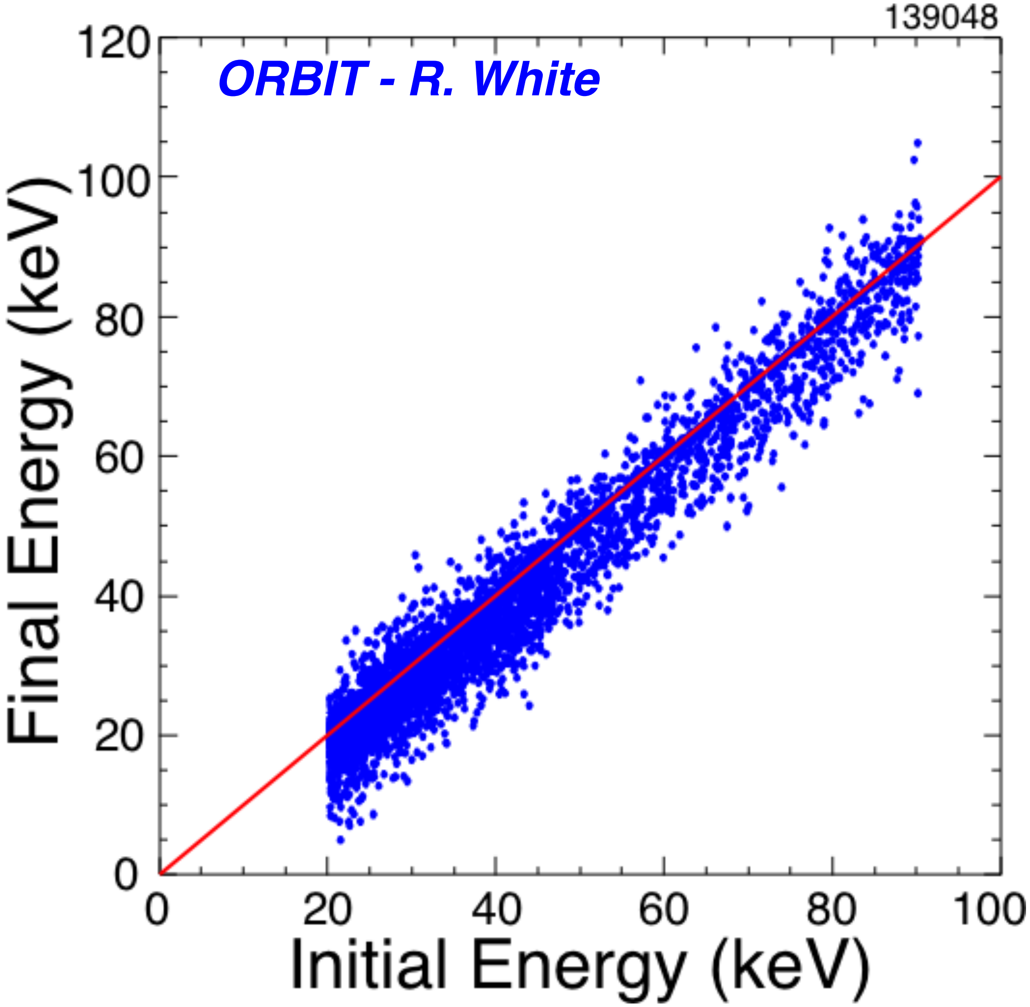




# *In presence of multiple modes, with disparate frequencies, beam ions are scattered in energy*

- *Energy diffusion present at all radii, pitch angles and energies.*
- *Redistribution in energy appears diffusive, as if from stochastic scattering.*
- *Fast ions can gain or lose energy w/multiple modes.*
- *Net ≈ 6% drop in fast ion energy, ≈ 11% drop in beam-target neutron rate:*
  - $S \sim \Sigma_N \sigma(E)v$

