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Reduced energetic particle transport model by low-f MHD for Integrated Tokamak Simulations

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Abstract

Low frequency instabilities such as kinks and fishbones are well know causes of enhanced energetic particle (EP) transport in tokamaks. However, physics-based models that account quantitatively for their effects in time-dependent integrated tokamak simulations are still missing. Development of such models is needed for more reliable projections of operating scenarios from today's devices to future burning plasmas such as ITER and FNSF. This work reports on recent developments of a reduced EP transport model by fishbones and kinks, based on the existing *kick model* infrastructure already implemented in the TRANSP code. For example, the rapid (~1-5 ms) sweep in frequency characteristic of a fishbone burst implies that different regions of energetic particle phase space are affected as time evolves. The kick model can account for such changes by representing the instability as superposition of multiple, fixed-frequency instabilities with time-dependent amplitudes. Based on the initial results from the kick model, prospects for the development of a self-consistent model for low-frequency MHD in TRANSP will be discussed.

Fishbones (FB) have large effect on confinement of energetic particles

- Well characterized instabilities driven by energetic particles

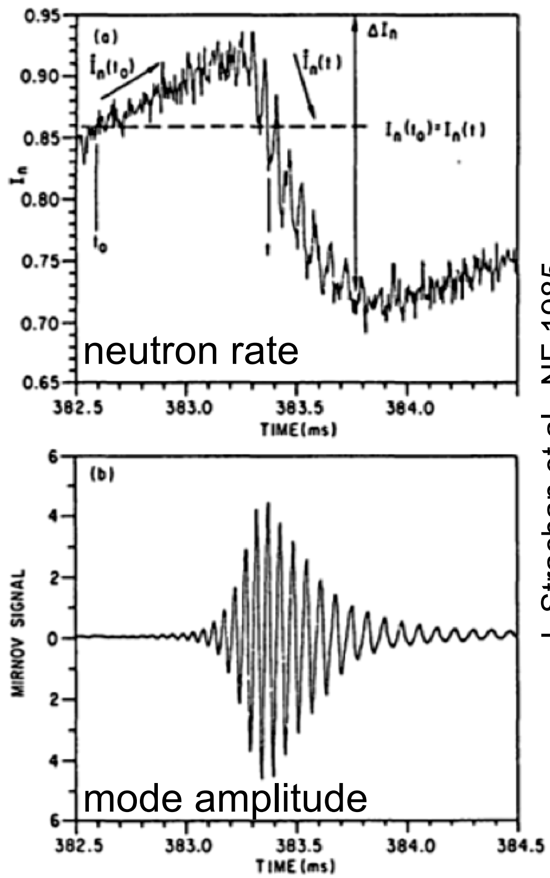


FIG.1. Time evolution of (a) the 2.5 MeV neutron emission and (b) the Mirnov signal through a fishbone instability having only a nominally 20 kHz oscillation.

J. Strachan et al., NF 1985

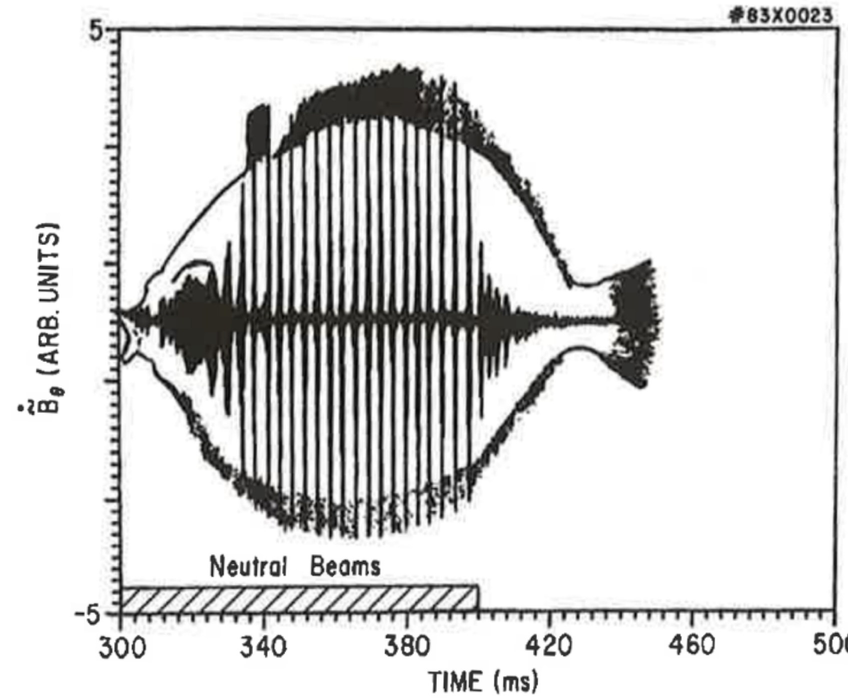


Fig. 7.1 Mirnov signal during fishbone mode, outline added by artist.

- Fishbones cause repetitive losses of EPs,
  - Modify EP distribution
  - Affect Neutral Beam current drive
  - Decrease overall plasma performance

Can a physics-based, quantitative model be developed for transport codes such as TRANSP?

- Ad-hoc FB model presently implemented in TRANSP
- Model requires guess for several parameters
  - Not physics-based
  - Not clear how to select a specific set of parameters

Fishbone_loss

```
Note (dmc Feb 2007): new options added to this model, see end of
section.

TRANSP has a very simple "fishbone" loss model for Monte Carlo fast
ions.  It has the following controls:

  NLFBON   ! LOGICAL set to .TRUE. to enable fishbone losses

  TFSHON   ! onset time of fishbones (seconds)
  TFSHOF   ! time of last fishbone (seconds)
  FSHPER   ! fishbone period (seconds) -- time btw spikes
  FSHWID   ! duration of individual fishbone spike (seconds)

  FBEMIN   ! minimum energy of affected fast ions (eV)
  FBEMAX   ! maximum energy of affected fast ions (eV)
  FVPVMN   ! minimum abs[ Vpll/V ] of affected fast ions
  FVPVMX   ! maximum abs[ Vpll/V ] of affected fast ions

  FBLTIM   ! characteristic fishbone loss time for affected ions (secs)

For purposes of fishbone loss, vpll/v is taken at the last two midplane
crossings; if |vppl/v| at either of these points falls within the
range FVPVMN to FVPVMX, and if the energy is in range, the ion is
eligible for loss.
```

- **This work: explore extension of *kick model* in TRANSP to account for FB-induced EP transport**
  - Kick model originally developed for Alfvénic modes
  - Leveraging on flexibility of kick model implementation
  - Same approach being pursued for sawteeth, NTMs
    - D. Kim et al., NF 2018
    - W. Heidbrink et al., NF 2018; L. Bardoczi, PPCF 2018 (submitted)

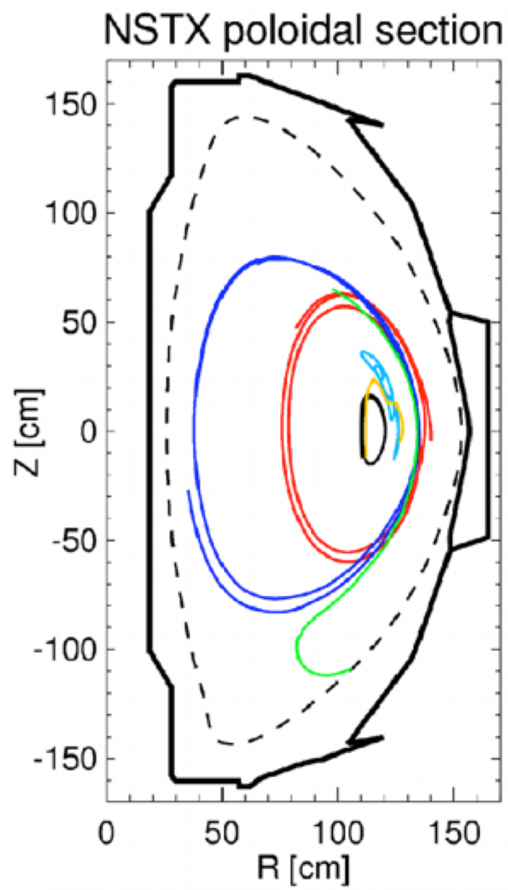
Constants of Motion are convenient set of variables to describe resonant wave-particle interaction

Each orbit characterized by:

