NSTX-U

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

Development of a reduced model for resonant fast ion transport in TRANSP

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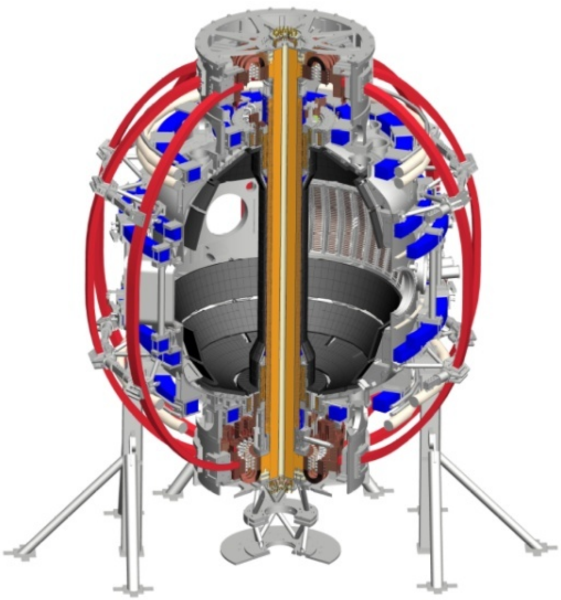

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Abstract

A new reduced fast ion transport model that captures the physics of resonant wave-particle interaction is being developed for the tokamak transport code *TRANSP*. The model is based on a probability distribution function to reproduce changes in phase space coordinates (energy, toroidal canonical momentum and – possibly – magnetic moment) of fast ions interacting with a given set of instabilities. The probability function can be derived from analytical theories as well as from particle-following codes such as ORBIT or SPIRAL. The basic principles of the new model and the progress in its implementation in TRANSP are described. Examples of the initial verification of the model for a specific NSTX scenario with multiple unstable Toroidal Alfvén Eigenmodes, leading to enhanced fast ion transport, are then discussed.

Work supported by DOE contract No. DE-AC02-09CH11466.

Four models are presently implemented in TRANSP for fast ion diffusion/convection coefficients, D_b & v_b

All have *diffusive* nature; little/no phase space selectivity:

[from http://w3.pppl.gov/~pshare/help/transp.htm]

1) $D_b = k_{ADIFB} \times D_e$

k_{ADIFB} : *multiplier*
$D_e(x,t)$: electron particle diffusivity

2) $D_b = k_{ADIFB} \times D_e^{WP}$

$D_e^{WP}(x,t)$: electron particle diffusivity from Ware-pinch corrected flux

3) $\Gamma_{fi} = -D_b \nabla n_b + v_b n_b$

diffusion/convection model

4) $D_b(E,t,x) = \Sigma_k \alpha_k D_k$

$D_k(E,x,t)$: diffusivity for deeply trapped, barely trapped, co-barely passing, ...

New model introduces selectivity in phase space, generalizes "diffusive transport" paradigm

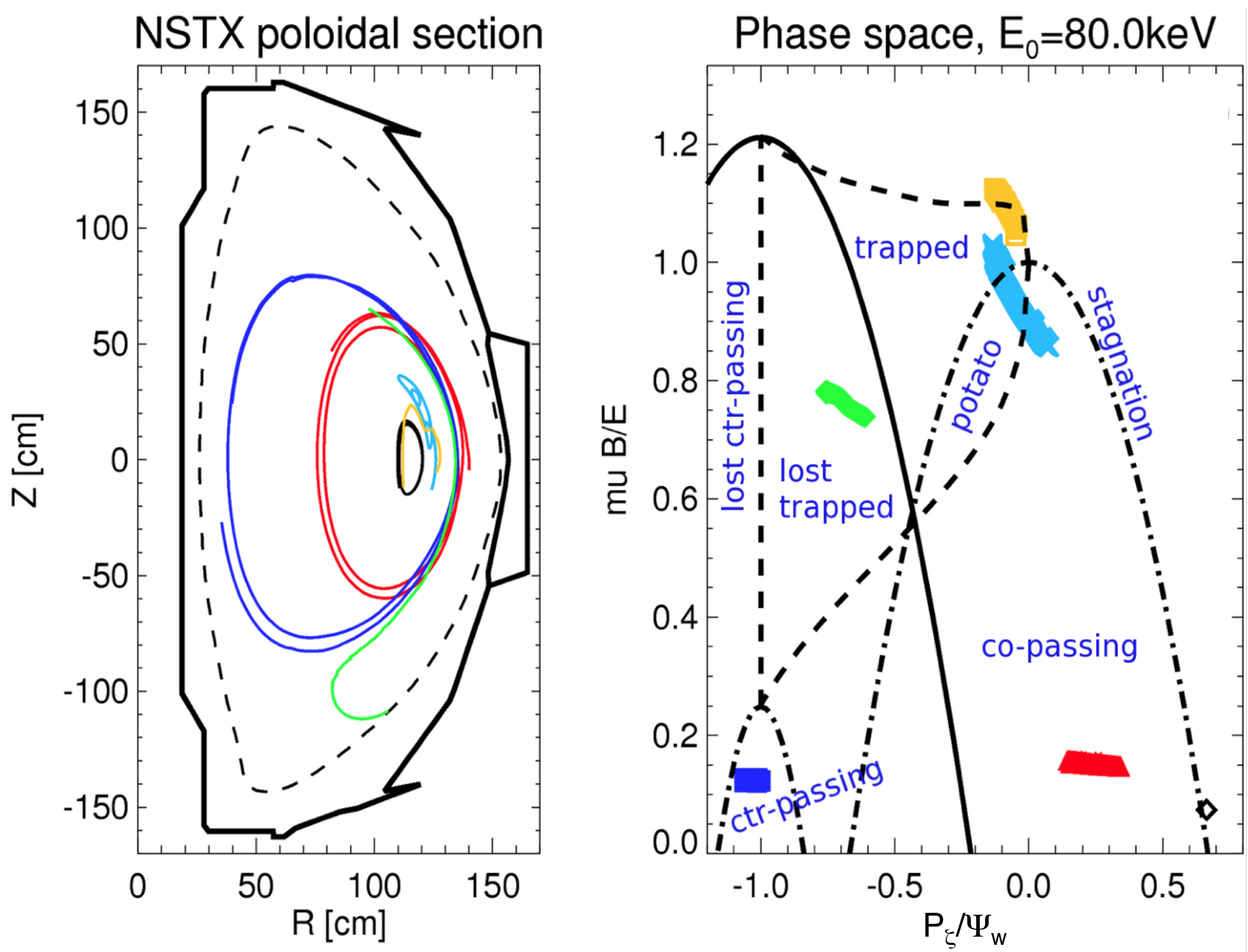
- Info on phase space dynamics is of paramount importance for Verification&Validation of codes, theory-experiment comparison : *need phase-space representation*
- Steady-state ("fluid") equilibrium does not provide all information we need : *need fast ion energy, pitch details and their evolution*
  - E.g. phase space transiently (and selectively) modified by *AE bursts : effects propagate during slowing-down
  - ⇒ *Solutions for F_{nb} based on integral quantities (f.i. density, neutrons, E_r/rotation, NB-driven I_p, ...)* ***not unique***
- Time-scale τ_{res} for resonant/stochastic transport can be faster than diffusion time : *take advantage of time-scale separation*

  $\tau_{transit} \leq \tau_{res} < [d(\log A_{modes})/dt]^{-1} \quad << \quad \tau_{diff}$ (typically)

- *The new model must be "simple enough" to be included in TRANSP/NUBEAM for routine use : "reduced" model*
  - *Retain only minimum required amount of information to improve TRANSP modeling of resonant/stochastic fast ion response to *AEs*
  - *e.g., no attempts to follow or discriminate single-particle orbits*

‘Constants of motion’ are the natural variables to describe resonant wave-particle interaction

- Each orbit fully characterized by:
  - E, energy
  - P_ζ, canonical angular momentum
  - μ, magnetic moment

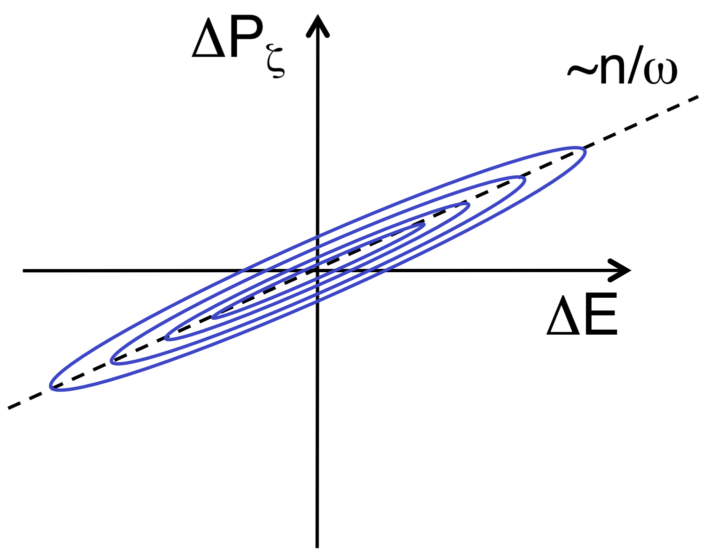


‘Kick Model’ is based on a *probability distribution function* for particle transport

- Single (isolated) resonance introduces simple constraints on particle’s trajectory in (E,P_ζ,μ)
- From Hamiltonian formulation – single mode:

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

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



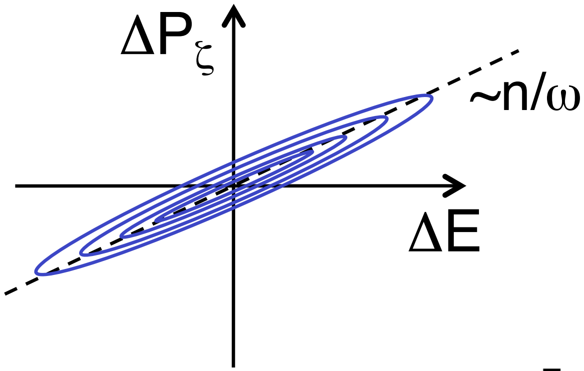
For each bin in (E,P_ζ,μ), steps in $\Delta E,\Delta P_\zeta$ can be described by

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

which incorporates the effects of multiple modes/resonances:

Correlated random walk

Single-resonance case: introducing the *probability distribution function* for particle transport



For each *bin* in (E,P_ζ,μ), steps in ΔE,ΔP_ζ can be described by bivariate $p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu, A)$

$$p = p_0 \, e^{-\frac{1}{2(1-\rho)}\left[\frac{(\Delta E-\Delta E_0)^2}{\sigma_E^2}+\frac{(\Delta P_\zeta-\Delta P_{\zeta 0})^2}{\sigma_{P_\zeta}^2}-2\rho\frac{(\Delta E-\Delta E_0)(\Delta P_\zeta-\Delta P_{\zeta 0})}{\sigma_E\,\sigma_{P_\zeta}}\right]}$$

