NSTX-U

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Effects of MHD instabilities on Neutral Beam current drive

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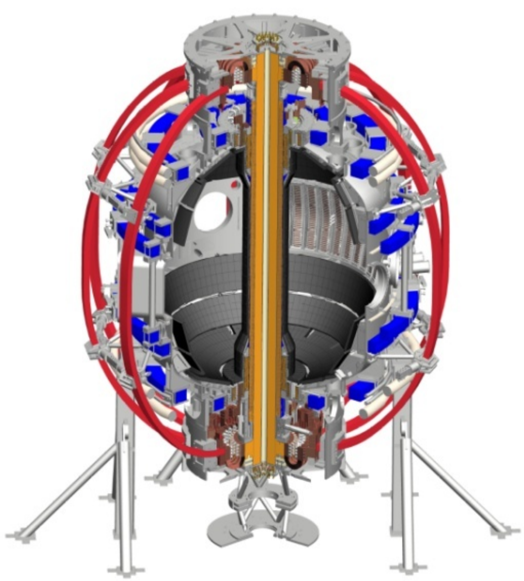

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Reliable, quantitative predictions of Energetic Particle (EP) dynamics are crucial for burning plasmas

- 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

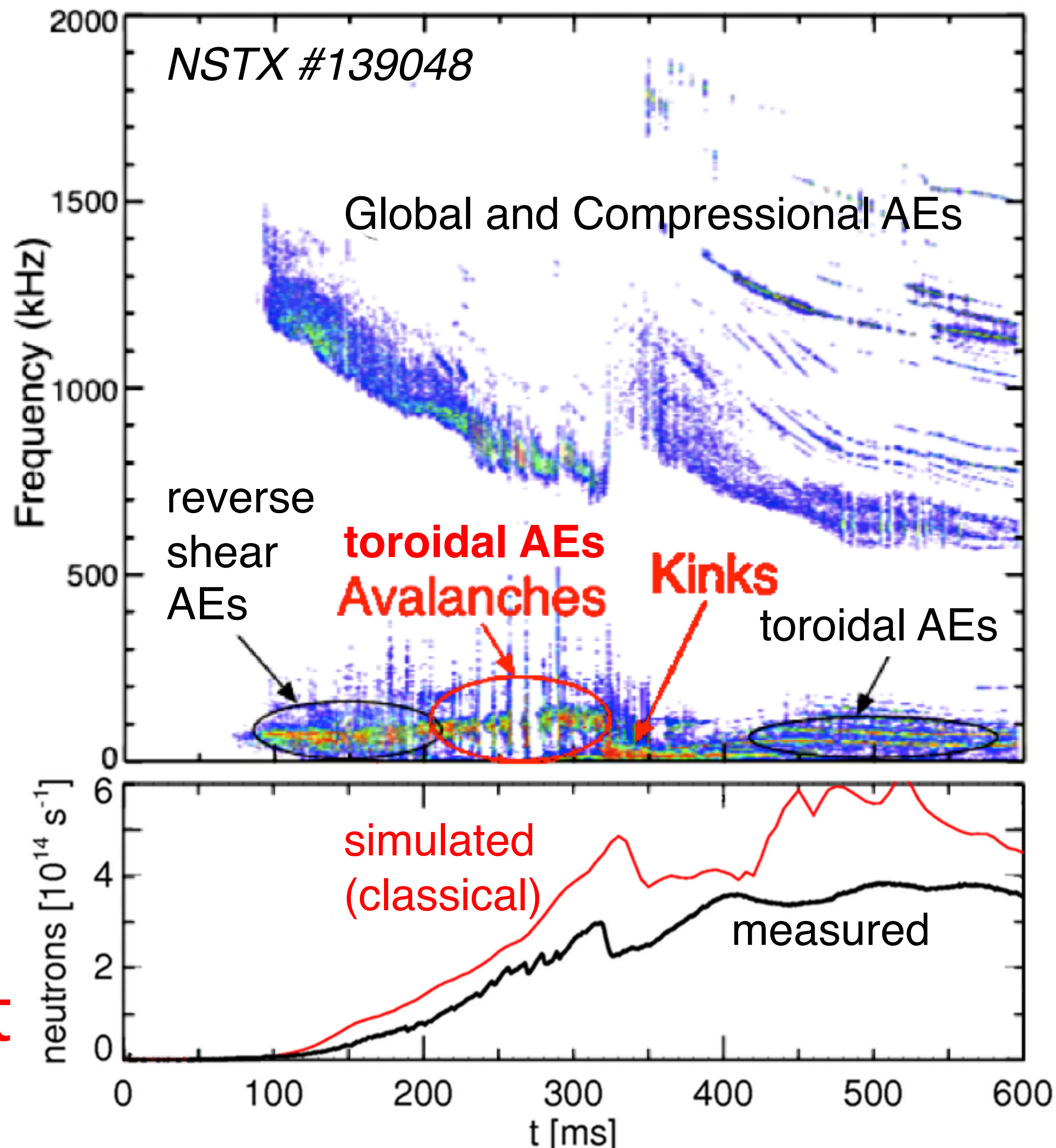
Neutral Beam sources:

$P_{NBI} \leq 6$ 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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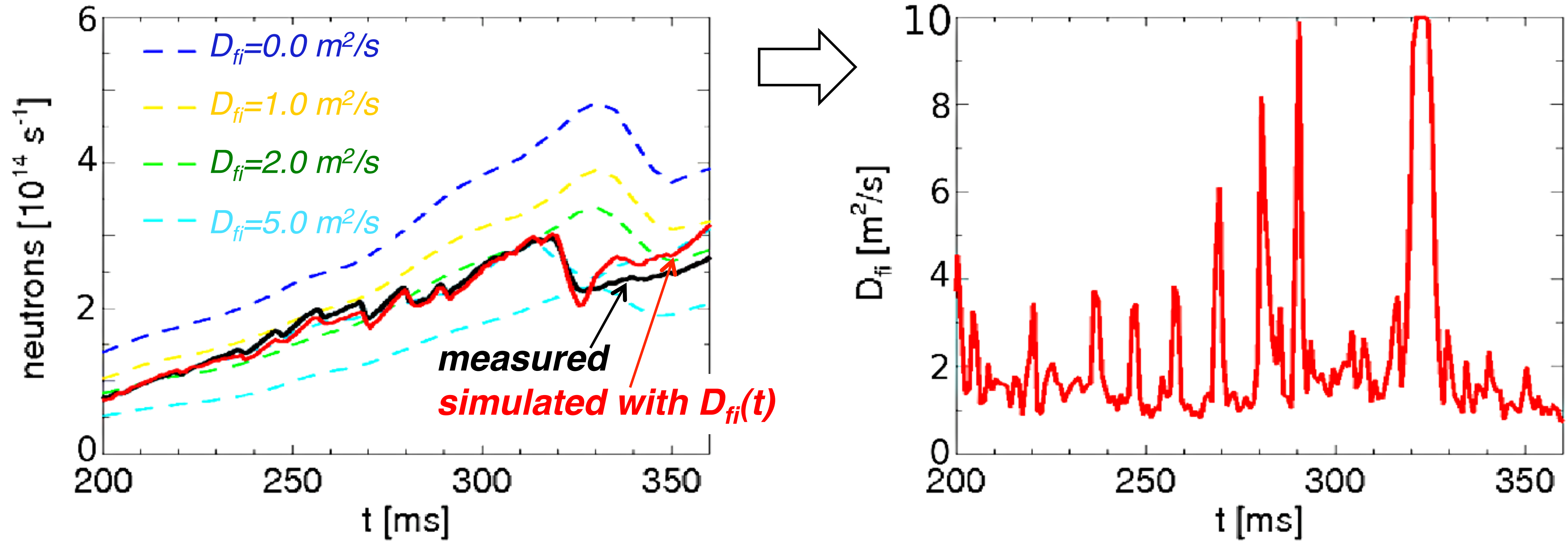
Transport code TRANSP includes NUBEAM module for classical fast ion physics

- 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}

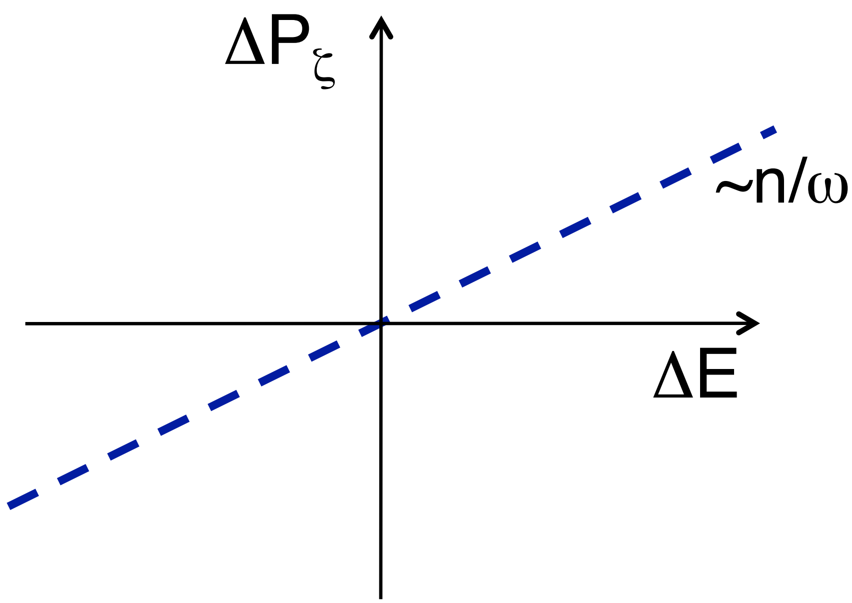


However: instabilities introduce fundamental constraints on particle dynamics

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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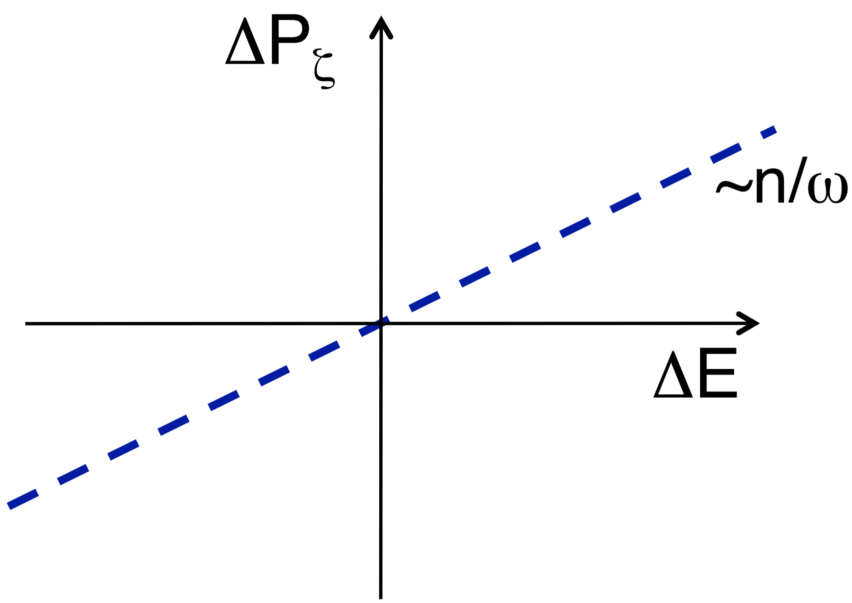

