Measurements and Modeling of Neutral Beam Ion Loss During TAE Avalanches in NSTX

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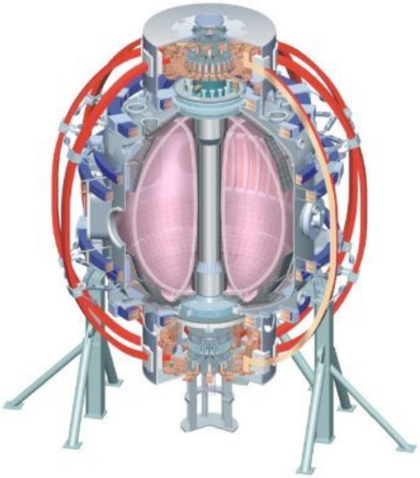

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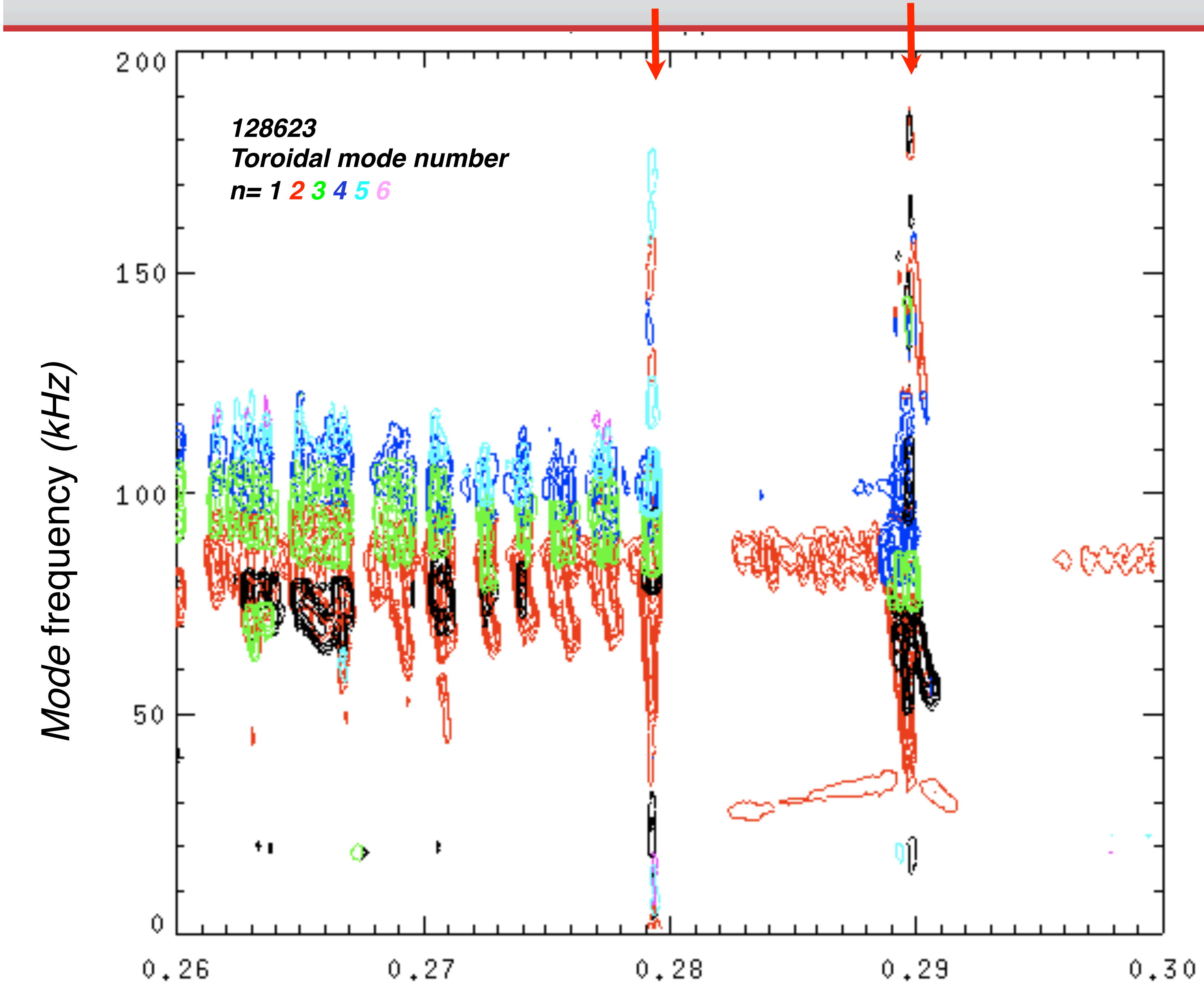
TAEs and avalanches

- Toroidal Alfvén eigenmodes (TAEs) are weakly damped Alfvén waves in a toroidal plasma, often driven by ions whose velocity approaches the Alfvén velocity (or a fraction thereof)
- A TAE is characterized by a toroidal mode number, n, and may occur steadily or intermittently
- A burst in which several TAEs of differing n occur is termed an avalanche
- Avalanches produce drops in the neutron rate and losses of beam ions are sometimes observed concurrent with an avalanche

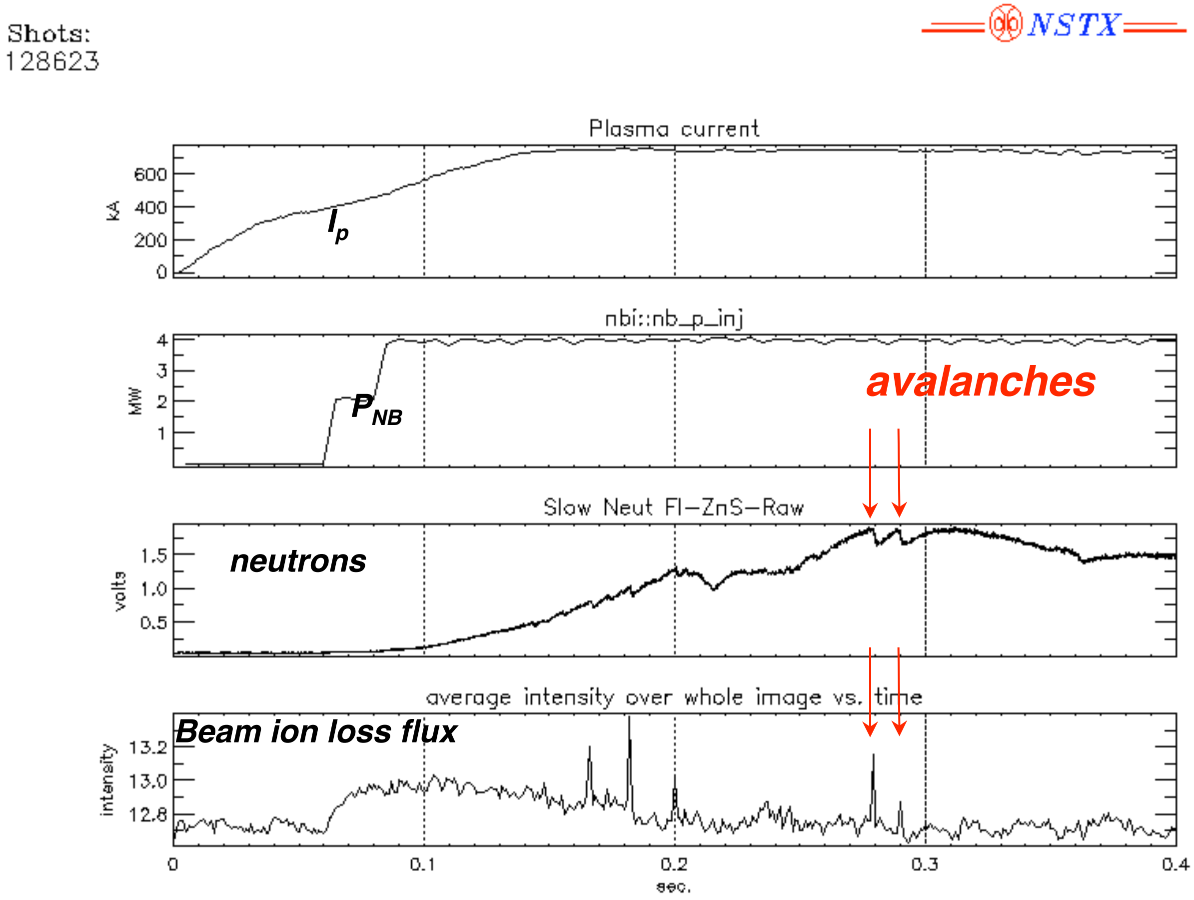
Typical avalanche in NSTX shows multiple n on Mirnovs



