NSTX-U

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TRANSP modeling of NB current drive including MHD effects

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and the NSTX-U Research Team

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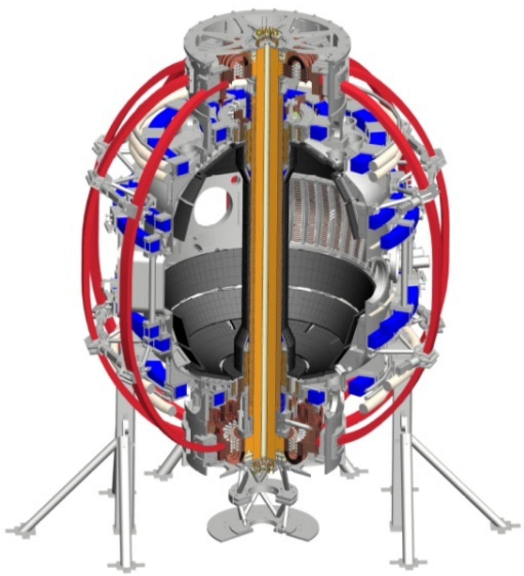

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Abstract

Simulations using a newly developed physics-based fast ion transport model are employed to understand and quantify MHD effects on neutral beam (NB) current drive efficiency. NSTX results confirm that toroidal Alfvén eigenmodes (TAEs) and kink-like instabilities can cause substantial decrease in the central NB-driven current and modify its radial profile. Quantitative analysis is performed through a new model, developed for the TRANSP code, which computes EP transport in phase space to account for resonant wave-particle interactions. Simulations show that so-called TAE avalanches can cause decrements of up to 30% in the core NB-driven current, and even larger (relative) changes toward the plasma edge. Perturbations of the current profile persist over a considerable fraction of the slowing down time, with a recovery rate set by the NB injection rate. In contrast to ad-hoc diffusive models previously available in TRANSP, the new model captures the feature that TAEs mainly affect fast ions with large parallel velocity, i.e. the most effective in driving current, leaving other portions of the fast ion distribution nearly unperturbed.

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

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 >> $\tau_{\text{slowing down}}$
  - 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

Comparison of reduced EP transport models developed/under development at PPPL

		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	OK 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 BP8.41, Lestz PP8.74**

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

NSTX

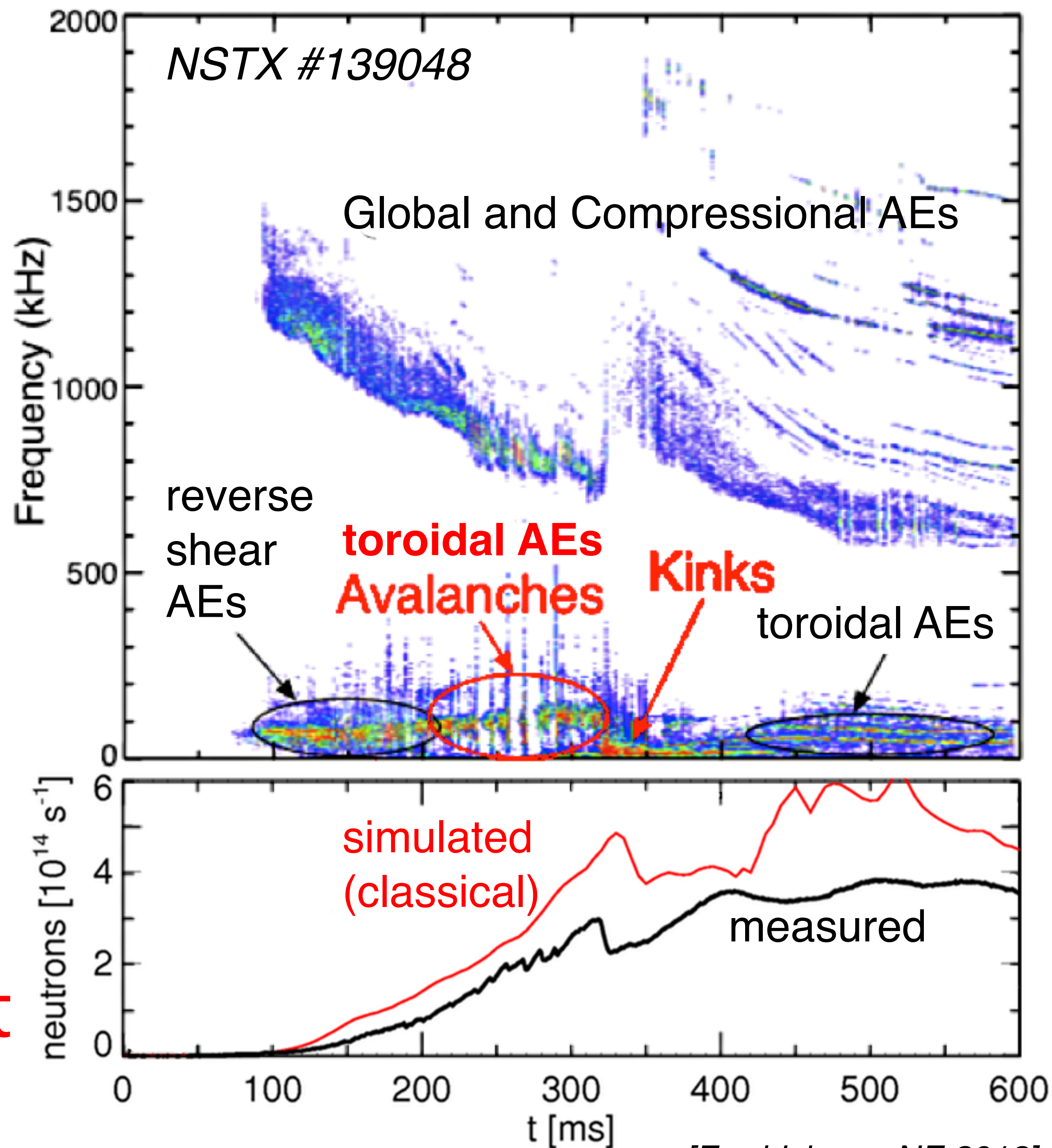
Major radius	0.85 m
Aspect ratio	1.3
Plasma current	~1 MA
Toroidal field	<0.55 T
Pulse length	<2 s
Neutral Beam sources:	

$P_{NBI} \leq 6$ MW

$E_{injection} \leq 95$ keV

$1 < v_{fast}/v_{Alfvén} < 5$

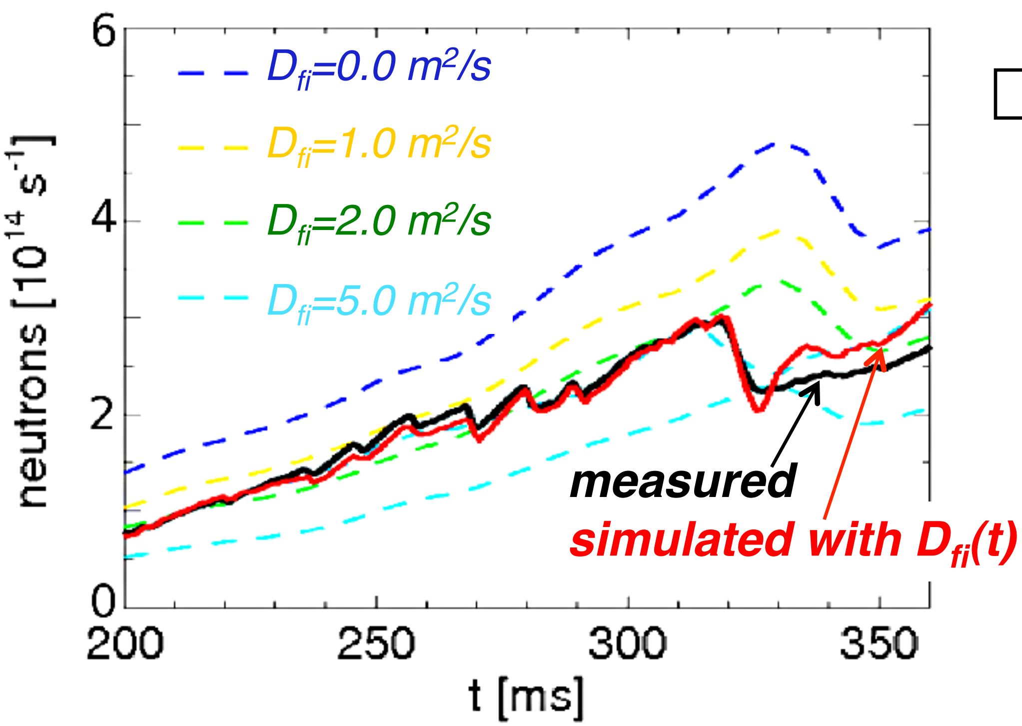
Super-alfvénic ions, high β_{fi}: plethora of fast ion driven instabilities

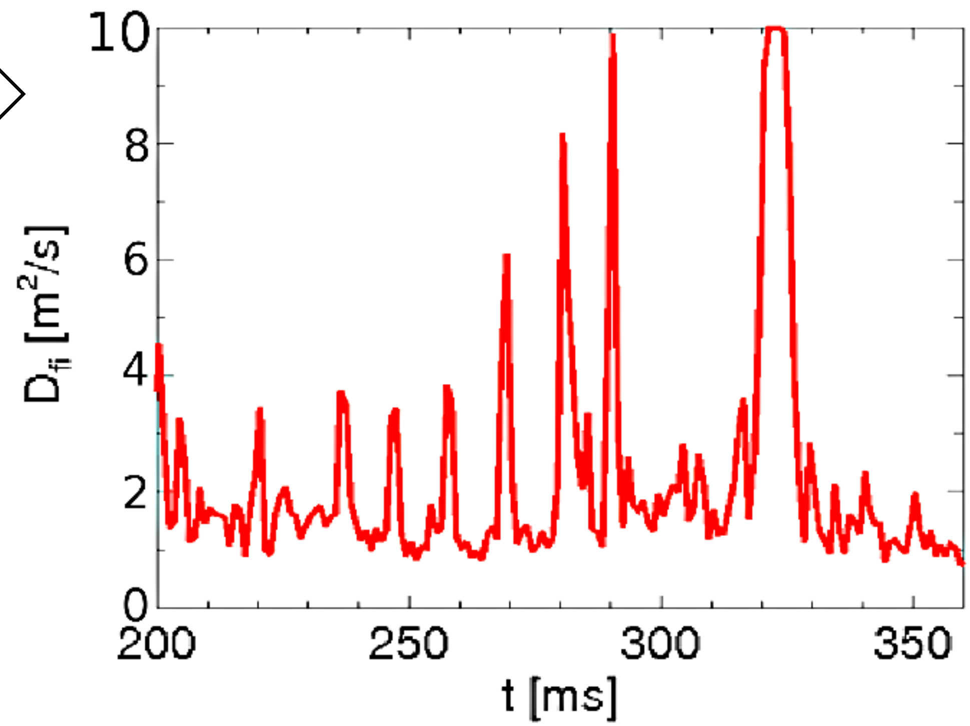


[Fredrickson, NF 2013]