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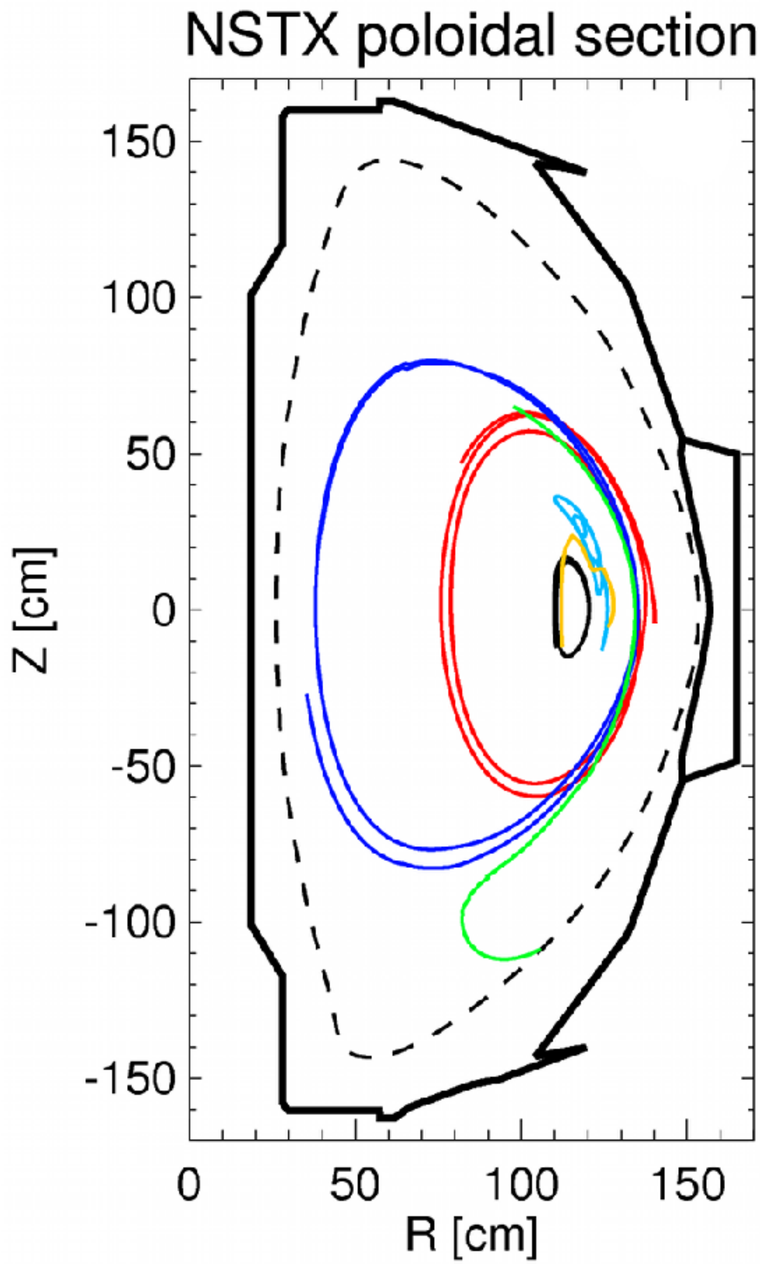
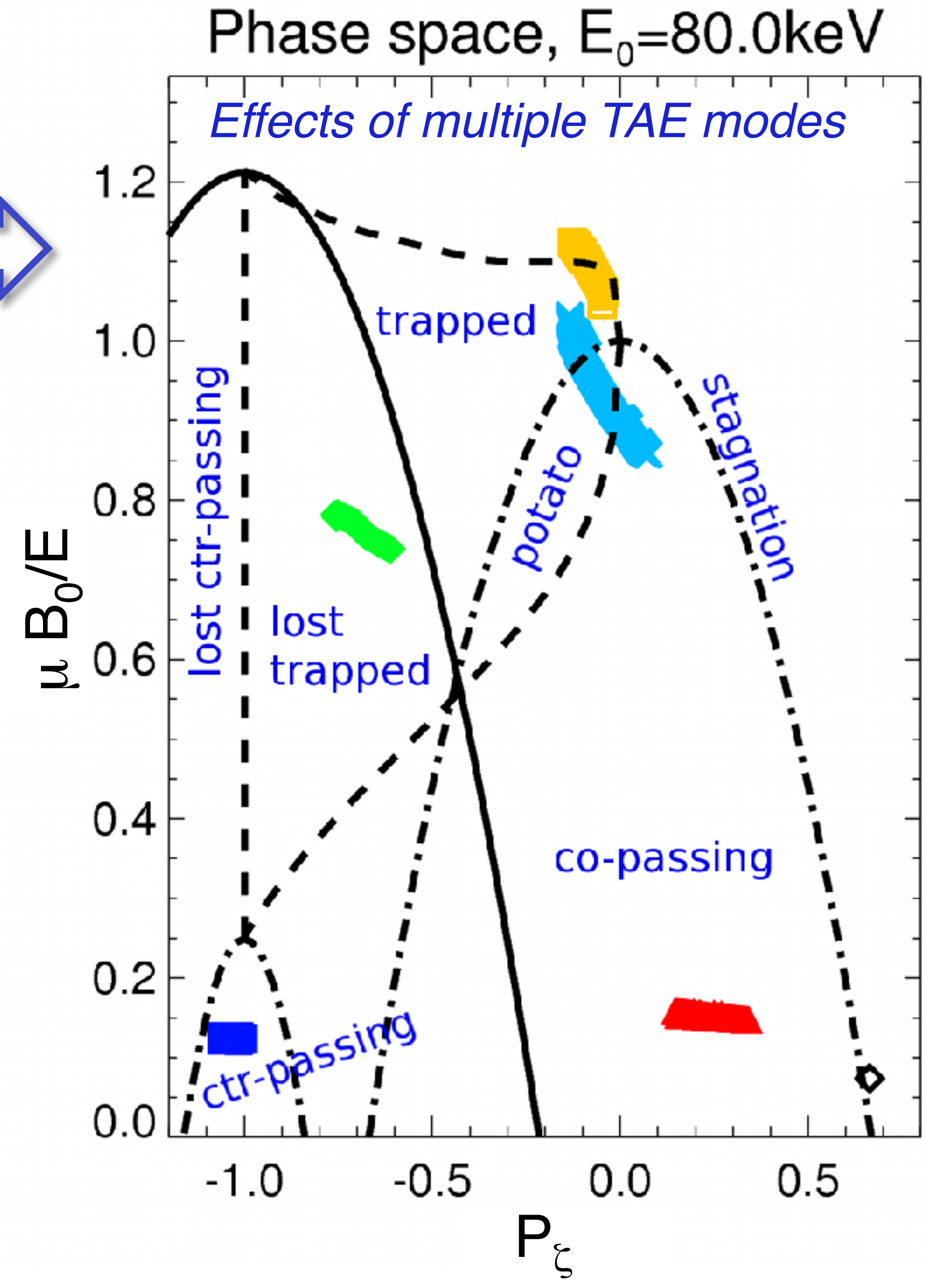
These effects are not accounted for by ad-hoc D_{fi}.

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





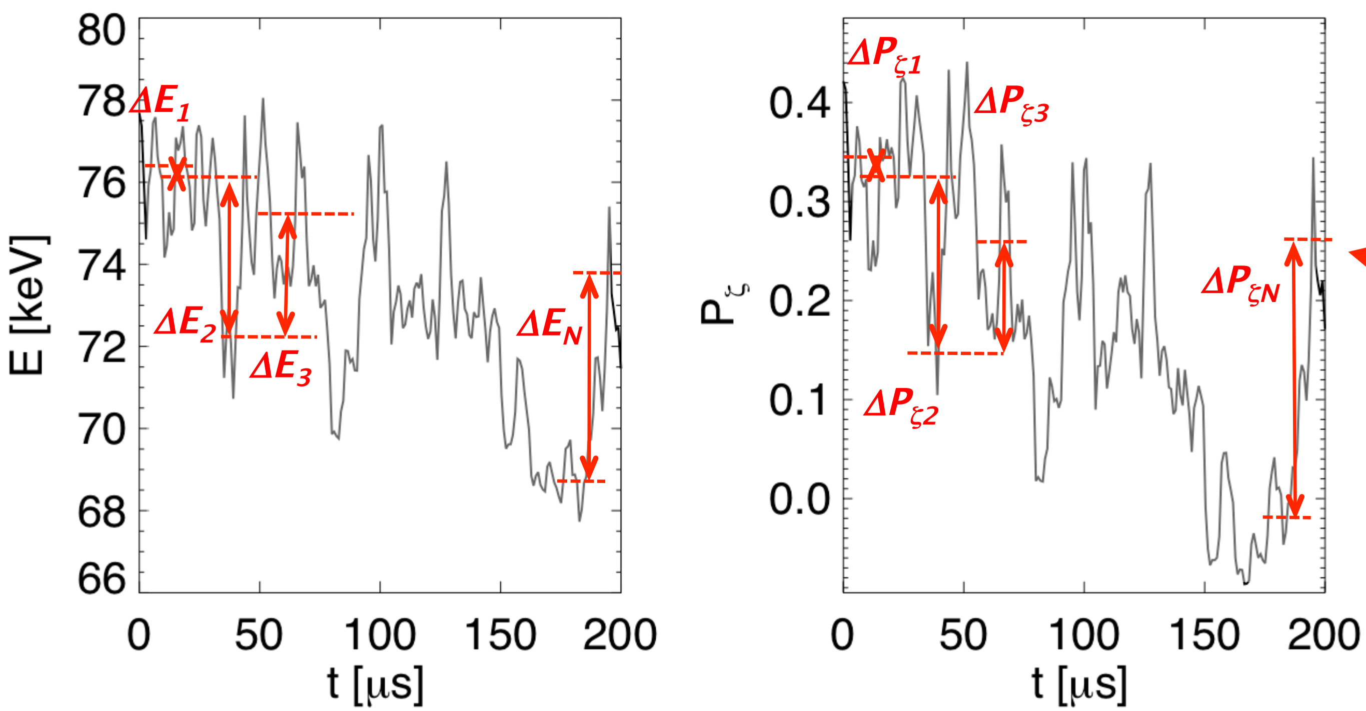
R. B. White, Theory of toroidally confined plasmas, Imperial College Press (2014)