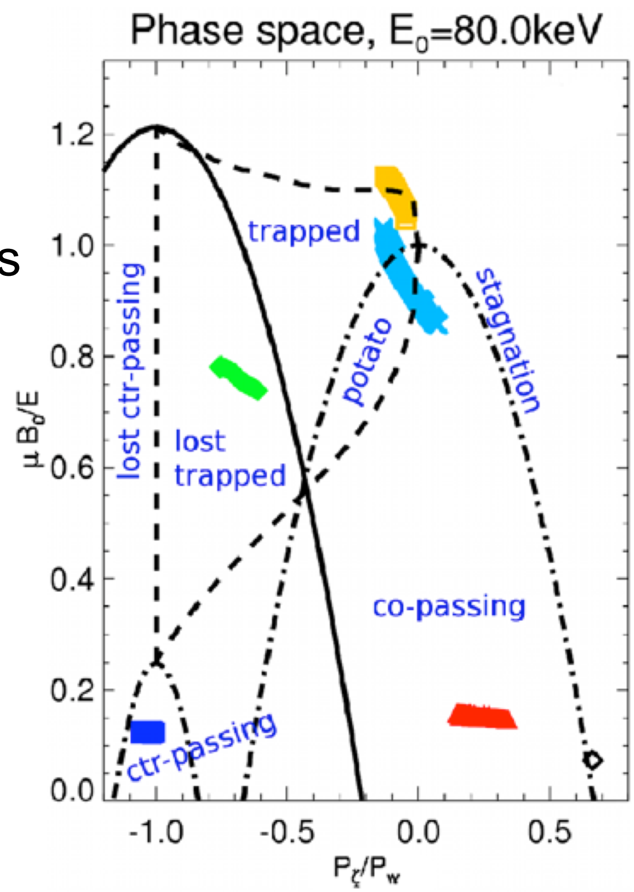
- E, energy
- $P_\zeta \sim mRv_{par} - q\Psi$, canonical momentum
- $\mu \sim v_{perp}^2/B$, magnetic moment

Energy exchange rate:

$$\gamma \propto \omega \frac{\partial F_{nb}}{\partial E} + n \frac{\partial F_{nb}}{\partial P_\zeta}$$



Complex orbits in real space translate in simple trajectories in phase space



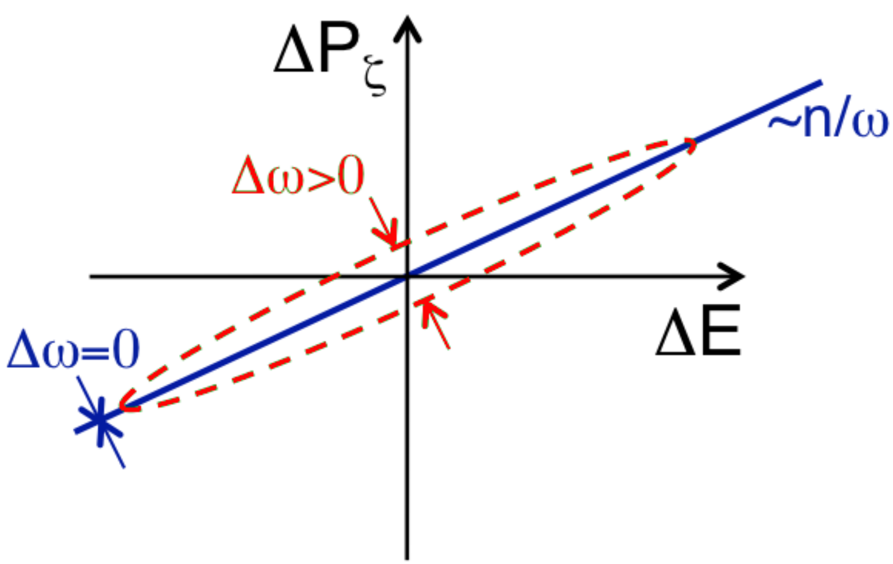
R. B. White, Theory of toroidally confined plasmas, Imperial College Press (2001)

Kick Model: use a *probability distribution function* to describe EP transport in MonteCarlo code NUBEAM

- Resonances introduce fundamental constraints on particle trajectory in (E,P_ζ,μ)
- 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



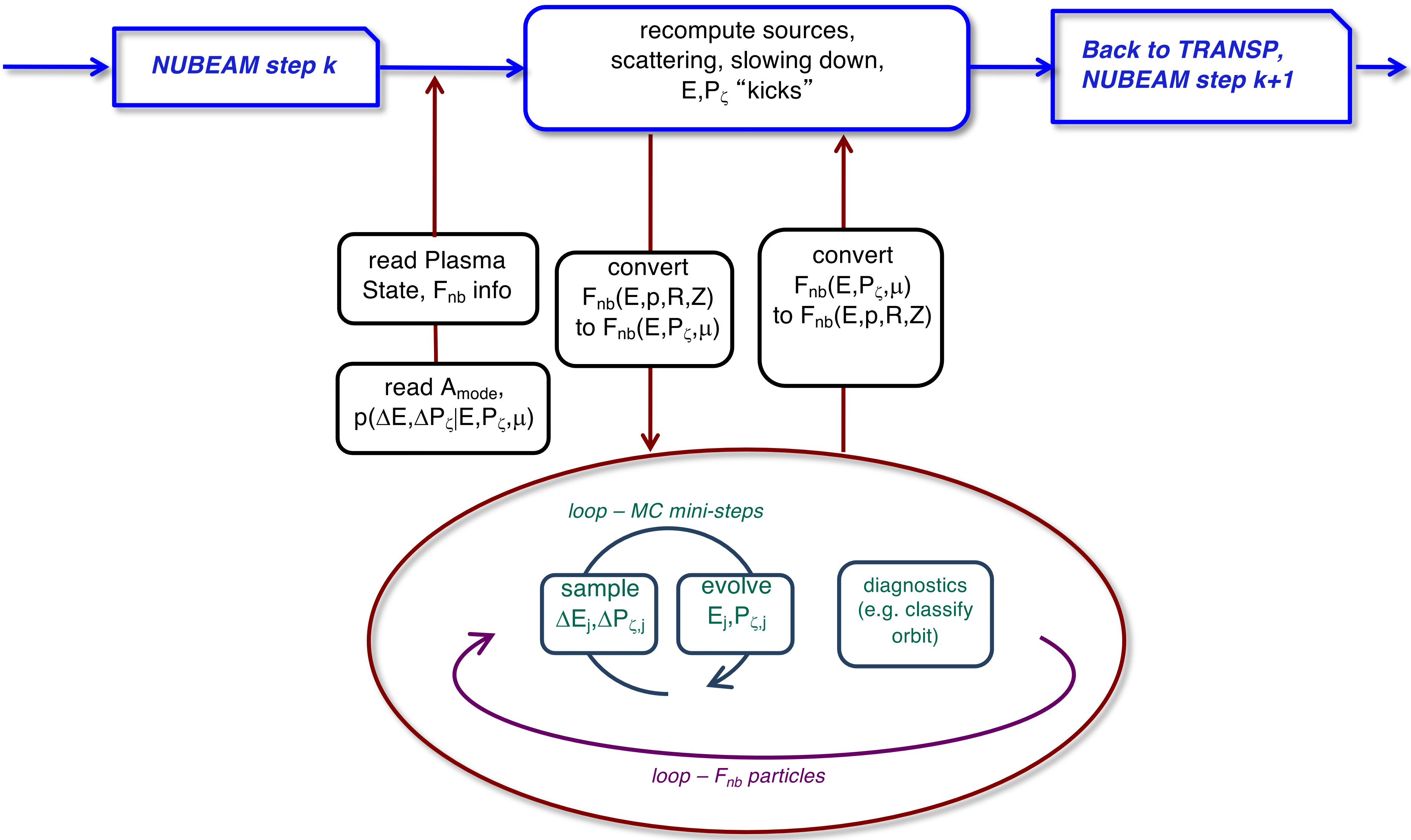
For each bin in (E,P_ζ,μ), kicks in $\Delta E,\Delta P_\zeta$ are described by

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

- *Can incorporate effects of multiple modes & resonances:*
- *Computed from particle-following codes such as ORBIT*

[M. Podestà et al., PPCF 2014 and PPCF 2017]

