NSTX-U

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

Effects of MHD instabilities on Neutral Beam current drive

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and the NSTX-U Research Team

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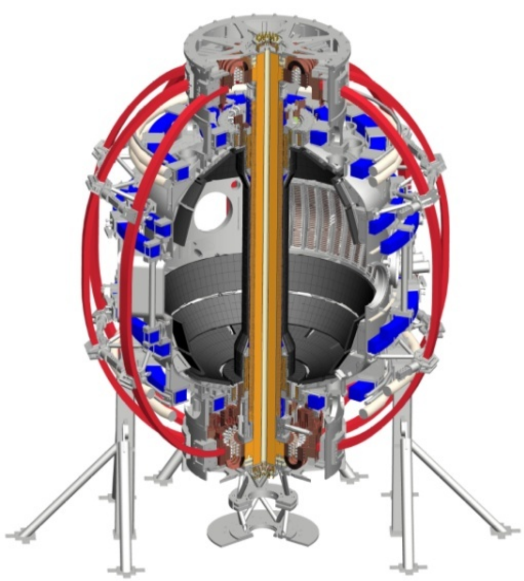
St Petersburg, Russian Federation
13-18 October, 2014



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Reliable, quantitative predictions of Energetic Particle (EP) dynamics are crucial for burning plasmas

- EPs from Neutral Beam (NB) injection, alphas, RF tails drive instabilities,
  - e.g. Alfvénic modes – AEs
- With instabilities, 'classical' EP predictions (e.g. for NB heating, current drive) can fail

> *Predictive tools are being developed, validated for integrated modeling of these effects in present and future devices (ITER, Fusion Nuclear Science Facility – FNSF)*

Outline

- NSTX discharges with strong MHD are used to test and validate EP transport models
- Modeling methods beyond ‘classical’ EP physics are developed to account for MHD effects
- New model captures MHD modifications of EP phase space leading to Neutral Beam current redistribution

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Alfvénic modes (AEs) and kink-like modes degrade fast ion confinement, plasma performance

	NSTX
Major radius	0.85 m
Aspect ratio	1.3
Plasma current	~1 MA
Toroidal field	<0.55 T
Pulse length	<2 s

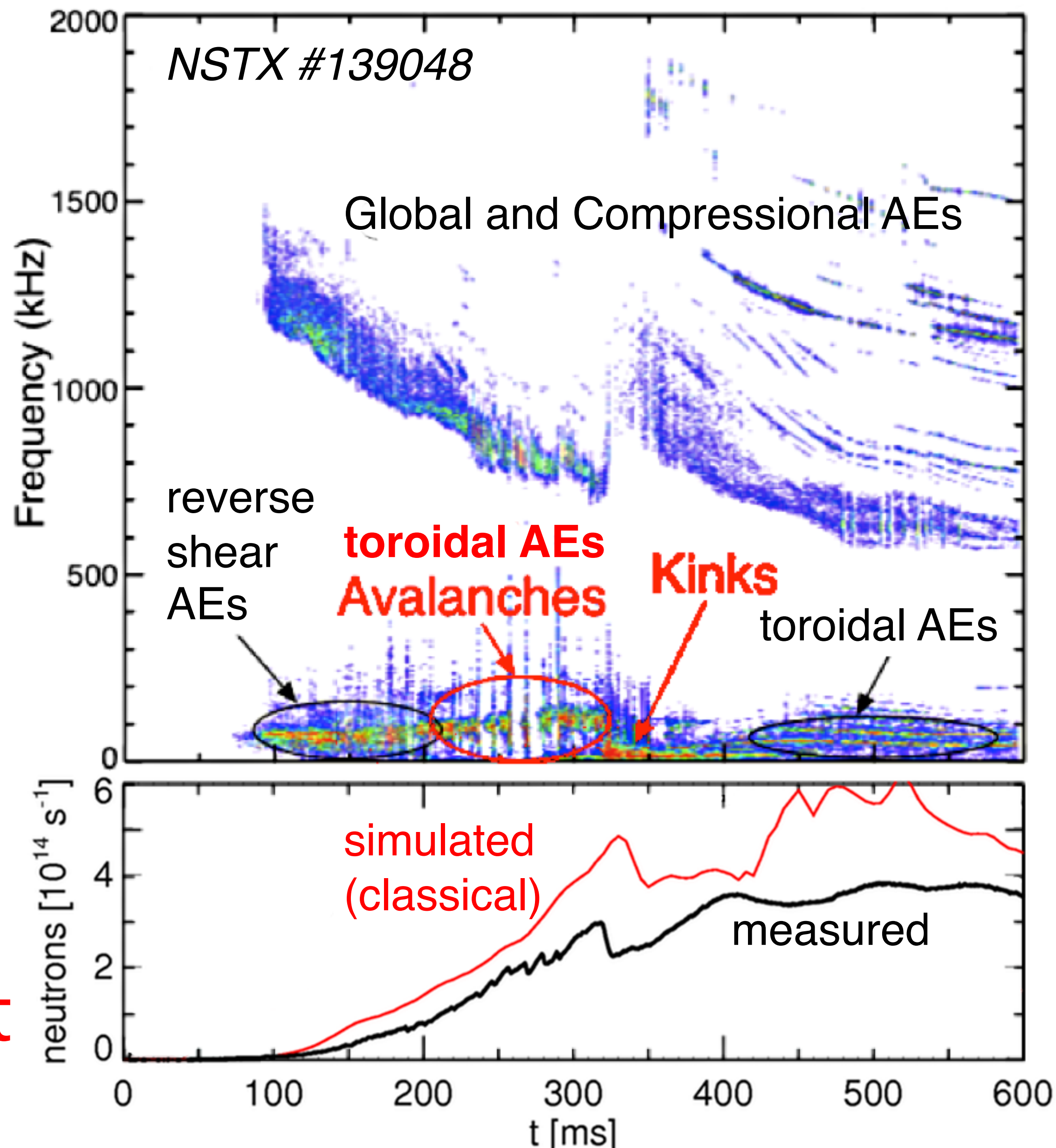
Neutral Beam sources:

$P_{NBI} \leq 6$ MW

$E_{injection} \leq 95$ keV

⇨ $1 < v_{fast}/v_{Alfvén} < 5$

Super-alfvénic ions, high β_{fi}: plethora of fast ion driven instabilities



[Fredrickson, NF 2013]

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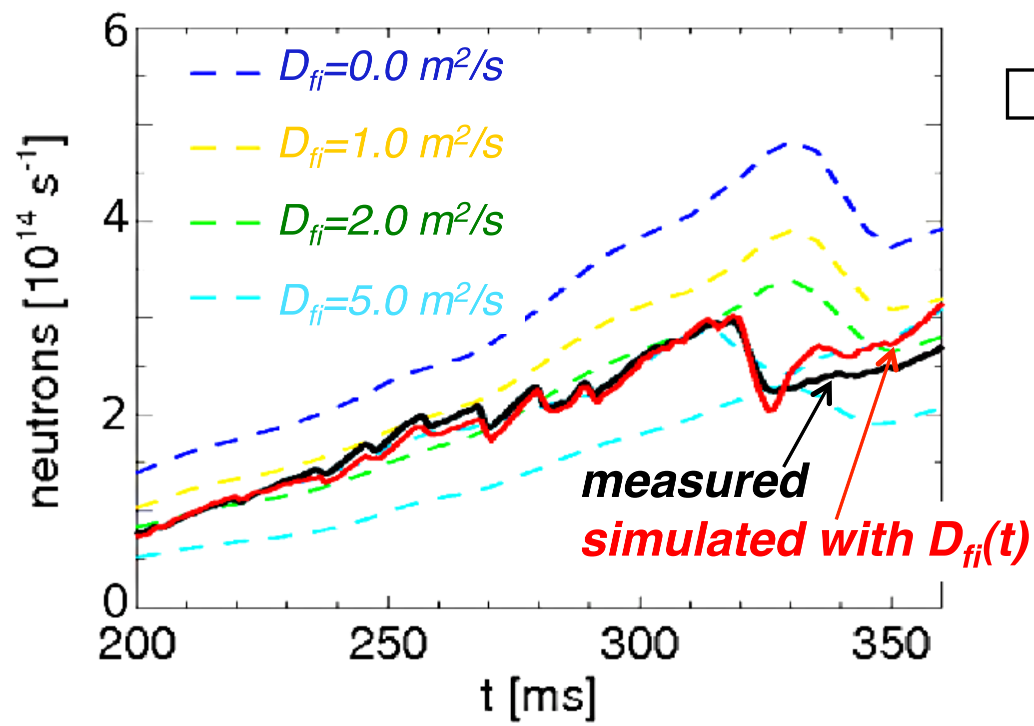
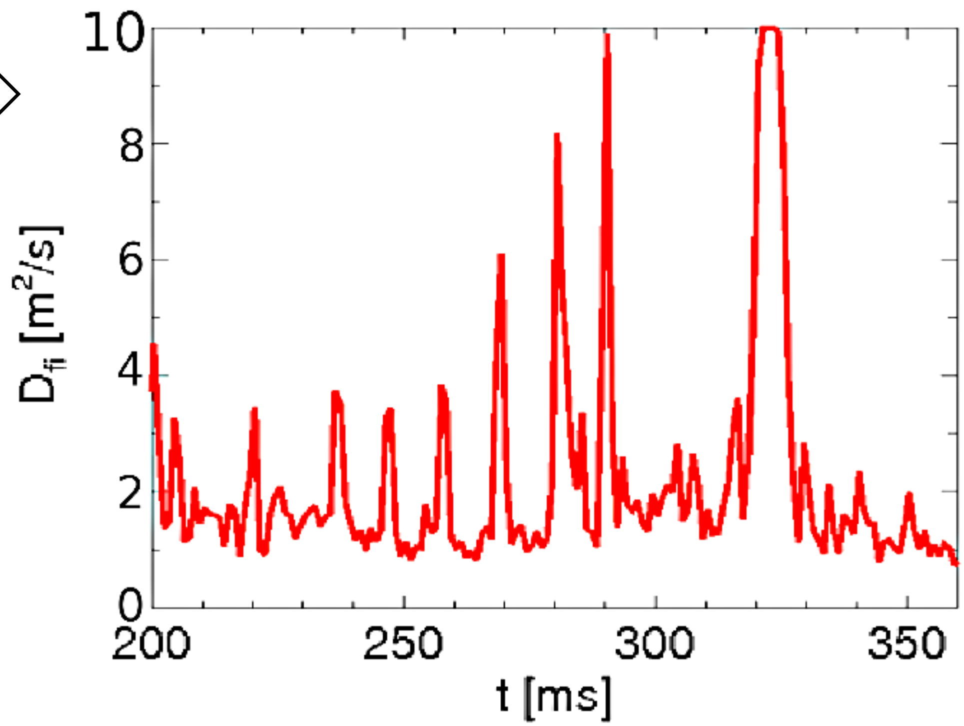
Transport code TRANSP includes NUBEAM module for classical fast ion physics

- Additionally, *ad-hoc* diffusivity D_{fi} is used to mimic enhanced fast ion transport
  - Assumed uniform in radius, pitch, energy in this work
- Metric to set D_{fi}: match neutron rate, W_{mhd}



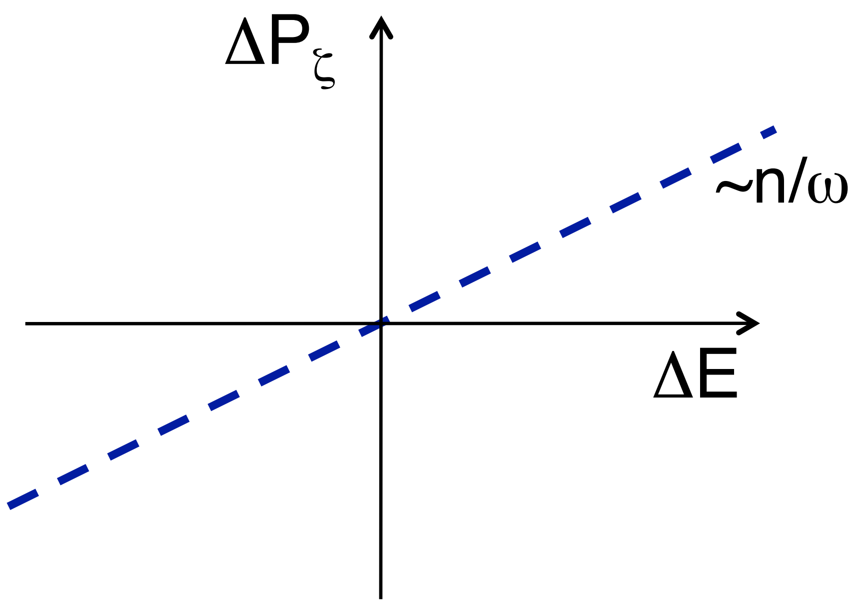


However: instabilities introduce fundamental constraints on particle dynamics

From Hamiltonian formulation – single resonance:

$$\omega P_\zeta - nE = const. \Longrightarrow \Delta P_\zeta/\Delta E = n/\omega$$

$\omega=2\pi f$, mode frequency n, toroidal mode number



E, energy
$P_\zeta \sim mRv_{par}-\Psi$, canonical angular momentum
$\mu \sim v_{perp}^2/(2B)$, magnetic moment
where Ψ : poloidal flux
R : major radius
m : mass

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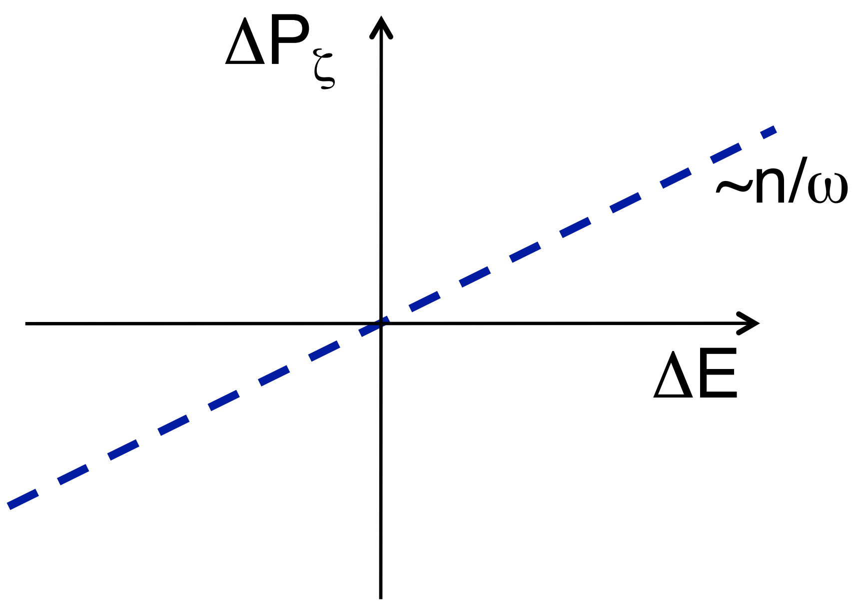