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}



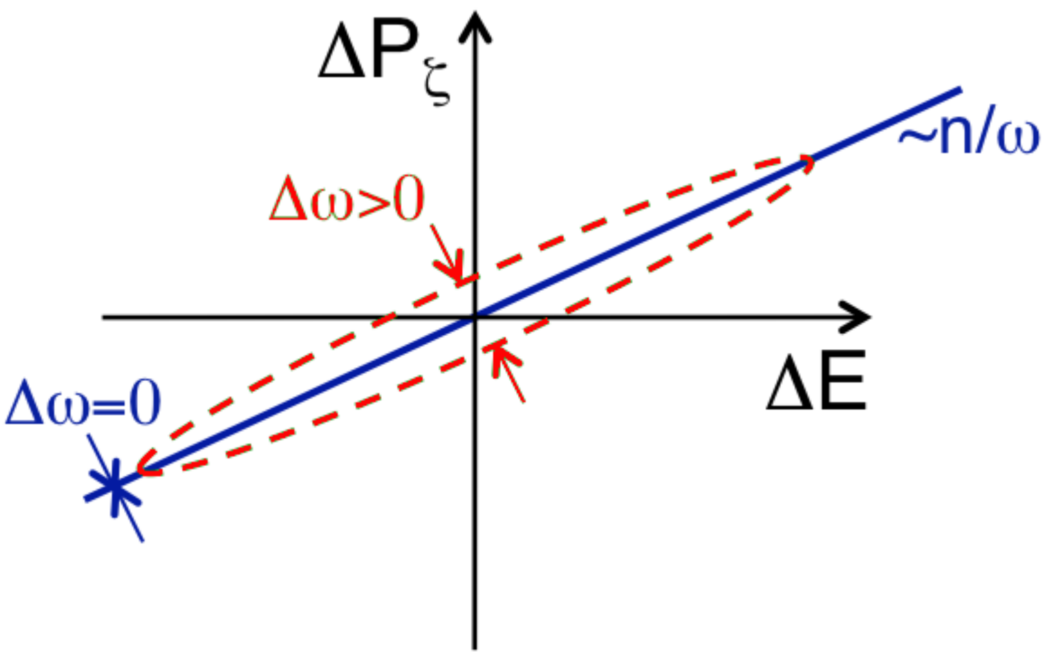


However: instabilities introduce fundamental constraints on particle dynamics

From Hamiltonian formulation – single resonance:

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

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



E, energy

$P_\zeta \sim mRv_{par} - \Psi$, canonical angular momentum

$\mu \sim v_{perp}^2/(2B)$, magnetic moment

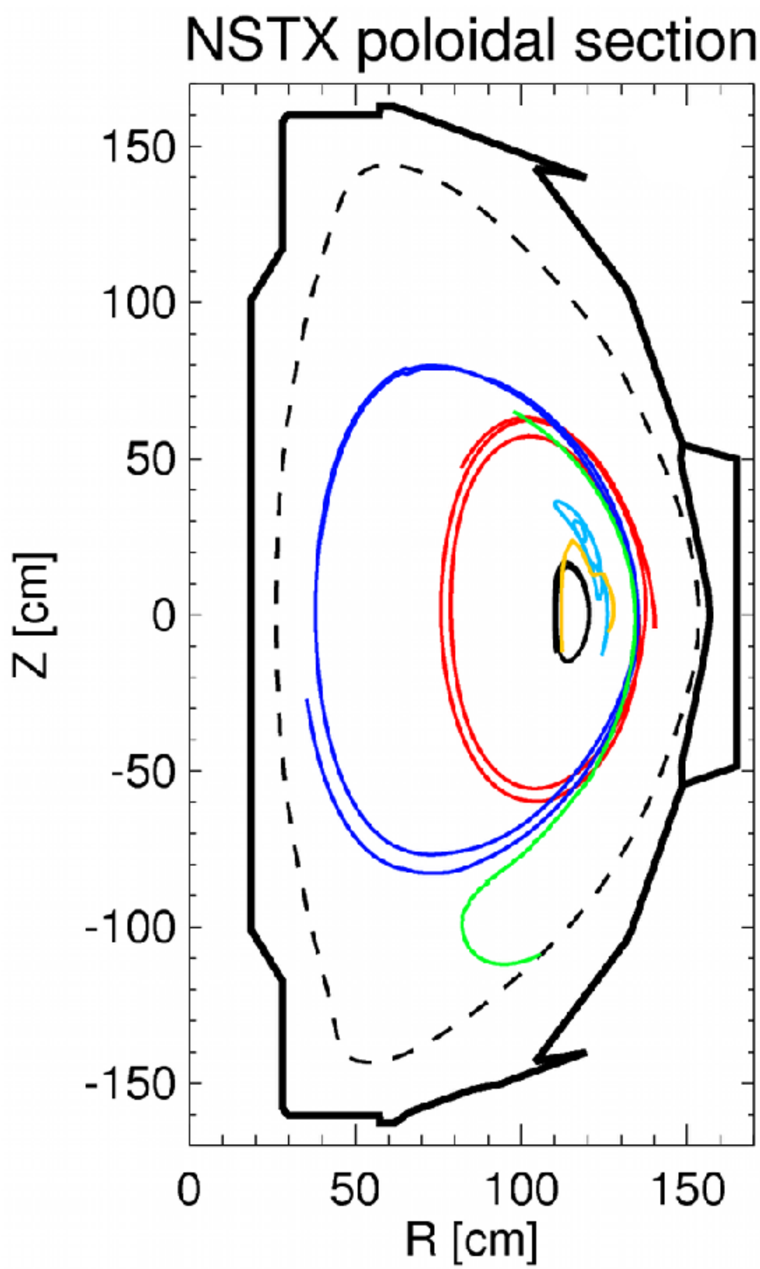
where Ψ : poloidal flux

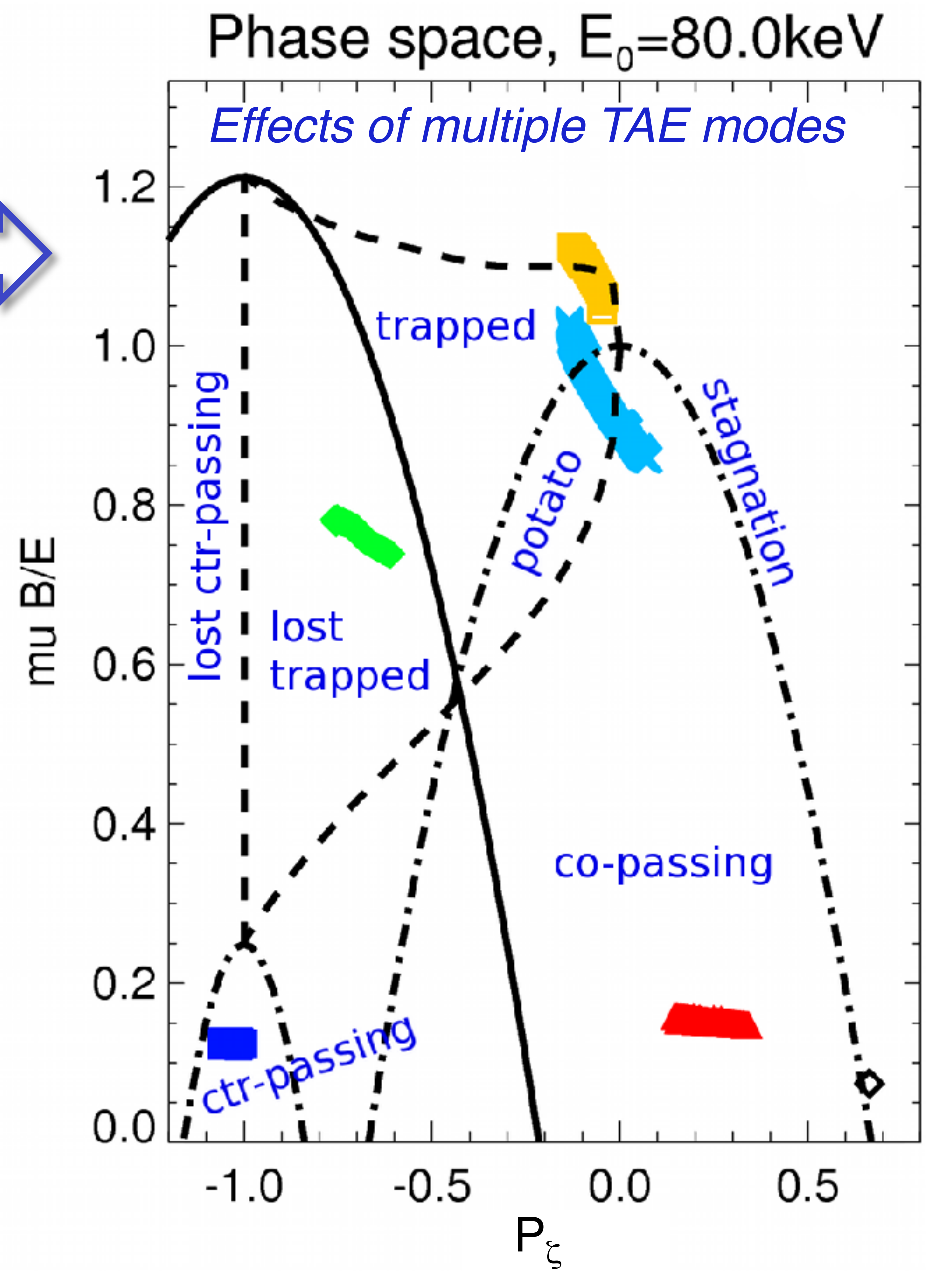
R : major radius

m : mass

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





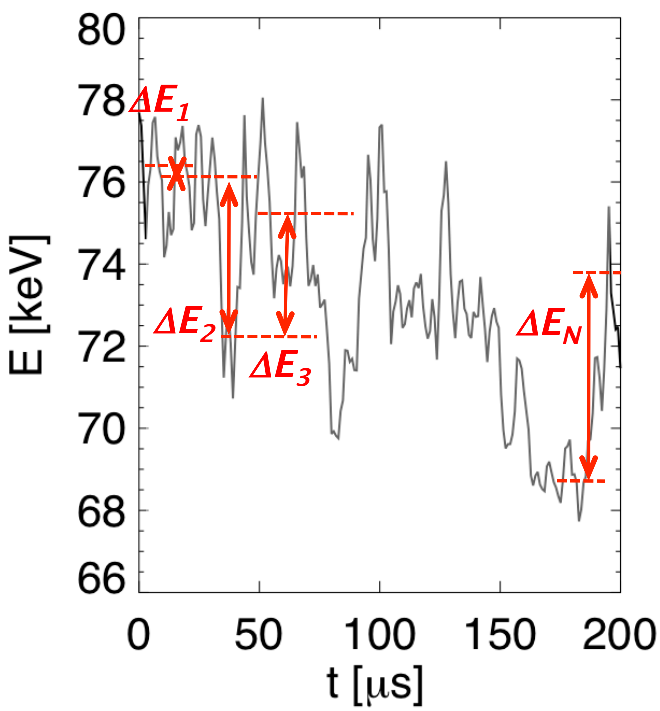
R. B. White, Theory of toroidally confined plasmas, Imperial College Press (2014)

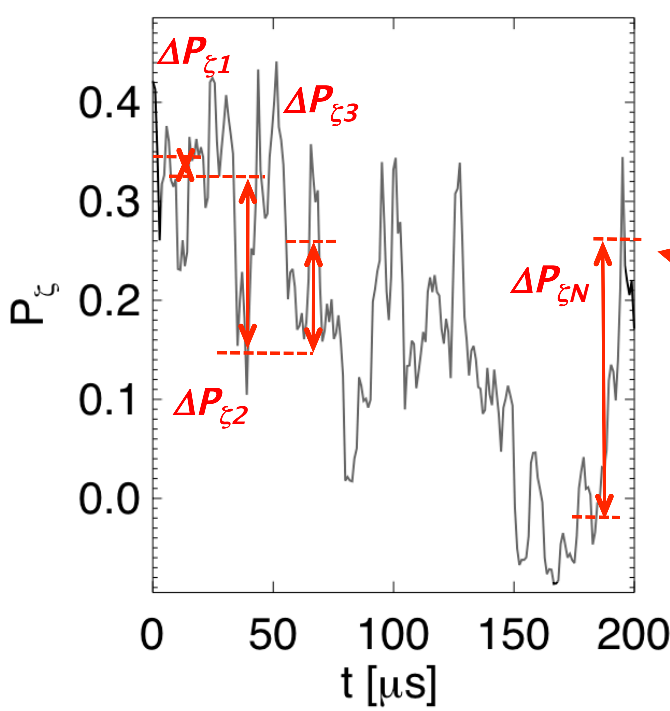
Particle-following codes are used to extract distribution of ‘kicks’ ΔE, ΔP_ζ for each *bin* (E,P_ζ,μ)