Scheme to push fast ions according to transport probability in NUBEAM/TRANSP



add "kicks" to F_{nb} variables

Fishbones present specific aspects, different from Alfvénic modes

- Kick model mostly used for AE-induced EP transport

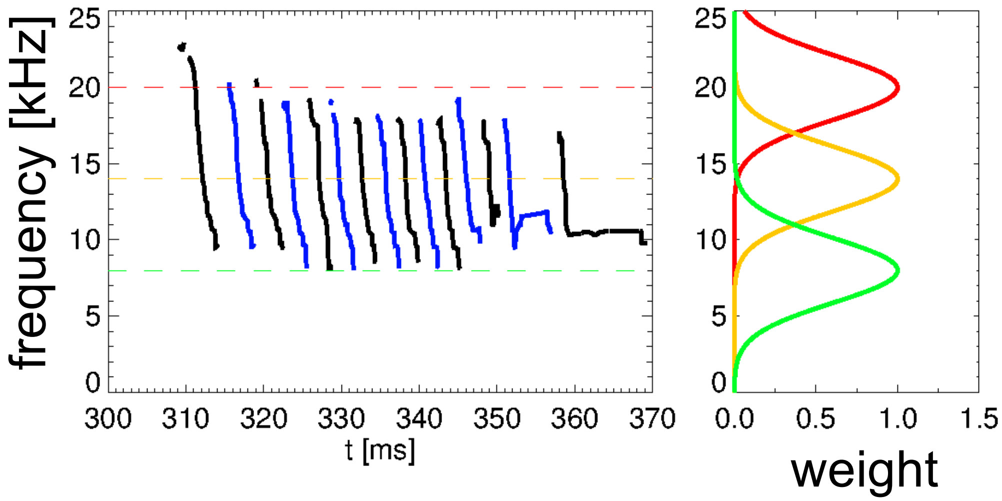
Fishbones:

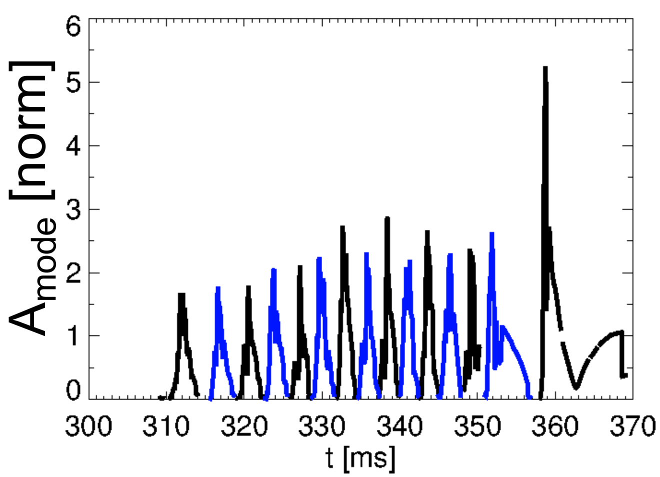
- Considerable frequency sweep over ~1ms
- Rapid change in amplitude
- May induce *convective* EP transport
- Global modes, most plasma regions affected

- *This work: use simple analytical expressions for the fishbone radial displacement*
  - *Use ORBIT code to compute kick probability matrices*

Approach: decompose FB in ~3 "sub-modes" with fixed *f* to mimic frequency sweep

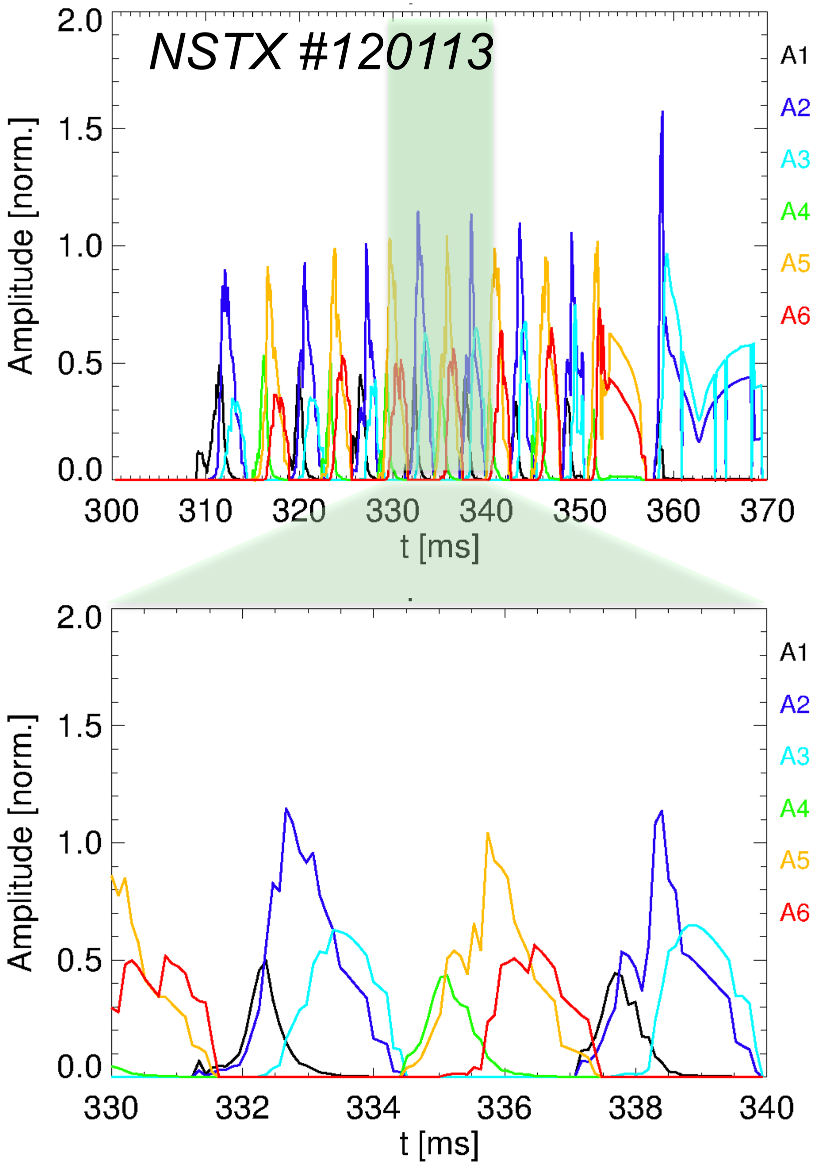
- Kick model in TRANSP can include up to 10 "modes"





- Identify frequency and "amplitude" evolution from Mirnov coils
  - Or other, internal diagnostics
- Infer amplitude "weights" for selected frequencies during the frequency sweep
- In time-dependent simulation, construct "instantaneous FB mode" as weighted superposition of *sub-modes*
  - Mimic frequency sweep

Example from NSTX: closely spaced fishbones represented through 6 *sub-modes*



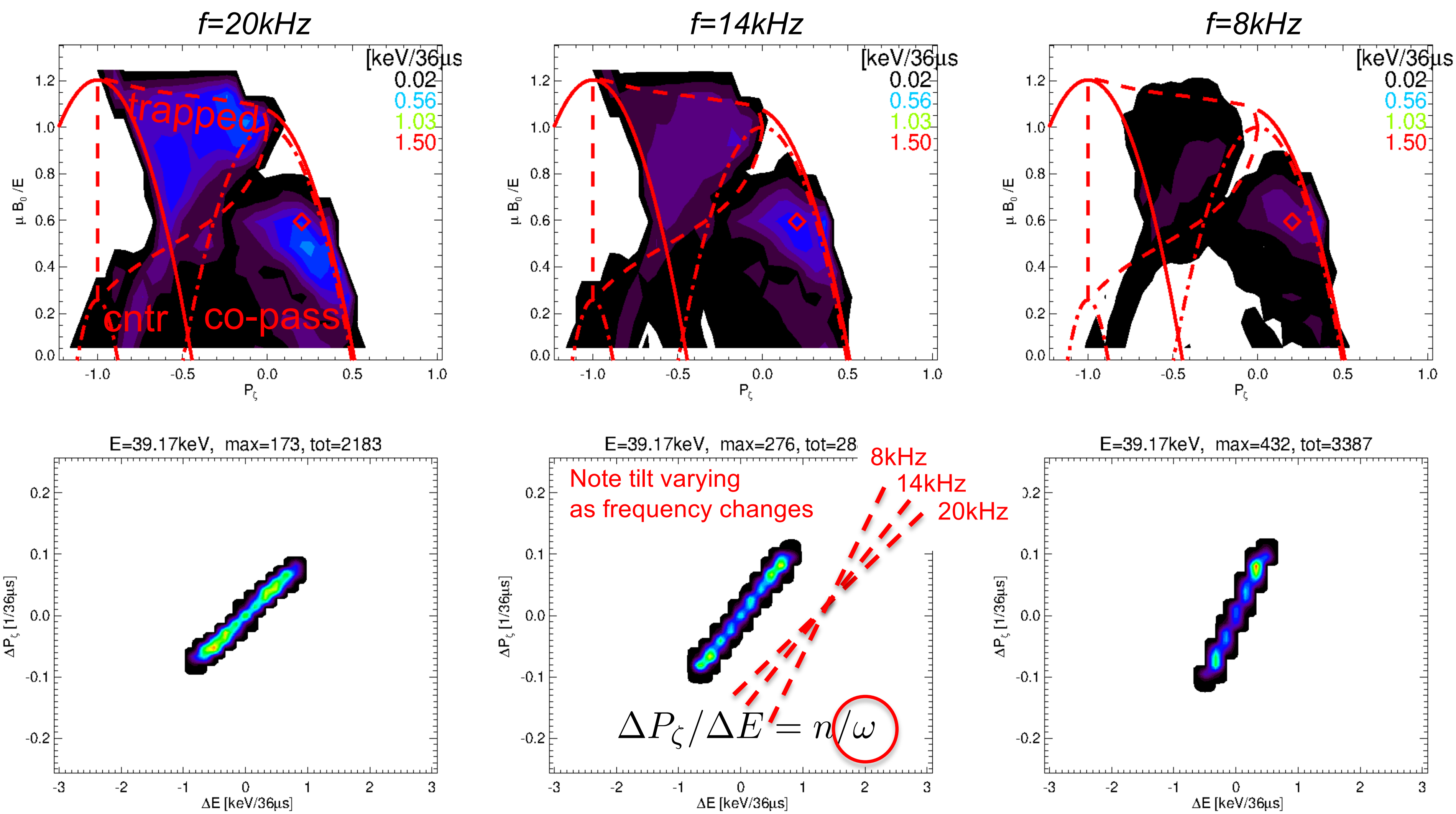
- FB events partly overlap in time
- Need to split events into two groups
- Represent modes from each group with 3 sub-modes