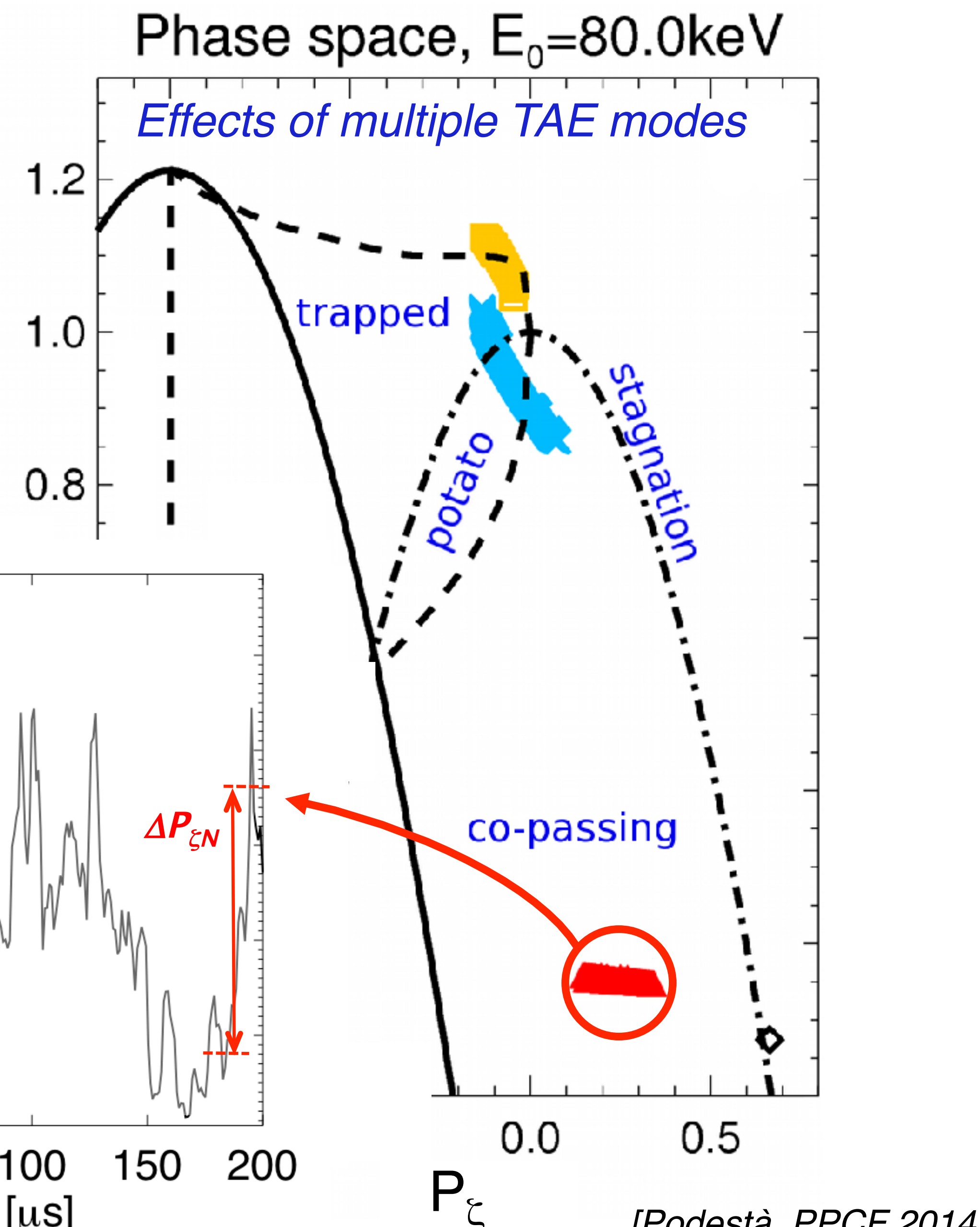
Particle-following codes are used to extract distribution of 'kicks' ΔE, ΔP_ζ for each *bin* (E,P_ζ,μ)

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

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

- Re-bin for each (E,P_ζ,μ) region





[Podestà, PPCF 2014]

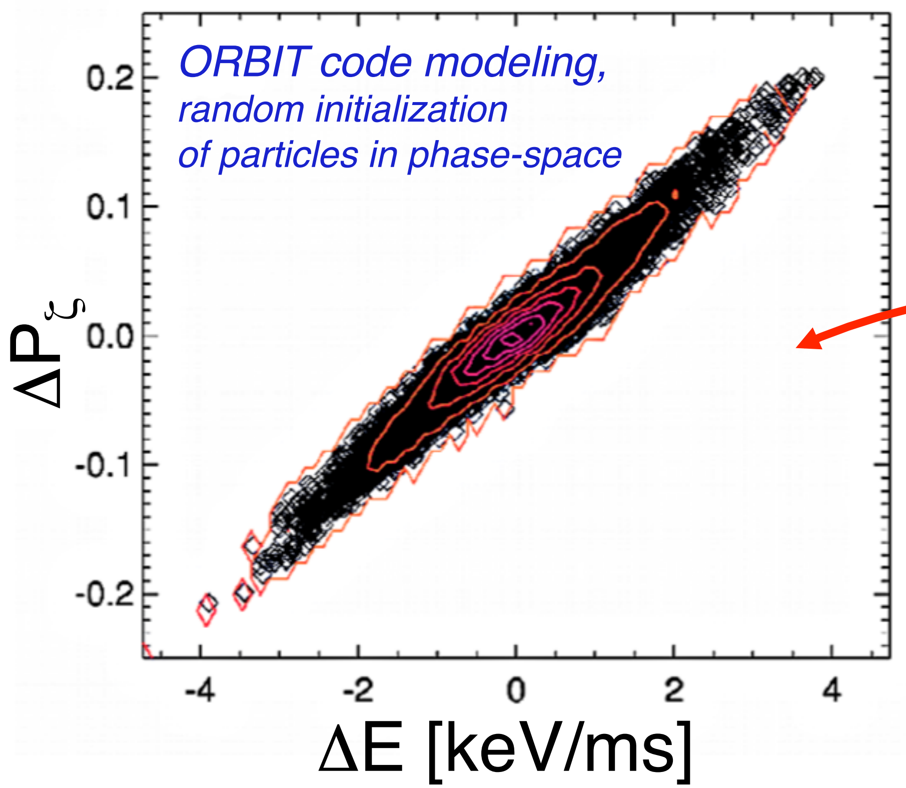
New ‘kick model’ uses a *probability distribution function* for particle transport in (E,P_ζ,μ) space

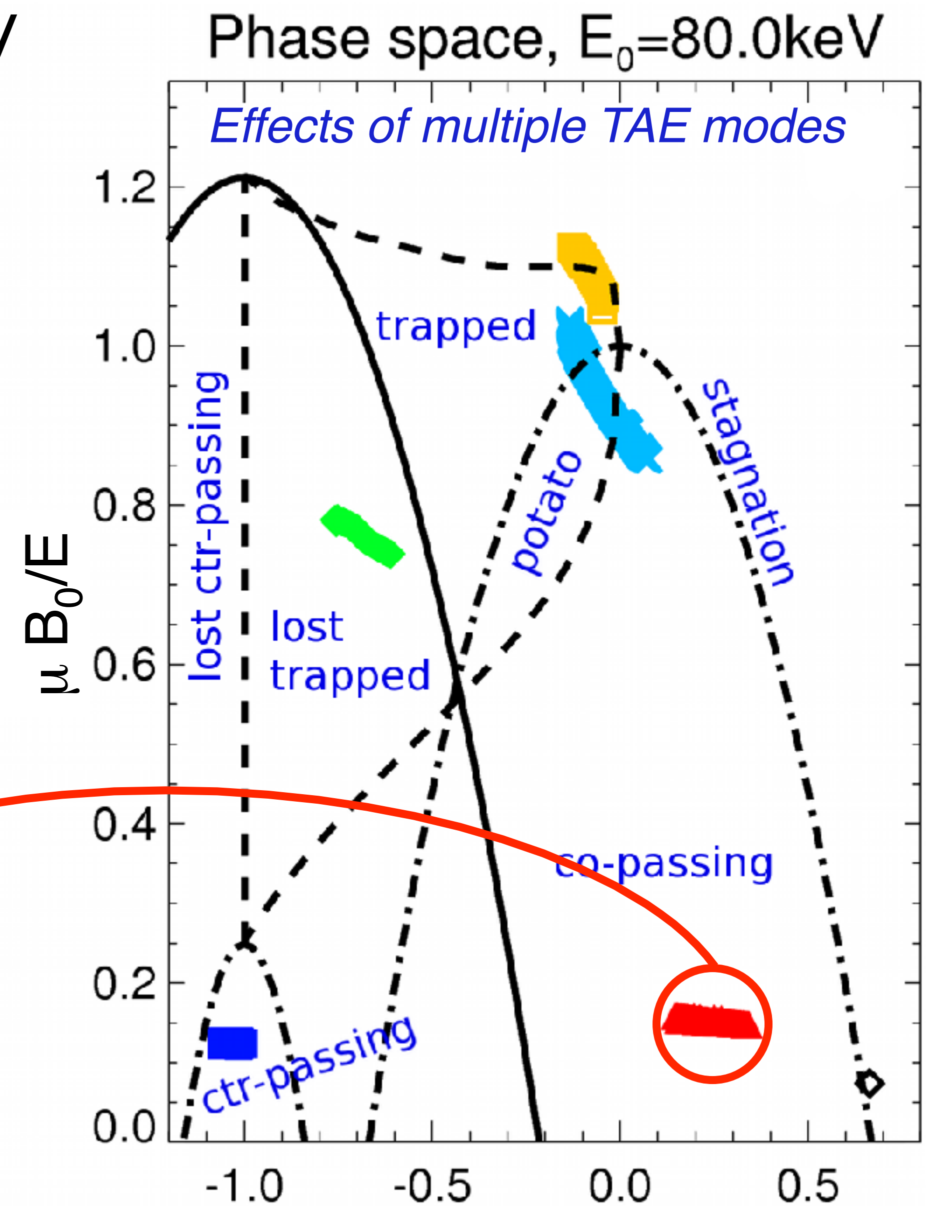
Kicks $\Delta E, \Delta P_\zeta$ are described by

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

which includes the effects of <u>multiple</u> modes, resonances.

