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Stochastic Loss of Neutral Beam Ions During TAE Avalanches in NSTX

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NSTX-U Physics Meeting
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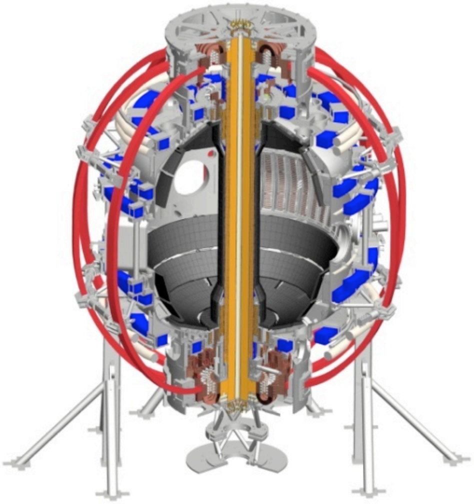

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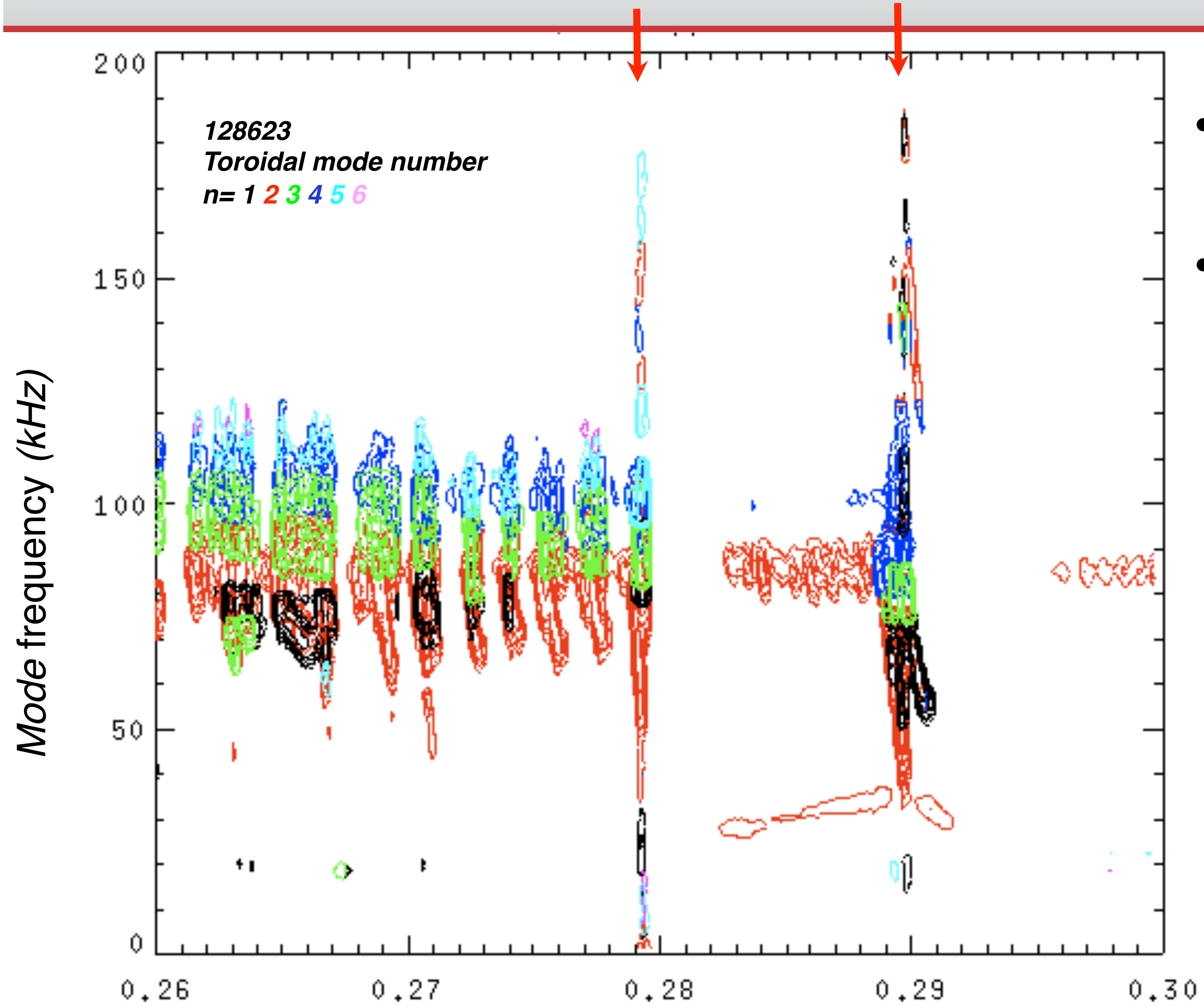
TAEs and avalanches

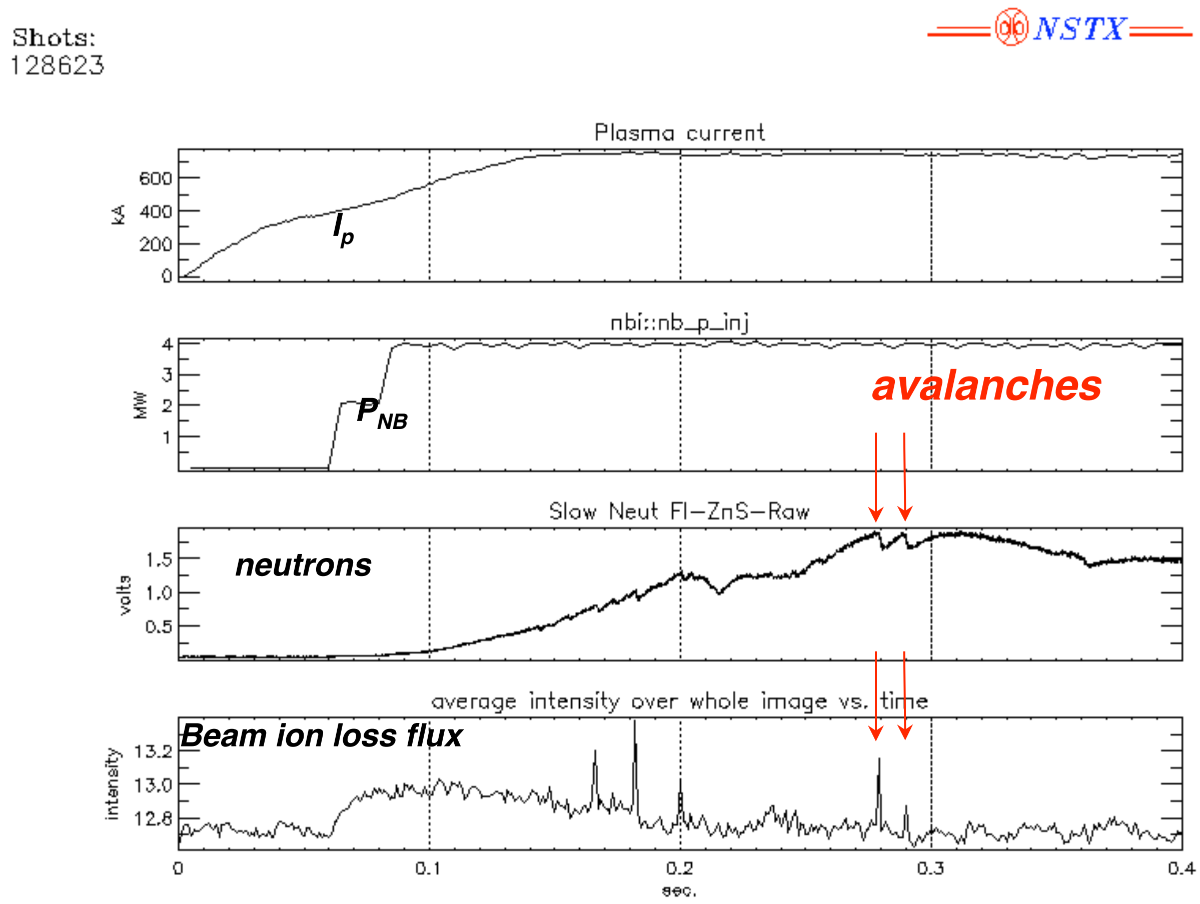
- Toroidal Alfvén eigenmodes (TAEs) are weakly damped Alfvén waves in a toroidal plasma, often driven by ions whose velocity approaches the Alfvén velocity (or a fraction thereof)
- A TAE is characterized by a toroidal mode number, n, and may occur steadily or intermittently
- A burst in which several 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



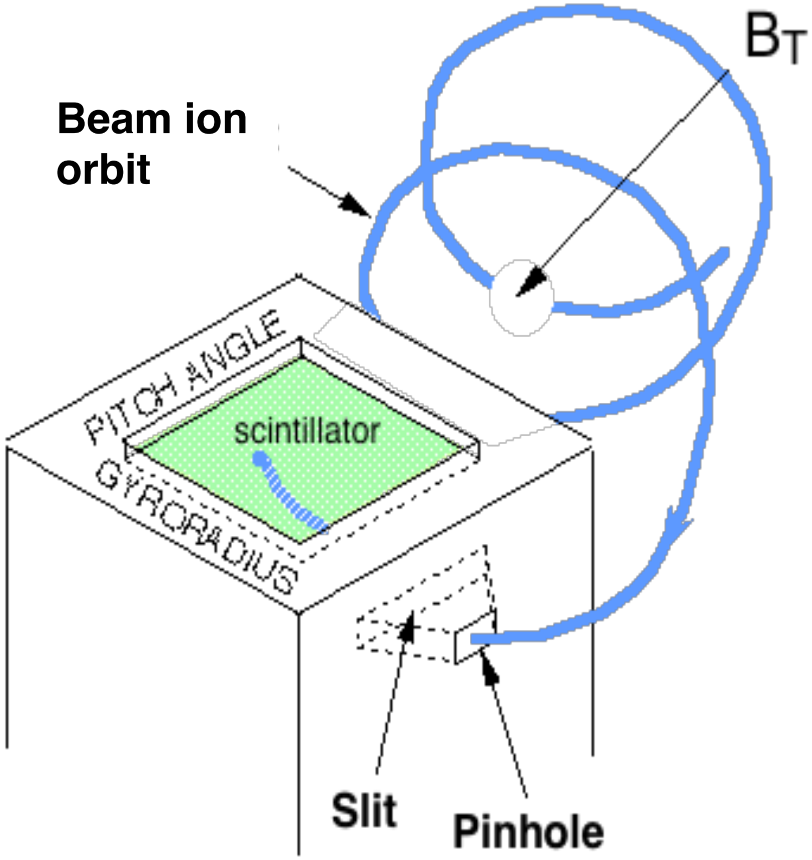
- TAEs appear as burst
- Beam ion redistribution stabilizes modes for a time