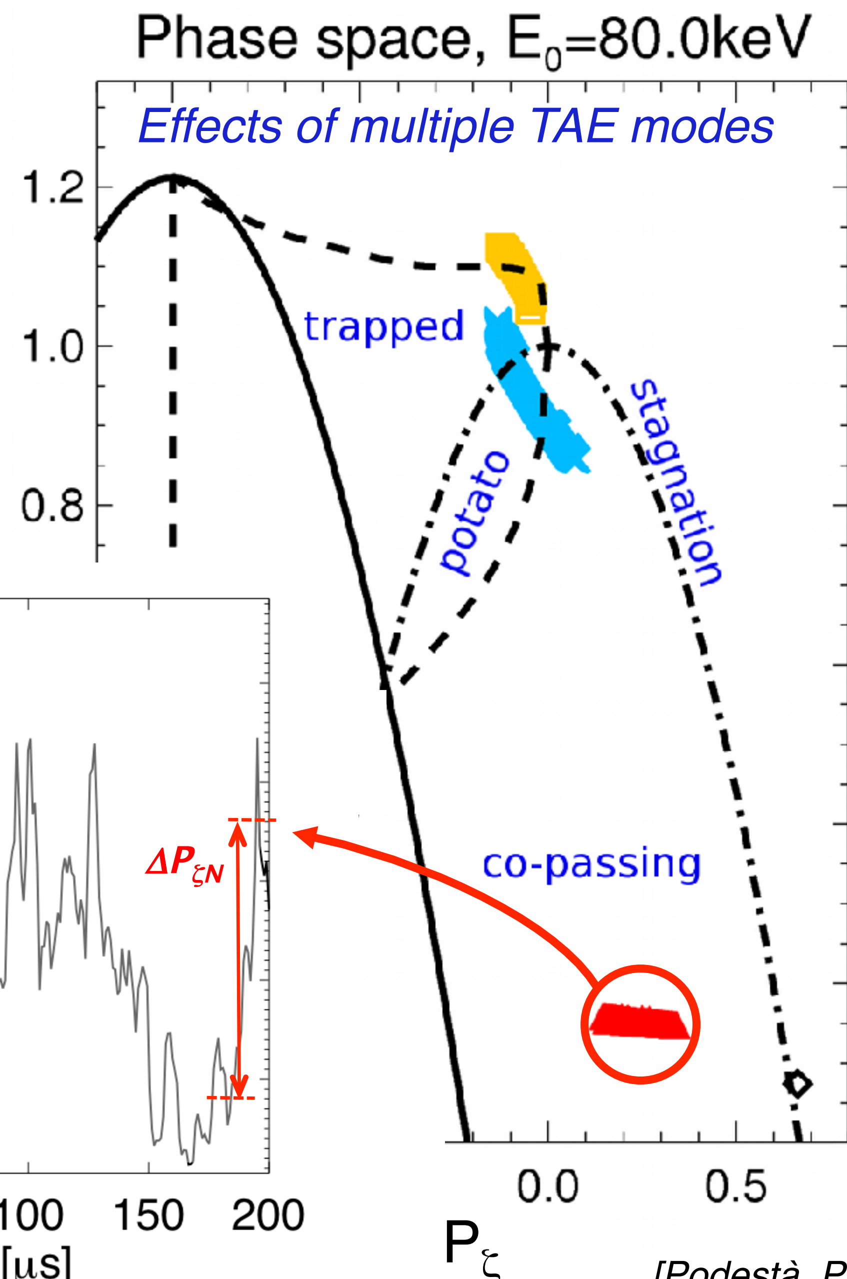
- ORBIT code: record E,P_ζ,μ *vs.* time for each particle
- Compute <u>average</u> kicks over multiple wave periods:

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

- Re-bin for each (E,P_ζ,μ) region







[Podestà, PPCF 2014]

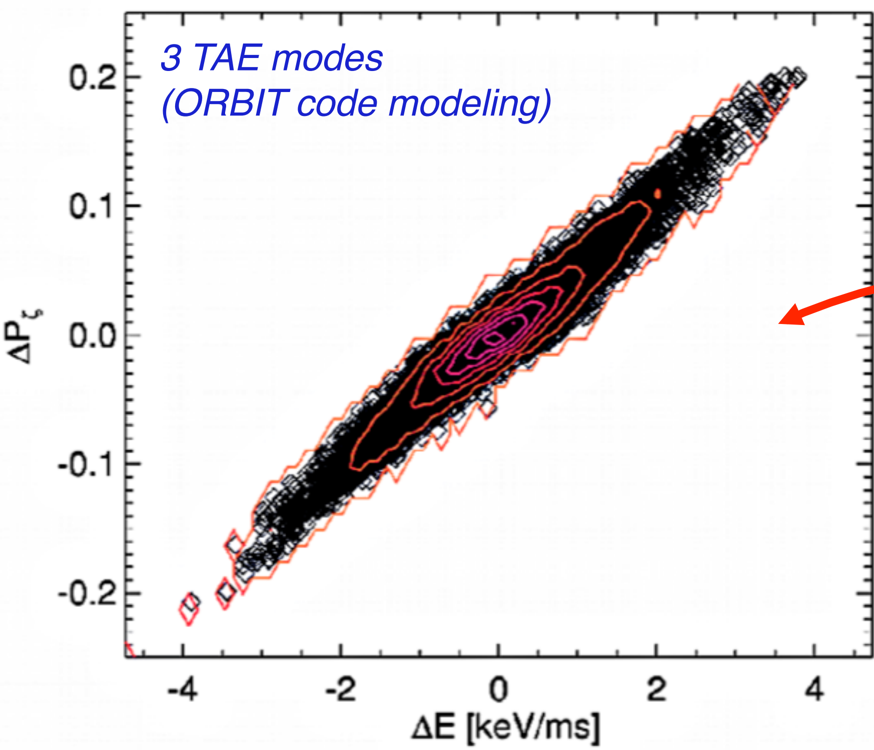
New 'kick model' uses a *probability distribution function* for particle transport in (E, P_ζ, μ) space

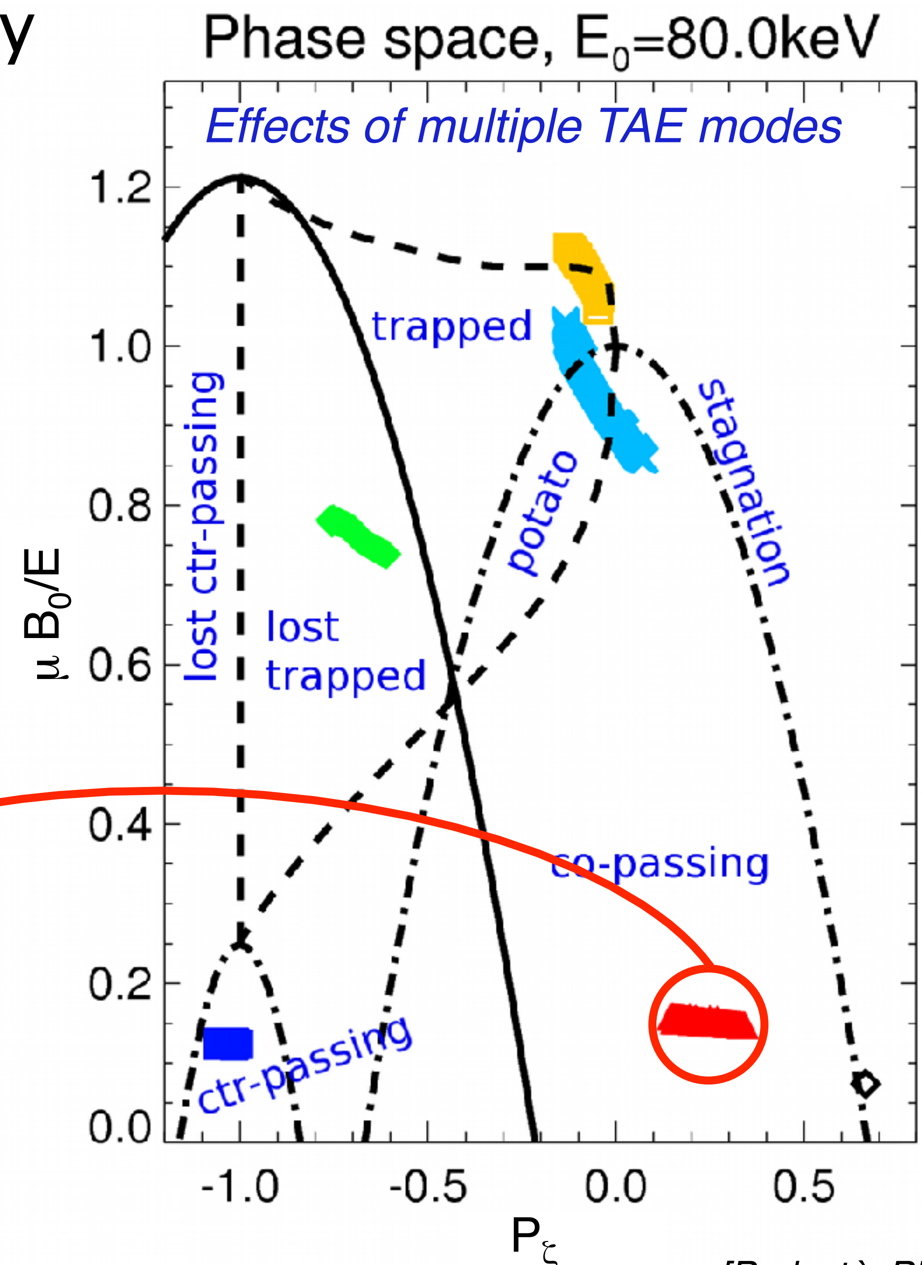
Kicks ΔE, ΔP_ζ are described by

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

which includes the effects of multiple modes, resonances.

