NSTX-U

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Effects of TAE avalanches on the neutral beam driven current profile in NSTX & NSTX-U plasmas

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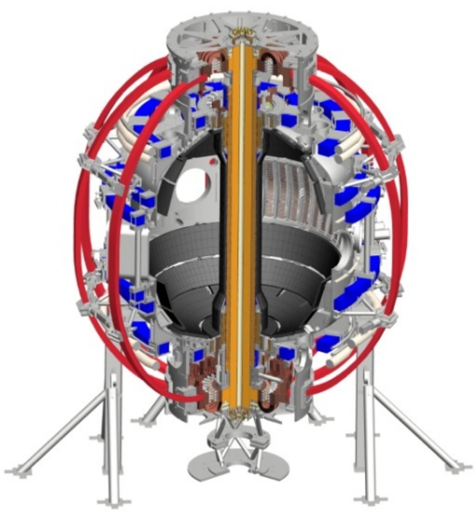

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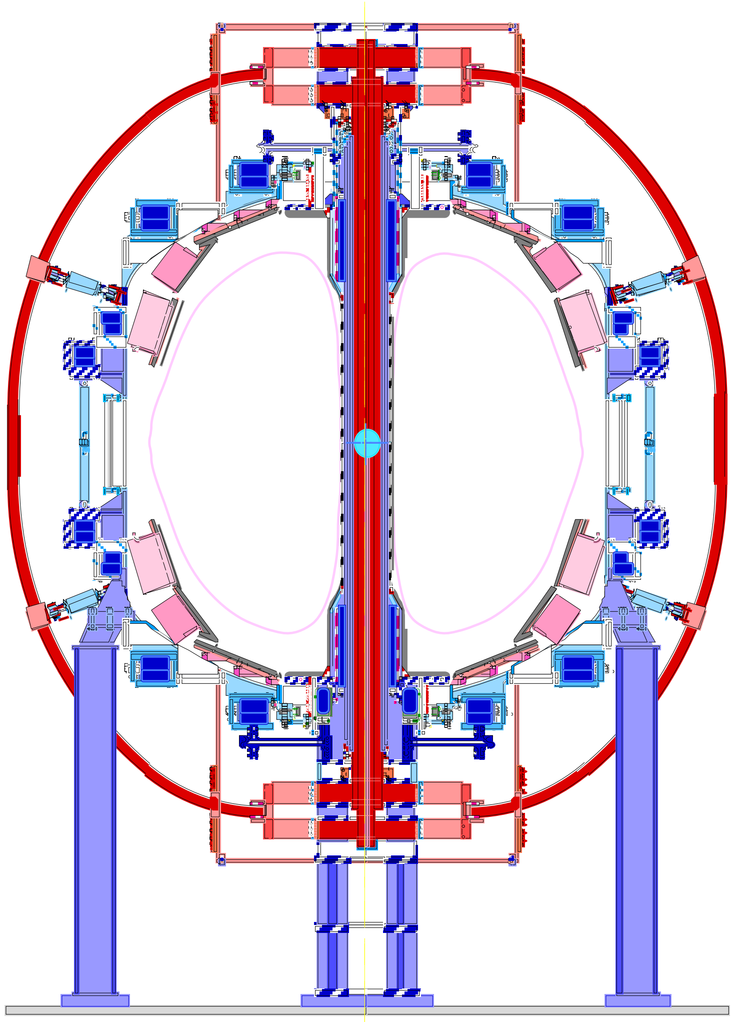
NSTX is a spherical tokamak with substantial NBI

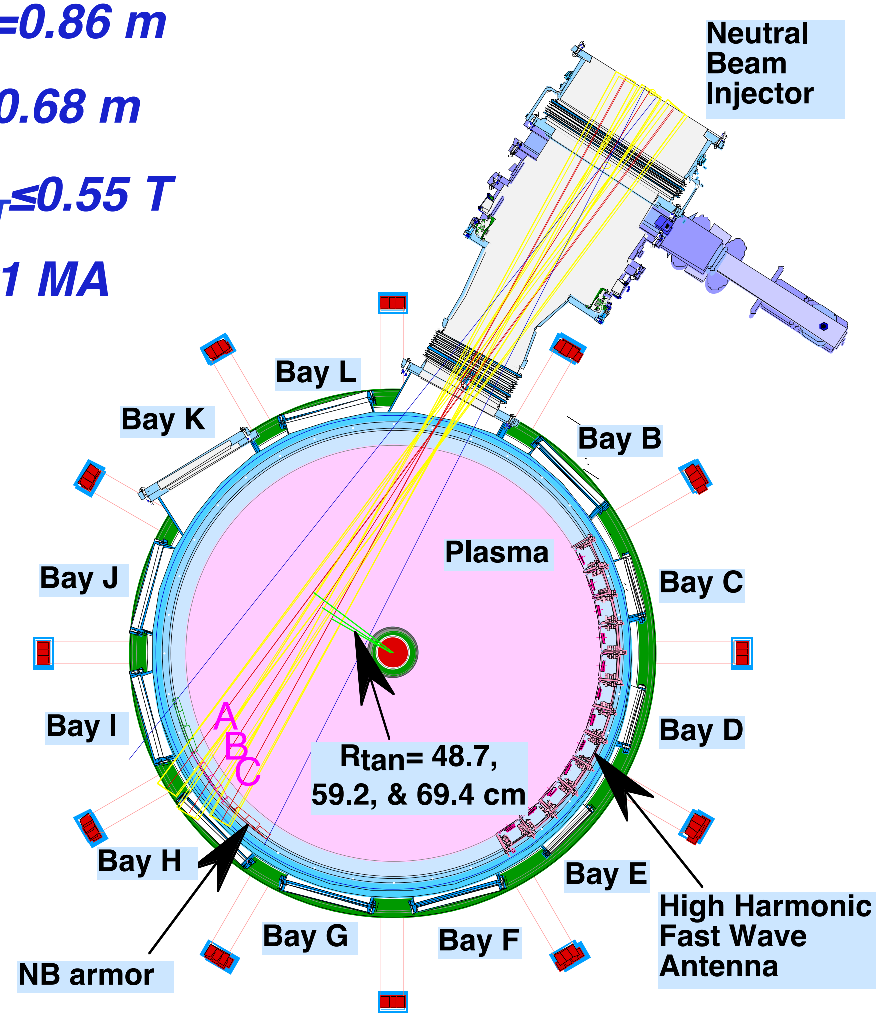


R_0=0.86 m

a=0.68 m

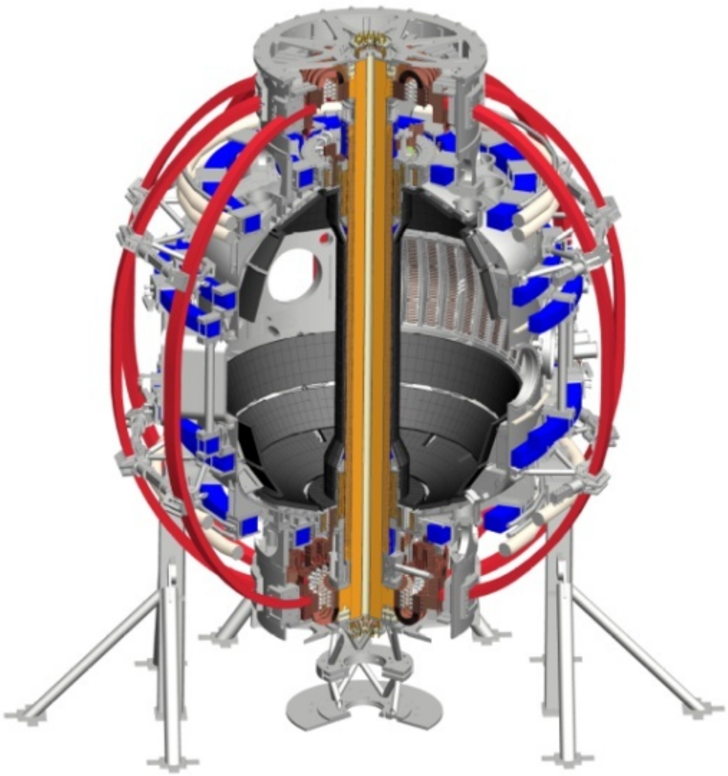
B_{0T}≤0.55 T

I_p≤1 MA



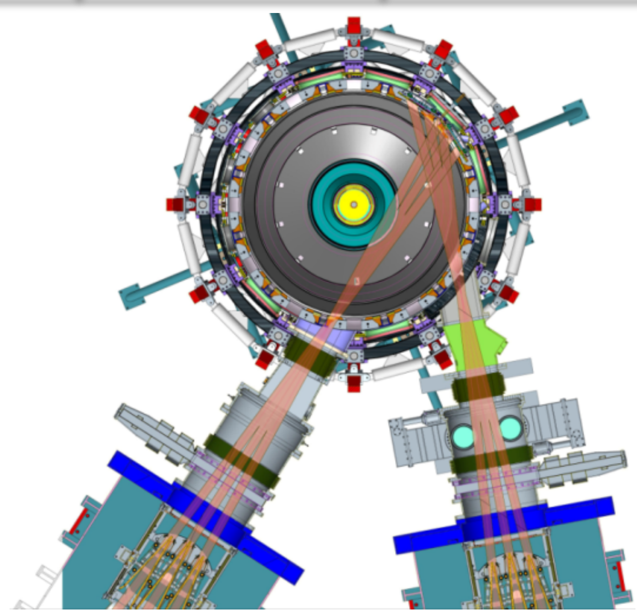
- 3 beam sources inject 90 kV D, ≤6 MW

NSTX Upgrade : double plasma current, toroidal field & injected NB power; pulse length extended to ~5 sec.



