NSTX-U

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

Effect of TAE avalanches & energetic particle mode bursts in NSTX on neutral beam ion confinement, loss & current drive

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
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 Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

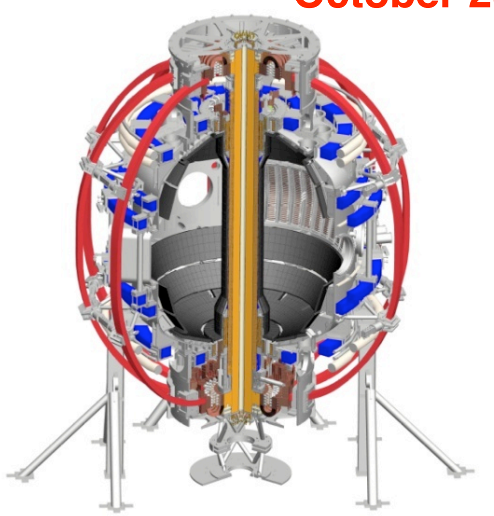
D. S. Darrow (PPPL)

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

and the NSTX Research Team

American Physical Society, Division of Plasma Physics Meeting, Providence, RI

October 29-November 2, 2012

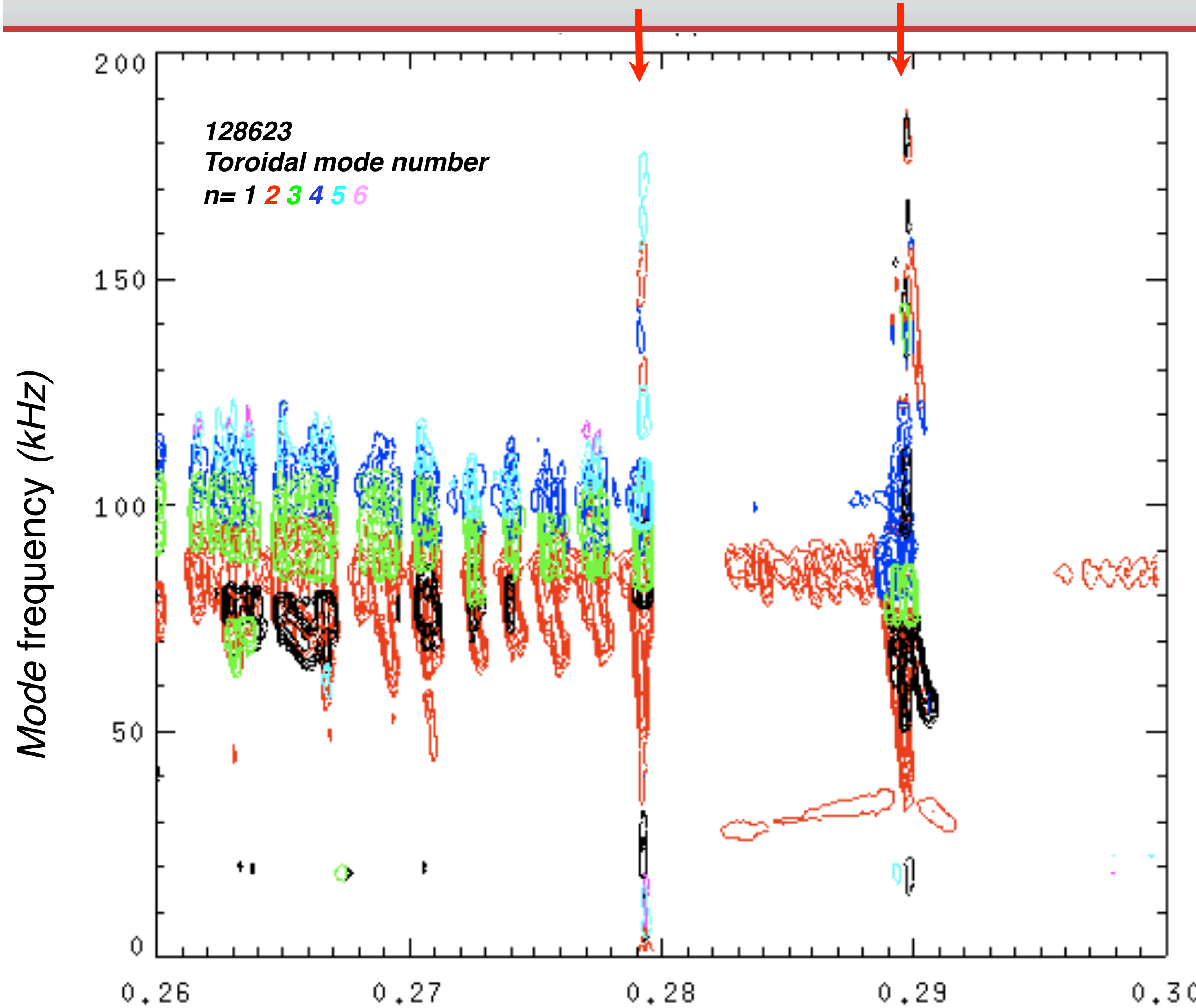


Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

TAEs and avalanches

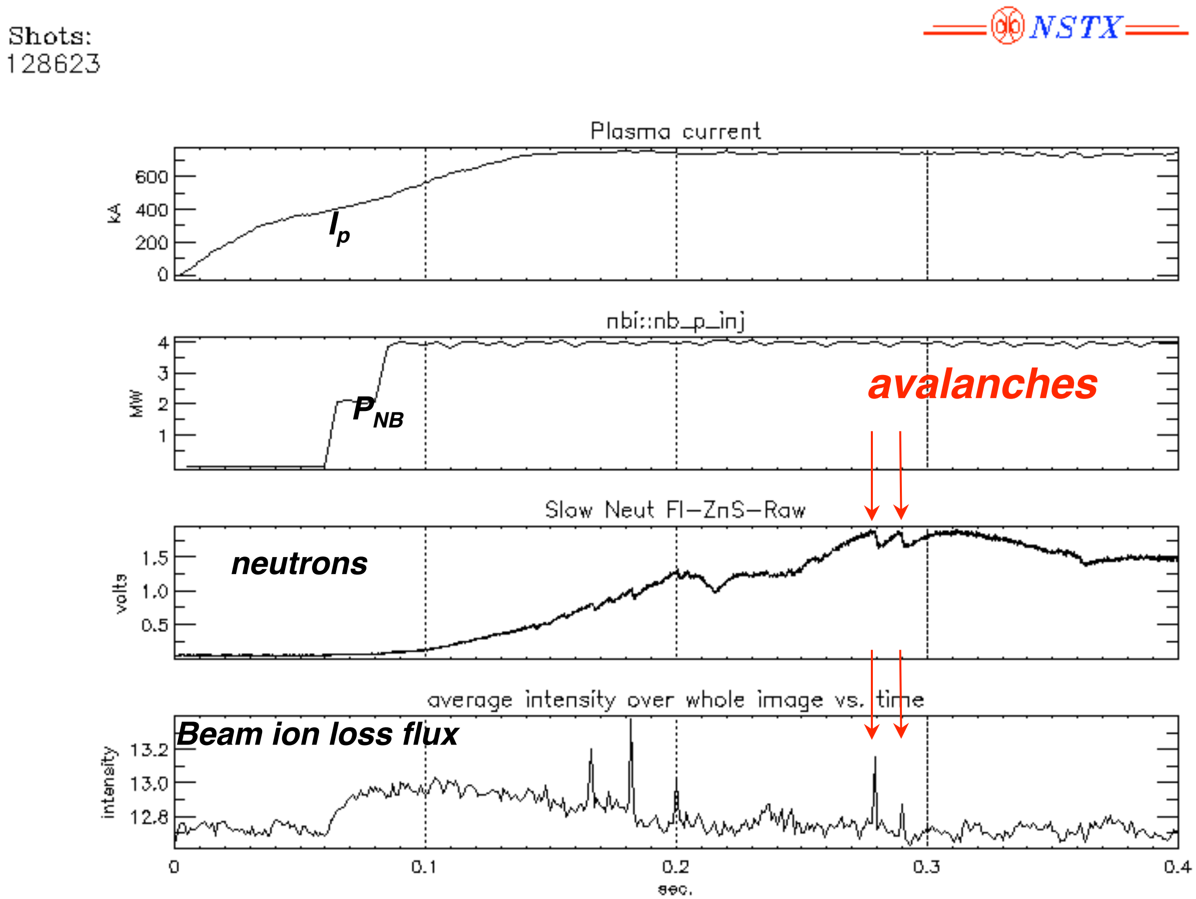
- Toroidal Alfvén eigenmodes (TAEs) are weakly damped Alfvén waves in a toroidal plasma, often driven by ions whose velocity approaches the Alfvén velocity (or a fraction thereof)
- A burst in which several TAEs of differing n occur is termed an avalanche; these produce **drops in the neutron rate** and, often, losses of beam
- Energetic particle bursts have characteristics similar to avalanches, and are seen repeatedly during I_p ramp up
- Beam ion losses during both types of bursts can change the total beam driven current and its profile