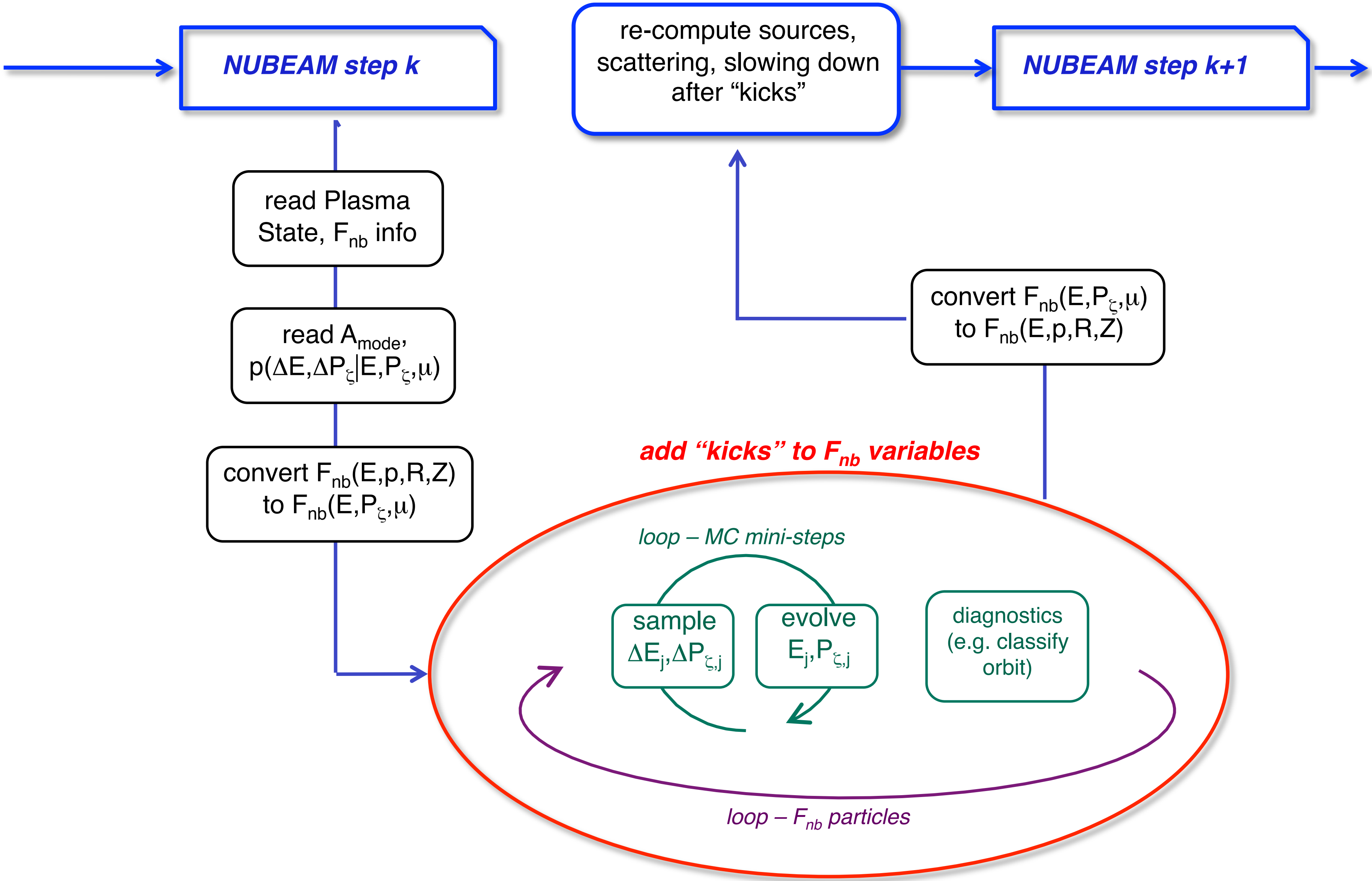
$$p_0 = \frac{1}{2\pi\,\sigma_E\,\sigma_{P_\zeta}\sqrt{1-\rho^2}}$$ *normalization*

$$\rho = \frac{< (\Delta E - \Delta E_0)(\Delta P_\zeta - \Delta P_\zeta 0) >}{\sigma_E\,\sigma_{P_\zeta}}$$ *correlation parameter,*

such that $\Delta P_\zeta(\Delta E) = \Delta P_{\zeta 0} + sign(\rho) \times \frac{\sigma_{P_\zeta}}{\sigma_E}(\Delta E - \Delta E_0)$

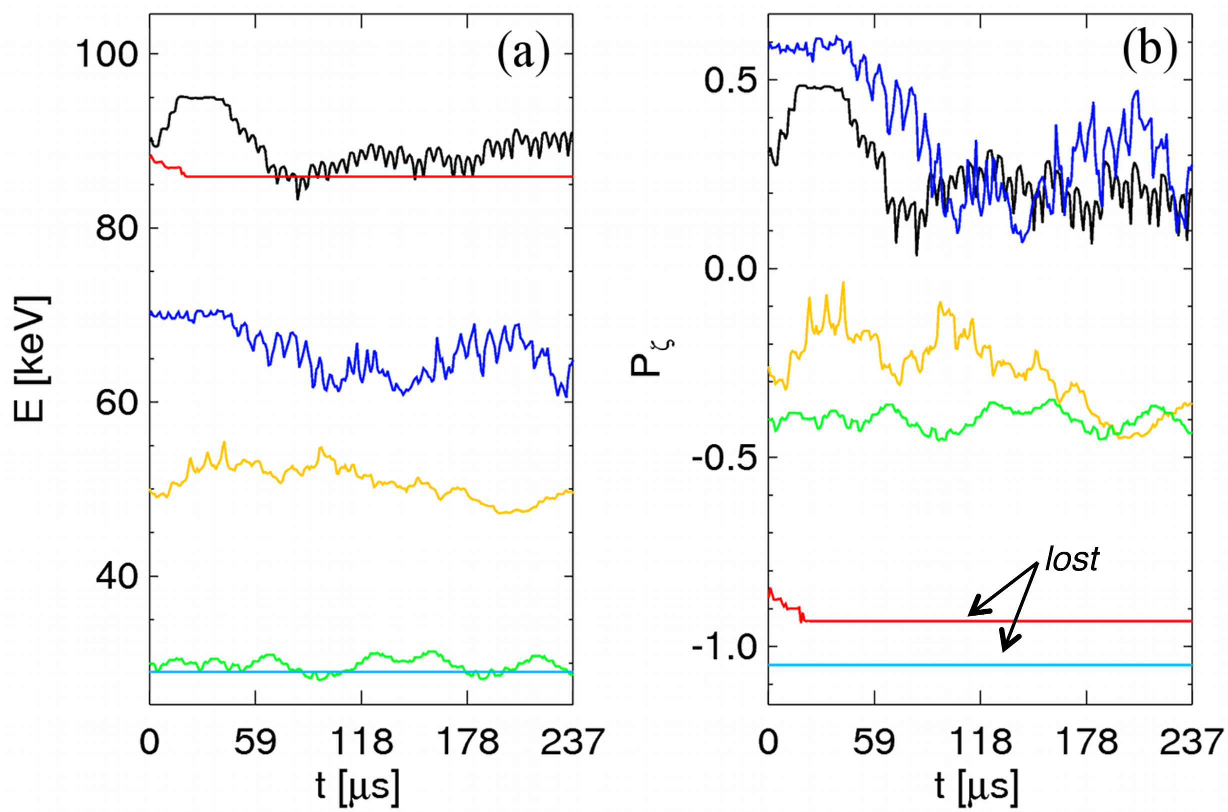
…and all parameters depend, in principle, on the mode amplitude A=A(t)

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

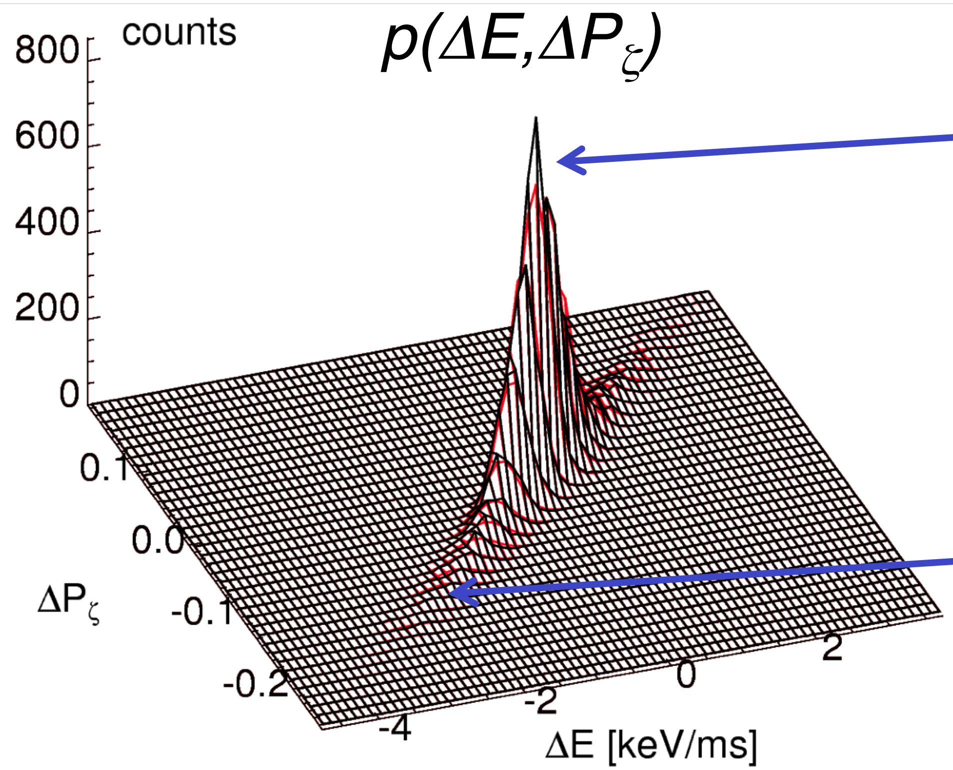


Scheme to evolve F_{nb} takes into account (in a semi-empirical way) constraints of resonant interaction

- Particle's motion is characterized by different time-scales:
  - Fast oscillation in wave field – *neglected*
  - 'Jumps' $\Delta E, \Delta P_\zeta$ around instantaneous energy, P_ζ
  - Slow (secular) drift from initial energy, P_ζ



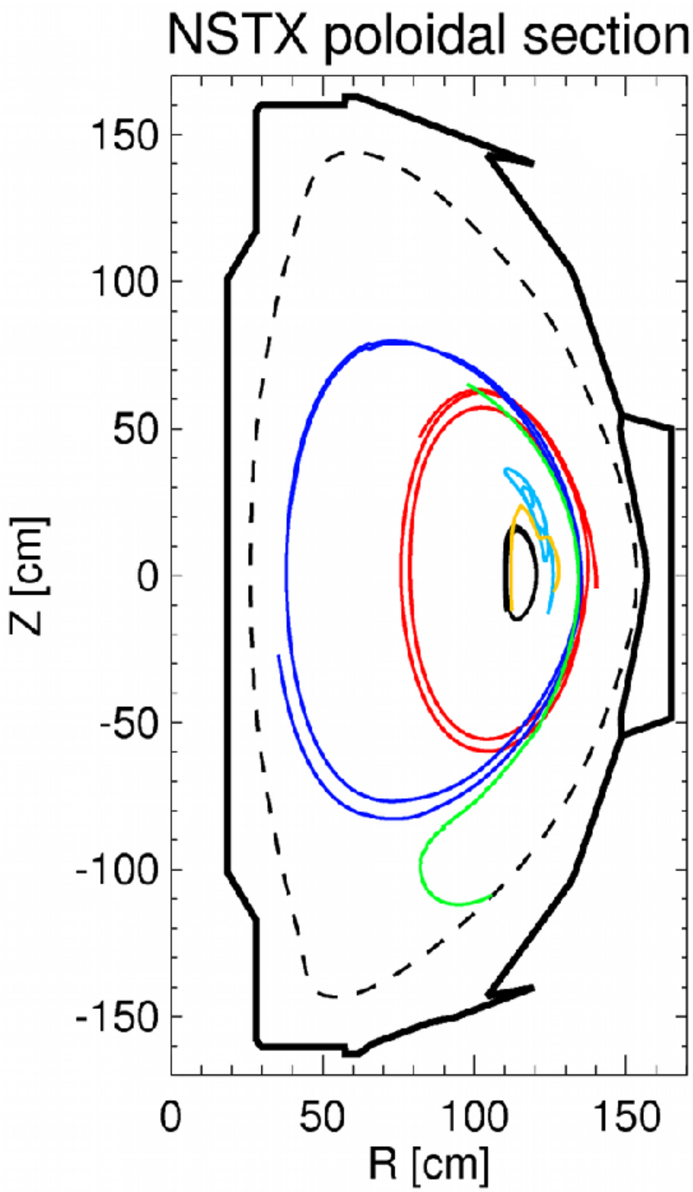
Discrete bins in (P_ζ,E,μ) can contain both *resonant* and *non-resonant* particles