Avalanches can cause drop in neutron rate and sometimes 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

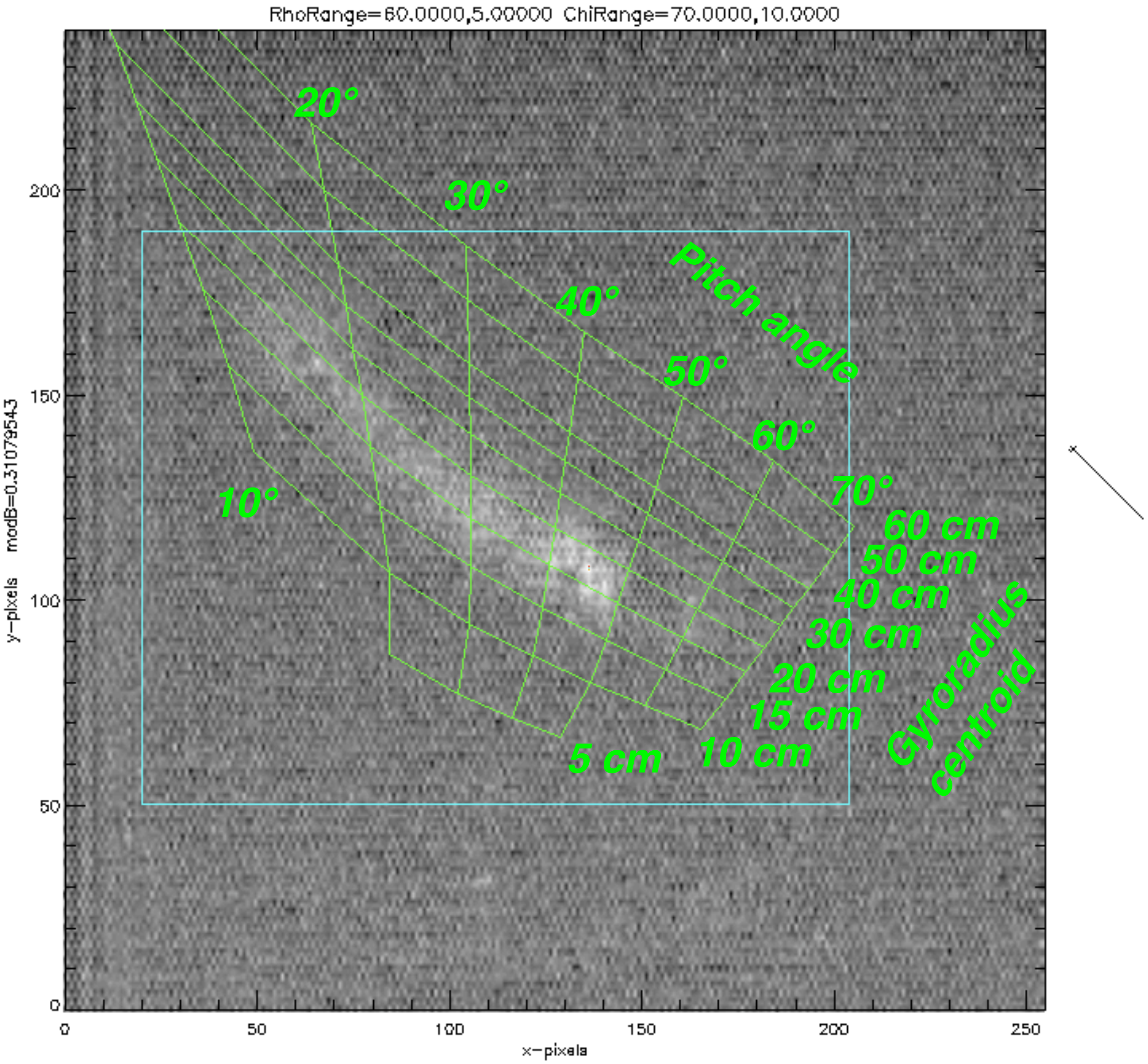
$\Gamma_{\text{loss}}(\rho, \chi, t)$

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

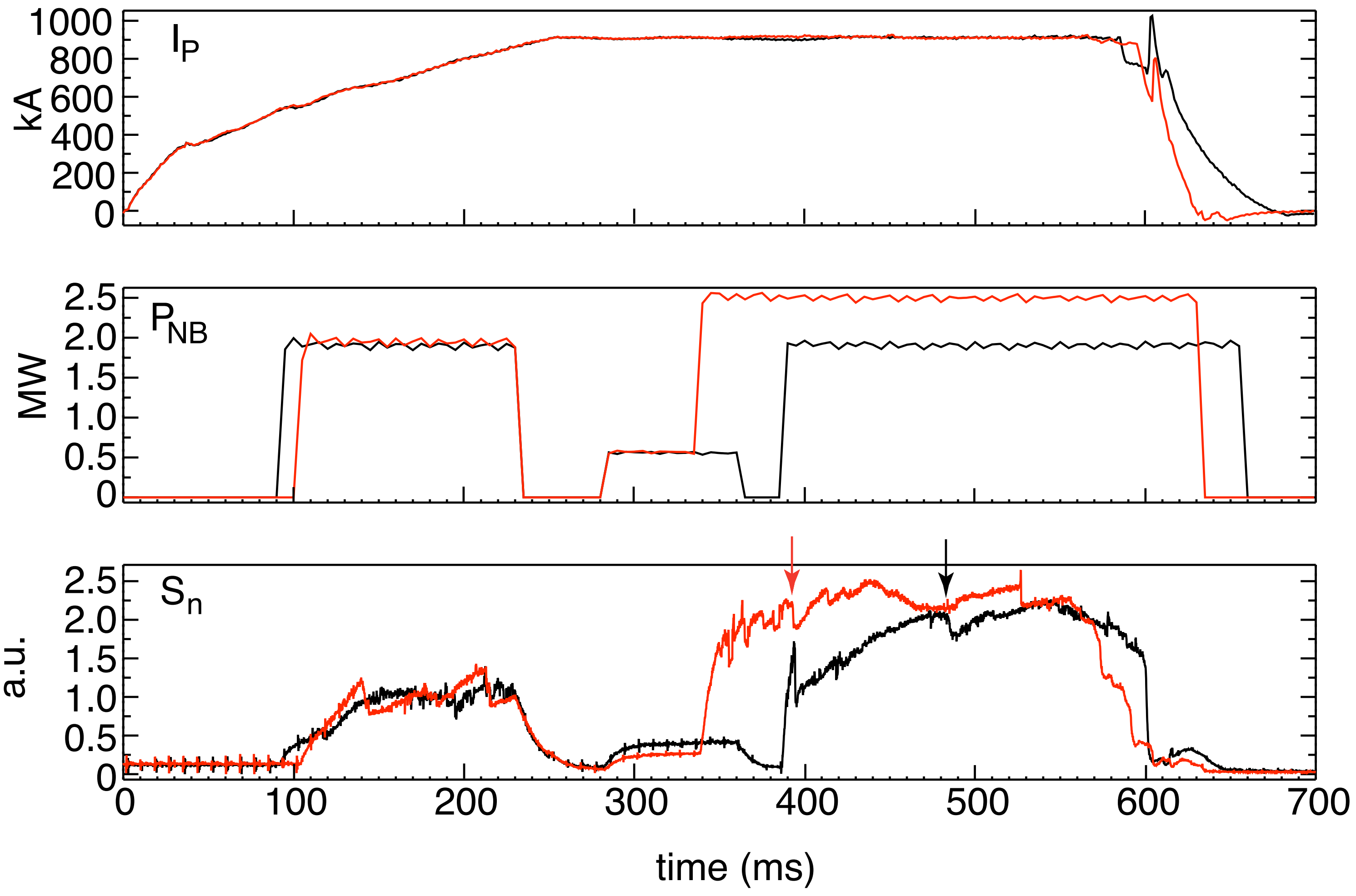
- Interpreted as beam ion phase space being stochastized by multiple modes