TAEs appear as burst

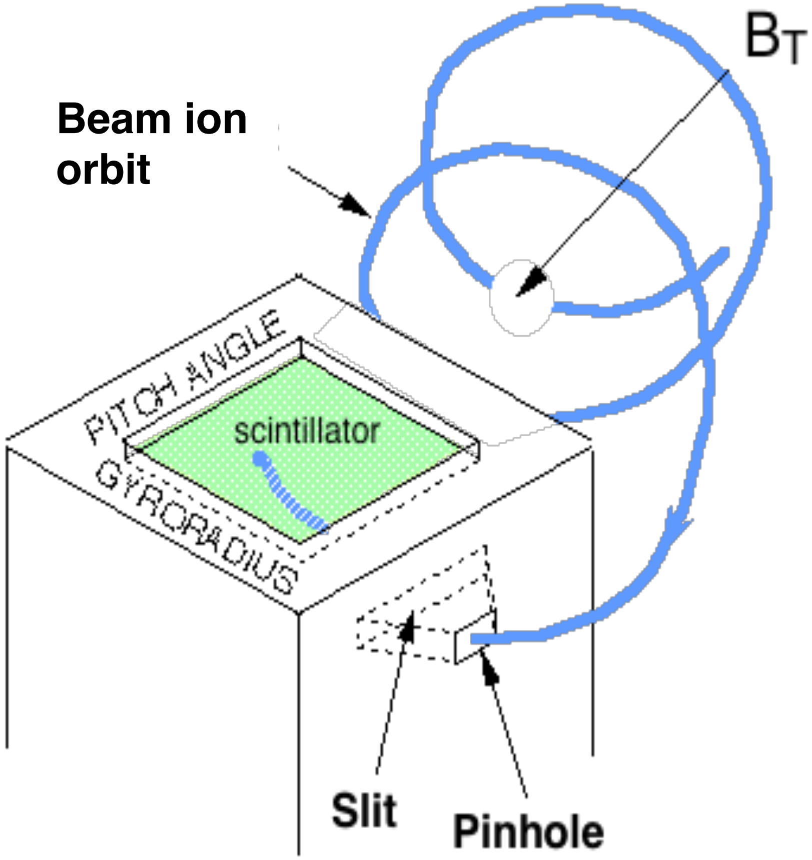
Beam ion re-distribution stabilizes modes for a time

Avalanches can cause drop in neutron rate and burst of loss



- But, loss is not observed with every avalanche
- Pitch angle distributions of loss during avalanches sometimes differ

Any avalanche induced beam ion loss is measured with scintillator probe



Scintillator probe:

Combination of aperture geometry & **B** acts as magnetic spectrometer

Fast video camera captures luminosity pattern on scintillator as function of time

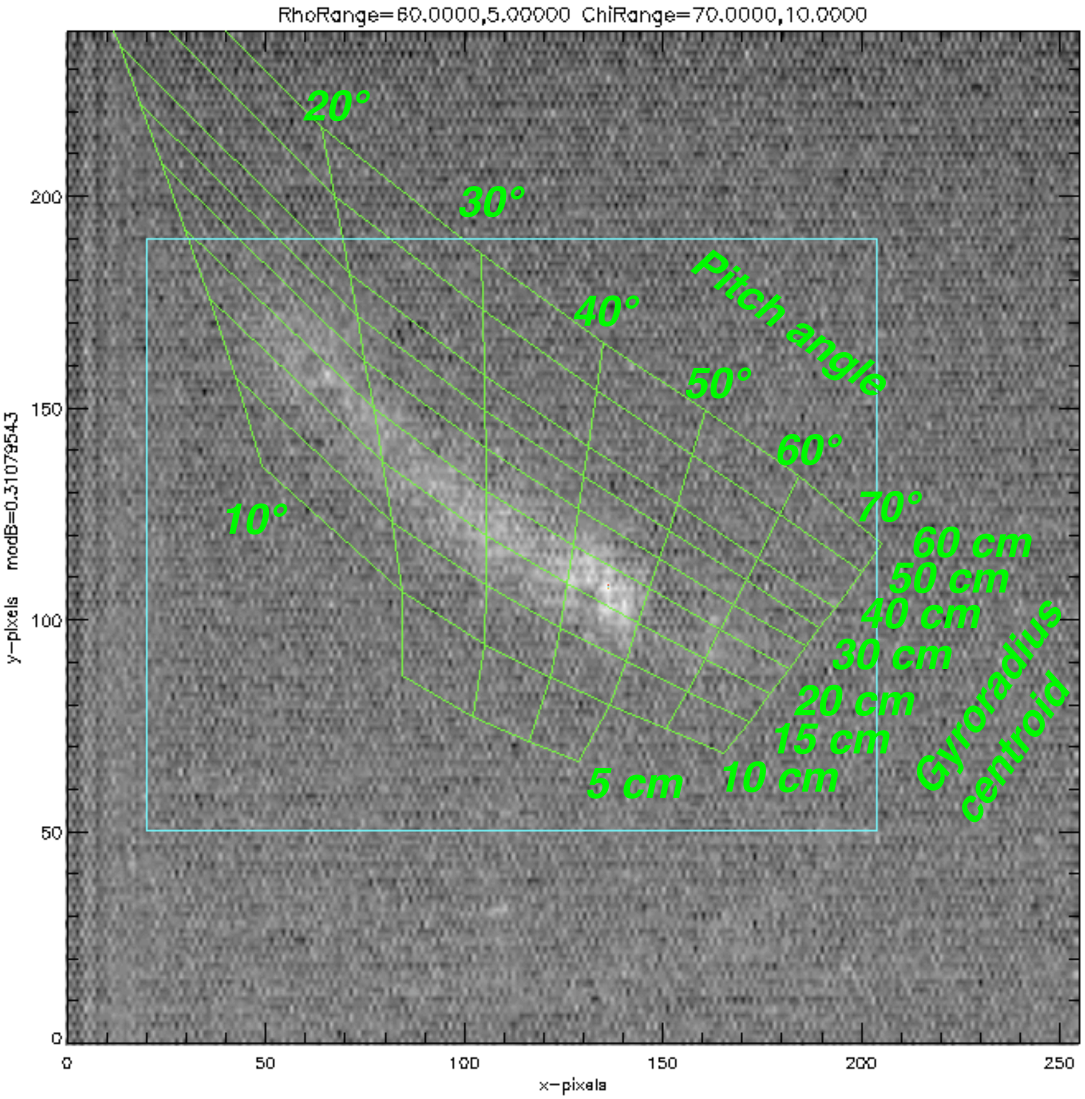
$\Gamma_{\text{loss}}(\rho, \chi, t)$

NSTX probe:

5 cm ≤ ρ ≤60 cm

15° ≤ χ ≤ 80°

Avalanche induced loss often occurs over a wide range of pitch angles



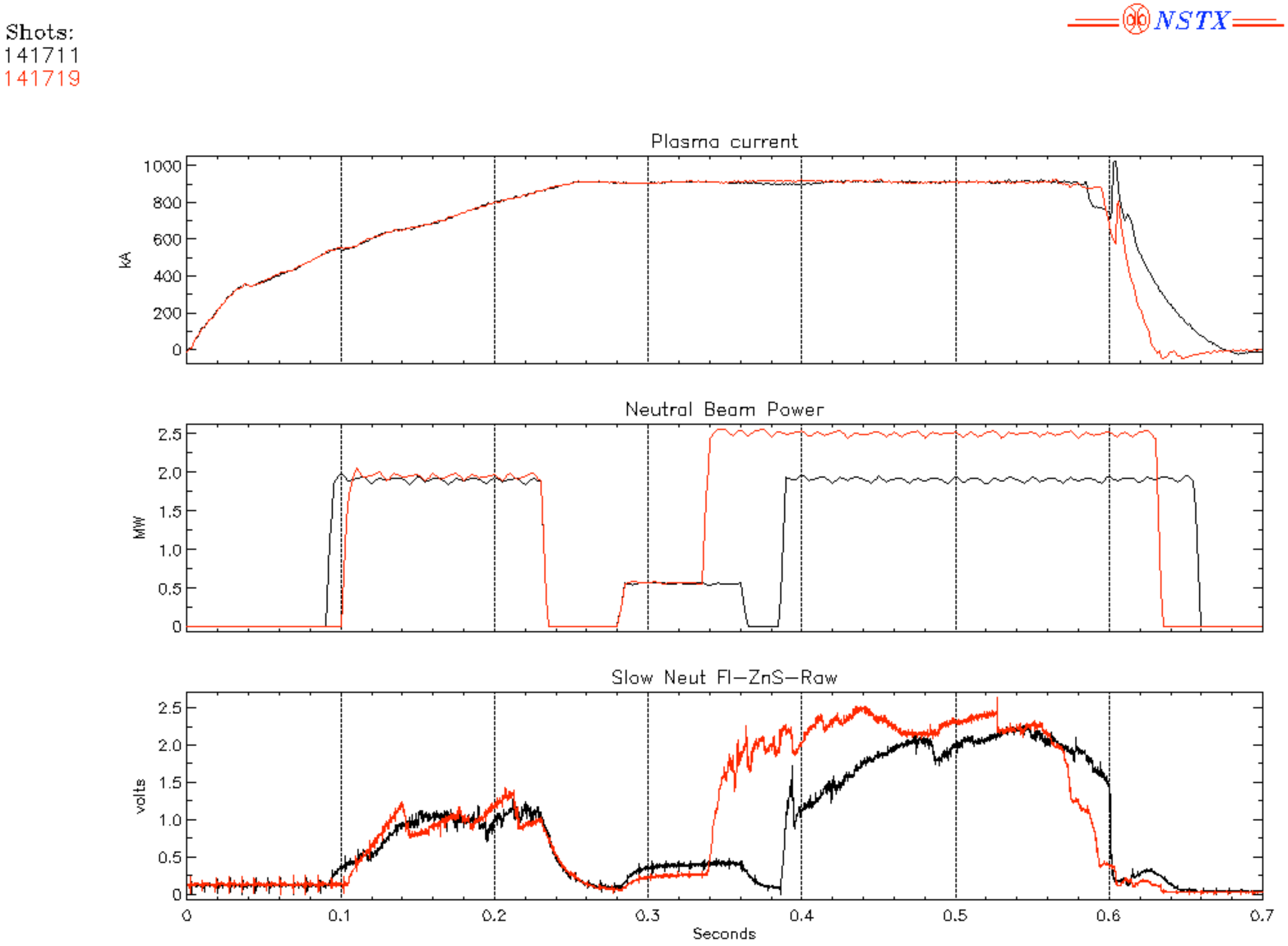
128623, 290 ms

- Interpreted as beam ion phase space being stochastized by multiple modes

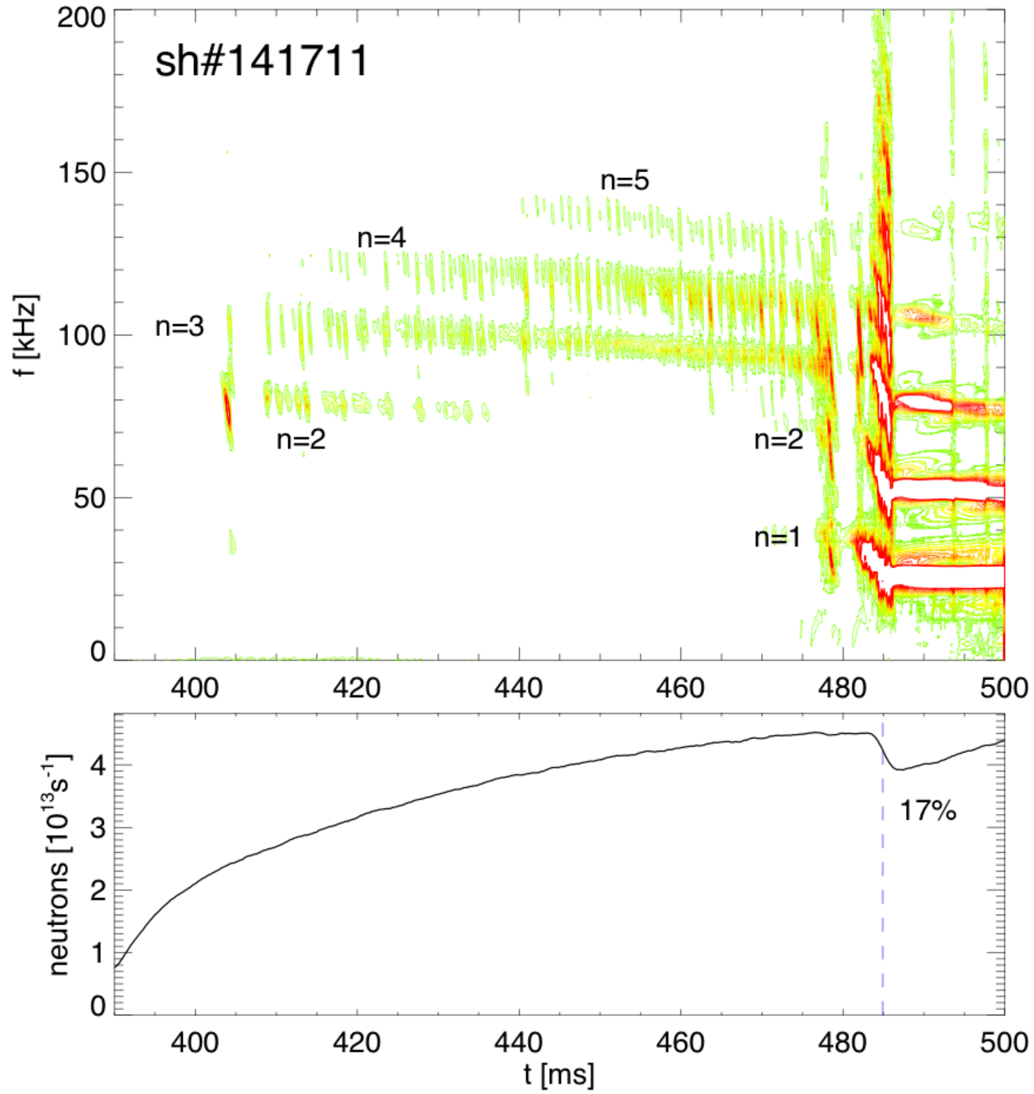
Goal: compare measured and modeled lost ion pitch angle distributions