- ‘Non-resonant’ particles have small fluctuations around initial (E, P_ζ)
- ‘Resonant’ particles can experience large ΔE, ΔP_ζ variations

- To keep track of particle’s class:
  - Sample steps σ_E, $\sigma_{P\zeta}$ at first step only
  - This mimic the “correlated random walk” experienced by the particles
  - Exception: particle move to a different bin -> re-sample

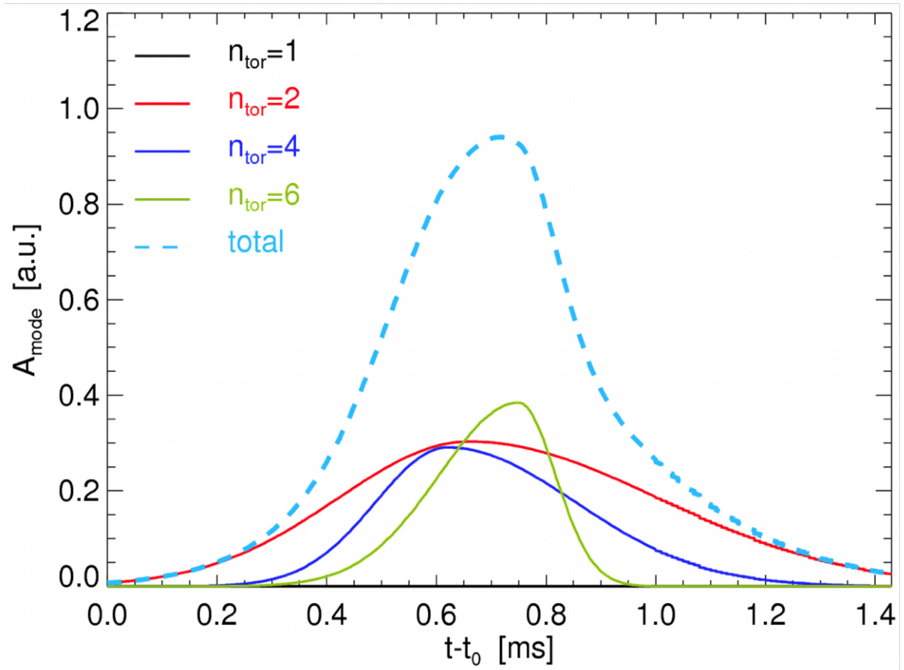
‘Transport probability’ $p(\Delta E,\Delta P_\zeta|P_\zeta,E,\mu)$ can be computed through numerical codes (e.g. ORBIT) or theory



- Run ORBIT with A_{mode}=1, constant
- Simulation time long enough (~1ms) to capture *AE effects
- Track (P_ζ,E,μ) in time for each particle, steps δt_{sim}~25-50μs
- Compute $\Delta E,\Delta P_\zeta,\Delta\mu$
- Re-bin over (P_ζ,E,μ) space

> *Get $p(\Delta E,\Delta P_\zeta|P_\zeta,E,\mu)$ for each bin*

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

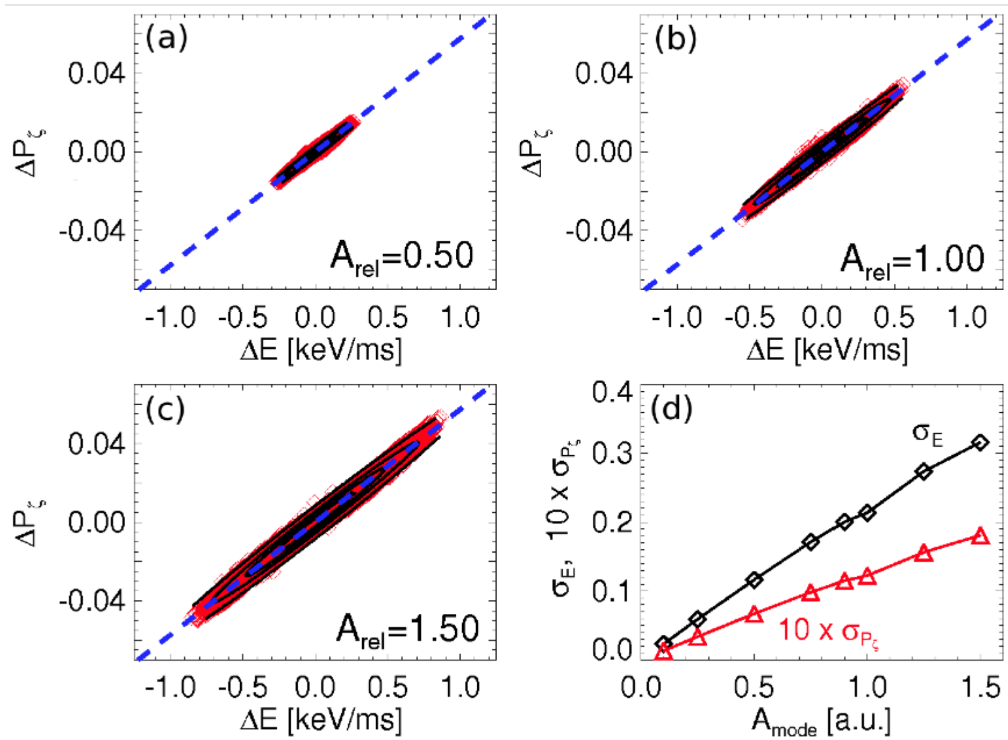


F_{nb} evolution must be computed as a sequence of sub-steps

- 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



$p(\Delta E,\Delta P_\zeta|P_\zeta,E,\mu)$ can be skewed to positive/negative $\Delta E,\Delta P_\zeta$, causing overall "drift" of $F_{nb}(P_\zeta,E,\mu)$

- Introduce 'random sign' for *i*–th step in MC procedure, $S_{r,i}$
- For each particle (e.g. pair of correlated steps σ_E, $\sigma_{P\zeta}$), calculate $S_{r,i}$ from probability of positive vs. negative steps
  - From $p(\Delta E,\Delta P_\zeta)$ compute

$$p_+ \doteq p(\sigma_{E,i},\sigma_{P_\zeta,i}) \quad ; \quad p_- \doteq p(-\sigma_{E,i},-\sigma_{P_\zeta,i})$$

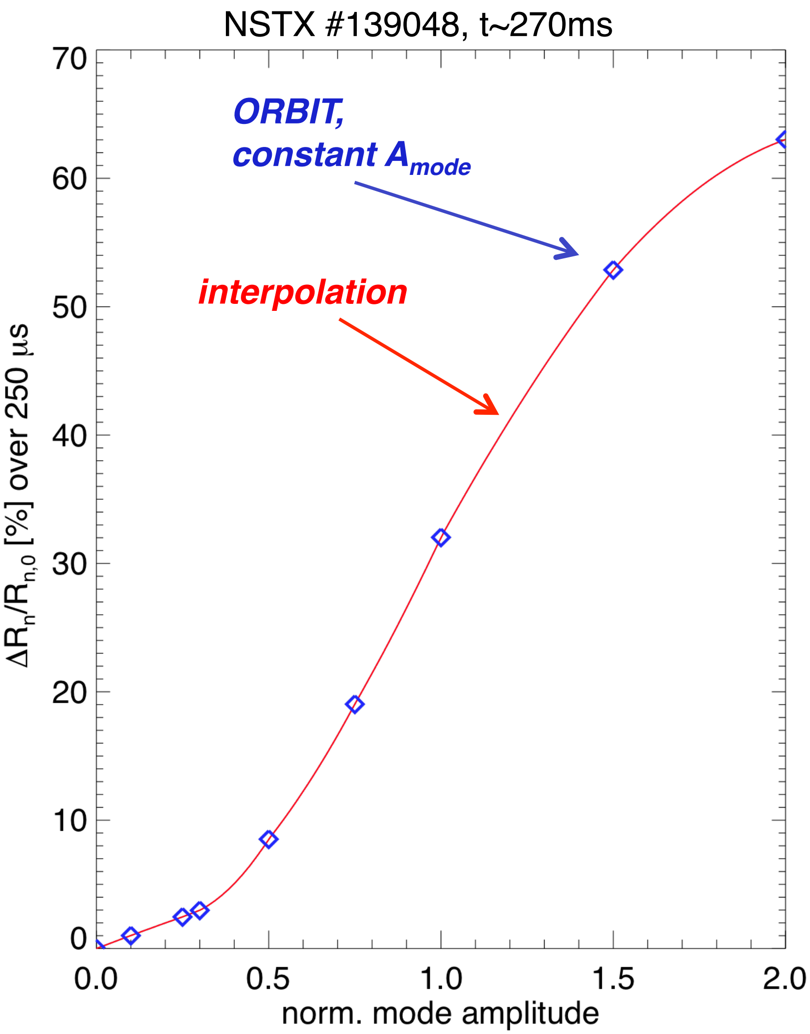
  - Then define f_{sign}:

$$f_{sign} = \frac{p_+}{p_+ + p_-}$$

  - Finally, use $0<f_{sign}<1$ to bias random extraction of $S_{r,i}=+1,-1$

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

– Best option: use experimental data (e.g. reflectometers, ECE)



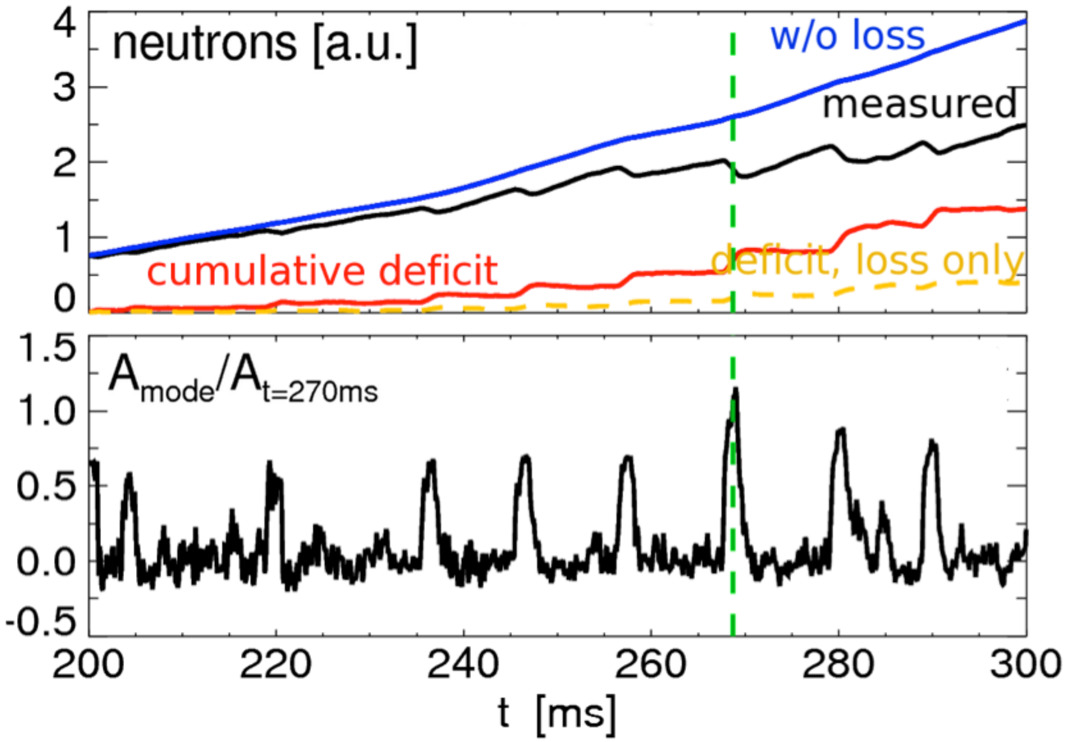
– If no exp. data available, A_{mode} can be estimated based on other measured quantities