Goal: compare measured and modeled lost ion pitch angle distributions

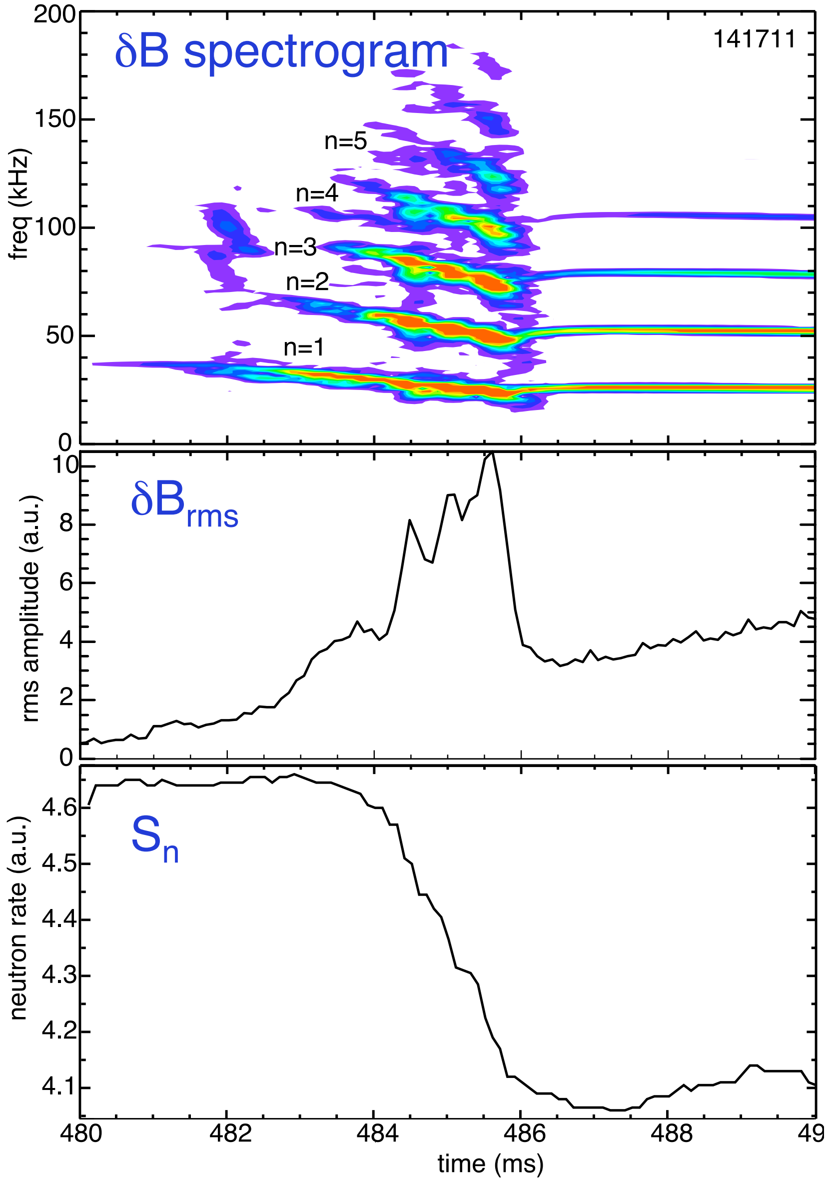
- Measured distribution recorded by scintillator probe
- Loss distribution modeled by guiding center orbit code that incorporates:
  - Measured TAE n numbers, frequencies (Mirnov coils)
  - Radial mode structures and amplitudes (multichannel microwave reflectometer data coupled to NOVA-K calculations of eigenmodes)
  - Deposited beam ion distribution function from TRANSP
  - Focus on recently deposited beam ions since losses appear at or very close to injection energy of 90 keV
- Prior work by Fredrickson, *et al.*, has successfully used this approach to model drops in the neutron rate
- Present work has more ambitious goal as loss flux should match at all pitch angles (not just matching scalar quantity)

Compare cases with and without losses to draw inferences about conditions when fast ions may be lost

141711 no loss
141719 with loss

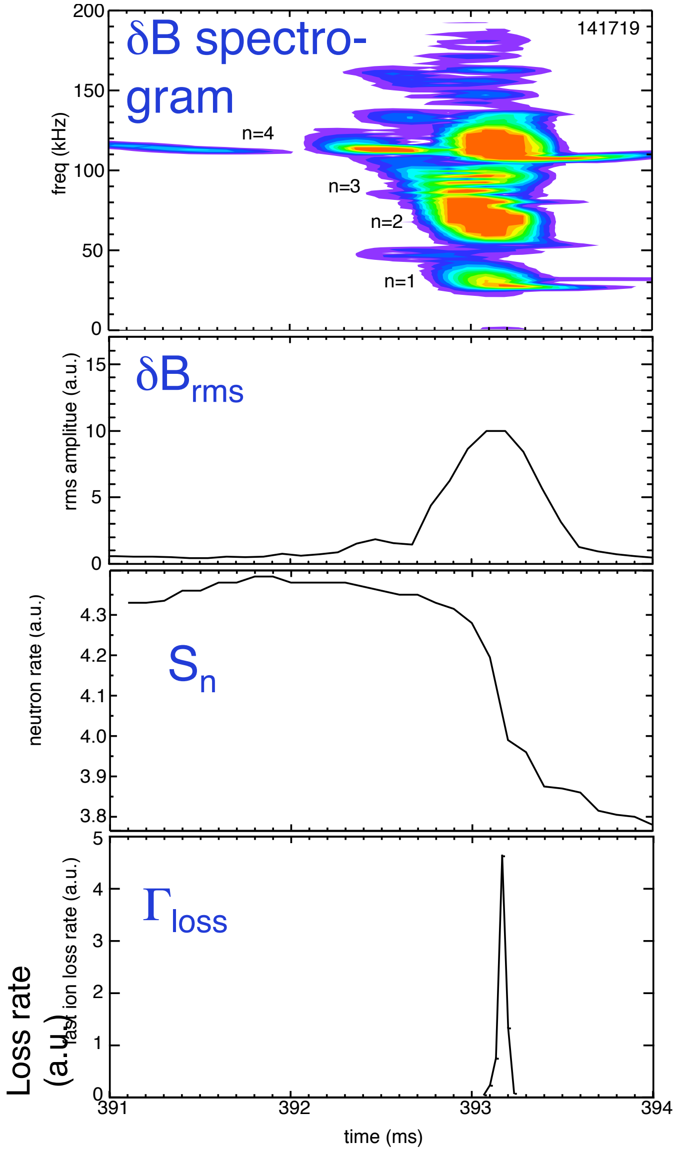


Example avalanche with no observed losses



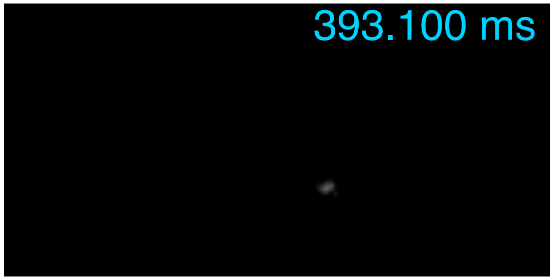
- n=2–5 concurrently present in 3 rapid bursts
- Neutron rate drops by 17%, yet no lost beam ions seen by detector
- Could there be loss, but not to detector position?
  - Possible, but see below
- Internal redistribution only?
  - Might occur if modes are more core-localized with small edge amplitudes, but ρ_{NB} large in NSTX
  - Orbit simulations suggest redistribution does occur

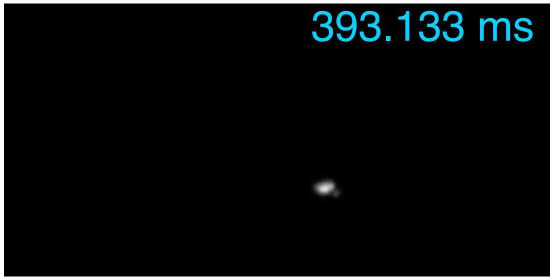
Avalanche with loss also has multiple n, and loss evolves rapidly during event

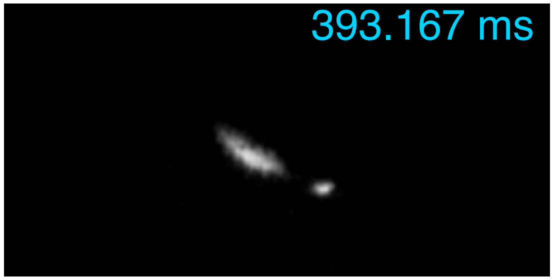


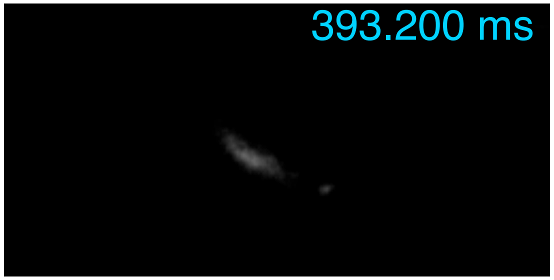
- Scintillator image sequence during avalanche →

- This avalanche also produces 17% drop in neutron rate
- Loss occurs over interval of only 100 μs, corresponding to a few tens of toroidal transits of beam ions
- Passing and trapped ions lost simultaneously, over range of pitch angles