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



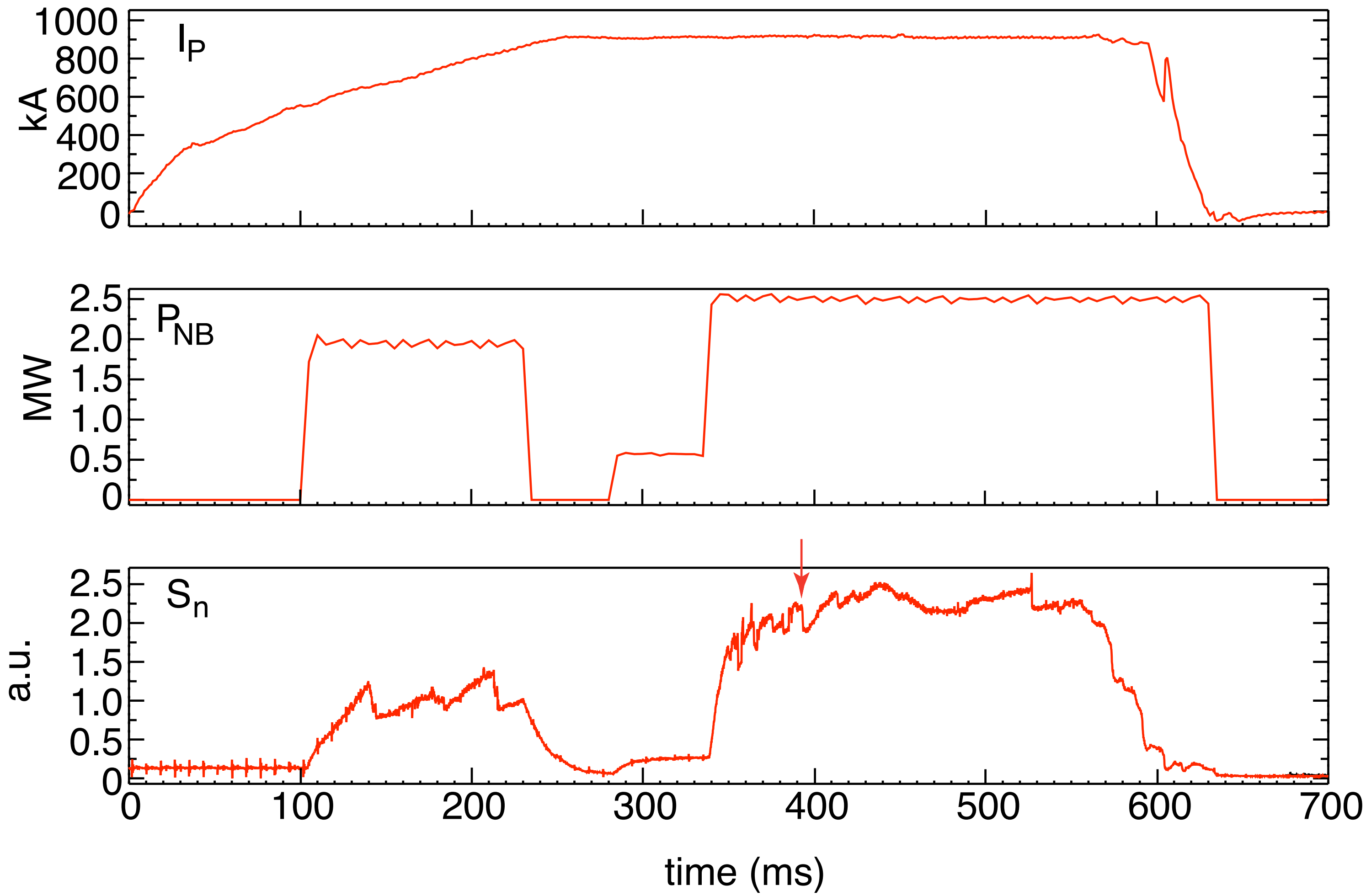
- But, loss is not observed with every avalanche
- Pitch angle distributions of loss during avalanches sometimes differ

Goal: Use computed effects of bursts on beam ion distribution to model effects on current profile

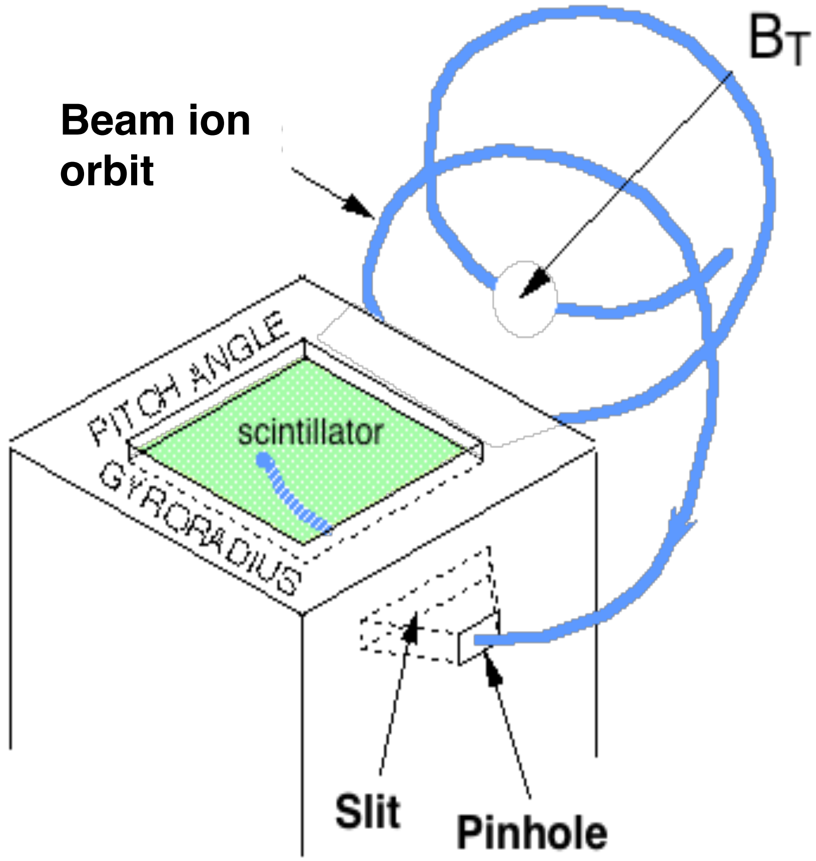
- Beam ion distribution modeled by guiding center orbit code that incorporates:
  - Measured TAE n numbers, frequencies (Mirnov coils)
  - Radial mode structures and amplitudes (multichannel microwave reflectometer data coupled to NOVA-K calculations of eigenmodes)
  - Deposited beam ion distribution function from TRANSP
  - Focus on recently deposited beam ions since losses appear at or very close to injection energy of 90 keV
- Prior work has successfully used this approach to model drops in the neutron rate and beam ion loss distribution
- Present work seeks to extend modeling results to J(r) profile