Kick model matrices:

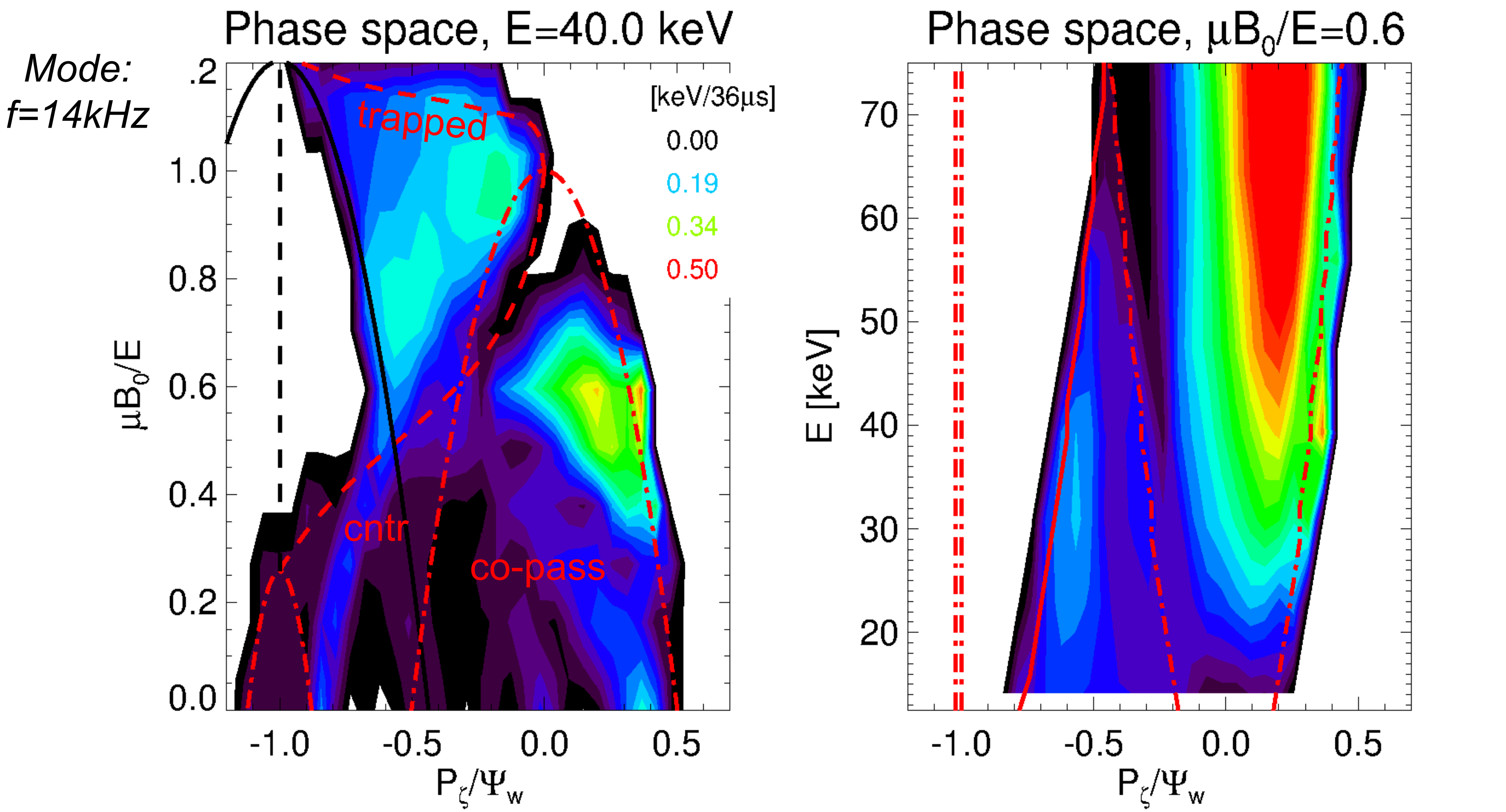
- Compute kick probability for each component
- Pass to TRANSP/NUBEAM with time-dependent kick scaling factors

Kick transport matrix shows energy dependent resonant regions in phase space

- Top row: *rms* energy kicks for E~40keV fast ions
- Bottom row: example of transport probability for P_ζ~0.2, μB/E~0.6



Particles with different orbit type contribute differently to resonant interaction



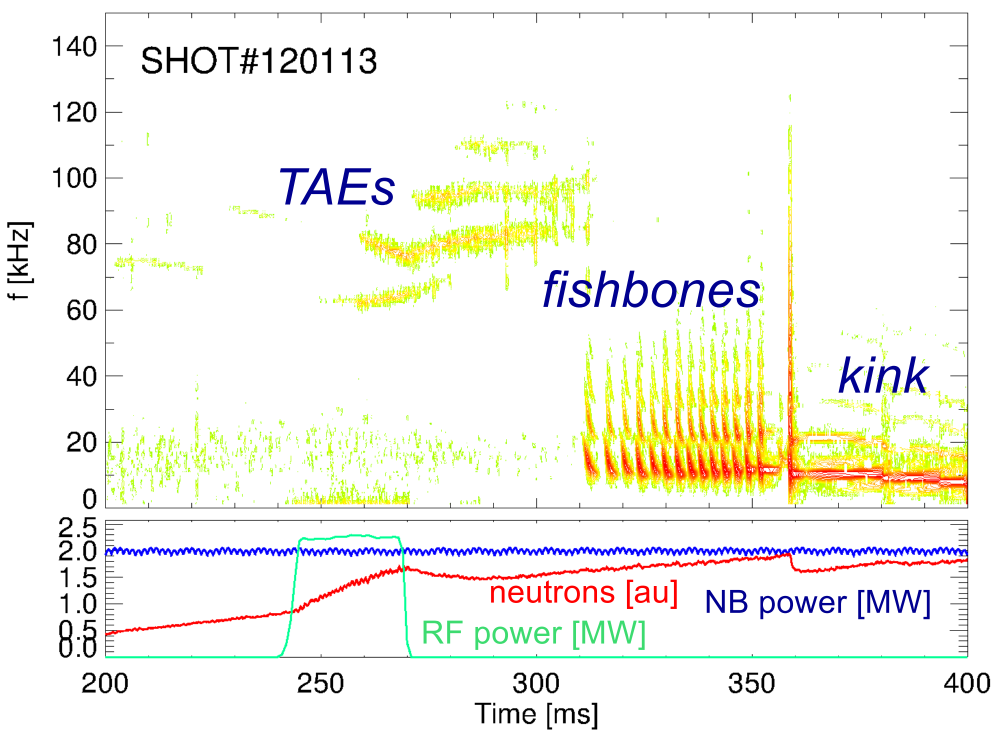
This detailed information is missing in the simple FB model in TRANSP