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





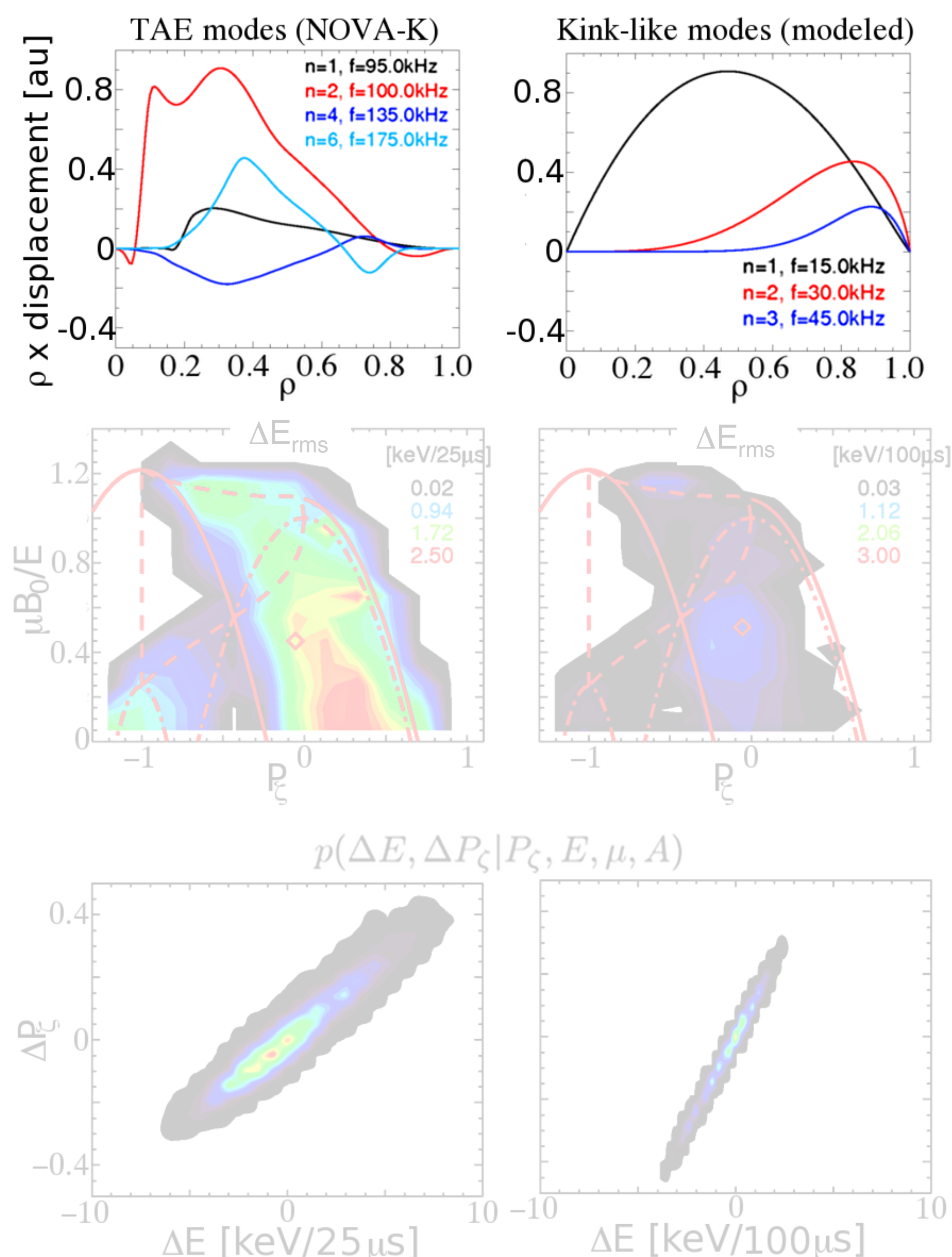
[Podestà, PPCF 2014]

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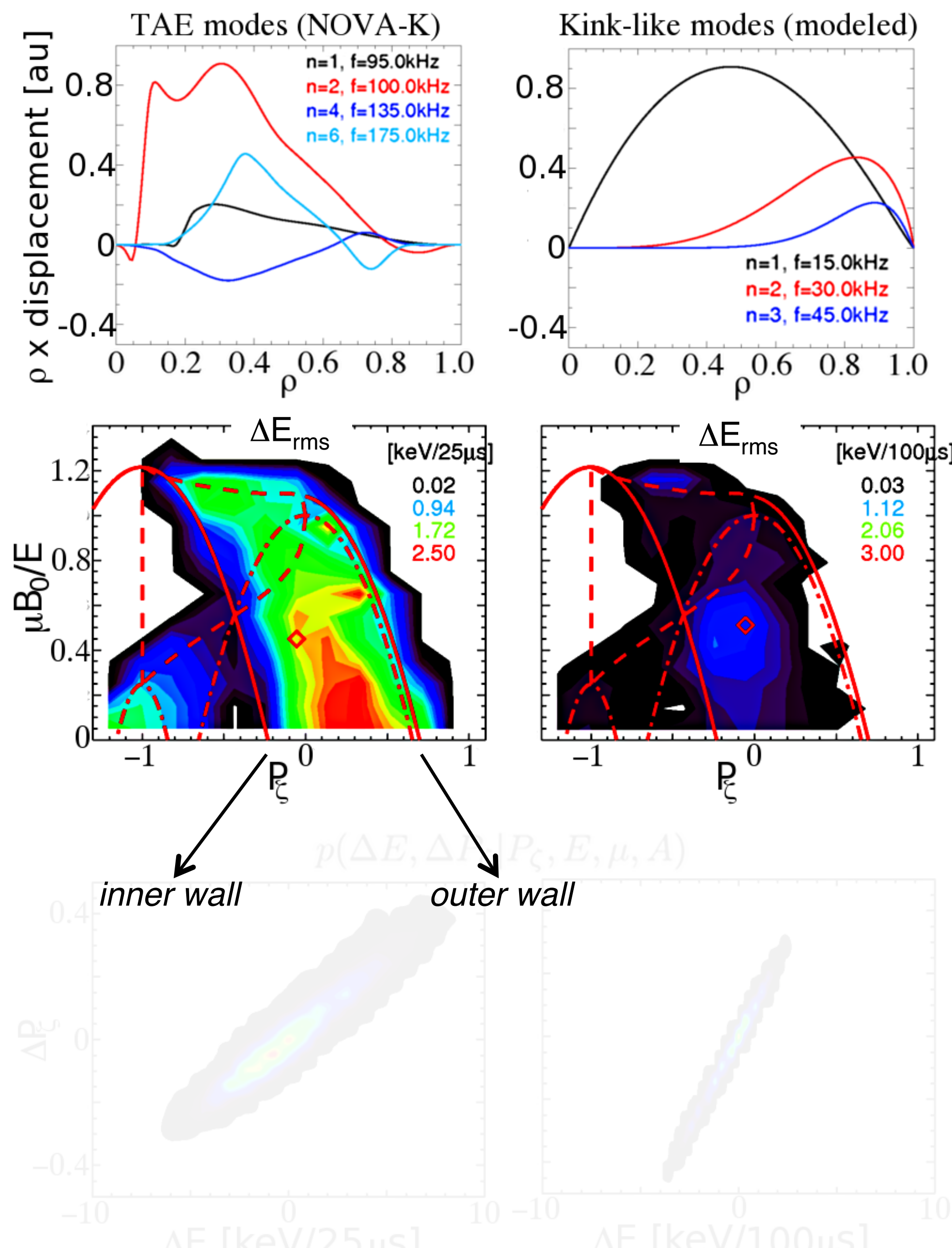

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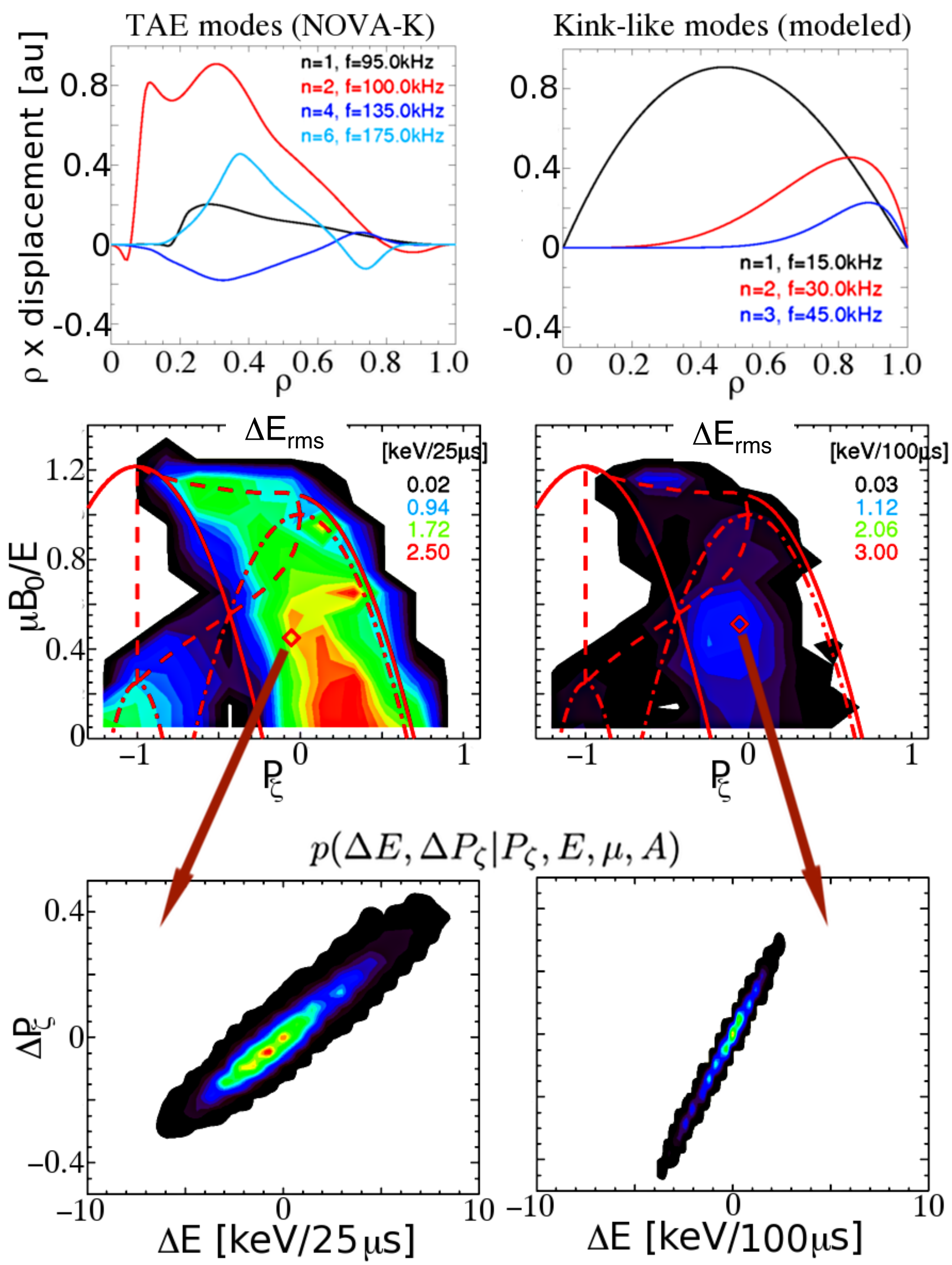