$\rho_L/R \approx 0.06 - 0.14$



# *For low amplitudes, neutron rate drop is mostly from fast ion energy loss, not loss of fast ions.*

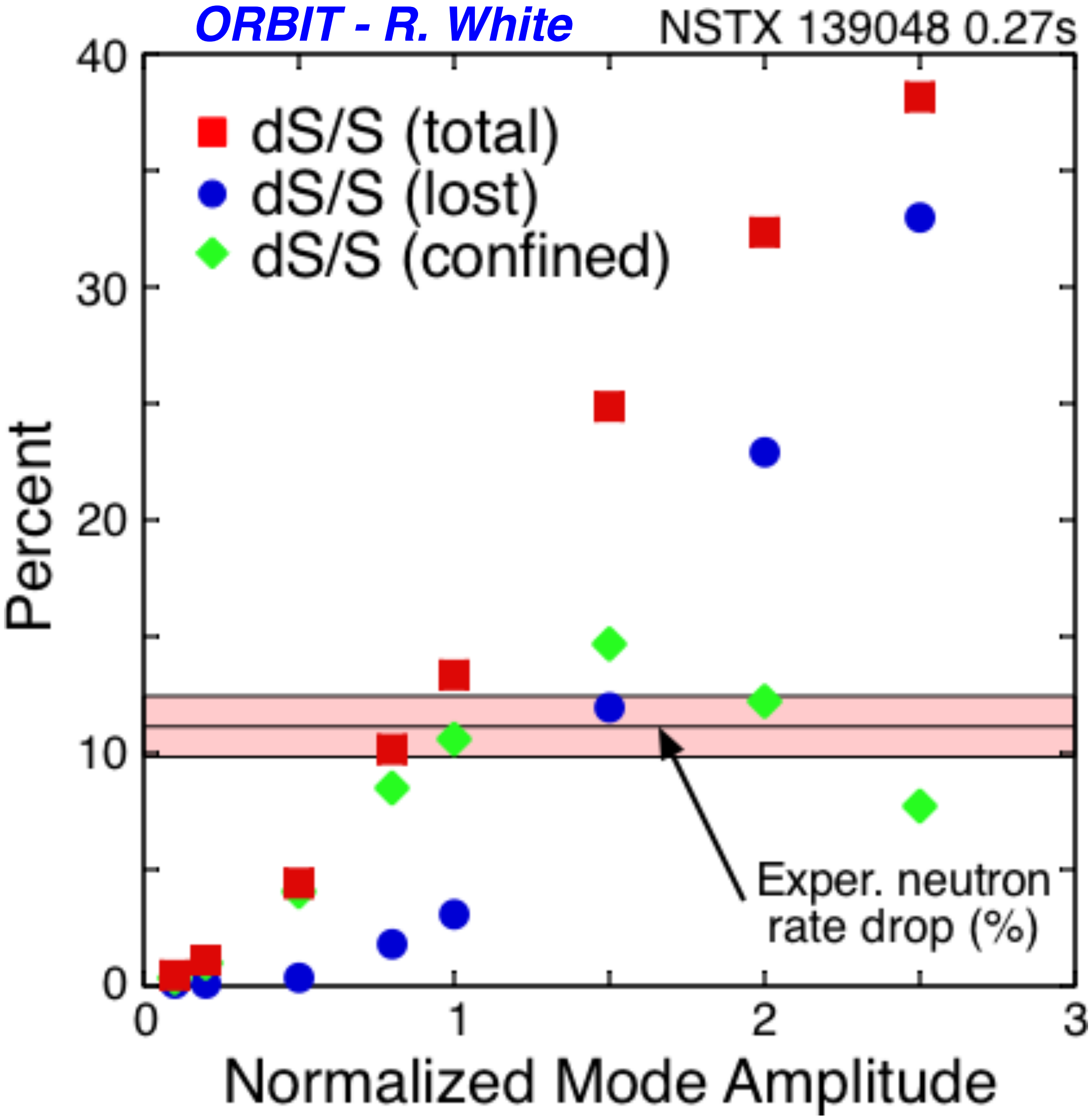
- *Neutron drop estimated by assuming flat density, beam-target dominant source of neutrons.*

- *Fast ion losses have threshold for onset of losses, consistent with avalanche model.*

- *Cooling of fast ion population appears nearly linear with mode amplitude – no stochastic threshold?*