Target scenarios from NSTX and NSTX-U: single *vs* multi-mode cases

NSTX, single mode

B_t~0.45T, I_p~0.8MA

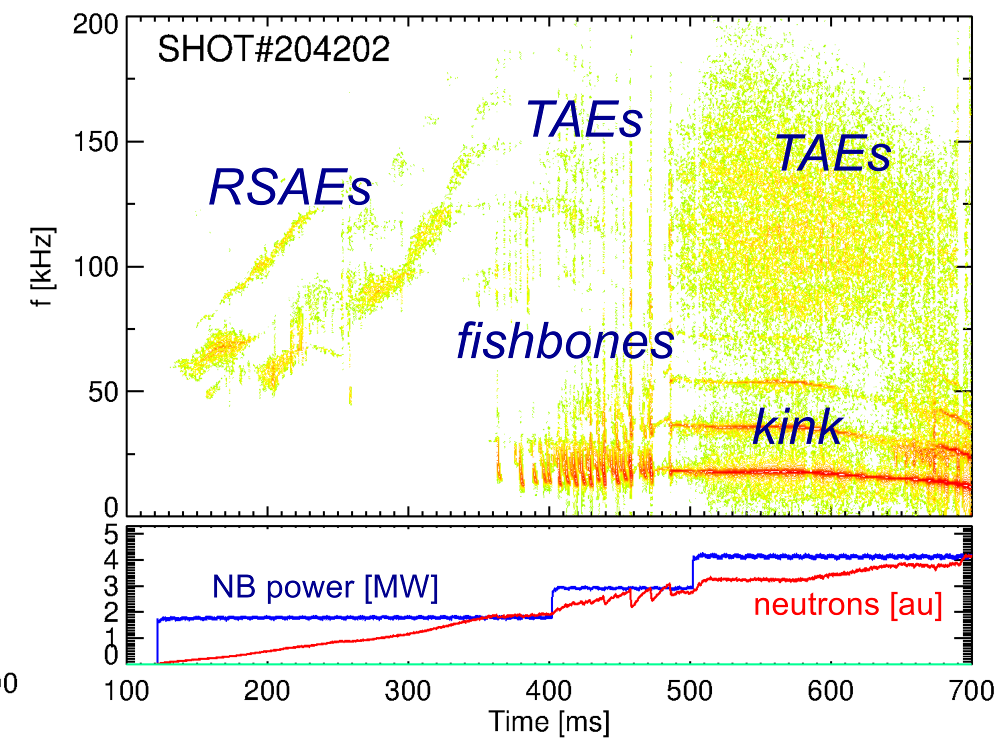
$n_{e,0}$~4x10^{19}m^{-3}, $T_{e,0}$~1.2keV



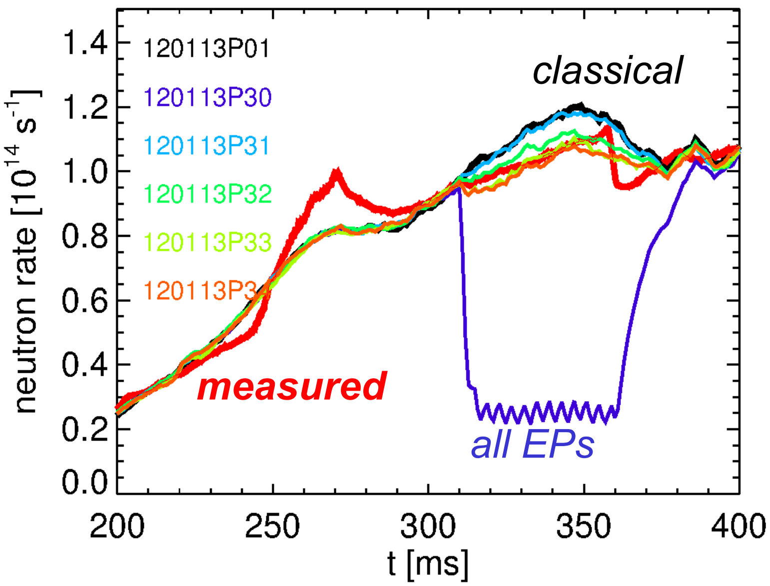
NSTX-U, multi-mode

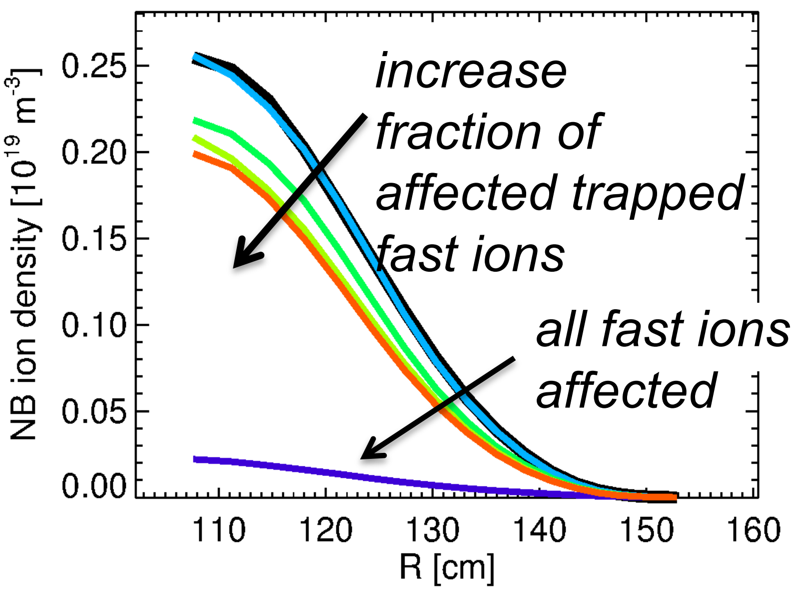
B_t~0.65T, I_p~0.7MA

$n_{e,0}$~4x10^{19}m^{-3}, $T_{e,0}$~1.5keV



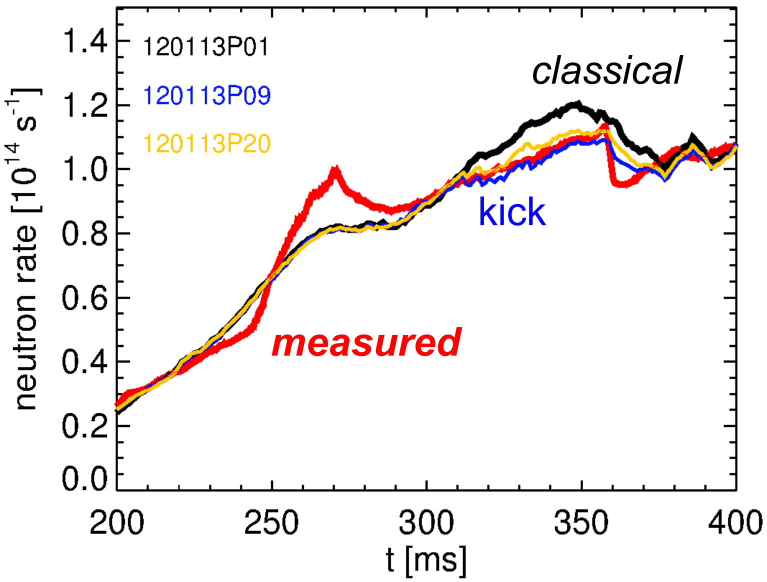
TRANSP FB model *can* reproduce observed neutron rate by tuning free parameters

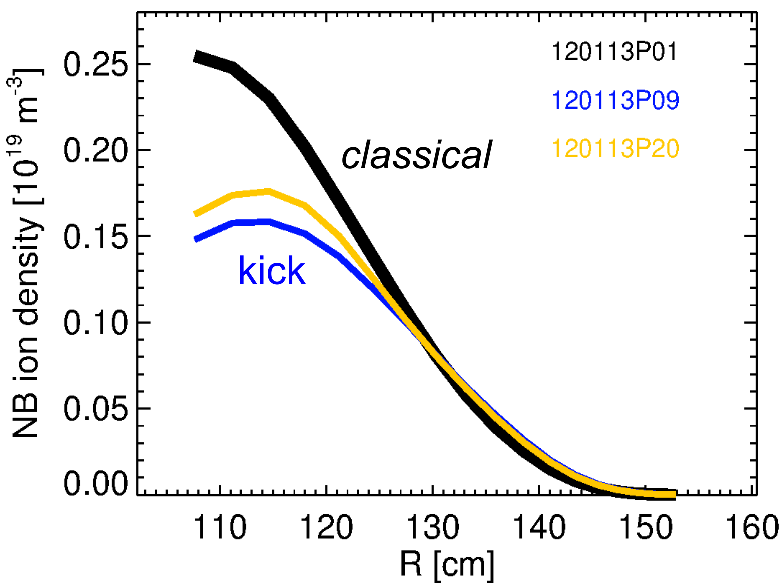




- If all fast ions are affected, computed neutron rate is 5x lower than the measured rate
- Runs P31-P34: vary fraction of trapped particles affected by FB
- Reasonable match with measurement for 25-50% of trapped fast ions affected (exclude barely trapped particles)
- ***But: this is not going to work for predictive simulations!***

Kick model reproduces observed neutron rate; kick scaling factor is free parameter