Study single, well-documented avalanche as first case

141719



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

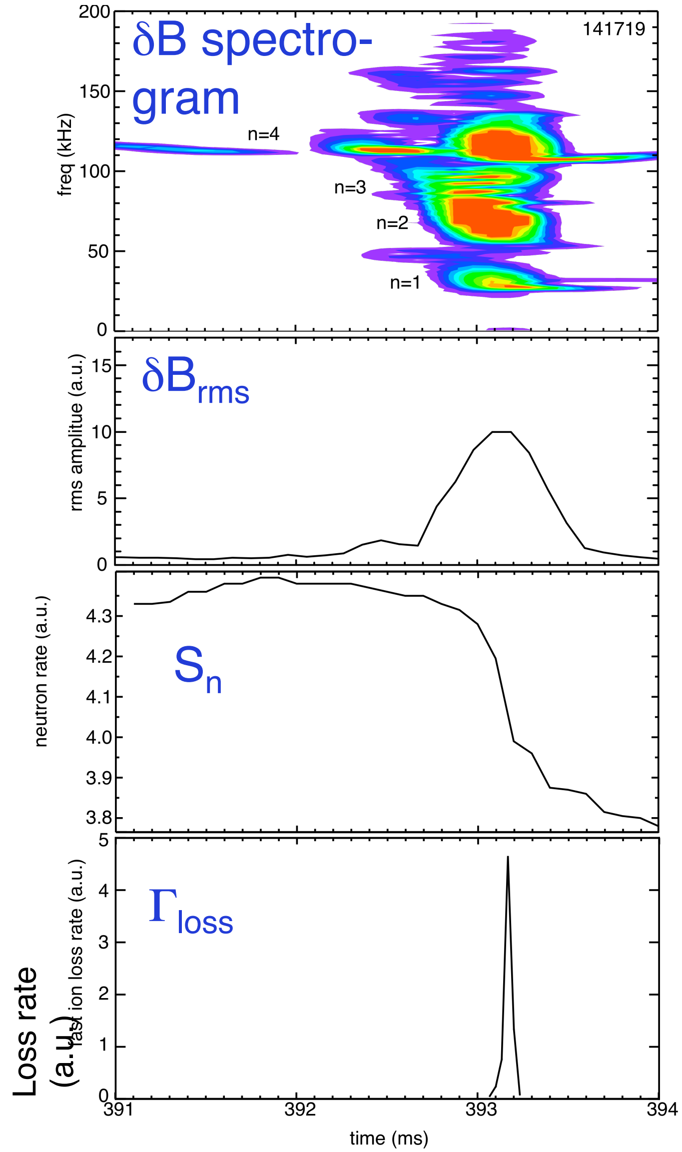
$\Gamma_{loss}(\rho, \chi, t)$

NSTX probe:

5 cm ≤ ρ ≤60 cm

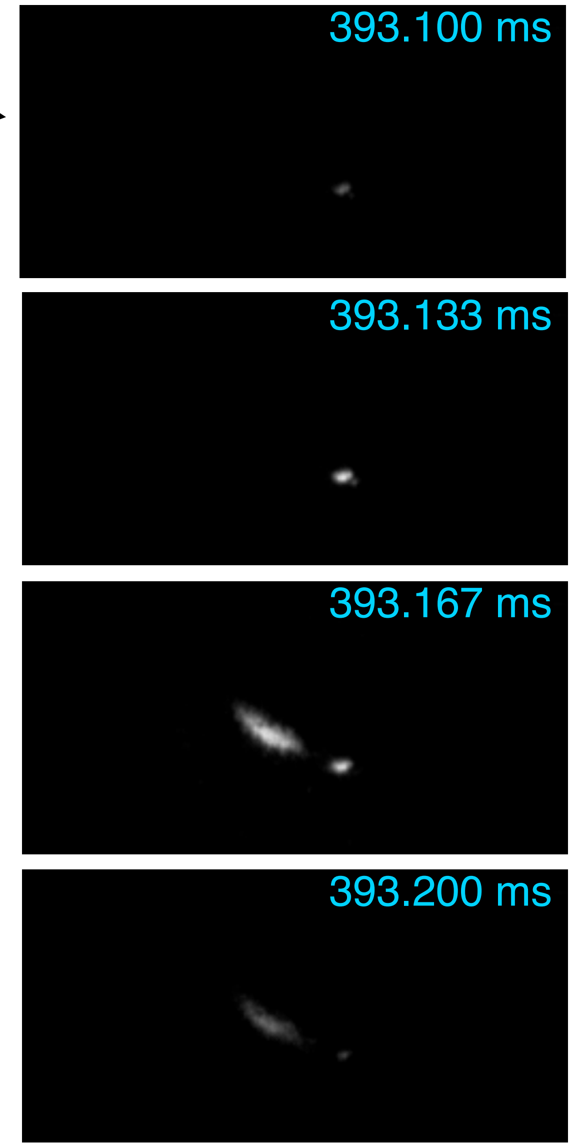
15° ≤ χ ≤ 80°

Avalanche has multiple n, and loss evolves rapidly during event

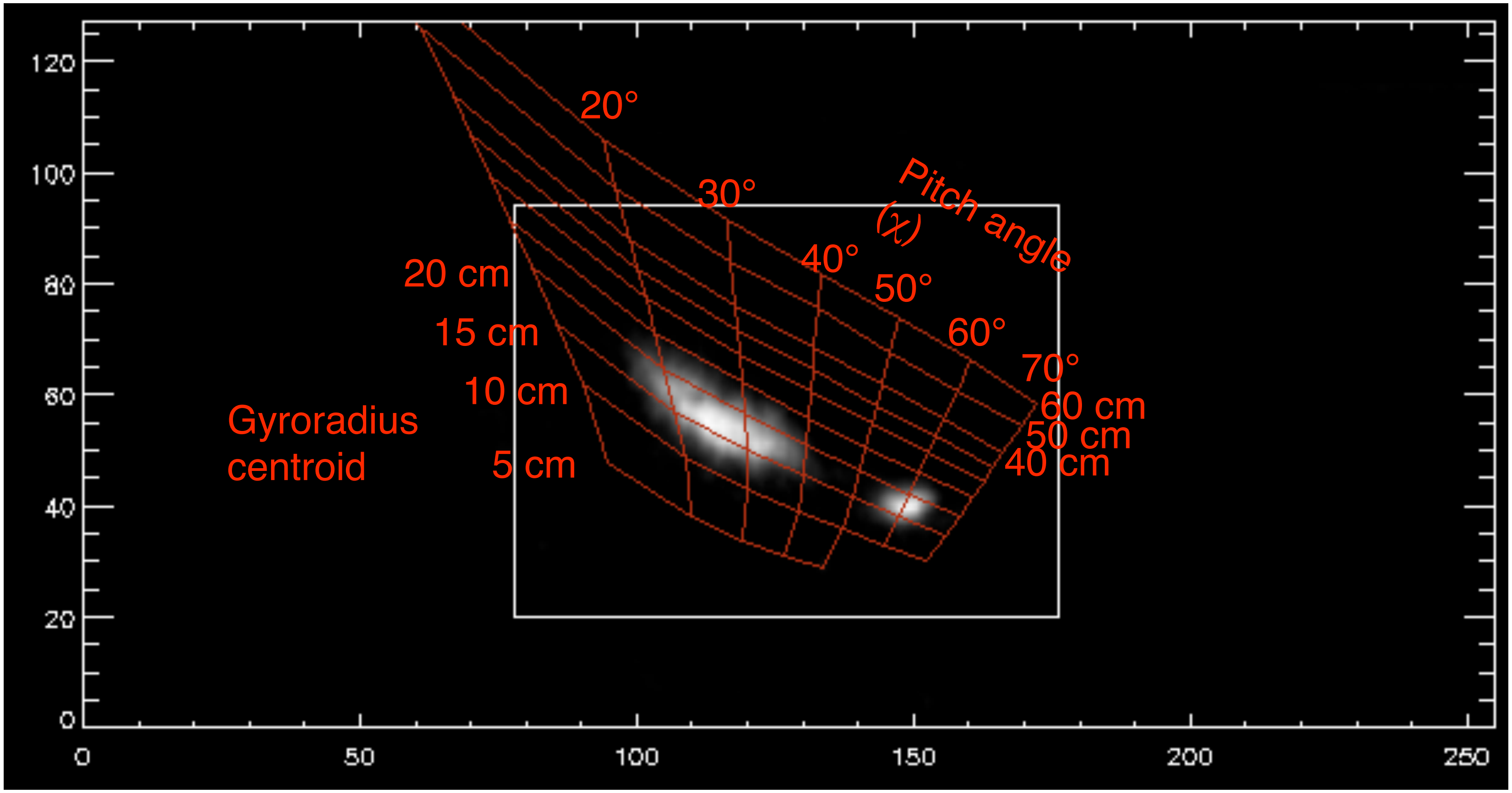


- Scintillator image sequence during avalanche

- 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

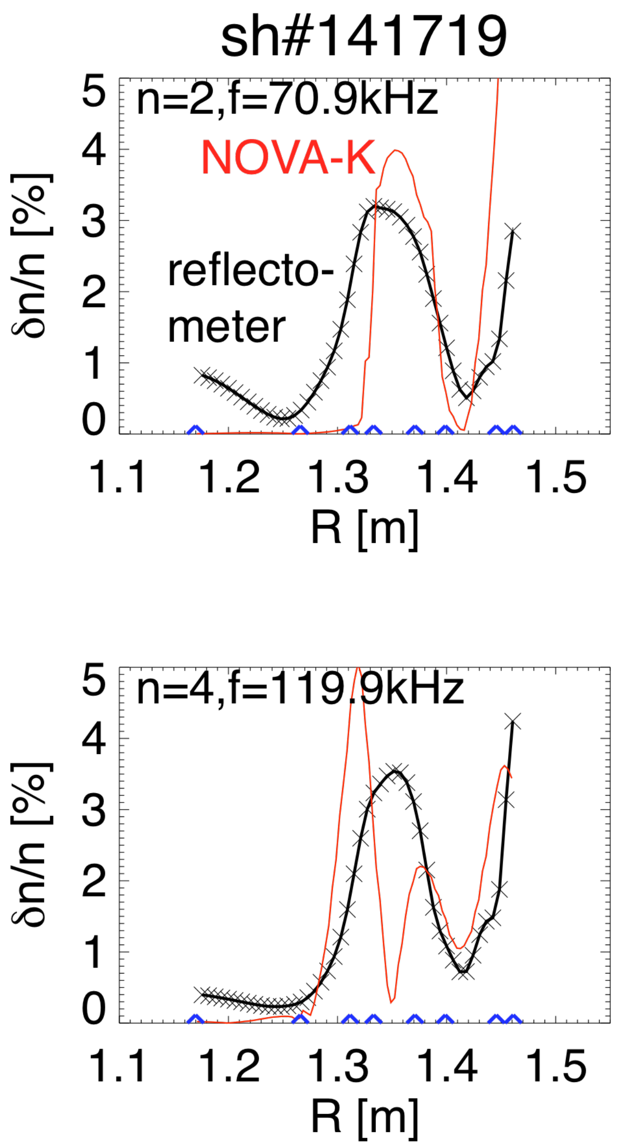


60° pitch angle loss appears first, then range of lower pitch angles



- 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

For modeling ion orbits, use NOVA-K TAE radial eigenfunctions fit to reflectometer fluctuation profiles

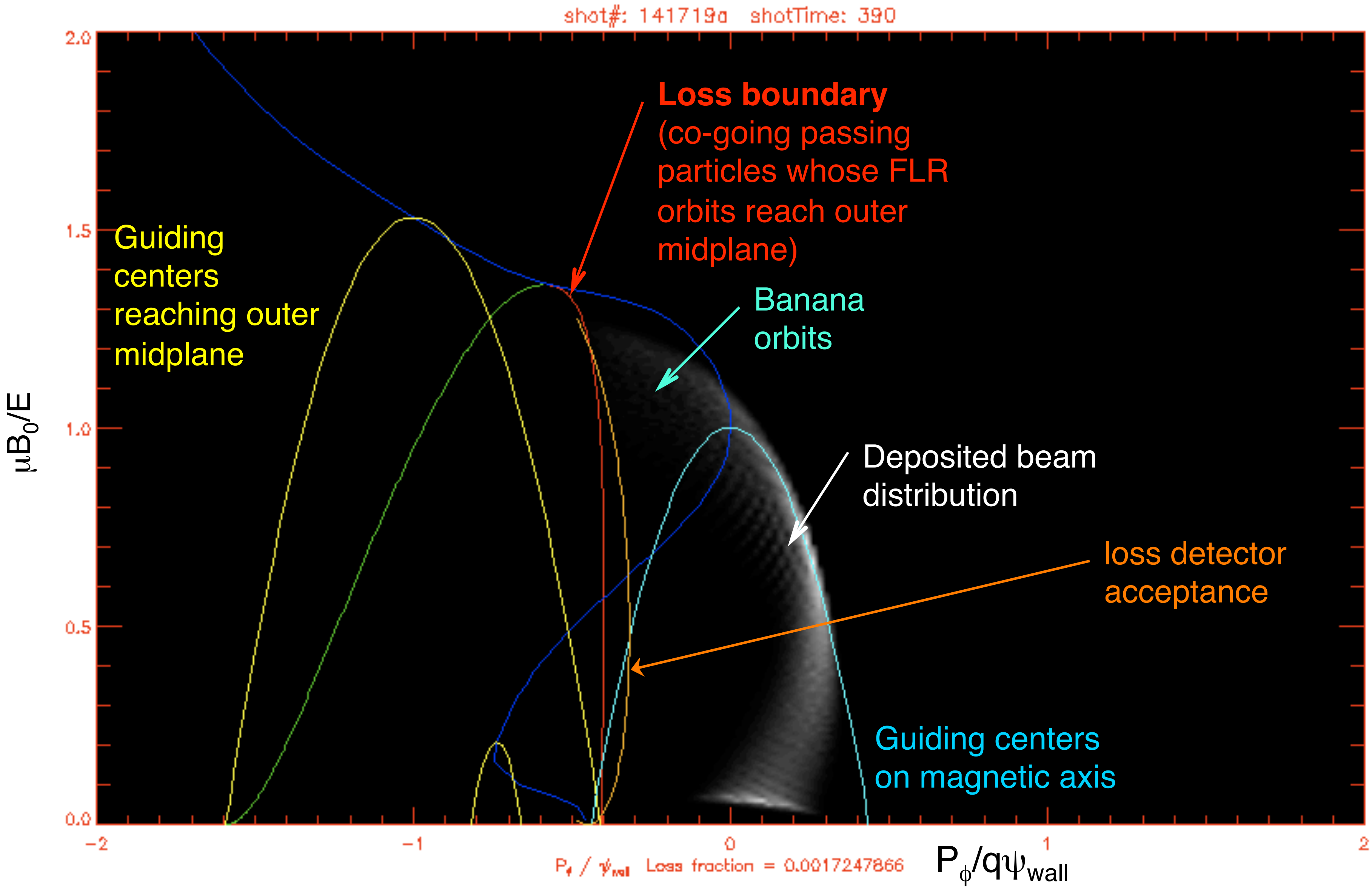


- Density fluctuation or displace-ment can be matched, giving absolute amplitudes of various n modes for input into orbit following code