Major radius [m]	0.85	0.9
Aspect ratio	1.3	1.5
I_{plasma} [MA]	<1.3	2
B_{tor} [T]	<0.55	1
Pulse length [s]	<2	5

NB sources	3	6
P_{NBI} [MW]	$\leq$7	$\leq$14
$E_{injection}$ [keV]	$\leq$95	
	$1<v_{fast}/v_{Alfvén}<5$	



Present NBI New 2^{nd} NBI

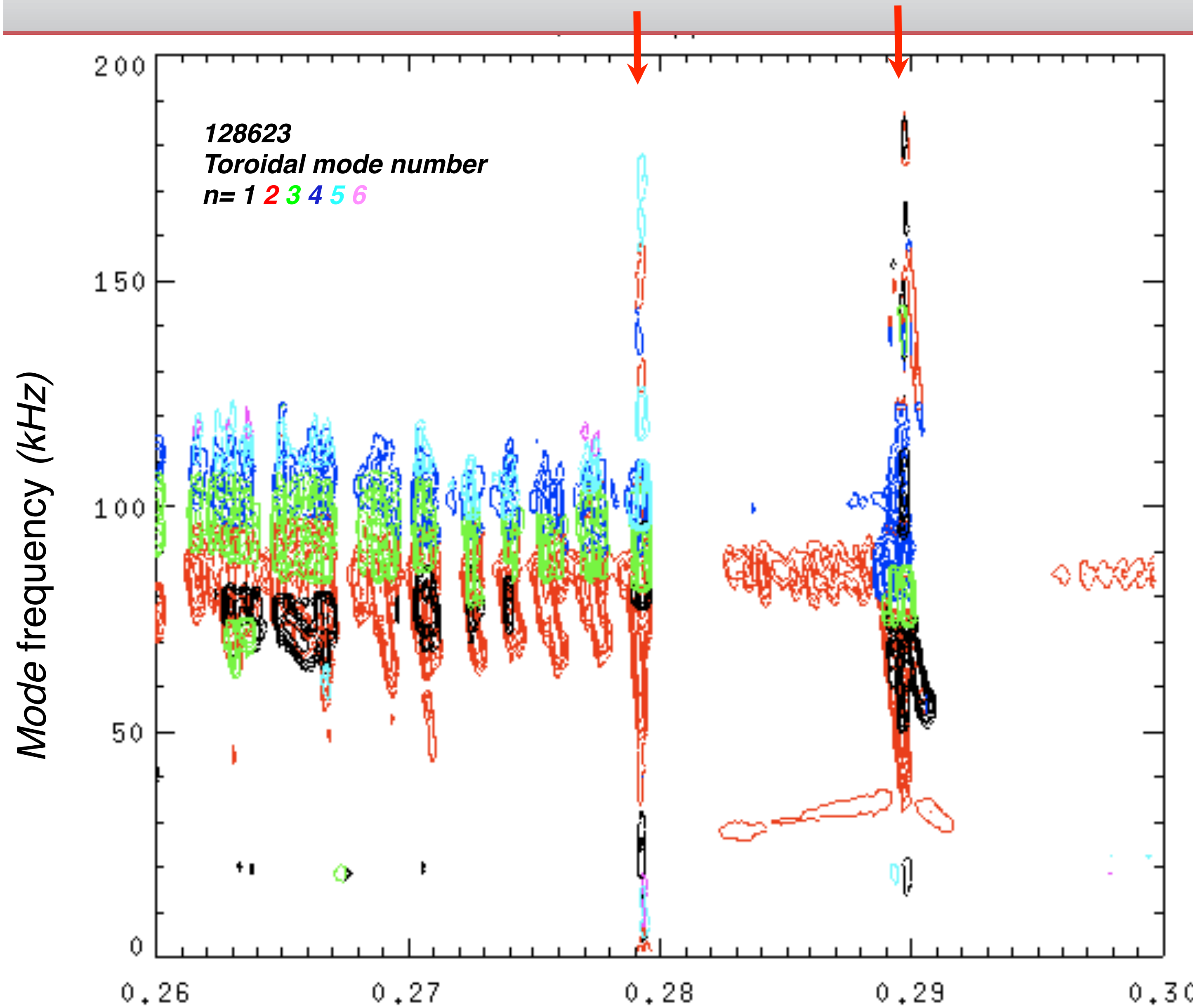
NSTX-U will extend performance with 2x higher I_p, B_T, & P_{NB}

- $I_p \leq 2$ MA
- $B_T \leq 1$T
- $P_{NB} \leq 12$ MW
- 3 new neutral beam sources are aimed much more tangentially: R_{tan}=1.1, 1.2, & 1.3 m (vs. 0.5, 0.6, & 0.7 m for NSTX)
- One important objective of new beams is current drive to extend pulse length, since STs have limited flux swing in the OH transformer
- In the ideal case, bootstrap current + beam driven current could sustain an ST

TAEs and avalanches seen in NSTX and can affect beam ion distribution

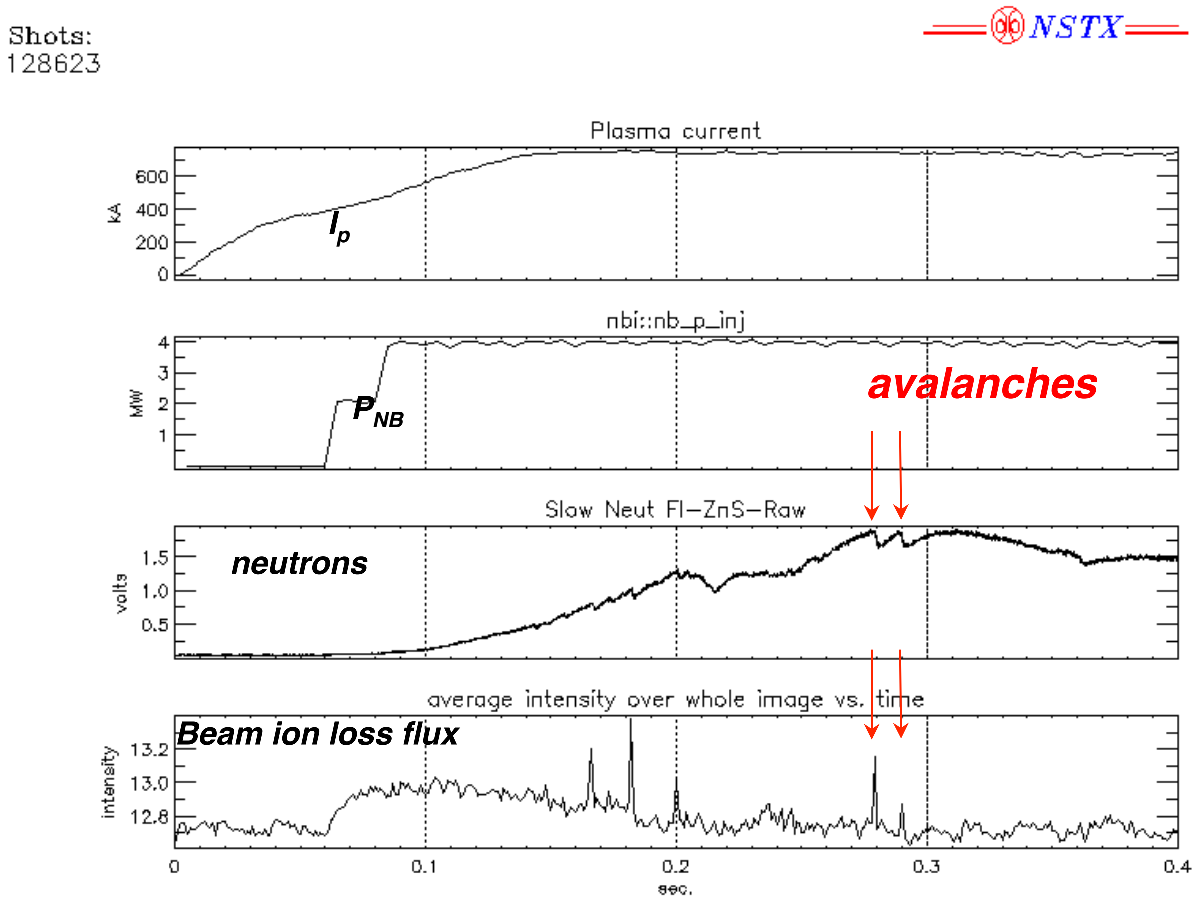
- Toroidal Alfvén eigenmodes (TAEs) are weakly damped Alfvén waves in a toroidal plasma, often driven by ions whose velocity approaches the Alfvén velocity (or a fraction thereof)
- A burst in which several TAEs of differing *n* occur is termed an *avalanche*; these produce **drops in the neutron rate** and, often, losses of beam ions
- Avalanches 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 result In fast ion redistribution and loss



Question: how would an avalanche in NSTX-U affect the current profile driven by the new beams?