- Measured distribution recorded by scintillator probe
- Loss distribution modeled by guiding center orbit code that incorporates:
  - Measured TAE n numbers, frequencies (Mirnov coils)
  - Radial mode structures and amplitudes (multichannel microwave reflectometer data coupled to NOVA-K calculations of eigenmodes)
  - Beam ion distribution function from TRANSP

Compare 2 similar discharges with avalanches to draw inferences about conditions when fast ions may be lost

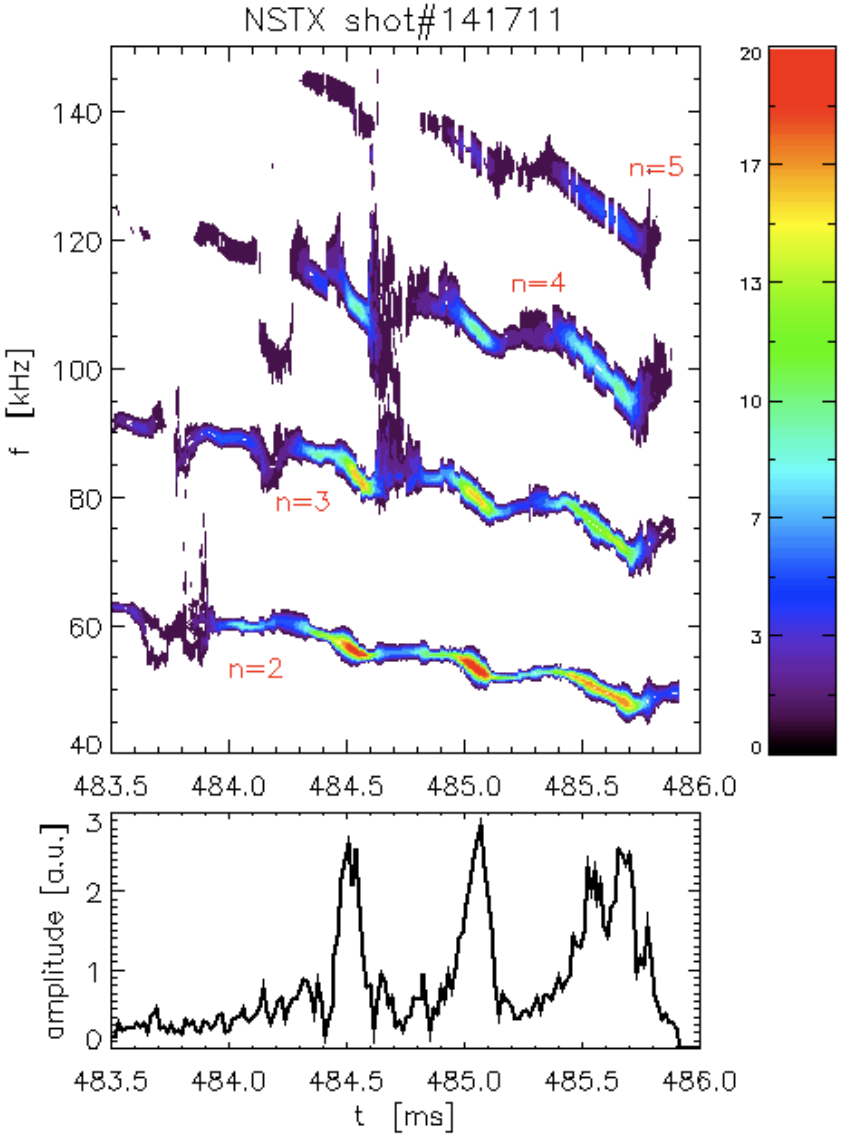


Example avalanche with no loss observed



- n=2–5 present, but no loss evident on scintillator probe
- Neutron rate drops 17%
- Single beam injecting at 90 kV