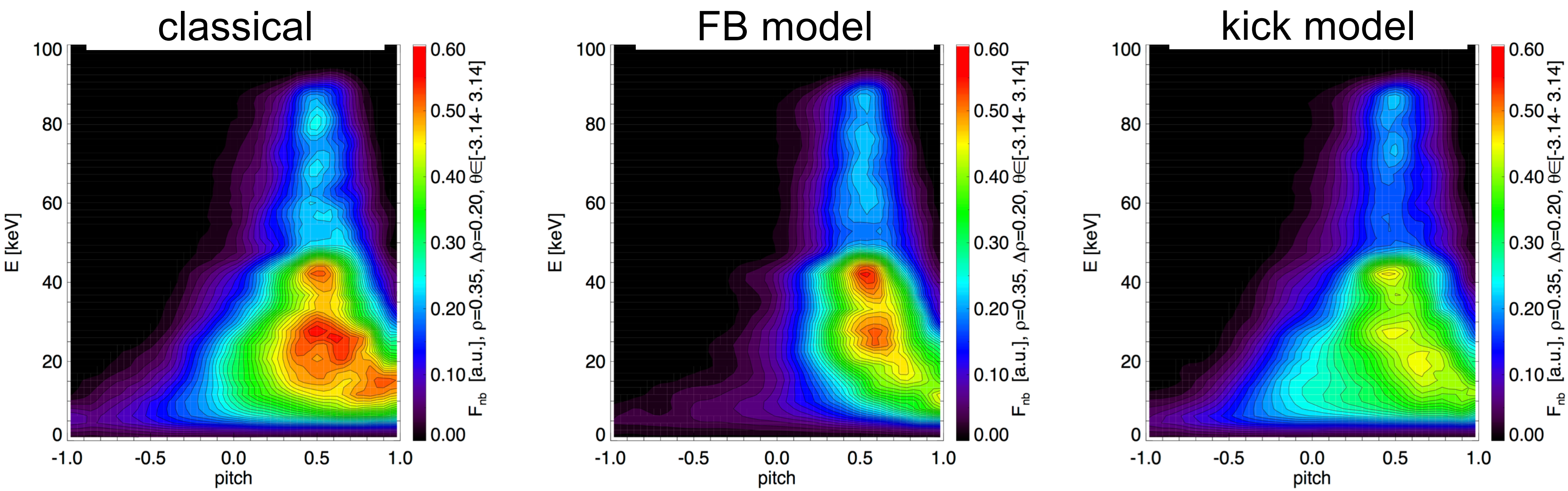




- Lack of internal, absolute measurements of mode amplitude for this case
- Simulations use $\delta B/B \sim 5 \times 10^{-2}$ for dominant (m,n)=(1,1) component
  - Reasonable value (?)
- 2 kick simulations shown here: vary amplitude by +/-10%

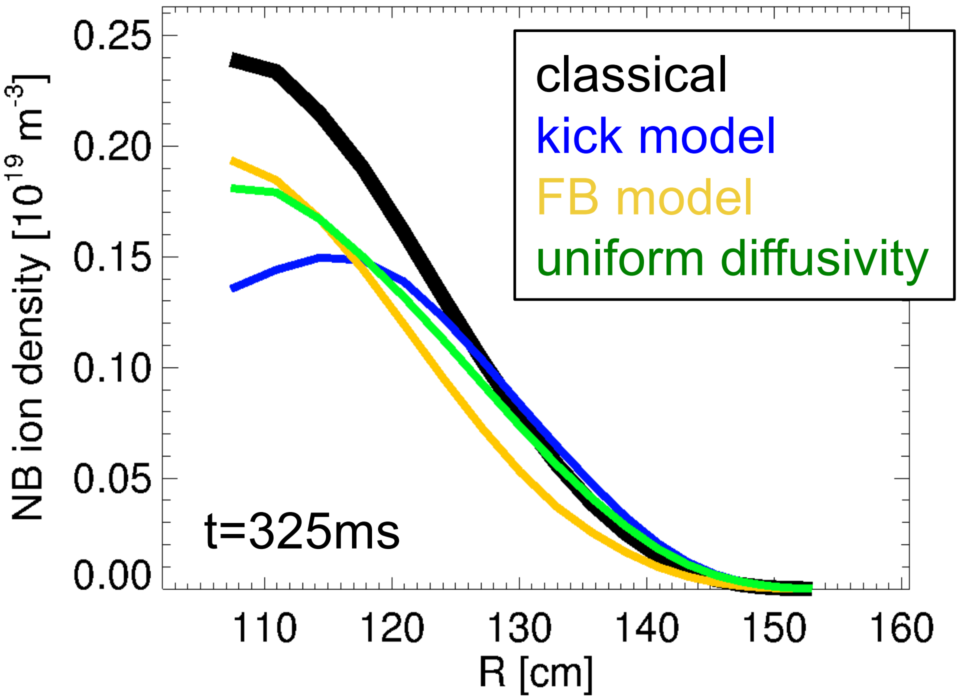
Kick and simple FB model result in considerably different fast ion distributions

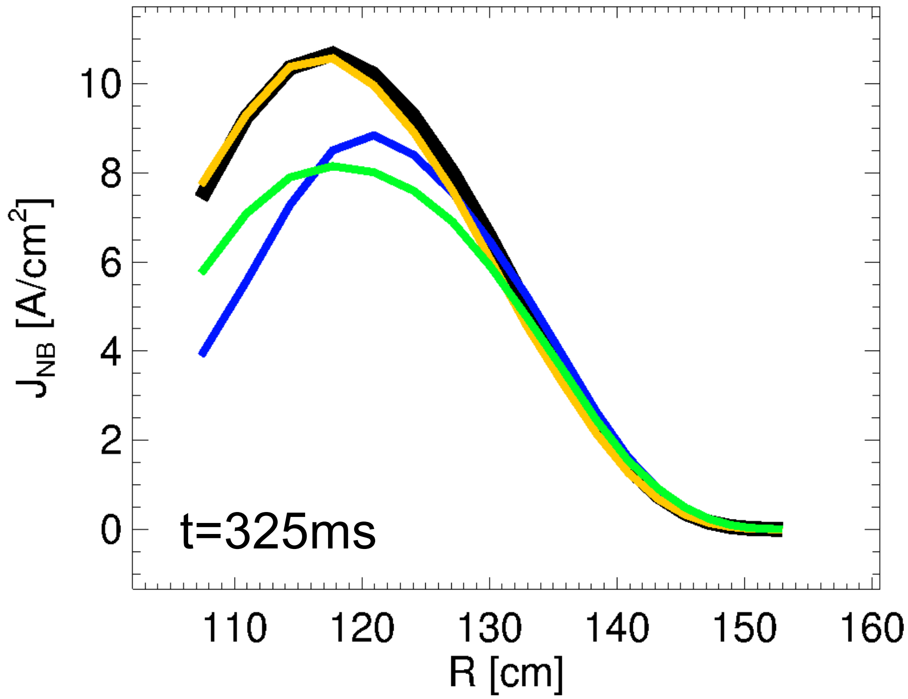
Fast ion distribution F(E,pitch), rho~0.35, t=325ms



- Simple FB model only acts on trapped particles
- Kick model acts on all orbit types depending on location of resonances as computed by ORBIT code