- Conduct **computational experiment** with a well-characterized avalanche in NSTX
- Use diagnostic measurements of n numbers, frequencies, amplitudes, and mode structures
- Follow a model population of beam ions from TRANSP, using the guiding center code ORBIT, including equilibrium +TAE fields
- Evaluate $J(\rho)$ profile before & after avalanche

Use well-characterized NSTX avalanche as basis for modeling

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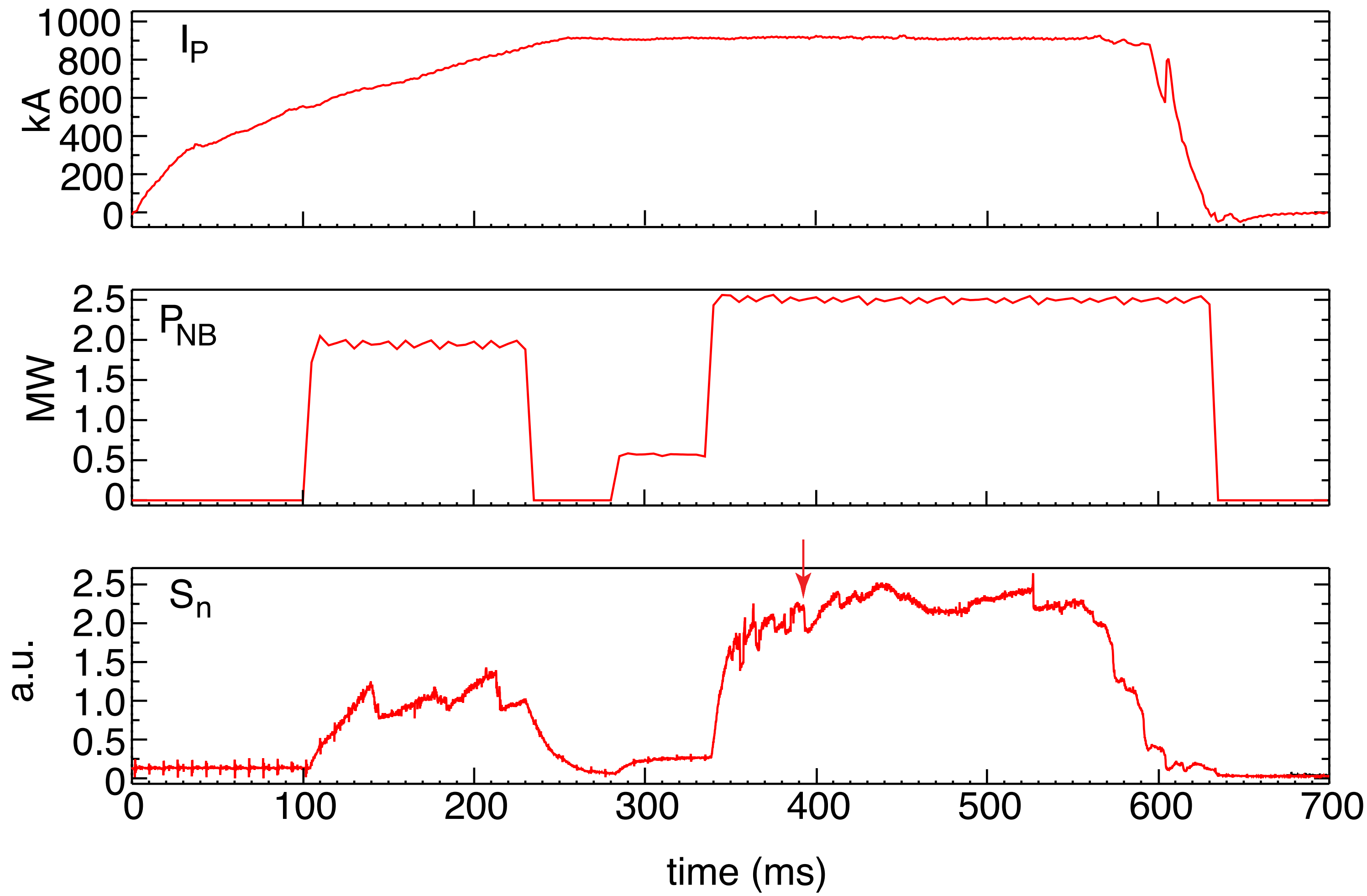

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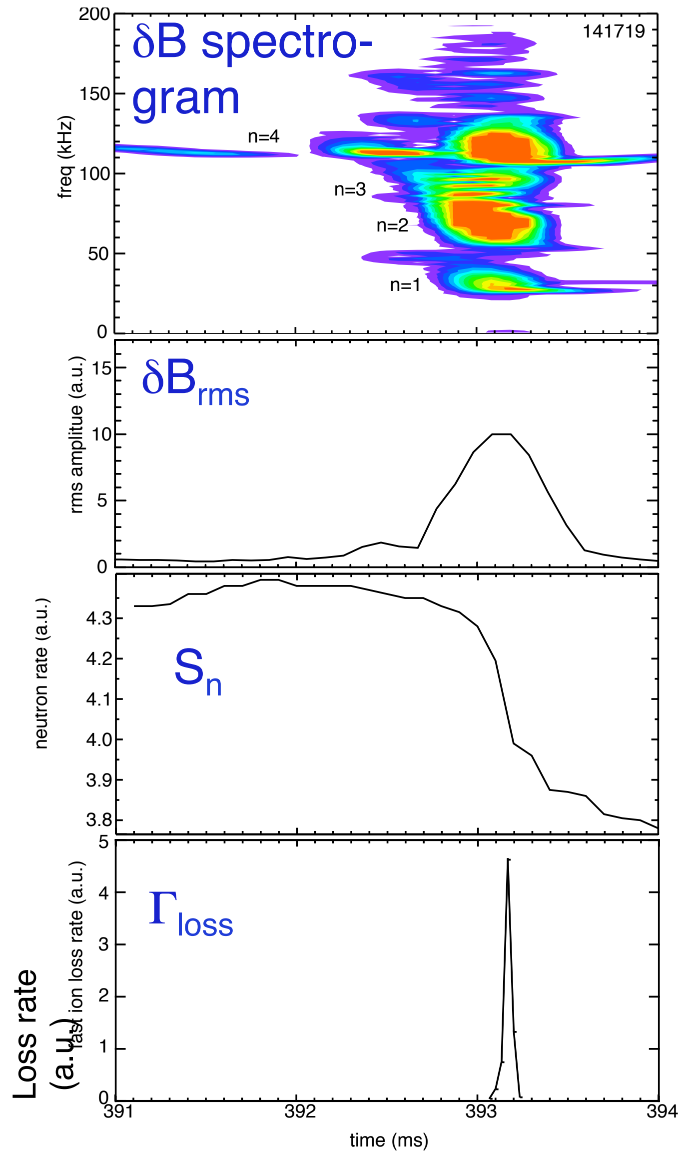
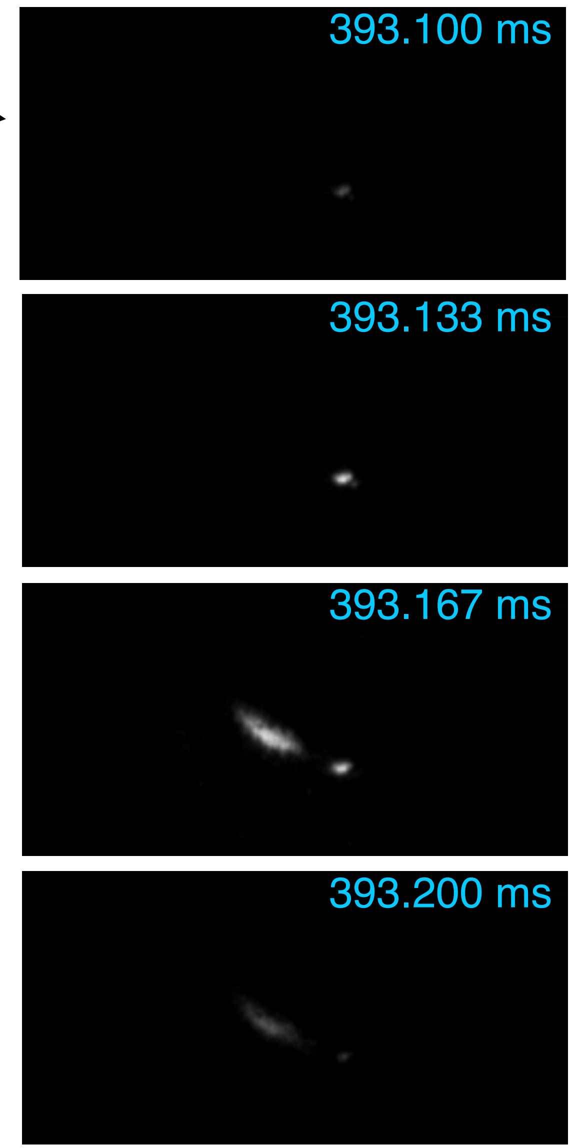
Avalanche has multiple n, and loss evolves rapidly during event