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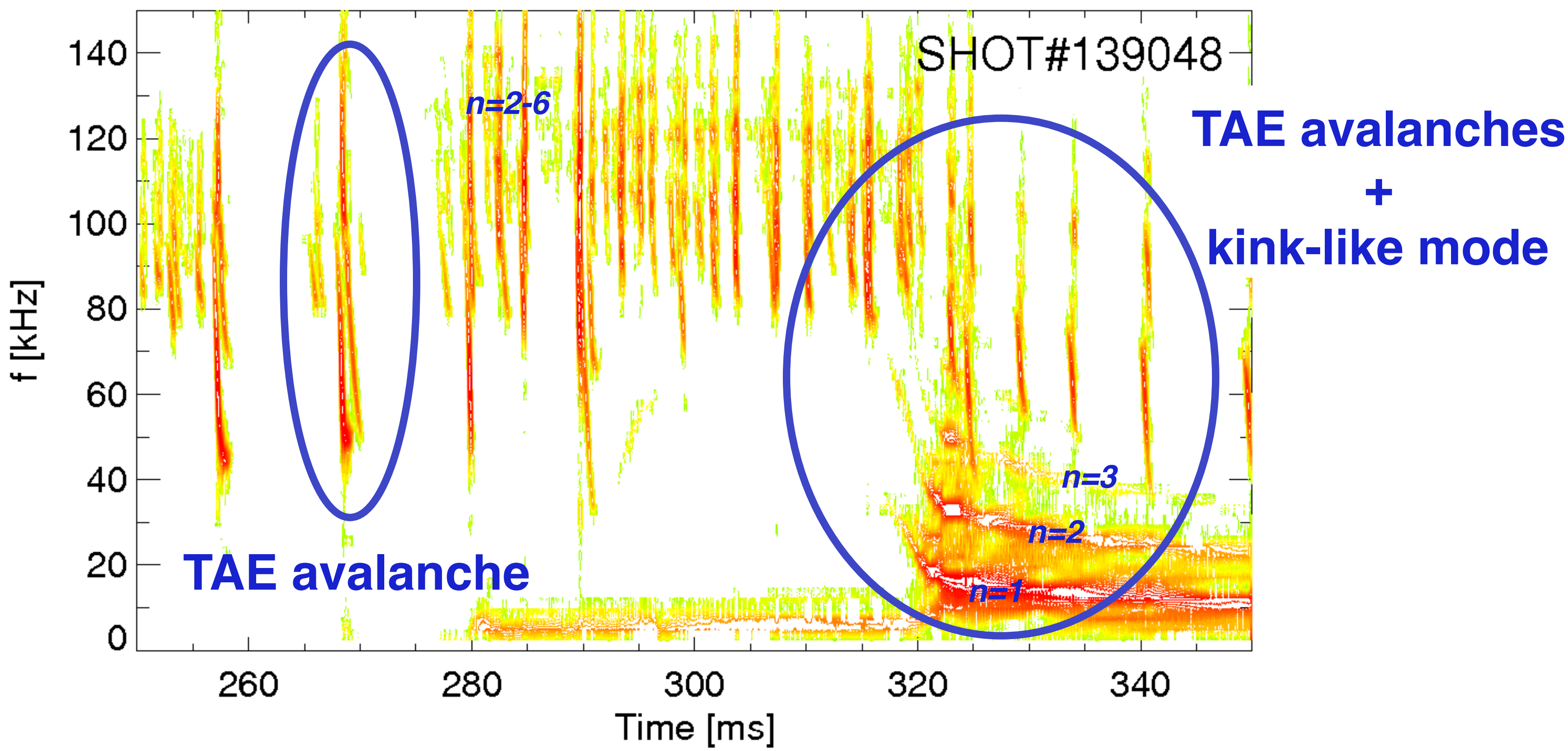
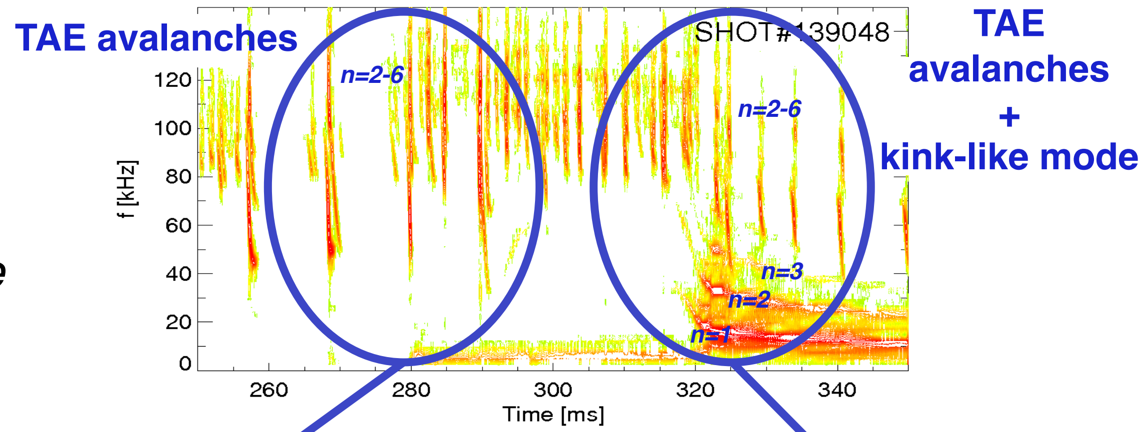
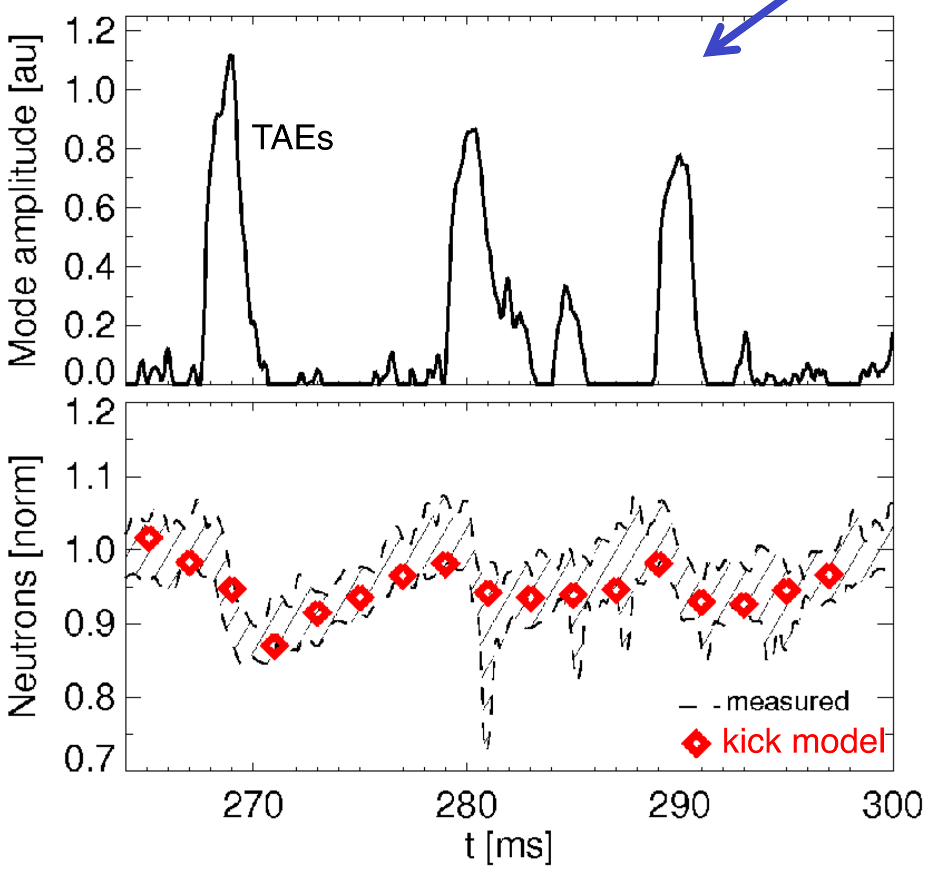
Two NSTX cases are analyzed in detail: TAE avalanche and avalanche + kink-like mode (multi-mode scenario)

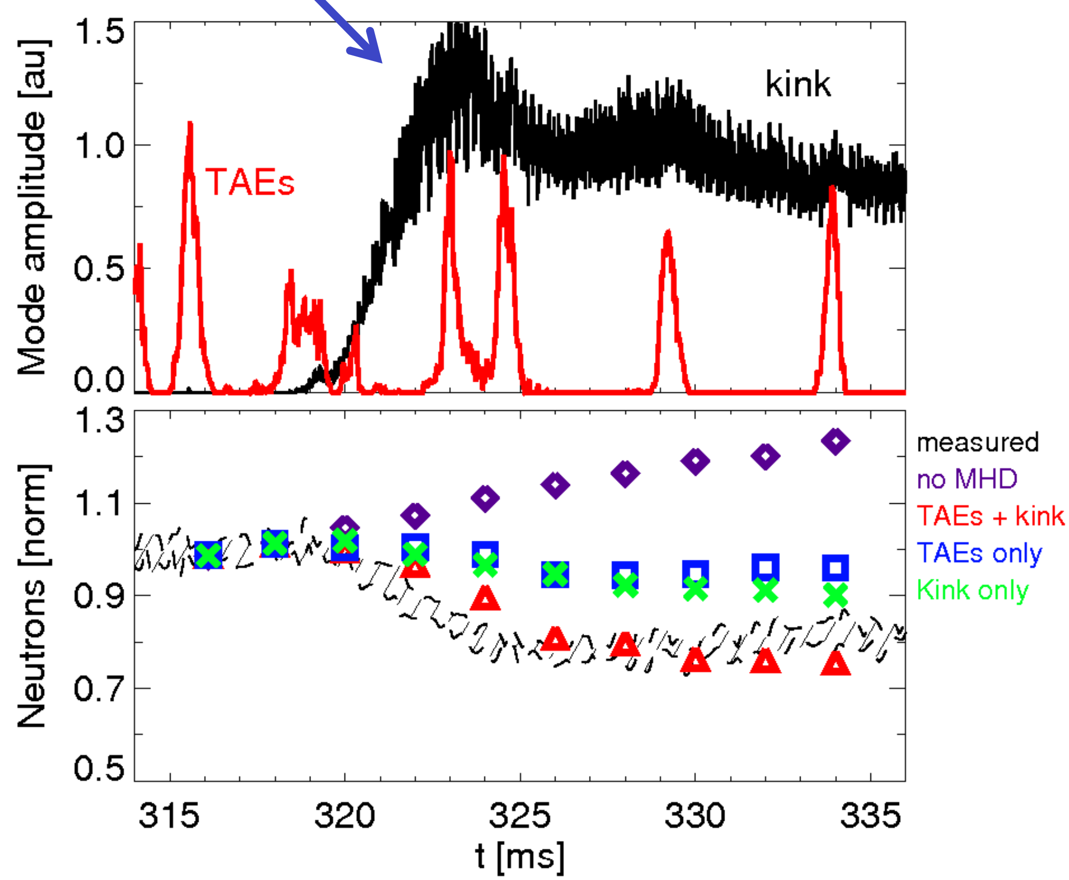


Simulated neutron rate agrees with experiments for both TAE avalanches & multi-mode cases