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where Ψ : poloidal flux

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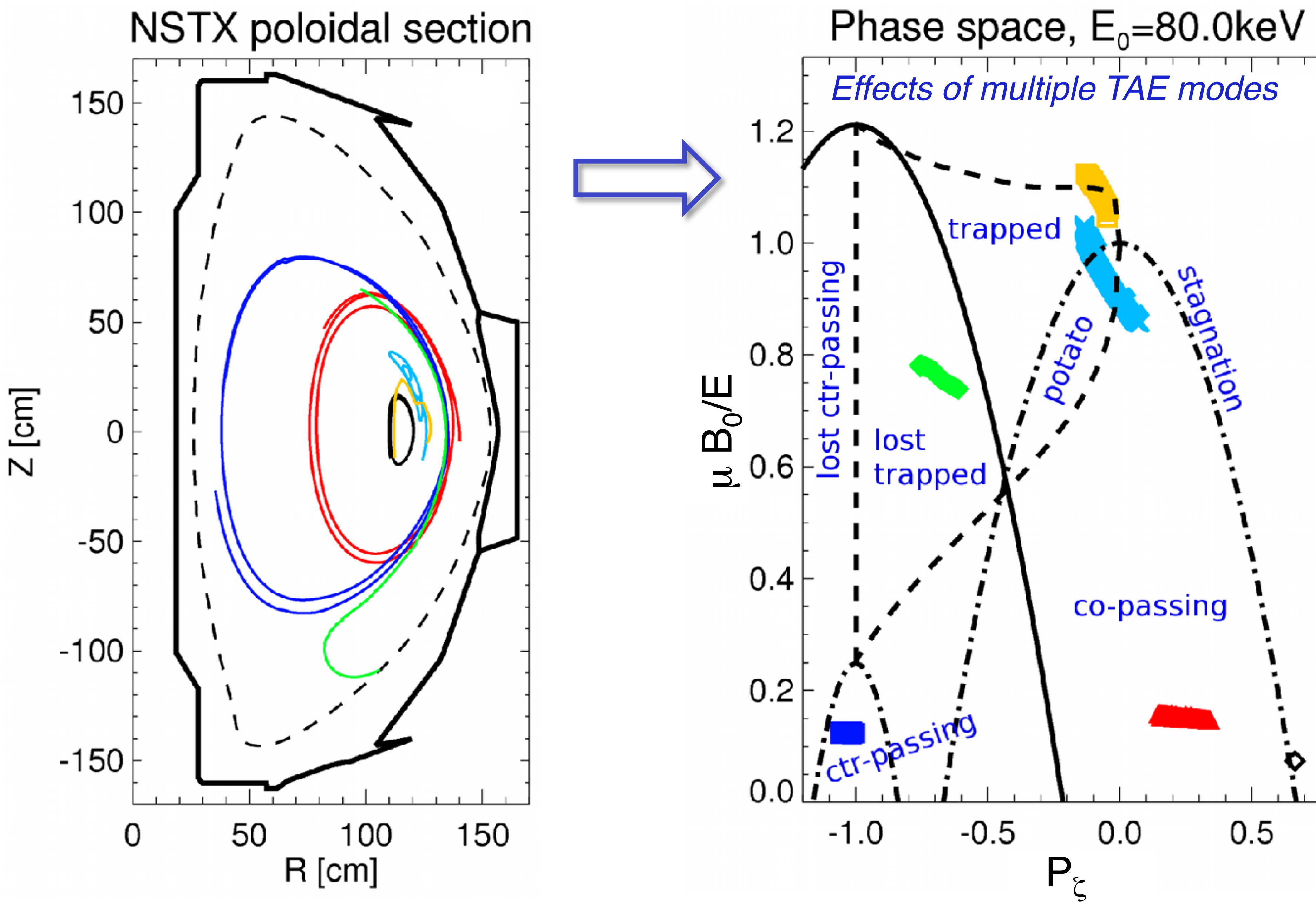
These effects are not accounted for by ad-hoc D_{fi}.
A new method is needed to include them in integrated modeling.

Constants of motion (E,P_ζ,μ) are the natural variables to describe wave-particle interaction



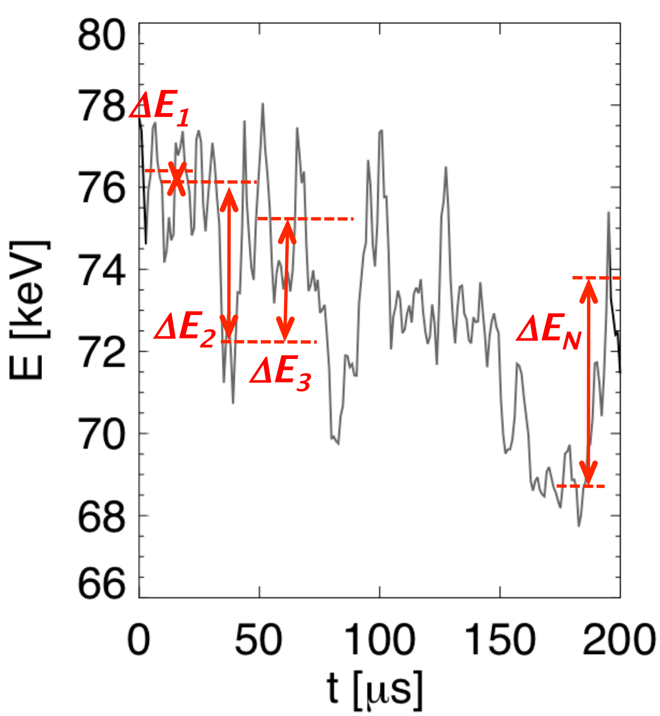
R. B. White, *Theory of toroidally confined plasmas*, Imperial College Press (2014)

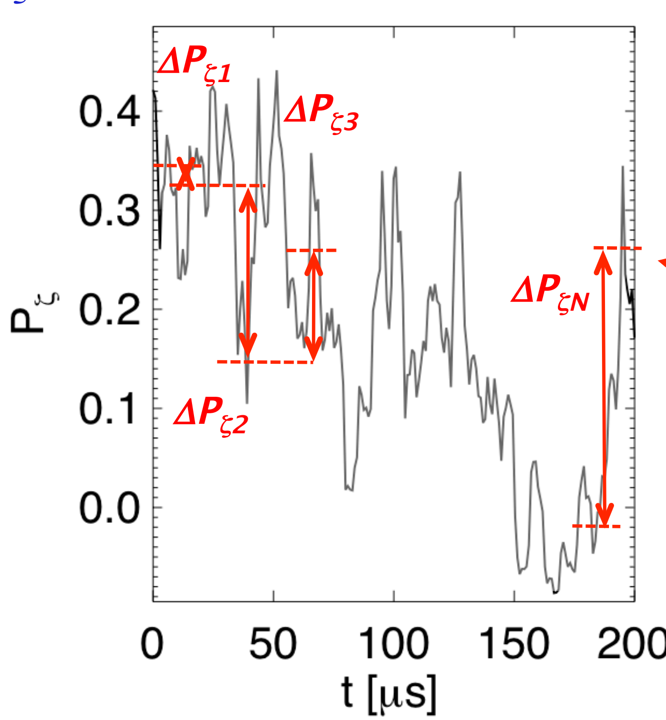
Particle-following codes are used to extract distribution of ‘kicks’ ΔE, ΔP_ζ for each *bin* (E,P_ζ,μ)

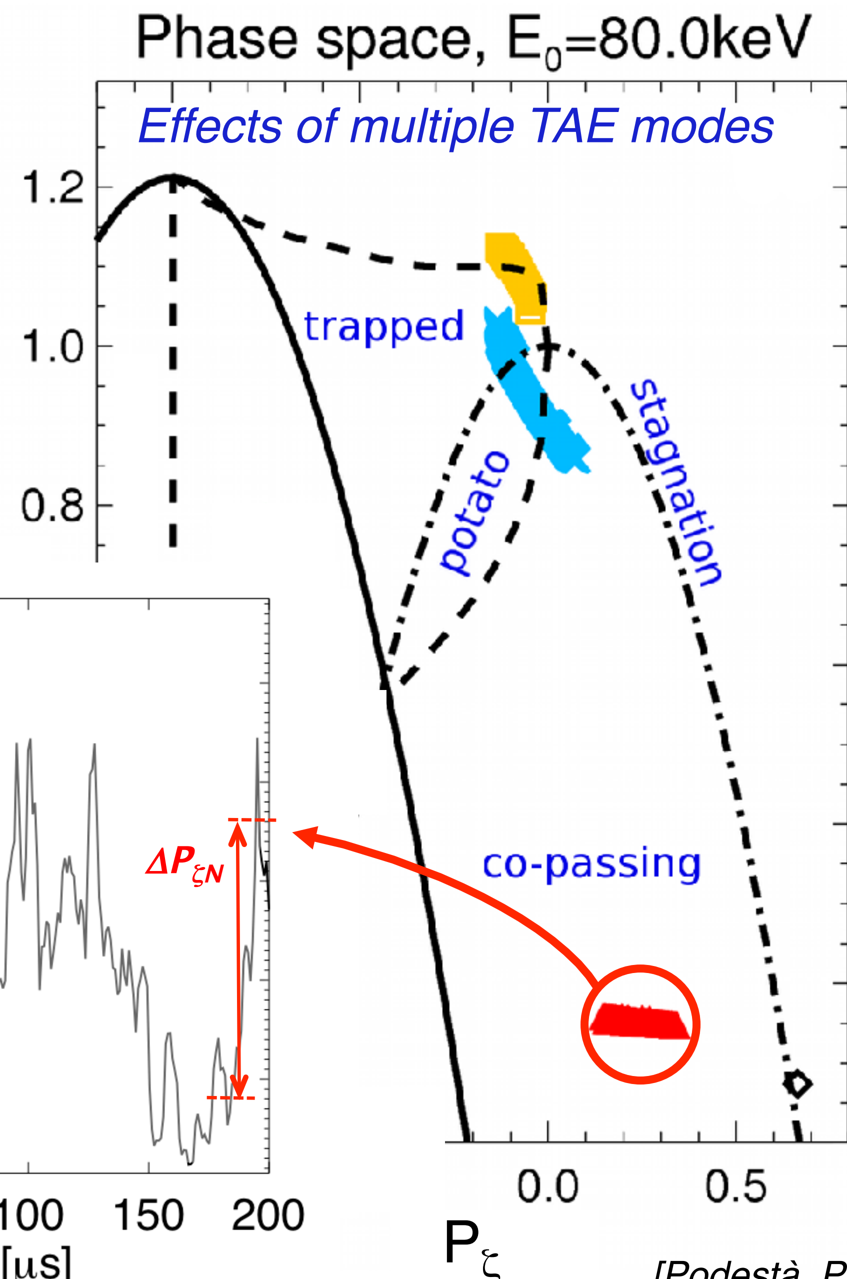
- ORBIT code: record E,P_ζ,μ *vs.* time for each particle
- Compute average kicks over multiple wave periods:

$$\underbrace{1/f_{wave}}_{\text{neglected}} < \underbrace{\tau_{resonance}}_{\text{relevant time scale}} < \underbrace{\tau_{collisions}}_{\text{classical}}$$

- Re-bin for each (E,P_ζ,μ) region







[Podestà, PPCF 2014]

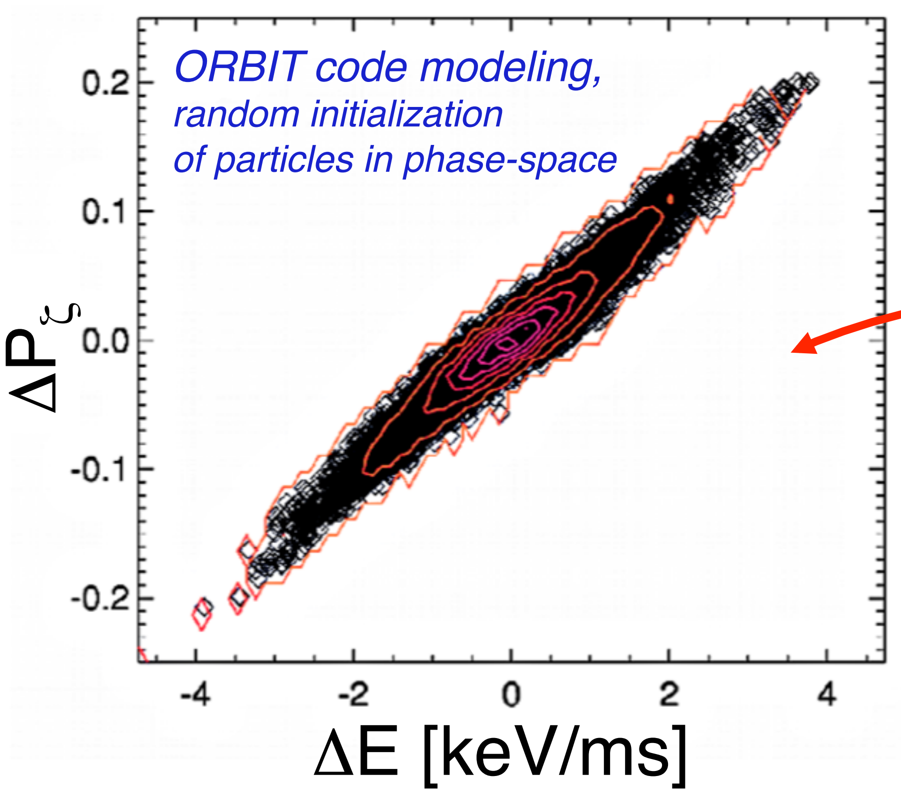
New 'kick model' uses a *probability distribution function* for particle transport in (E,P_ζ,μ) space