***(Assuming Flat Density Profile!)***

***ORBIT - R. White***

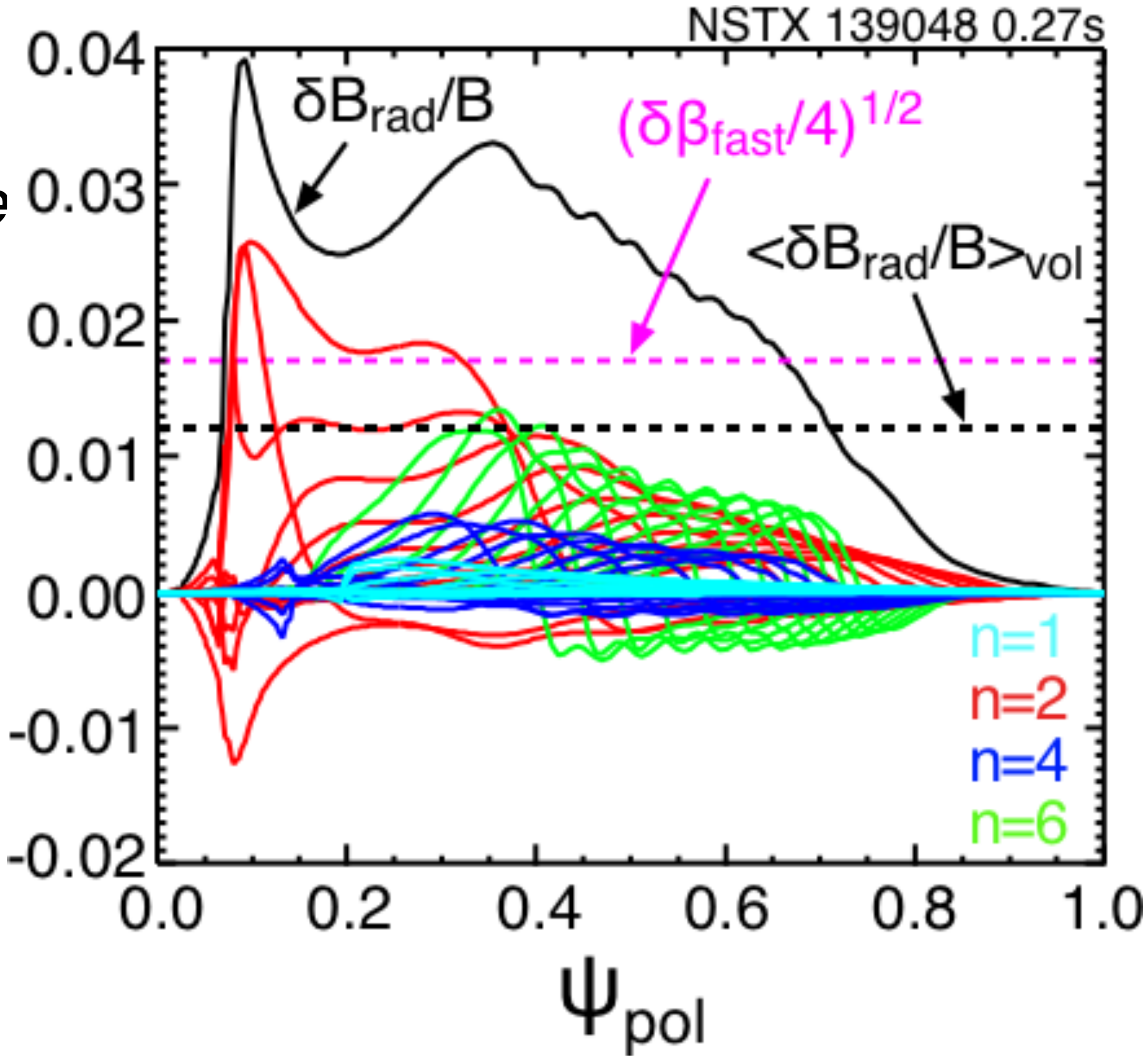


# *Energy taken from beam ion population comparable to energy in Alfvén waves*

- *Magnetic fluctuation amplitude profile from NOVA is used to estimate energy in TAE;*

$\delta E_{TAE}/B^2 \approx 2x2x(\delta B_{rad}/B)^2$.