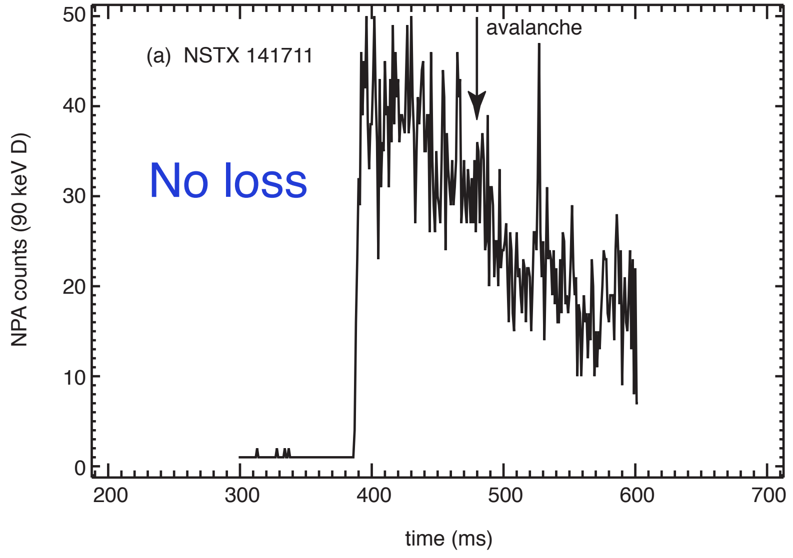


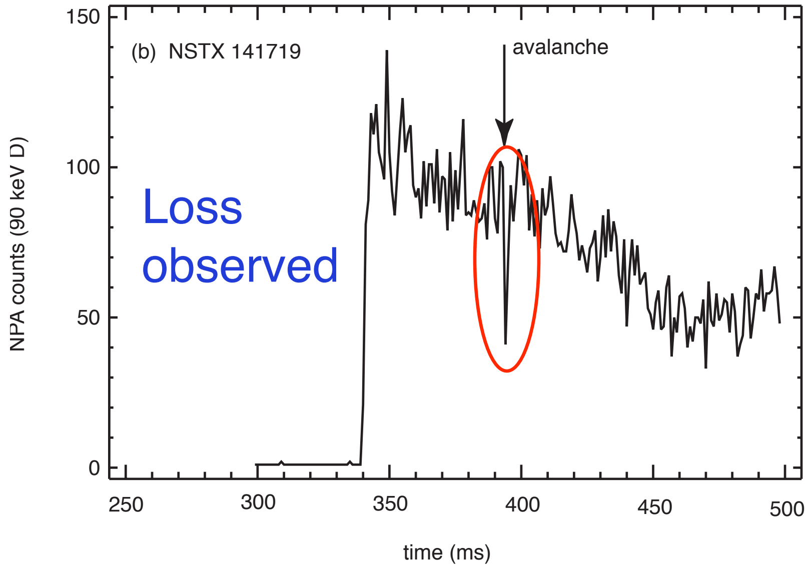






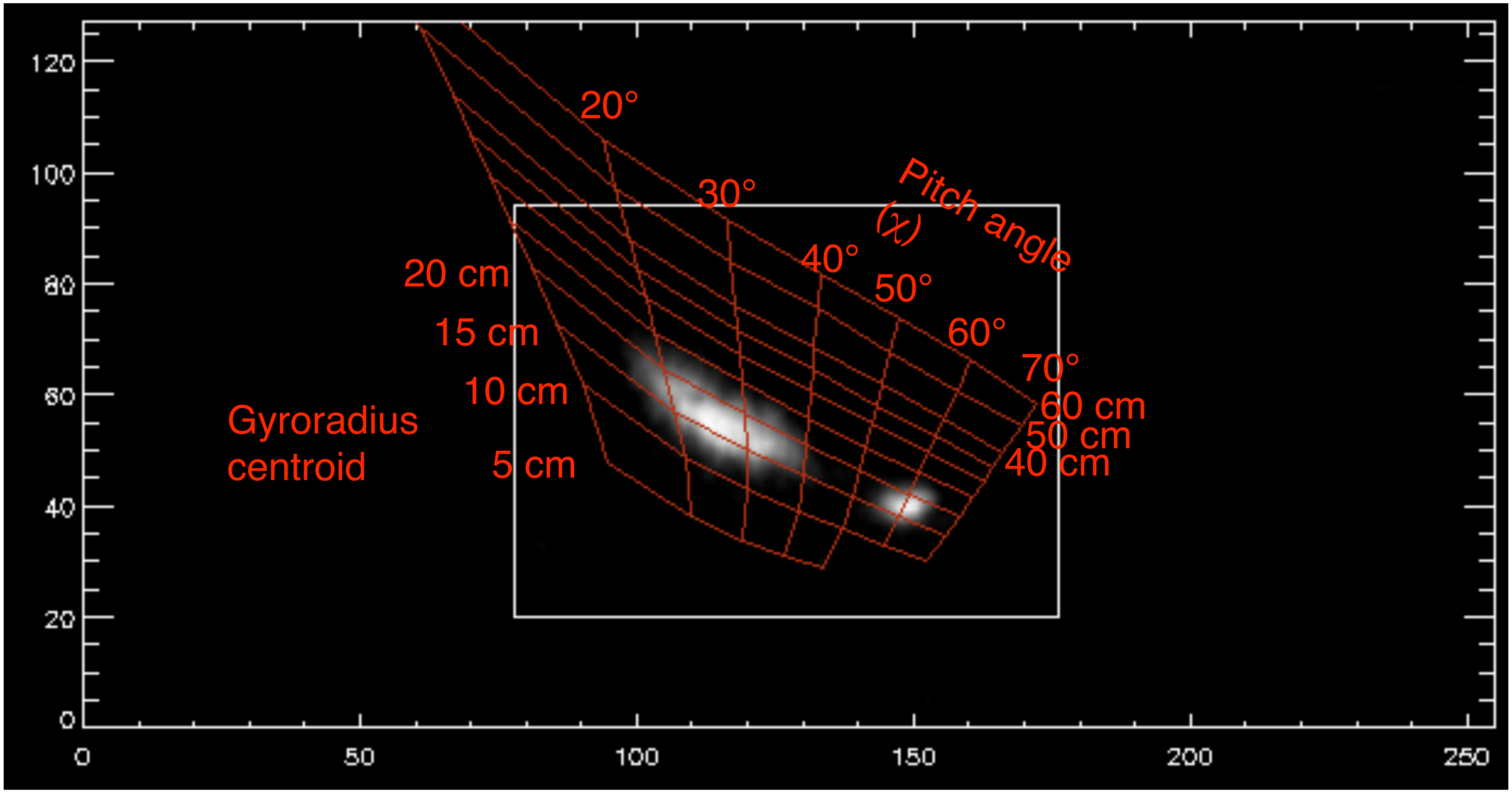
E||B NPA flux at 90 keV confirms loss/no loss behavior





- Sharp drop in energetic neutral flux seen concurrent with large beam ion loss
- No drop in NPA signal in no-loss case
- Confirms loss probe measurements are representative of fast ion changes inside plasma

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

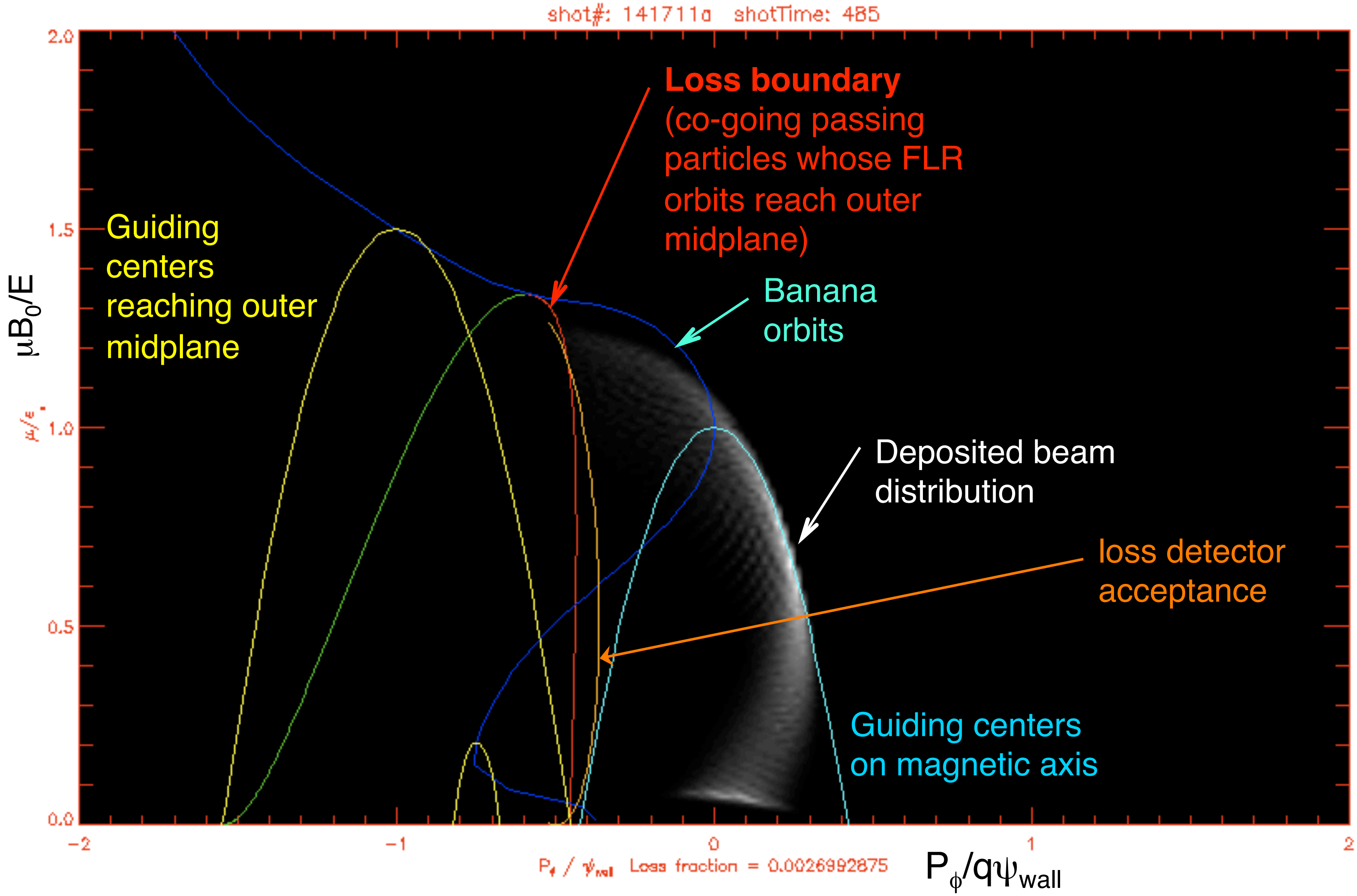


- Rapid appearance of wide pitch angle spot (18°–40°) in 33 μs (≤10 toroidal transits) indicates transport of fast ions is very strong during avalanche

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

- $E = ½ mv^2$ (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
- $\mu = ½ mv_{perp}{}^2/B$ (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) (a.k.a. P_ζ)
  - 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

