Energetic particle transport in NSTX-U multi-mode scenarios through integrated simulations

M. Podestà
Princeton Plasma Physics Laboratory, Princeton, NJ - USA

Acknowledgements: P. Bonofiglo, V. Duarte, E. Fredrickson, M. Gorelenkova, N. Gorelenkov, D. Kim, F. Poli, J. Yang, R. White, G. Wright and TRANSP Team (PPPL), W. Heidbrink, D. Liu (UCI), L. Bardoczi, C. Collins, M. Van Zeeland (GA), D. Spong (ORNL), NSTX-U & DIII-D Teams, US SciDAC EP and ITPA-EP

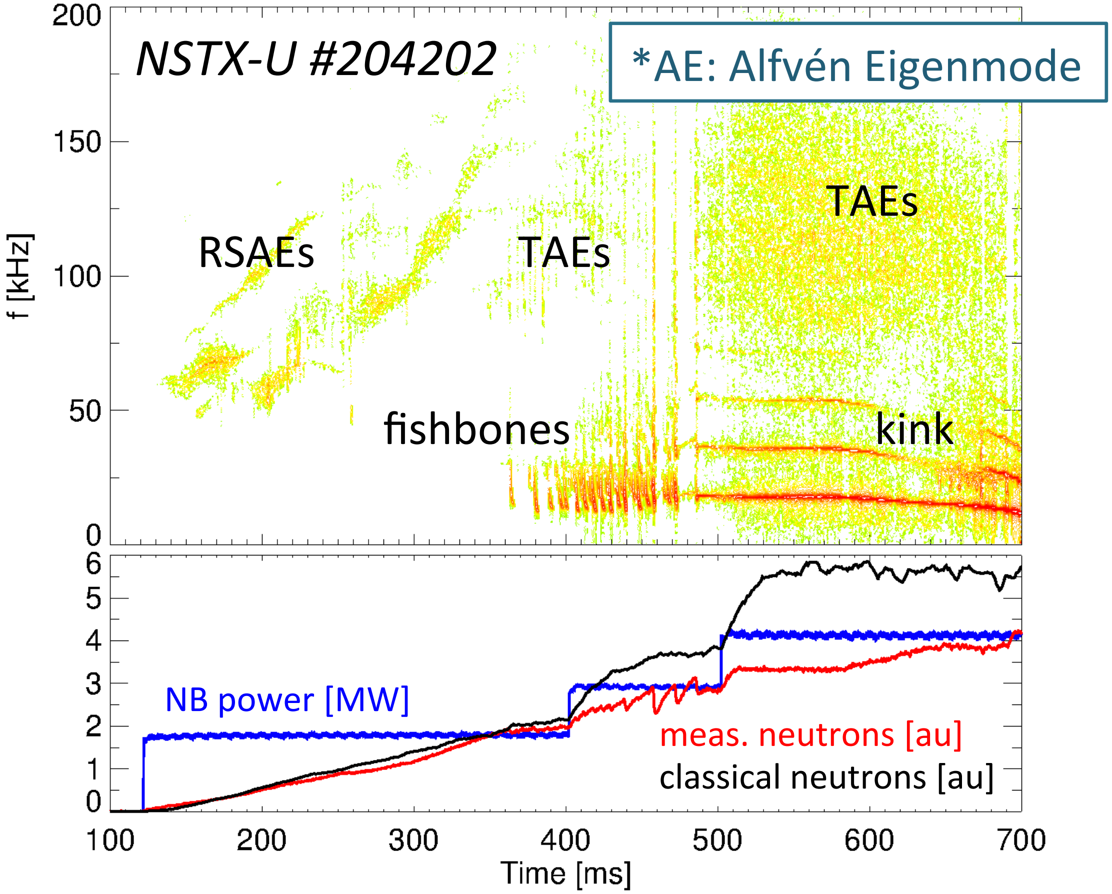
16th IAEA Technical Meeting on Energetic Particles
in Magnetic Confinement Systems & Theory of Plasma Instabilities
September 3 – 6, 2019
Shizuoka City, Japan

Work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under contract numbers DE-AC02-09CH11466.
NSTX-U at Princeton Plasma Physics Laboratory is a DOE Office of Science User Facility

Validated energetic particle (EP) models are required in integrated tokamak simulations

EPs (alphas, NB ions, RF tails) provide main source of heating, momentum, current drive in burning plasmas

- But: EPs drive instabilities, instabilities affect EPs
- *Also: multiple types of instabilities can be present at the same time*



This work:

- ***Can we reliably <u>model & predict</u> EP transport in scenarios with multiple instabilities?***