– Example: use measured neutron rate

- Compute ideal modes through NOVA
- Rescale relative amplitudes from NOVA according to magnetics
- 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

Example: ‘mode amplitude’ $A_{mode}(t)$ computed from *observable* quantity, e.g. neutron rate

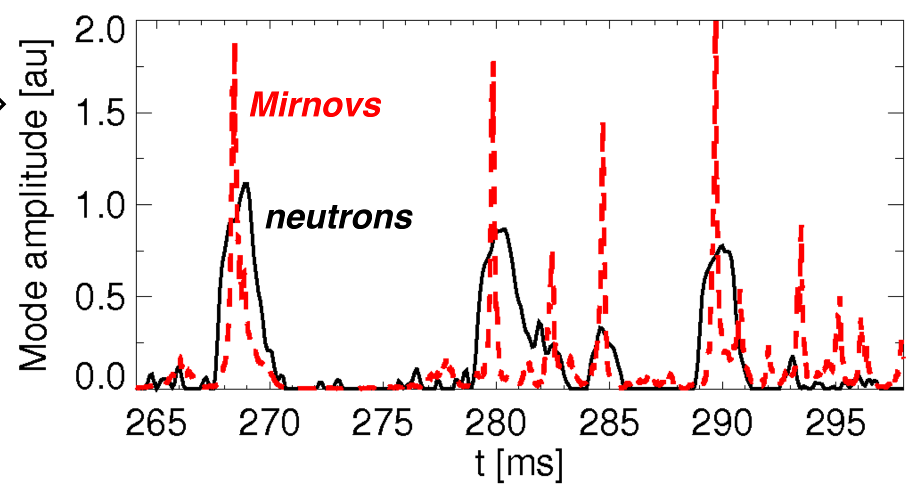
Get *A(t)* from measured neutrons+table look-up:



– Compute fractional R_n drops vs. time

– Use table from previous slide to find corresponding (normalized) mode amplitude

–Comparison w/ $A_{mode}(t)$ from Mirnov coils



–Do different waveforms lead to differences in fast ion evolution? *Under investigation...*

Putting all together

- At each 'macroscopic' NUBEAM step:
  I. Re-normalize bins (P_ζ,E,μ) based on q-profile, fields, ...
  II. Identify 'bin' in (P_ζ,E,μ) for current 'particle' (i.e. orbit)
  III. Extract steps σ_E,$\sigma_{P\zeta}$ (σ_μ) from multivariate p(ΔE,ΔP_ζ,$\Delta\mu$)
  IV. Compute sign $S_{r,i}$ from p(ΔE,ΔP_ζ)
  V. Rescale steps based on A_{modes}(t):
  VI. Advance E, P_ζ (μ): $\begin{cases} \overline{\Delta E}_i = S_{r,i} \times A_{mode}(t = \bar{t}) \times \sigma_{E,i} \\ \Longrightarrow E_i = E_i + \overline{\Delta E}_i \end{cases}$
  VII. Compute slowing down, scattering
  VIII. Advance particle's trajectory in phase space

Loop over particles

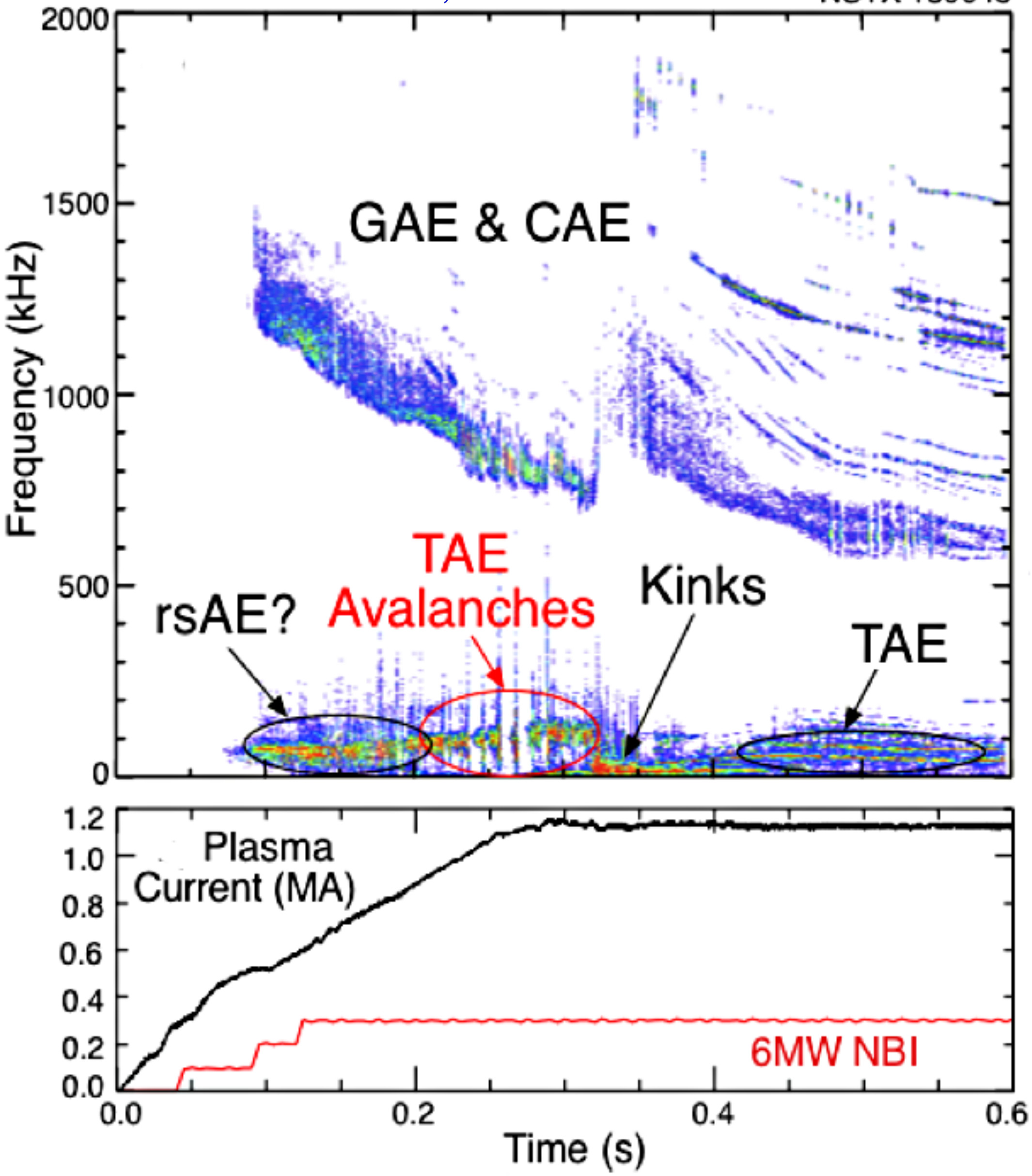
where steps III–VII are divided in sub-steps for each particle

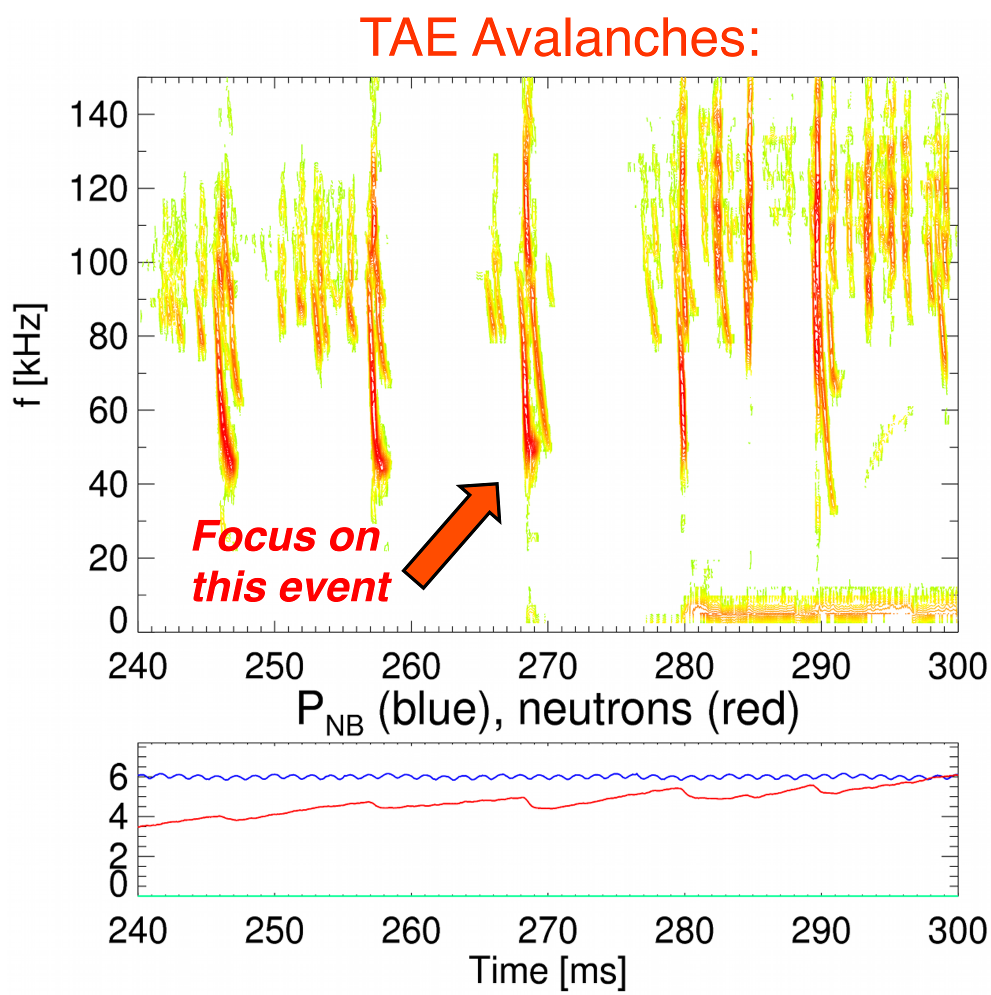
Required input:

scaling factor ("mode amplitude") A_{mode}, probability p(ΔE,ΔP_ζ)