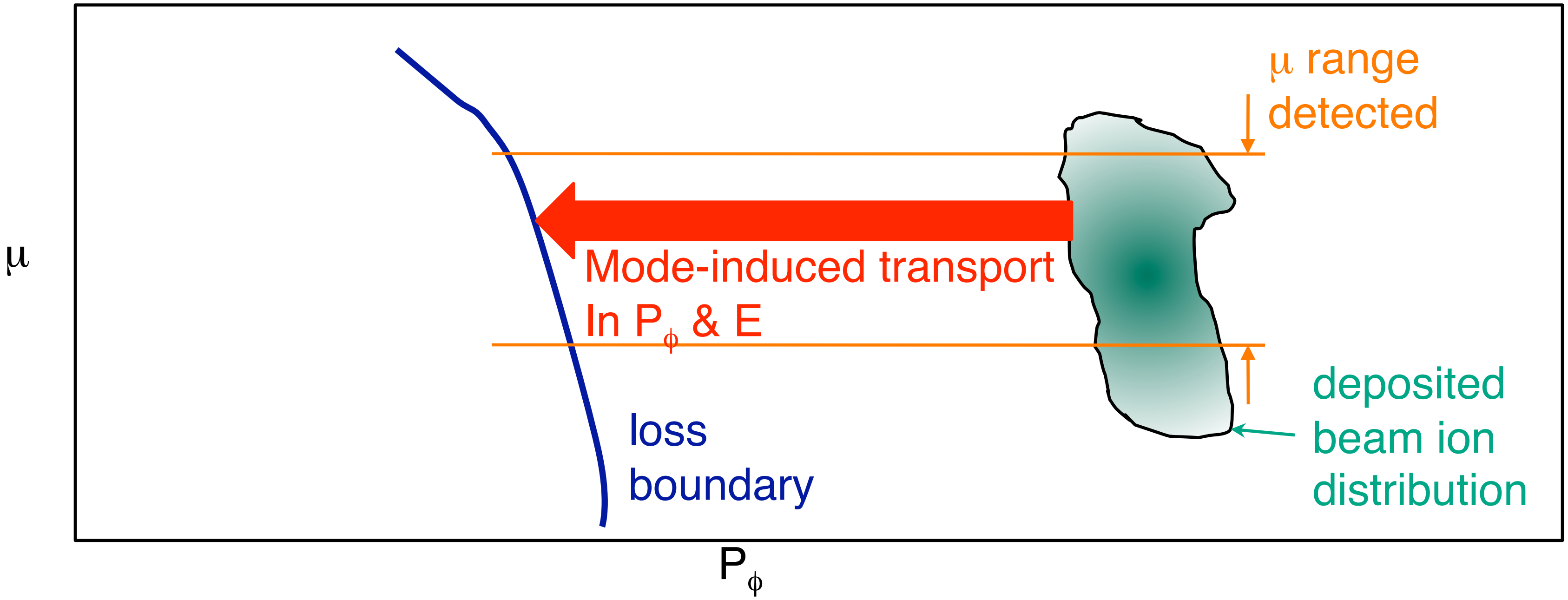
loss detector acceptance

Guiding centers on magnetic axis

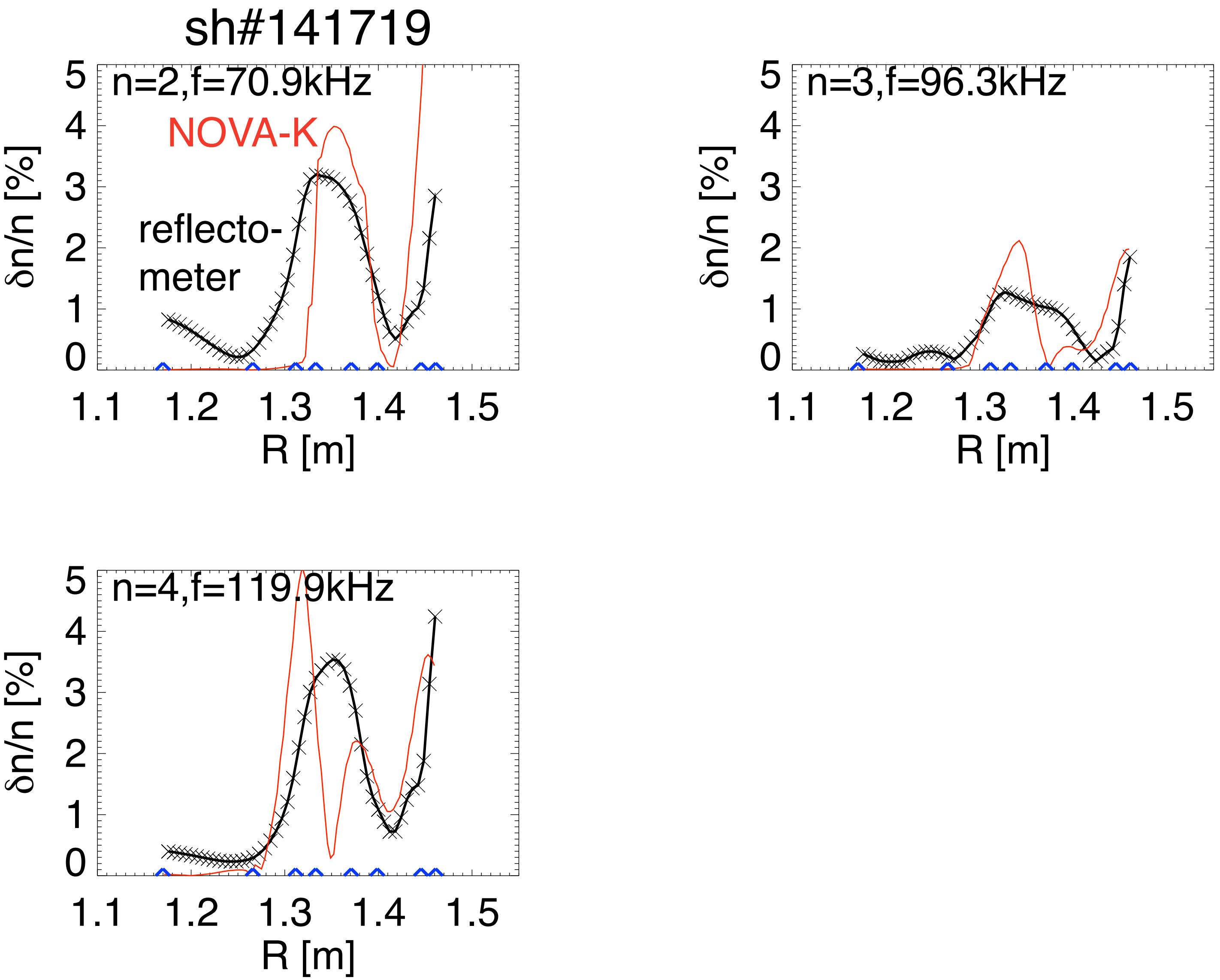
Phase space model also helps understand MHD loss

- Observed MHD frequencies <<Ω_{ci}, so μ will be conserved
- Mode destroys toroidal symmetry, so P_ϕ no longer constant
- A single n mode moves particles along a line $nE-\omega P_\phi$=const in diffusive fashion, at fixed μ
- Multiple n in avalanche can cause broader transport

Beam ion phase space at fixed E



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

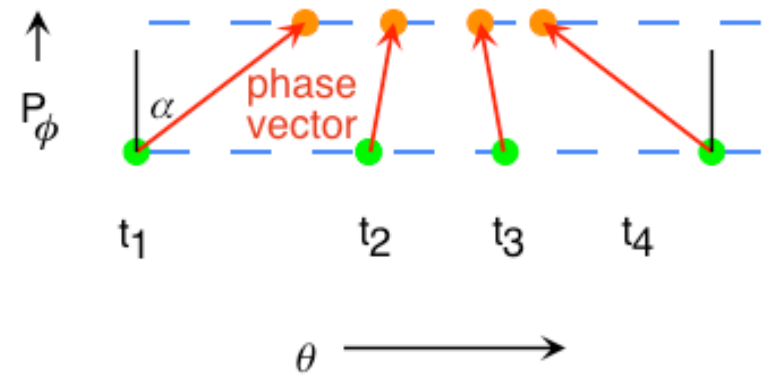


- Density fluctuation or displacement can be matched, giving absolute amplitudes of various n modes for input into orbit following code

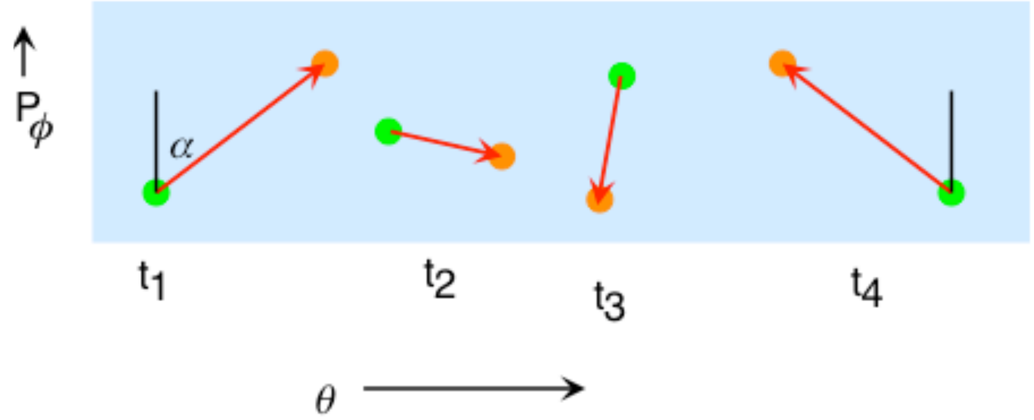
Mode structures and amplitudes can be used to determine regions of phase space subject to stochasticity

- Use guiding center code ORBIT to follow nearby pairs of ions for multiple toroidal transits, then create Poincaré plots
- If "phase vector" between particles in action/angle space rotates by more than π, then that region of phase space is stochastic
- Repeat process for many particle pairs, spanning phase space, and shade volumes of phase space in plot to designate stochastic domains