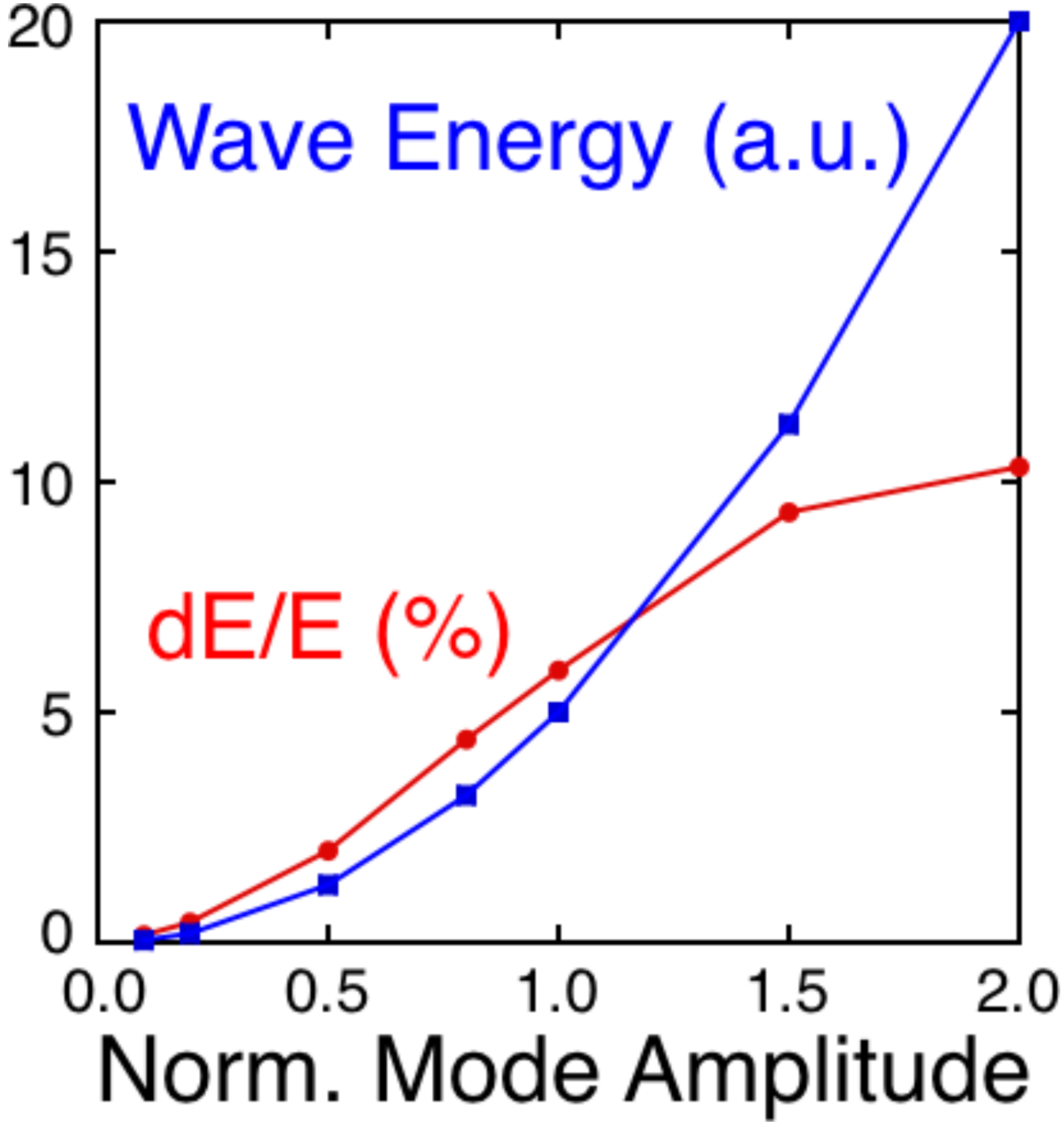
- *Dashed line indicates change in $\beta_{fast}$ estimated from ORBIT simulation.*
- *Very few fast ions were actually lost.*
- *Could be a form of '$\alpha$-channeling'*?*