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

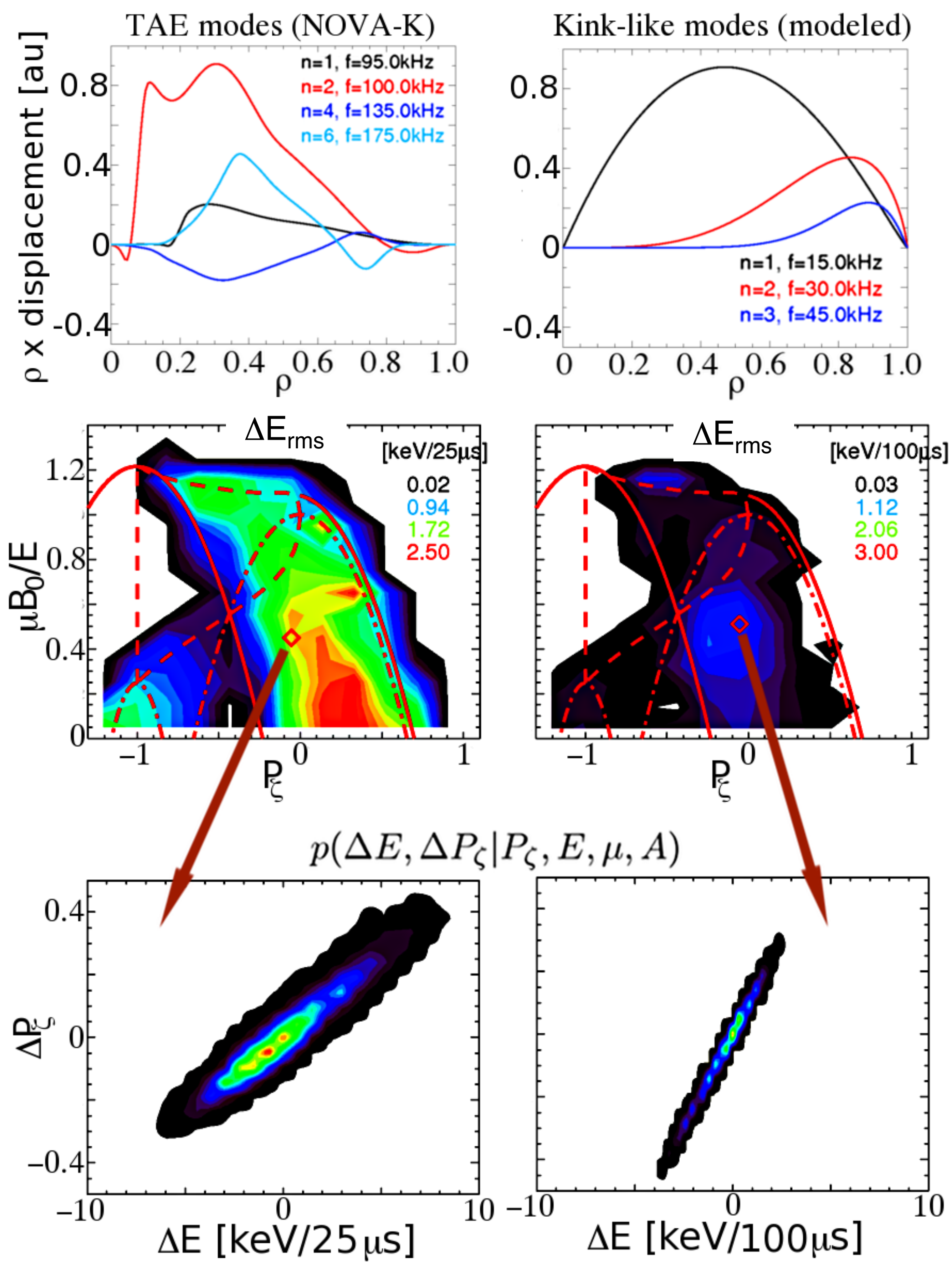




[Podestà, PPCF 2014]

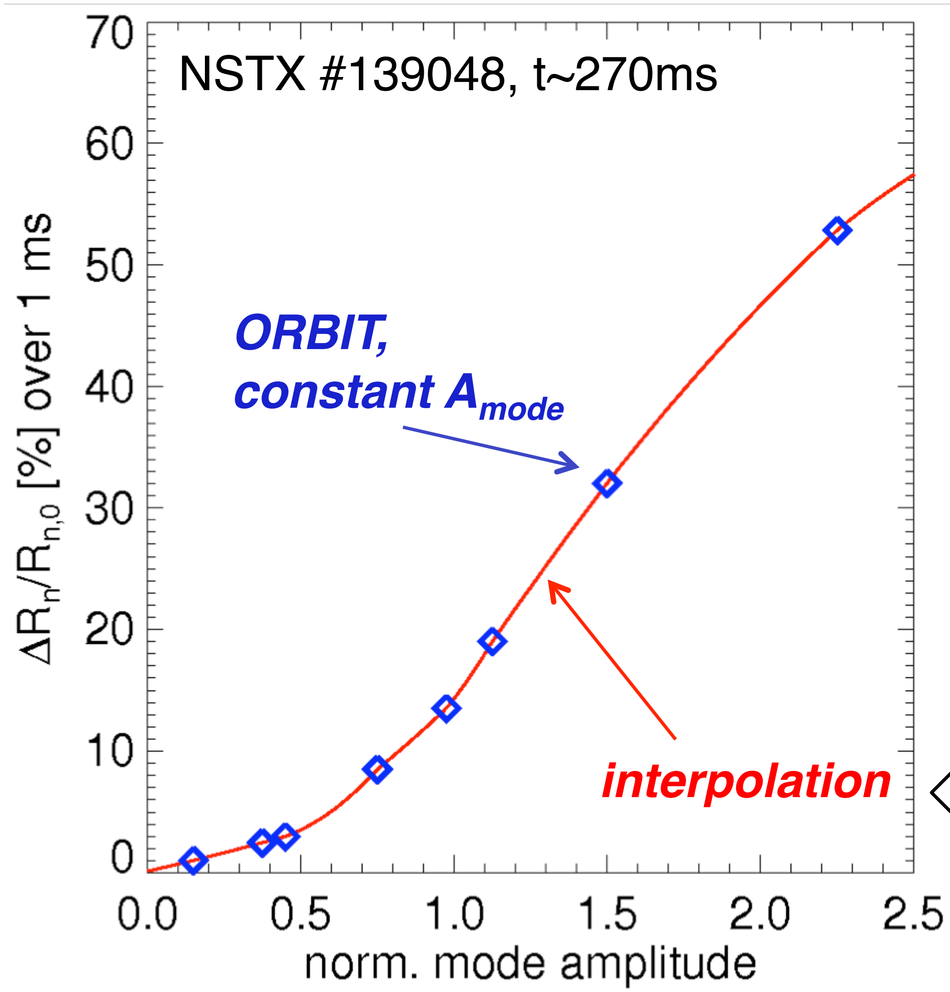
$p(\Delta E,\Delta P_\zeta|P_\zeta,E,\mu)$ and a time-dependent 'mode amplitude scaling factor' enable multi-mode simulations

- 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



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

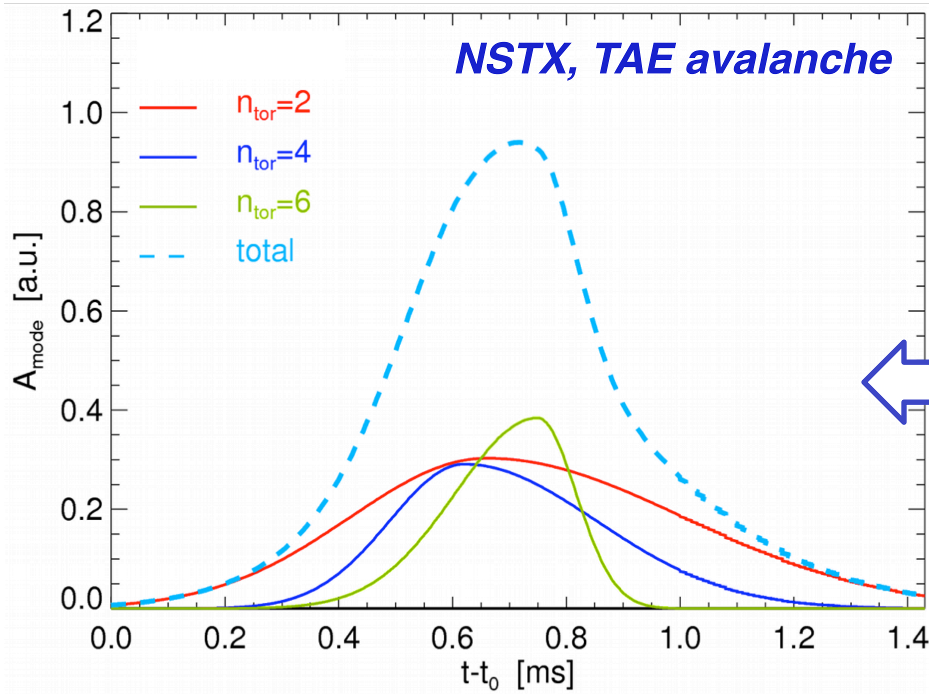
– If no mode data directly available, A_{mode} can be estimated based on other measured quantities



Example:
use measured neutron rate

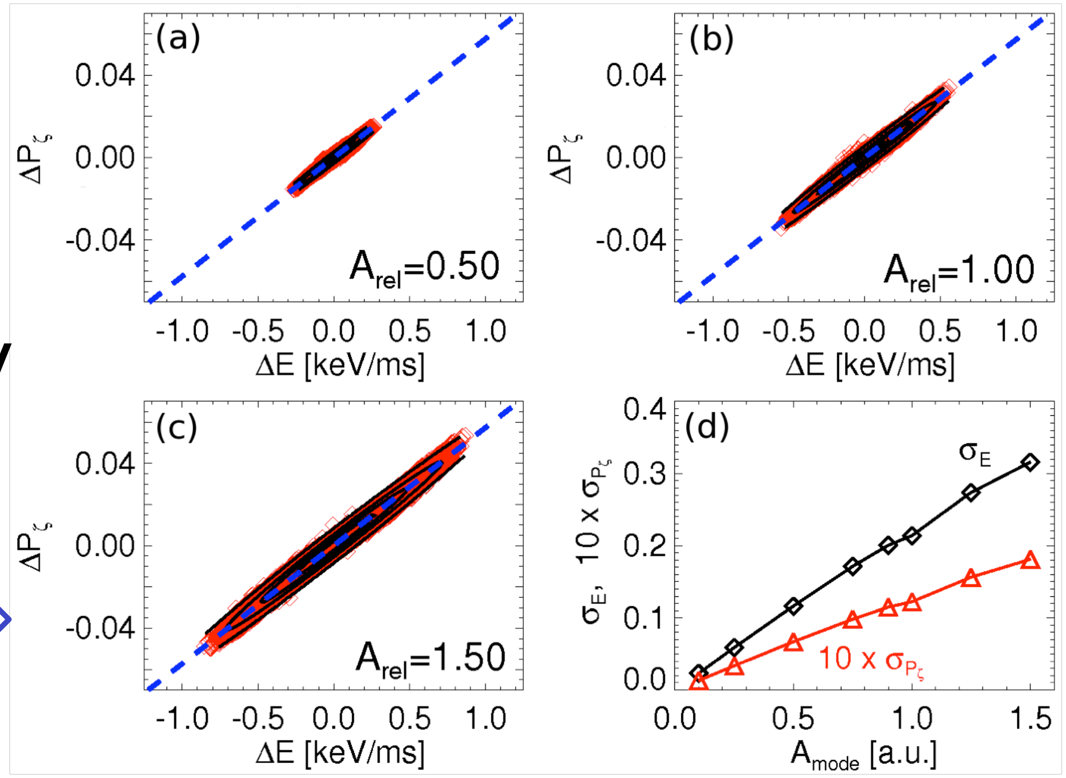
- Compute ideal modes through NOVA
- Rescale relative amplitudes from NOVA according to reflectometers
- Rescale total amplitude based on computed neutron drop from ORBIT
- Scan mode amplitude w.r.t. experimental one, $A_{mode}=1$: get table
- Build $A_{mode}(t)$ from neutrons vs. time, table look-up