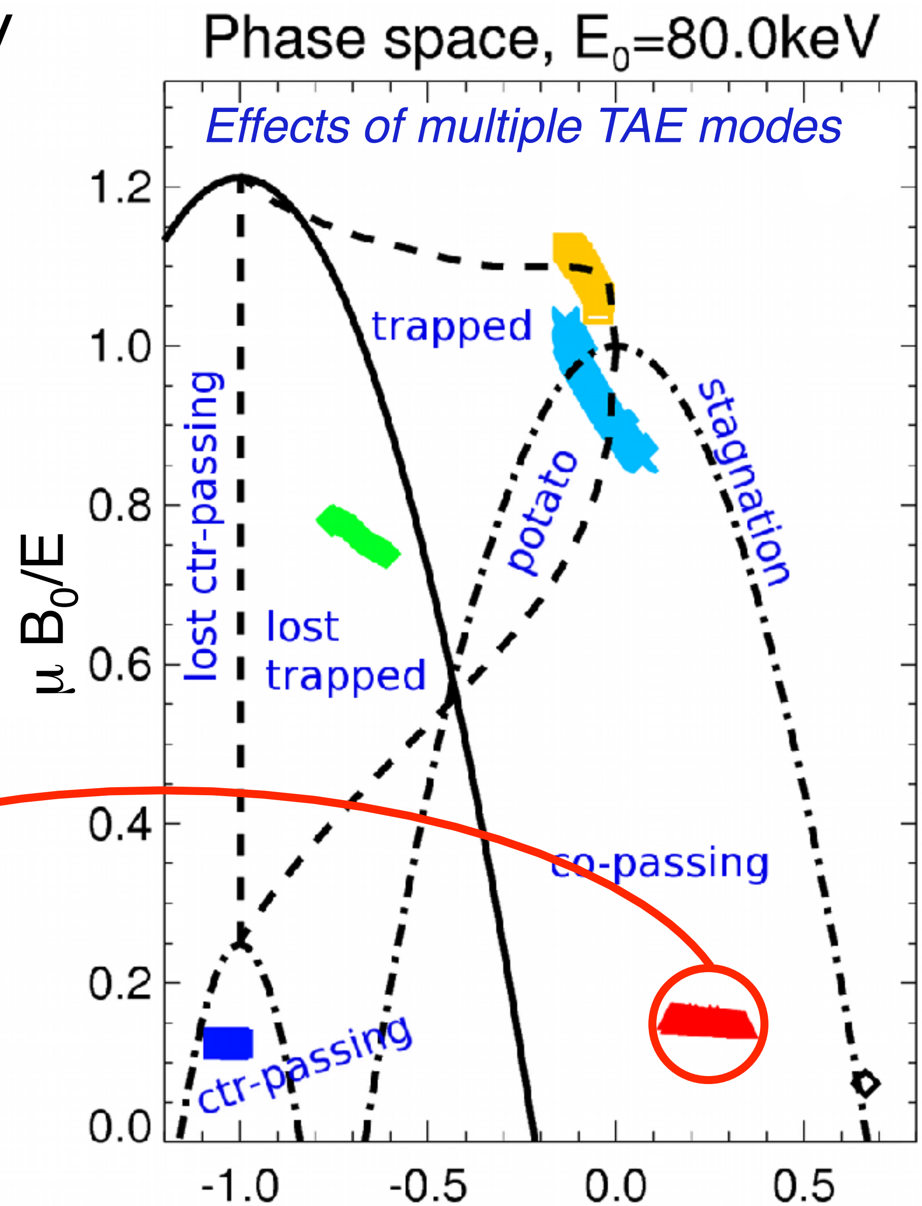
Kicks $\Delta E,\Delta P_\zeta$ are described by

$$p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu, A)$$

which includes the effects of multiple modes, resonances.

⇨ ***correlated random walk in E, P_ζ***

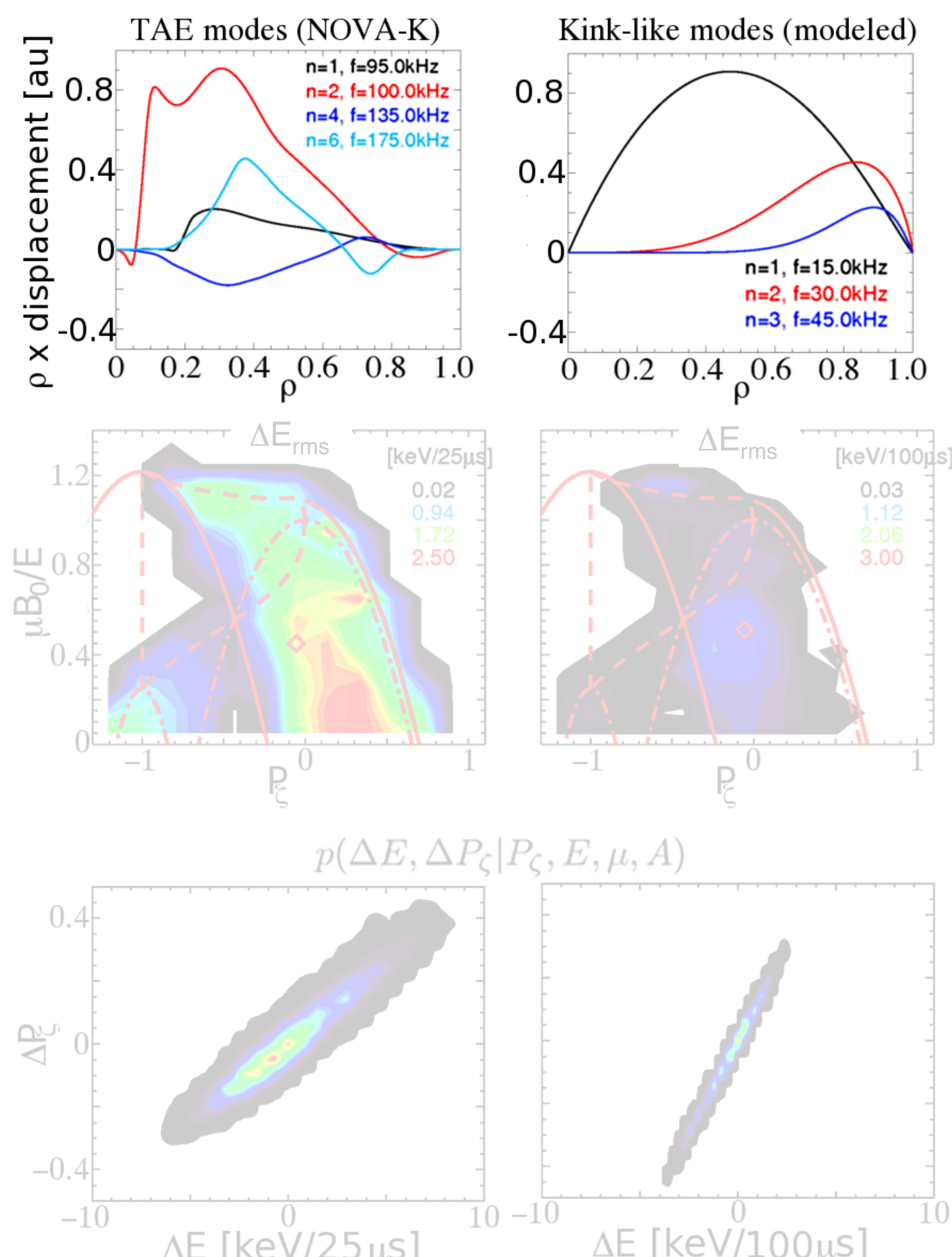




[Podestà, PPCF 2014]

$p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu)$ and a time-dependent 'mode amplitude scaling factor' enable multi-mode simulations

- Example: toroidal AEs (TAEs) and low-frequency kink
- $p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu)$ from particle-following code ORBIT
- Each type of mode has separate $p(\Delta E, \Delta P_\zeta)$, $A_{mode}(t)$
- TAEs and kinks act on different portions of phase space
- Amplitude vs. time can differ, too
- Effects on EPs differ
  > TAEs: large ΔE, ΔP_ζ
  > kinks: small ΔE, large ΔP_ζ



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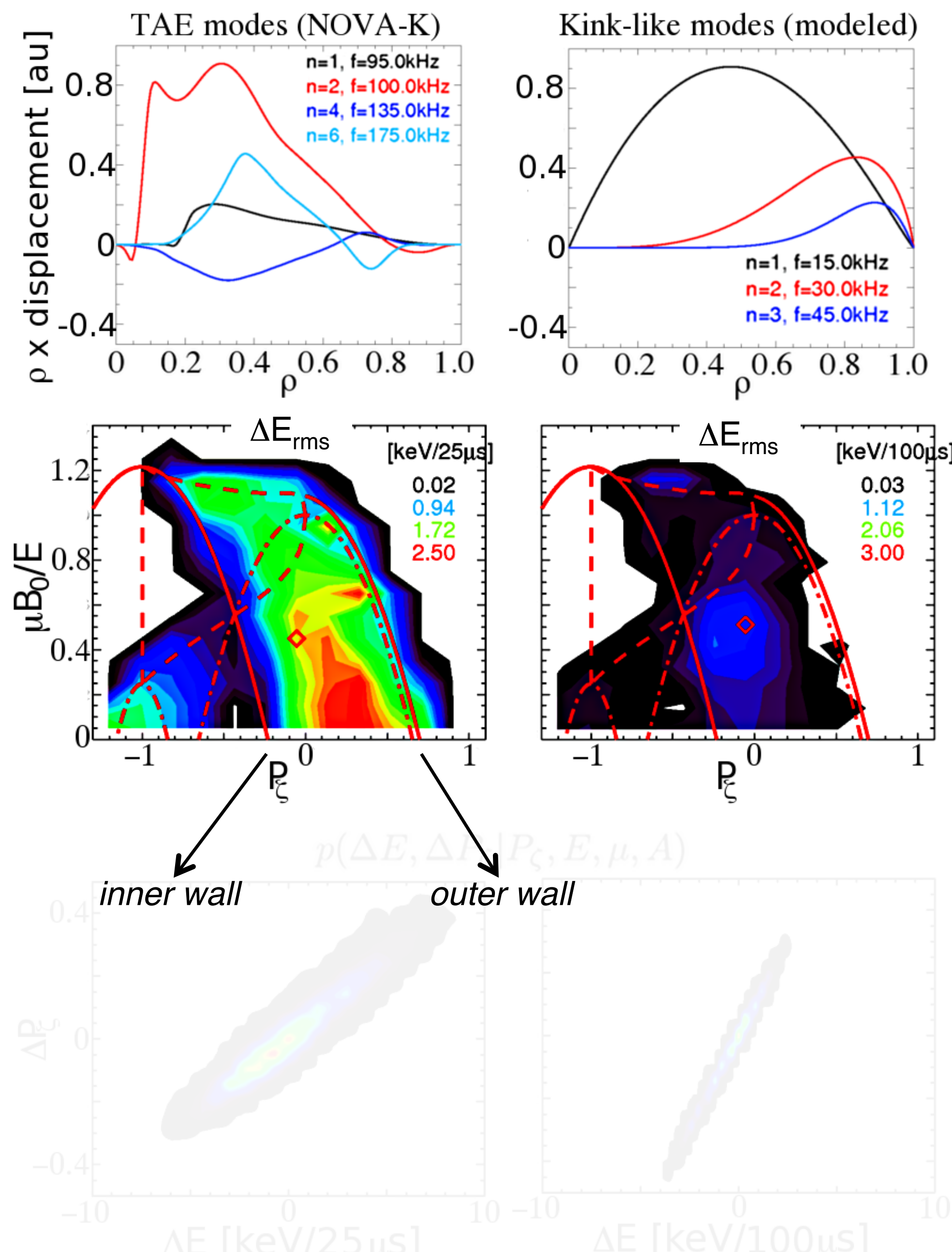

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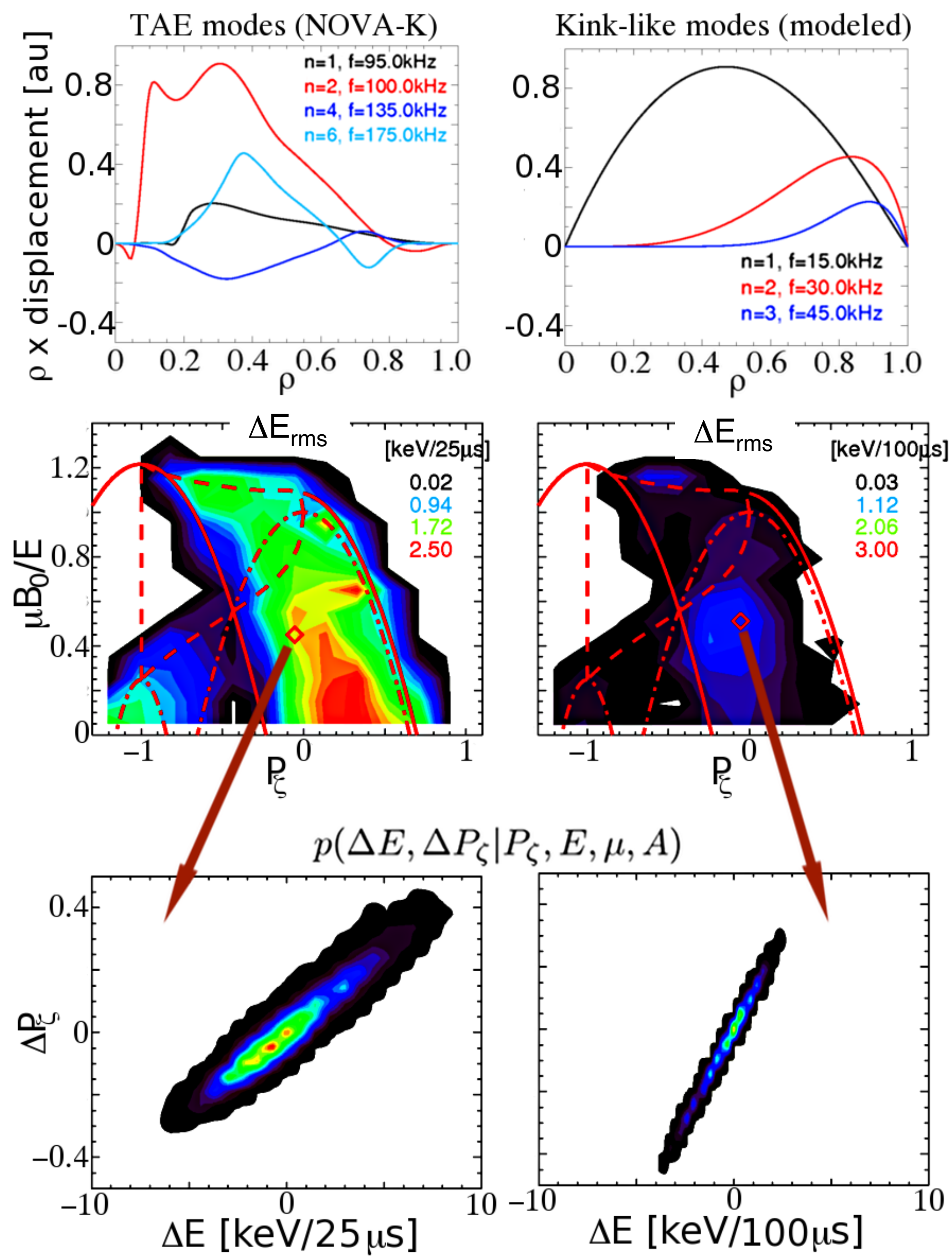