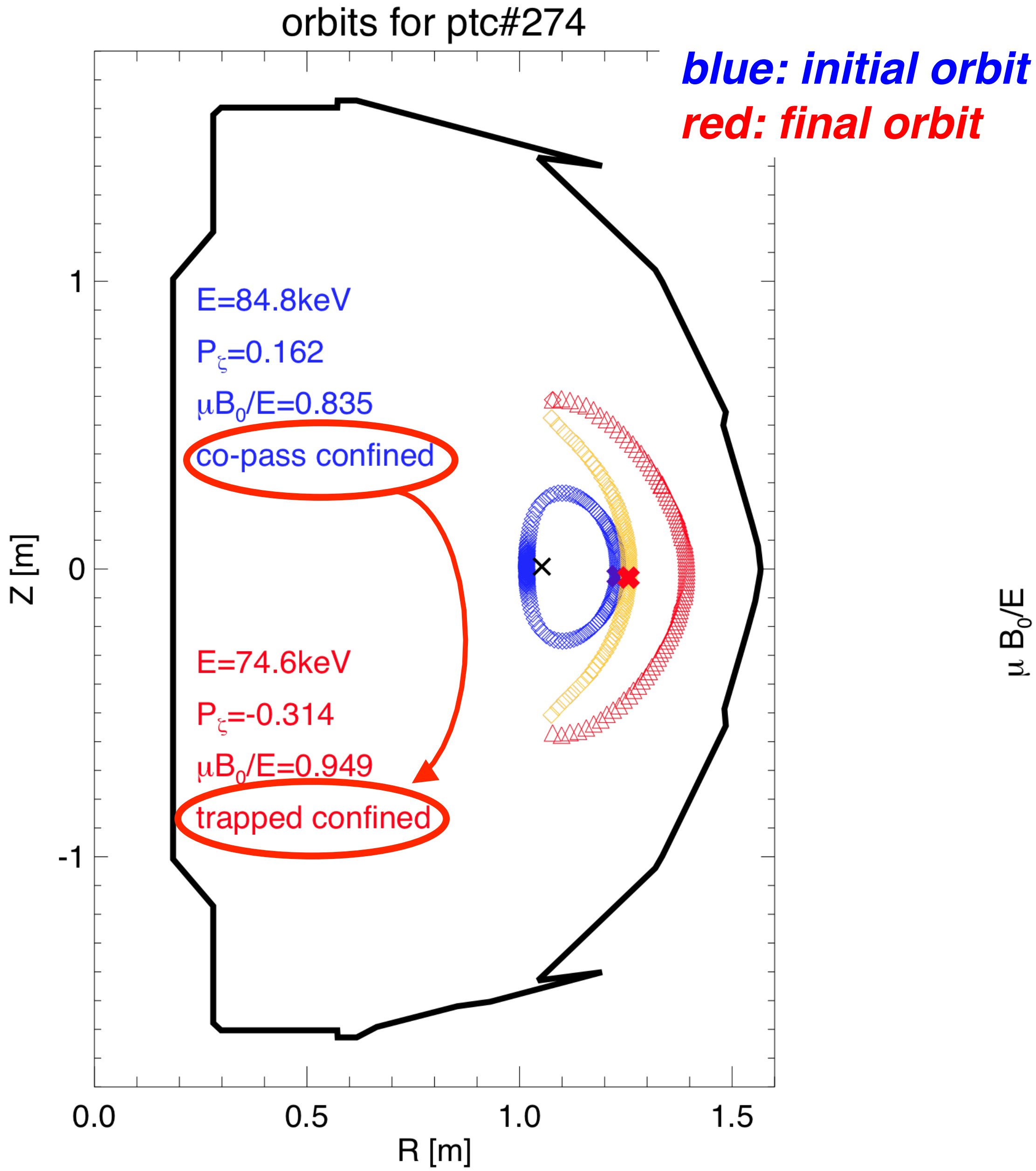
Experimental scenario for tests presented in this work: NSTX H-mode plasma with bursts of TAE activity

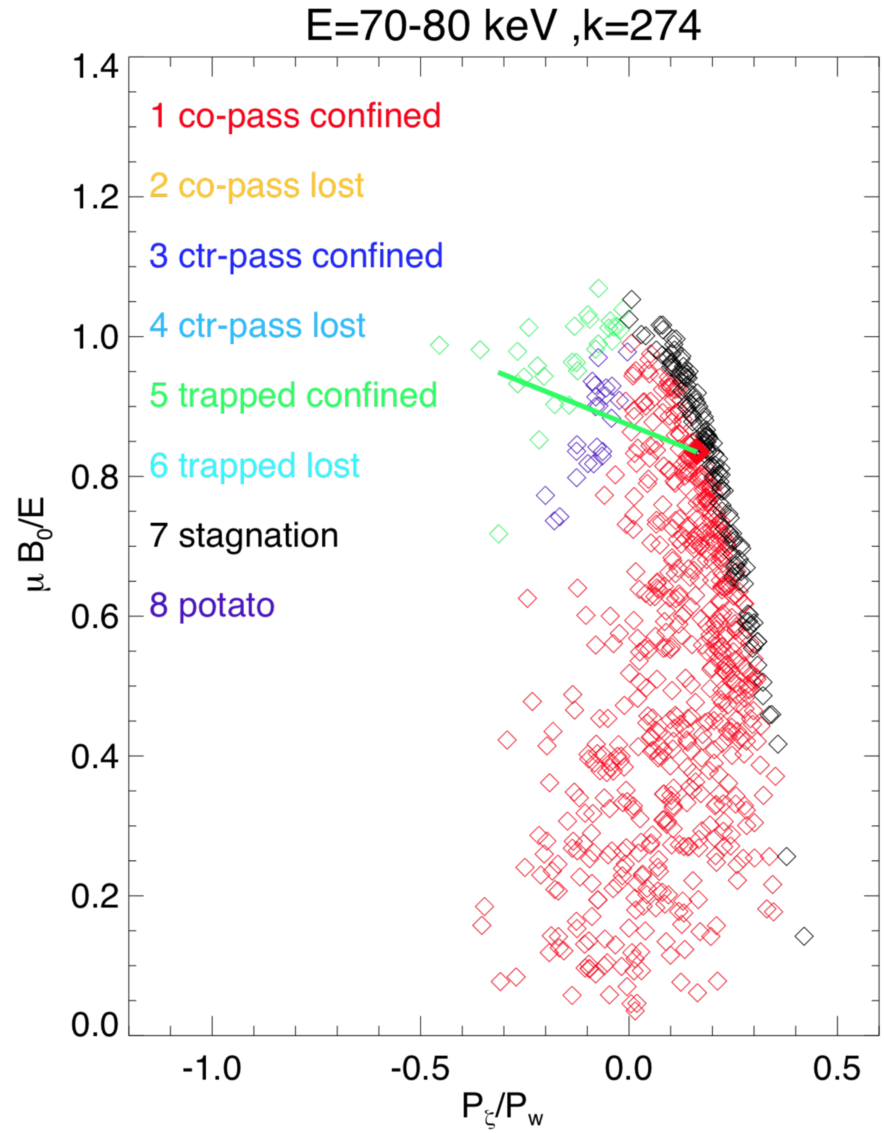
E. Fredrickson et al., Nucl. Fusion 2013





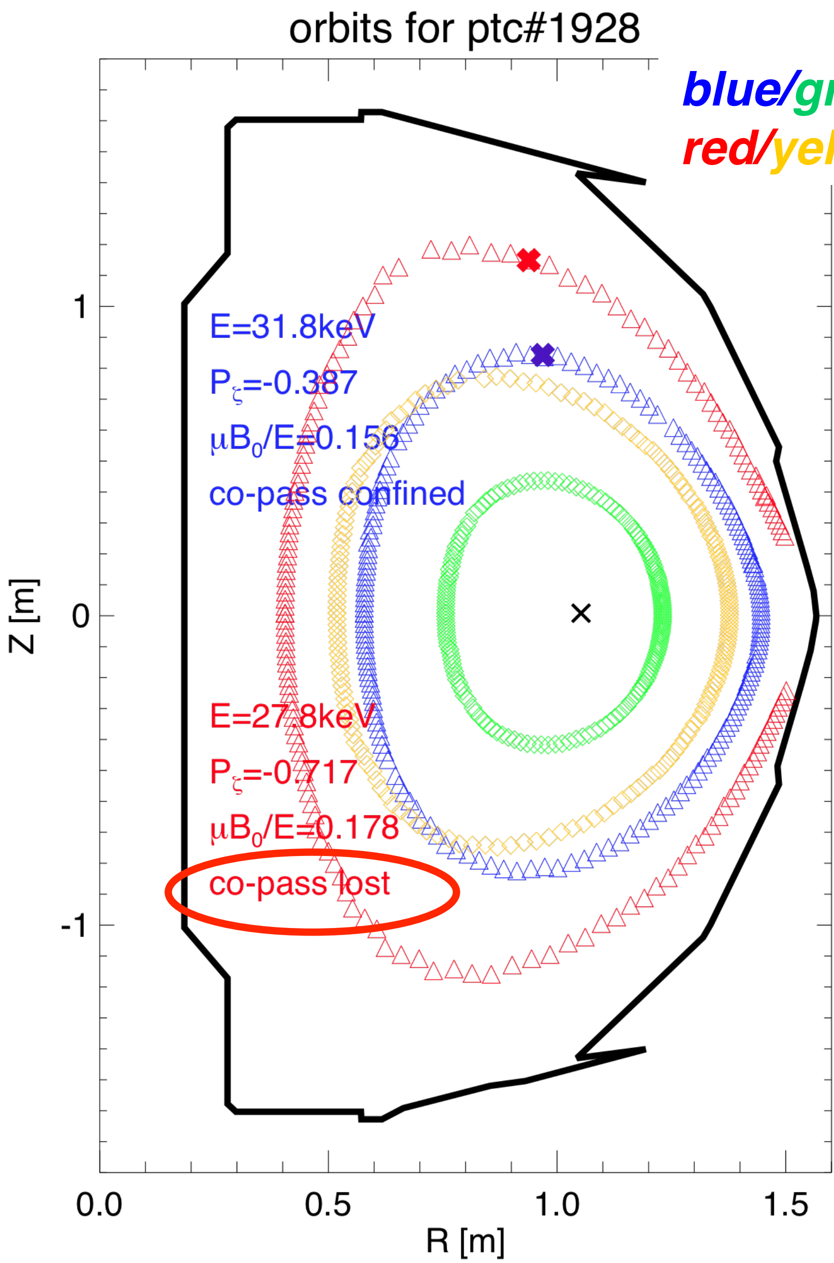
Change in orbit type observed for some particles: fast ions *are* kicked around in phase space by TAEs

