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Toroidal Alfvén Eigenmode Avalanches in NSTX*

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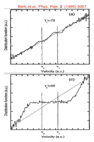
Validated Models for Fast Ion Redistribution Needed for Design of Next Generation Devices

- Next step devices (ITER, NHTX, ST-CTF, etc) will have large, super-Alfvénic fast ion populations to excite instabilities (energetic particle modes, Alfvén modes).
- Fast-ion driven instabilities cause diffusion and loss of fast ions increasing ignition thresholds.
- Intense, transient fast-ion losses can damage PFCs.
- Fast-ion redistribution affects beam-driven current profiles in AT operating regimes.
- Small ρ^* means transport is more likely through interaction of multiple modes.
- Understanding non-linear collective behavior is key to predictions for ITER.

Multi-mode interaction of Toroidal Alfvén Eignmodes can greatly enhance fast ion transport



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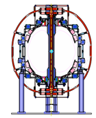
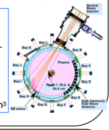
- Large amplitude modes overlap in fast-ion phase-space.
- Interaction accesses more free energy; resulting in stronger modes, destabilizes new modes; more fast ion transport.
- Interaction of multiple modes can also move ions further in phase-space, again enhancing losses.
- TAE avalanches have strong mode bursts consisting of multiple modes.
- TAE have multiple resonances, more complex physics.

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.
- Typical beam injection energy 60 - 100 kV, $V_{fast} \approx 2.6 - 3.1 \times 10^6$ m/s
- Reactors would have higher field, fusion α's and $V_{fast}/V_{Alfvén} > 1$

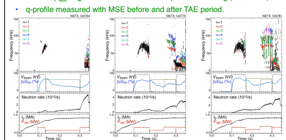


$R_0 = 0.86$ m
$a = 0.68$ m
$B_0 = 0.3\text{-}0.55$ T
$I_p \leq 1.2$ MA
$\beta_{tor} \leq 40\%$
$n_e \leq 10 \times 10^{19}/m^3$

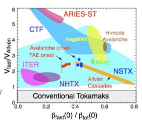


TAE Avalanches identified and threshold scaling explored relative to ITER/NHTX/CTF

- Scan of β_{fast} begins below TAE threshold up to Avalanching (in L-mode).
- q-profile measured with MSE before and after TAE period.



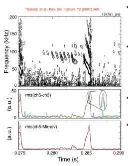
- Cartoon at right illustrates NSTX operational space, as well as projected operational regimes for ITER, ST-CTF and ARIES-ST.
- Also shown are parameters where typical fast particle modes (FPMs) have been studied.
- Conventional beam heated tokamaks typically operate with $V_{fast}/V_{Alfven} < 1$.
- CTF in avalanche regime motivates studies of fast ion redistribution.
- Higher ρ^* of NSTX compensated by higher beam beta



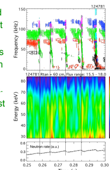
Cartoon is simplified; there are other dependencies.

Mode amplitudes, fast ion losses are measured during Avalanche events

- Avalanches onset with 70 keV beam ions.
- Amplitude at time of avalanche much greater than earlier bursts.
- Relative amplitude tracks well through multiple modes, suggesting fixed mode structure...
- ...except toward end of last burst, which suggests mode is becoming more core-localized.

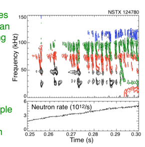


- Neutron drops correlated with D-alpha spikes - fast ions are lost.
- Neutral particle analyzers (NPA) measure spectrum of charge-exchanged neutral ions from plasma.
- Transport appears largest at lower energies.
- Chirping may play important role in fast ion loss.

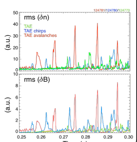


Bursting, Chirping and Multiple Modes Seen with Higher Energy Beams, but Weak Transport

- Internal (core) mode amplitude is 2 - 3 times larger in amplitude than in TAE or TAE-chirping cases.
- Magnetic fluctuation amplitudes closer in TAE-chirping and avalanche cases.
- Strong chirping, multiple modes, similar amplitude, no neutron drops or quiescent periods.



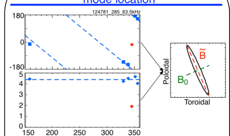
- 90 kV beams rather than 70 kV, and more tangential injection.
- Very weak effect on neutron rate.
- Weak or no correlation with NPA signals.
- Perhaps resonant with lower energy fast ions?