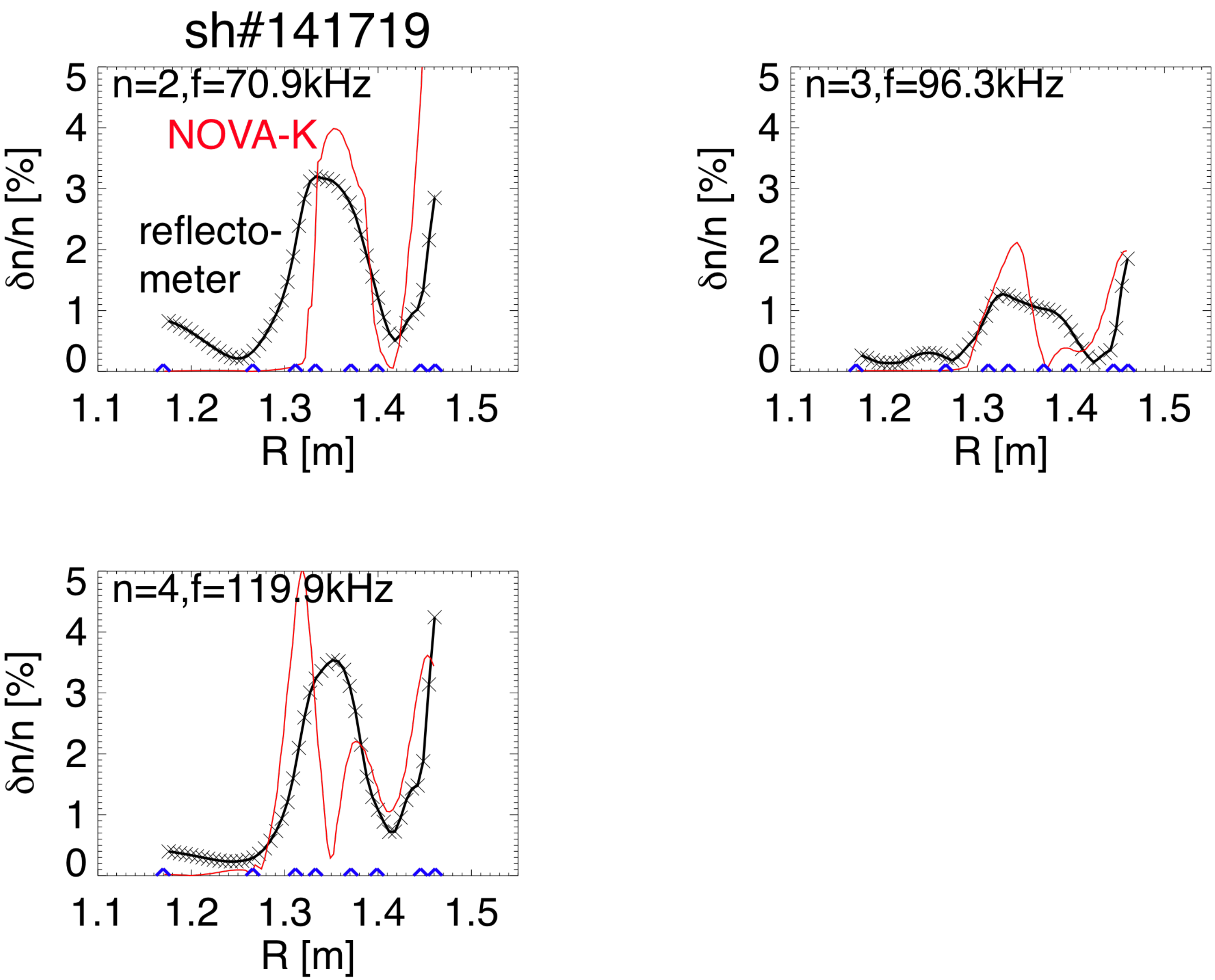


- Scintillator loss image sequence during avalanche



- 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

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

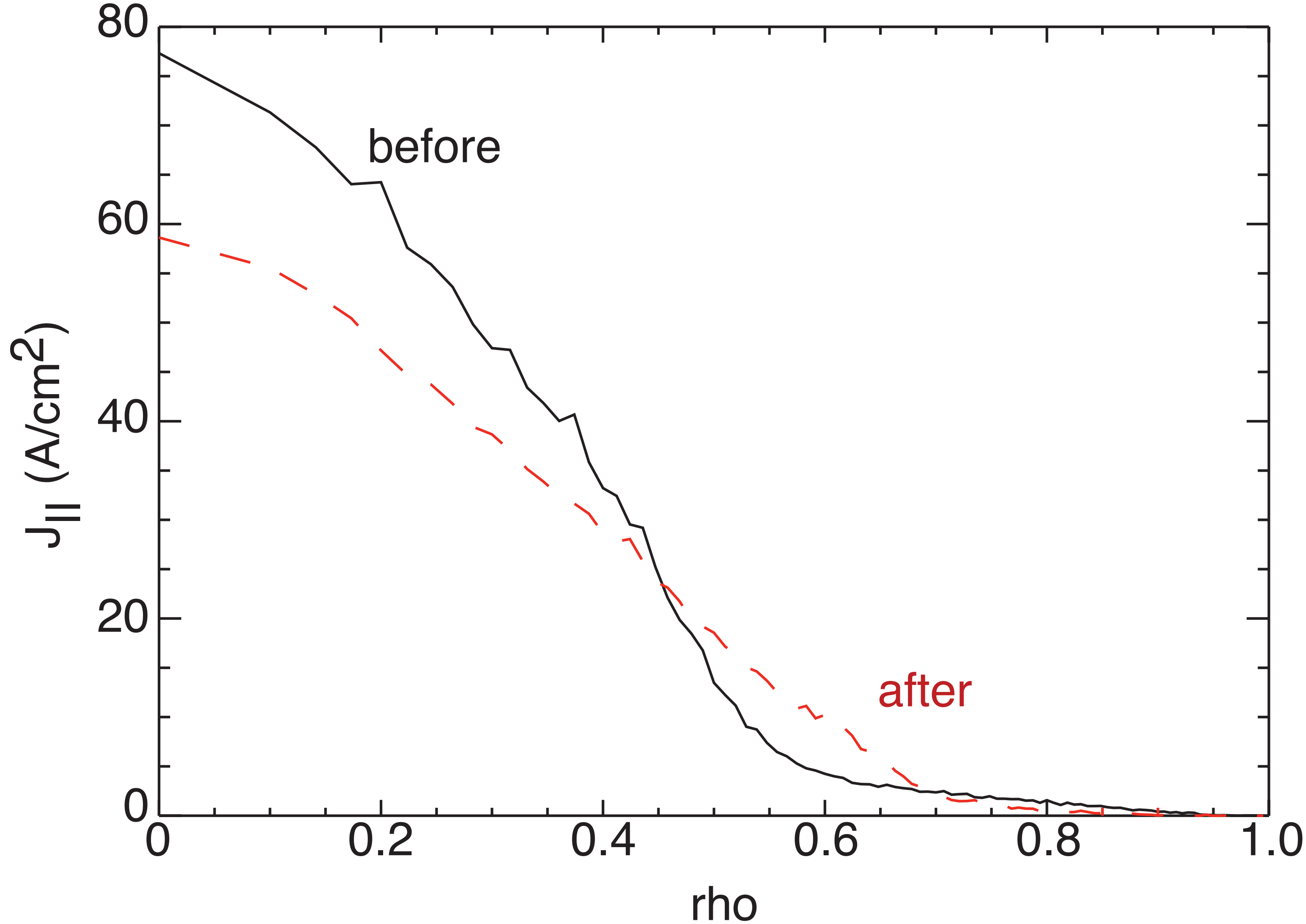


- Density fluctuation or displace-ment can be matched, giving absolute amplitudes of various n modes for input into guiding center orbit code