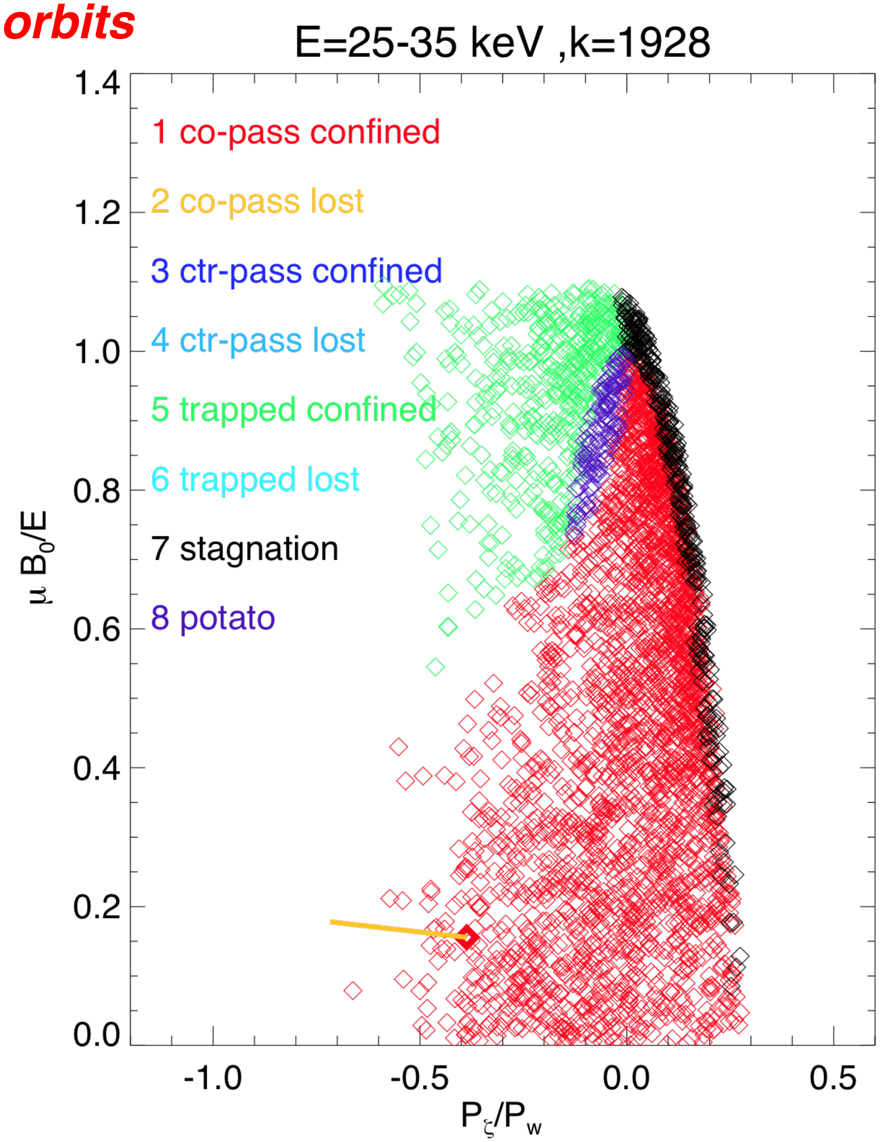




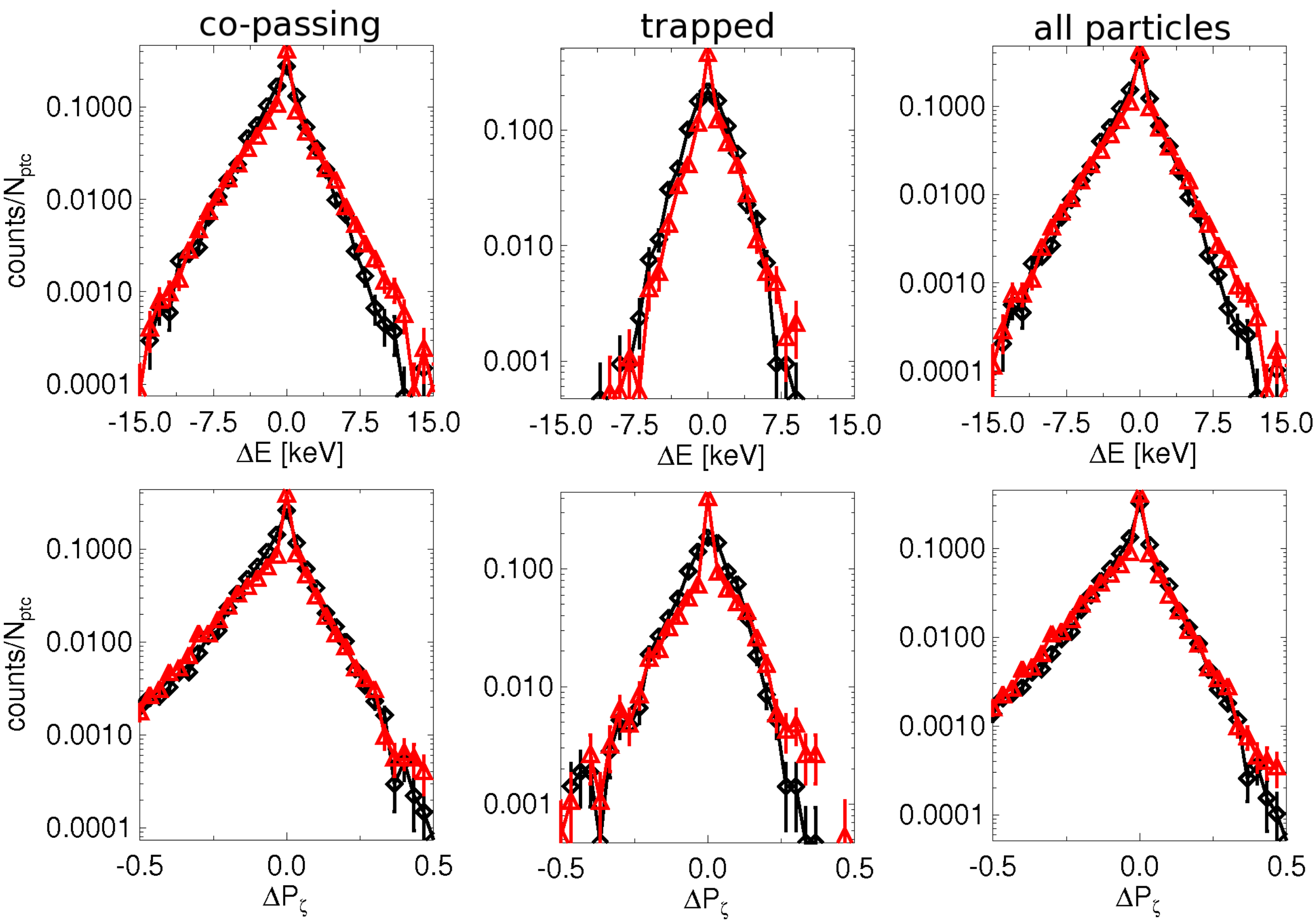
Only a few particles (~0.1%) are actually *lost* for the cases examined here; redistribution dominates

blue/green: initial orbits
red/yellow: final orbits





Good agreement with ORBIT is preserved when evolving F_{nb} over 5 ms, typical macro-step of NUBEAM



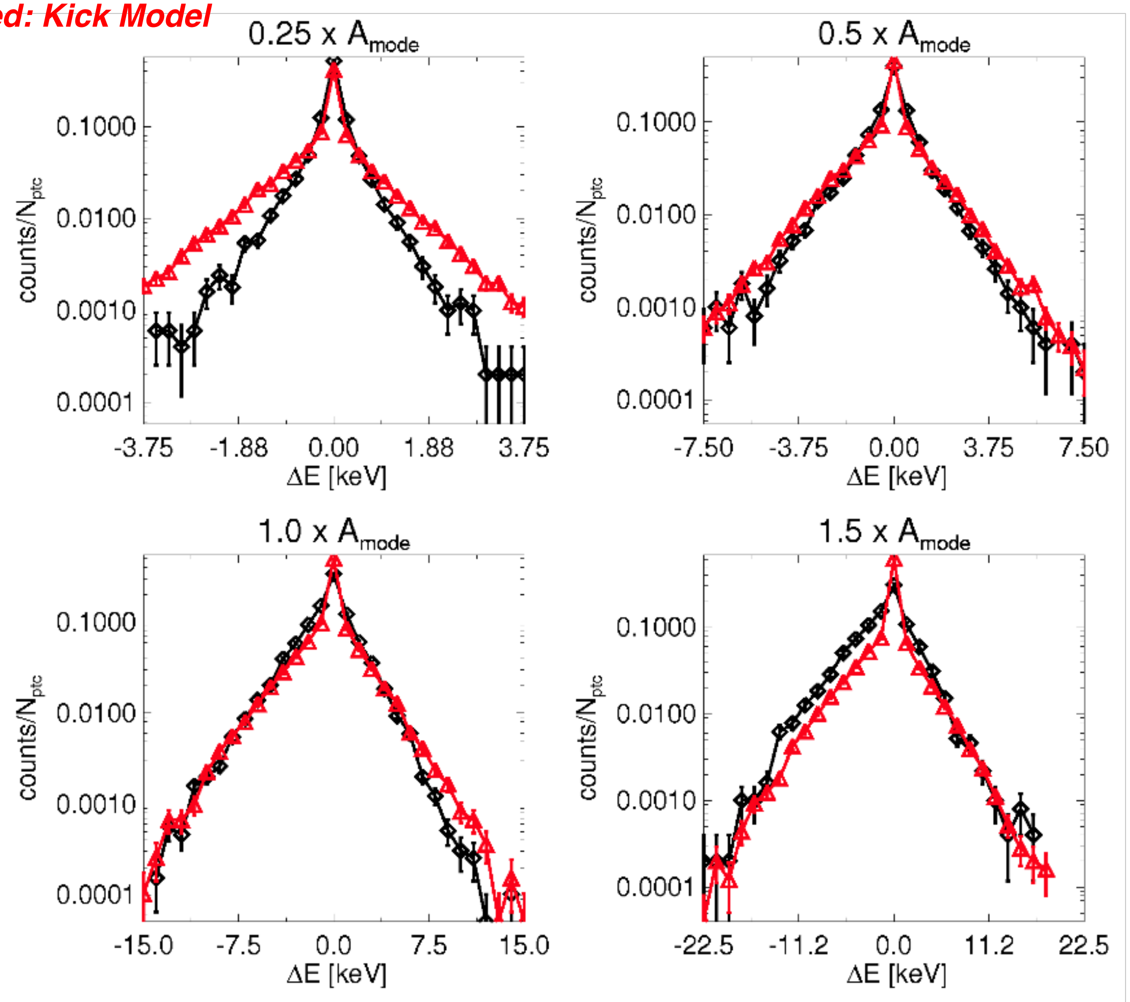
black: ORBIT

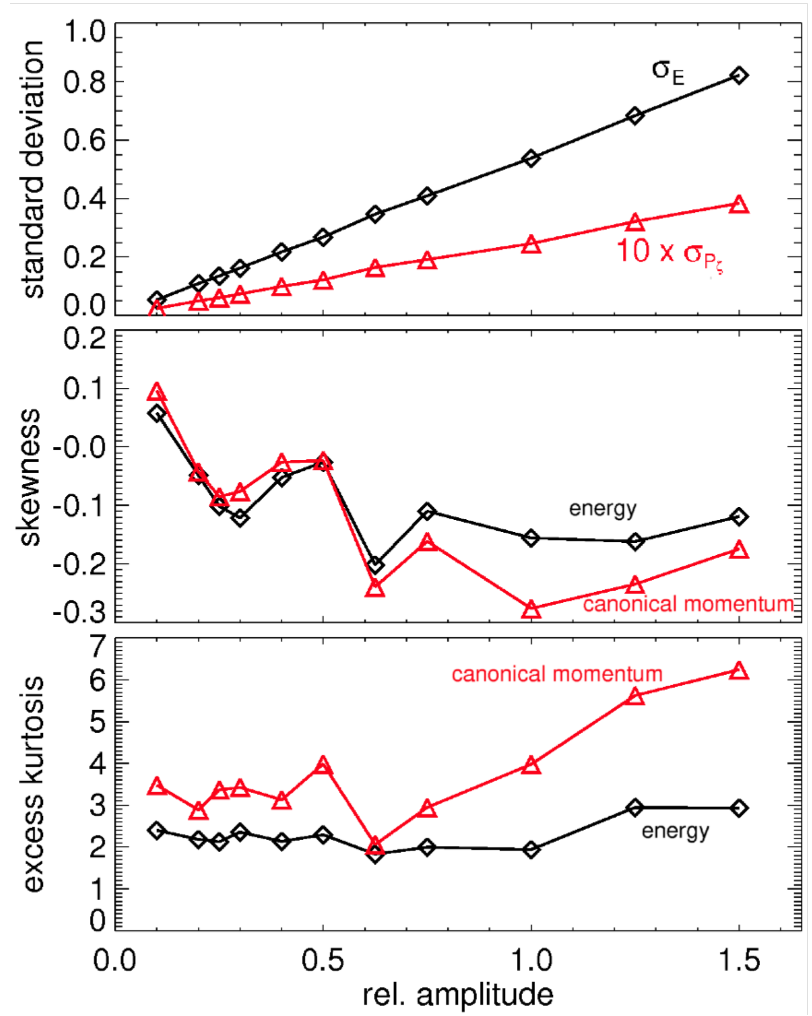
red: Kick Model

Reconstruction is satisfactory for different classes:
co-, trapped (, counter- not present in *this* input F_{nb})