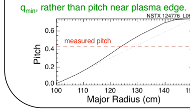
Non-linear physics of Alfvénic and Energetic Particle modes is research priority

- Fast ion transport and losses enhanced by Alfvénic or Energetic Particle modes can:
  - Change beam-driven current profiles,
  - Raise ignition threshold or damage PFCs on ITER.
- Non-linear physics necessary to understand saturation amplitudes, frequency chirps and fast ion transport.
- NSTX experiments simulated by linear and non-linear codes.
  - NOVA and ORBIT: Non-linear effects simulated by incorporating experimental data such as mode amplitude and frequency evolution, triggering of multiple modes.
  - M3D-k: Some non-linear effects described here (enhanced fast ion transport from multiple modes, larger amplitude, frequency chirps) have been studied with M3D-k*.

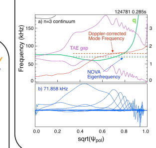
External δB pitch indicates mode location



- Pitch of magnetic fluctuations is measured with an array of coils.
- Within uncertainty, phase/amplitude relation of poloidal and toroidal fluctuations consistent with expected shear-type Alfvén mode.
- However, pitch of fluctuating magnetic field matches equilibrium field pitch near radius of q_{min}, rather than pitch near plasma edge.



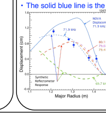
Mode frequency sits in TAE gap, but multiple modes



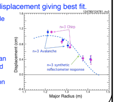
- Magenta curves show β-corrected Alfvén continuum.
  - Solid red line shows n = 3 mode frequency in local plasma frame.
- Green curve shows q-profile
- Poloidal harmonics of one n=3 TAE mode (blue).
- Multiple eigenmodes found, Which eigenmode is right?
- Is linear eigenfunction shape good match to experiment?
- Are non-linear effects during mode growth significant?

"Best fit" of experimental mode profile is to NOVA eigenmode at 72 kHz

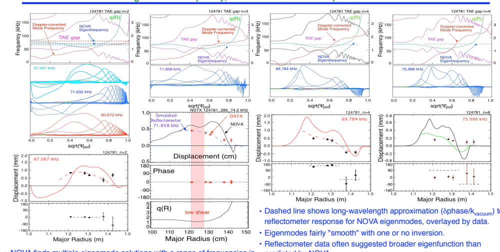
- Synthetic reflectometer responses are shown for the five TAE-like eigenmodes at frequencies of ≈ 69 kHz, 72 kHz and three at ≈ 80 kHz.
- In blue are shown the five reflectometer measurements of mode amplitude, interpreted by simple "mirror" model.
- The solid blue line is the NOVA outboard displacement giving best fit.



Measured mode structures are very similar for n=3 chirp and avalanche. Eigenmodes can be scaled, used in ORBIT to simulate fast-ion losses.



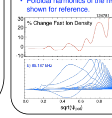
NOVA simulations good fit to frequency, radial structure and amplitude for 4 dominant modes



- NOVA finds multiple eigenmode solutions with a range of frequencies in the TAE gap, even more that enter the continuum.
- Effect of sheared rotation is not included in NOVA analysis, will change gap structure and character of eigenmodes.
- Some eigenmodes show resemblance to rsAE or Cascade modes.
- Dashed line shows long-wavelength approximation (δphase/k_{vacuum}) to reflectometer response for NOVA eigenmodes, overlayed by data.
- Eigenmodes fairly "smooth" with one or no inversion.
- Reflectometer data often suggested broader eigenfunction than predicted by NOVA.
- Red curve shows local, Doppler corrected mode frequency.
- Comparison of Doppler-corrected mode frequency with NOVA eigenfrequency, and comparison of radial eigenmode profile with reflectometer data is used to pick best match.

ORBIT simulations show redistribution of fast ions

- Fast ions are redistributed towards edge in ORBIT run simulating Avalanche event, red.
- Poloidal harmonics of the n=3 eigenmode are shown for reference.



- NOVA doesn't support separatrix, edge q is approximate.
- Conducting wall boundary reduces mode amplitude at edge.

Avalanche modes identified as TAE by comparison with NOVA simulations

- Threshold for Avalanche onset found in scan from quiescent to Avalanching conditions.
- Avalanche onset at ≈ 30% higher fast-ion-ß than TAE threshold.
- Plasma equilibrium reconstructed using MSE data; these avalanches are in reversed-shear plasma:
  - TAE coupling to Cascade modes(rsAE) may be important.
- Avalanches have 1) long, low amplitude period followed by strong increase in amplitude, 2) large, downward frequency chirp and 3) multiple modes.
- Mode radial structure measured with 5-channel reflectometer; localization deduced from magnetic polarization measurement consistent with reflectometer data.
- Fast-ion loss indicated by neutron drops (D_α bursts) and redistribution measured with NPA.
- Fast-ions lost down to 30 keV (< half of full beam energy).
- Mode structure shows small changes during 1 ms frequency chirp.
- NOVA simulations find reasonably good agreement in mode structure and eigenmode frequency (pre-chirp).
- Fast-ion losses are being simulated using measured mode amplitudes to scale NOVA eigenfunctions.