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

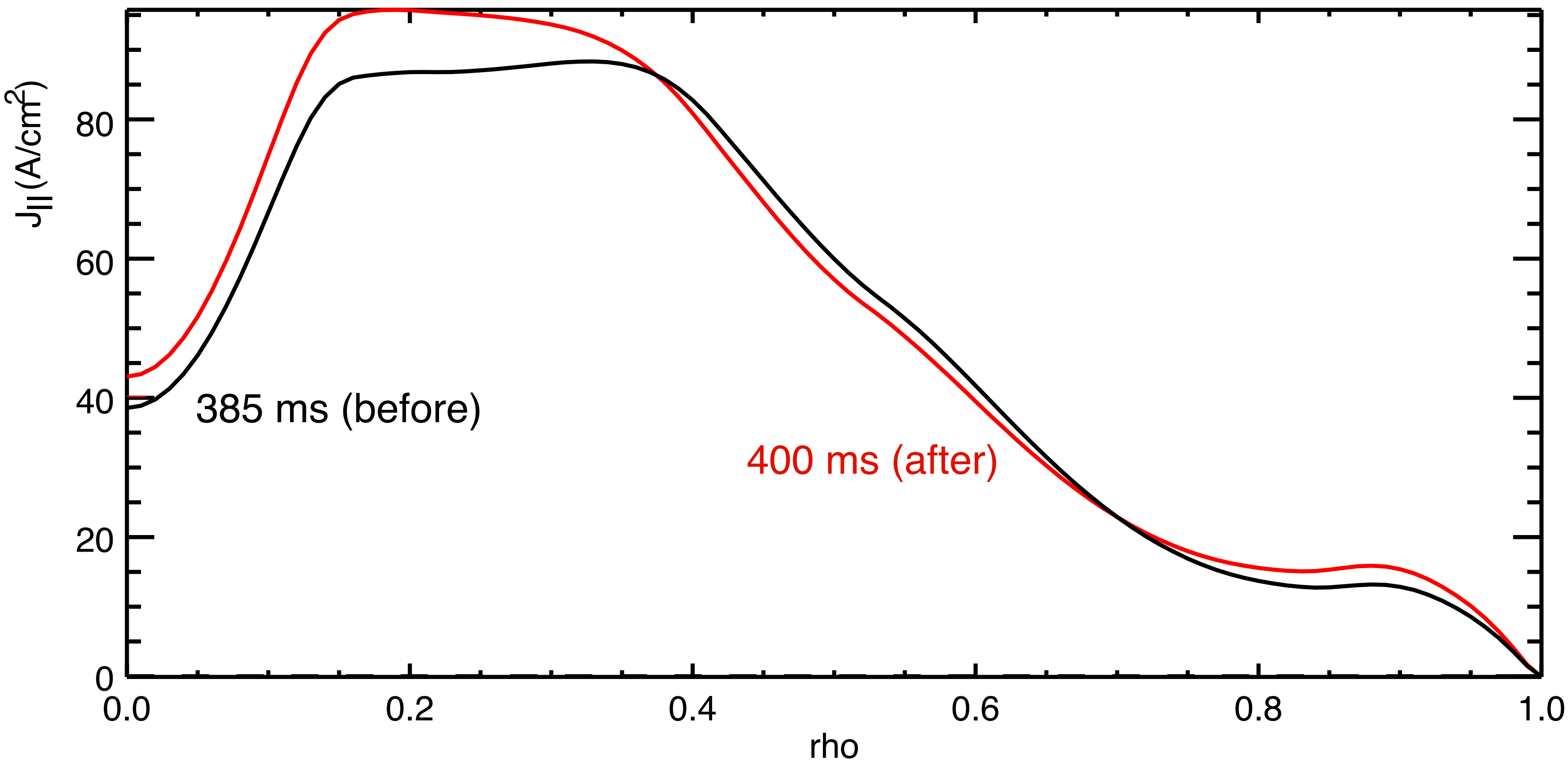
- Since modes can affect the beam ion velocities and positions, in addition to causing loss, they can alter the beam driven current profile
- Compute model $J_{||}(\psi)$ as $\Sigma nqv_{||}$ for all beam ions in a given annulus in ψ
- Compare profile before and after avalanche
- Model does not yet include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

Modeled beam $J_{||}(\rho)$ profiles for R_{tan} = 0.7 m show decrease near center and increase at mid-radii after avalanche



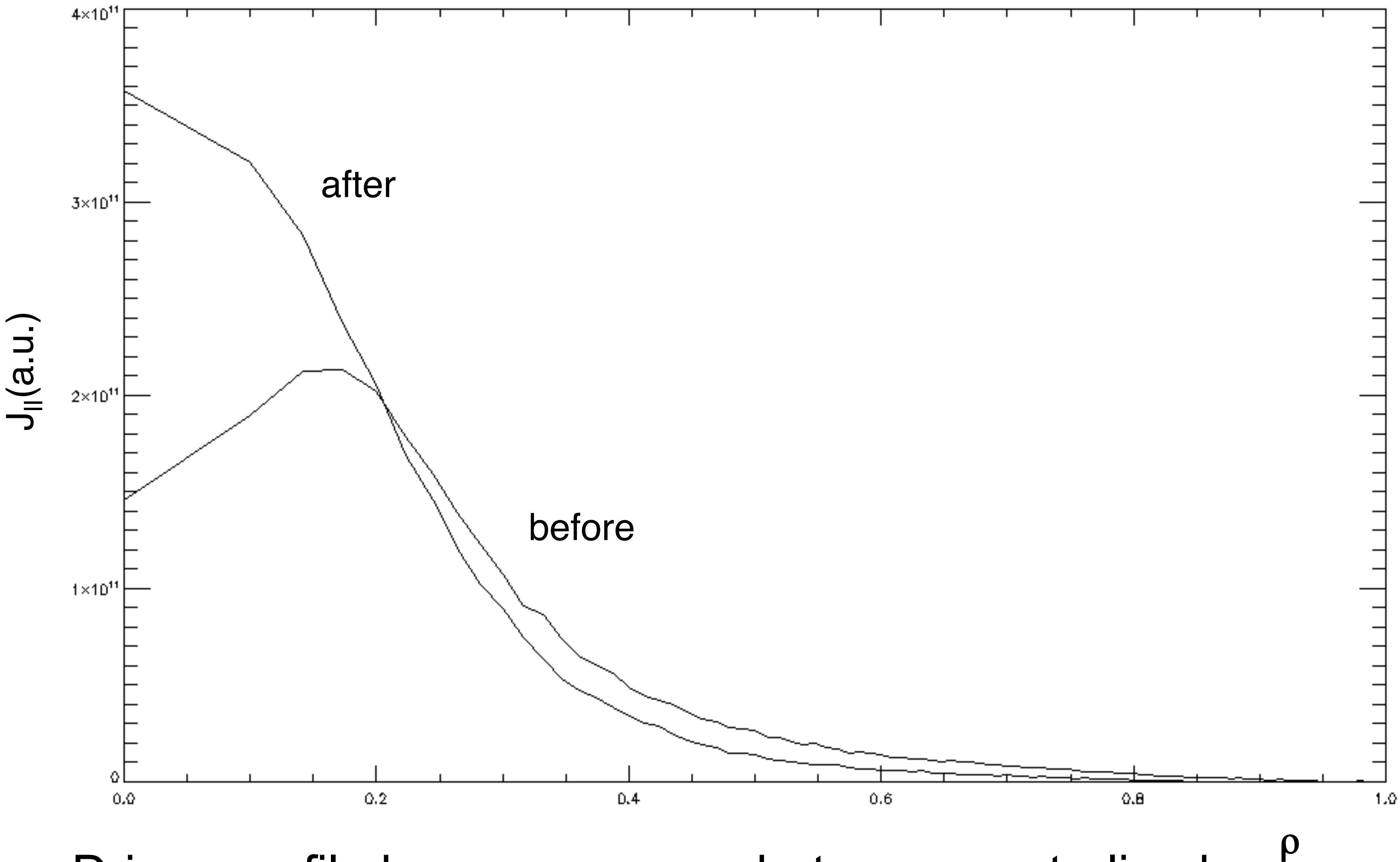
Raw ion current only for actual beam used, at R_{tan} = 0.7 m

For actual beam used, measurements show increase in central current density, and edge, with drop between



