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

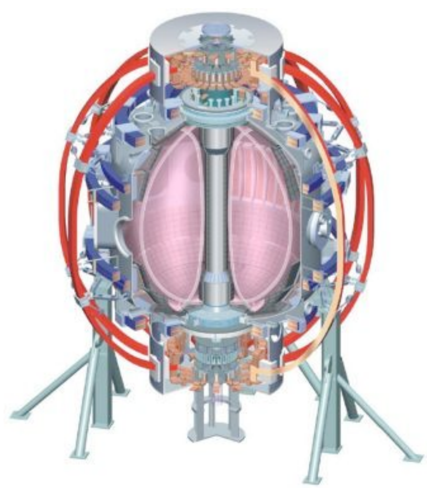
Comparison of Measurements and Modeling of Beam Ion Loss During TAE Avalanches in NSTX

D. S. Darrow (PPPL)

N. Crocker (UCLA), E. Fredrickson (PPPL), N. Gorelenkov (PPPL), M. Podestà (PPPL), L. Shi (PPPL), R. White (PPPL)

and the NSTX Research Team

American Physical Society, Division of Plasma Physics
Salt Lake City, UT
November 14-18, 2011



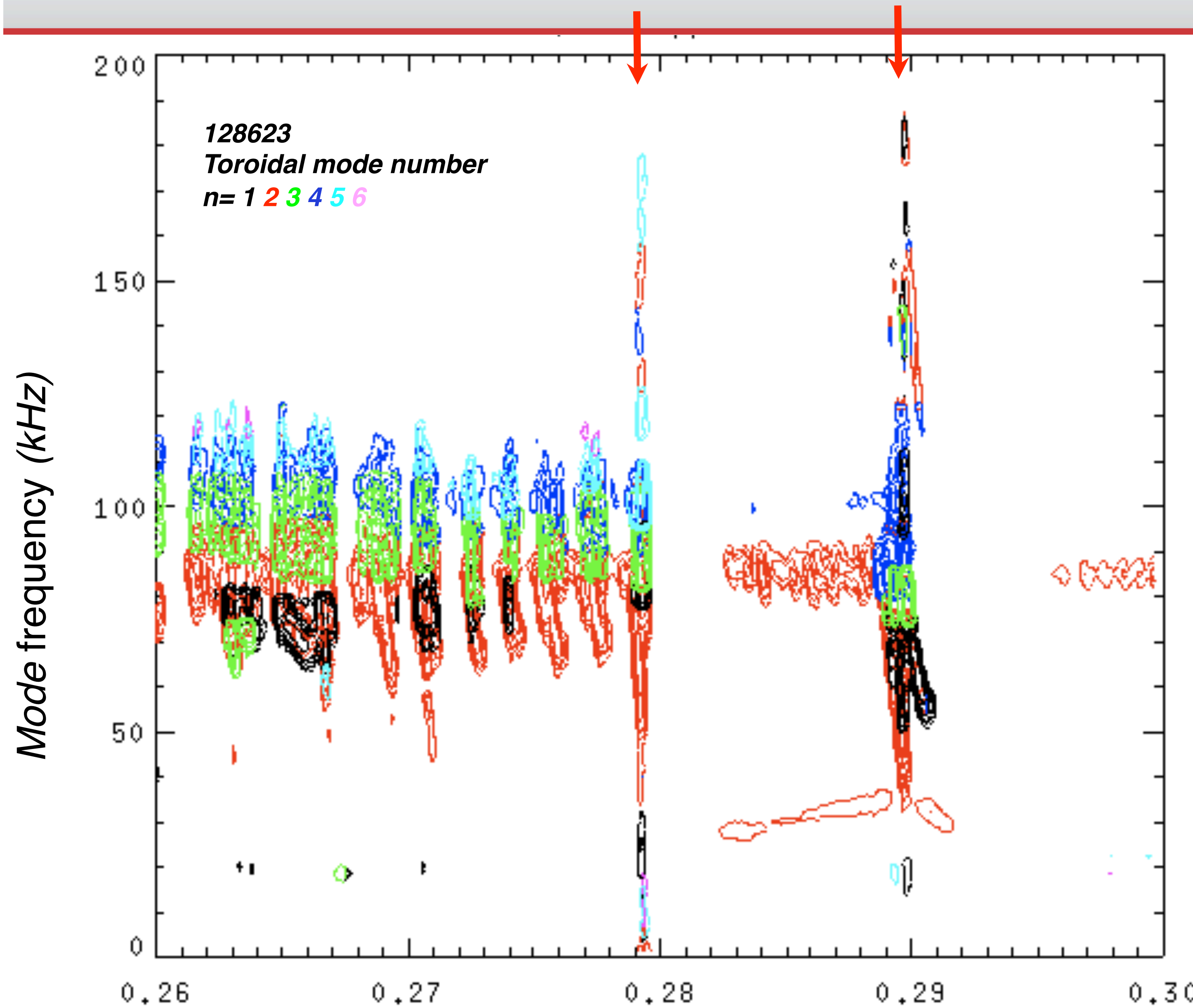
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

TAEs and avalanches

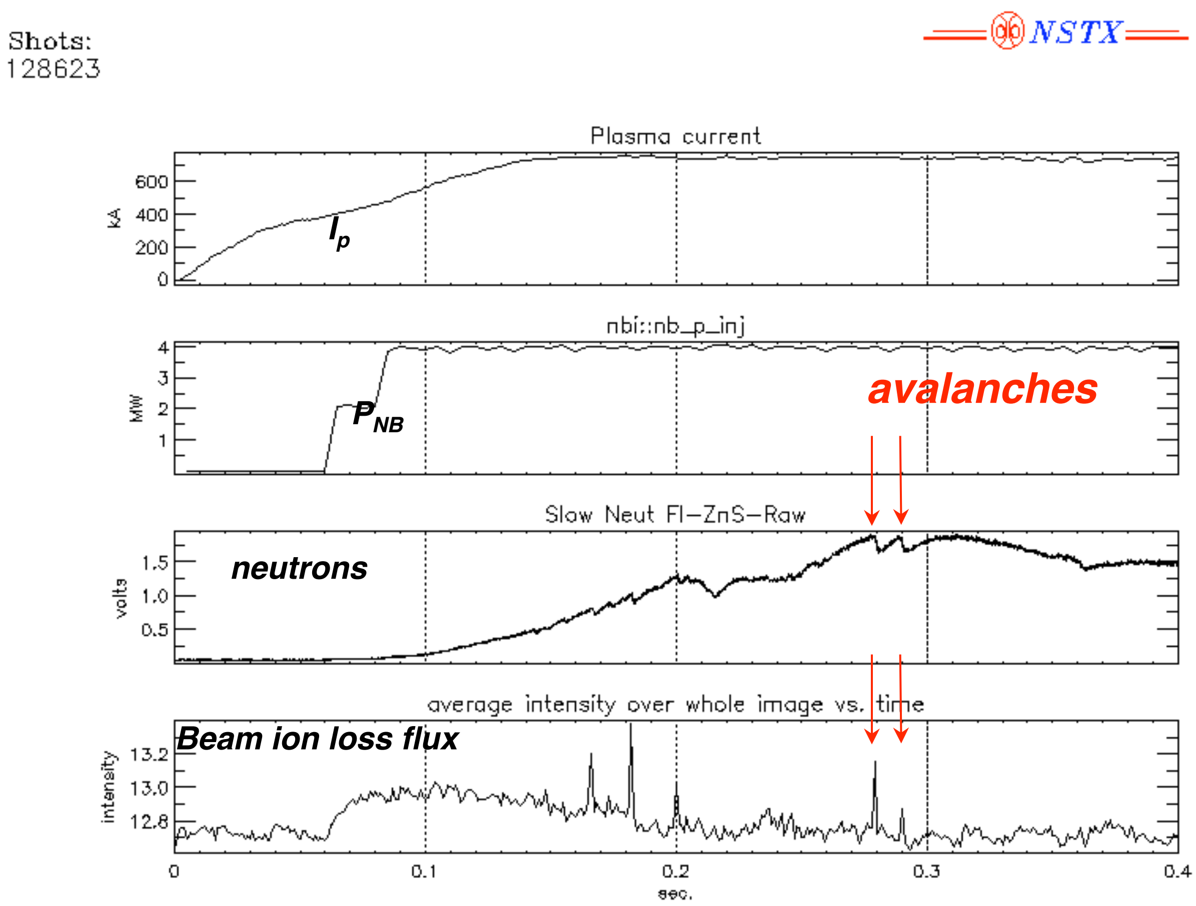
- Toroidal Alfvén eigenmodes (TAEs) are weakly damped Alfvén waves in a toroidal plasma, often driven by ions whose velocity approaches the Alfvén velocity (or a fraction thereof)
- A TAE is characterized by a toroidal mode number, n, and may occur steadily or intermittently
- A burst in which several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



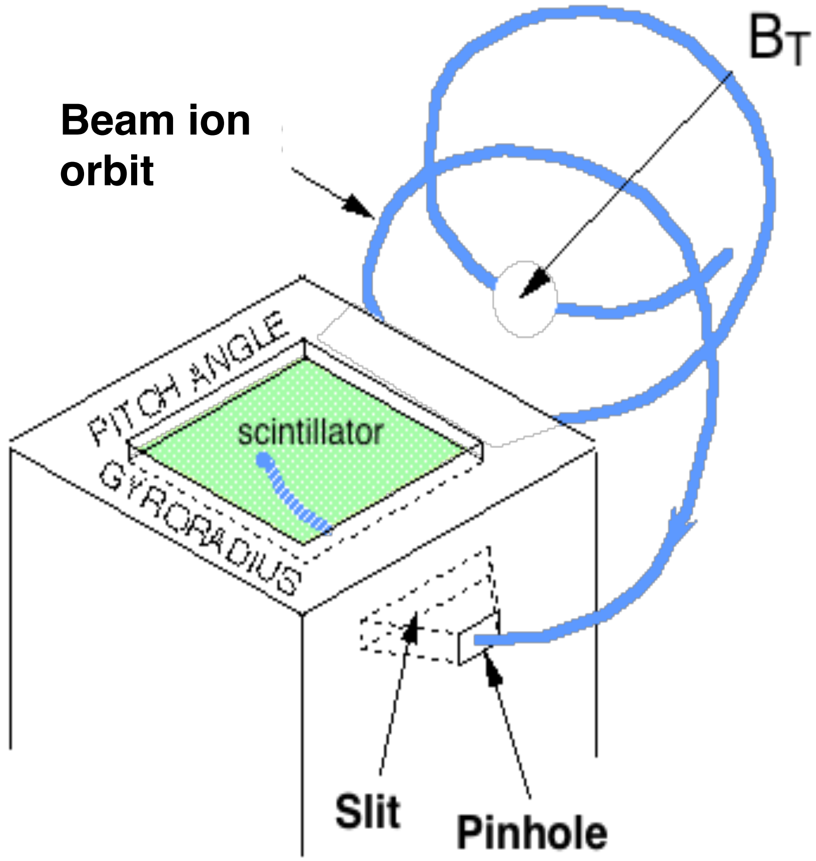
- TAEs appear as burst
- Beam ion redistribution stabilizes modes for a time