Good KAM surfaces: $\Delta\alpha \leq \pi$

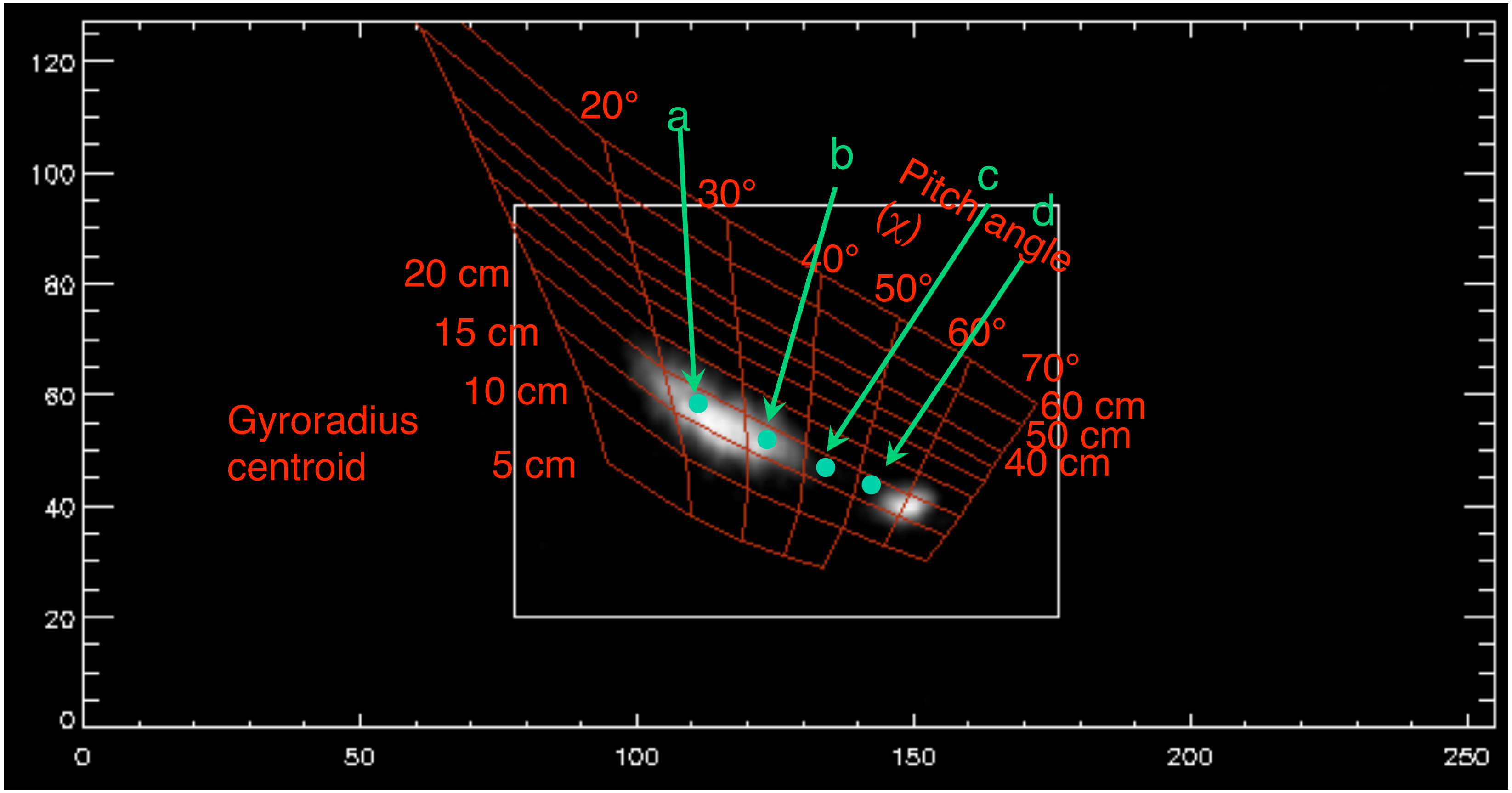


Stochastic region: $\Delta\alpha$ arbitrarily large

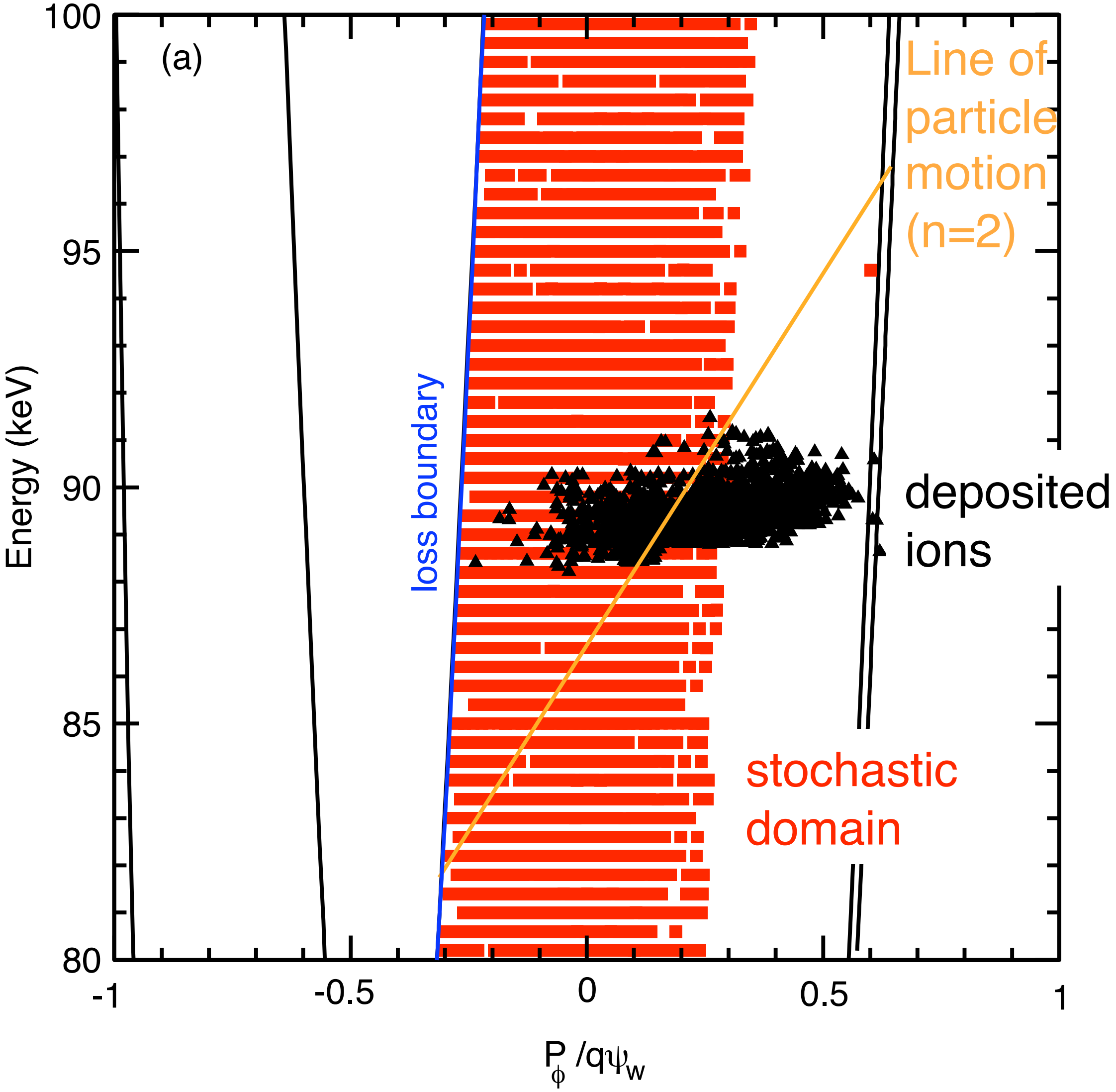


Test whether code-modeled stochastic domain presence coincides with lost pitch angle ranges

- Stochastic maps shown on following slides for 4 pitch angles marked (4 μ values)