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

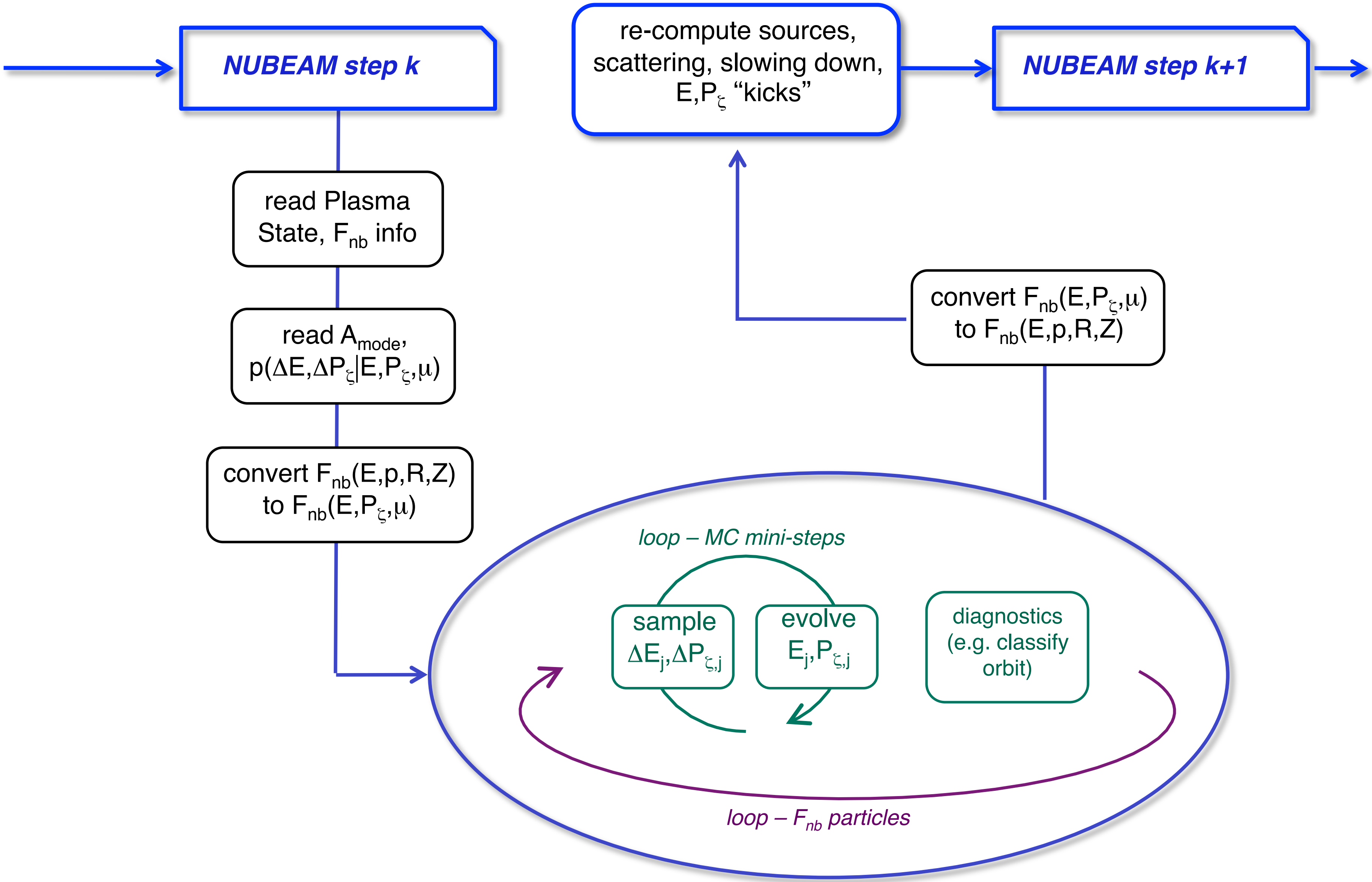
- Duration δt_{step} sufficiently shorter than time-scale of mode evolution
- Examples here have δt_{step}~25-50 μs



Energy and P_ζ steps assumed to scale linearly with mode amplitude

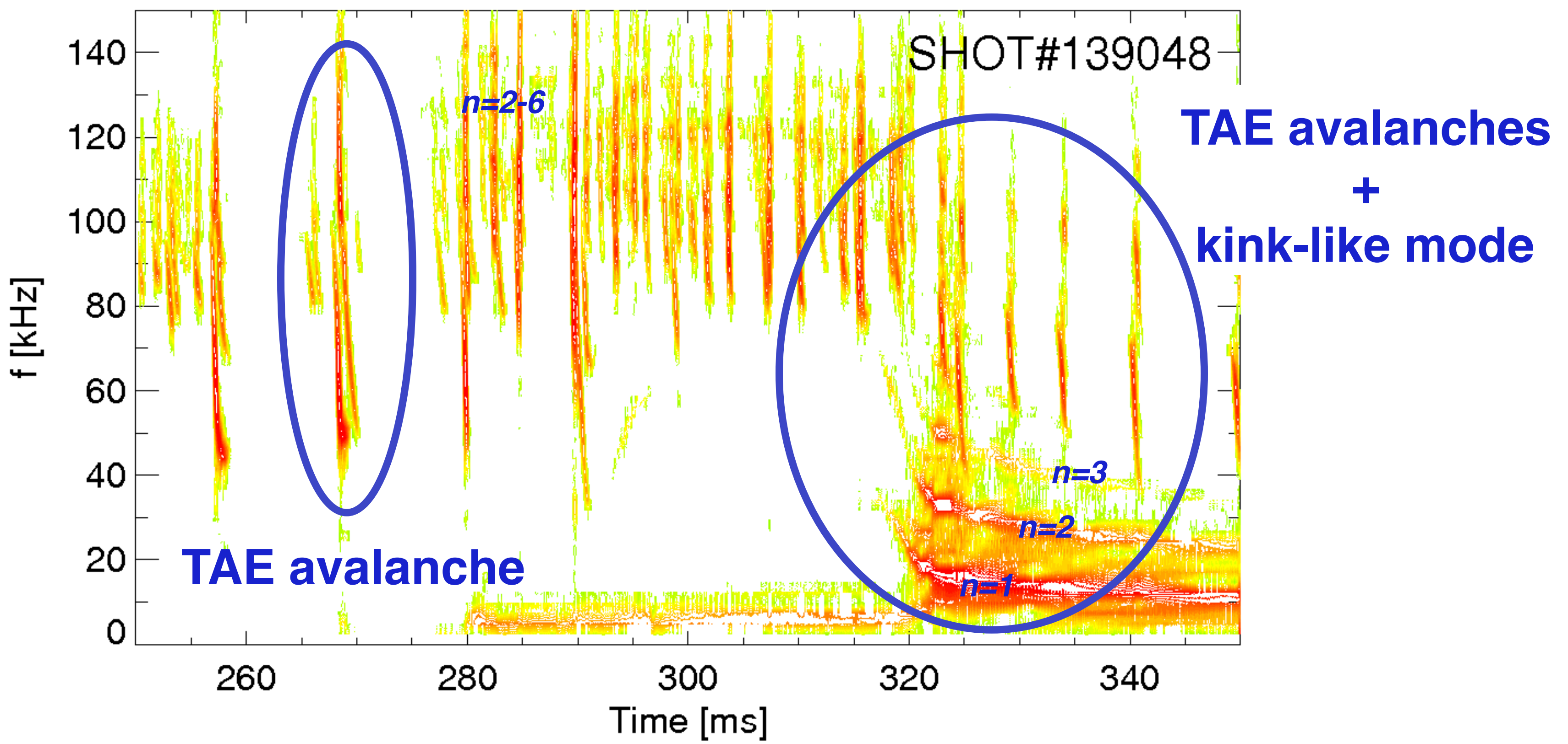
- Roughly consistent with ORBIT simulations