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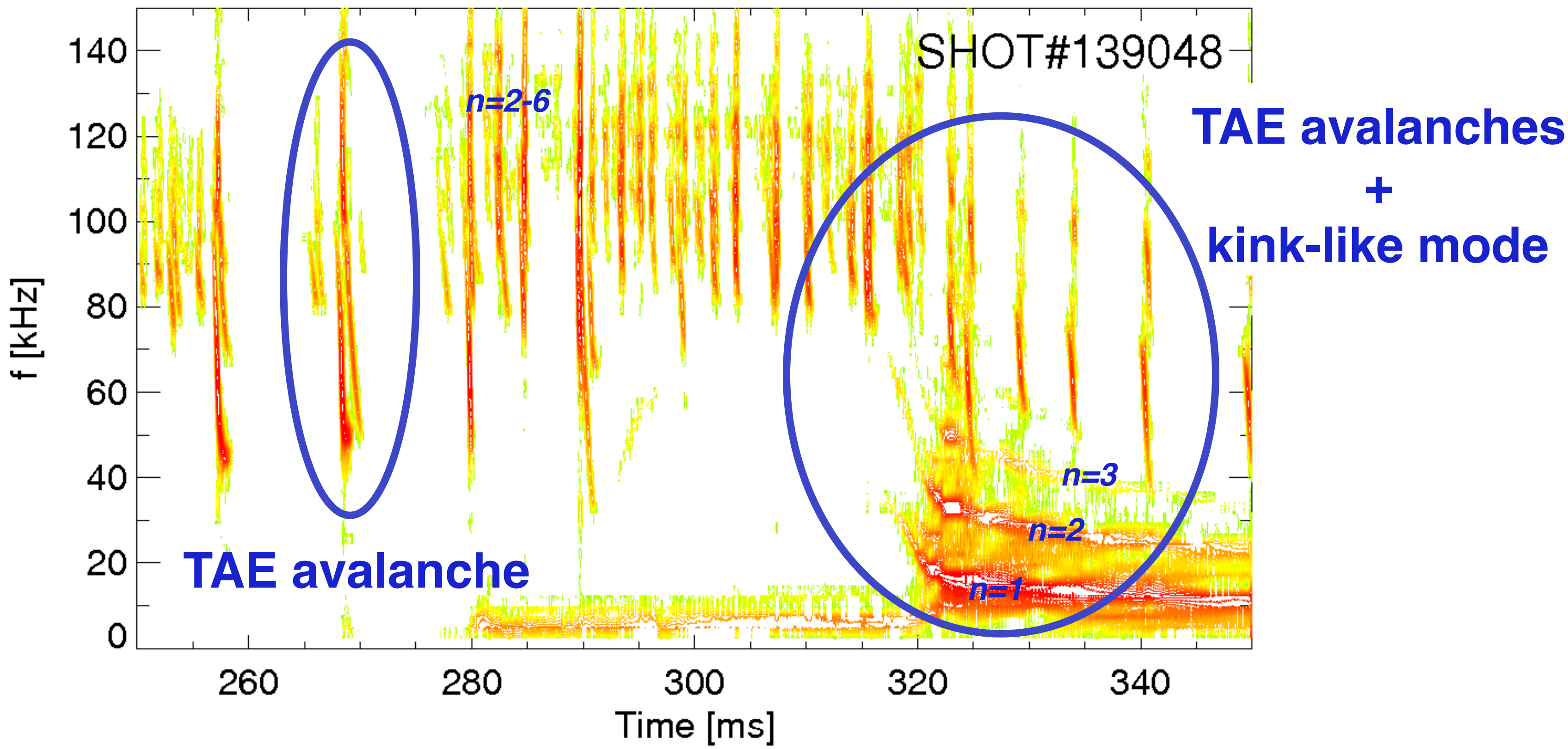
Two NSTX cases are analyzed in detail: TAE avalanche and avalanche + kink-like mode (multi-mode scenario)



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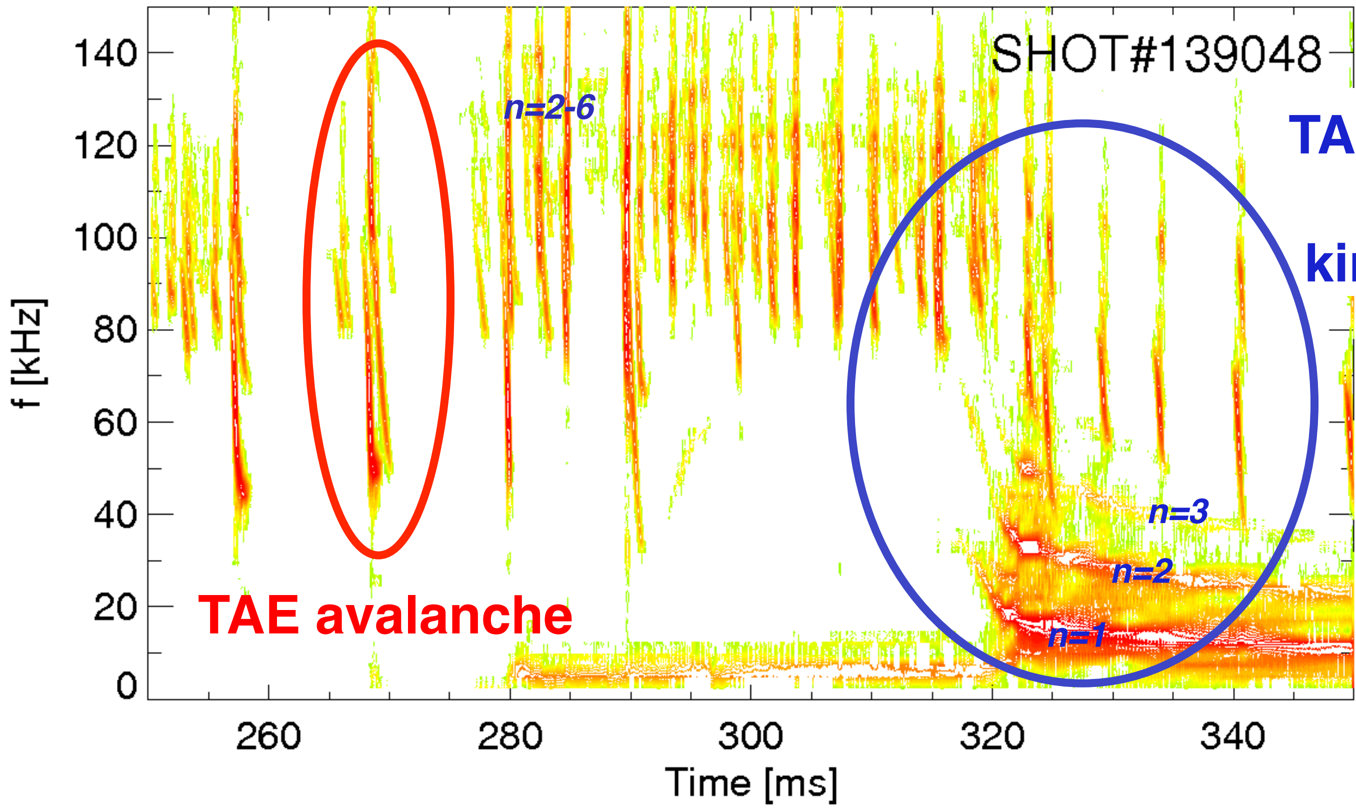
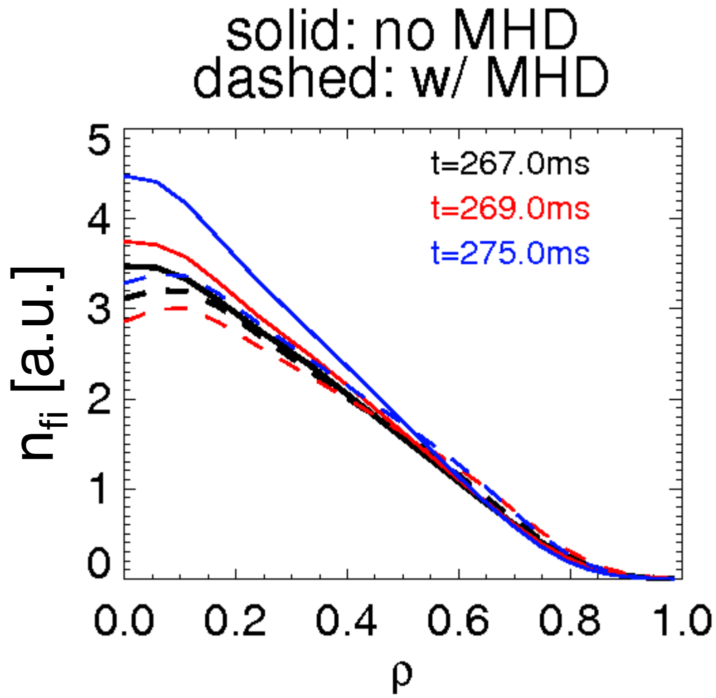


TAE avalanches + kink-like mode

TAE avalanches cause an abrupt drop in fast ions and up to ~40% reduction in local NB-driven current density



- Results from 'kick model'
- Fast ions redistributed outward, lose energy
  - Consistent with constraints from resonant interaction:

$$\Delta P_\zeta / \Delta E = n/\omega$$

- NB-driven current J_{nb} is also redistributed out
- $J_{nb}(r)$ modification largely unpredicted by *ad-hoc* D_{fi} in this case

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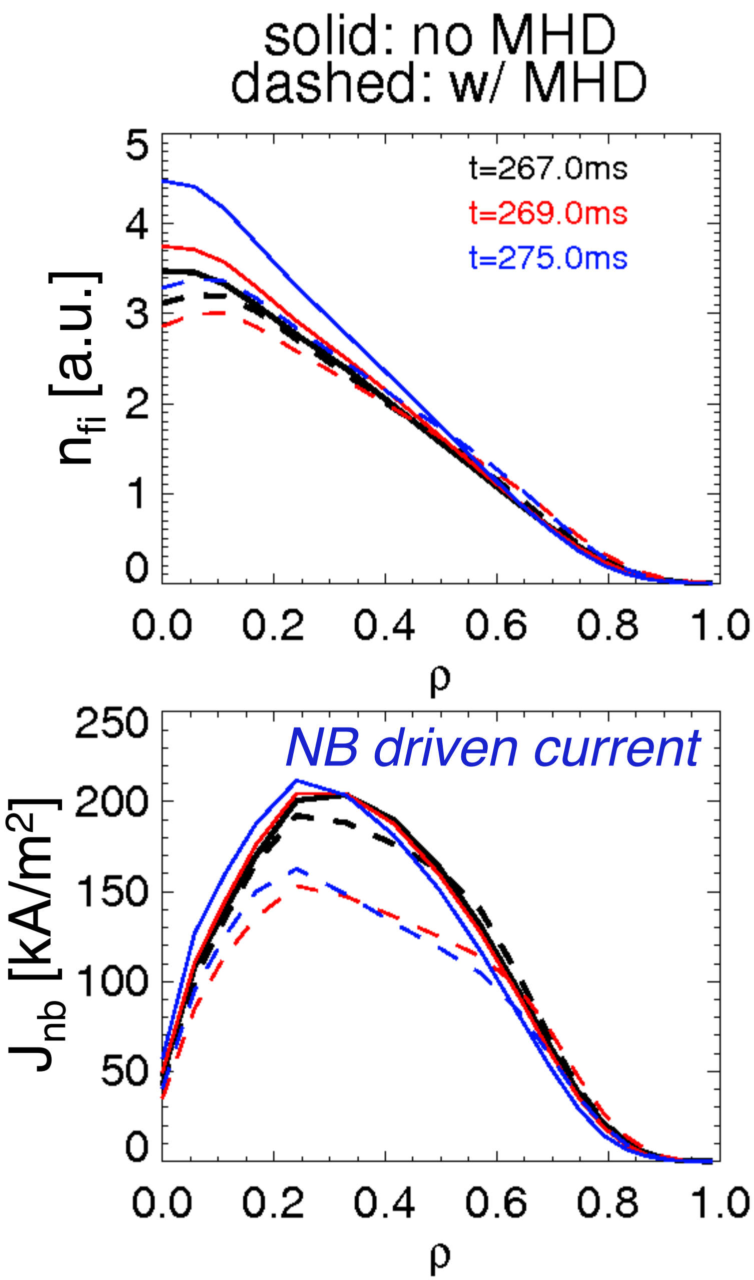

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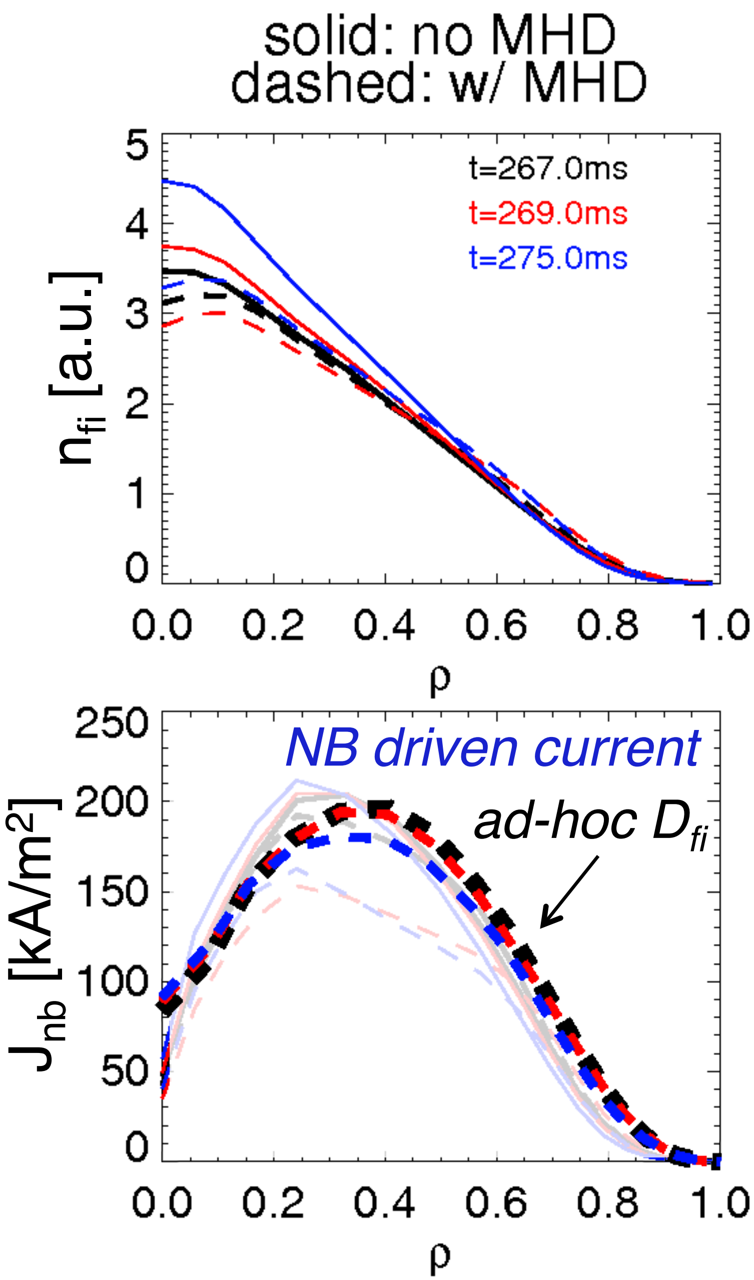