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

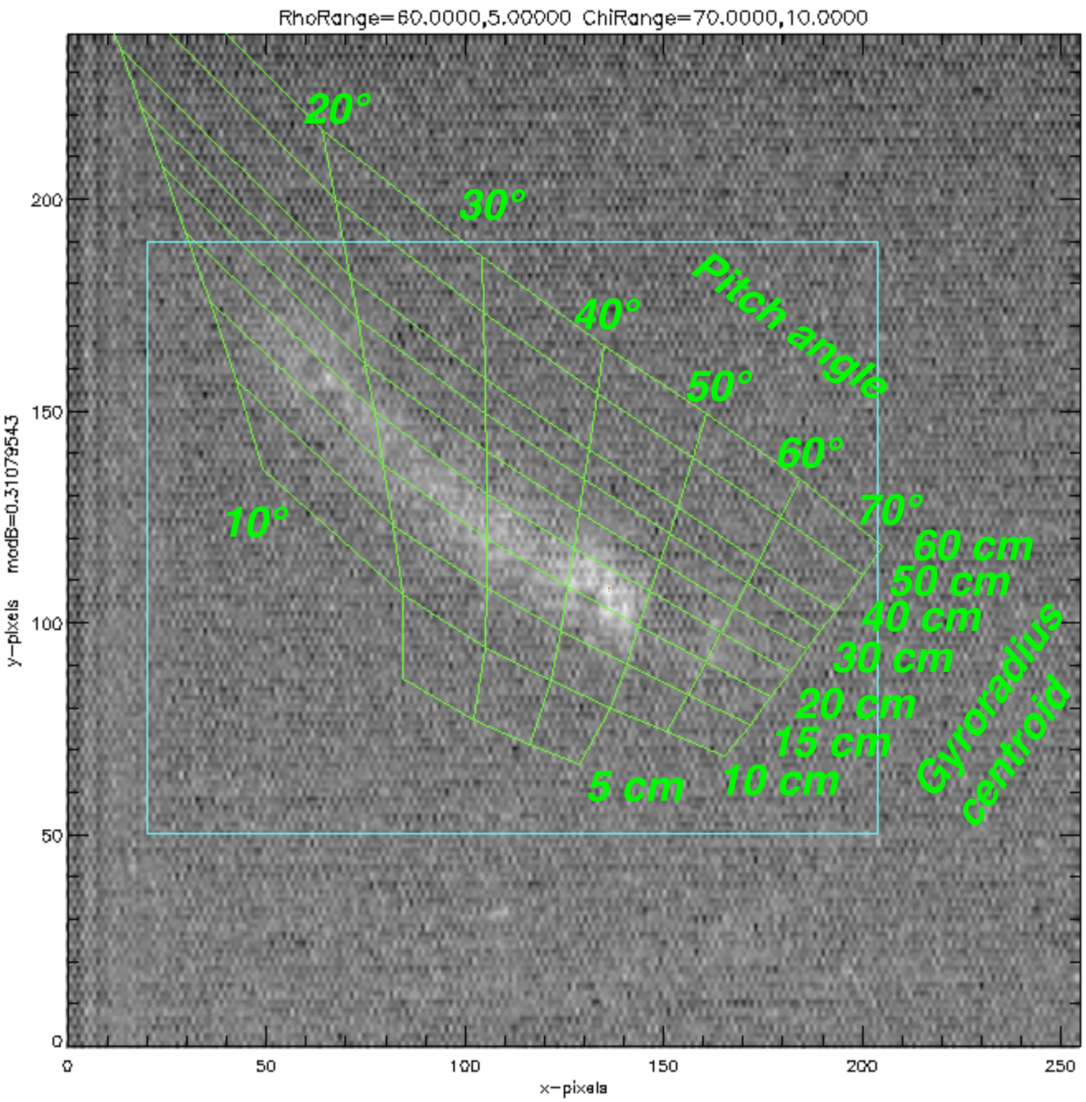
$\Gamma_{loss}(\rho, \chi, t)$

NSTX probe:

5 cm ≤ ρ ≤60 cm

15° ≤ χ ≤ 80°

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



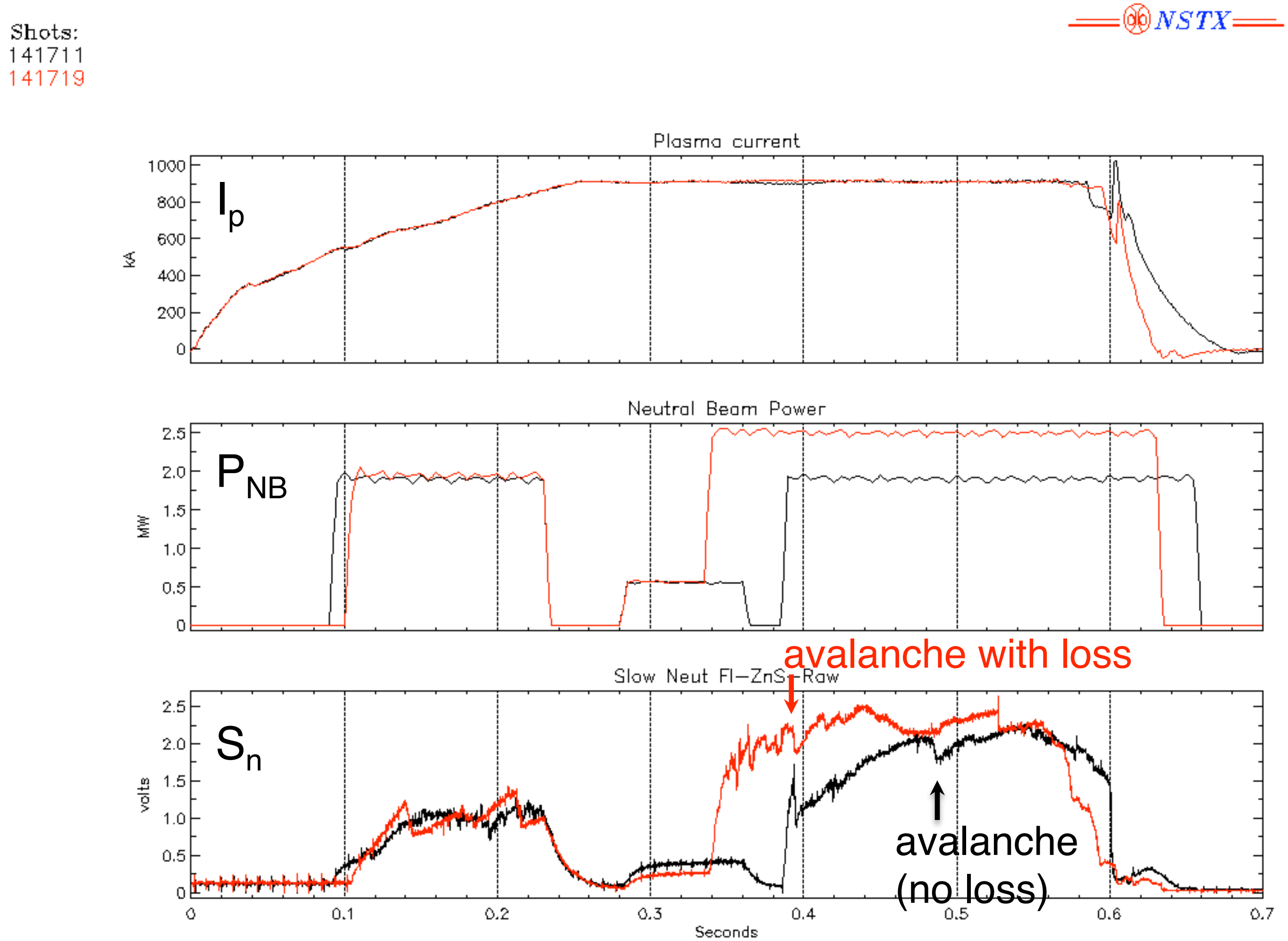
128623, 290 ms

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

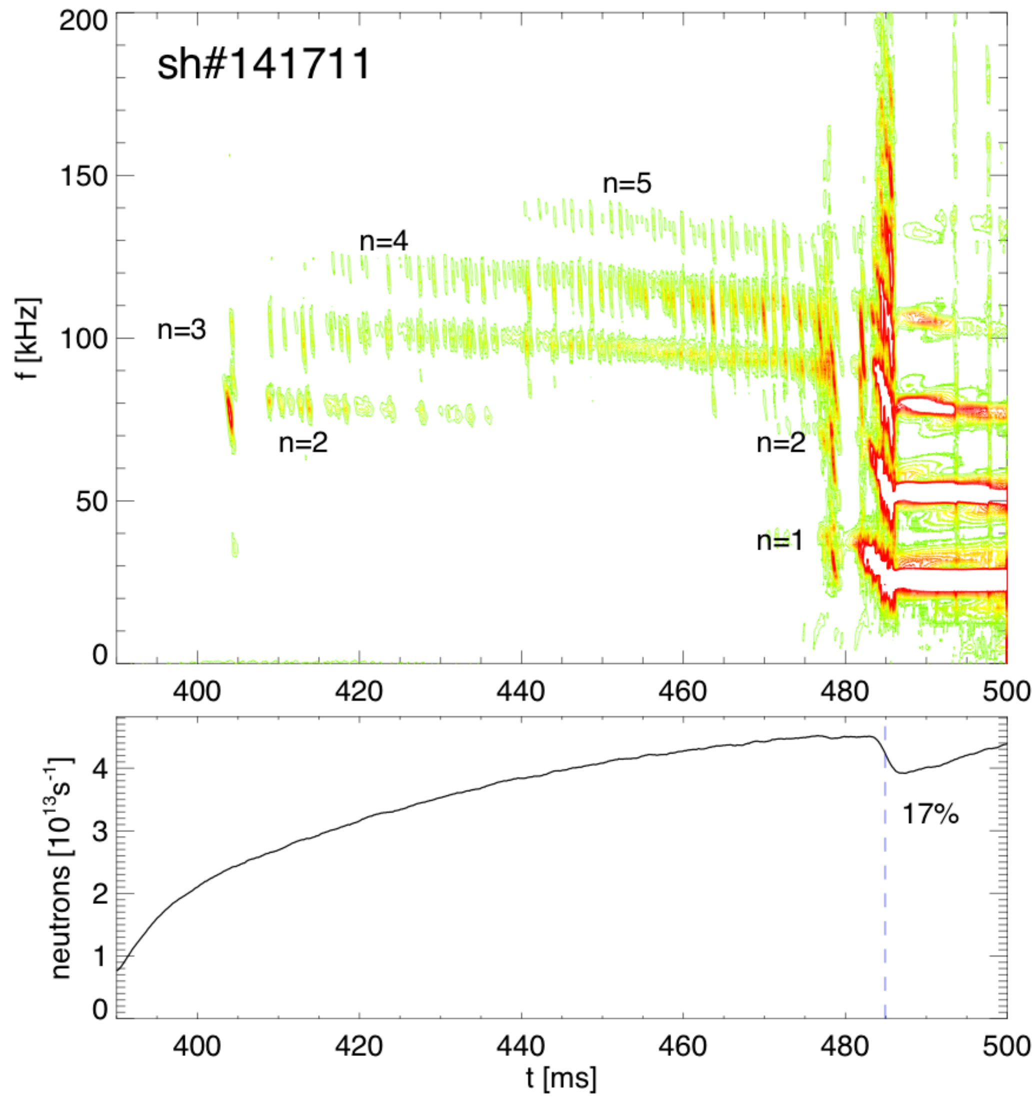
Goal: compare measured and modeled lost ion pitch angle distributions

- 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

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

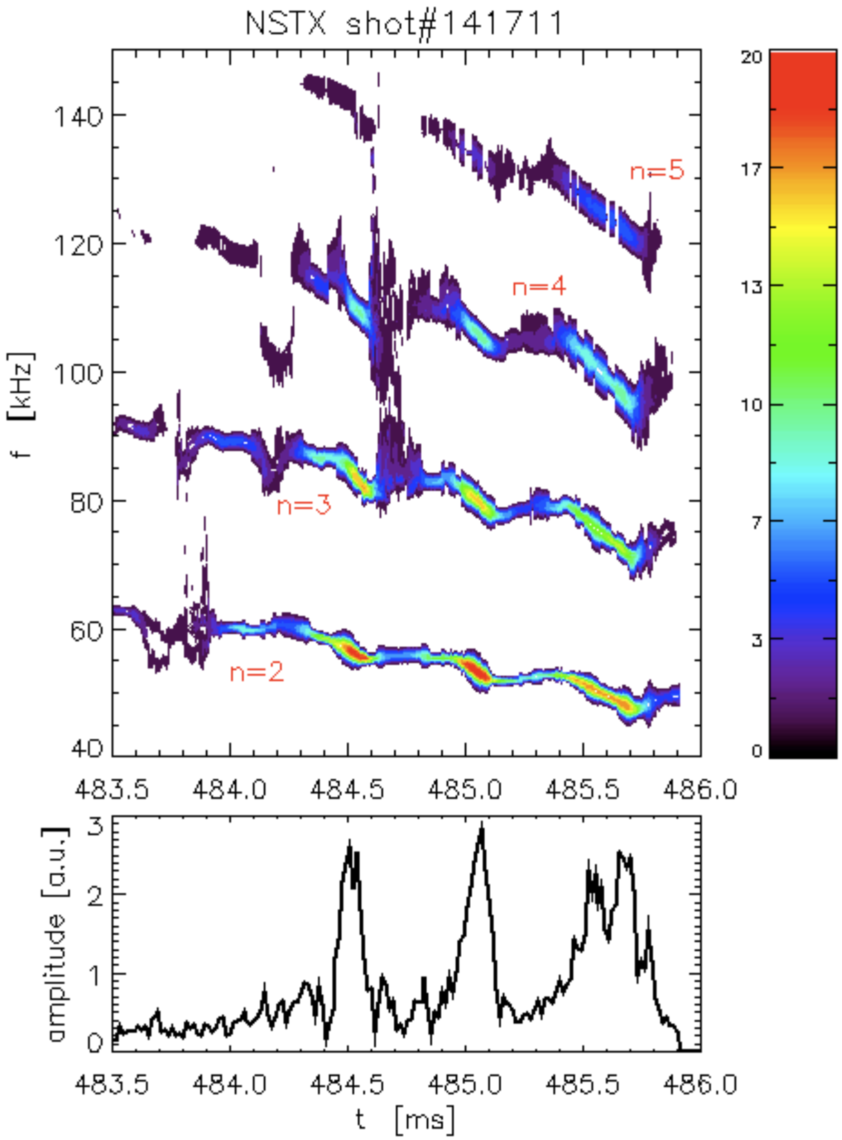


Example avalanche with no loss observed



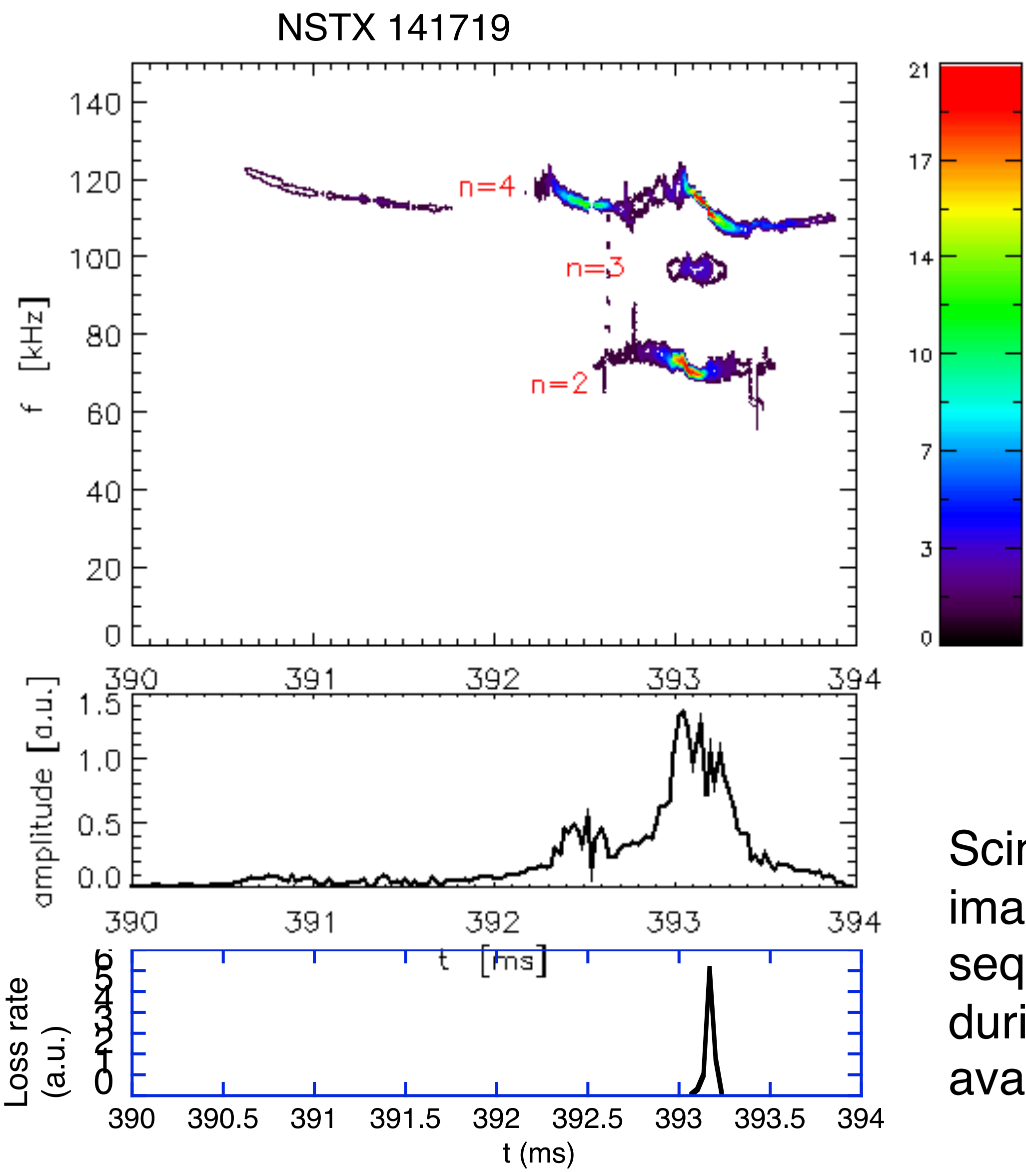
- n=2–5 present, but no loss evident on scintillator probe
- Neutron rate drops 17%
- Single beam injecting at 90 kV