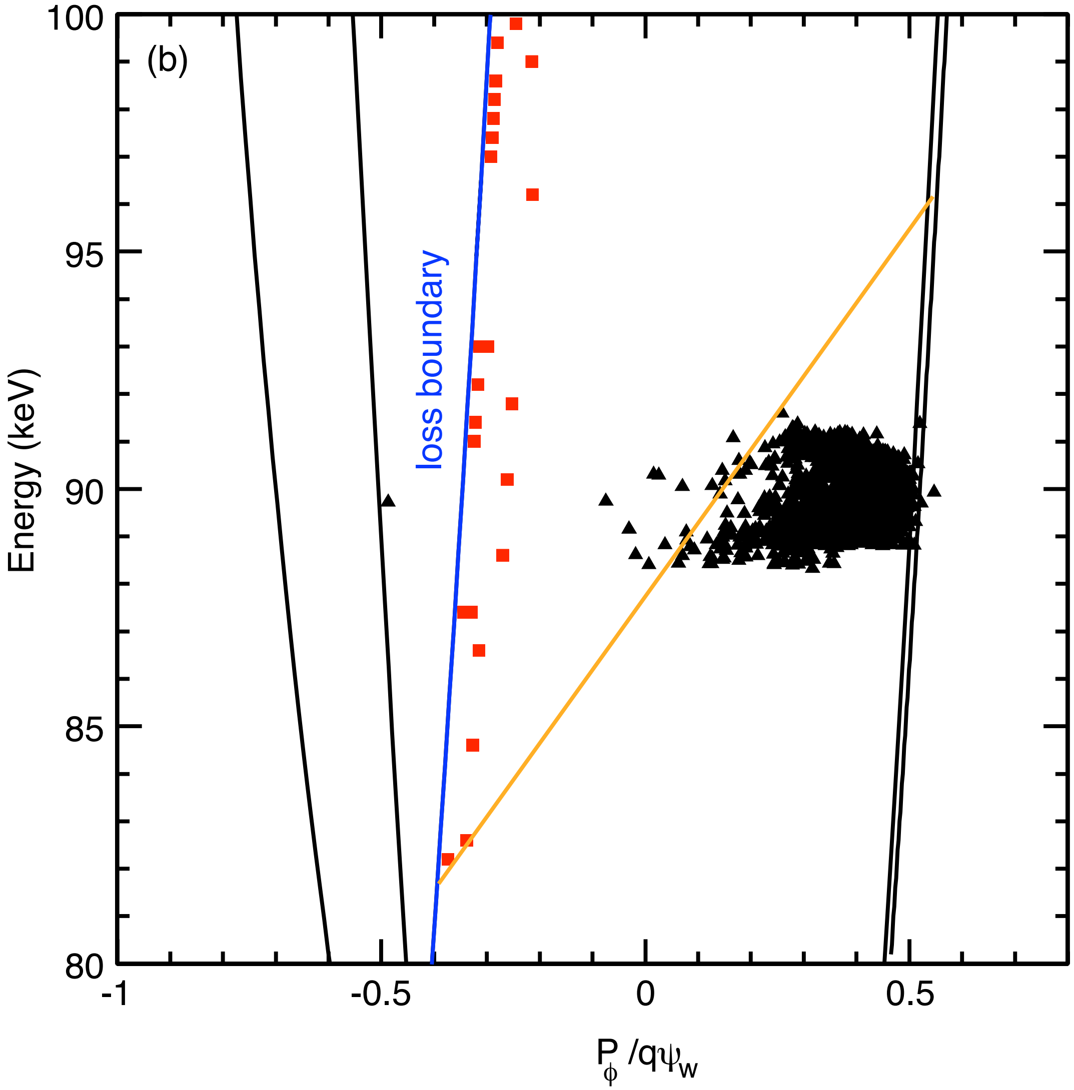


Case a (23°) is near center of a detected loss spot & model predicts loss



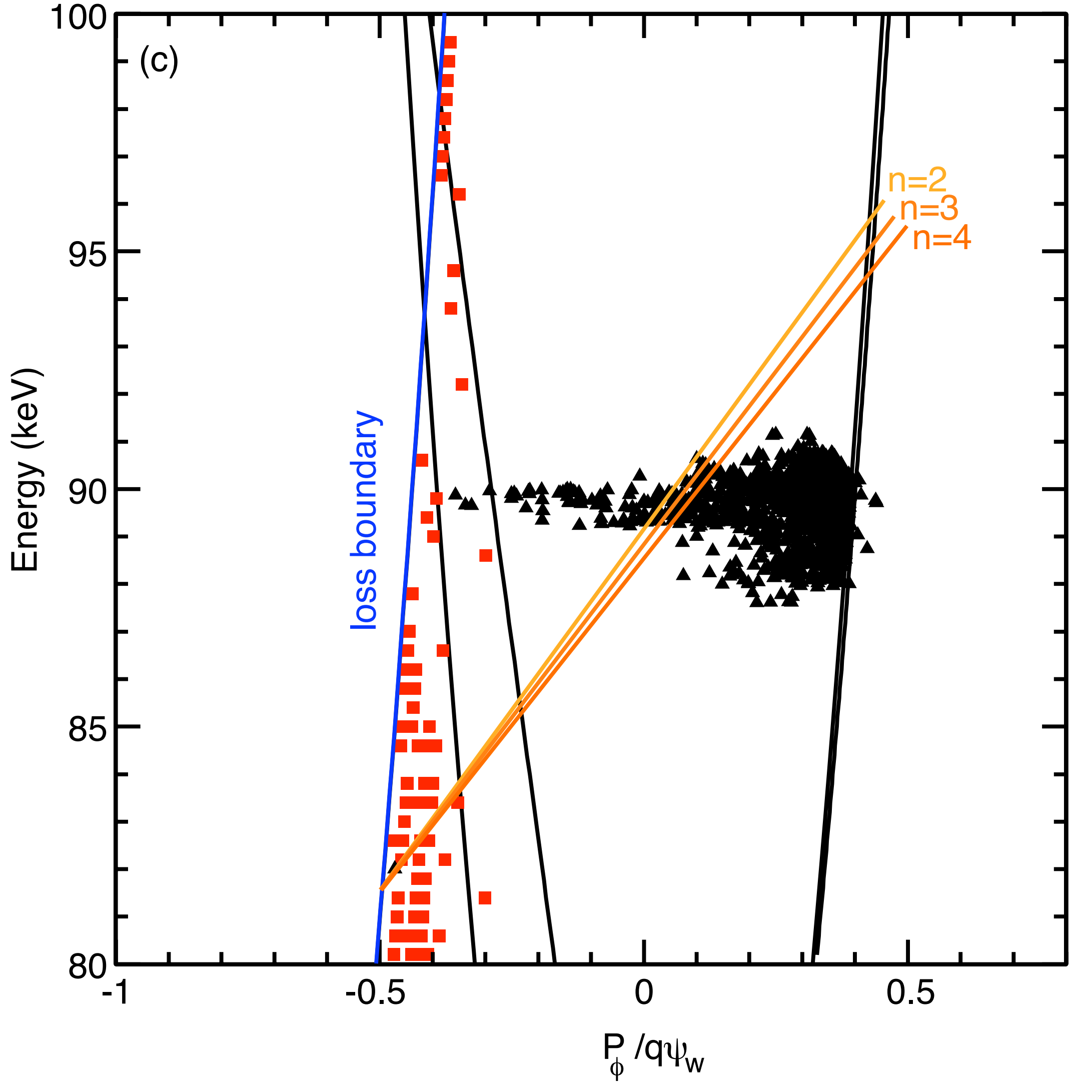
- Beam ions deposited in stochastic region
- Particles move along orange line (or parallel lines) under influence of n=2 mode
- Particles clearly deposited in stochastic region and that region extends to loss boundary

Case b (33°) is near boundary of no-loss region & model shows deposition only on good surfaces



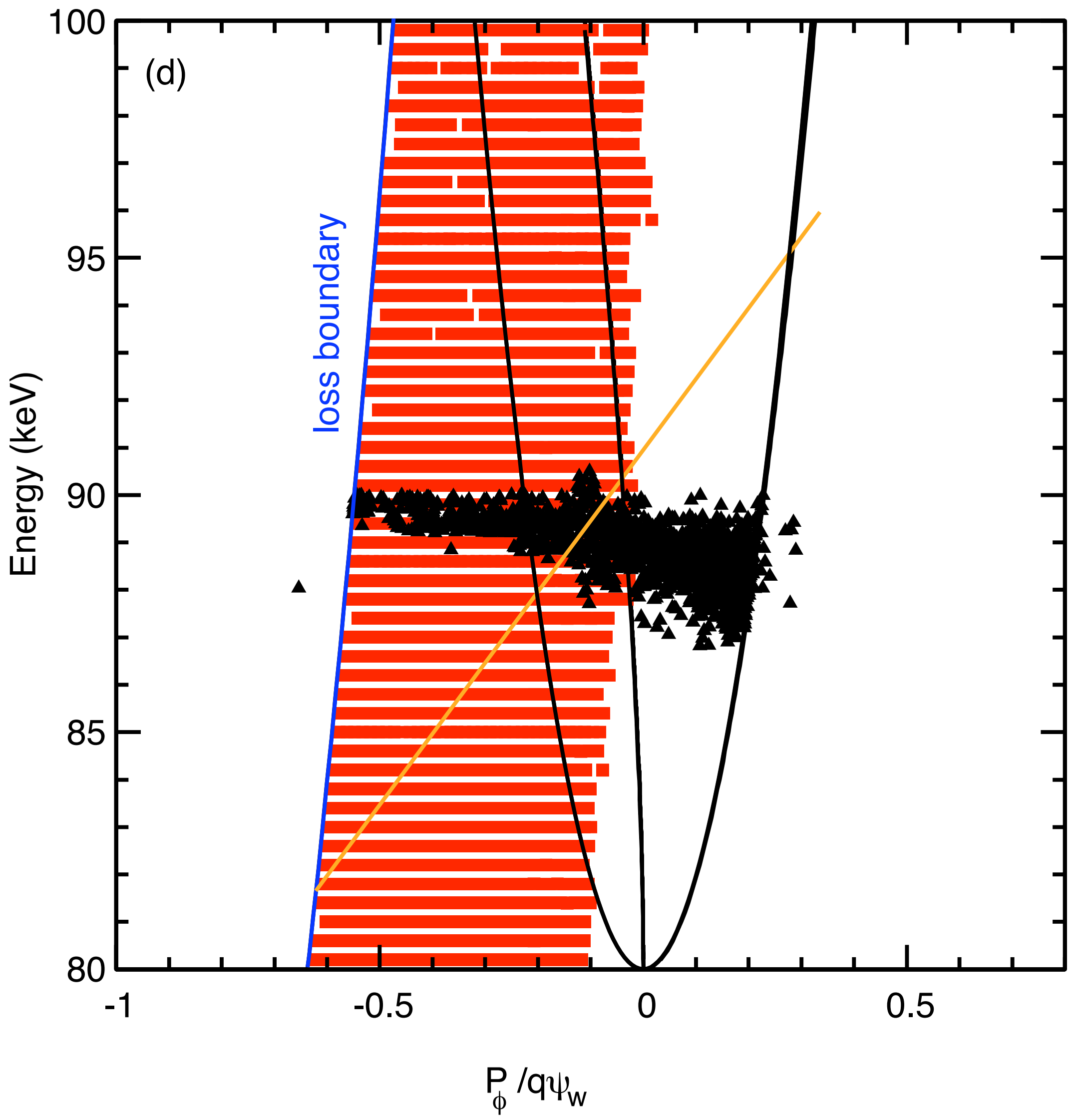
- Deposition in a region of good surfaces in phase space means beam ions have no chance to be transported to loss boundary, even though stochasticity exists at other locations
- Experiment still shows loss at this pitch angle, but loss tapers away at slightly higher pitch angle