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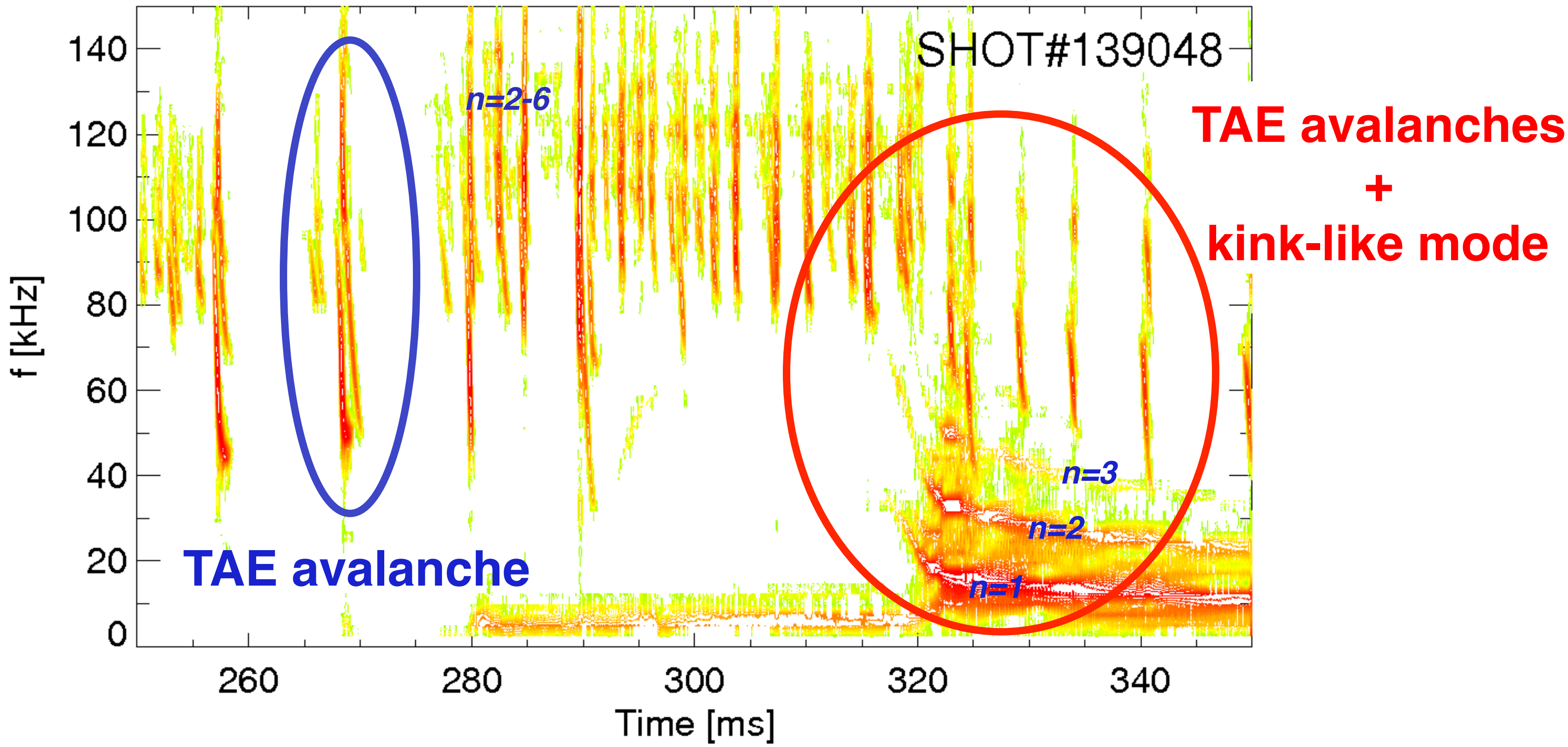
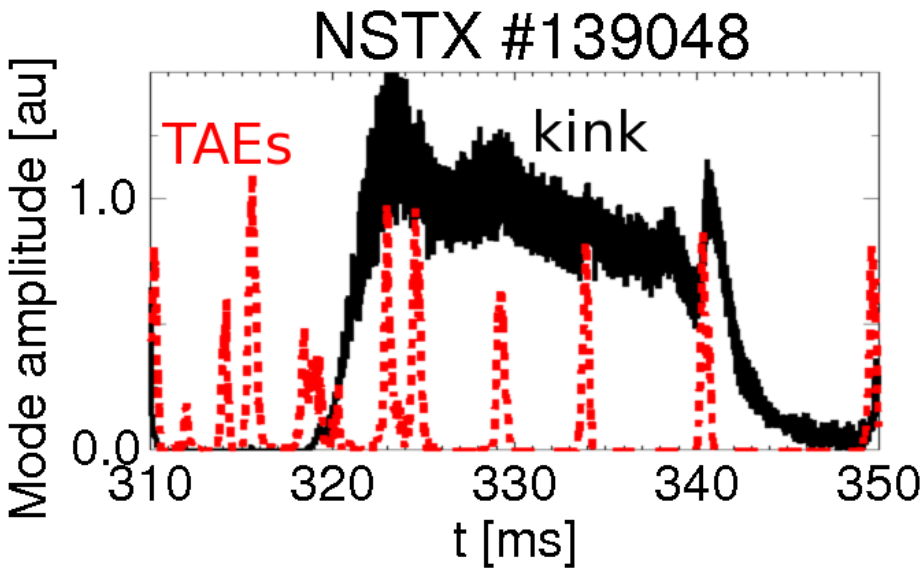


Synergy between different classes of instabilities modifies MHD effects on $J_{nb}(r)$ – not captured by *ad-hoc* D_{fi}



- Kinks have broad radial structure, connect core to boundary

> *Synergy arises from mode overlap <u>in phase space</u>*

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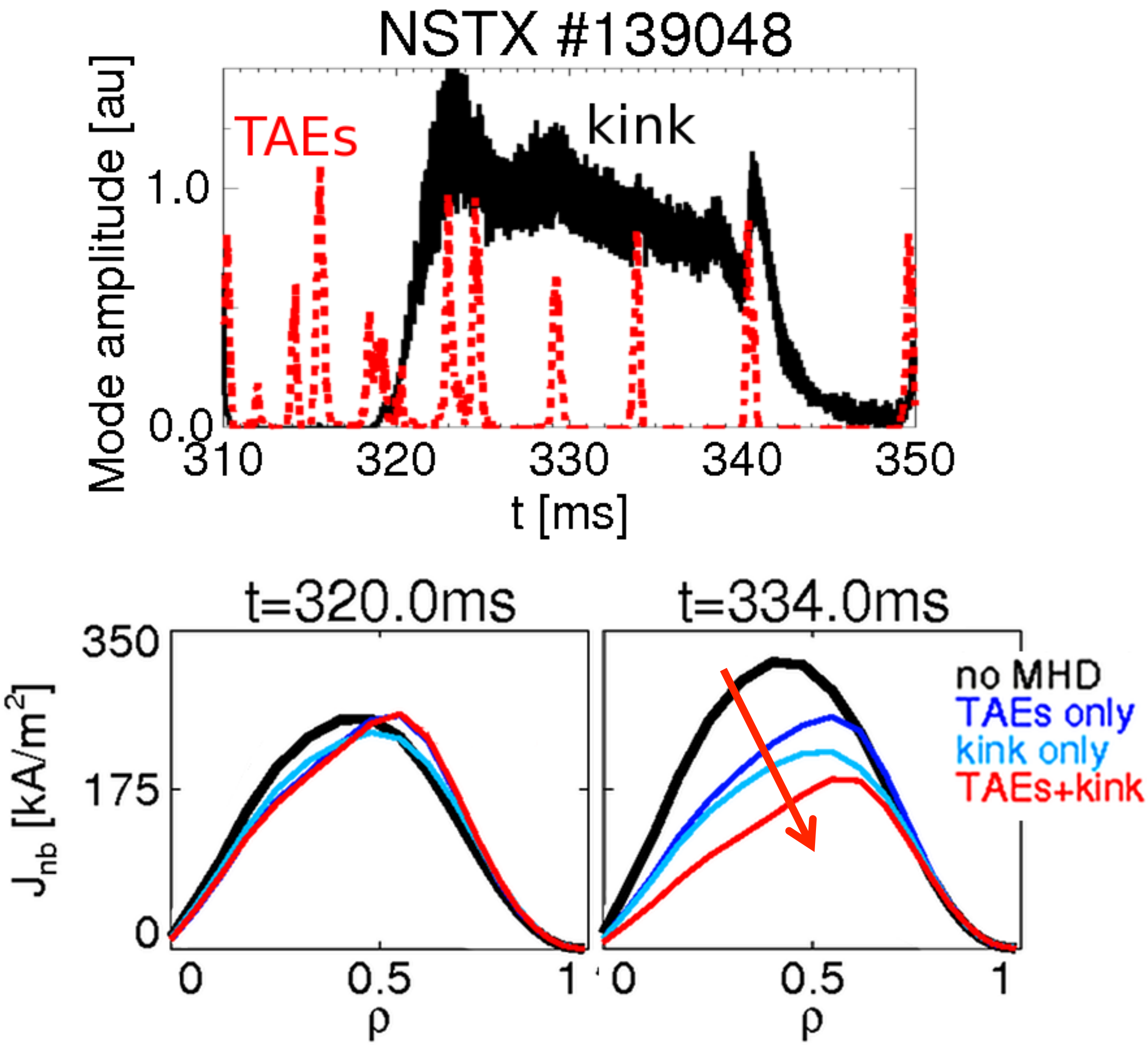
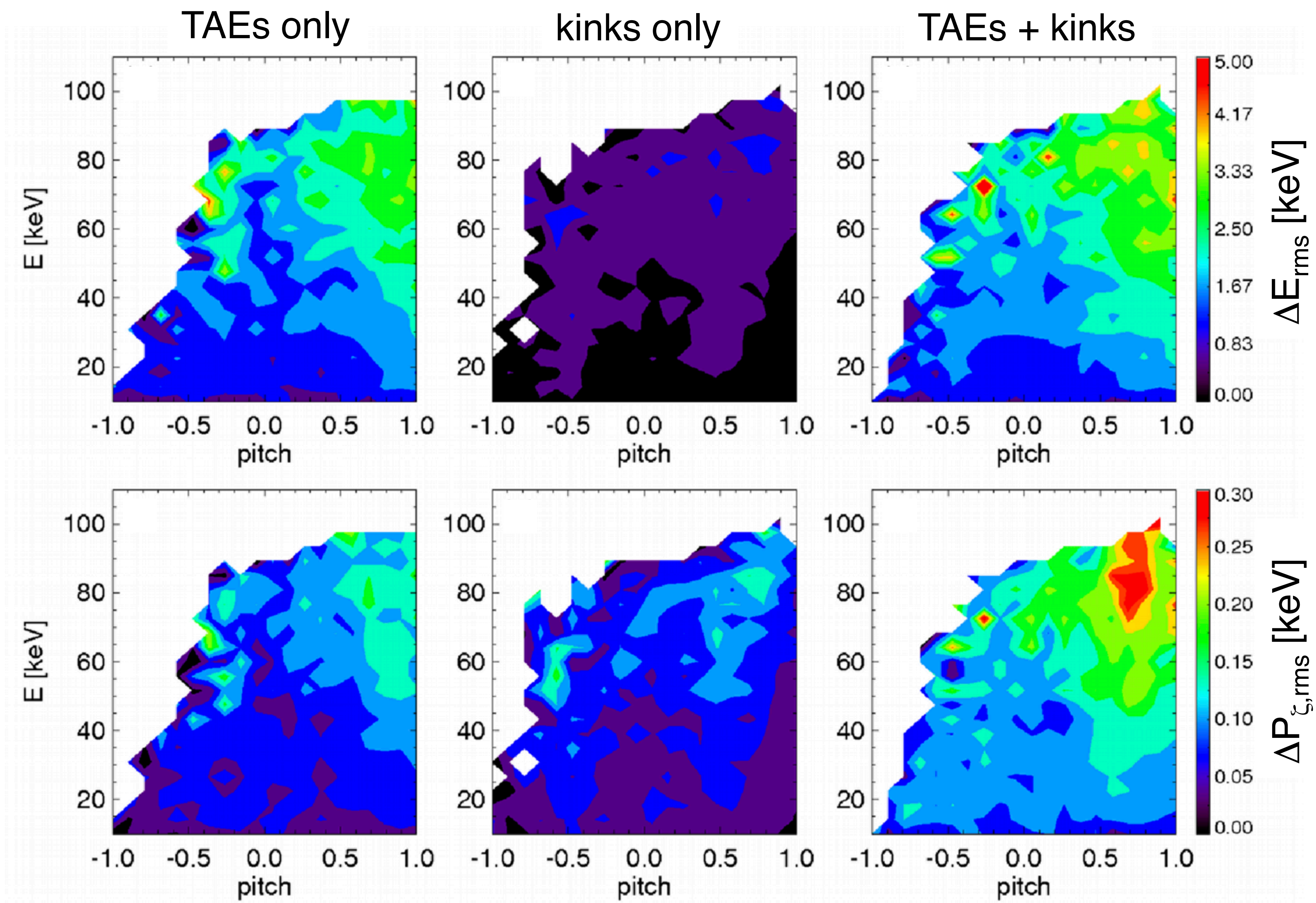


- Kinks have broad radial structure, connect core to boundary

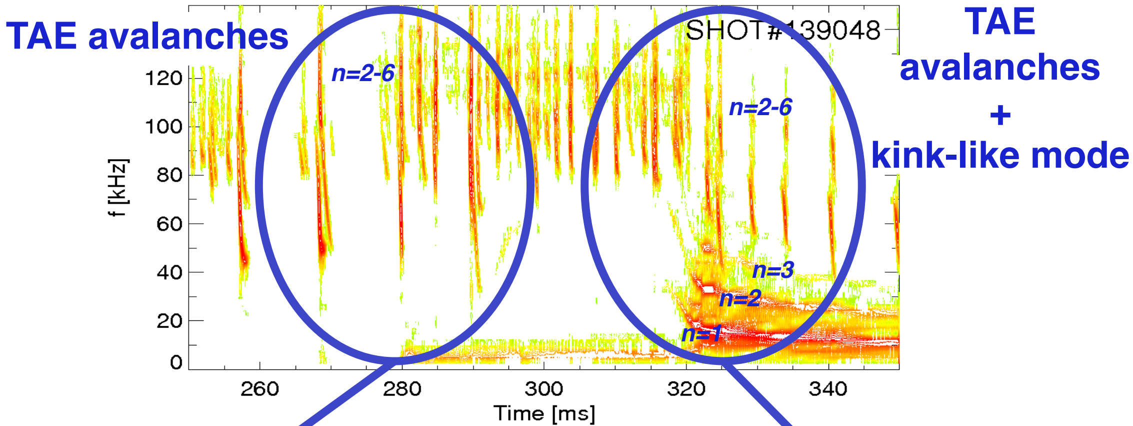
> *Synergy arises from mode overlap <u>in phase space</u>*