Use 'kick model' coupled to stand-alone NUBEAM







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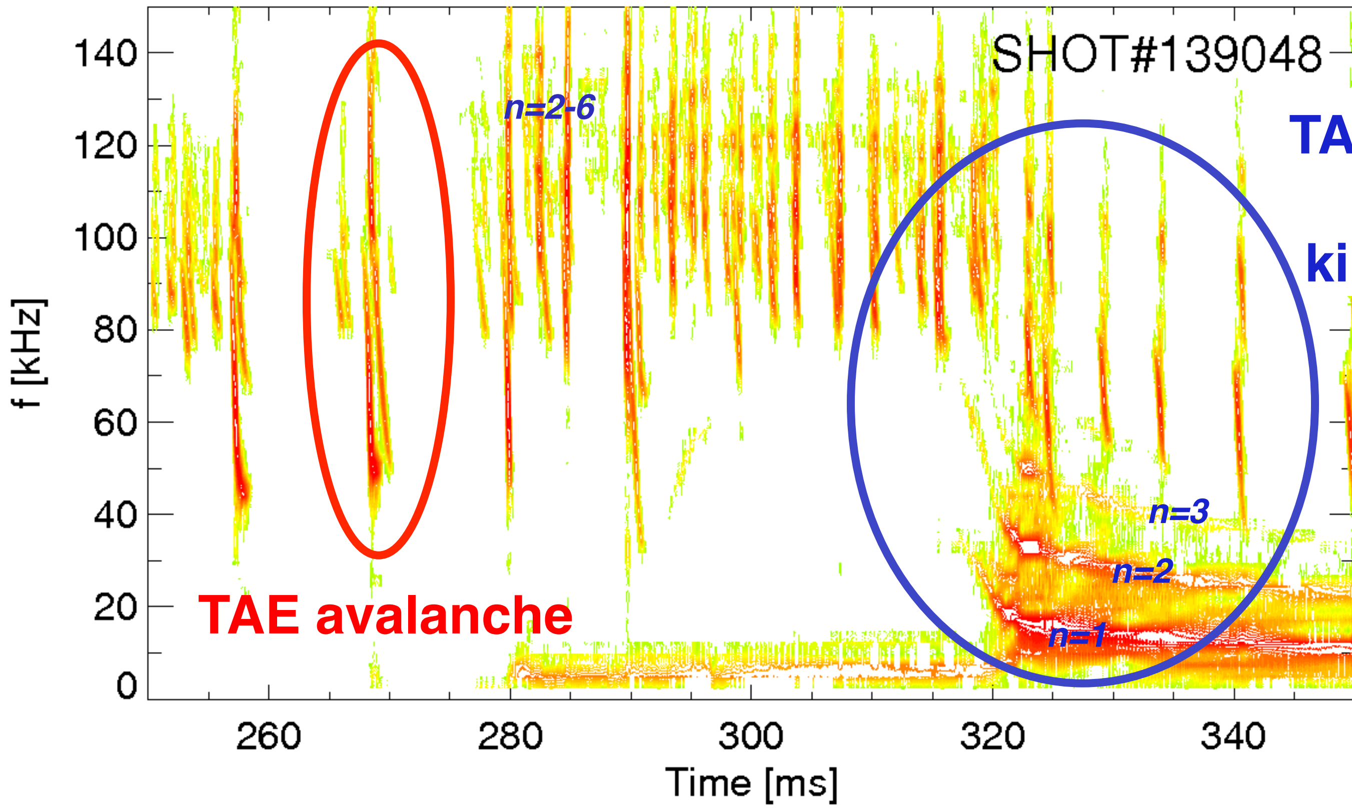
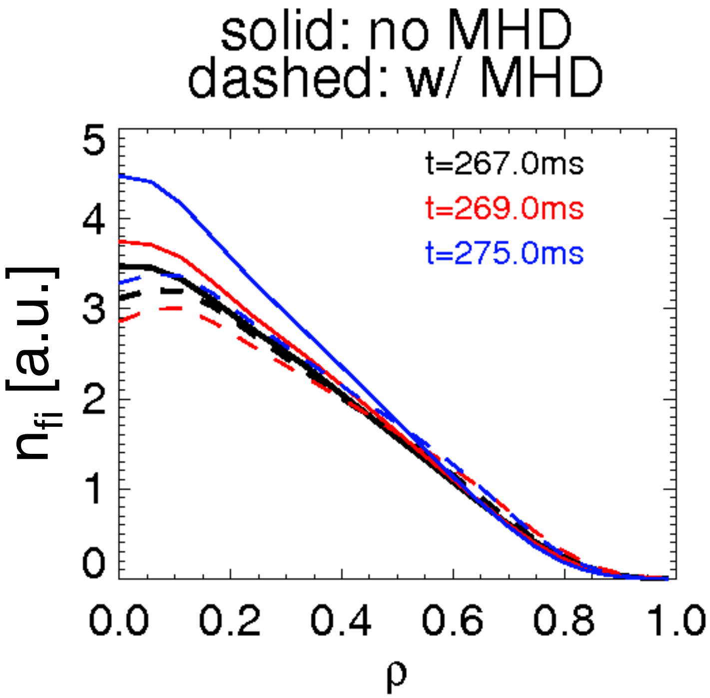


TAE avalanches
+
kink-like mode

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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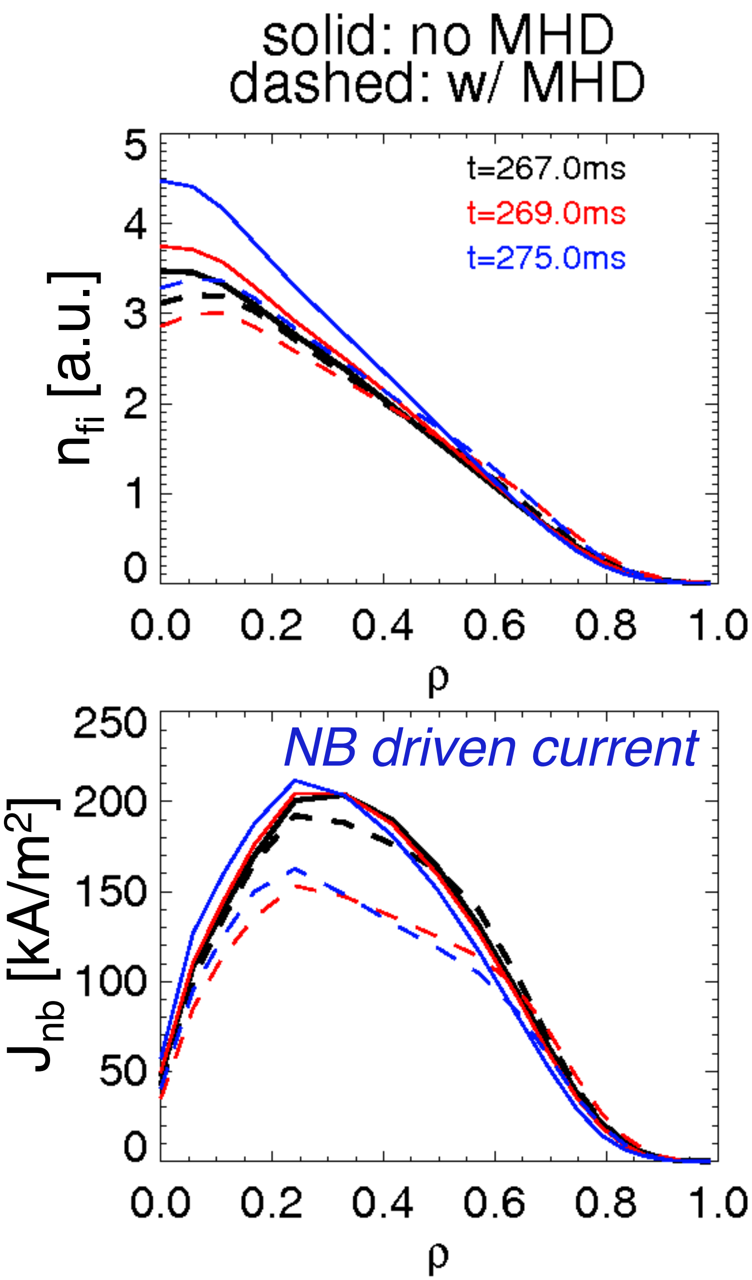

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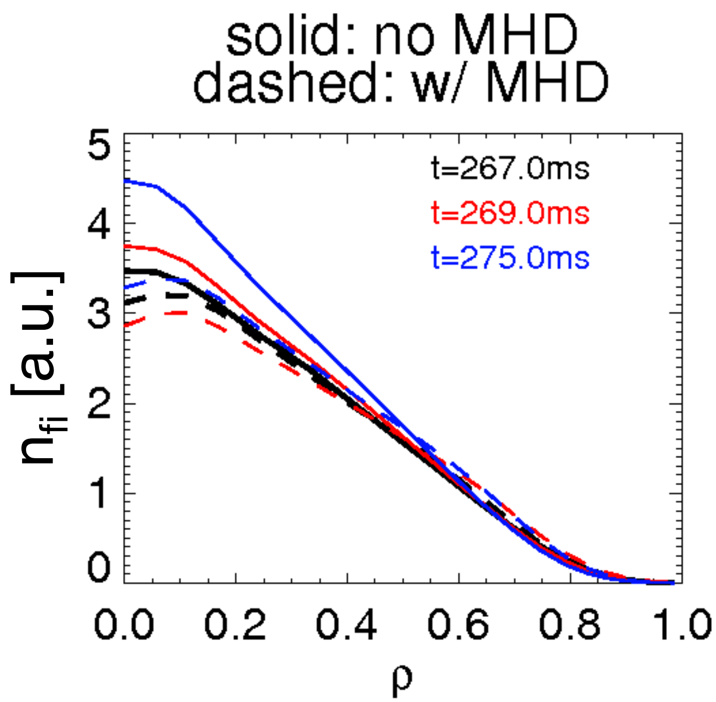