Case of no observed losses

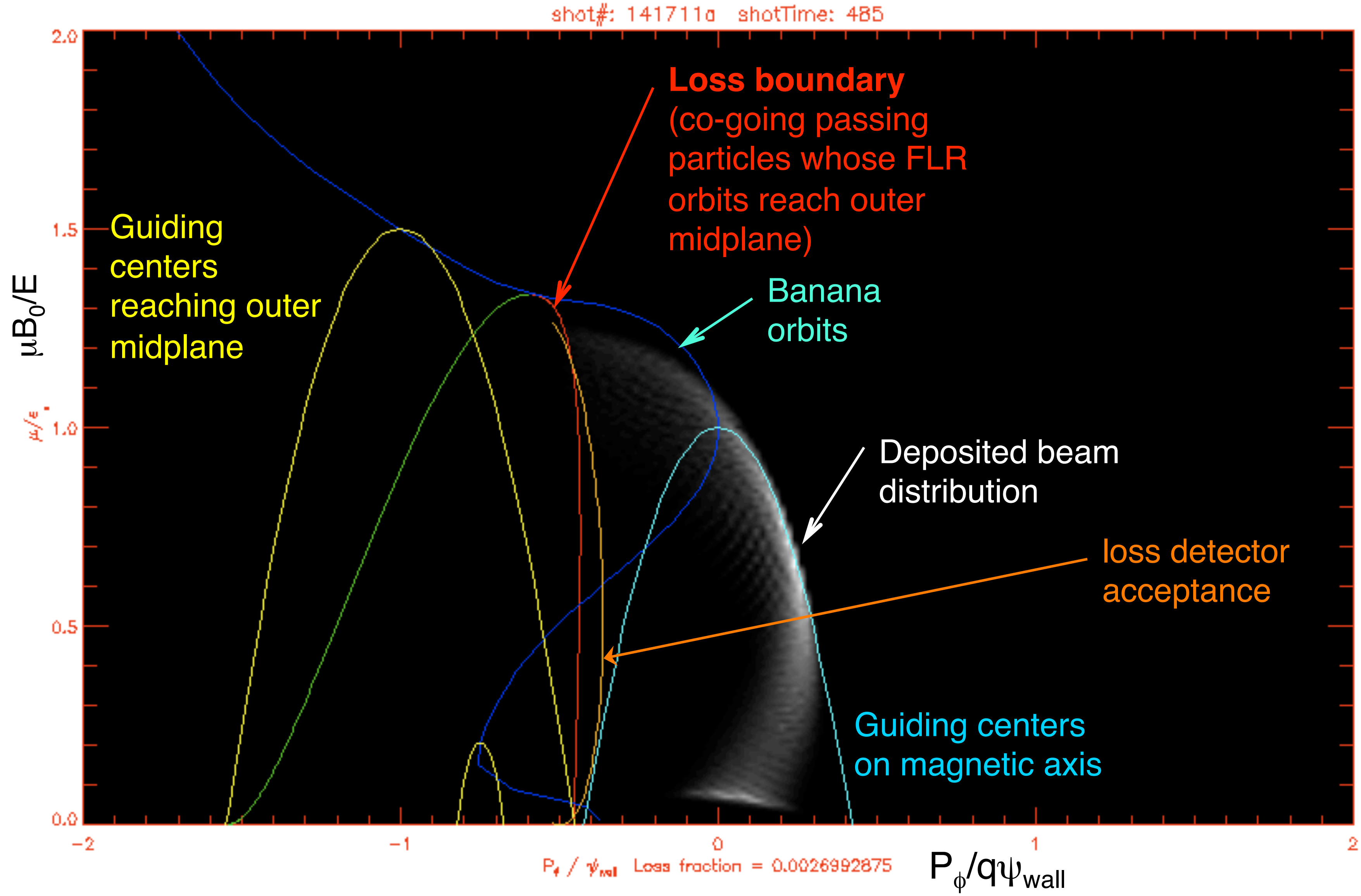


- n=2–5 concurrently present in 3 rapid bursts
- Neutron rate drops by 17%, yet no lost beam ions seen by detector
- Internal redistribution only?
  - Might occur if modes are more core-localized with small edge amplitudes, but ρ_{NB} large in NSTX
- Could there be loss, but not to detector position?
  - Not reasonable, given nature of transport and detector position (see following)

Beam ion orbits can be completely characterized by 3 constants of the motion

- $E = \frac{1}{2} mv^2$ (kinetic energy)
  - Conserved on time scales short compared to collisional slowing down time; also roughly conserved in avalanche losses as these ions lost at injection energy
- $\mu = \frac{1}{2} mv_{perp}{}^2/B$ (magnetic moment)
  - Conserved in the absence of fields varying near the particle's cyclotron frequency or field gradients shorter than length ρ_i
- $P_\phi = mv_\phi R + q\psi_{pol}$ (canonical angular momentum)
  - Conserved in axisymmetry (i.e. in absence of nonaxisymmetric MHD or error field correction coil fields)
- Conservation conditions usually satisfied in NSTX
- Knowledge of these 3 parameters **fully determines orbit** (except toroidal position, ϕ, and gyromotion, which are not used in this work)
- This approach equivalent to guiding center orbit following

Deposited full energy beam distribution can be represented in (μ, P_ϕ) space, along with certain phase space boundaries



Loss boundary
(co-going passing particles whose FLR orbits reach outer midplane)