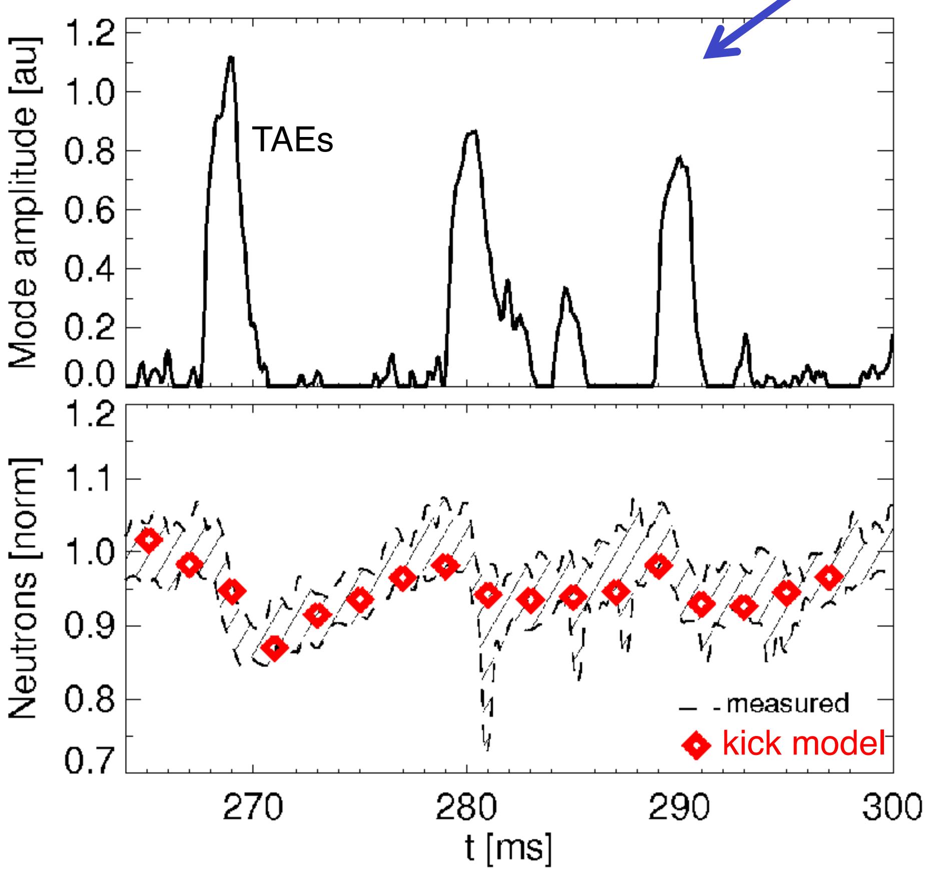
Phase-space is *selectively* modified by instabilities: TAEs -> $\Delta P_\zeta/\Delta E = n/\omega$, kinks -> mostly ΔP_ζ

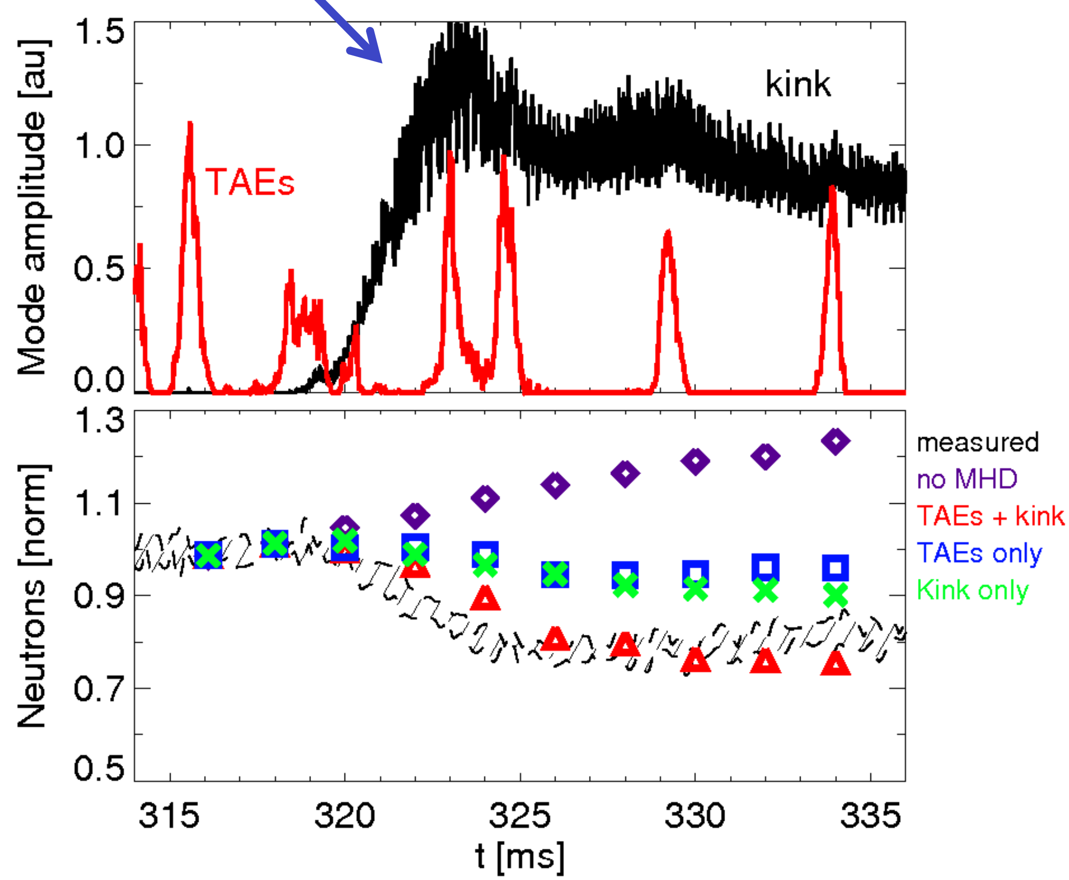


Simulated neutron rate agrees with experiments for both TAE avalanches & multi-mode cases

Use 'kick model' coupled to stand-alone NUBEAM







Summary

- NB-driven current profile can be strongly affected by MHD instabilities
  - Not all effects properly captured by classical EP physics

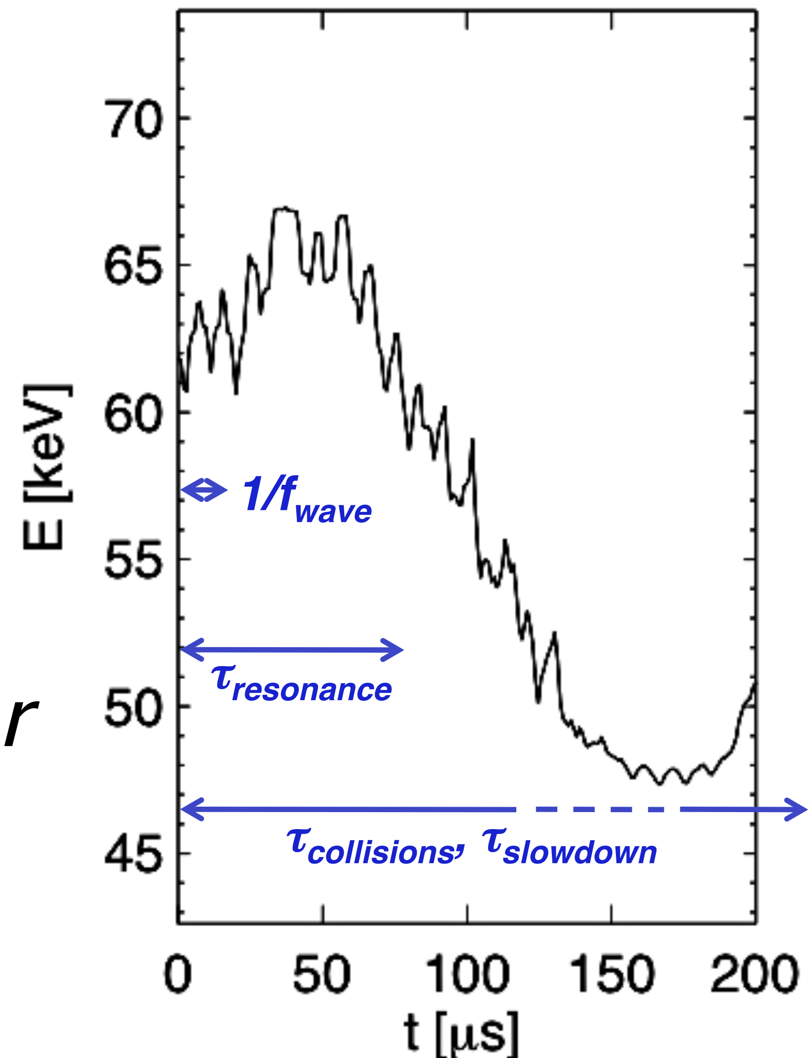
- A new model is implemented in TRANSP for EP simulations including phase-space details
  - Validation within TRANSP framework is in progress

- New tools will improve scenario development on NSTX Upgrade & future devices
  - NB current drive optimization
  - NB-driven current profile control for high-q_{min} steady state operations

Backup slides

'Kick' model exploits separation of typical time scales between instabilities and collisional processes

- 3 time scales characterize particle motion in the presence of instabilities:
  - $1/f_{wave} \sim$ 10's μs
  - $\tau_{resonance} > 10x\tau_{transit} >$ 100's μs
  - $\tau_{collisions}, \tau_{slowdown} >>> 1$ ms
- Relevant time scale for *secular* $\Delta E, \Delta P_\zeta$ by waves is $\tau_{resonance}$
- Classical mechanisms already included in IM codes (TRANSP)
  - E.g. collisions, slowing down, atomic physics



Reduced models offer advantages for Integrated Modeling (IM), plasma control over *first-principles* codes

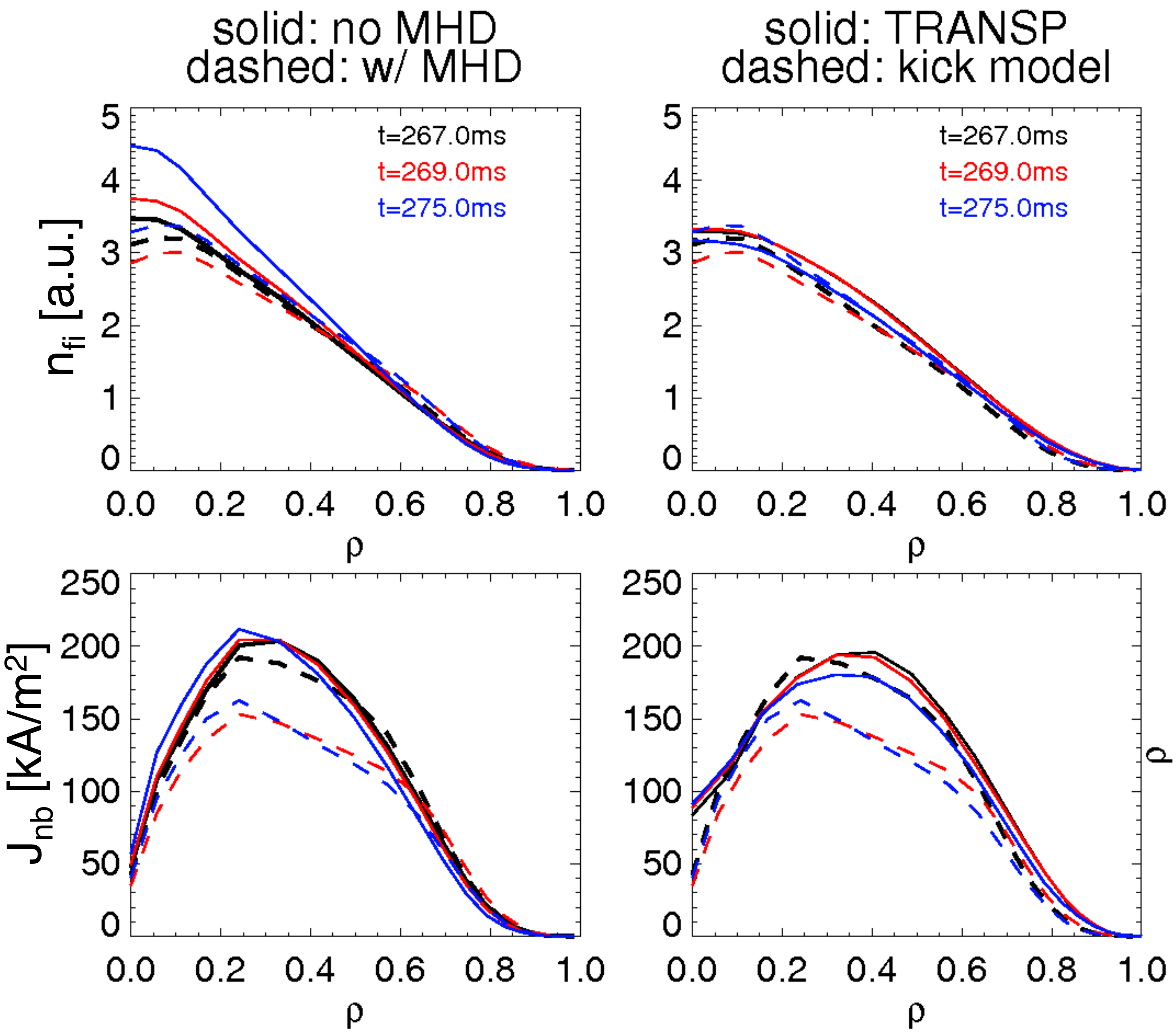
- *First-principles* codes not (yet) suitable for extensive 'scans' with multiple shots, long time-scale simulations
  - Inclusion in real-time control schemes also unpractical
- IM codes (e.g. TRANSP) have accurate treatment of atomic physics, 'classical' mechanisms
  - Reduced models for EP transport are good complement
- IM codes have much broader scope than just EP physics
  - Physics-based reduced models improve accuracy of simulations, retaining 'generality' of IM codes