Case of no observed losses

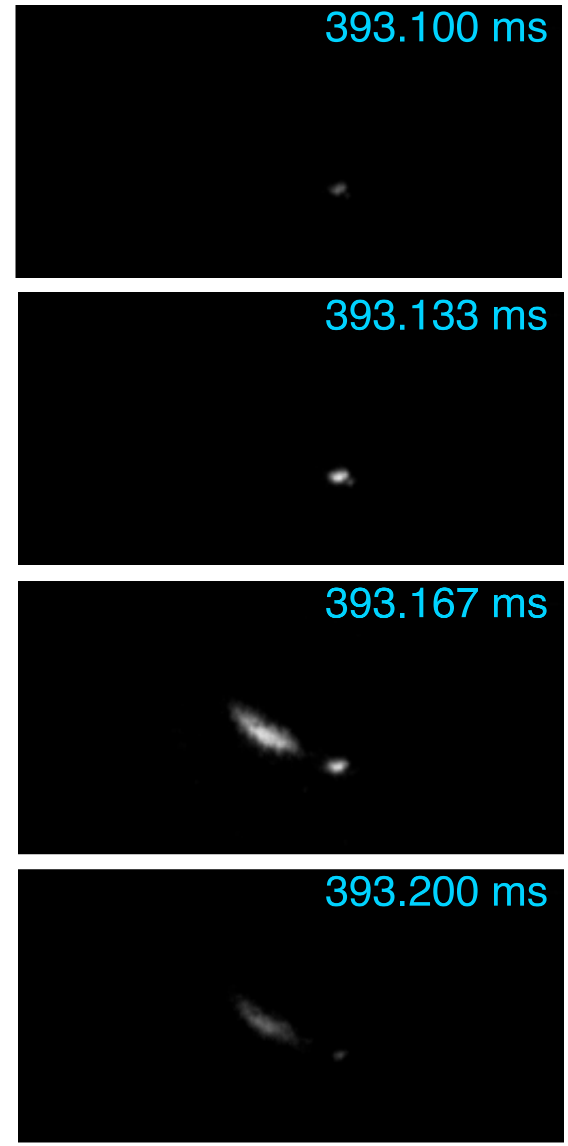


- n=2–5 concurrently present in 3 rapid bursts
- Neutron rate drops by 17%, yet no lost beam ions seen by detector
- Could there be loss, but not to detector position?
  - Possible, but see below
- Internal redistribution only?
  - Might occur if modes are more core-localized with small edge amplitudes,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

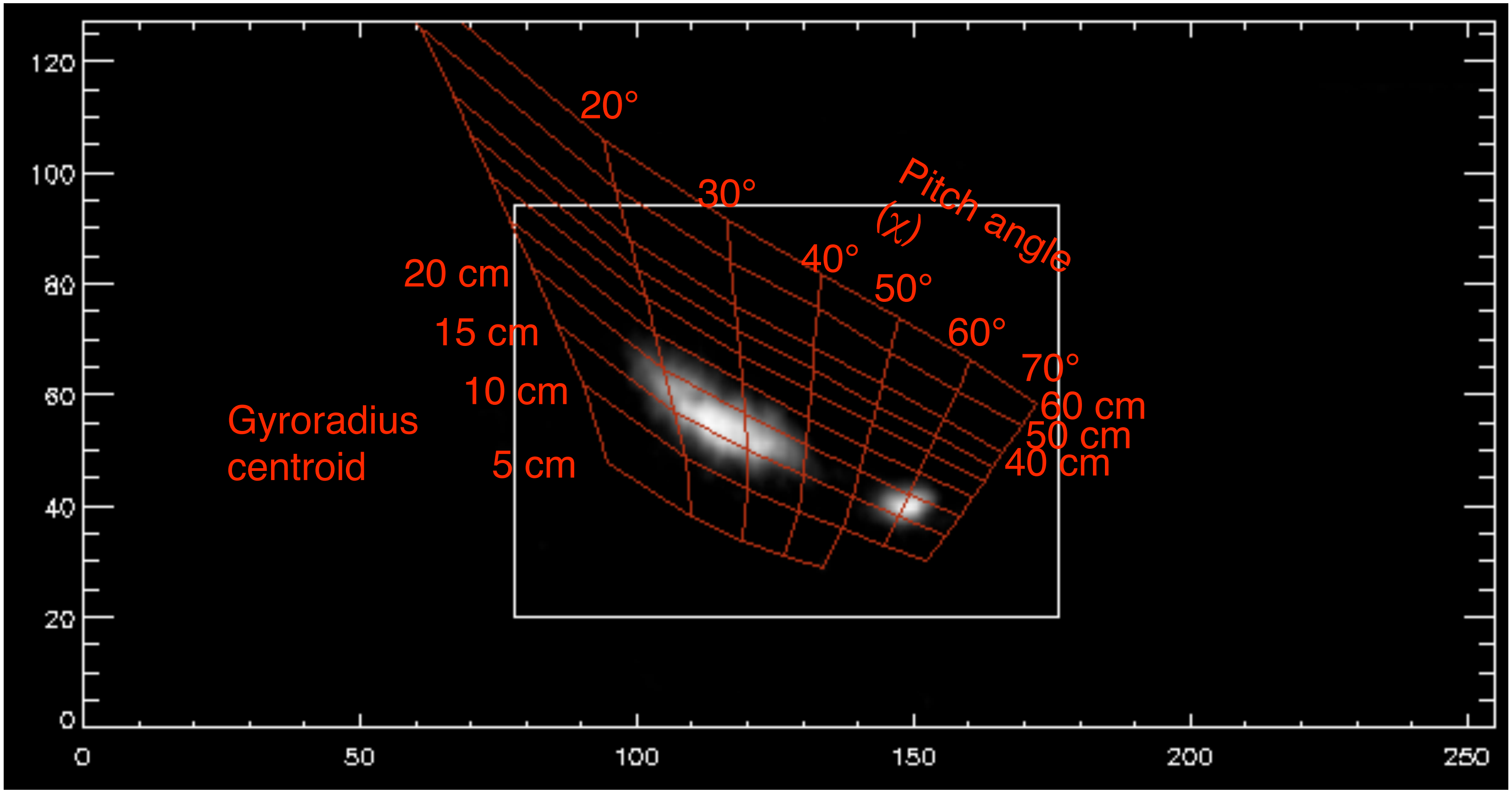
Avalanche with loss also has multiple n, and loss evolves rapidly during event



Scintillator image sequence during avalanche



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

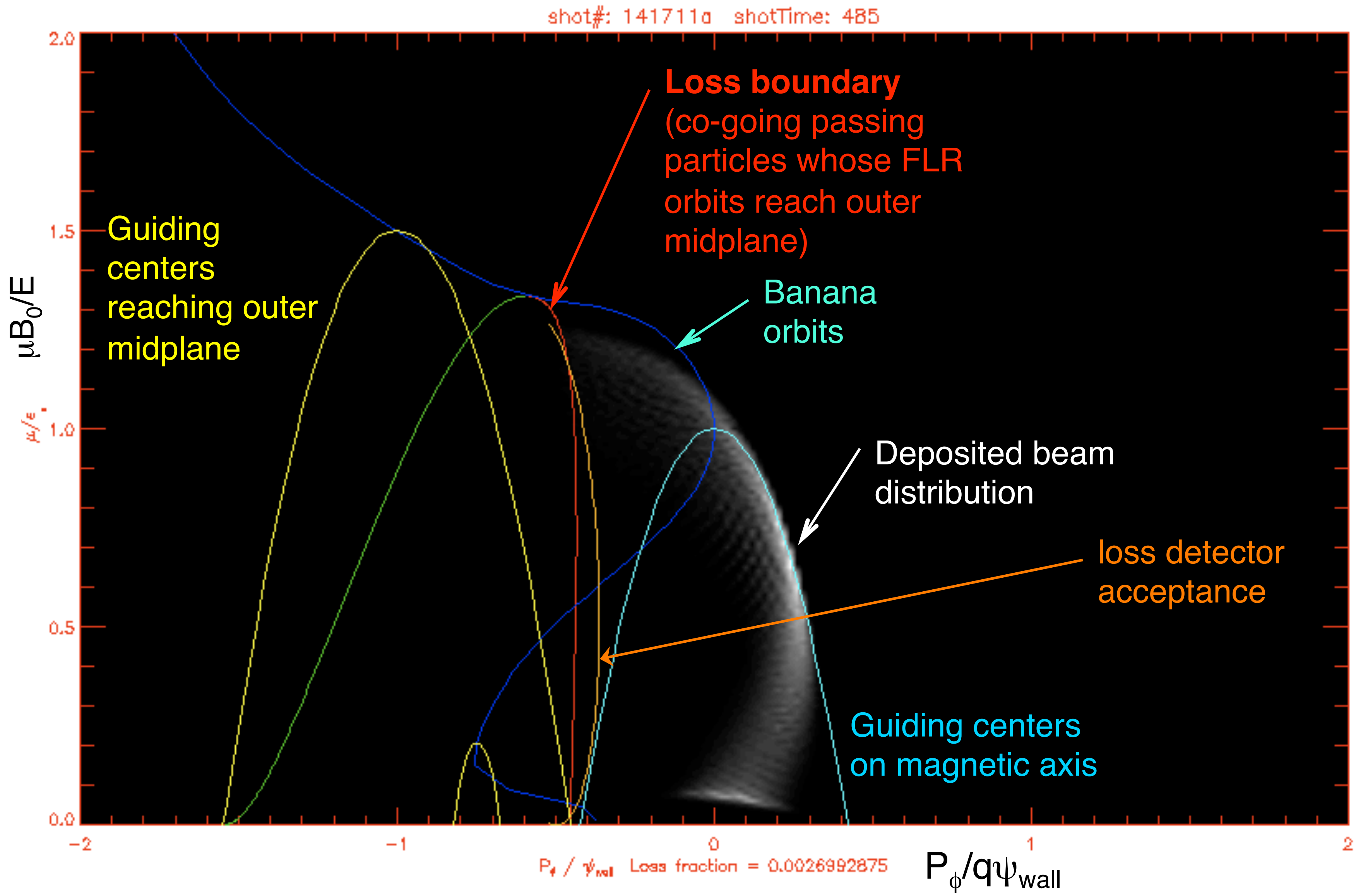


- Rapid appearance of wide pitch angle spot (18°–40°) in 33 μs (≤10 toroidal transits) indicates transport of fast ions is very strong during avalanche

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

- $E = \frac{1}{2} mv^2$ (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) (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