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

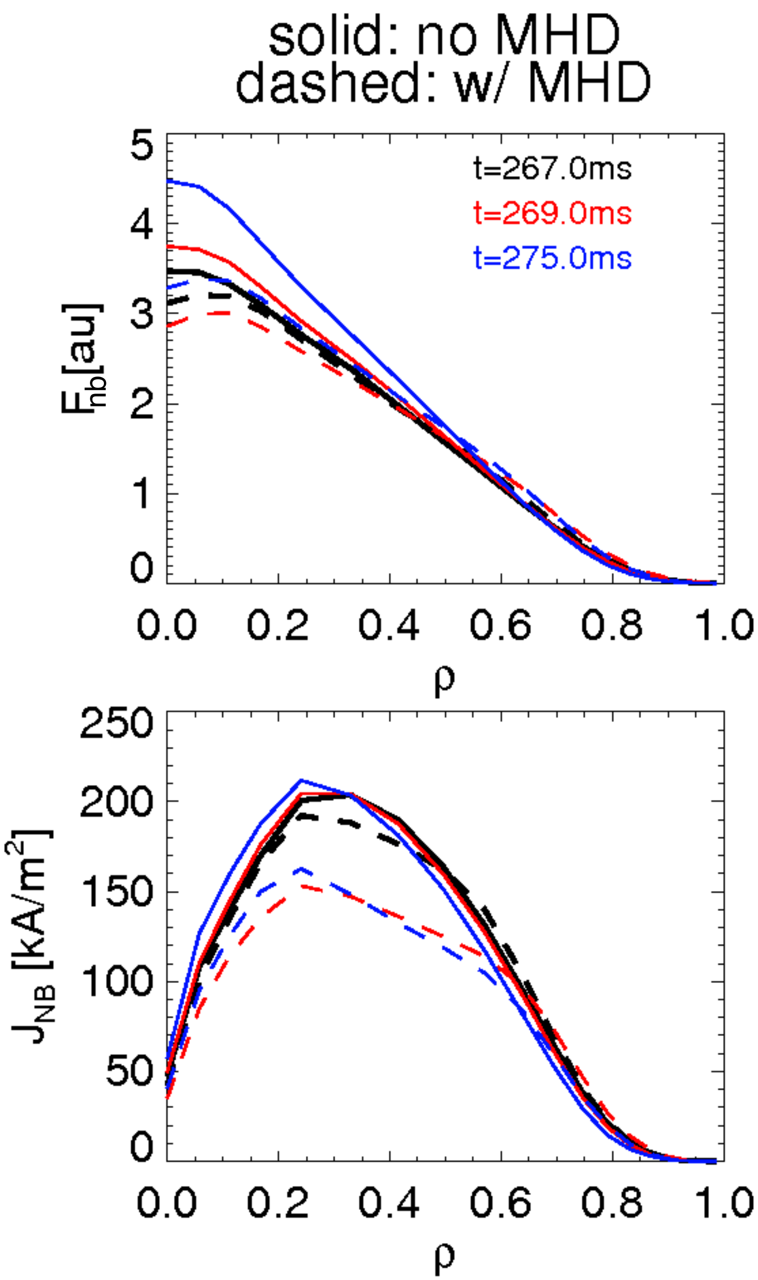


add "kicks" to F_{nb} variables

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



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

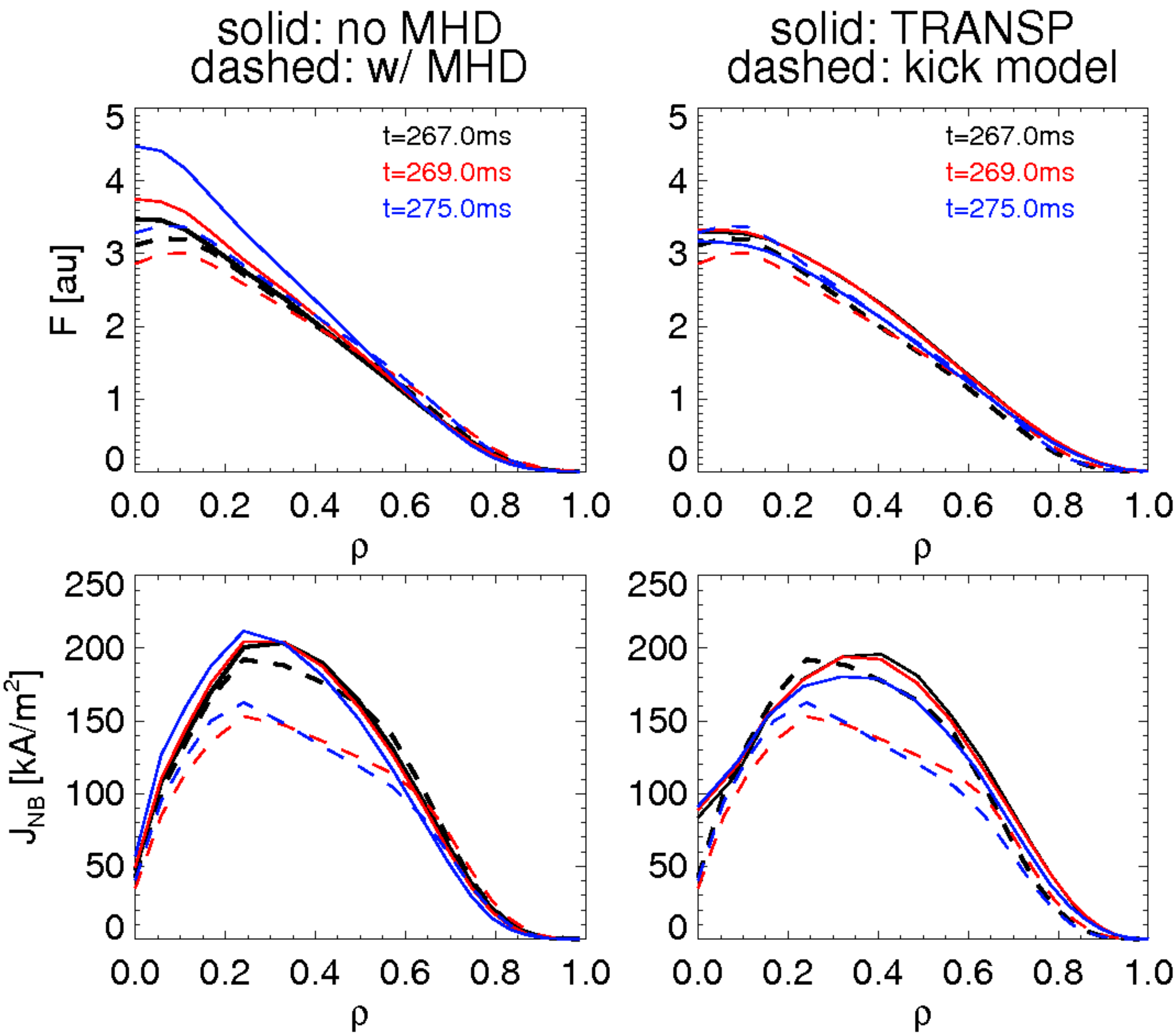


- Results from 'kick model'
- Fast ions redistributed outward, lose energy
  - Consistent with constraints from resonant interaction:

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

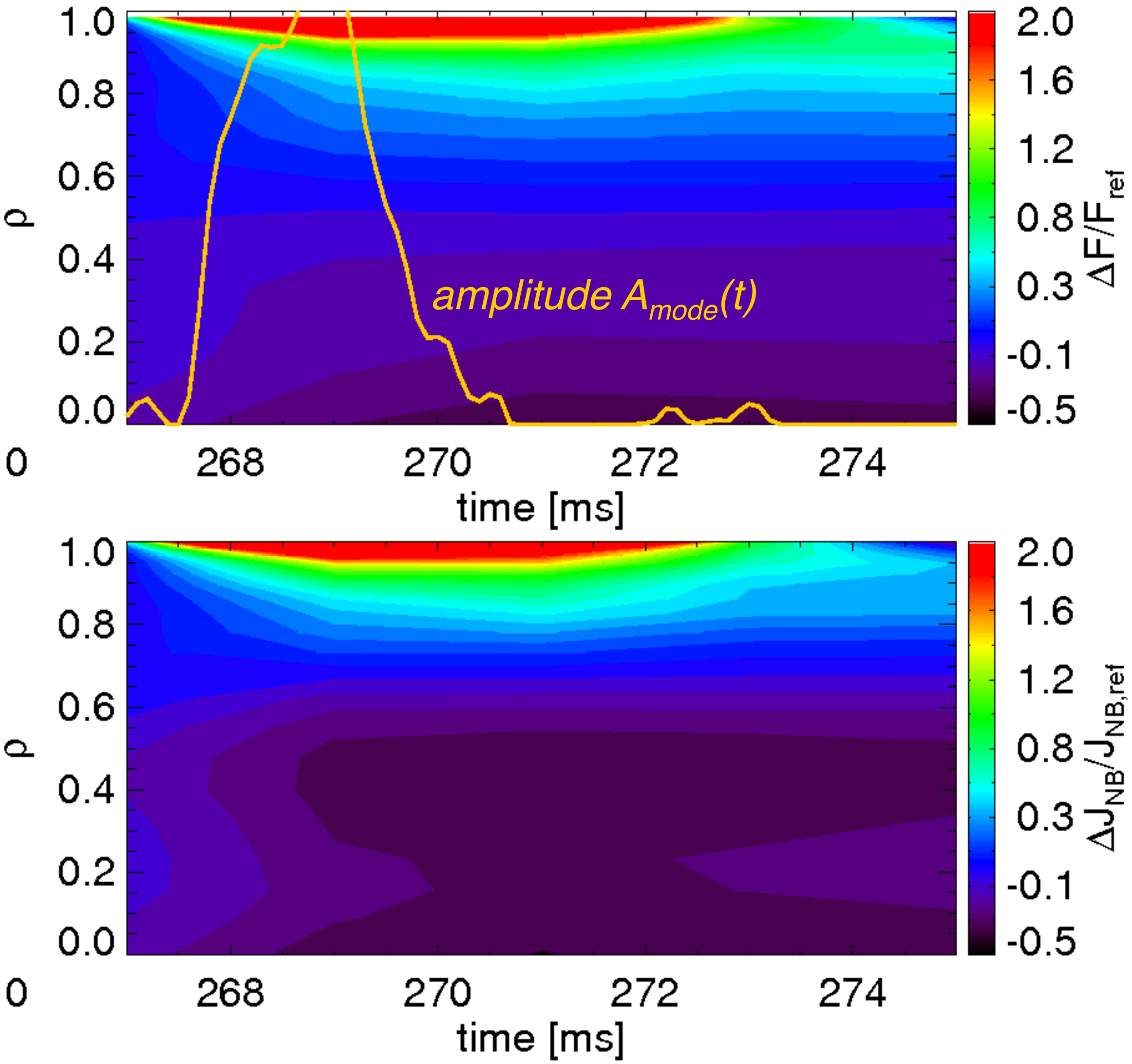
- NB-driven current J_{nb} is also redistributed out
- $J_{nb}(r)$ modification largely unpredicted by *ad-hoc* D_{fi} in this case

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



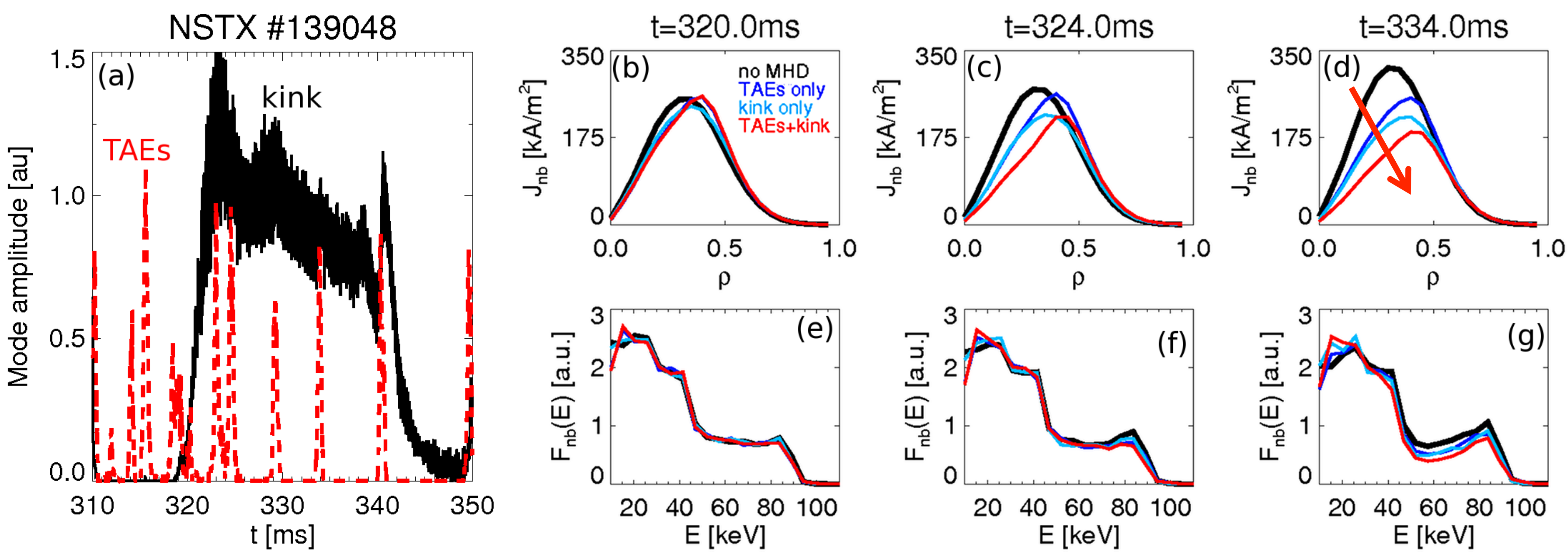
- Uniform D_{fi} acts in the same way on *all* particles at *all* radii
- No constraints from wave-particle interaction

Reduced model + NUBEAM reproduces fast ion redistribution; NB-driven current strongly affected, too



- Model finds fast ion redistribution induced by each TAE avalanche
- Clear effects on NB-driven current, J_{nb}
  - Stronger effect than on F_{nb}
- AE effects persist on slowing down time scales
  - Constant NB injection counteracts F_{nb}, J_{nb} depletion
- *Resonance patterns* form in $F_{nb}(E,P_\zeta,\mu)$