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

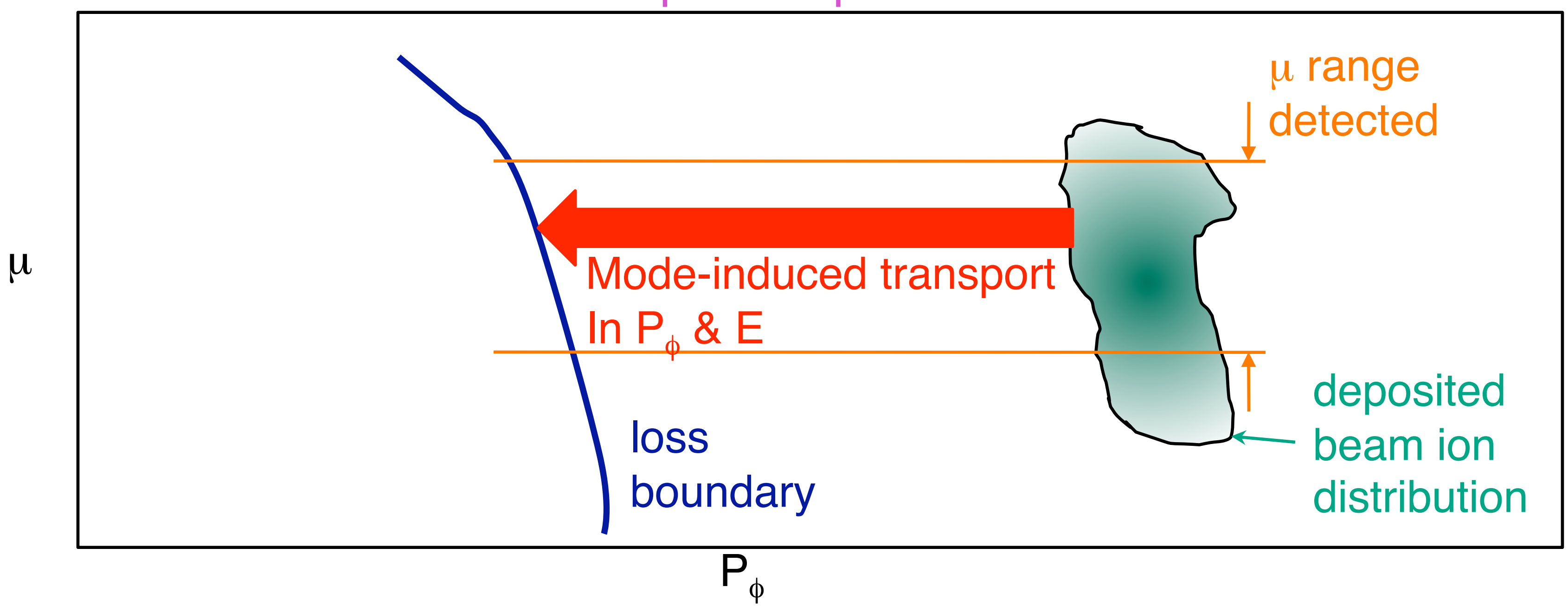
Deposited full energy beam distribution can be represented in (μ, P_ϕ) space, along with certain phase space boundaries



Modes transport beam ions radially, some to loss boundary

- 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

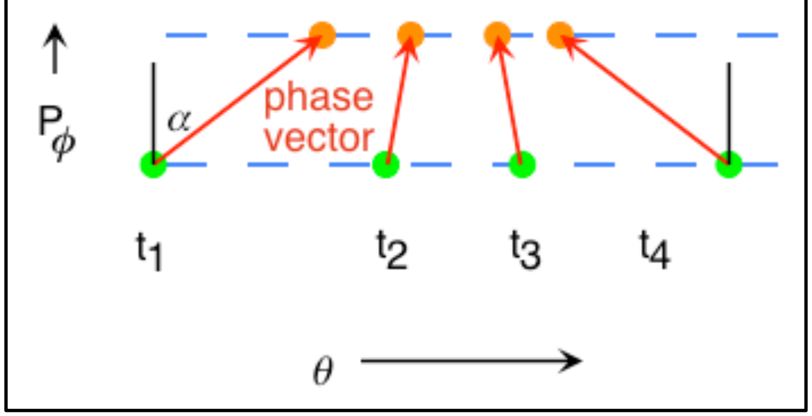
Beam ion phase space at fixed E



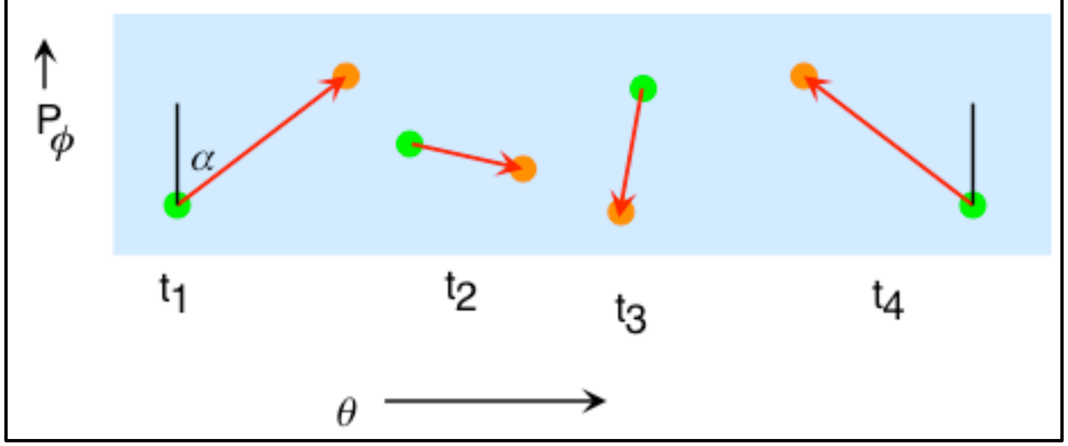
Mode structures and amplitudes can be used to determine regions of phase space subject to stochasticity