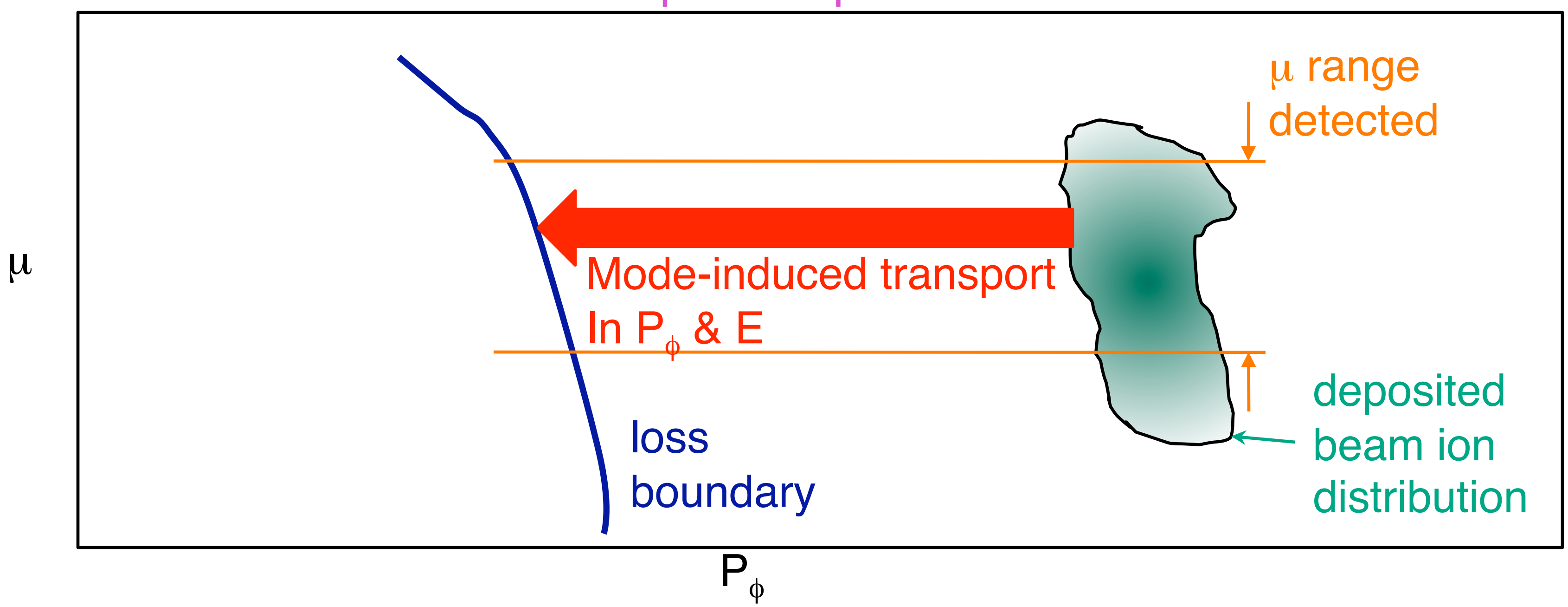
Deposited full energy beam distribution can be represented in (μ, P_ϕ) space, along with certain phase space boundaries



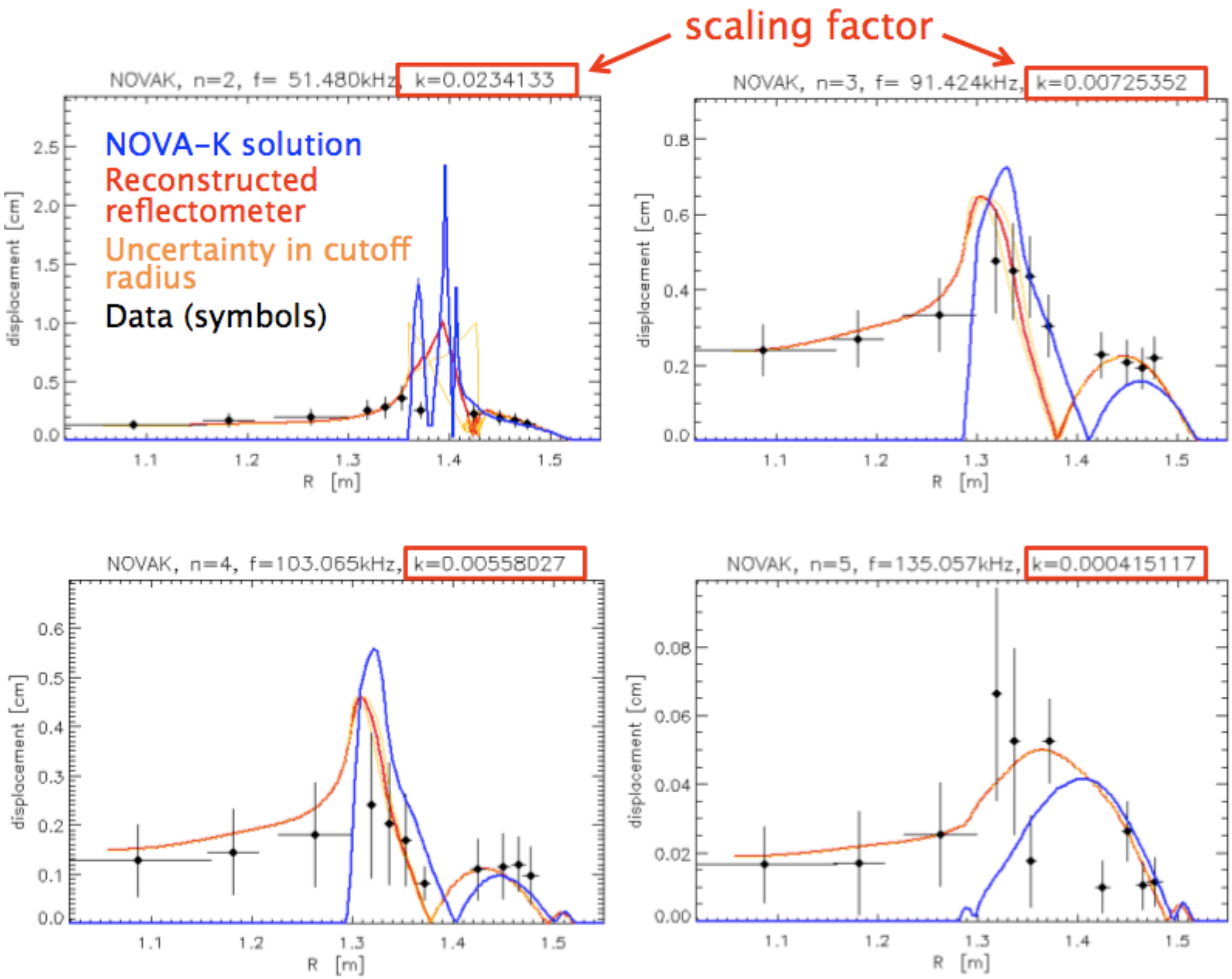
Phase space model also helps understand MHD loss

- Observed MHD frequencies $<<\Omega_{ci}$, so μ will be conserved
- Mode destroys toroidal symmetry, so P_ϕ no longer constant
- 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

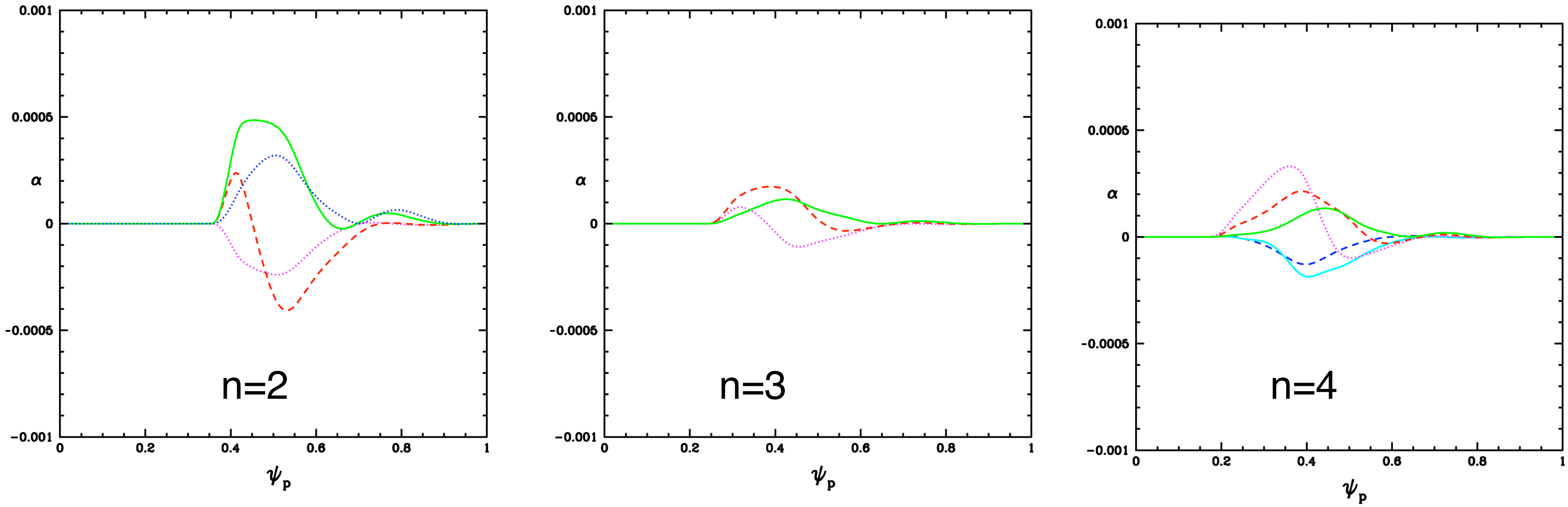


NOVA-K TAE radial eigenfunctions can be fit to reflectometer fluctuation profiles of principal modes