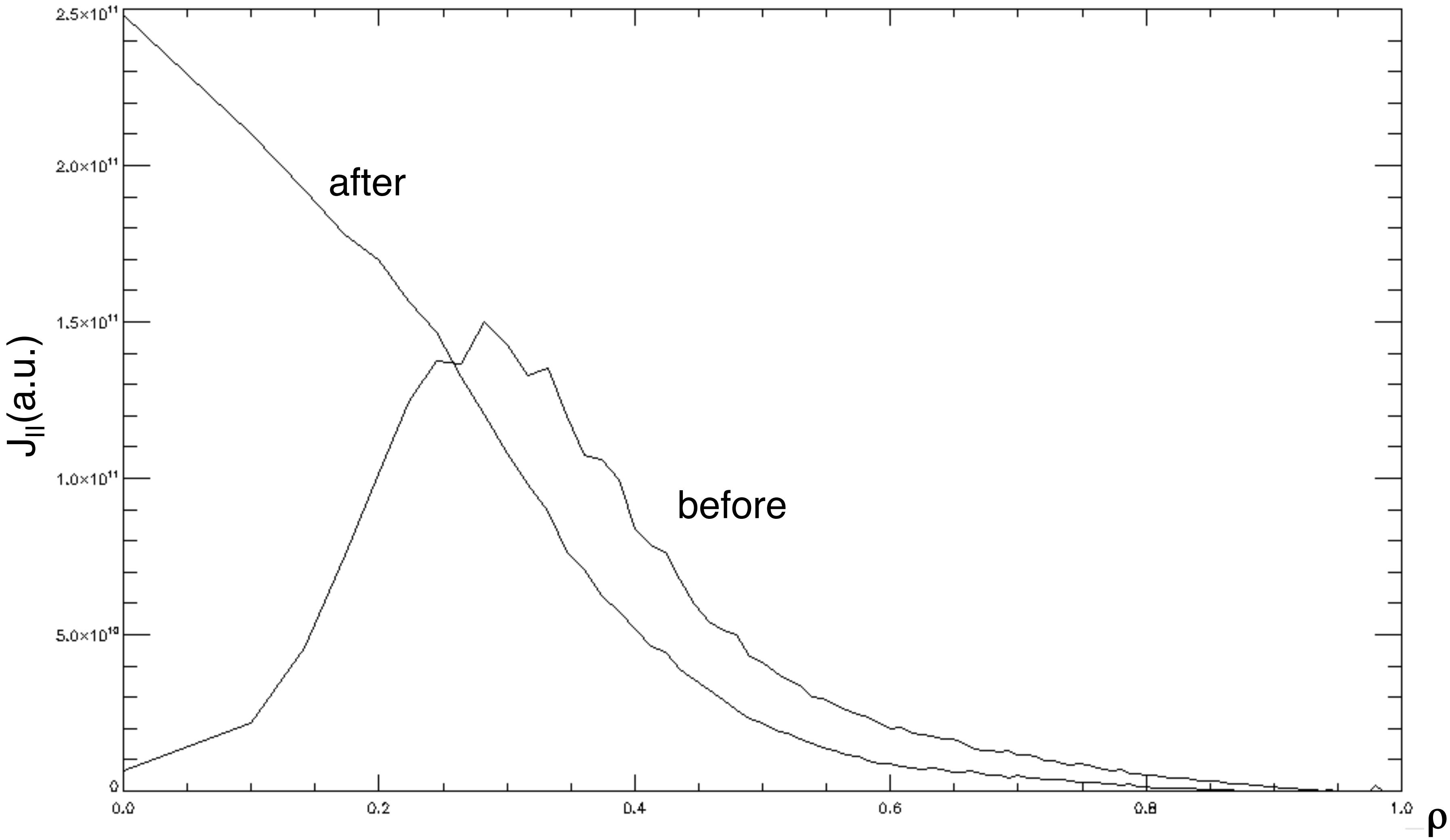
- $J_{||}$ profiles from MSE-constrained LRDFITs before and after avalanche shown
- Model differs from measurements
- But, differences well within errors of fit

Model of new beam predicts higher on-axis current density for R_{tan}=1.1 m after avalanche, with depletion at ρ>0.25



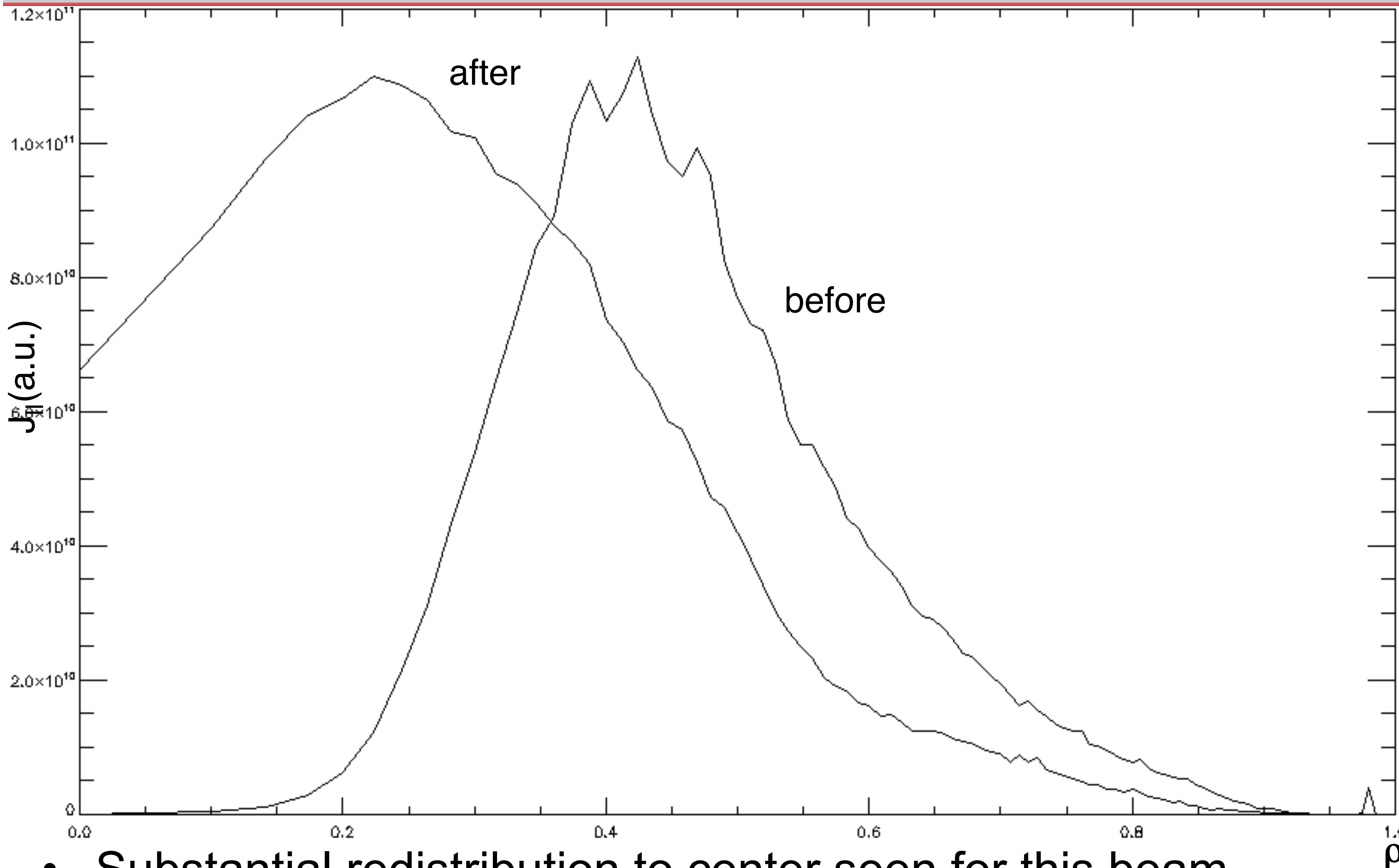
- Driven profile becomes somewhat more centralized

Modeled current profile shows similar central peaking for R_{tan}=1.2 m



- Effect is more pronounced than for more central beam injector

Modeled current profiles for outermost beam, R_{tan}=1.3 m) show largest change



- Substantial redistribution to center seen for this beam

Effect of TAEs will differ in NSTX-U for several reasons

- B will be higher in NSTX-U
  - TAE drive predicted to be stronger as v_b/v_A~2
  - But, gyroradius of beam ions will be 2x smaller, meaning radial step size during transport will be smaller, and loss boundary will not extend as far into plasma

- Multiple n numbers still predicted to be unstable in NSTX-U, esp. n=4–8, maintaining possibility of driving avalanches
- More work needed to predict modes in an NSTX-U avalanche and compute their effects on beam current