* N.J. Fisch, J-R. Rax, Phys. Rev. Lett. 69 (1992) 612

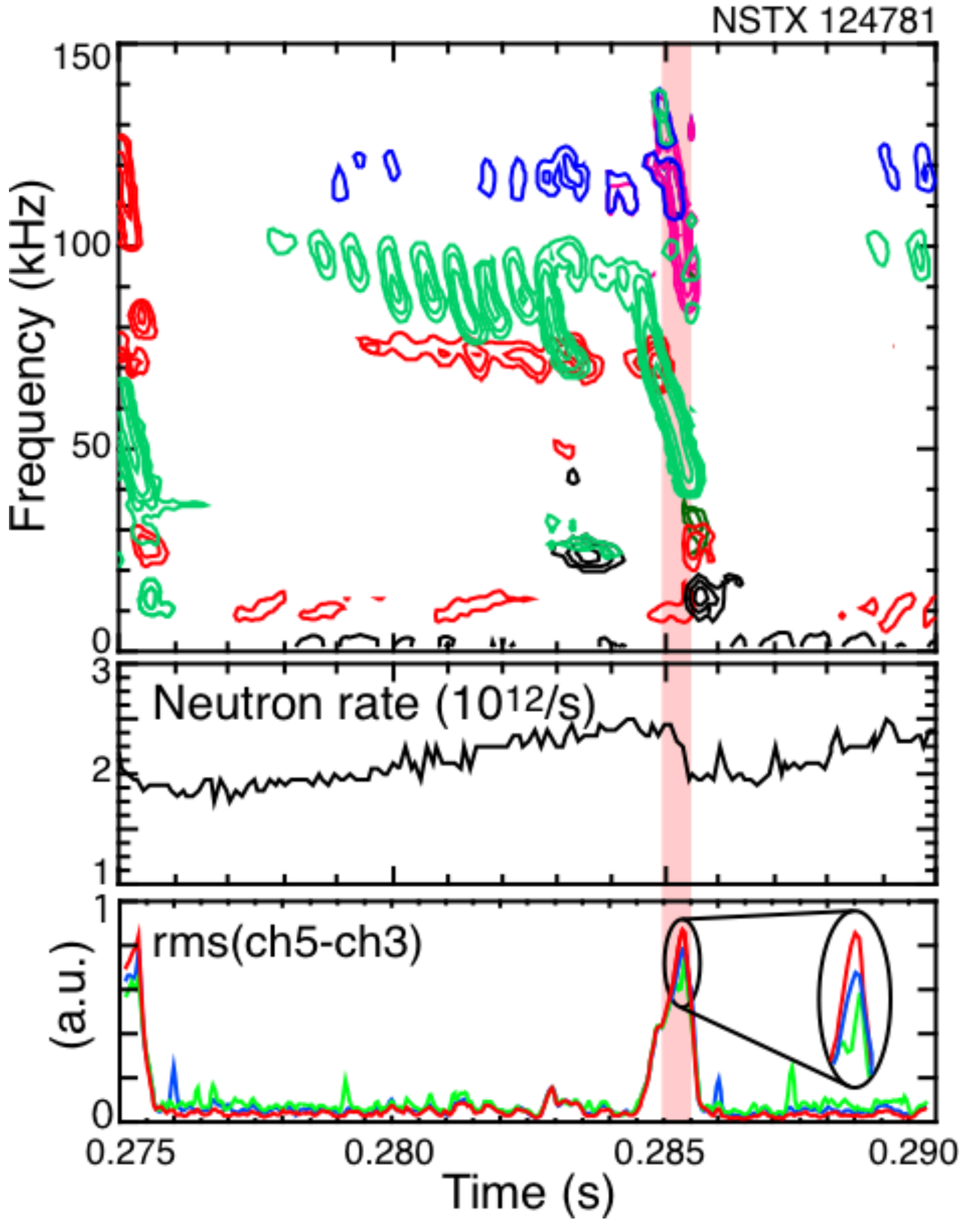
# *ORBIT Modeling demonstrates potential approach for predicting saturation amplitude, avalanches.*

- *Wave energy increases quadratically with mode amplitude, but energy loss from fast ions saturates.*
- *Time-dependent ORBIT simulation could predict mode growth, saturation and decay.*
- *Fast ion losses have threshold for onset of losses, consistent with avalanche model.*