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

In this avalanche, n=2 has largest amplitude

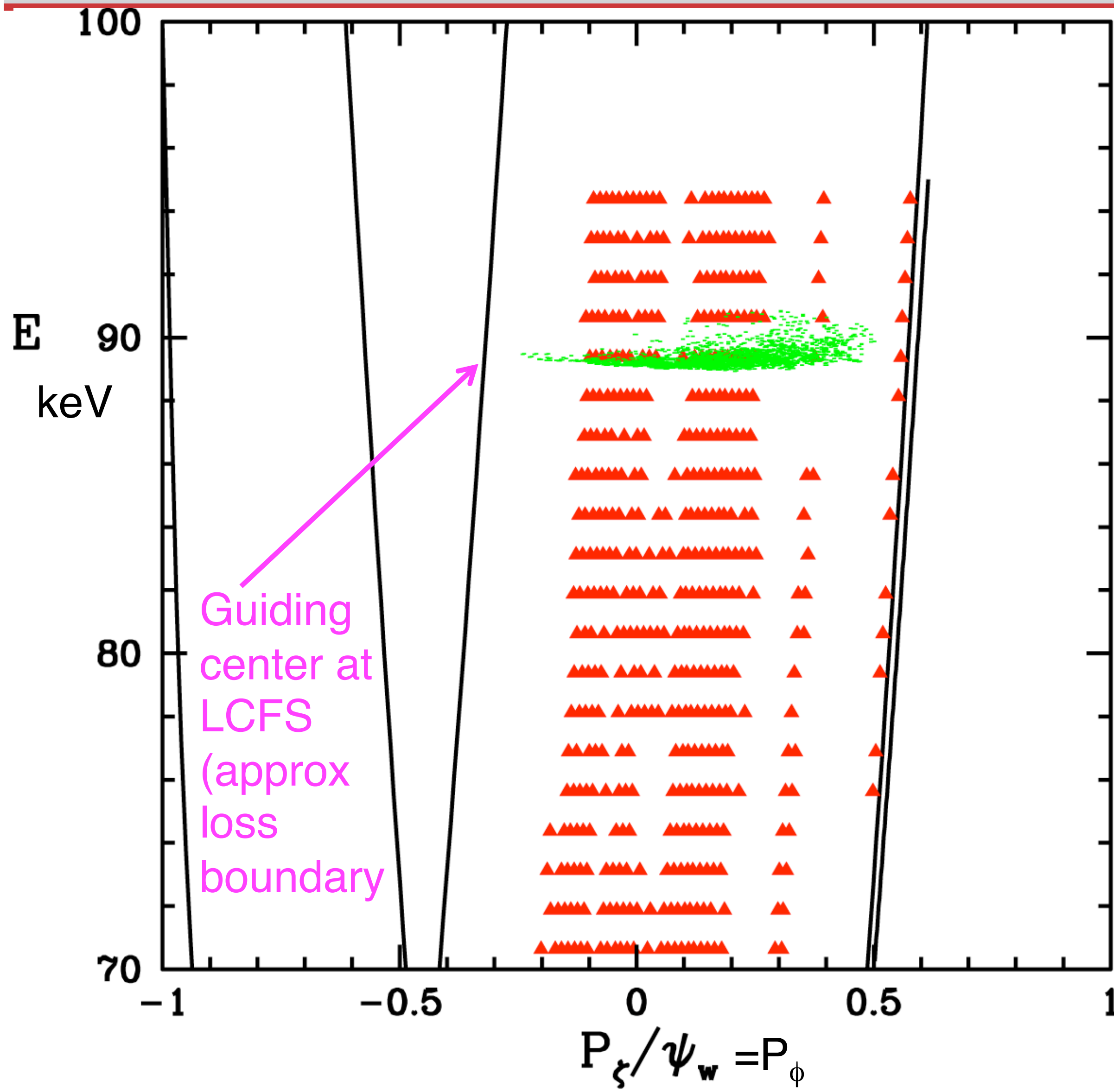


- n=2 also has the largest amplitude near edge, likely contributing to NBI loss

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 a number of toroidal transits
- If 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
- Since losses are near injection energy, overlay full energy beam particle deposition on stochastic region map to ascertain which particles may be lost via this channel

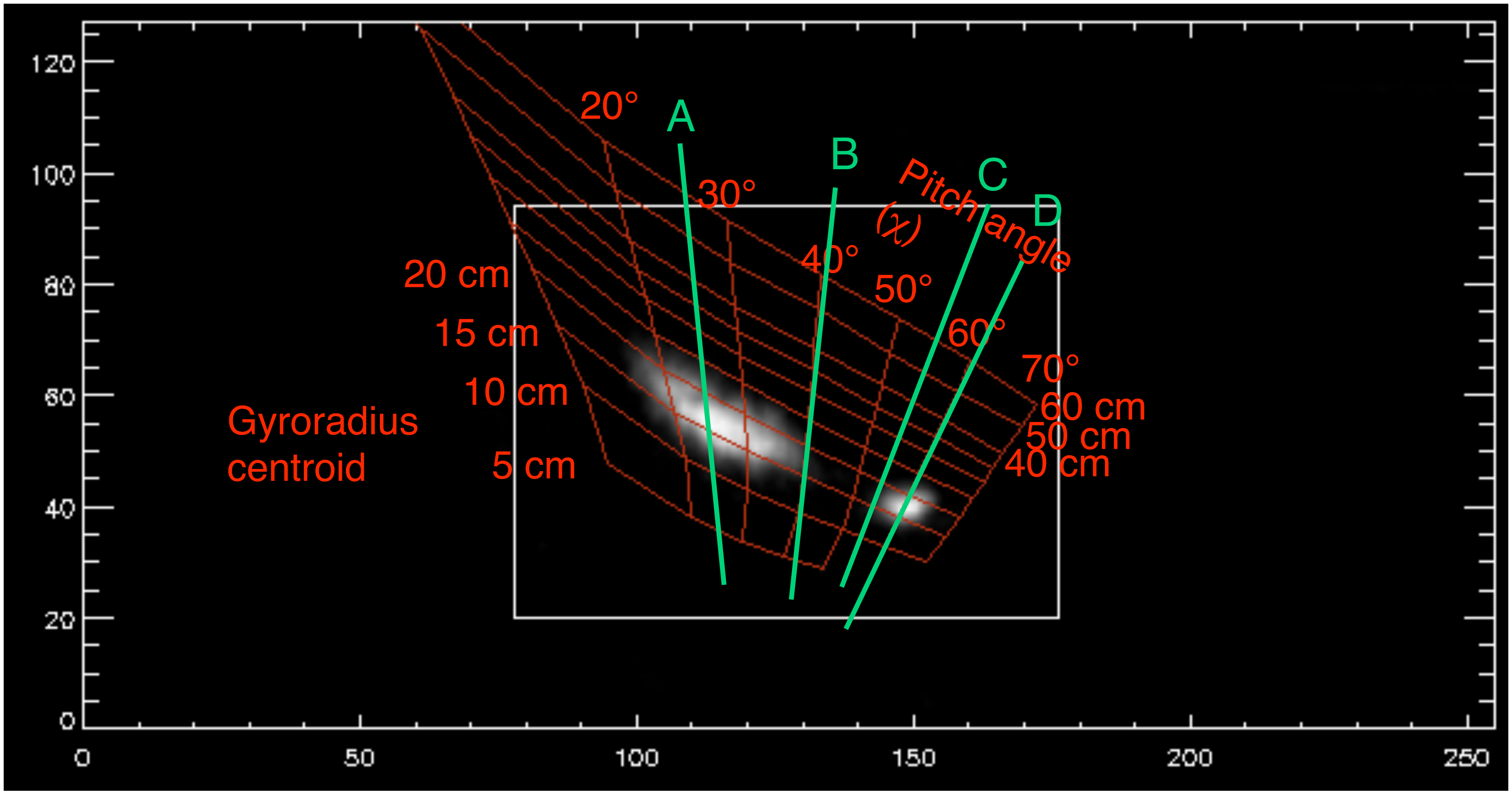
Example plot of stochastic domains at fixed μ



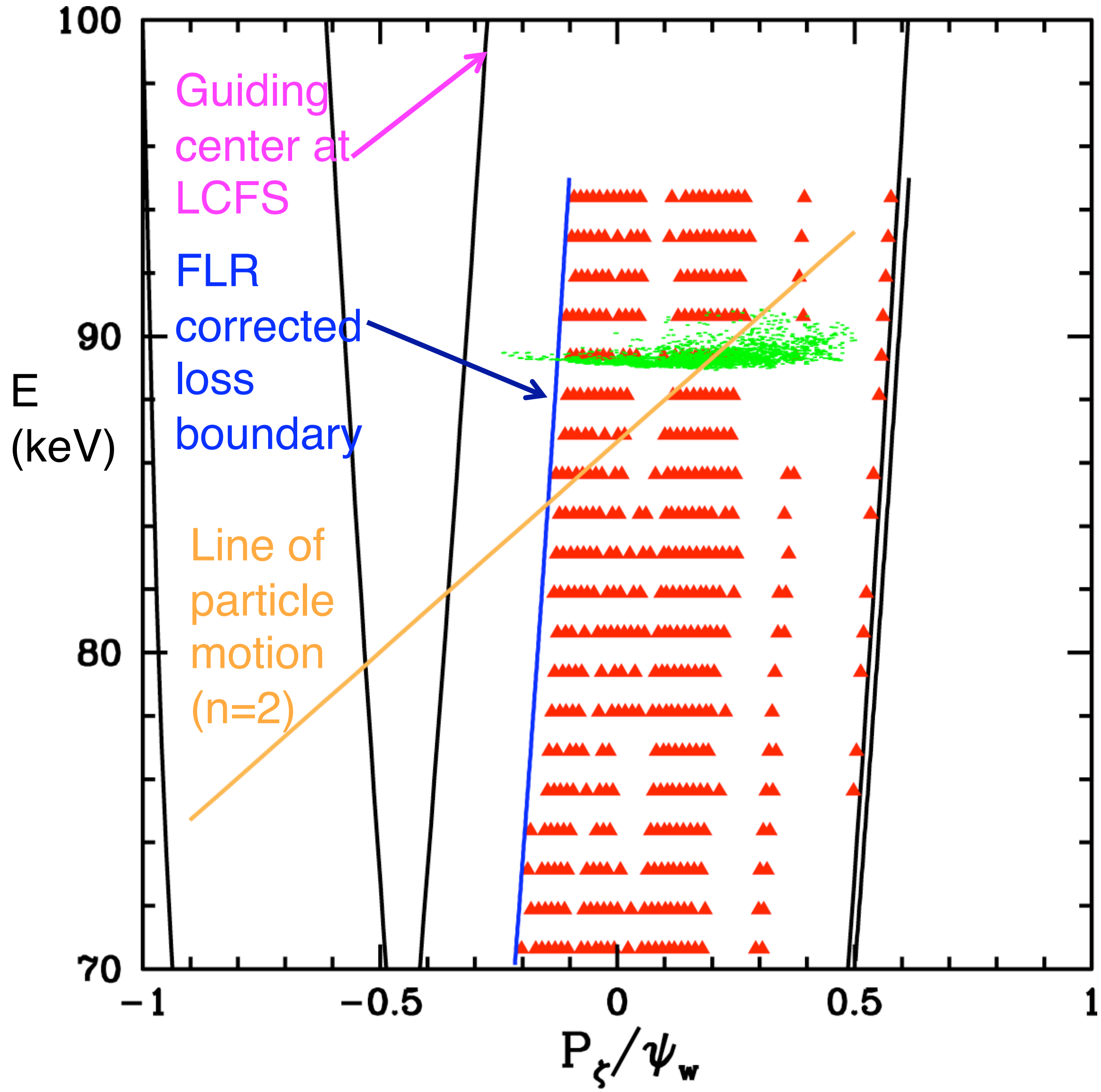
- Evaluate stochastic condition on grid in (E, P_ϕ) plane
- Red triangles mark stochastic locations
- White space extending in P_ϕ direction indicates good surfaces in phase space with no stochasticity
- Green points: TRANSP deposited beam ions