Tests assuming different mode amplitudes are satisfactory, though not perfect…

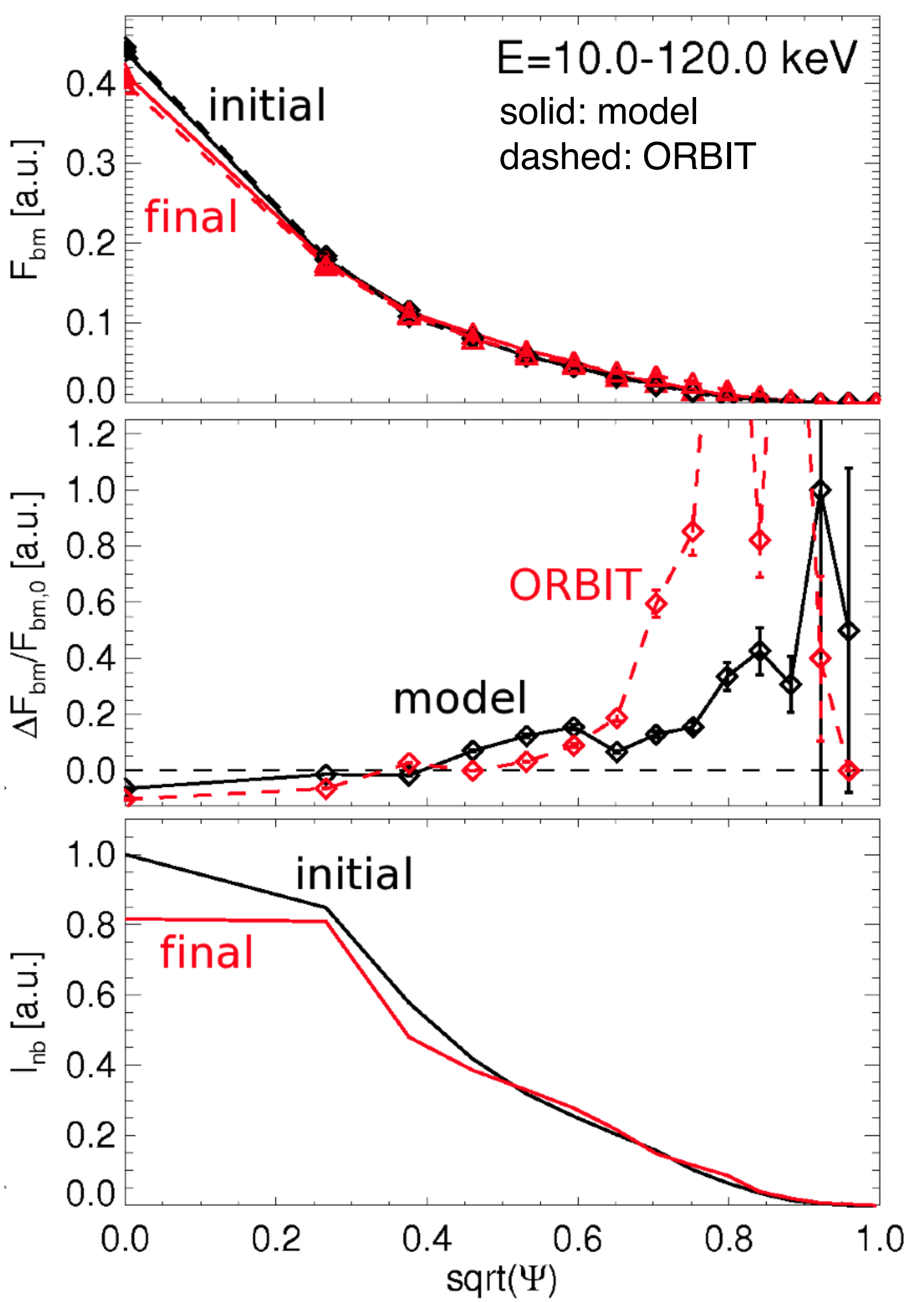
black: ORBIT
red: Kick Model





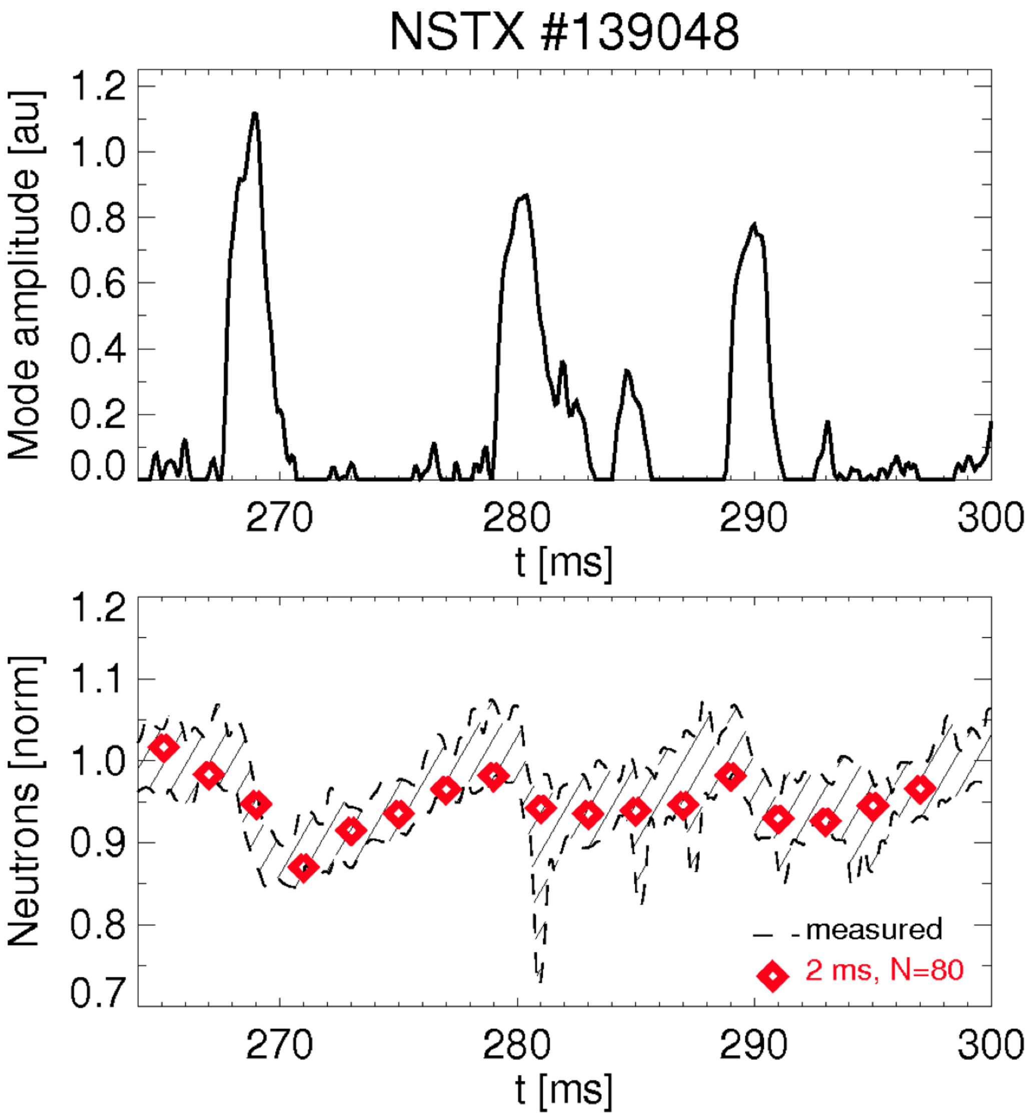
- Reconstruction vs. amplitude is satisfactory
- Differences ascribed to simplifications in $p(\Delta E,\Delta P_\zeta)$ scaling with A_{mode}: *shape* changes

F_{nb} after 5ms shows fast ion redistribution, only modest losses; NB driven "current" also affected.



- Compare full ORBIT simulation with reconstructions from reduced model
- F_{nb} drops in the core, fast ions redistributed to larger radii
- Define rough proxy for NB-driven (parallel) current, $I_{nb} \sim F_{nb}$ p v
  - Larger (relative) variations for I_{nb} than for F_{nb}
  - Need NUBEAM/TRANSP for more quantitative calculations of I_{nb}

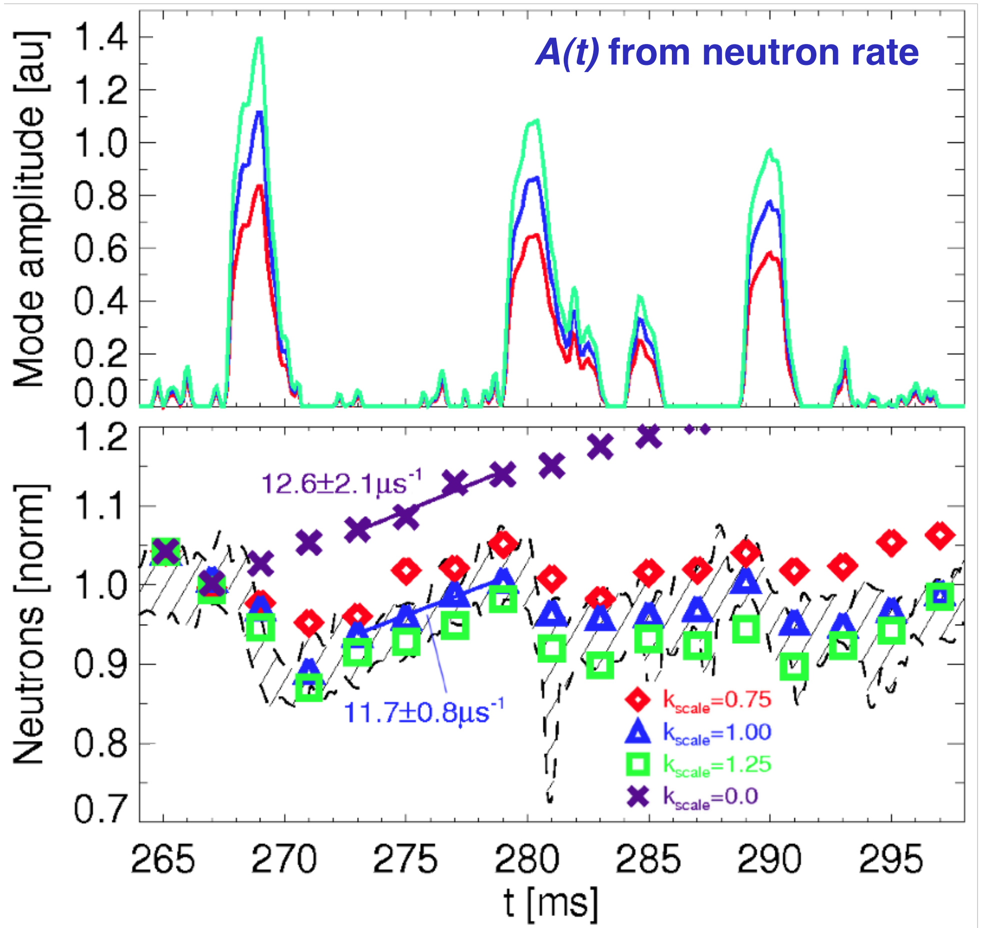
Reduced model qualitatively reproduces neutron trends for nominal $A_{mode}(t)$ from neutrons, Mirnovs