# *L-mode TAE avalanche studied previously showed similar characteristics*

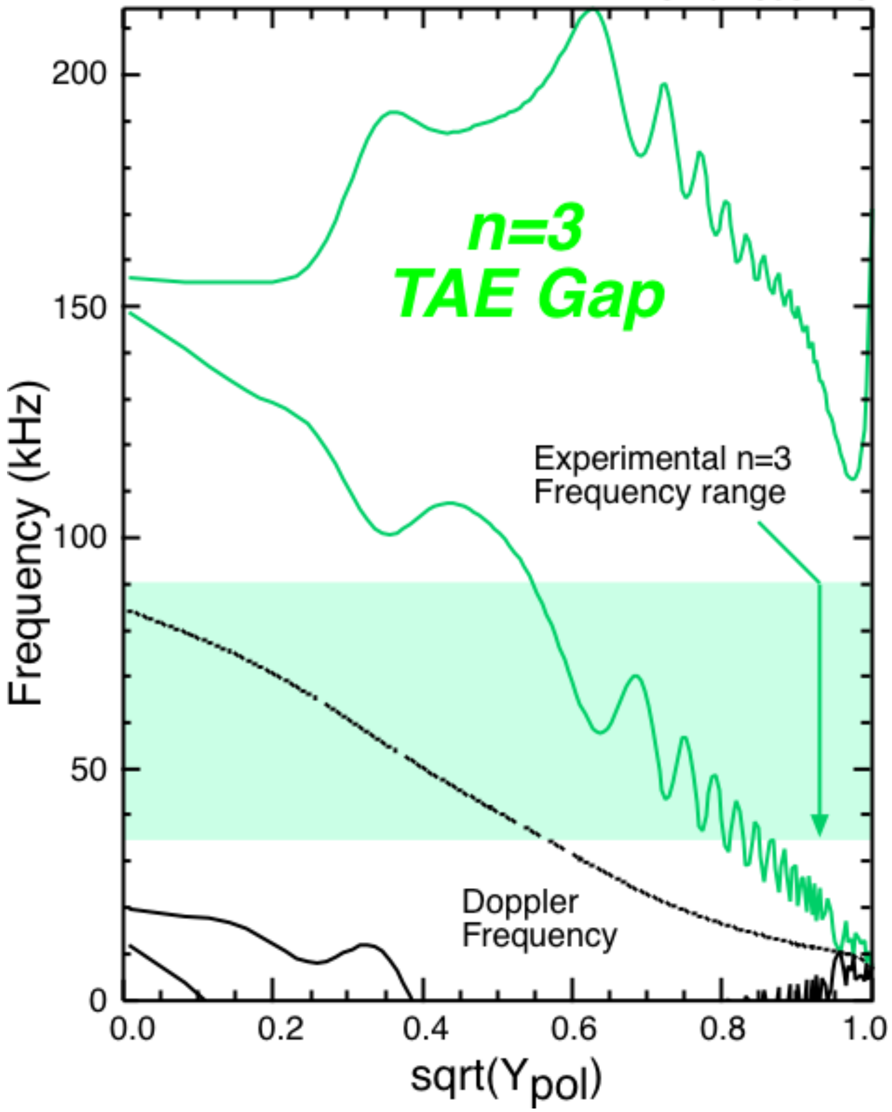
- *Mode numbers are indicated by the color of the contours.*
- *Mode amplitudes, profiles, fast ion losses are measured with reflectometer array.*
- *Avalanche bursts chirp; modeling has found only modest enhancement of losses correlated with frequency chirping.*



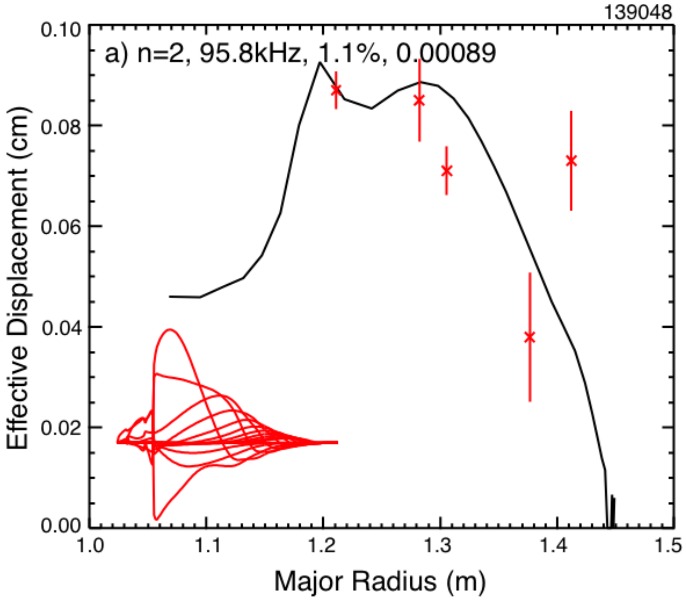
# *Qualitatively, TAE gaps similar in L-mode and H-mode; toroidal rotation important*

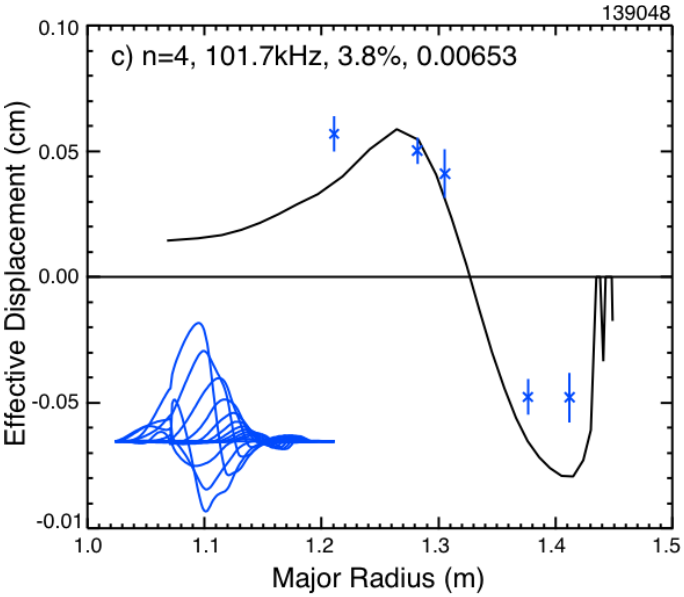
- *Low aspect ratio gives broad TAE gap, but near core, aspect ratio isn't low and gaps can be closed.*
- *Strong toroidal rotation distorts continuum, closing gaps near axis.*
- *Modes intersect continuum both L & H mode cases.*
- *Separatrix (large $q_a$) tends to close gap at plasma edge – NOVA needs finite q(a).*
- *Limited plasmas similar.*