Summary comparison of some reduced models used for EP transport

		ad-hoc D_{fi}	*CGM model (*)*	*kick' model*
physics-based		no	yes	yes
required input		$D_{fi}(\rho,t)$	growth/damping rates	probability, mode amplitude
applicability				
	multi-mode	indirectly	multiple AEs	AEs, kinks, NTMs. Fishbones/EPMs?
	steady-state	yes	yes	yes
	transients	yes	only for $\tau>\tau_{relax}$	yes
phase-space selectivity		modest	no	yes
predictive runs		requires guess D_{fi}	requires mode spectrum: growth/damping	requires mode spectrum, amplitude
improvements		none planned	extend to 2D in velocity space	remove μ conservation

(*) CGM – Critical Gradient Model
see Gorelenkov TH/P1-2, Heidbrink EX/10-1

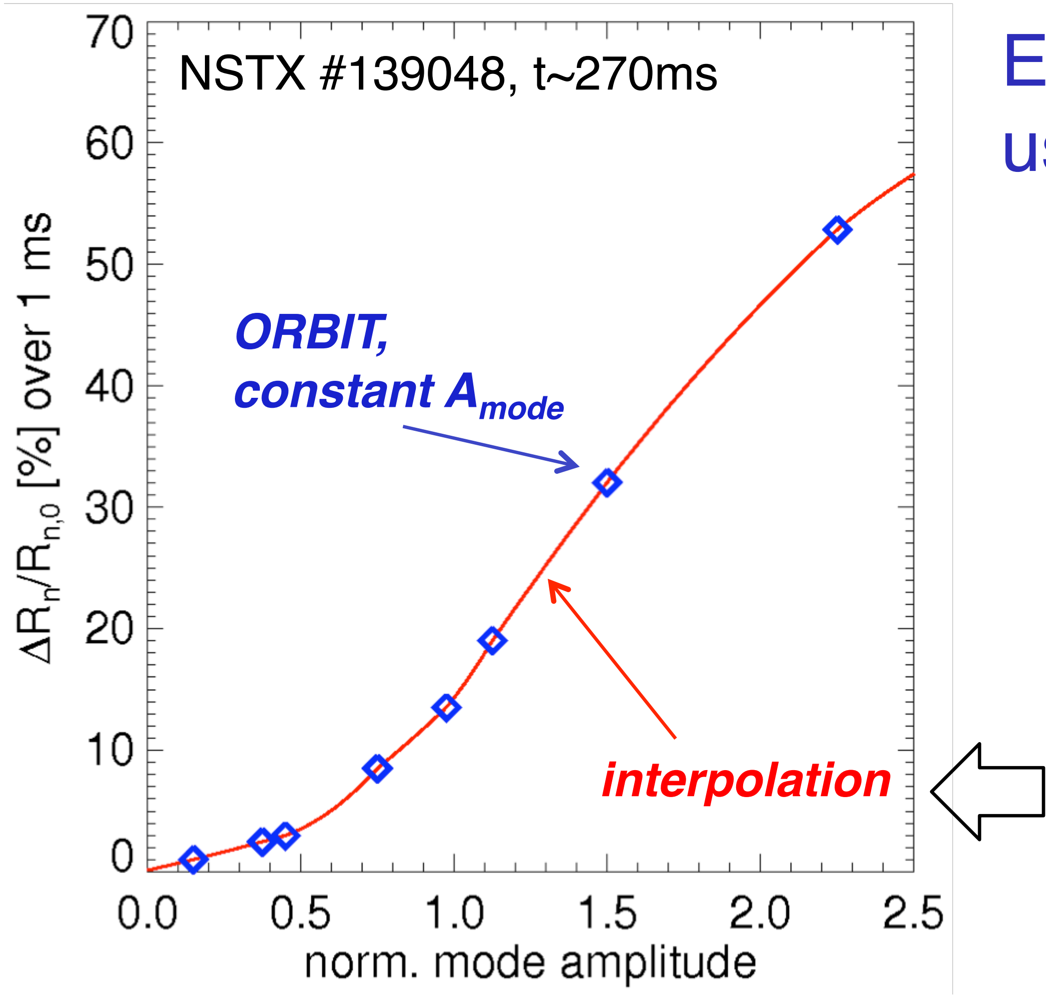
Simulations with *ad-hoc* D_{fi} show similar fast ion drops, but largely underestimate $J_{nb}(r)$ modification



- Uniform D_{fi} acts in the same way on *all* particles at *all* radii
- No constraints from wave-particle interaction

Scaling factor $A_{mode}(t)$ is obtained from measurements, or from other *observables* such as neutron rate + modeling

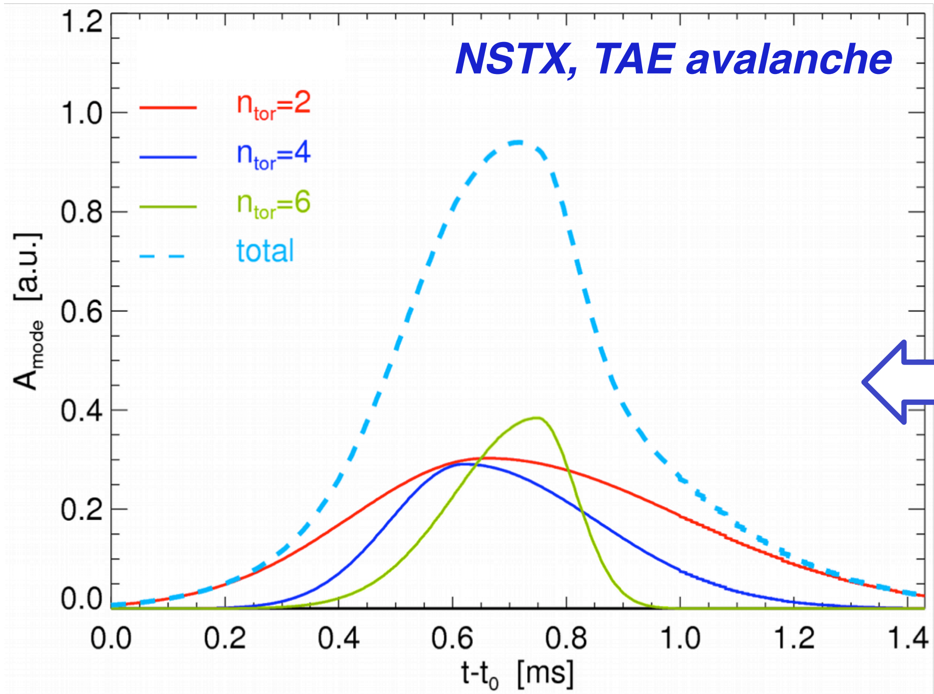
– If no mode data directly available, A_{mode} can be estimated based on other measured quantities



Example:
use measured neutron rate

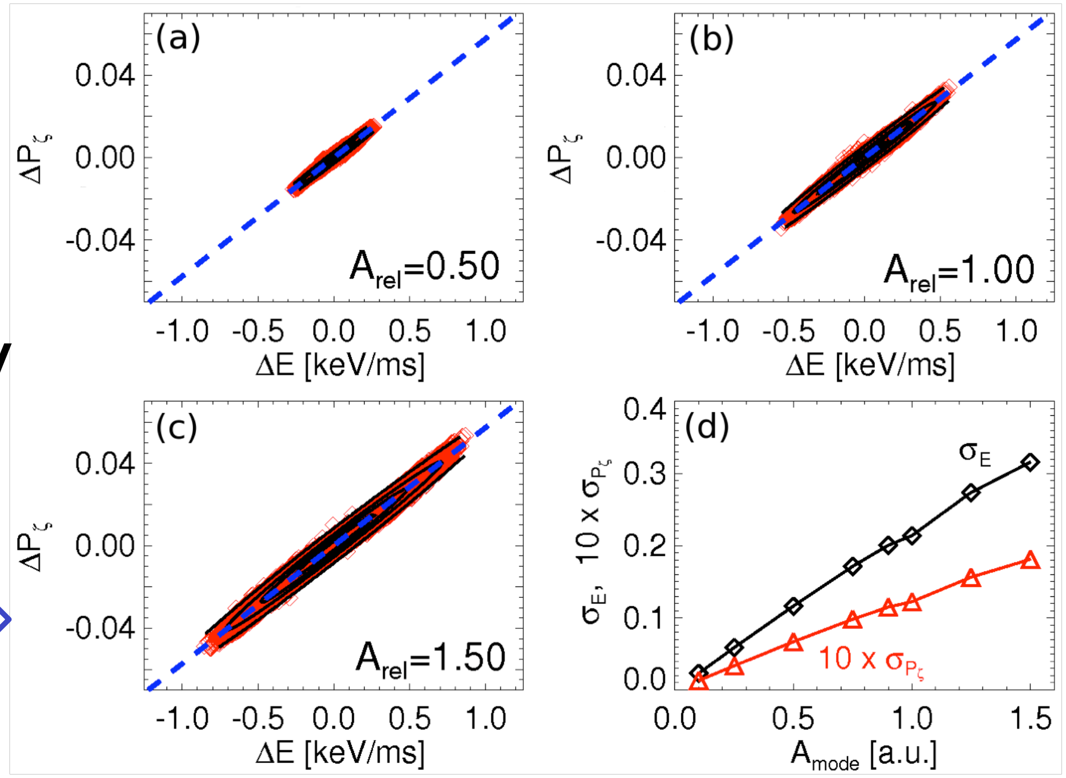
- Compute ideal modes through NOVA
- Rescale relative amplitudes from NOVA according to reflectometers
- Rescale total amplitude based on computed neutron drop from ORBIT
- Scan mode amplitude w.r.t. experimental one, $A_{mode}=1$: get table
- Build $A_{mode}(t)$ from neutrons vs. time, table look-up

Mode amplitude can evolve on time-scales shorter than typical TRANSP/NUBEAM steps of ~5-10 ms



F_{nb} evolution must be computed as a sequence of sub-steps

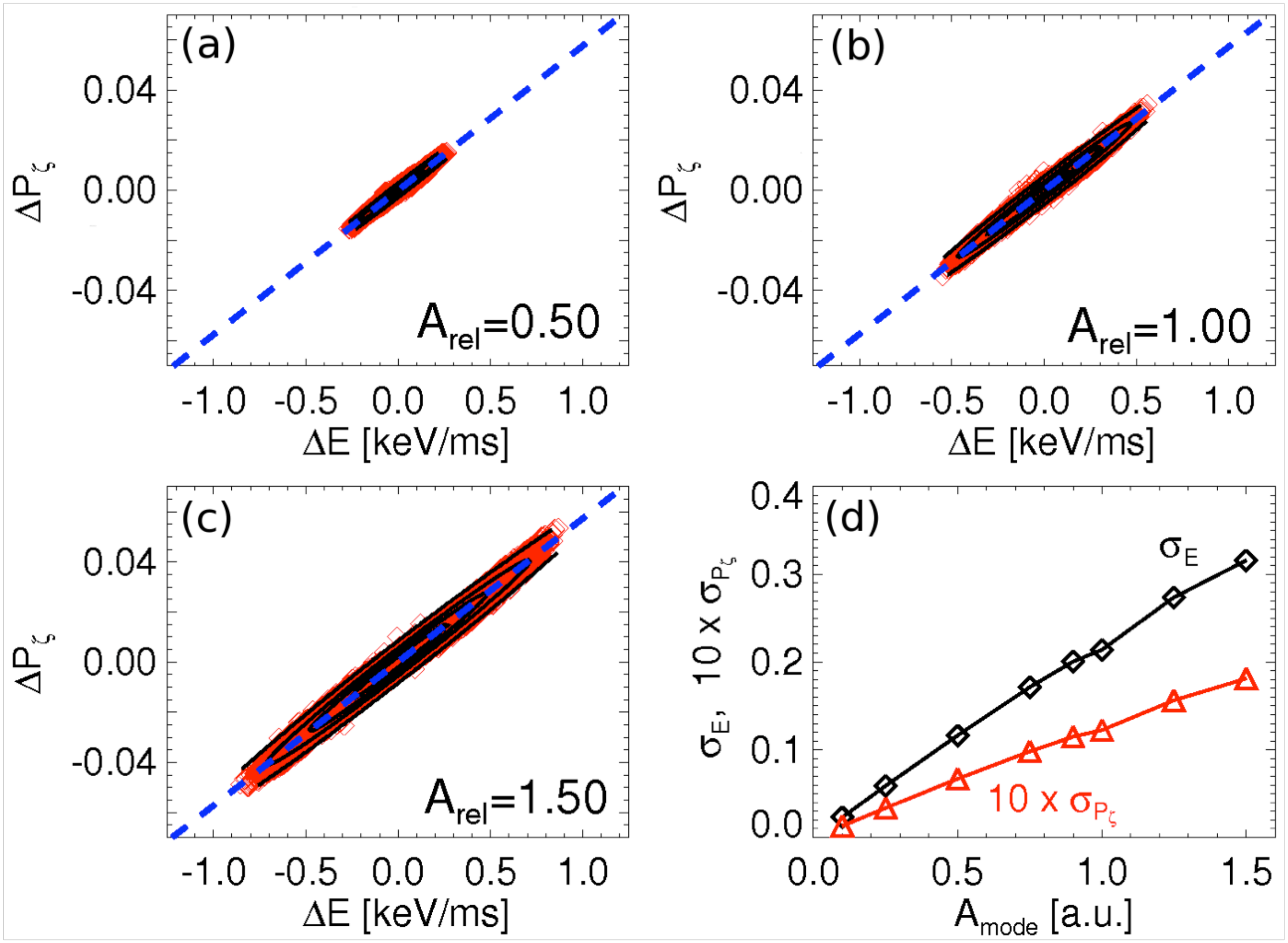
- Duration δt_{step} sufficiently shorter than time-scale of mode evolution
- Examples here have δt_{step}~25-50 μs