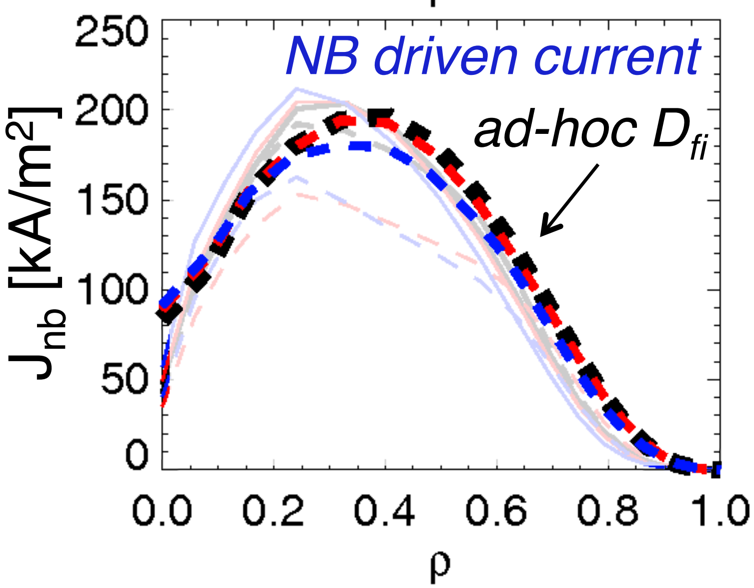

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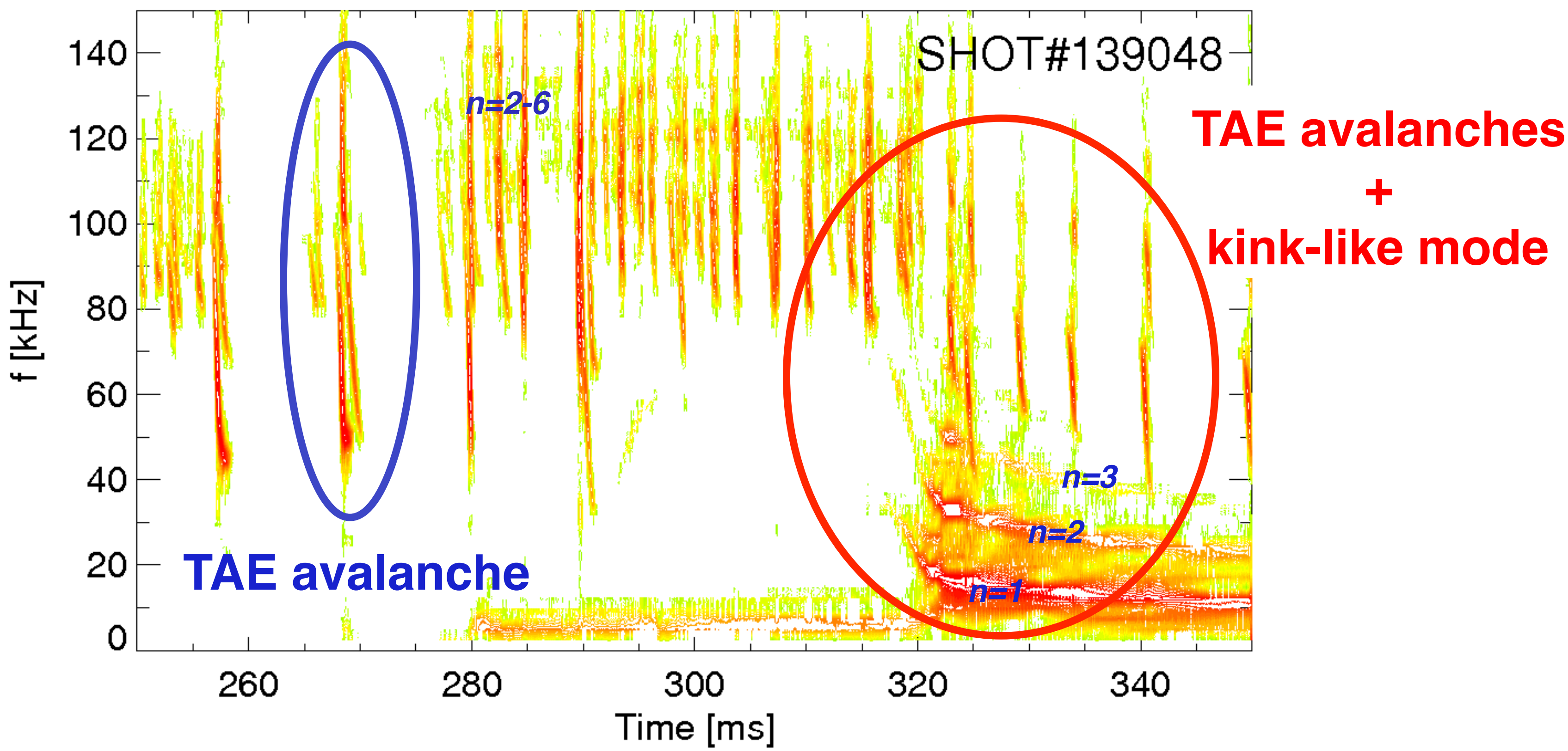
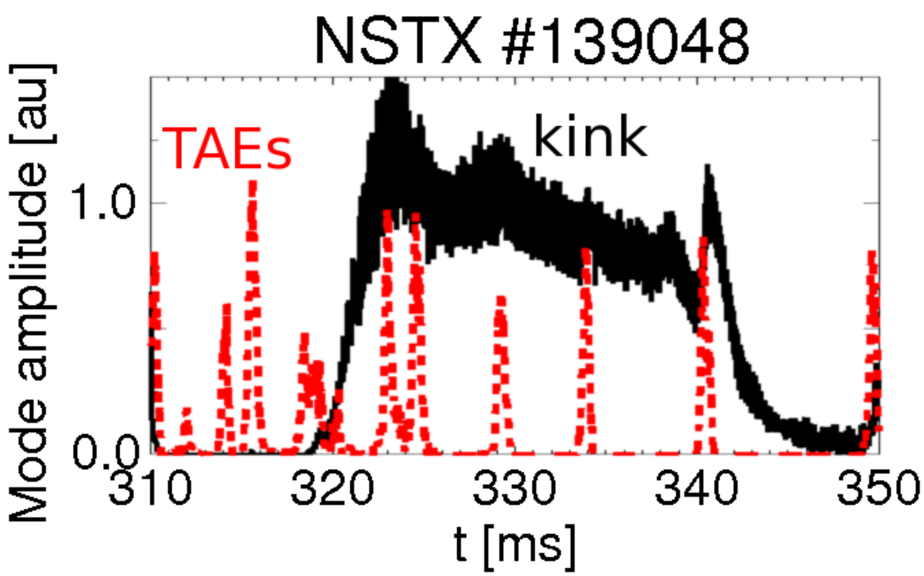


Synergy between different classes of instabilities modifies MHD effects on $J_{nb}(r)$ – not captured by *ad-hoc* D_{fi}



- Kinks have broad radial structure, connect core to boundary

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

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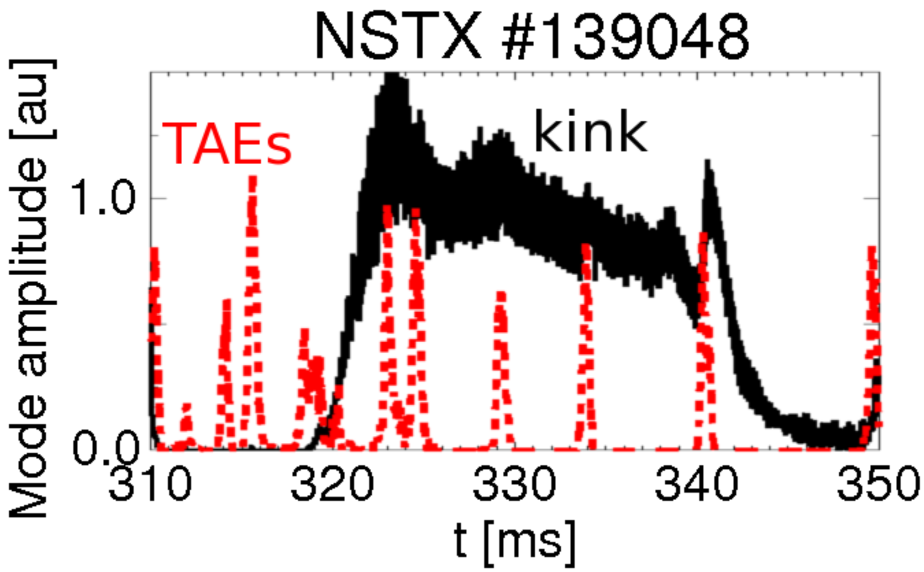