**G. Kramer - NOVA**

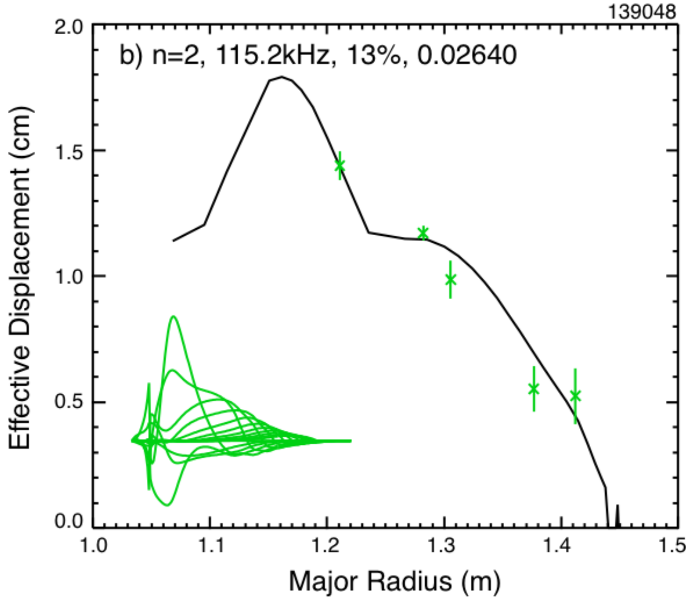


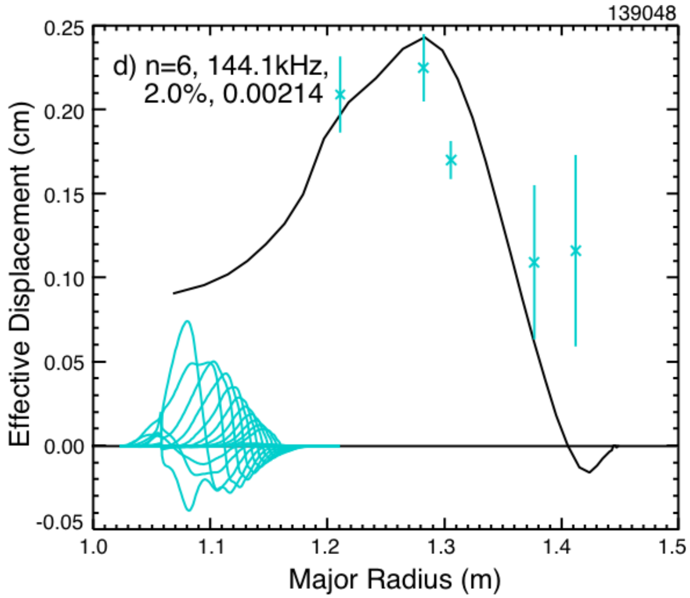
# *Eigenmodes for each toroidal mode are found with NOVA, best fit to frequency, profile is chosen*