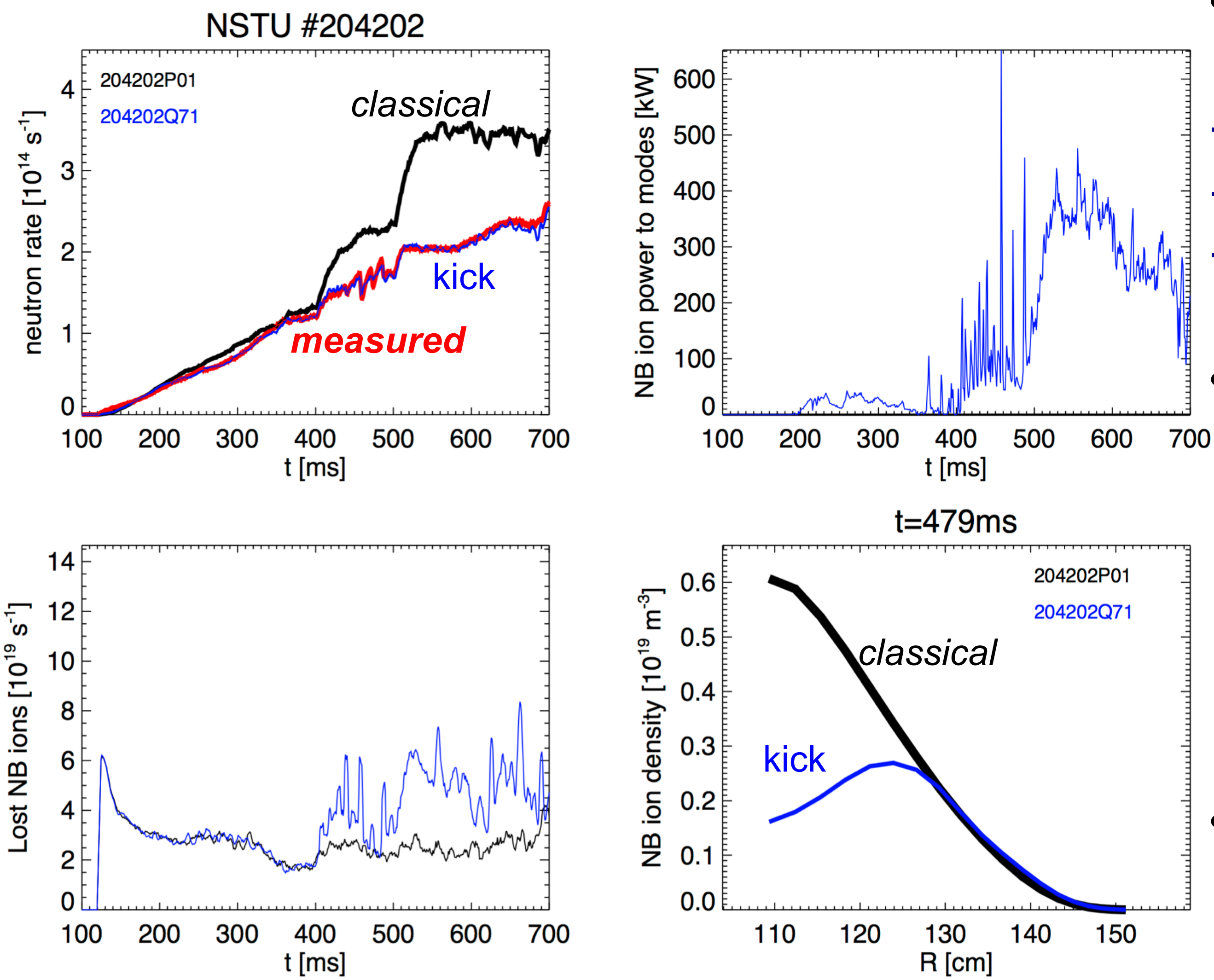
Quantities derived from EP distribution also vary across different transport models





- Reveals limitations of using neutron rate only as metric for *successful modeling*
- Confirm need for phase-space resolved EP diagnostics
- Confirm need for validation vs phase-space resolved measurements

Multi-mode case is more challenging, requires analysis for AEs, kink and fishbones



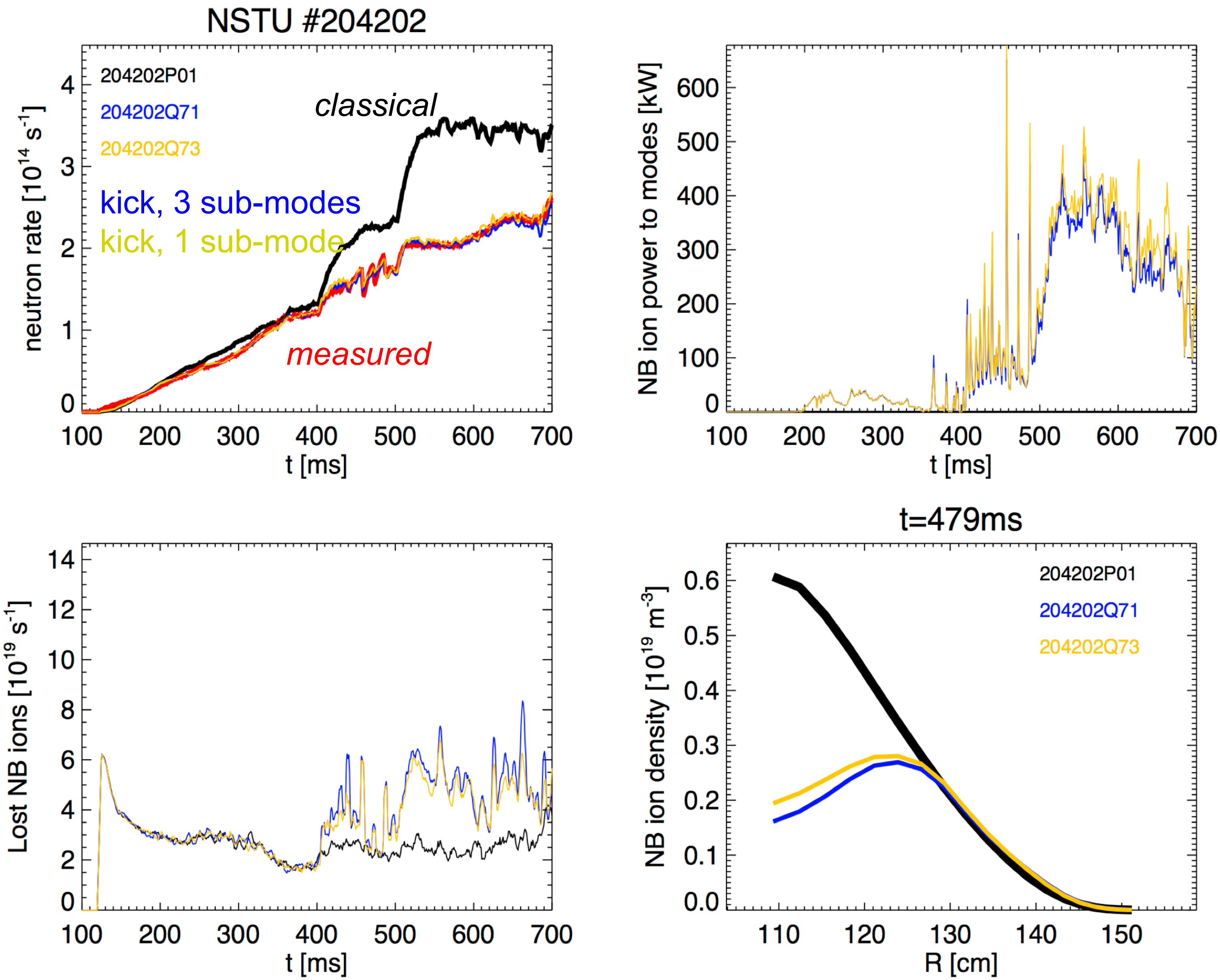
- Modes included in the simulation:
  - 2 RSAEs, t<400ms
  - 4 TAEs, t>400ms
  - 3 sub-modes for FB
- AEs from NOVA analysis
  - Estimate amplitude from power balance through kick model

[M. Podestà et al., PPCF 2017]

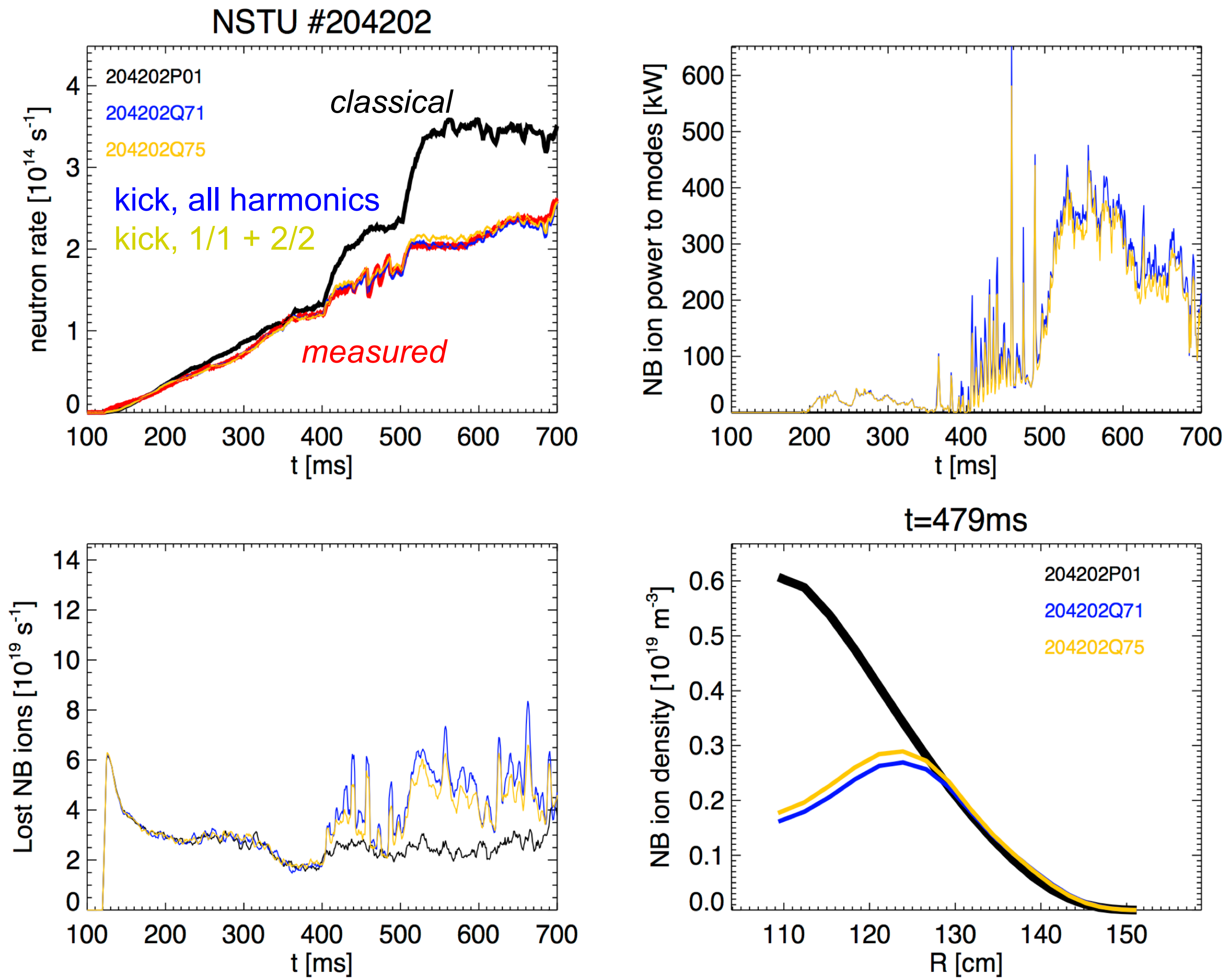
- Use $\delta B/B \sim 1 \times 10^{-2}$ for dominant (m,n)=(1,1) fishbone component