- 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: $\Delta\alpha \leq \pi$

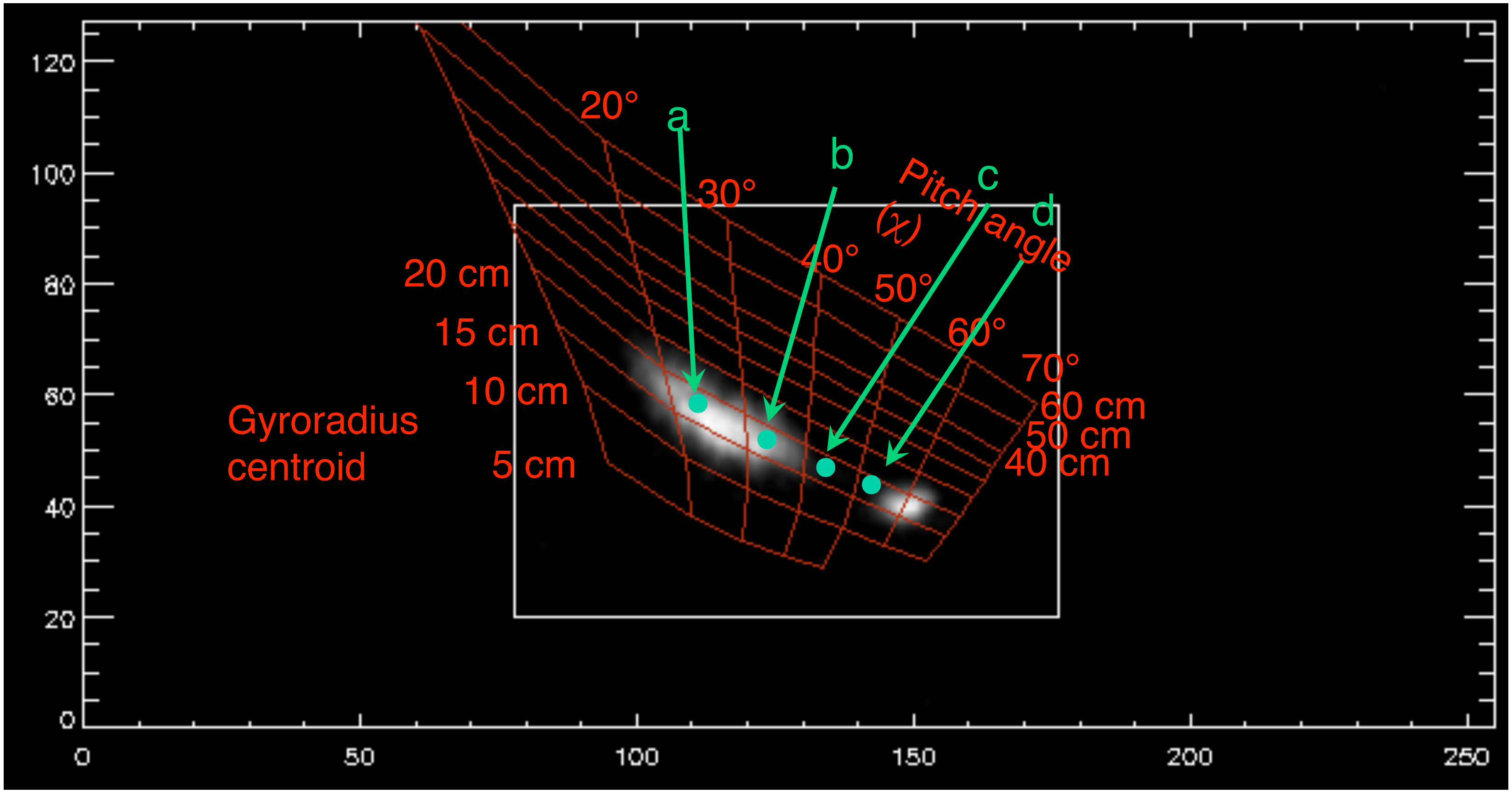


Stochastic region: $\Delta\alpha$ arbitrarily large

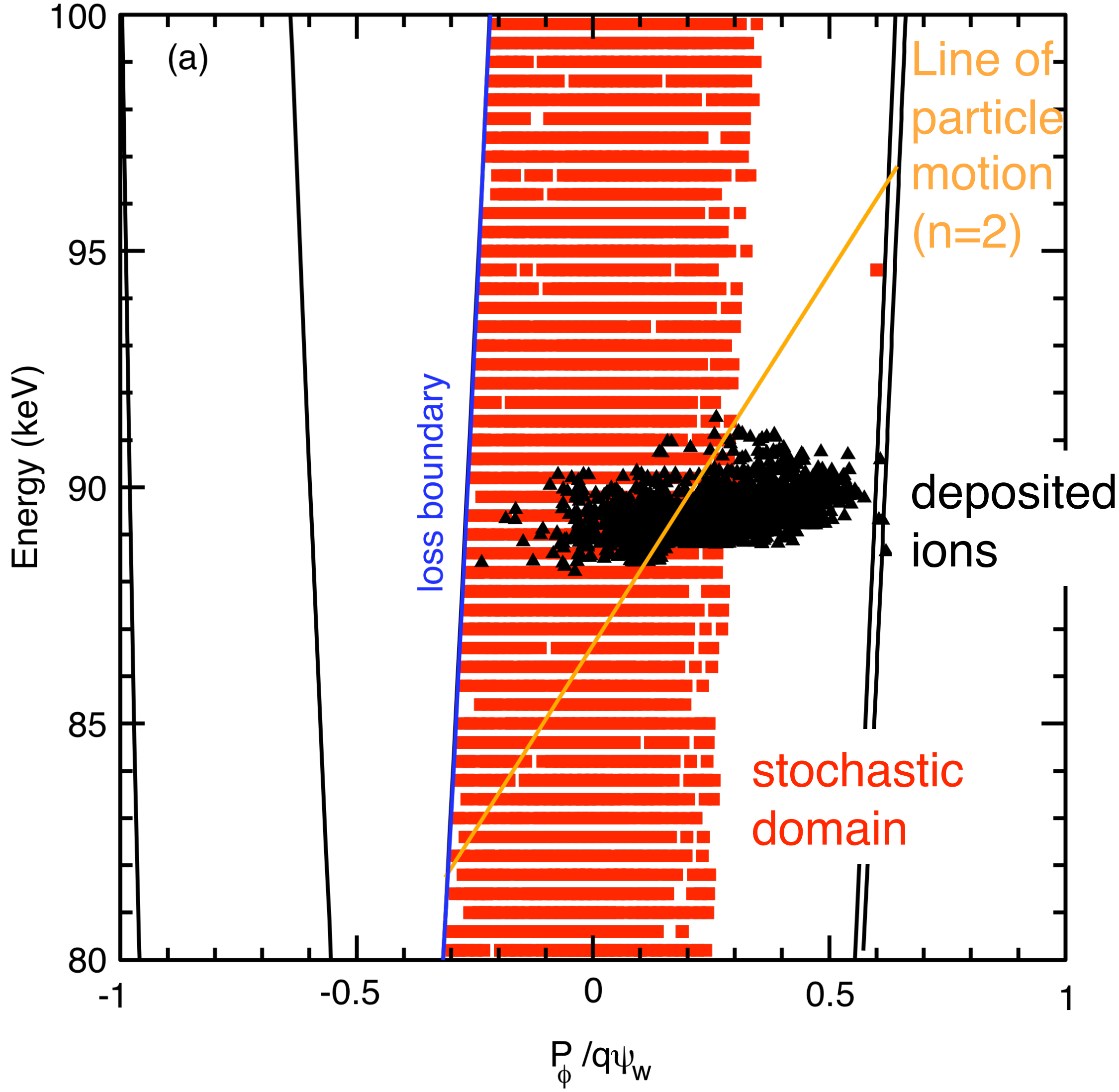


Test whether code-modeled stochastic domain presence coincides with lost pitch angle ranges

- Stochastic maps shown on following slides for several pitch angles marked below