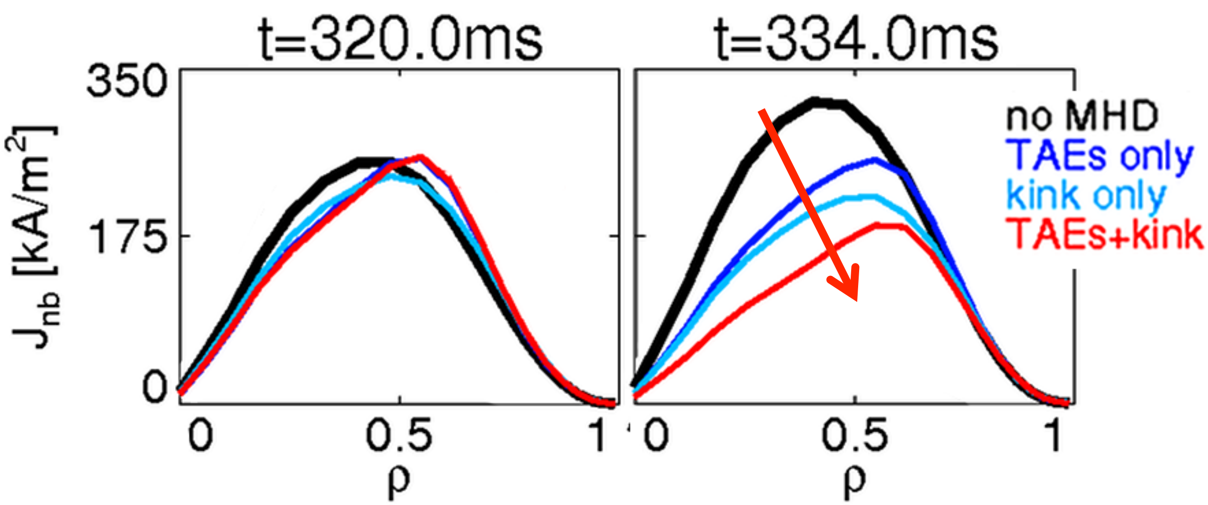

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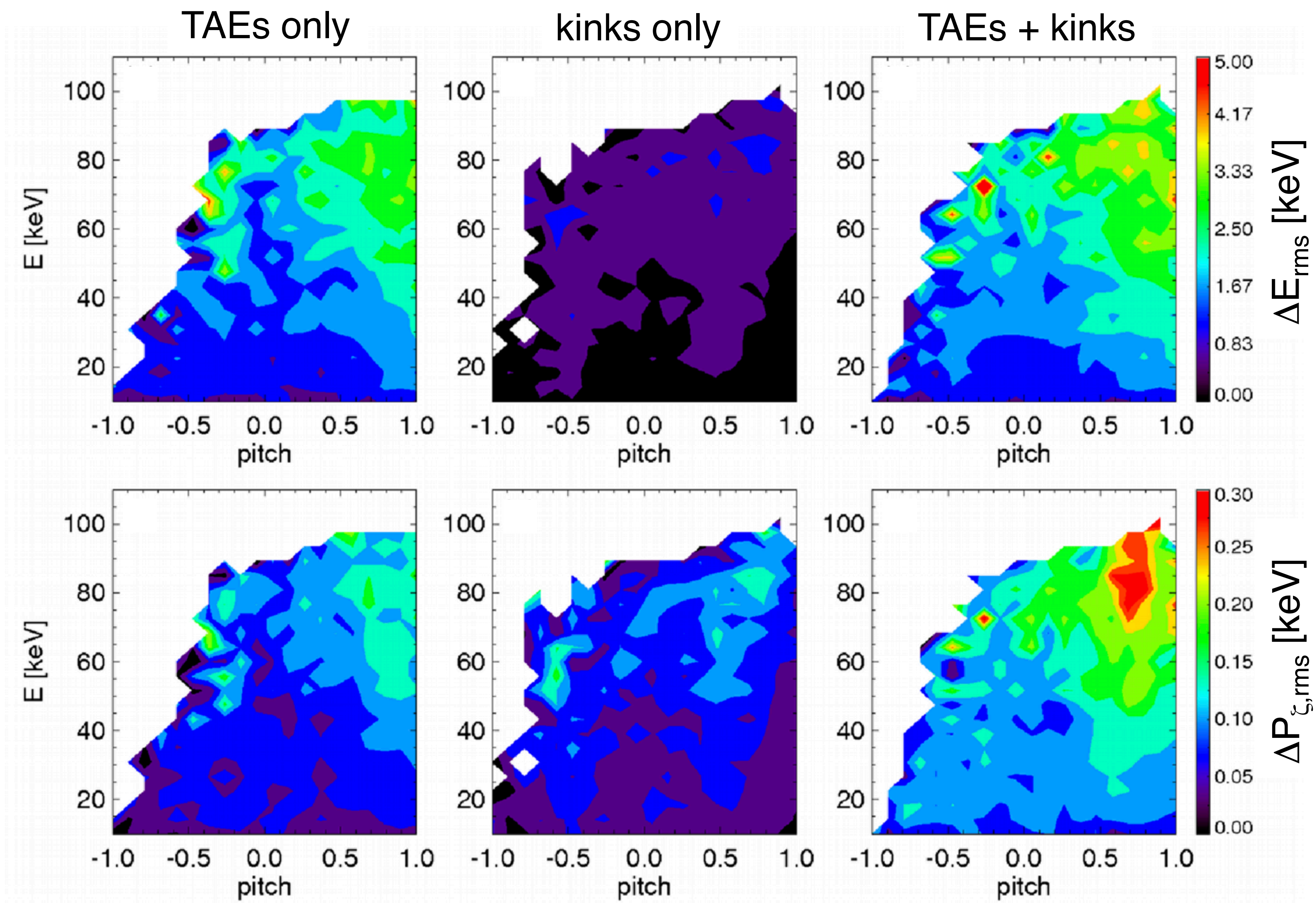
> *Synergy arises from mode overlap <u>in phase space</u>*

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



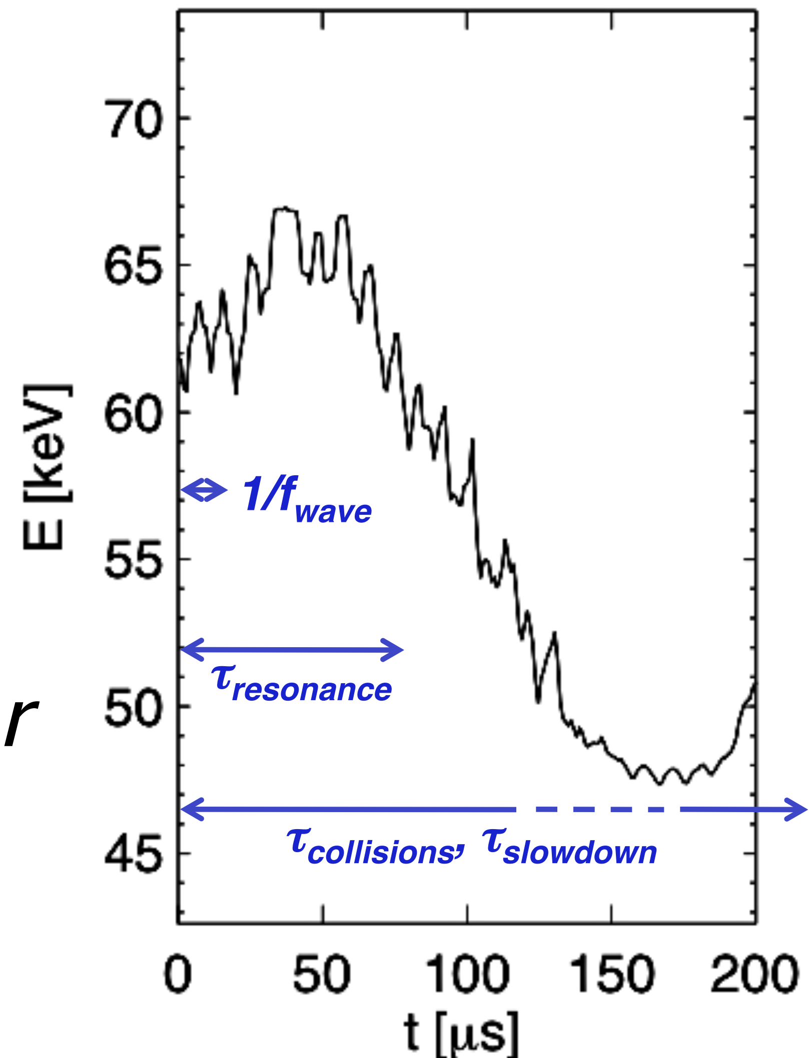
Summary

- 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



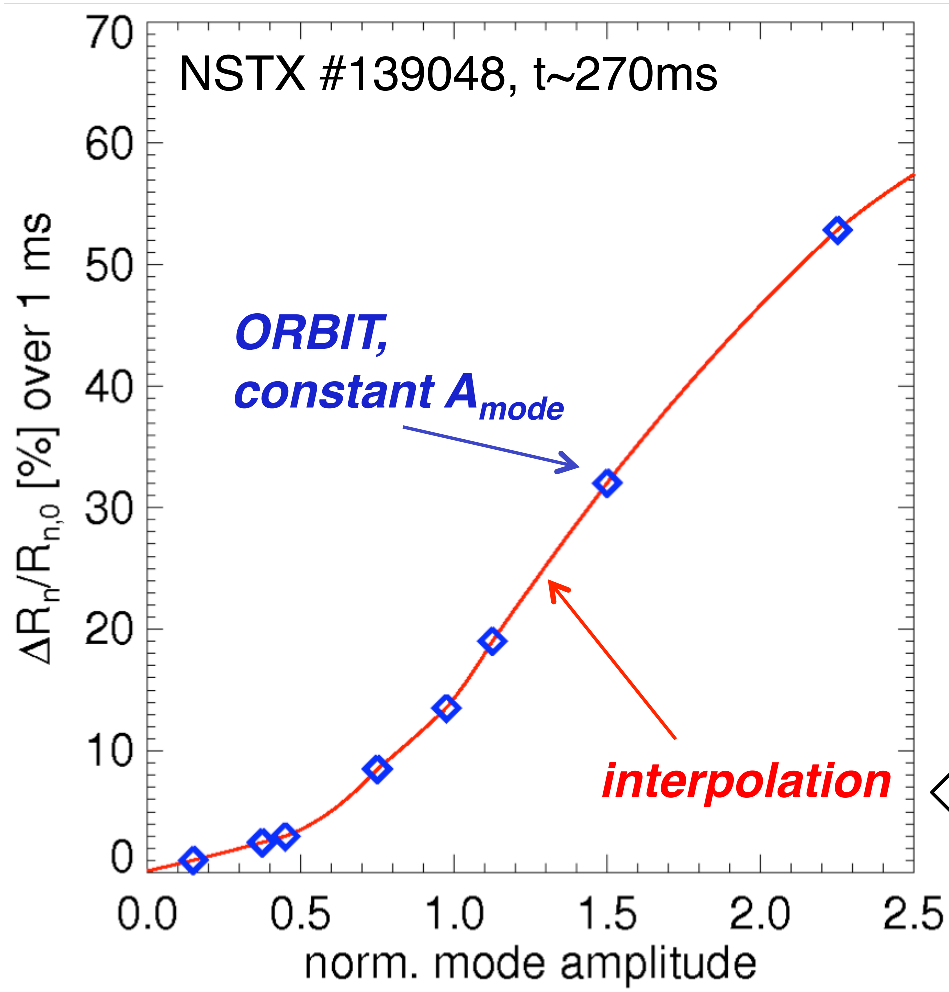
Summary comparison of some reduced models used for EP transport

		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

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

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