Guiding centers reaching outer midplane

Banana orbits

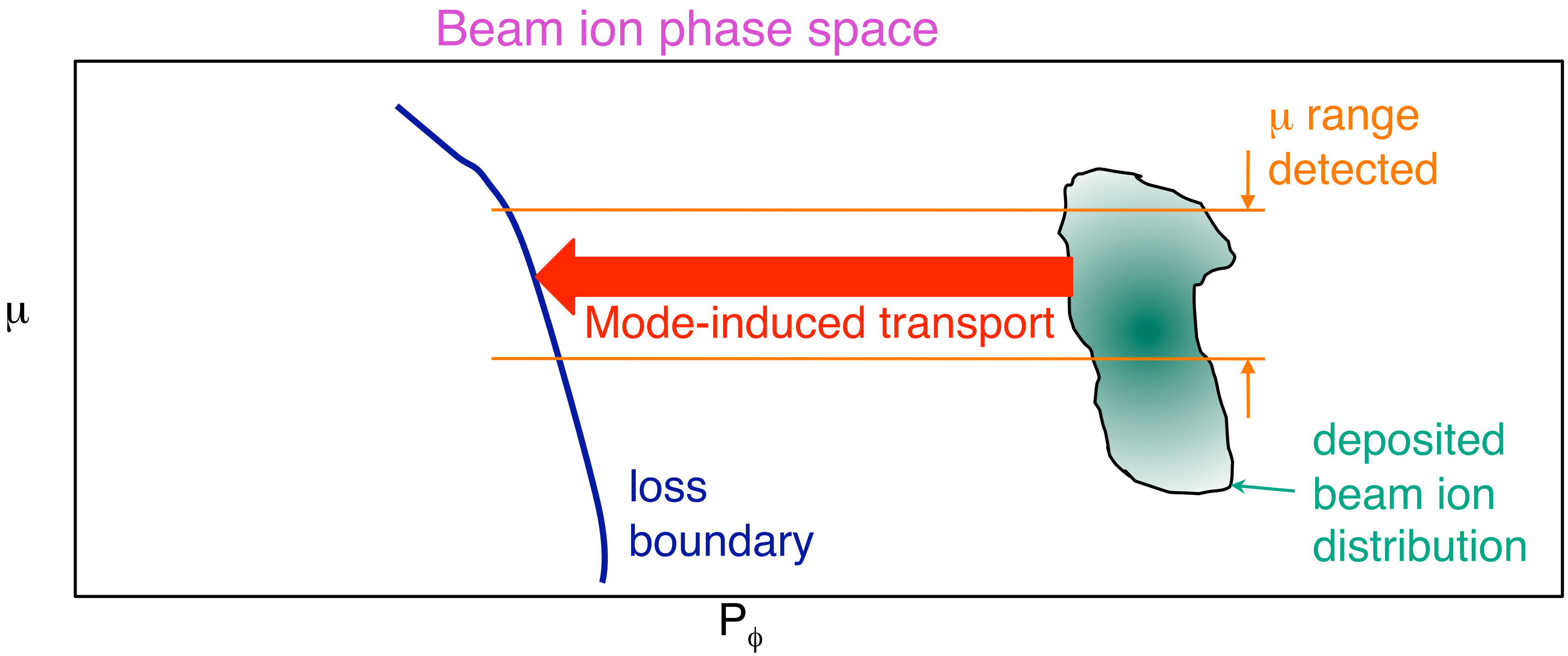
Deposited beam distribution

loss detector acceptance

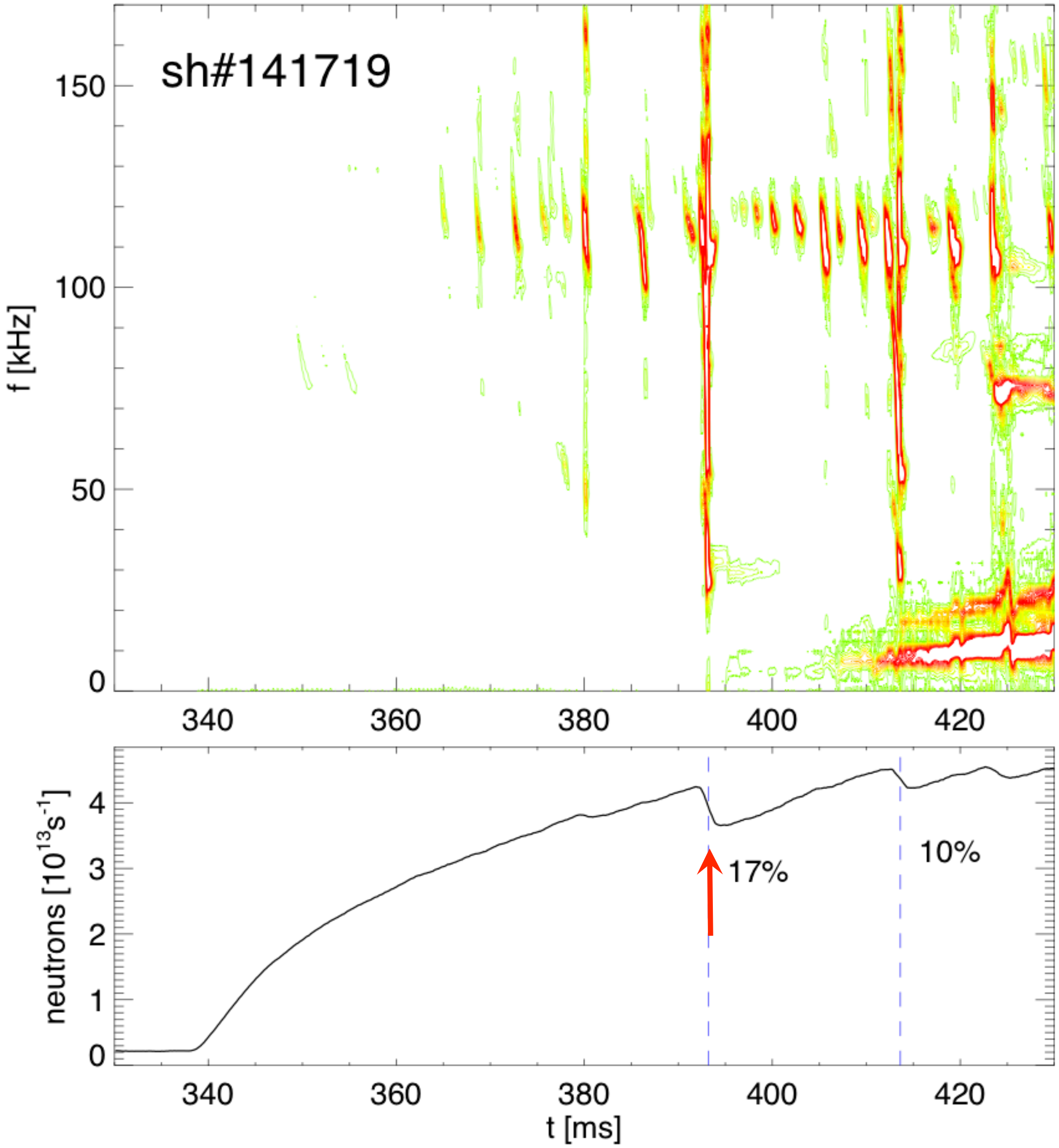
Guiding centers on magnetic axis

Phase space model also helps understand MHD loss

- Observed MHD frequencies $<<\Omega_{ci}$, so μ will be conserved
- Mode destroys toroidal symmetry, so P_ϕ no longer constant
- Often, $E_{loss} \approx E_{inj}$, so MHD convects ions at constant μ across loss boundary →observed lost μ range defines affected set
- Distance displaced in P_ϕ indicates strength of transport