Energy and P_ζ steps assumed to scale linearly with mode amplitude

- Roughly consistent with ORBIT simulations

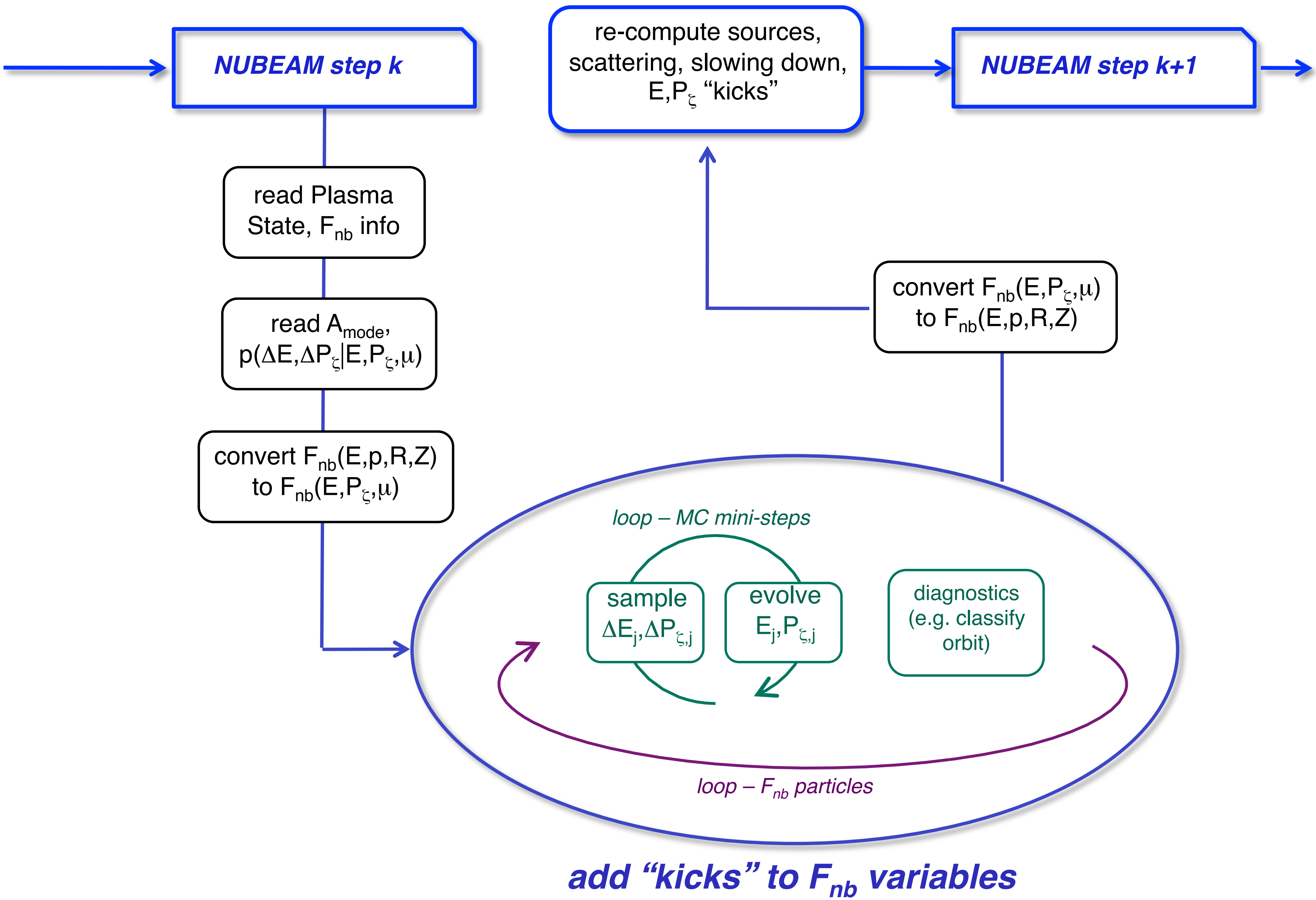
Each type of mode is characterized by its own amplitude vs time (e.g. from experiments)



For each type of mode, energy and P_ζ steps assumed to scale linearly with mode amplitude

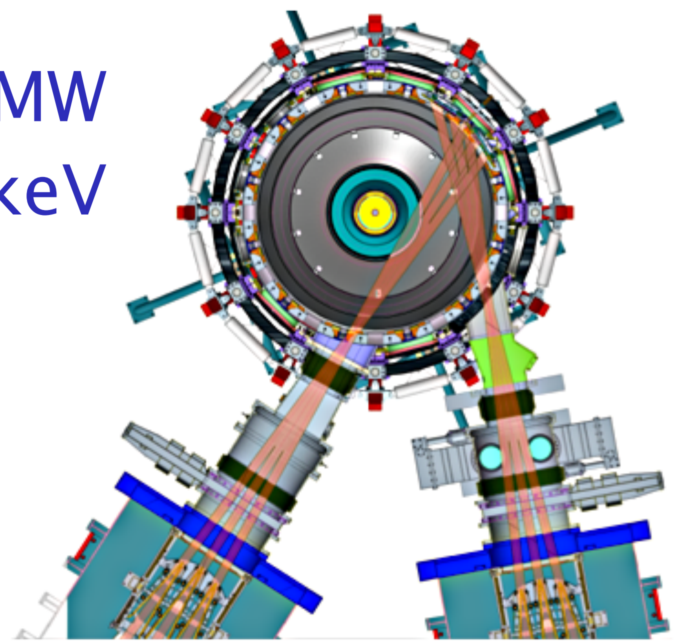
- Consistent with ORBIT simulations

Scheme to advance fast ion variables according to transport probability in NUBEAM module of TRANSP



Spherical torus NSTX is well suited for NB physics studies, model validation

	NSTX	NSTX-U
Major radius	0.85 m	0.9 m
Aspect ratio	1.3	1.5
Plasma current	~1 MA	<2 MA
Toroidal field	<0.55 T	<1 T
Pulse length	<2 s	<5 s
Neutral Beam sources:		
	$P_{NBI} \leq$ 6 MW	$\leq$ 12 MW
	$E_{injection} \leq$ 95 keV	$\leq$ 95 keV

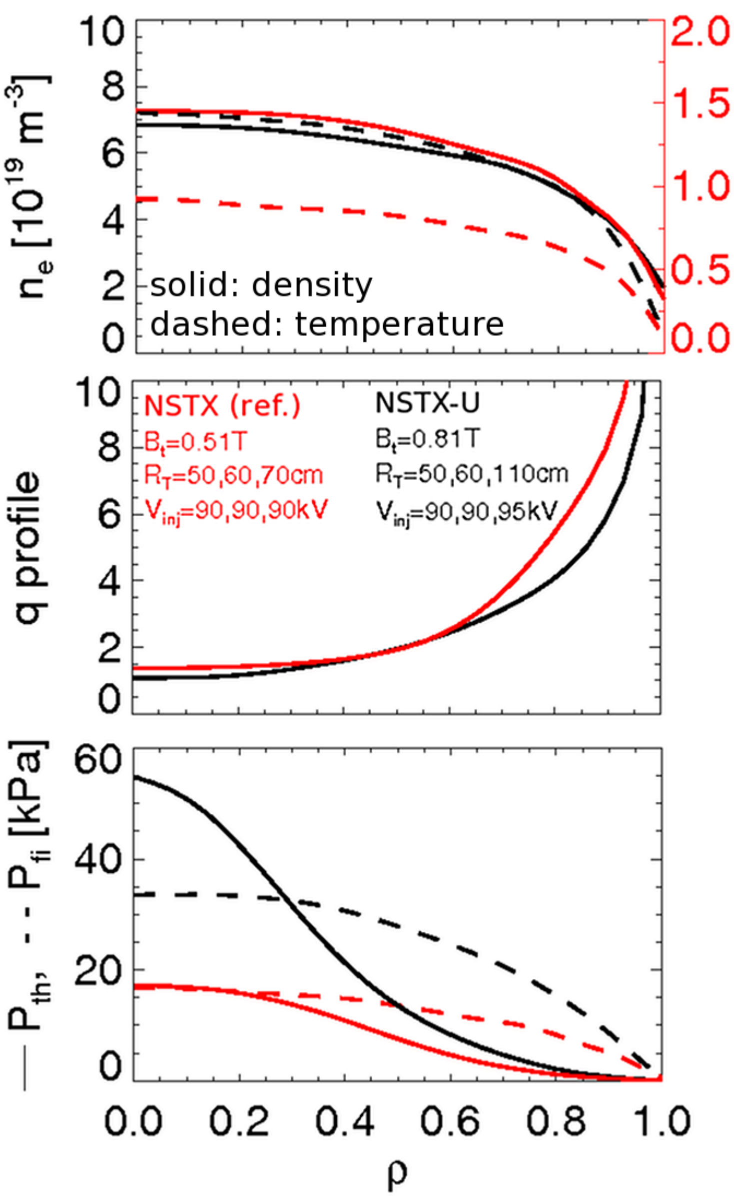


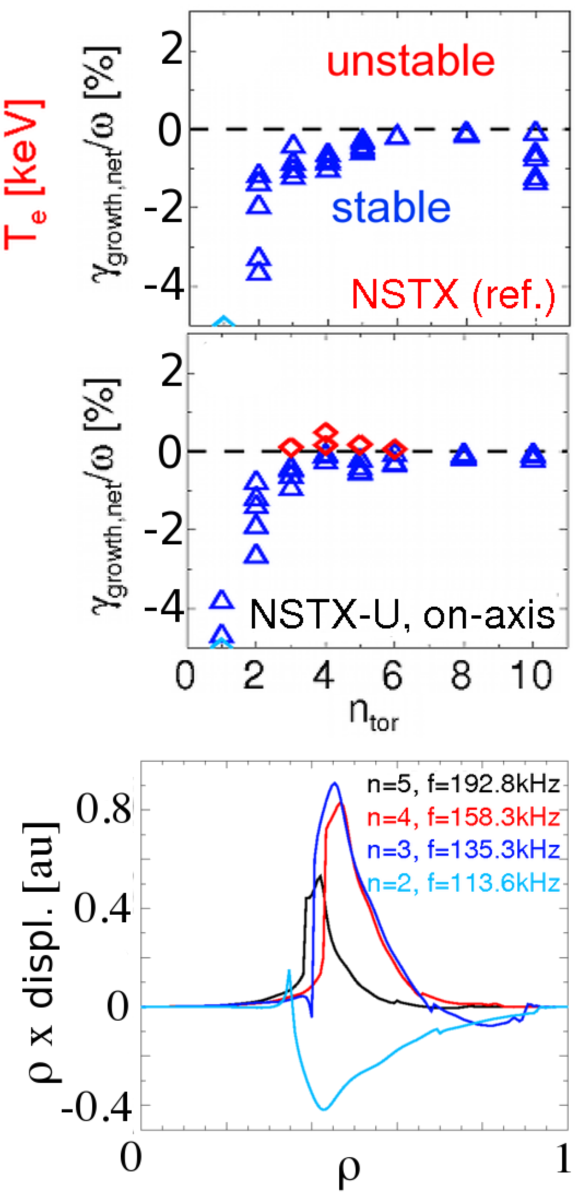
[Menard, NF 2012]

1st NB line *2nd NB line (upgrade)*

New NBI set on NSTX-U will enable more flexible NB current drive

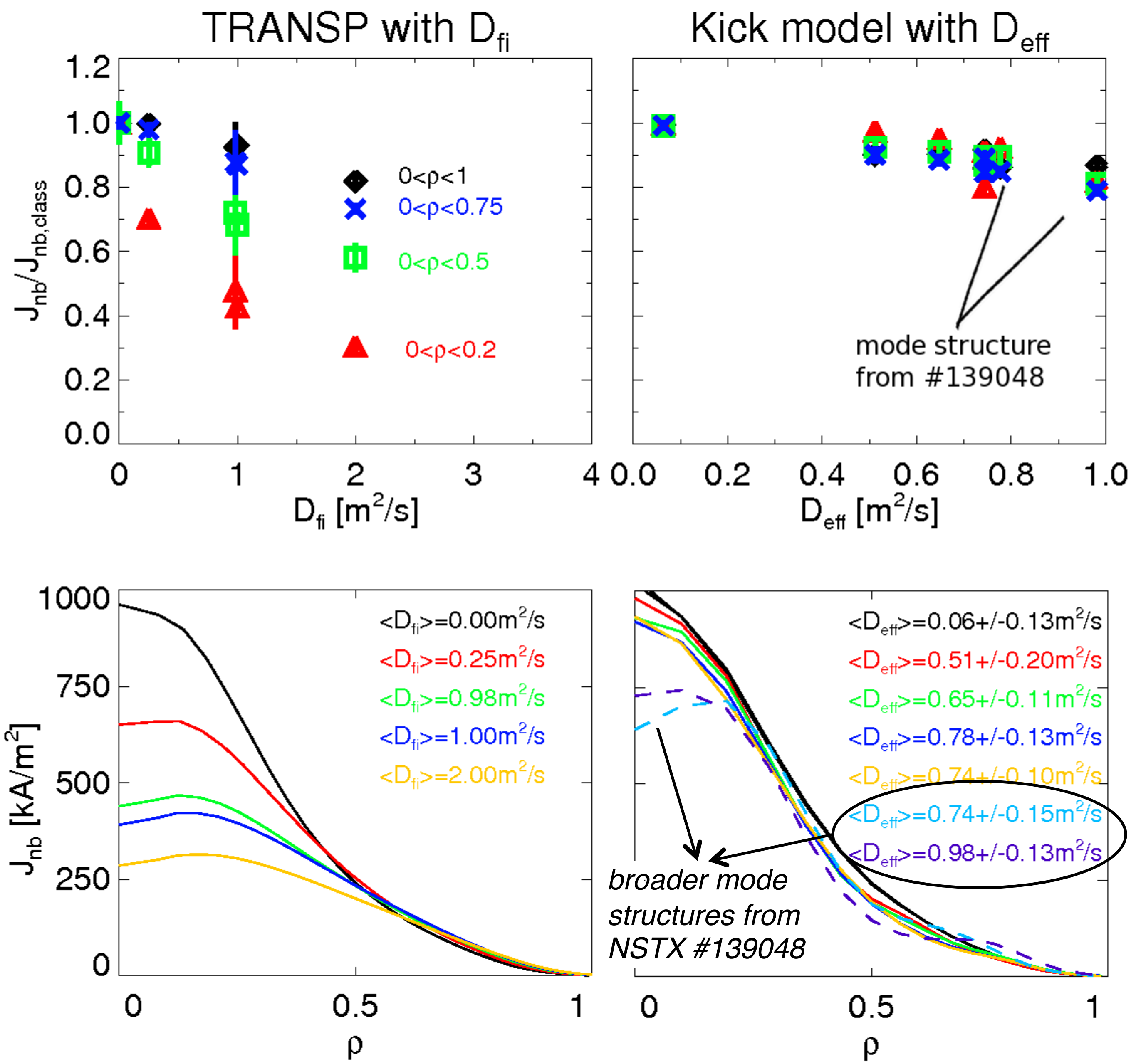
Predicted NSTX-U scenario with strongly peaked fast ion pressure has unstable TAEs





- Fast ion pressure is >2 times larger than in reference NSTX discharge
- NOVA-K finds spectrum of (linearly!) unstable TAEs with n=3-6
- Predicted mode structure is narrower on NSTX-U than for typical NSTX

'Kick' and *ad-hoc* D_{fi} models predict comparable reduction of total J_{nb} – but profiles are very different



- Reduction in total J_{nb} is modest, <20%
- Local $J_{nb}(r)$ changes are much larger
- 'Kick model' predicts localized reduction of $J_{nb}(r)$ because of narrow mode structures
- Non-linear physics may result in broader modes, though