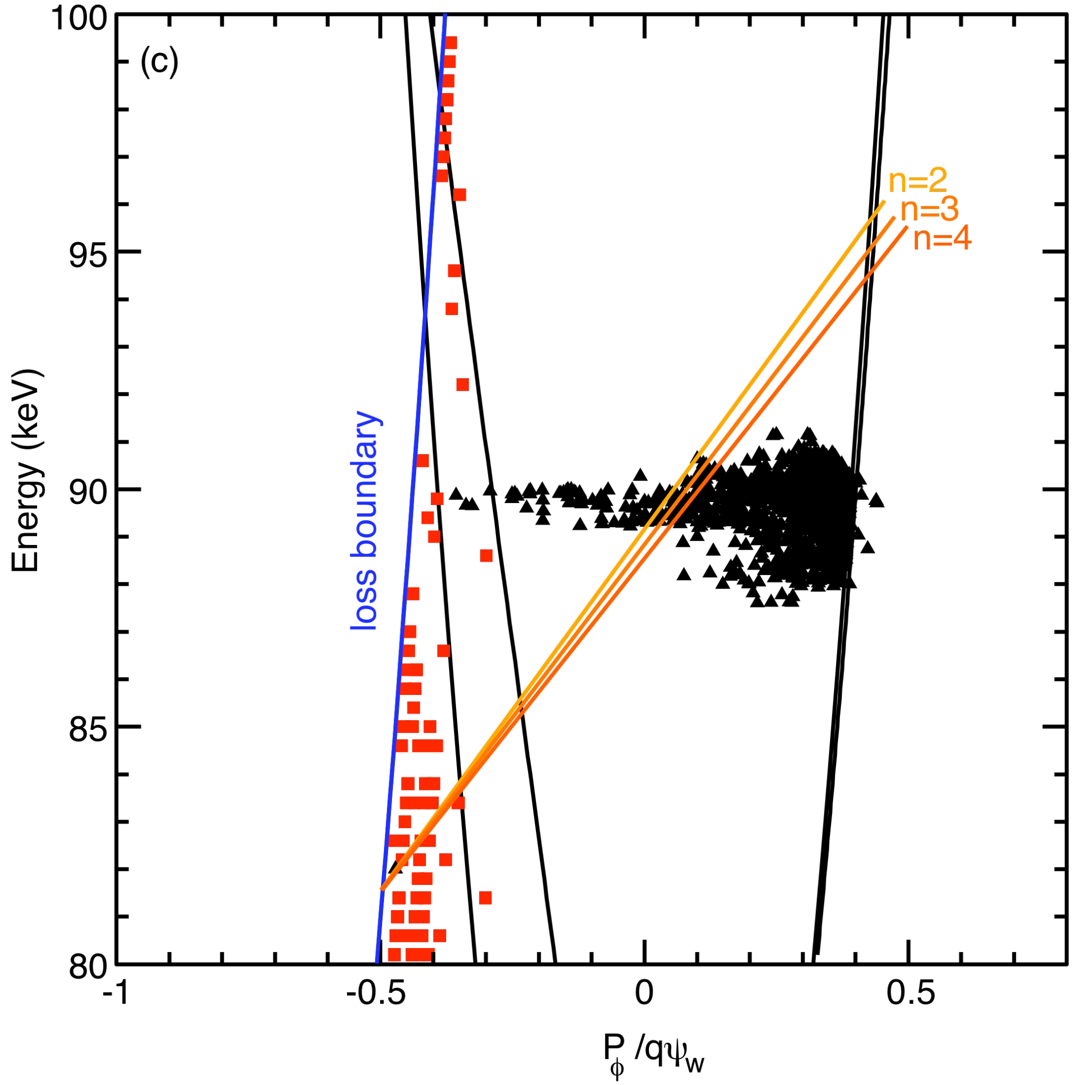


Case a (23°) is near center of a detected loss spot & model predicts loss



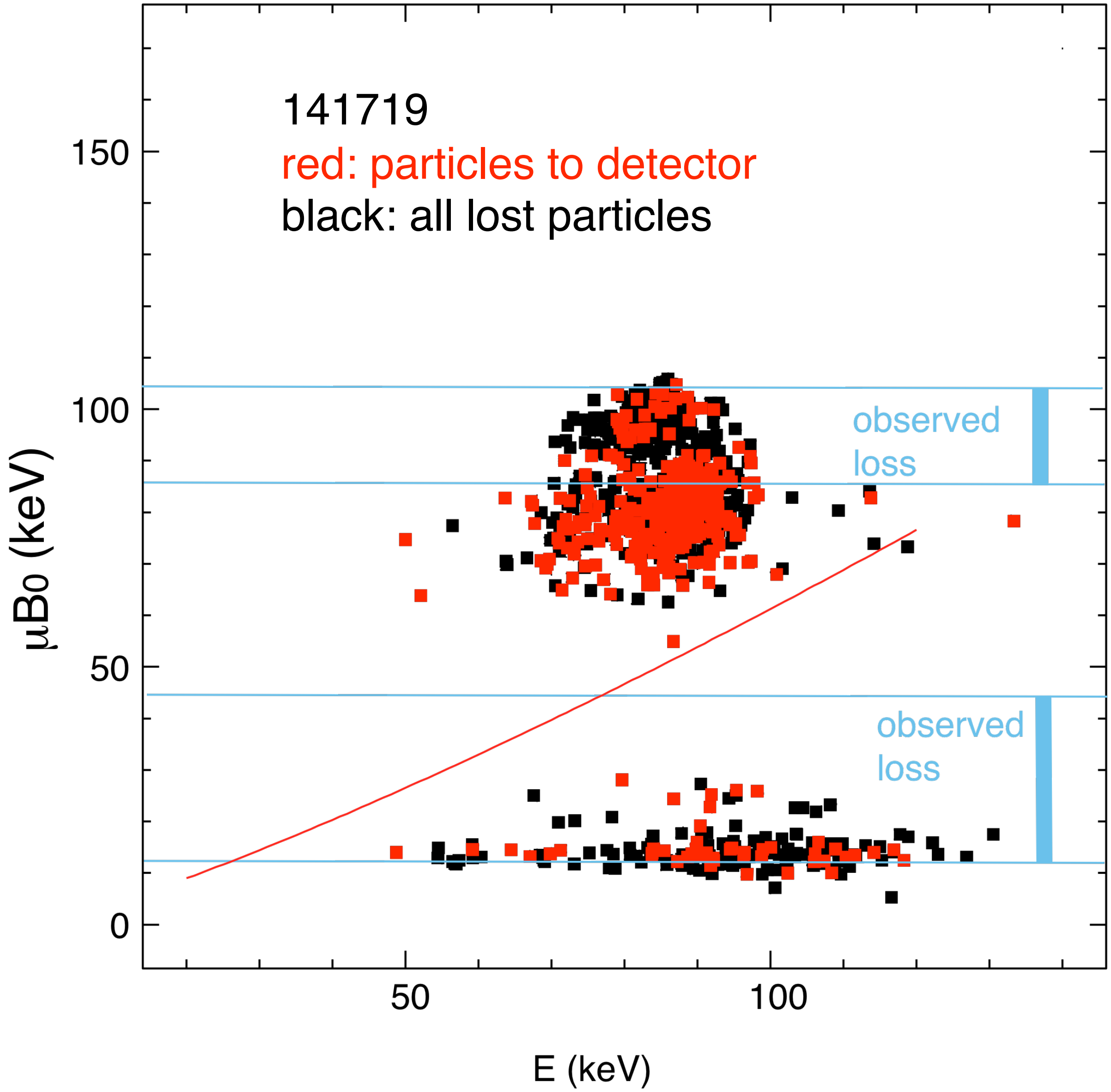
- Beam ions deposited in stochastic region
- Particles move along orange line (or parallel lines) under influence of n=2 mode
- Particles clearly deposited in stochastic region and that region extends to loss boundary

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



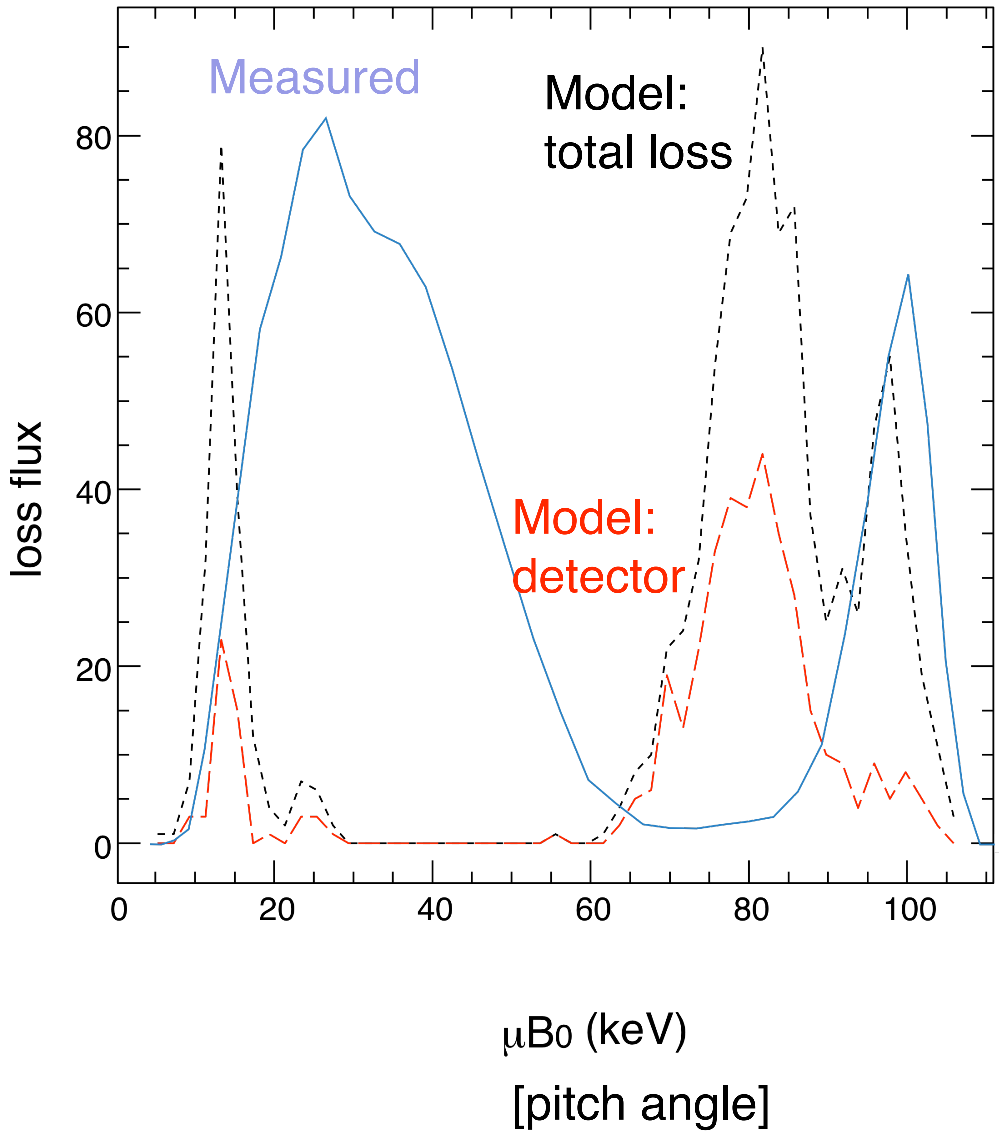
- Model consistent with observation at this pitch angle
- Slopes of lines of diffusion for n=3 & 4 also shown–they do not differ markedly from direction of transport for n=2 mode