How accurate has to be the representation of fishbones?

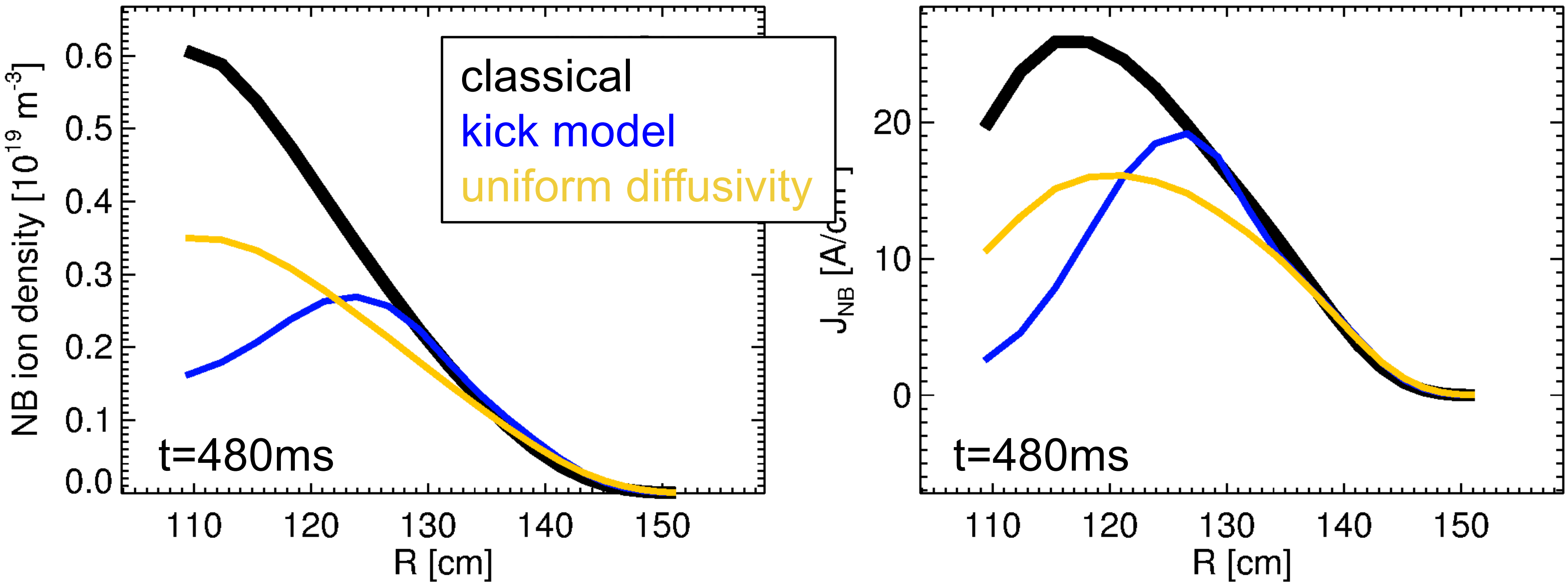
Reducing the sub-modes to 1 with sweeping frequency in ORBIT appears adequate



Retaining only two dominant FB harmonics (m/n=1/2 and m/n=2/2) also looks OK



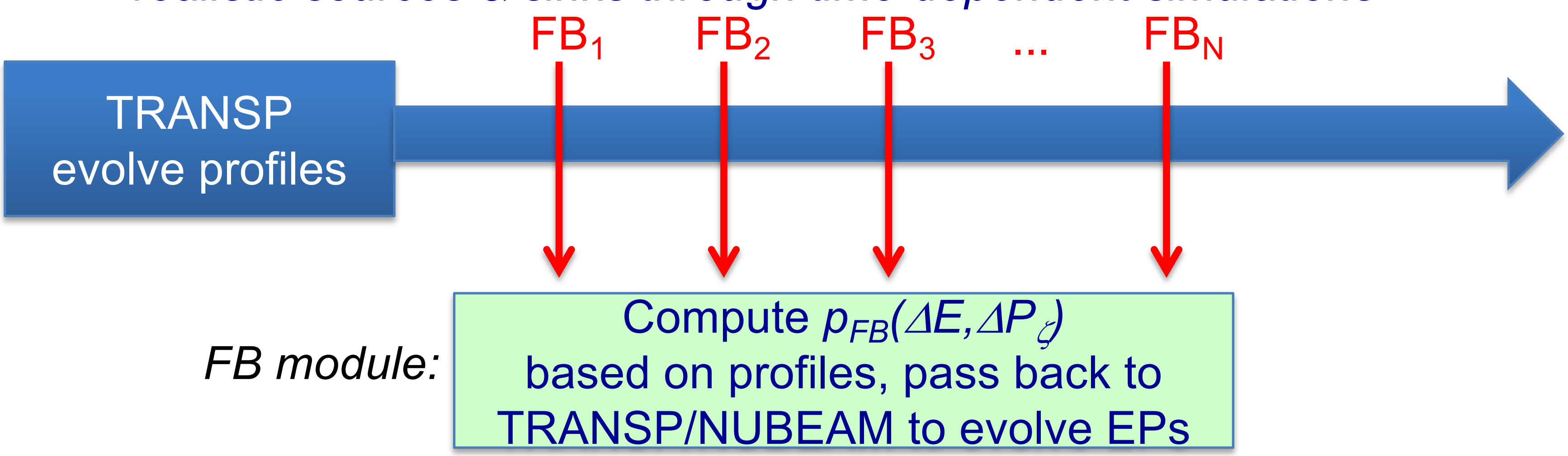
Multi-mode case highlights issues with simple transport models for quantitative simulations



- Mix of AEs, kinks, fishbones
  - *What model should be used???*
- As shown previously, ad-hoc diffusive model *can* match target quantity (e.g. neutron rate)
  - However, physics of each type of instability is lost
- *Kick model can provide more physics-based approach*

First application of the model indicates promising path forward

- Developing fast version of ORBIT
  - Compute kick transport matrices in ~minutes
  - Now it takes hours for good statistics
- Develop module for semi-automatic computation of $p_{FB}(\Delta E,\Delta P_{\zeta})$
  - Begin with “interpretive” module
  - E.g. User supplies “time of fishbones”, possibly amplitude
  - *Would enable quantitative analysis e.g. of FB trigger conditions with realistic sources & sinks through time-dependent simulations*



- Similar approach planned for NTMs, sawteeth
- AEs require more computational resources
  - More poloidal harmonics are required for AEs than for FBs, NTMs, sawtooth

Summary

- Tested procedure to include physics-based model for fishbone-induced EP transport in TRANSP, first results appear promising
  - Reproduce measured reduction in neutron rate with plausible mode amplitudes
  - Can deal with multi-mode case including AEs, fishbones [, NTM, kinks, sawteeth… *microturbulence*?]

- However: several shortcuts have been taken here
  - E.g. analytical expression for FB mode structure (displacement)

To be done: more sensitivity studies and <u>validation</u>

> *How many frequencies are required to model fishbone cycle?*

> *Implications for EP transport in phase space?*

> *Planning validation against fast ion data*

- *Compare to FIDA, NPA, FILD, Neutron Camera, Fusion Product Array...*

- ***Interested in helping with validation? Just let me know!***