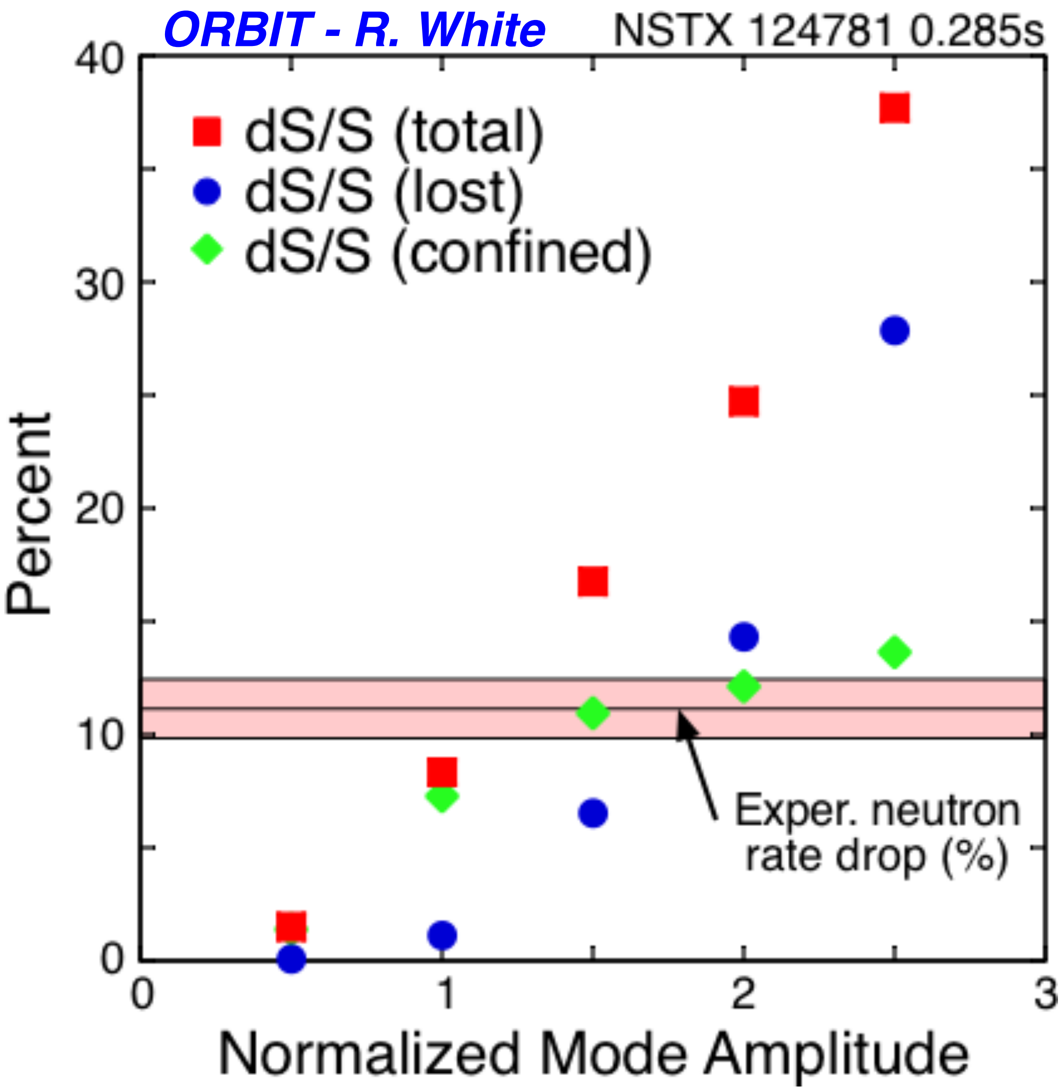
- *Somewhat better fits than H-mode case.*
- *Black curves are simulated reflectometer responses for NOVA eigenmodes (insets).*
- *Compression included.*





# *Neutron drop from fast-ion cooling less important in this L-mode case?*

- *Neutron drop estimated by assuming flat density, beam-target dominant source of neutrons.*
- *The secondary modes relatively weaker in this case.*
- *Cooling of fast ion population appears nearly linear with mode amplitude – no stochastic threshold?*



# *Modeling fast ion transport with linear ideal code, NOVA, and guiding center code, ORBIT, promising*

- *Bulk of neutron rate drop due to loss of energy from fast ion population,*
  - *Comparable to wave energy in mode + losses from damping?*
- *More work needs to be done on validating ORBIT calculations,*
  - *What is affect on current drive, heating profiles?*
  - *Will full-orbit calculations be necessary in low-field STs?*
- *Can ORBIT-NOVA be used to simulate avalanches?*
  - *Predict mode amplitudes in NSTX-U?*
- *Do we really capture the important effects of resonances from multiple modes, with non-self consistent simulations?*

# *Assumptions and approximations in NOVA-ORBIT modeling*

- *Calculate equilibrium, map kinetic data, run TRANSP to get fast ion density.*
- *Re-compute equilibrium with NOVA, but no separatrix.*
- *Scale ideal NOVA eigenfunctions using reflectometer data.*
- *Use experimental frequency evolution in ORBIT – may not properly track phase-space perturbations.*
- *Use unperturbed fast ion distribution from TRANSP to start ORBIT run; won't have history of fast ion phase space perturbations from previous TAE and other *AE and MHD.*
- *ORBIT calculates guiding-center orbits:*
  - *maybe fewer than 10 cyclotron periods from inboard to outboard*
  - *Larmor radius comparable to TAE structures, equilibrium scales.*