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)

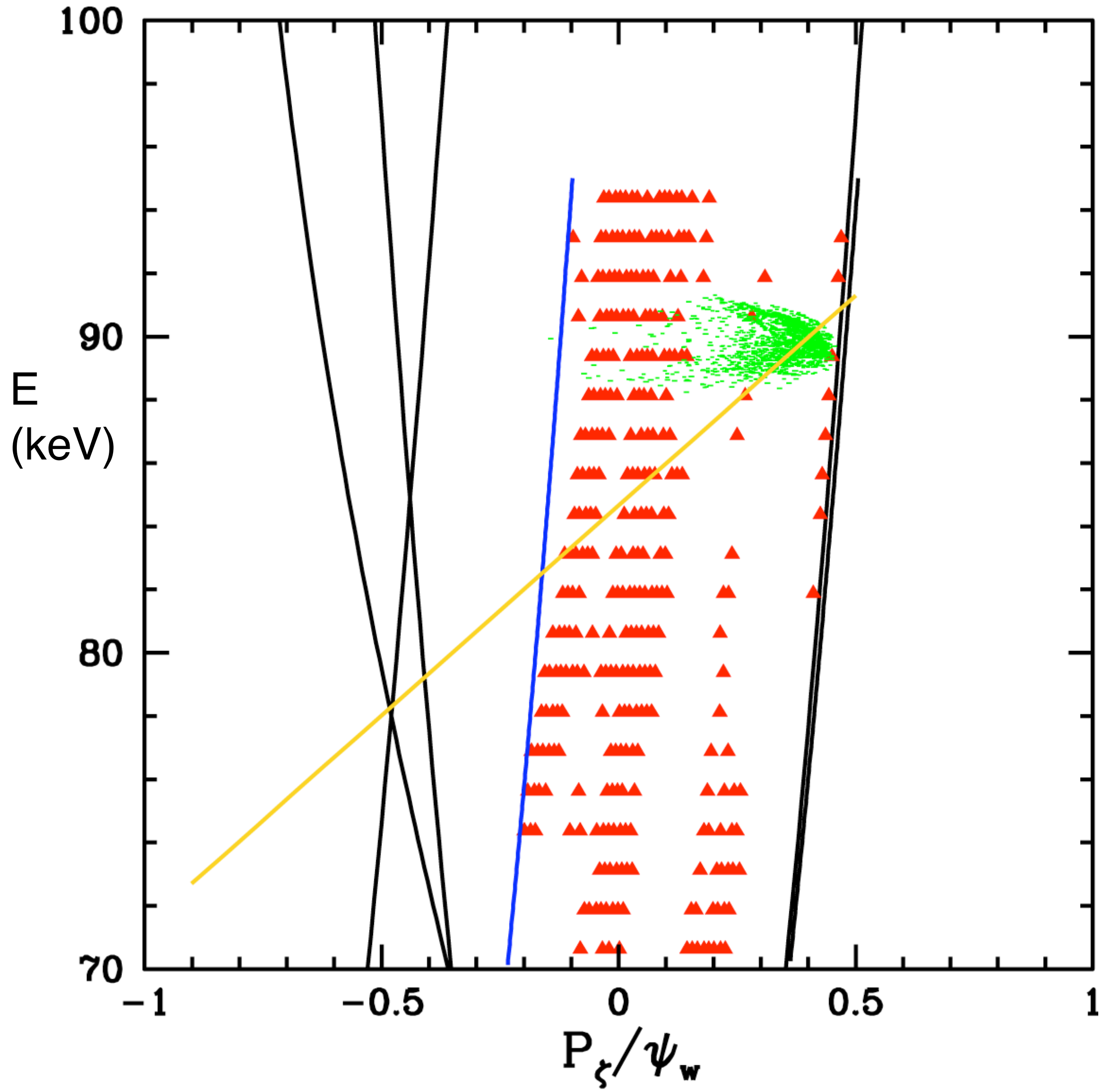


Case A (25°) is center of a detected loss spot & model predicts loss



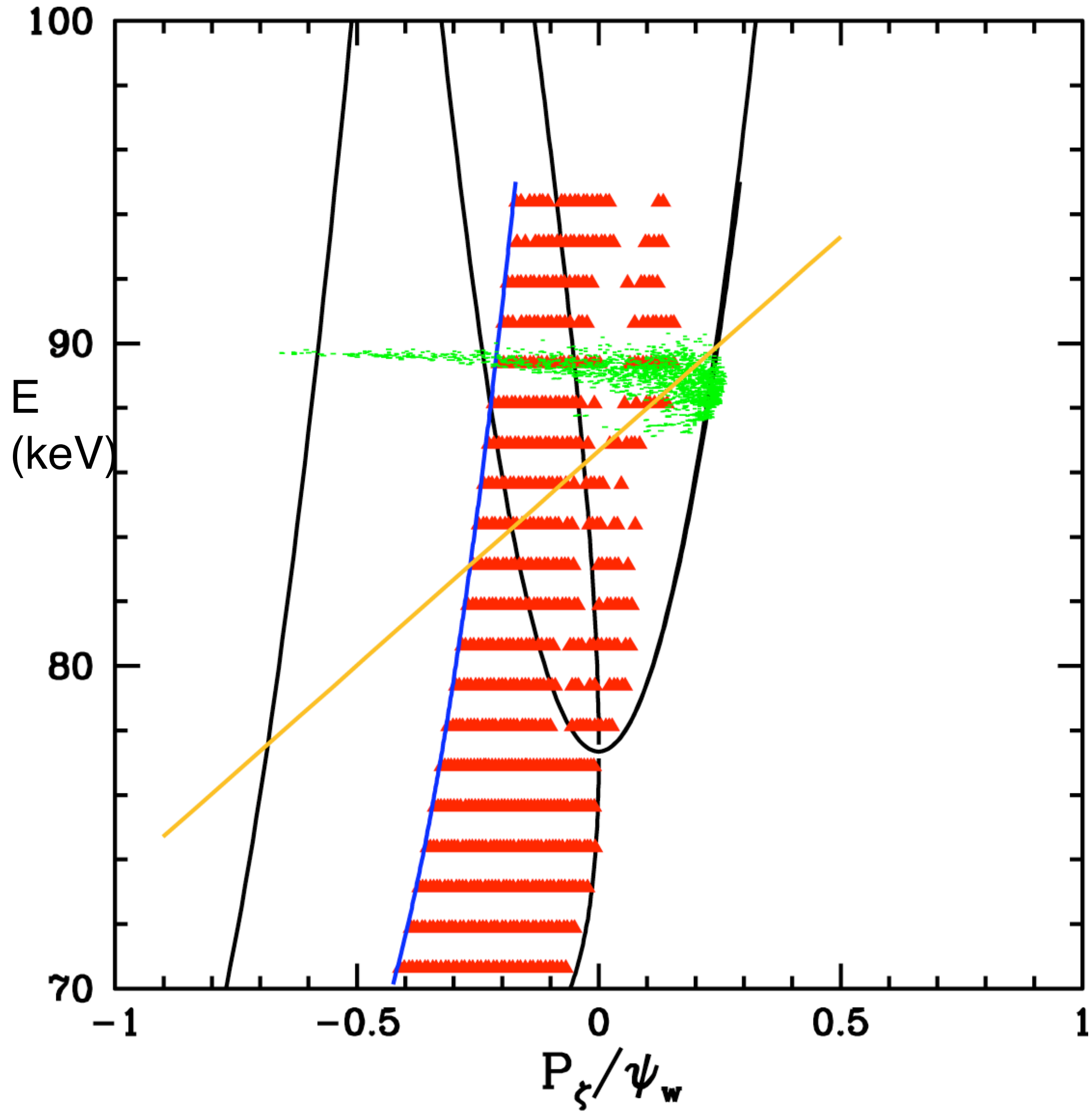
- Beam ions deposited in stochastic region
- Particles move along orange line (or parallel lines) under influence of n=2 mode
- Particles clearly deposited in stochastic region and that region extends to loss boundary

Case B (40°) is at boundary of no-loss region & model shows deposition only on good surfaces