Case c (43°) is in region of no loss; deposition evident only in region with good surfaces



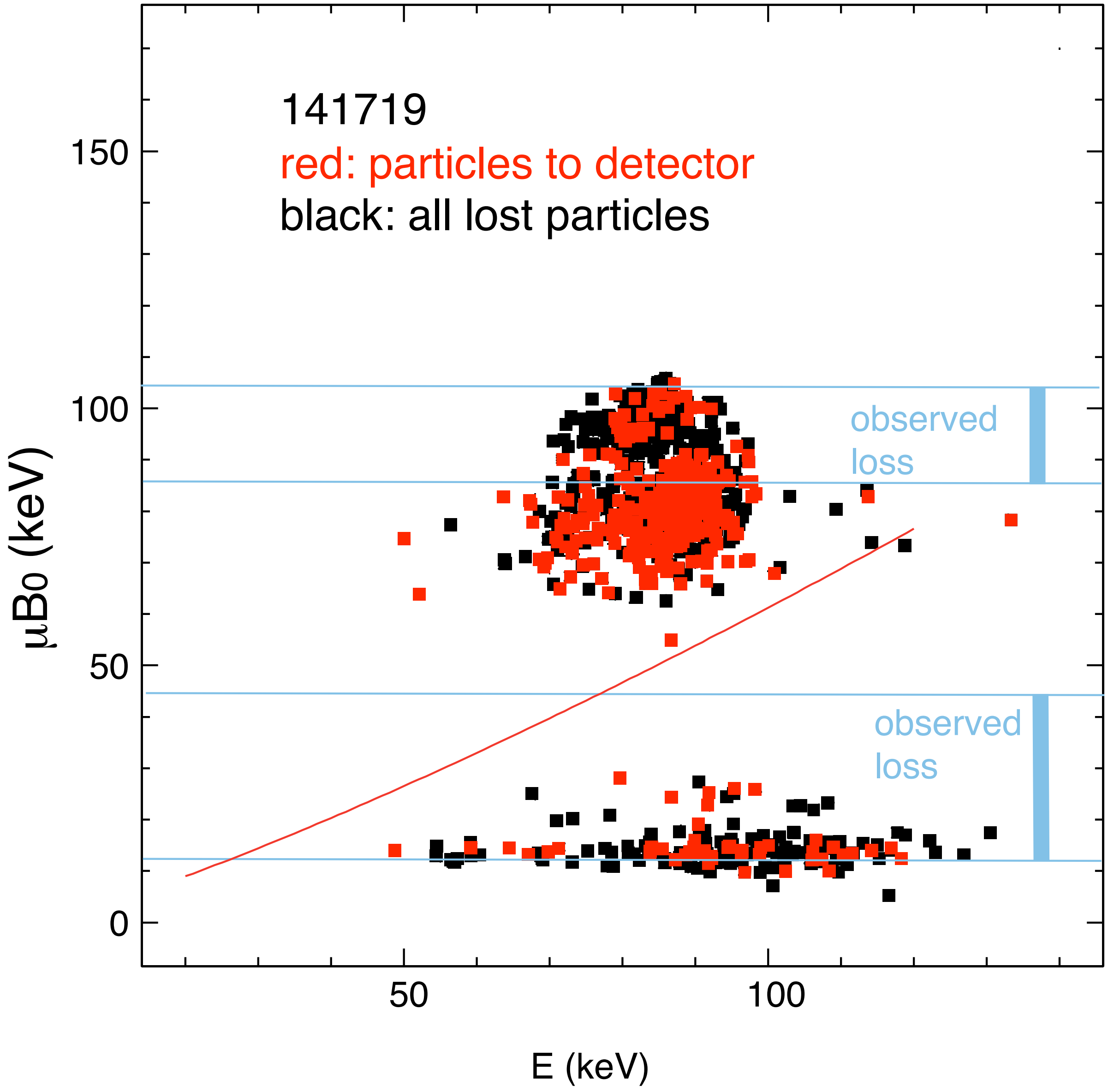
- Model consistent with observation at this pitch angle
- Slopes of lines of diffusion for n=3 & 4 also shown–they do not differ markedly from direction of transport for n=2 mode

Case d (52°) is near loss spot; deposition squarely in stochastic region again



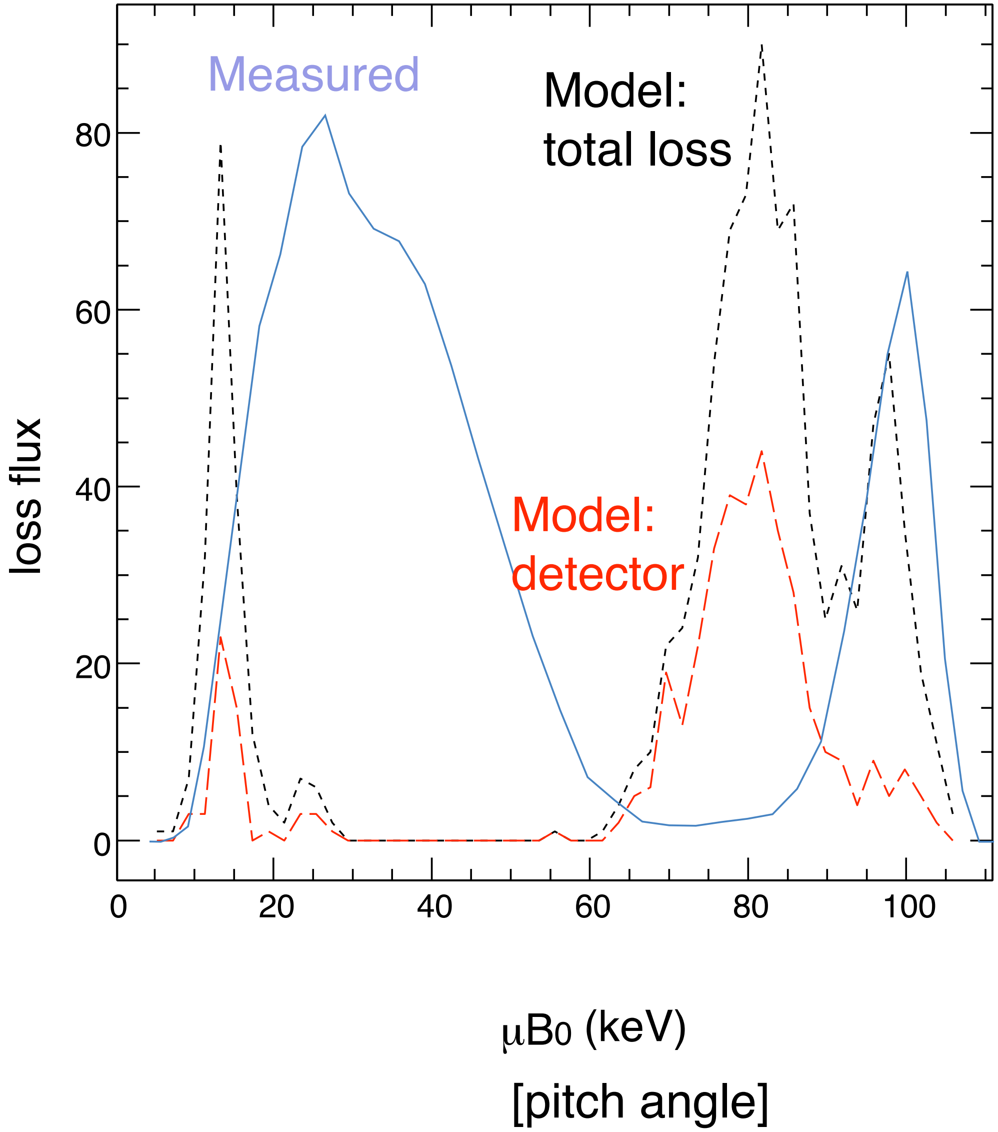
- Note that deposition is in stochastic region and that stochasticity exists along entire line of transport up to loss boundary
- Both conditions required for loss
- Experiment shows loss starting at slightly higher pitch angle, so slight inconsistency here

Orbit following including mode structure shows bimodal loss distribution in pitch angle, as observed



- Modeled loss boundaries agree with measurement at top and bottom of range, but not at intermediate values
- **Same simulation for no loss case shows very few particles reach detector**
- Note also that detector loss is representative of all losses

Modeled loss flux vs pitch angle differs from experiment



- Model, while predicting 2 peaks at detector, does not reproduce observed variation of loss flux with pitch angle

Various refinements to model inputs have not improved agreement with measurement

- Re-fit eigenfunctions to measured n_e profile, rather than TRANSP in-out symmetrized profile
- Added electric potential due to plasma rotation
- Increased number of particles
- Varied frequency and amplitudes of modes in time to match evolution during avalanche
- Enhanced mode amplitudes by factor of 3 above observed values
- Ran simulations several times longer than actual avalanche duration
- <u>None of these gave better agreement with pitch angle range of losses</u>
- **Suggests eigenfunctions are inaccurate in some way**

Summary

- TAE avalanches in similar NSTX plasmas sometimes produce observable fast ion loss at wall and sometimes do not
- To pursue differences between loss seen vs unseen, measured TAE amplitudes and structures were put into ORBIT code to compute stochastic orbit domains
- Loss appears at a given pitch angle only if:
  - Beam deposited in stochastic region
  - Stochasticity extends all the way to the loss boundary along the line of transport, with no intervening good surfaces
- Loss distribution at detector in ORBIT model shows 2 groups of lost particles, in agreement with measurement
- Beyond this qualitative agreement, there are some differences between model and experiment
- Fitted eigenfunctions may not represent real ones accurately

Future work

- Try newly-developed method of transferring eigenfunctions to ORBIT—avoids potential for singularities in evaluation of modes and their derivatives
- Investigate effect of beam ion transport and loss on beam driven current
- Extend analysis methods to the frequent EPM bursts that occur during I_p ramp up phase