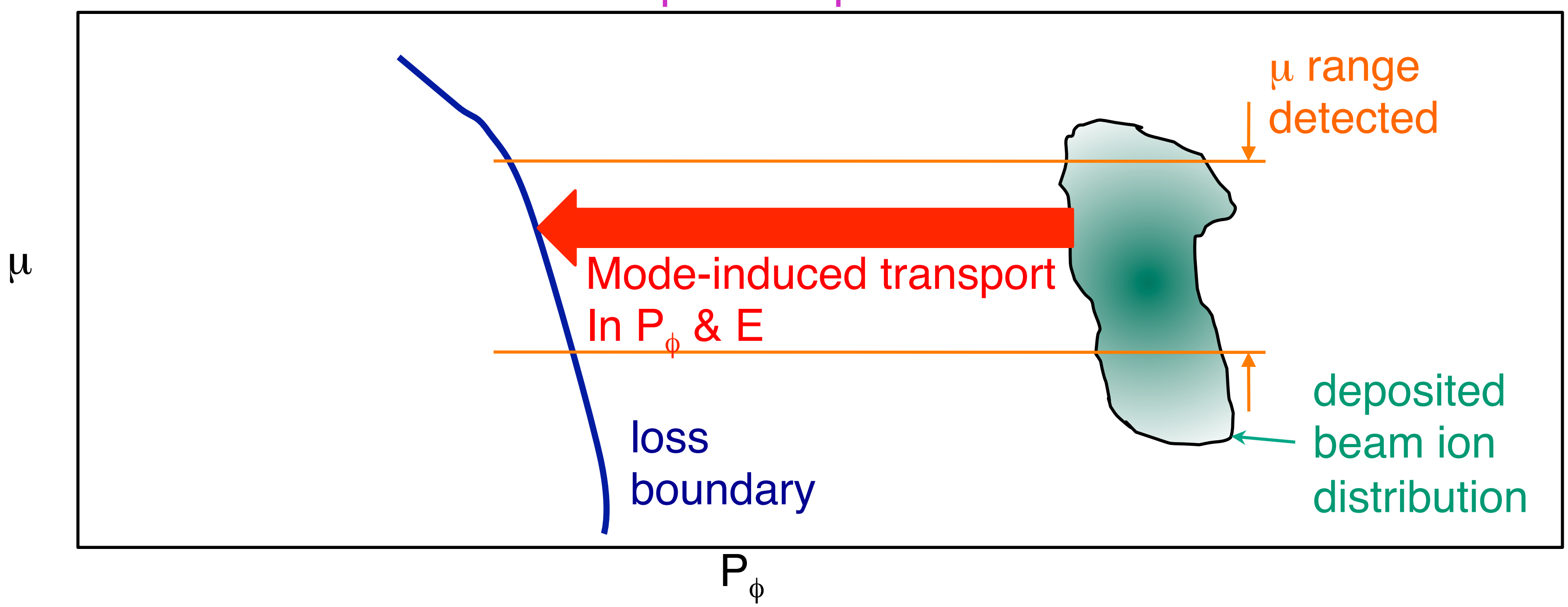
Beam ion orbits can be completely characterized by 3 constants of the motion

- $E = ½ mv^2$ (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 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

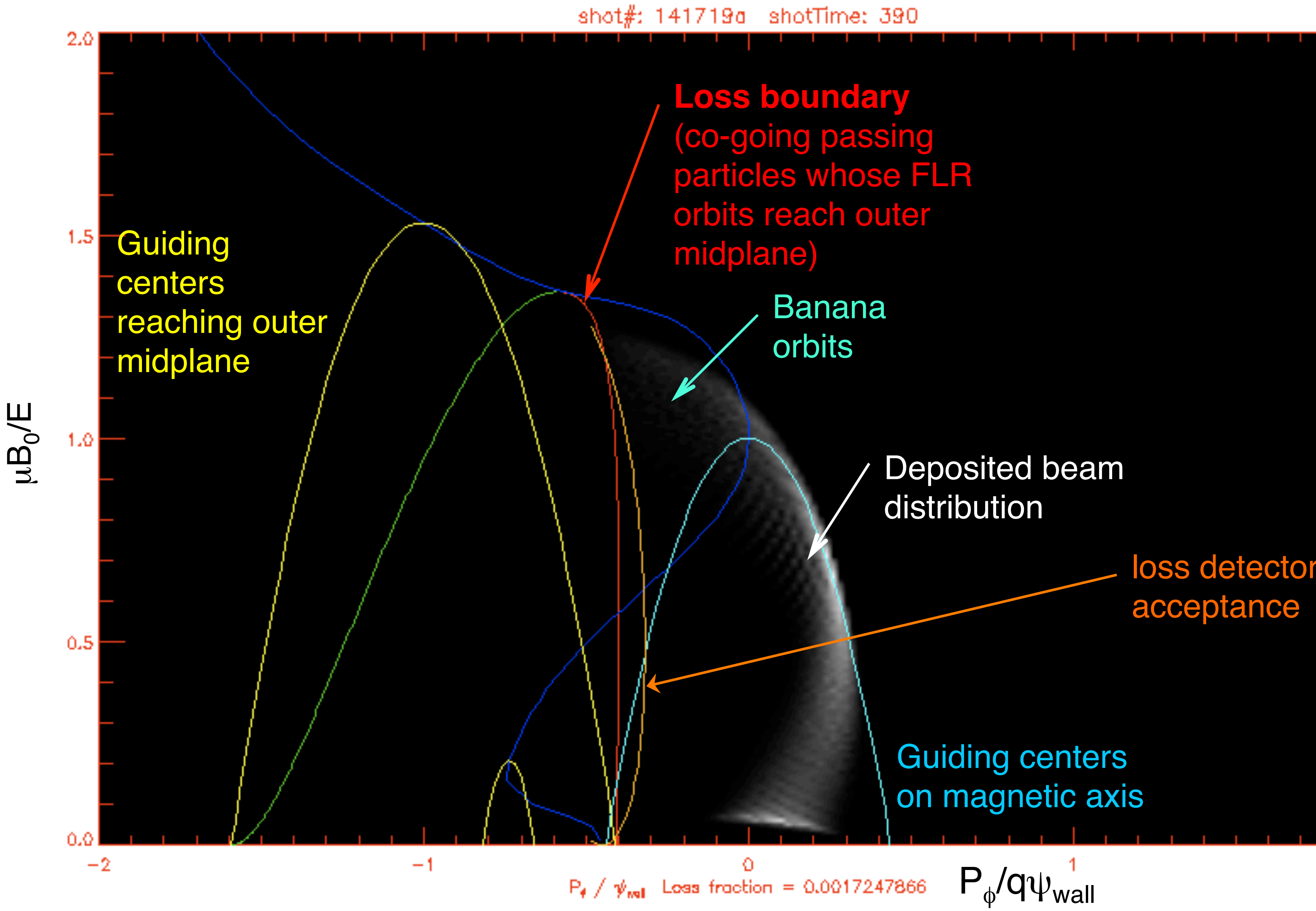
Modes transport beam ions radially, some to loss boundary