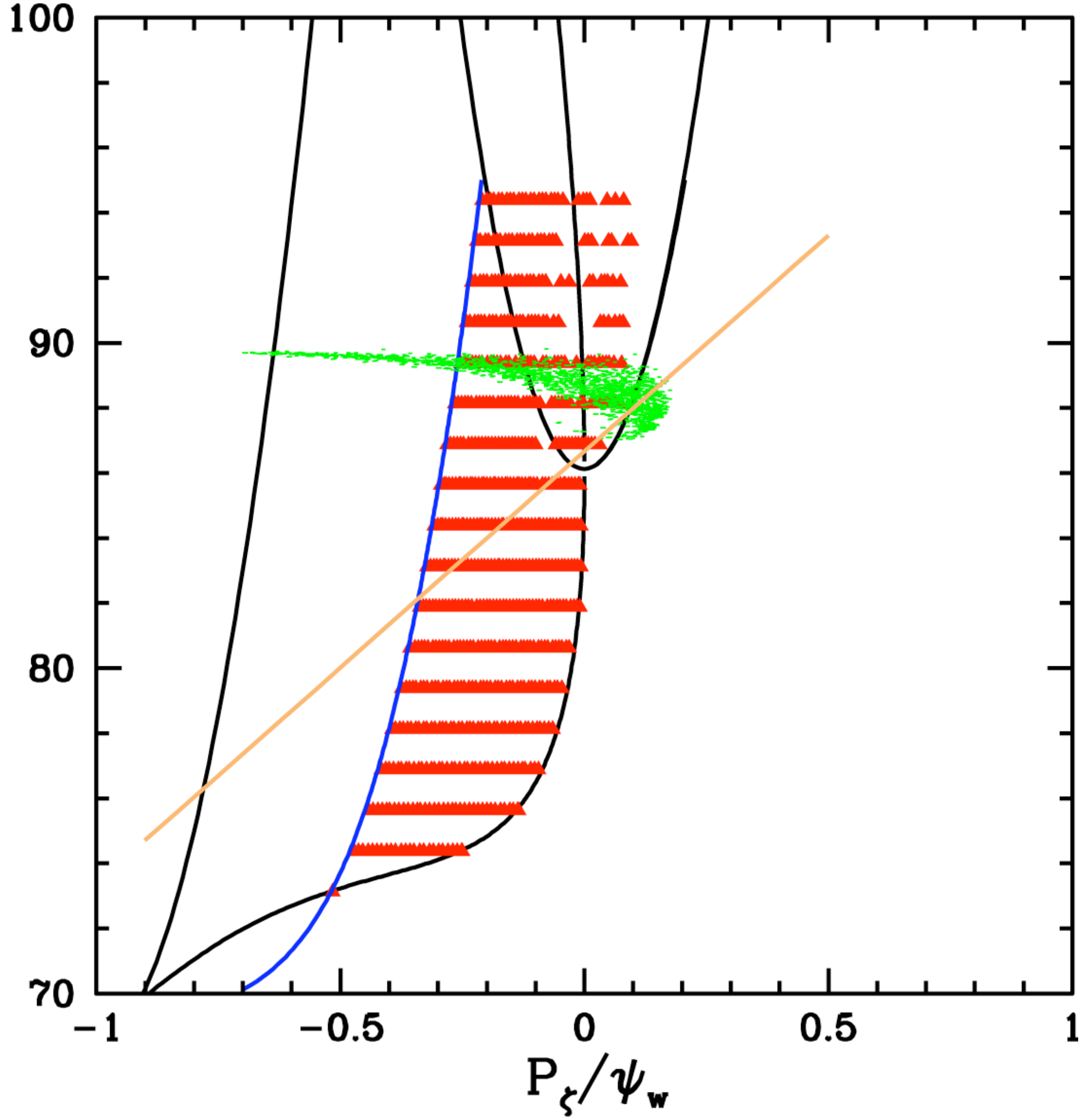
- Deposition in a region of good surfaces in phase space means beam ions have no chance to be transported to loss boundary, even though stochasticity exists at other locations
- Agrees with transition to no-loss pitch angle range

Case C (55°) is at boundary of a loss spot; deposition starts to appear in stochastic region again



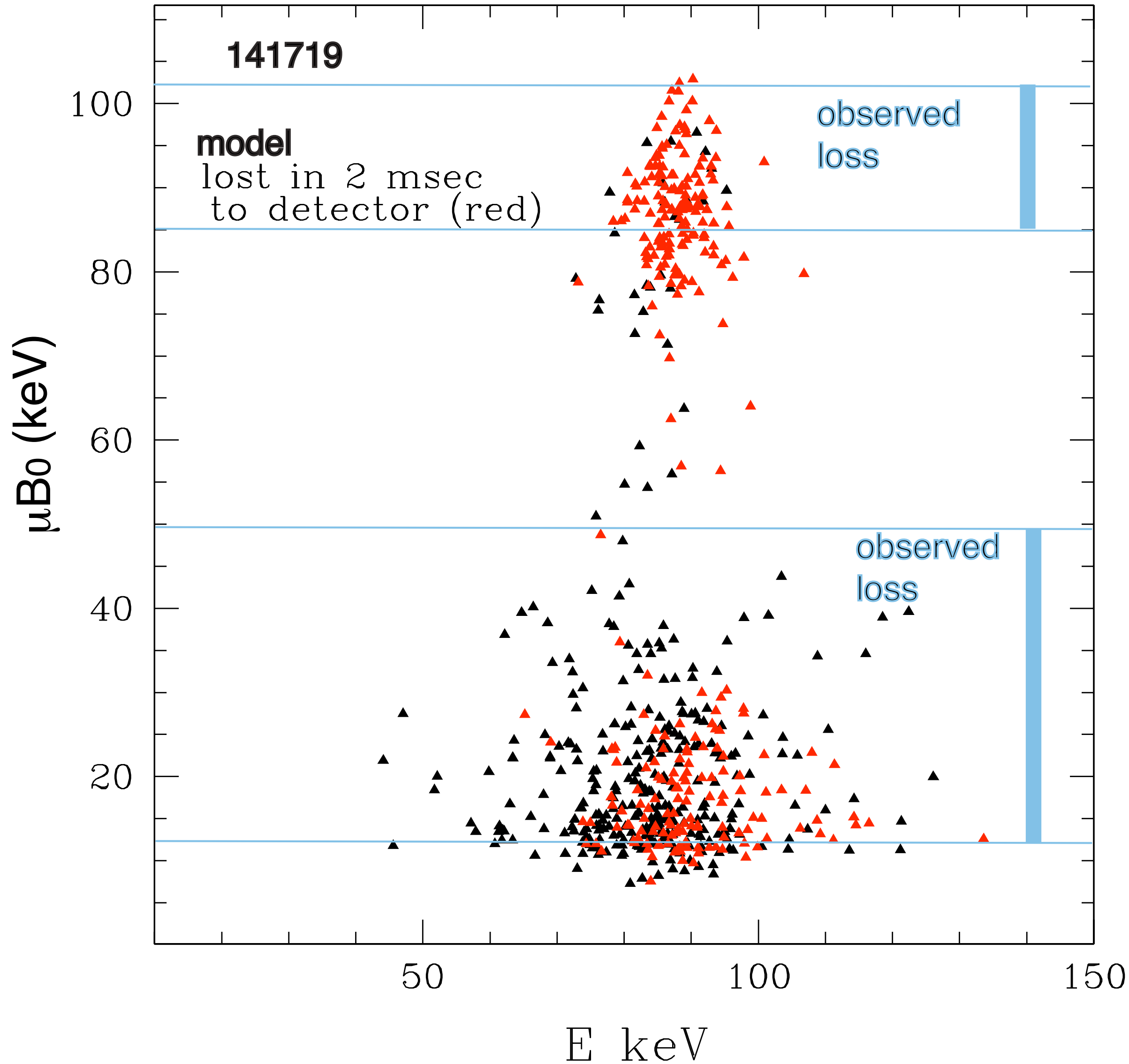
- Apparent good surfaces around P_ζ=0 & E> 85 keV may prevent some of deposited population from reaching loss boundary

Case D (60°) is in middle of loss spot; deposition squarely in stochastic region again



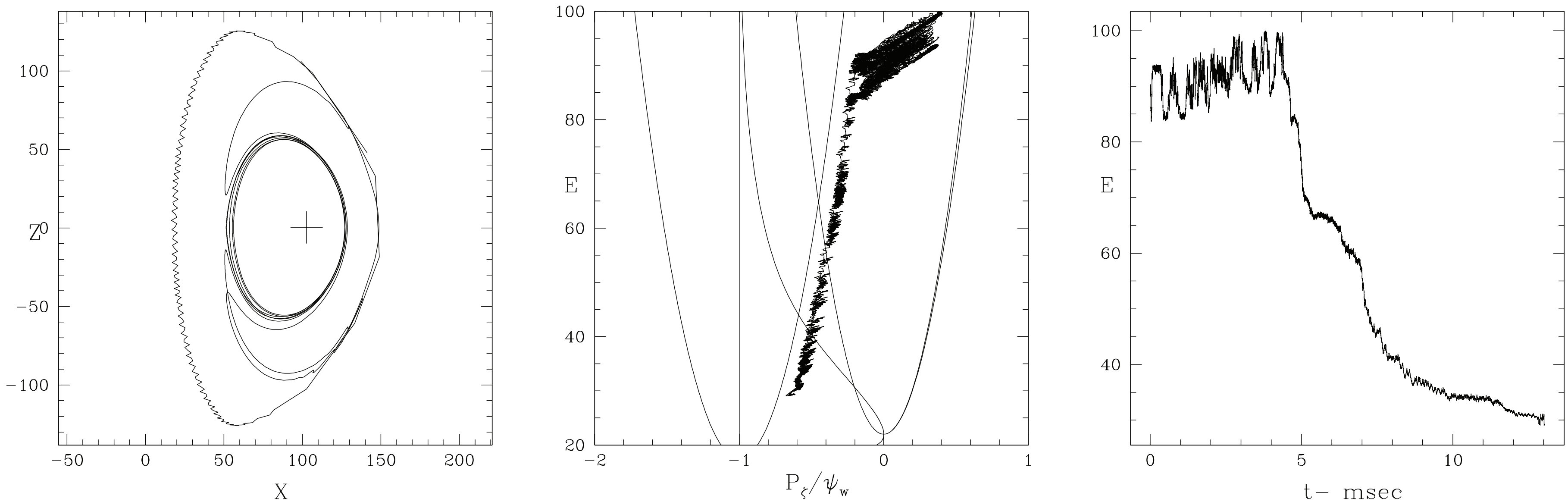
- Note that deposition is in stochastic region and that stochasticity exists along entire line of transport up to loss boundary
- Both conditions required for loss

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



- Modeled pitch angle boundaries roughly agree with measurement
- Same simulation for no loss case shows no particles reach detector!
- Note also that detector loss (red points) is representative of all losses (black points)

Modeling reveals some beam ions that remain barely confined while their energy is greatly diminished by modes



- Example is for particle in no loss shot (141711)
- Particle above starts passing, later becomes banana orbit
- Trajectory in (E, P_ϕ) plane skirts loss boundary, but stays confined
- Energy drops from 90 keV to 30 keV before loss
- Neutron reactivity drops rapidly as energy falls below 90 keV
- What features of modes cause this?

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
- Modeling reveals some beam orbits rapidly lose energy in avalanche but remain confined–may explain cases when no loss observed