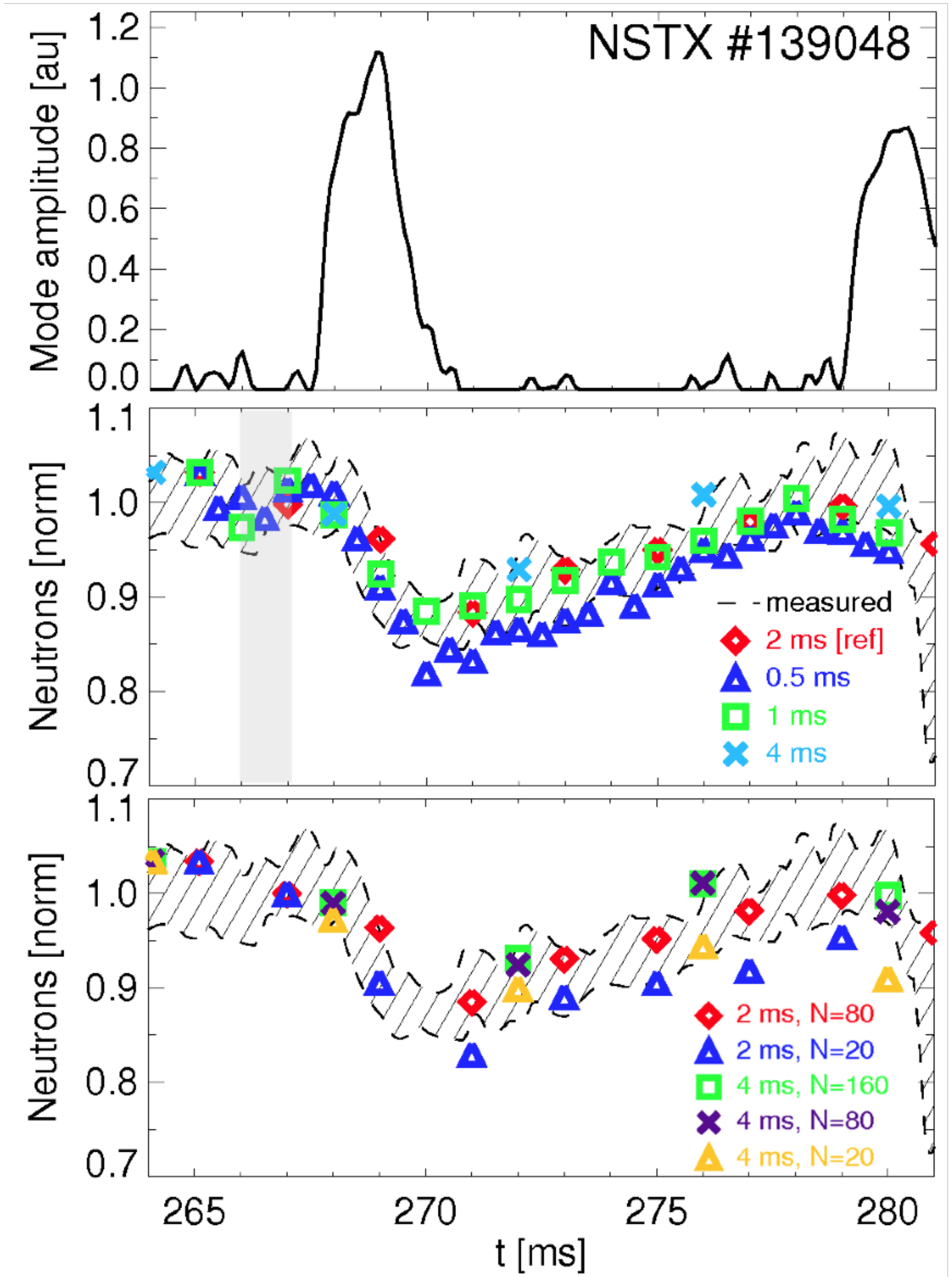


- Initial comparison of model predictions w/ experimental neutron rate
- Use stand-alone version of NUBEAM, iterate with reduced model
- Background plasma is fixed
  - Normalize exp. neutron rate to central ion density vs. time
  - Normalize all neutron rates to t=267 ms (before first burst)

Satisfactory agreement for A(t) from neutron rate, Mirnovs

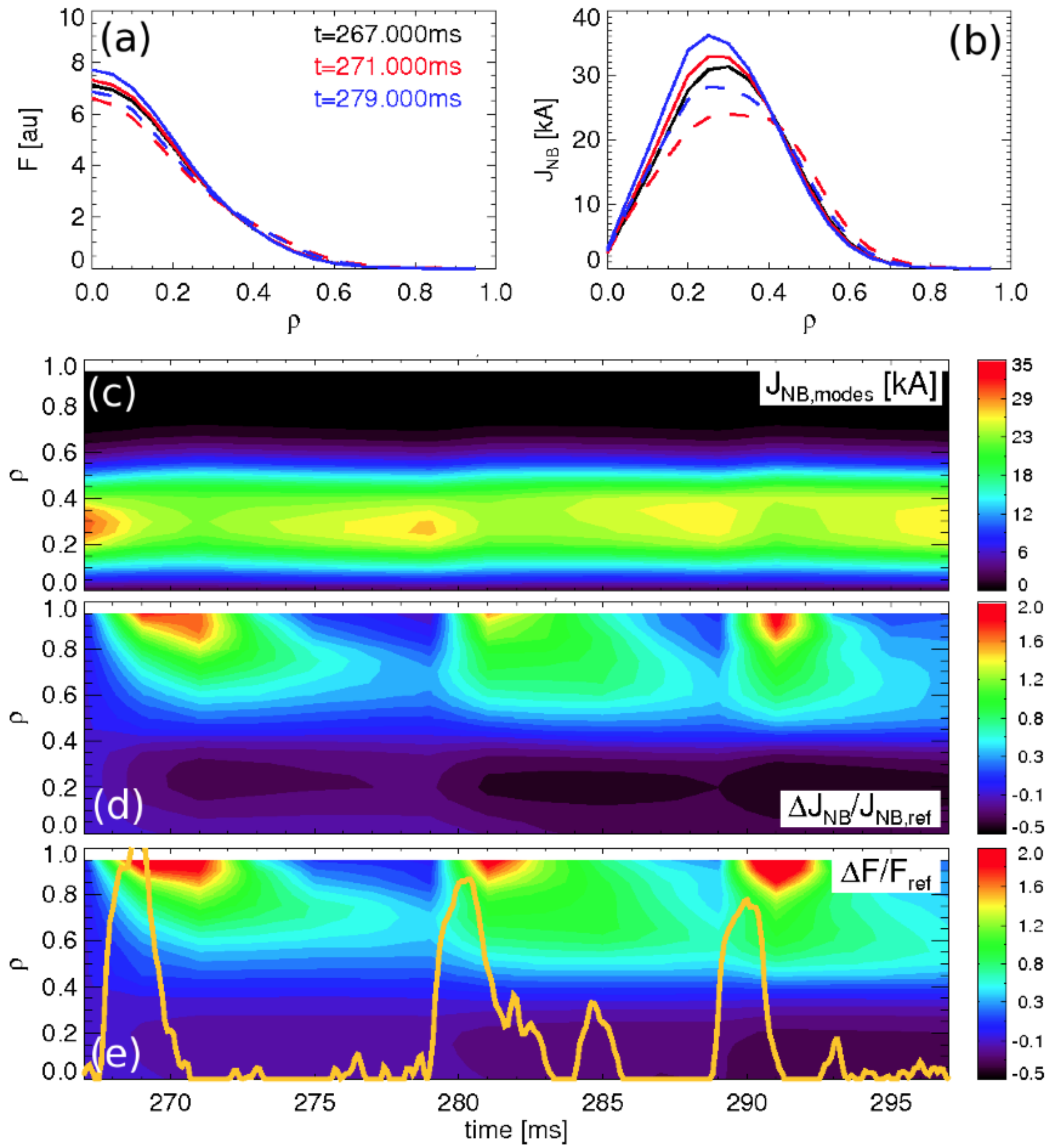
Results are sensitive to input mode amplitude; time steps must be chosen to satisfy "statistical" approach, approximations





- Typical time scales:
  - Slowing down: 15-30ms
  - Collisions: 2-5ms
  - AEs: 0.1-2ms
- N: number of micro-steps for MC particle evolution, duration 25μs

Reduced model + NUBEAM compute “measurable” fast ion redistribution; NB-driven current strongly affected



- Initial tests show 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

Summary

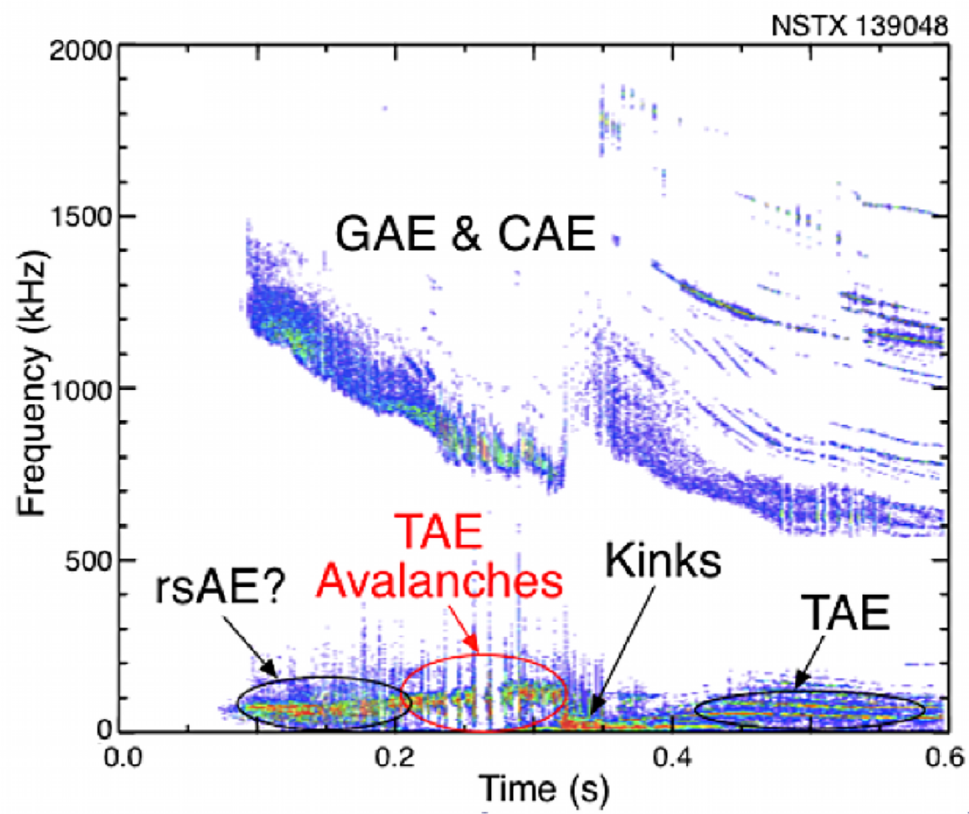
- Test algorithm for reduced fast ion transport model developed, being verified
  - Results compared with full ORBIT runs
  - Confirmed validity of approach for practical case
  - *Code not yet optimized, parallelized for best performance*

- Successful preliminary tests for one NSTX case with TAE modes (*avalanches*)
  - Shot#139048, t~265-300 ms: H-mode avalanches
  - Strong redistribution of fast ions observed
  - Modest losses, consistent with previous detailed modeling
  - NB-driven current J_{nb} is affected, too

- After further verification, ready for implementation in NUBEAM for validation.

Need to generalize the model to account for multiple classes of MHD modes at a given time?

- Scenarios with presence of more than one MHD type of modes are quite common
  - NSTX: kink + GAE/CAEs + TAEs
- Formulation discussed so far can only deal with one class of modes at the time
- However, this general case is of great interest
  - More realistic F_{nb} evolution when modes have comparable amplitude
  - Could mock-up scenarios such as ‘fast ion channeling’



> To extend the model to multi-class case, each class can be represented by its $p_k(\Delta E,\Delta P_\zeta,\Delta\mu)$, weighted by $A_{mode,k}$
  - Instantaneous $p(\Delta E,\Delta P_\zeta)=\Sigma_k\, A_{mode,k} \times p_k(\Delta E,\Delta P_\zeta,\Delta\mu)$

Can the model be used in 'predictive' mode?

- As it is, the model is OK to analyze 'real' discharges
  - Need mode structure to calculate $p(\Delta E,\Delta P_\zeta)$, e.g. from NOVA-K and reflectometers' data + ORBIT
  - Need data (Mirnovs, neutrons, etc.) to infer $A_{modes}(t)$
- Two possibilities for 'predictive' runs:
  - Find reasonable guess for unstable modes (e.g. NOVA-K)
  - Explore different scenarios w/ scan of $A_{modes}(t)$: weak *AE activity, bursts/avalanches, etc.

  or:
  - Have an additional module to compute $A_{modes}(t)$ self-consistently
  - Still requires mode structure, probably estimates for γ_{drive}, γ_{damp}
  - Let $A_{modes}(t)$ evolve according to F_{nb} evolution – how?
  - *Couple to other reduced models, e.g. 1.5D Quasi-Linear?*