- 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

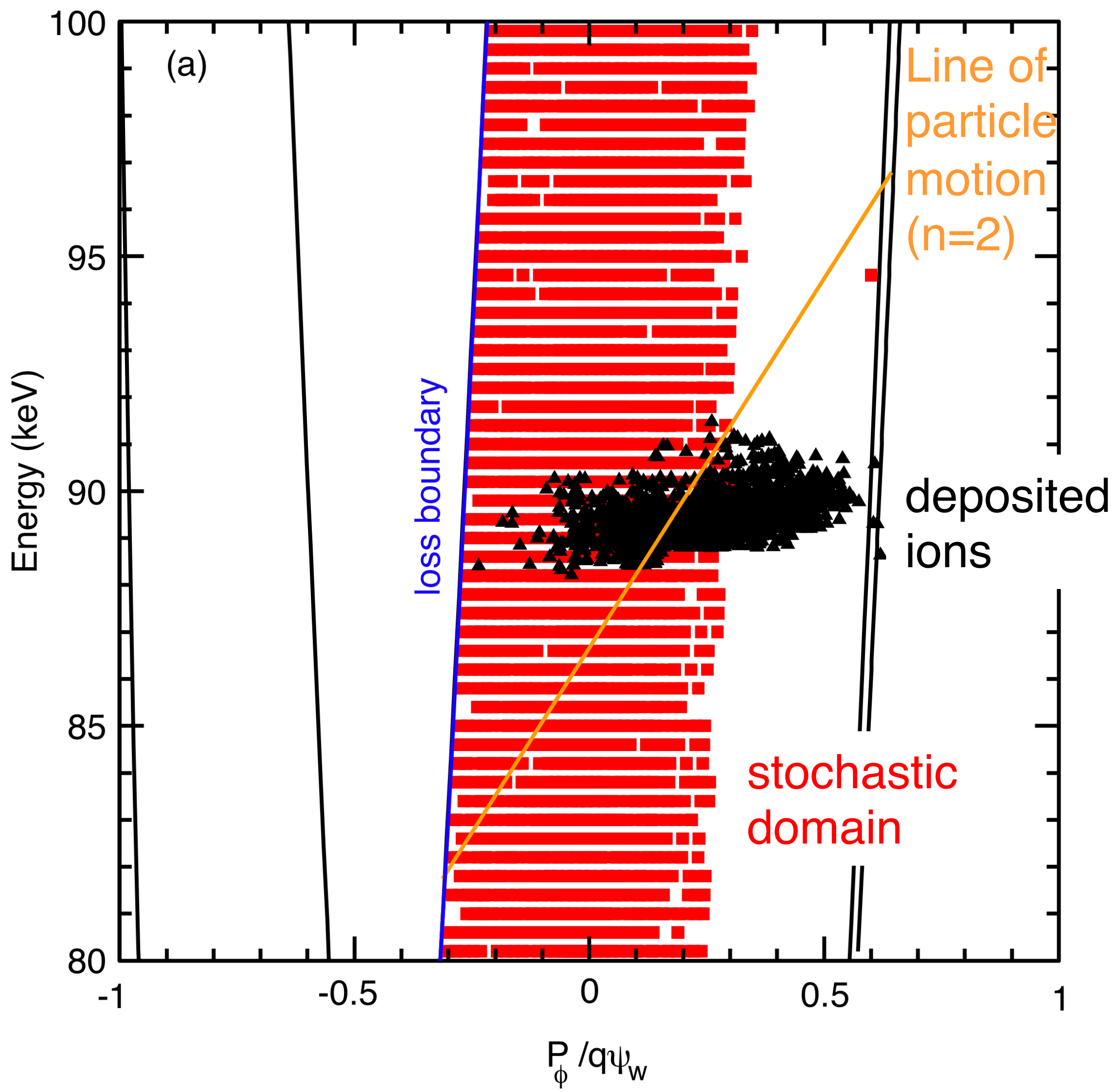
Beam ion phase space at fixed E



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

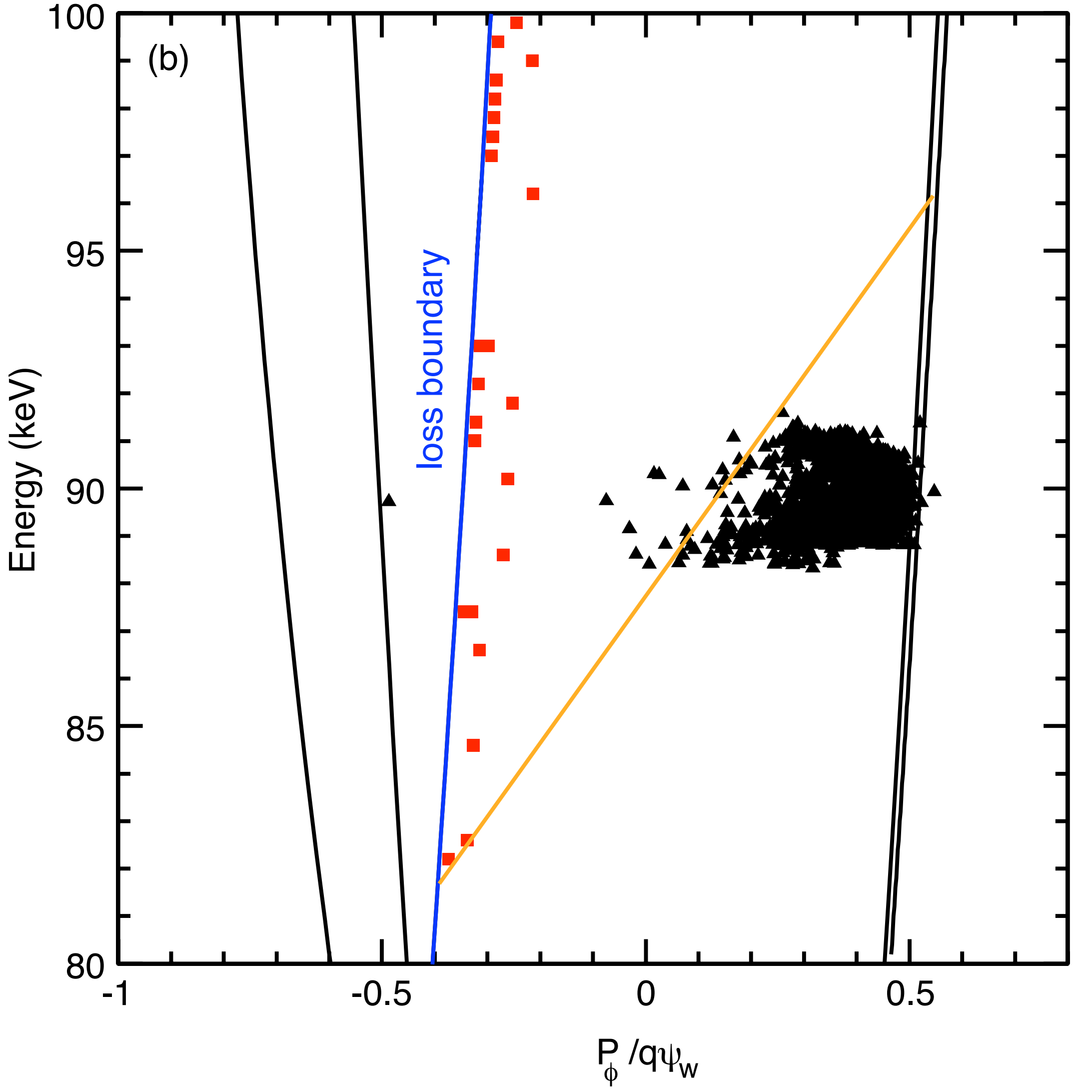


Case a (23°) is near center of a detected loss spot & model predicts loss



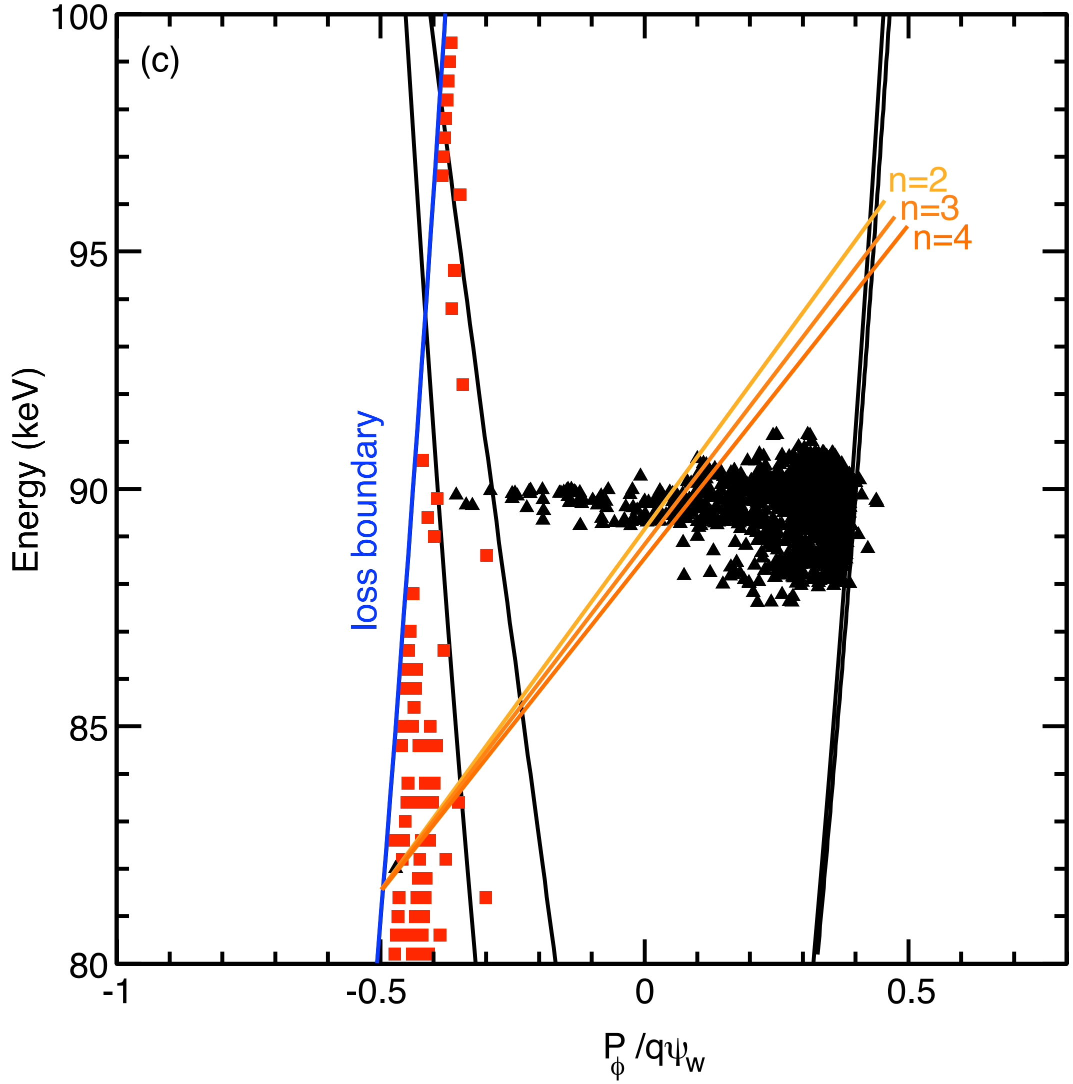
- Beam ions deposited in stochastic region
- Particles move along orange line (or parallel lines) under influence of n=2 mode
- Particles clearly deposited in stochastic region and that region extends to loss boundary

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

Summary

- TAE avalanches in NSTX plasmas can alter neutral beam driven current profile
- Modeling of the effect of an NSTX avalanche upon the new NSTX-U beam orientations predicts significant transport of beam current from mid-radii to near axis
- This redistribution could impair efforts to obtain an equilibrium maintain solely by bootstrap current and NB driven current
- Further work to extend modeling to realistic NSTX-U conditions is warranted