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

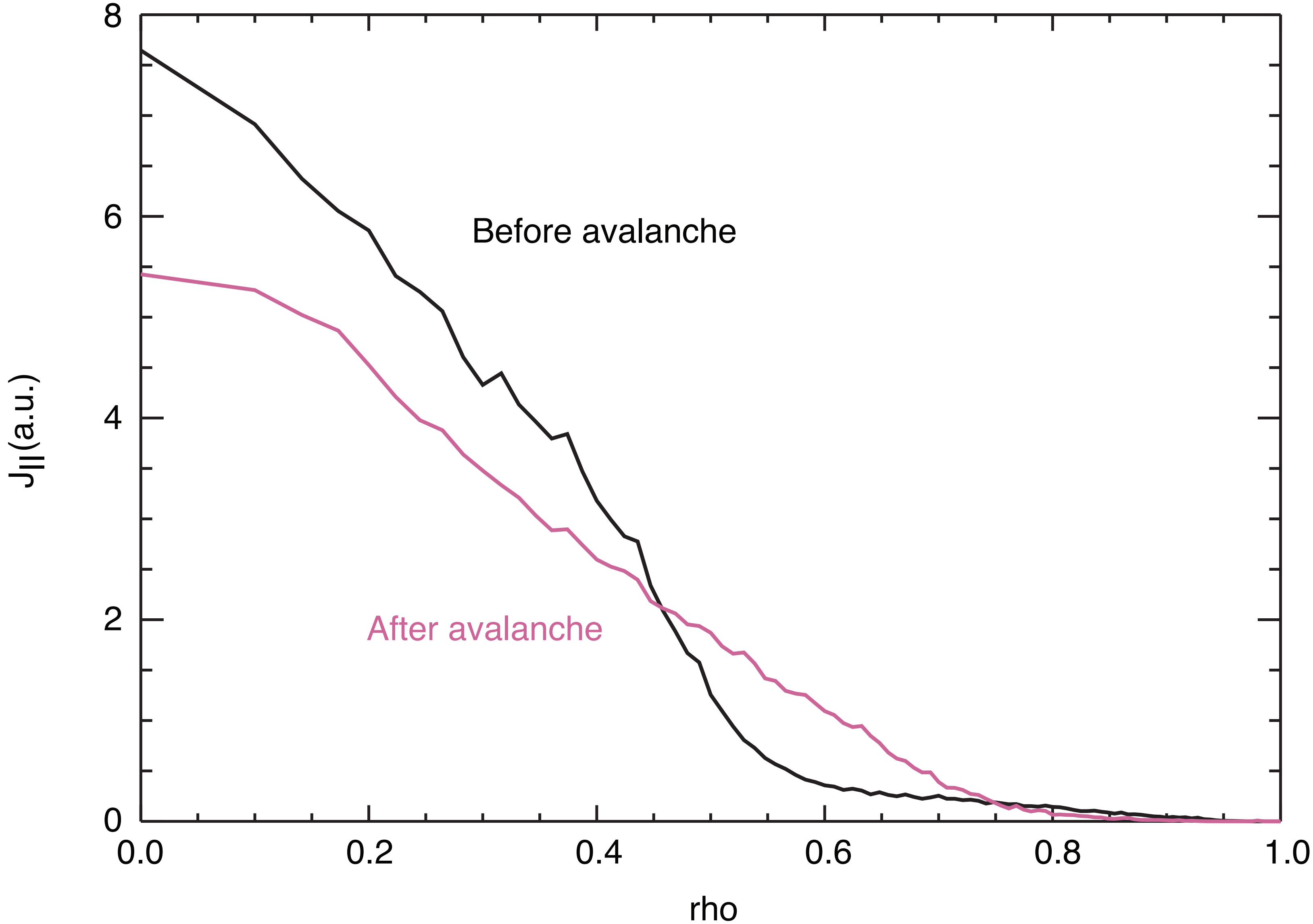


- Model, while predicting 2 peaks at detector, does not reproduce observed variation of loss flux with pitch angle

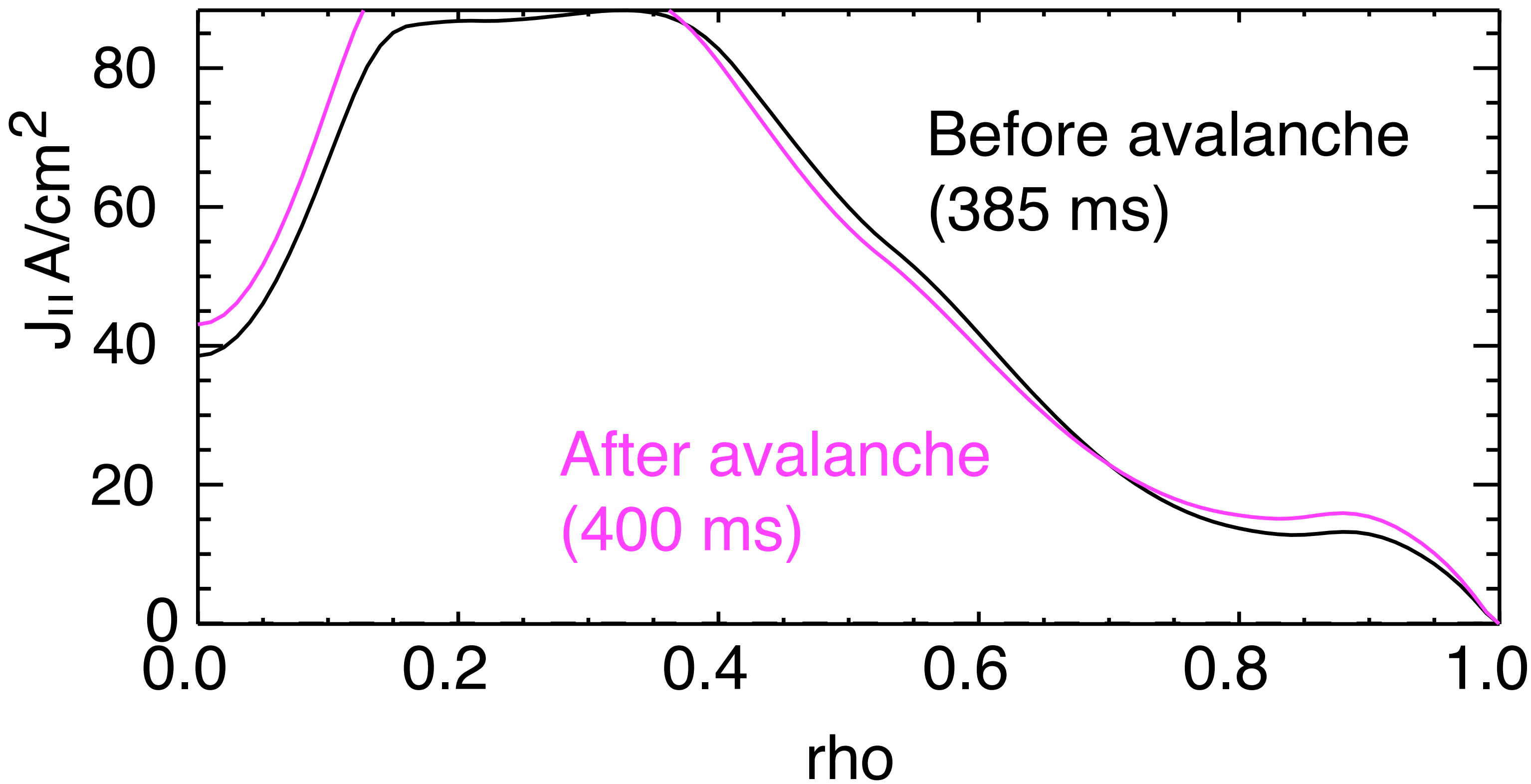
Beam ion data from calculation can be used to model mode effect on beam driven current

- Since modes can affect the beam ion velocities and positions, in addition to causing loss, they can alter the beam driven current profile
- Compute model $J_{||}(\psi)$ as $\Sigma nqv_{||}$ for all beam ions in a given annulus in ψ
- Compare profile before and after avalanche
- Model does not yet include screening of ions by electrons

Modeled beam-driven $J_{||}(\psi)$ profiles show drop near center, increase at mid-radii after avalanche



Equilibrium fits suggest opposite: small increase in central current density after avalanche



- $J_{||}$ profiles from MSE-constrained LRDFITs before and after avalanche shown
- Differences well within errors of fit

Summary

- TAE avalanches in NSTX plasmas can redistribute and expel neutral beam ions
- Representative case has been modeled extensively with ORBIT code to compute beam ion losses, with fair agreement between model and loss observations
- Use of same model shows redistribution of beam driven current from center of plasma to mid-radii, but no significant change of current profile is seen in equilibrium fits
- Related EPM bursts seen during plasma current ramp up
- Seek to validate computation of $\Delta J_{||}(r)$ with avalanches and apply to EPM bursts

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