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

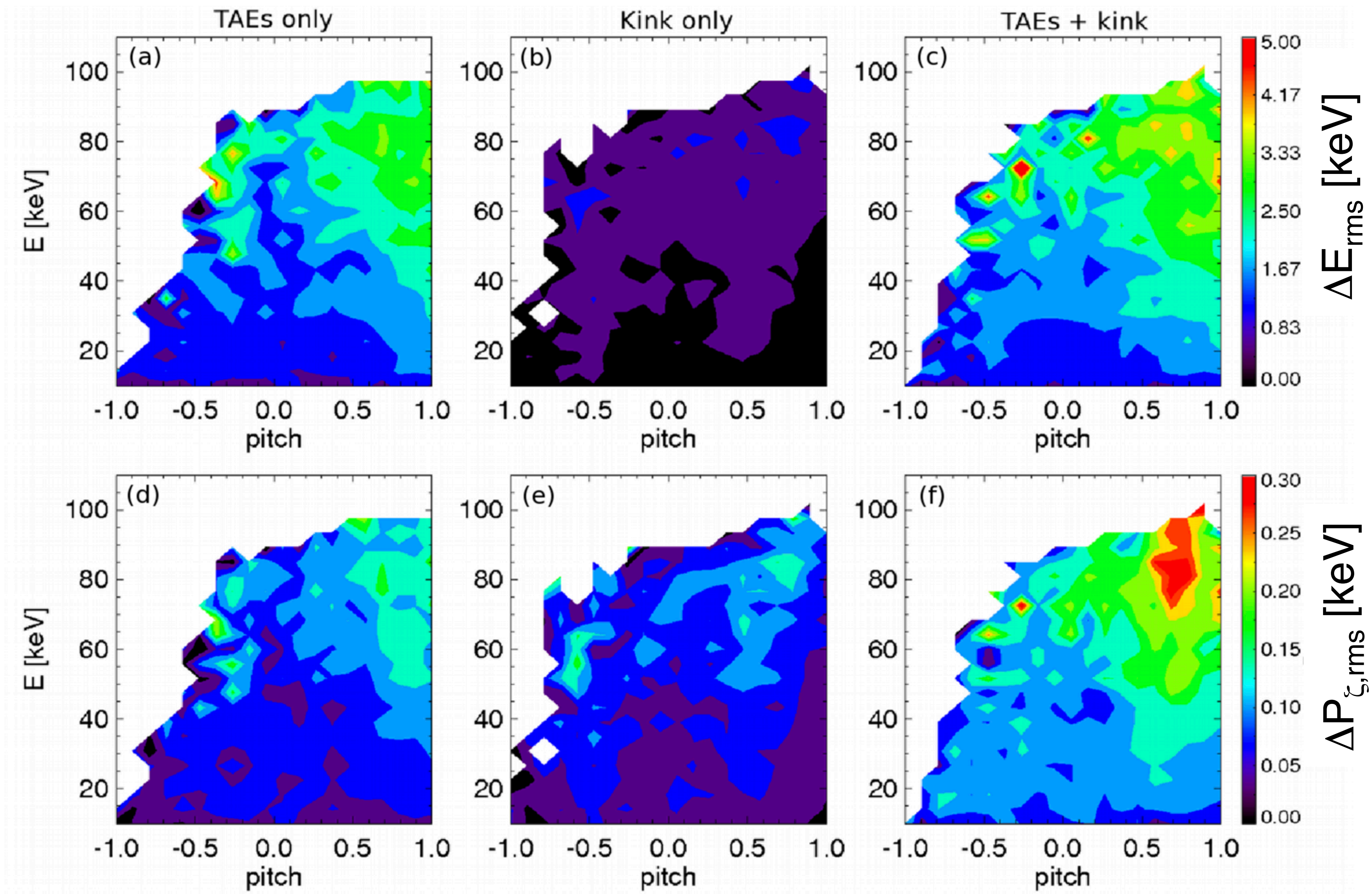


- Kinks have broad radial structure, connect core to boundary

> *Synergy arises from mode overlap in phase space*

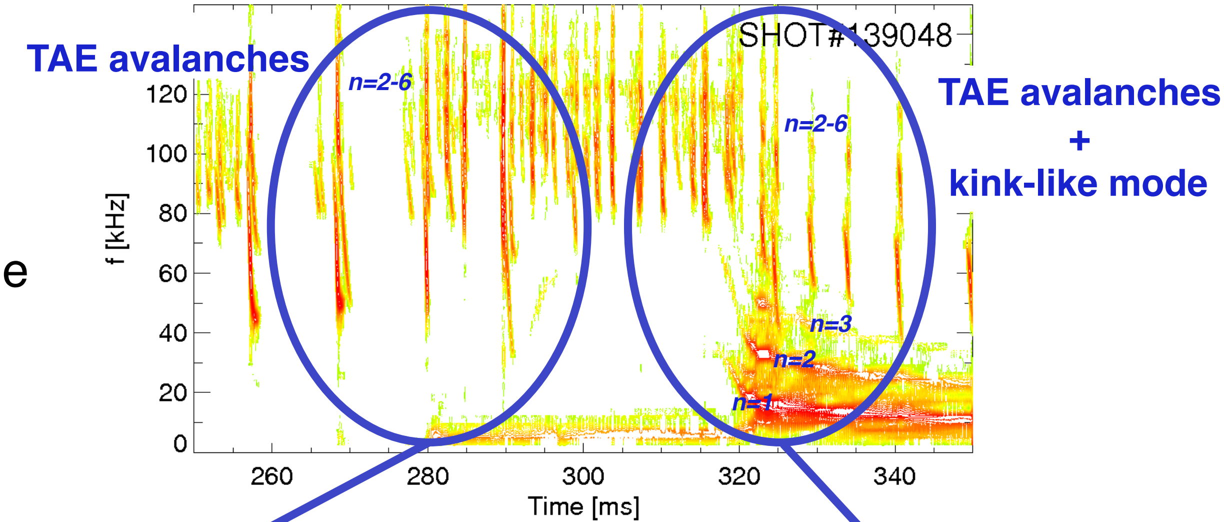
Phase-space is *selectively* modified by instabilities: TAEs -> $\Delta P_\zeta/\Delta E = n/\omega$, kinks -> mostly ΔP_ζ

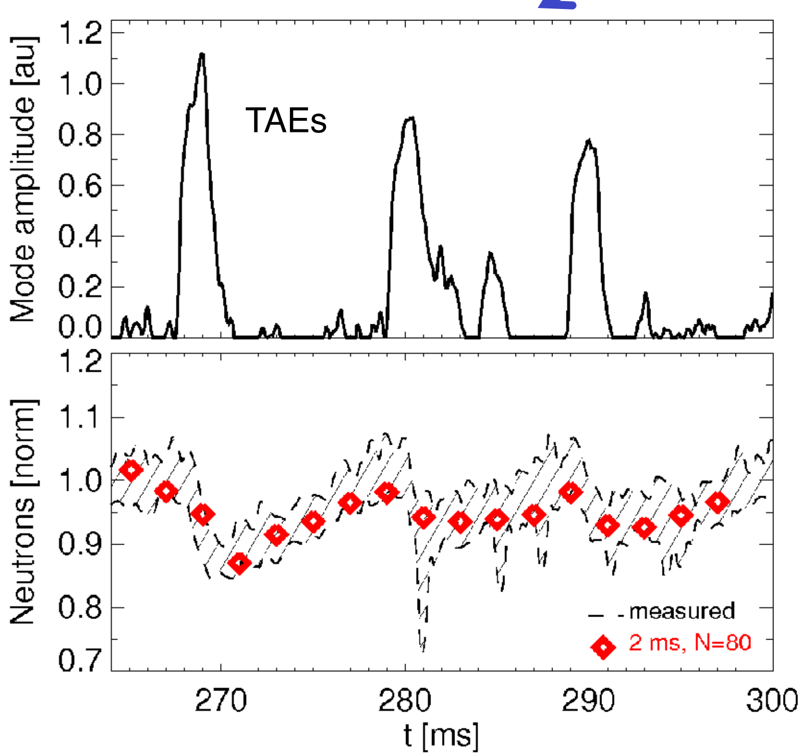
Synergy TAEs+kinks modifies radial EP transport $\propto \Delta P_\zeta$

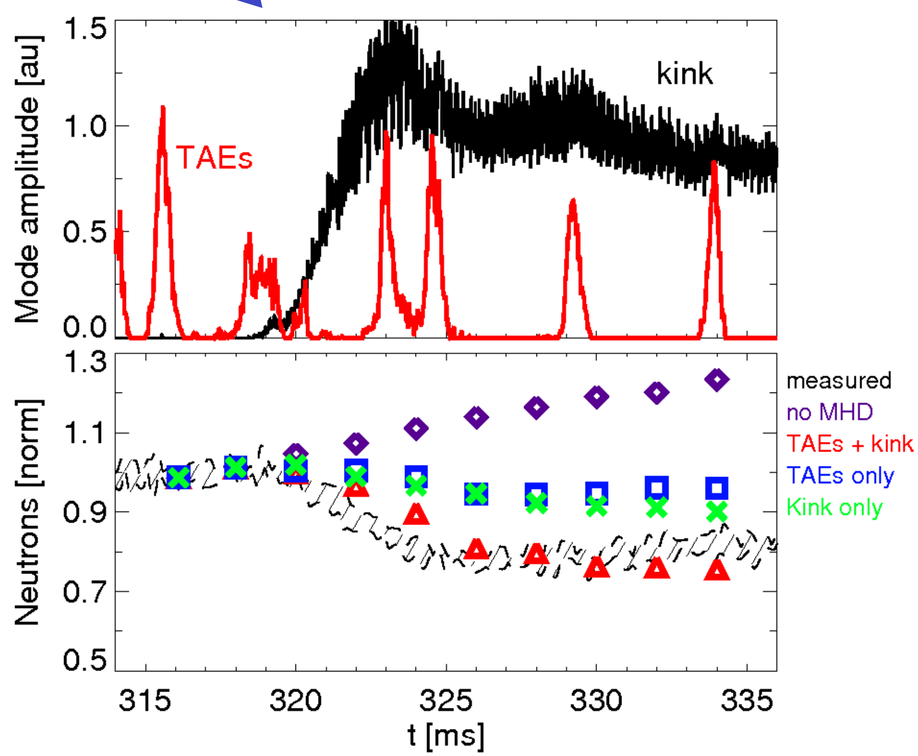


Simulated neutron rate agrees with experiments for both TAE avalanches & multi-mode cases

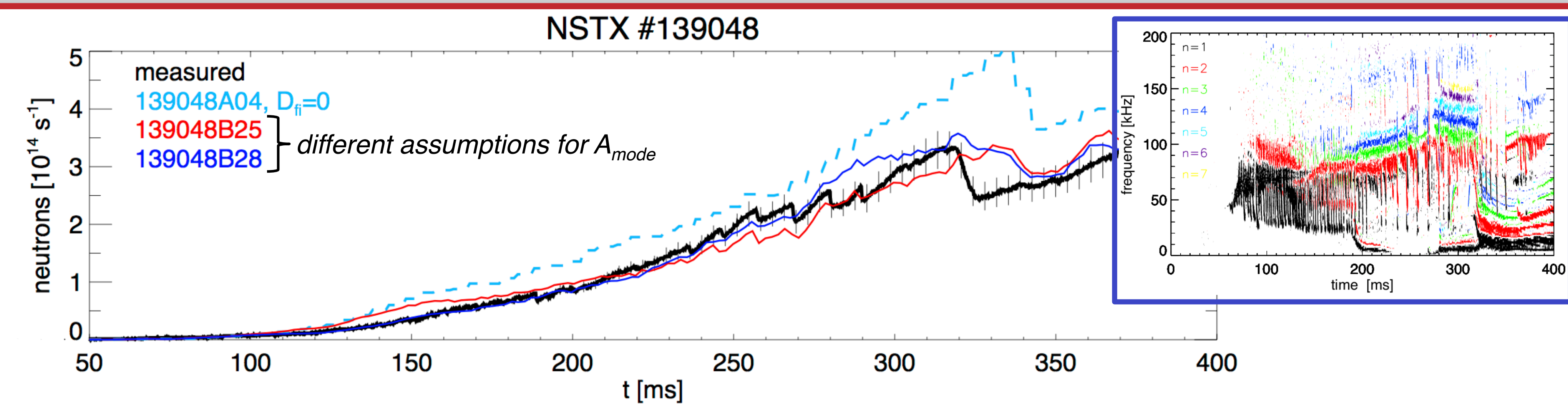
Use ‘kick model’ coupled to stand-alone NUBEAM

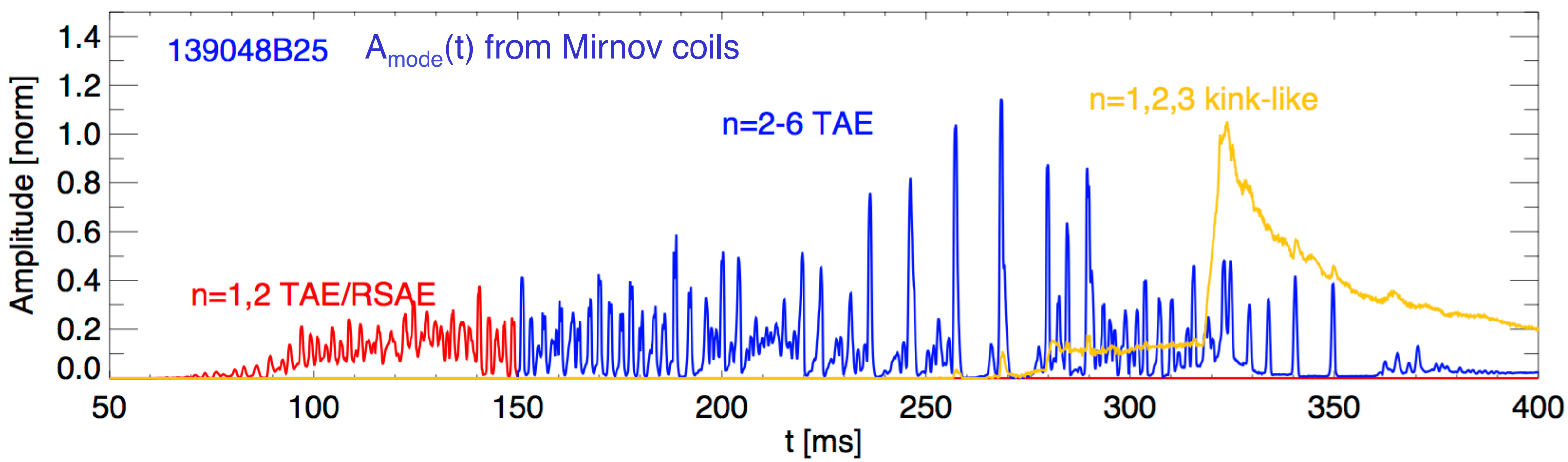






First TRANSP runs with "kick model" look promising for long time-scale, time-dependent multi-mode simulations