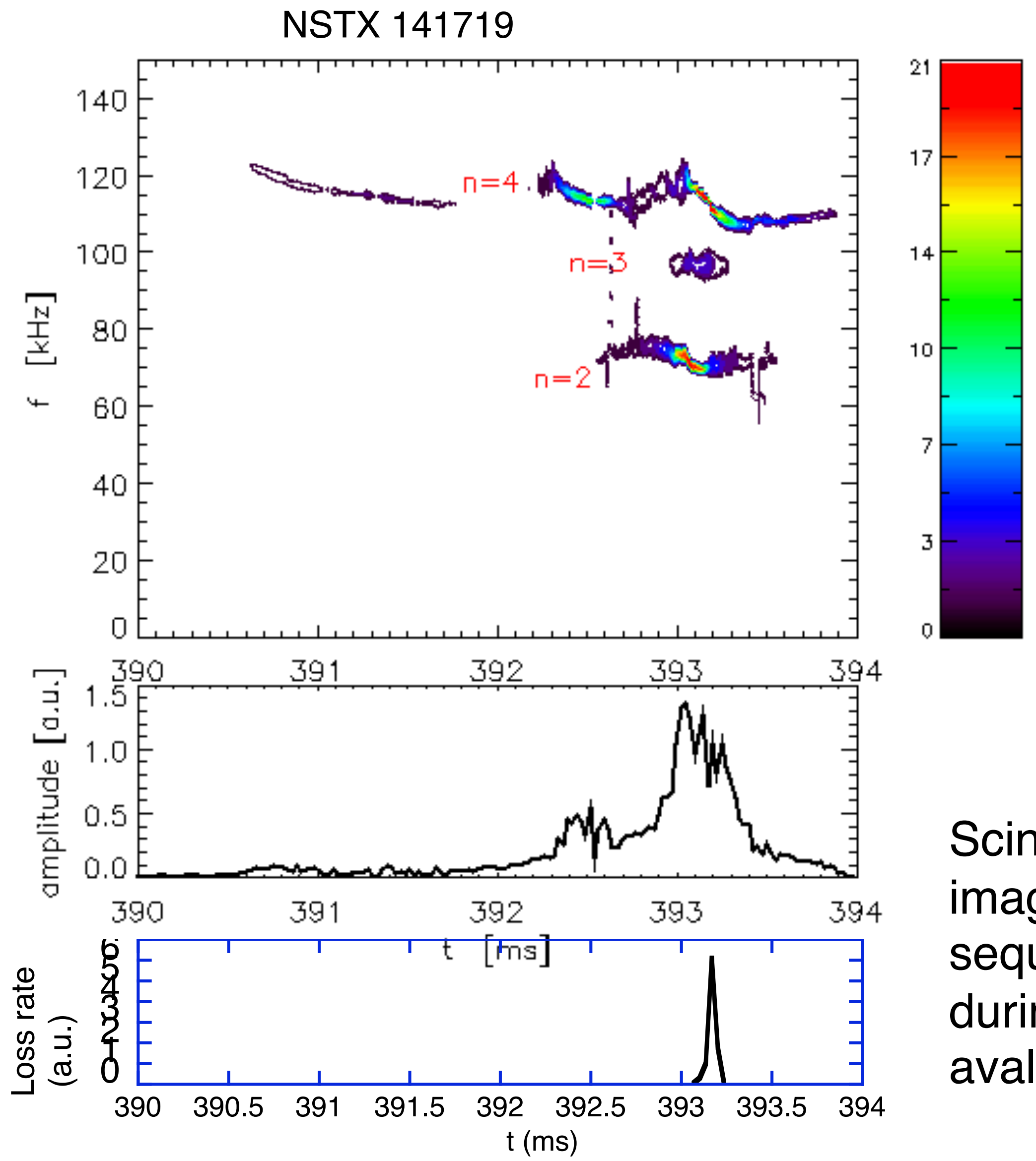


Avalanche with beam ion loss

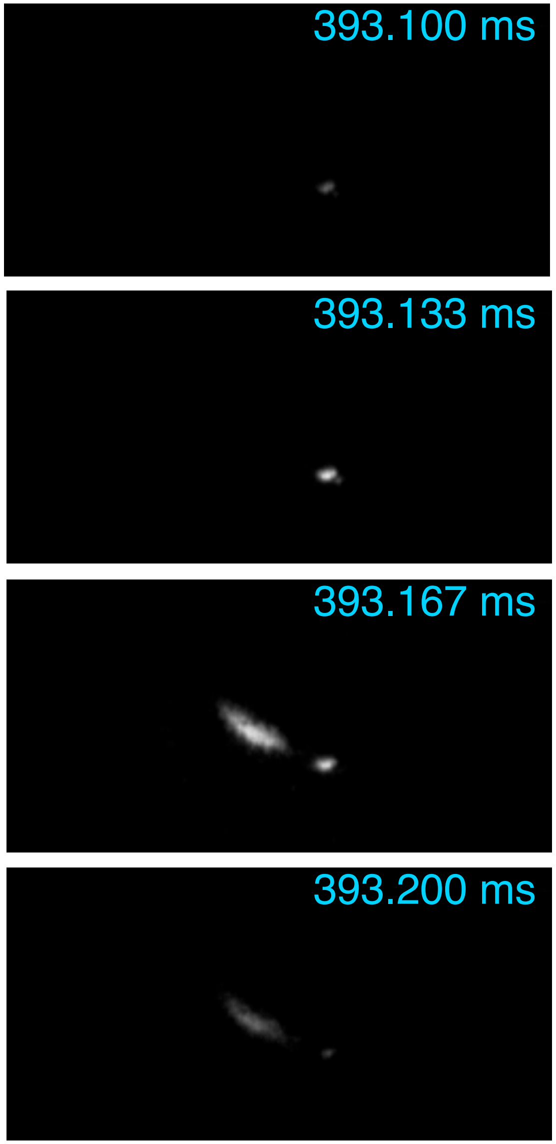


- As with previous avalanche, neutron rate drops 17%
- n=2–4 present

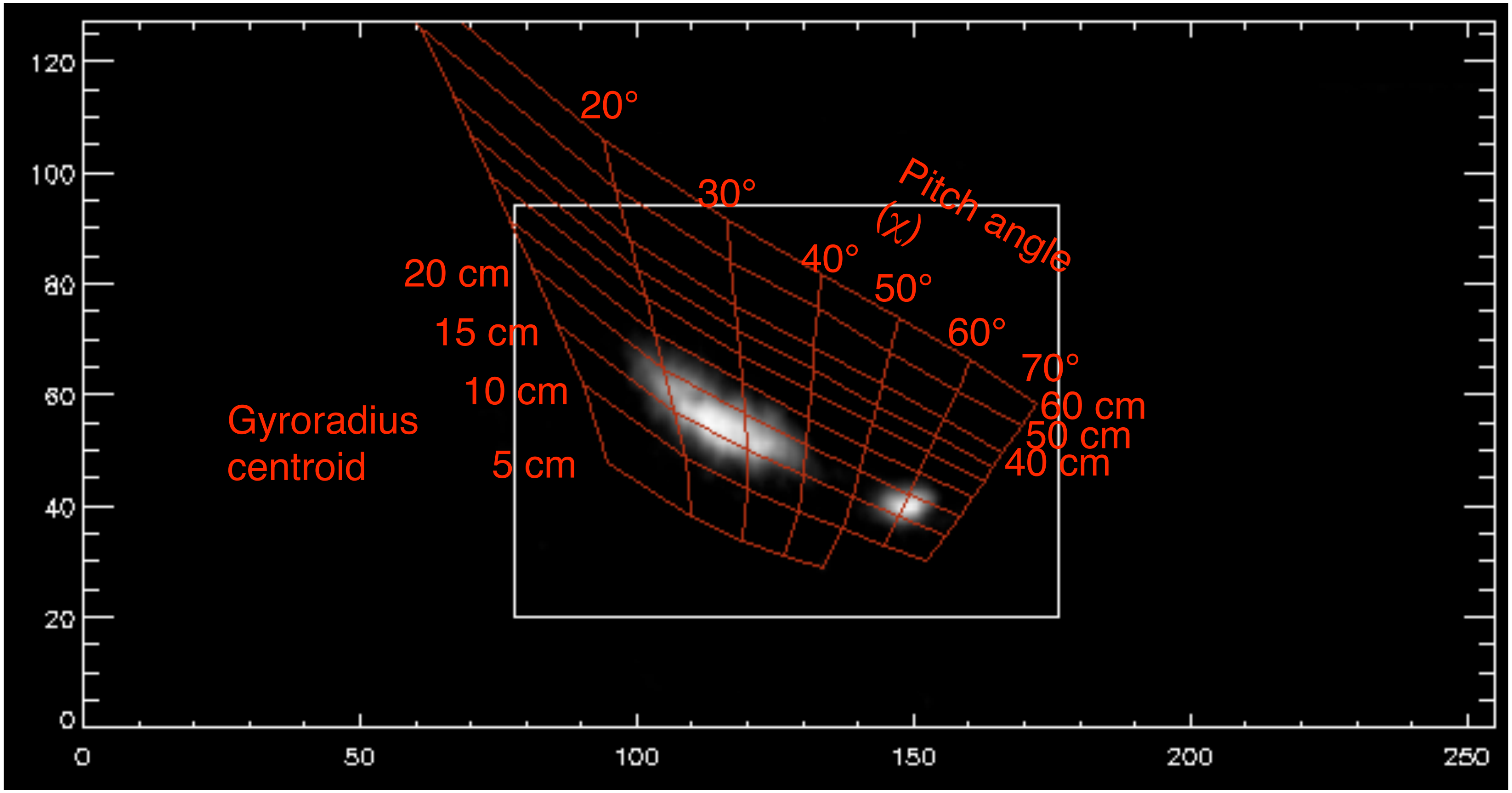
Loss evolves rapidly during avalanche



Scintillator image sequence during avalanche

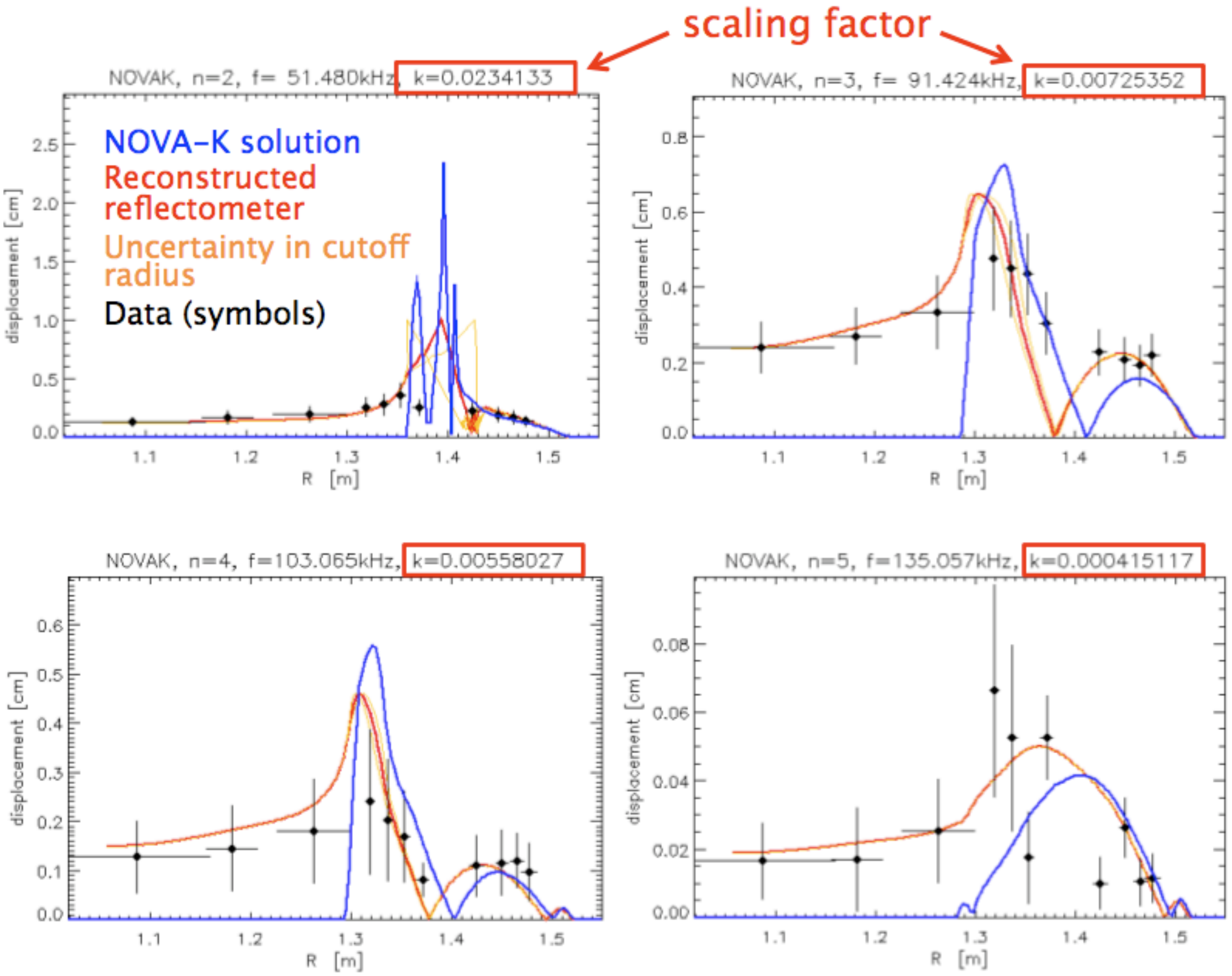


60° pitch angle loss appears first, then range of lower pitch angles



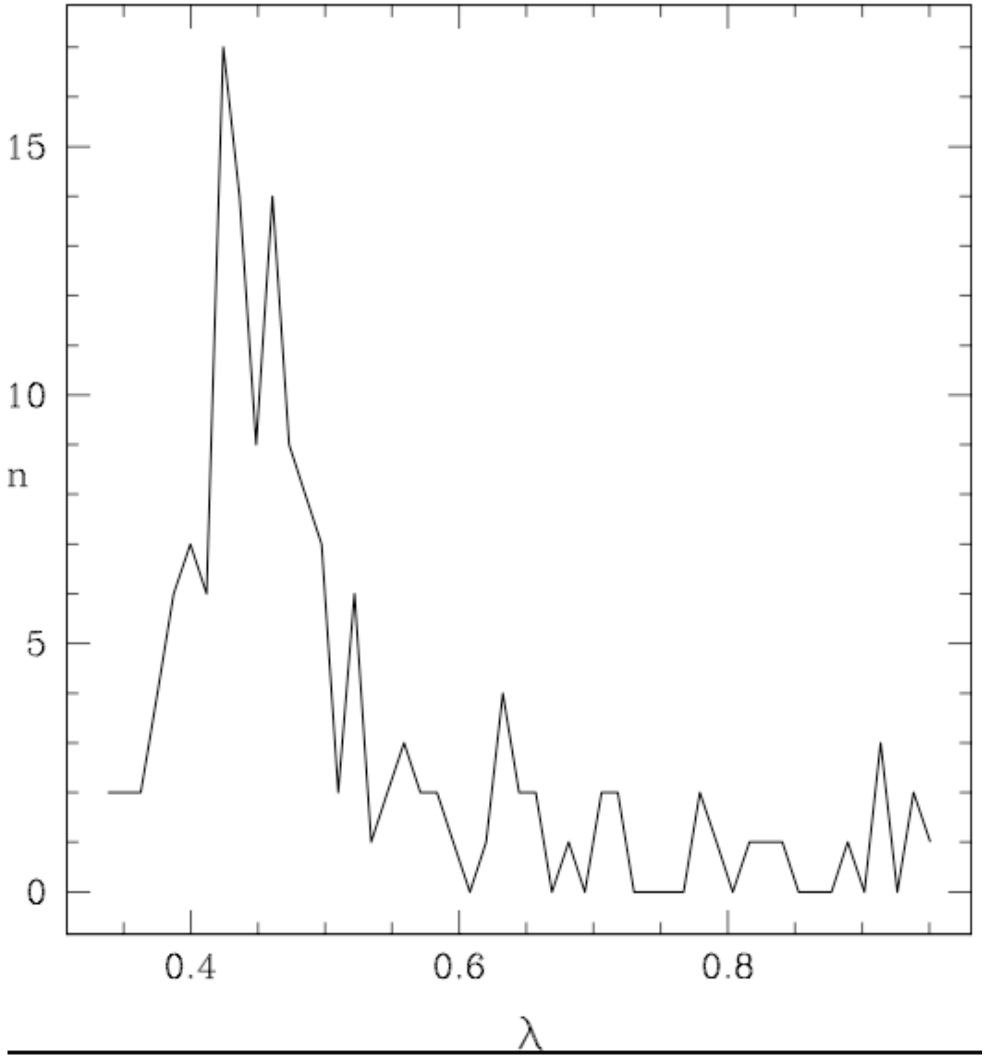
- Rapid appearance of wide pitch angle spot (18°–40°) in 33 μs (≤10 toroidal transits) indicates transport of fast ions is very strong during avalanche

NOVA-K TAE radial eigenfunctions can be fit to reflectometer fluctuation profiles of principal modes


scaling factor

- Displacement can be matched, giving absolute amplitudes of various n modes for input into orbit following code

Orbit calculations have some features of observed signals



$\lambda = v_{||}/v$

- ORBIT code (R. White) with modes & amplitudes of 141711 gives rapid loss at $\lambda=0.45$, ($\chi=63°$), in good agreement with first spot seen
- This is also μ where beam distribution is closest in P_ϕ to detector
- However, ORBIT runs thus far do not duplicate wider, low pitch angle spot
- ORBIT predicts losses for both shots, but losses seen in only one

Conclusions

- TAE avalanches in similar NSTX plasmas sometimes produce fast ion loss at wall and sometimes do not
- Measured TAE amplitudes can be put into ORBIT code to compute effect on fast ions
- ORBIT results agree in part with observations, but there are some discrepancies
- But, improved matching of modes to measurements may be possible, and time variation of mode amplitudes should be accounted for
- Mode radial extent may play some role in whether losses are observed or not