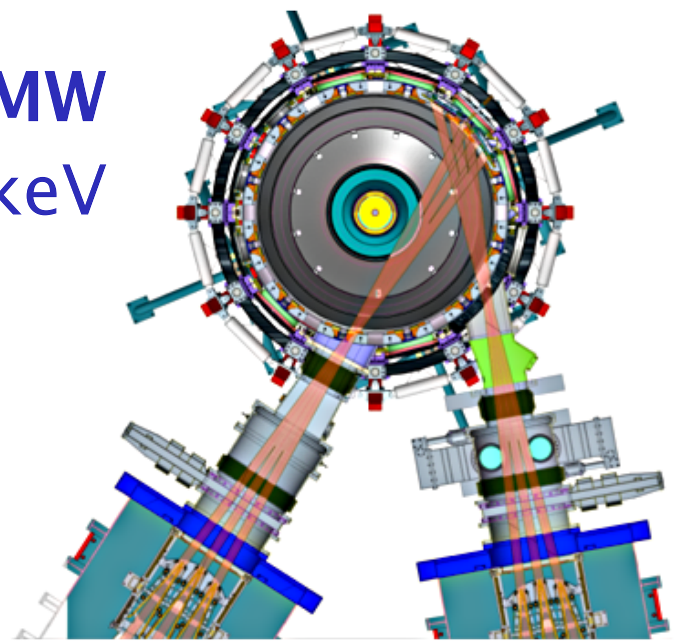




- Overall loss rate comparable to measurements
- Transient drops during AE bursts recovered
- More work required to infer correct $A_{mode}(t)$ for each class of modes

NSTX Upgrade 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

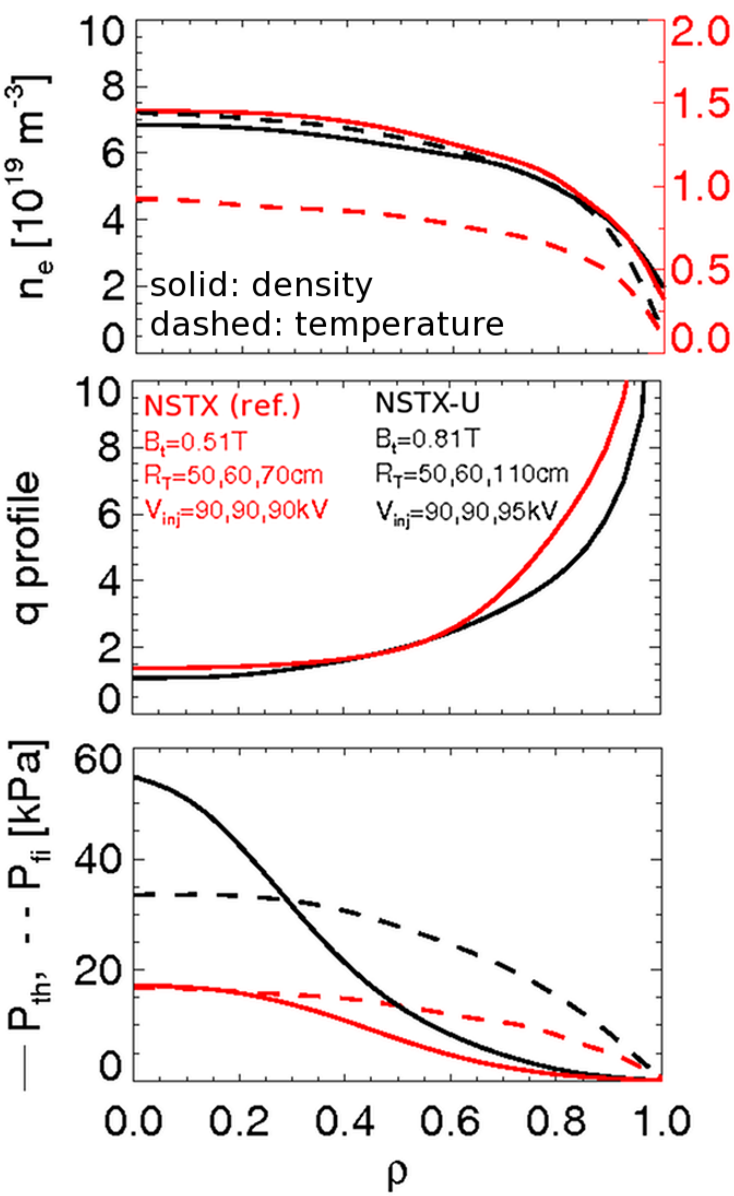


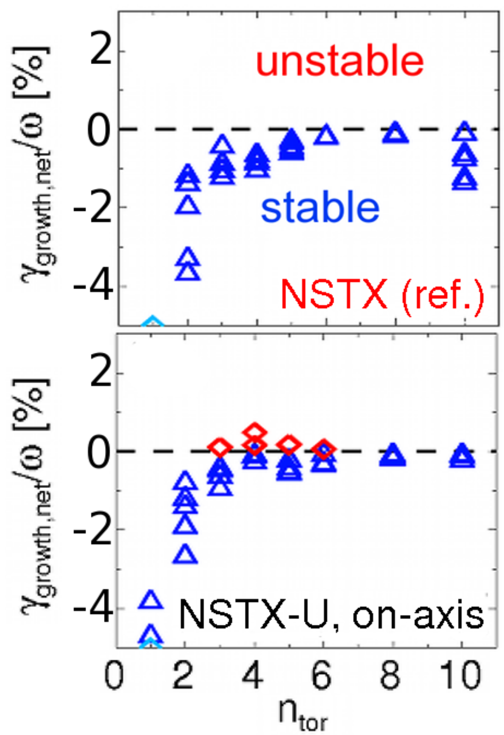
1st NB line *2nd NB line (upgrade)*

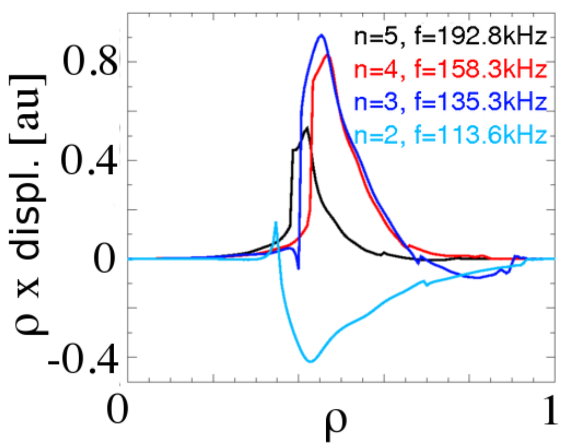
New NBI set on NSTX-U will enable more flexible NB current drive

[Menard, NF 2012]

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

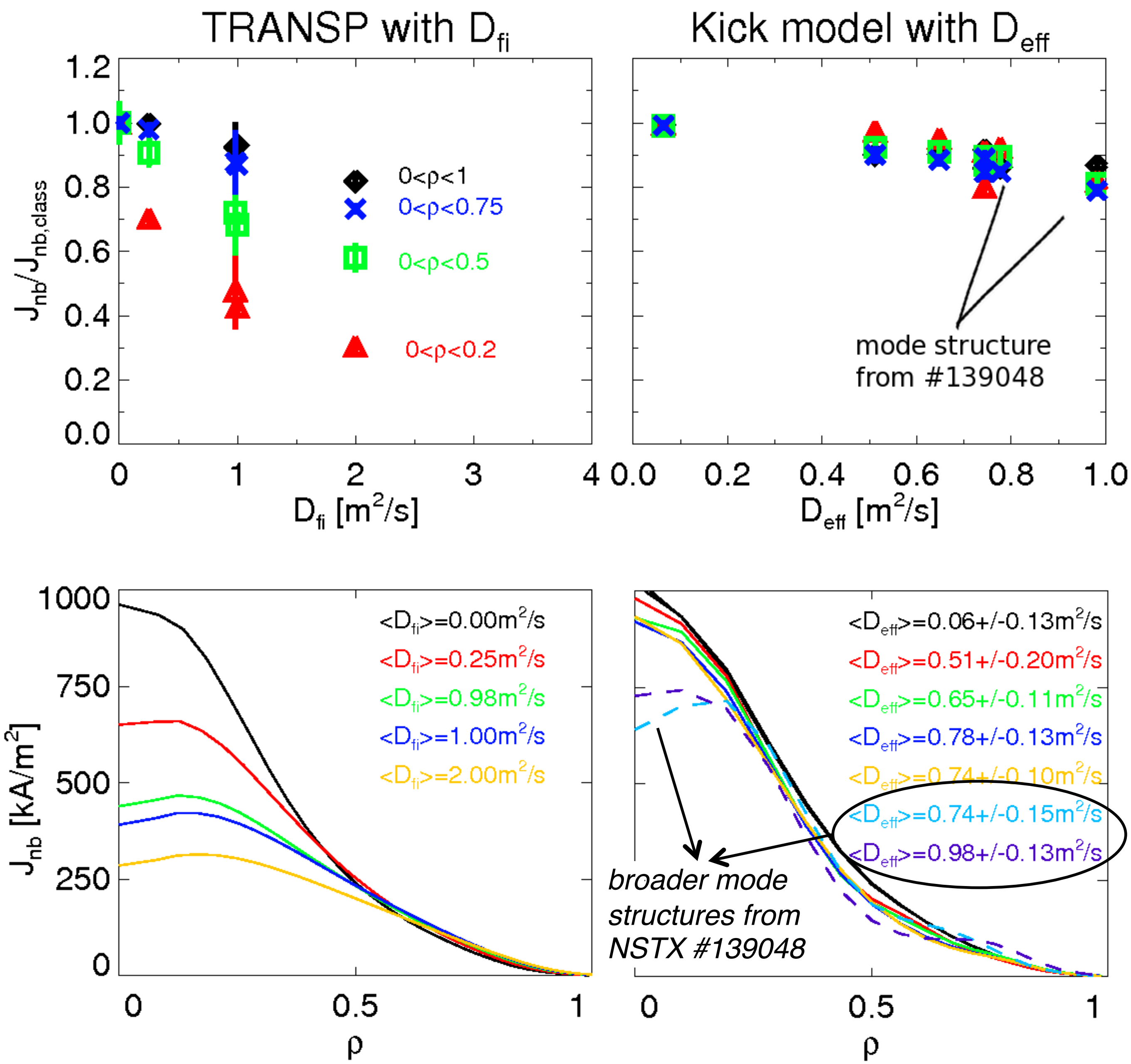






- Fast ion pressure is >2 times larger than in reference NSTX discharge
- NOVA-K finds spectrum of (linearly!) unstable TAEs with n=3-6
- Predicted mode structure is narrower on NSTX-U than for typical NSTX

'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

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 being implemented in TRANSP for EP simulations including phase-space details
- 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