Layout

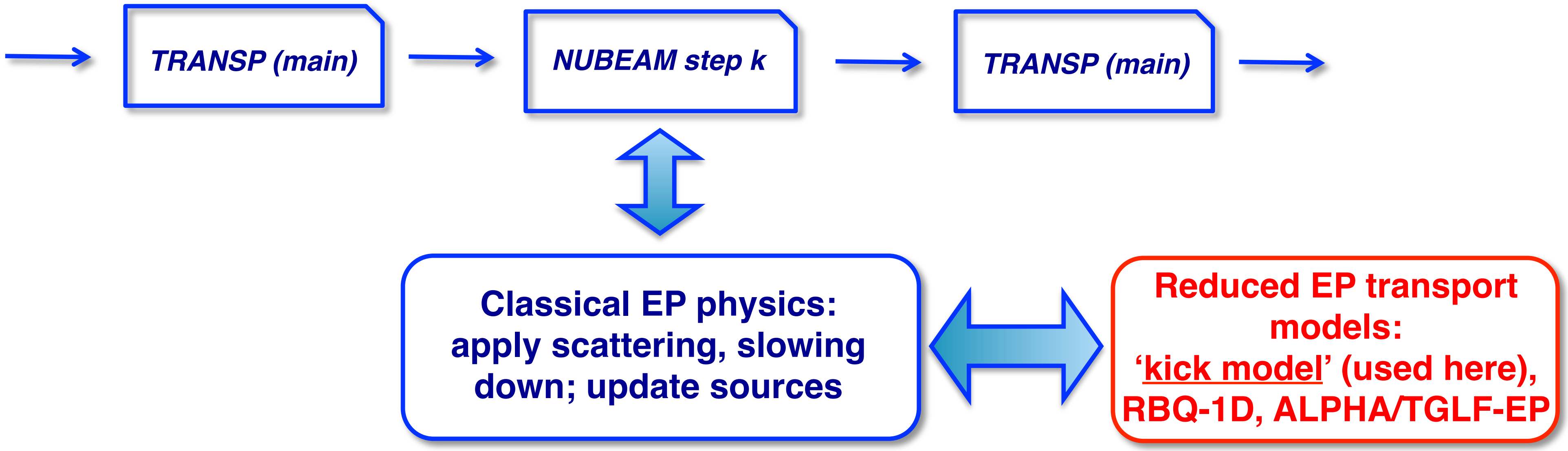
- Overview of analysis tools
- Experimental scenario and TRANSP analysis
- New insight from *stand-alone* analysis
- Conclusions & Future work

Layout

- **Overview of analysis tools**
- Experimental scenario and TRANSP analysis
- New insight from *stand-alone* analysis
- Conclusions & Future work

TRANSP code with new modules for EP transport is the main platform for Integrated Simulations

- NUBEAM module accounts for (neo)classical EP physics
  - Includes Coulomb scattering, slowing down, atomic physics



TRANSP (main)

NUBEAM step k

TRANSP (main)

Classical EP physics: apply scattering, slowing down; update sources

Reduced EP transport models: ‘kick model’ (used here), RBQ-1D, ALPHA/TGLF-EP

Podestà PPCF 2014, PPCF 2017

Physics-based models such as “kick model” enable quantitative assessment of EP transport

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

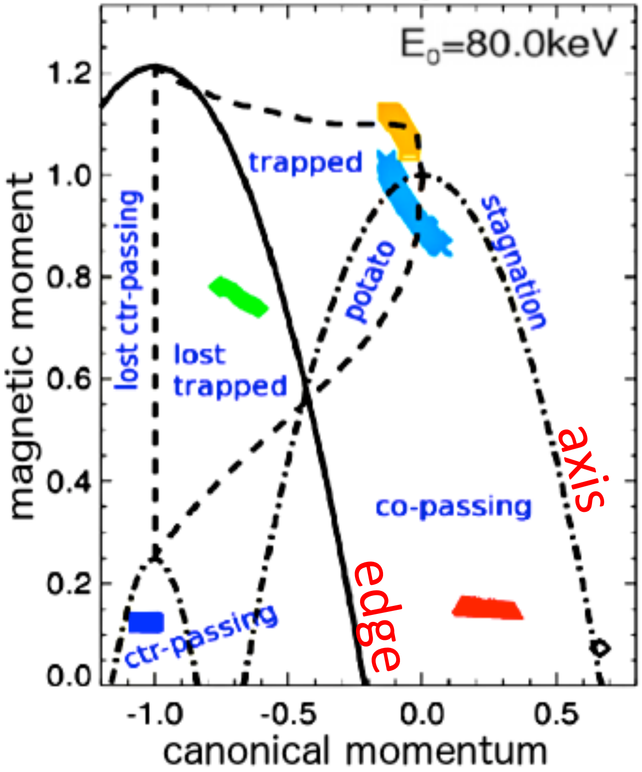
Each orbit characterized by:

E, energy

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

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

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



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

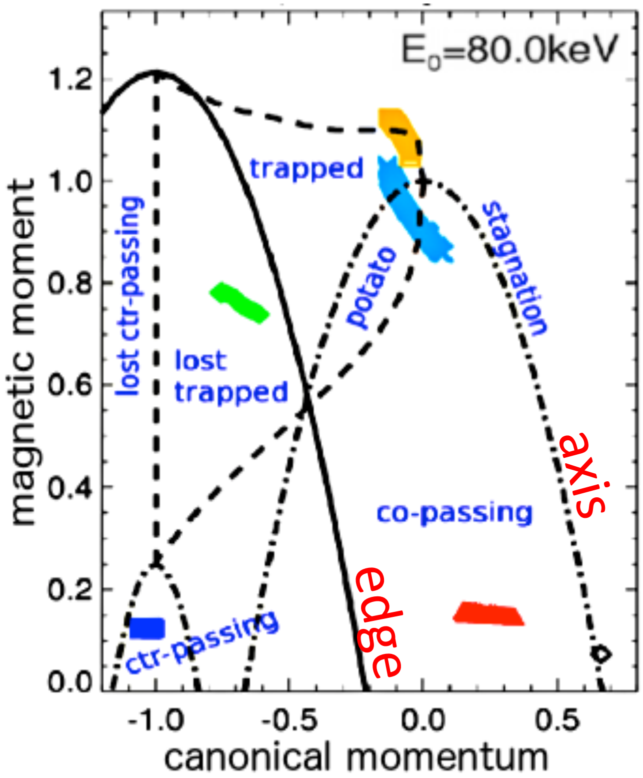
Each orbit characterized by:

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

Wave stability (drive):

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

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



- Resonant interactions obey simple rule:

$$\omega P_\zeta - nE = const.$$

$$\Downarrow$$

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

ω=2πf : mode frequency

n : toroidal mode number

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

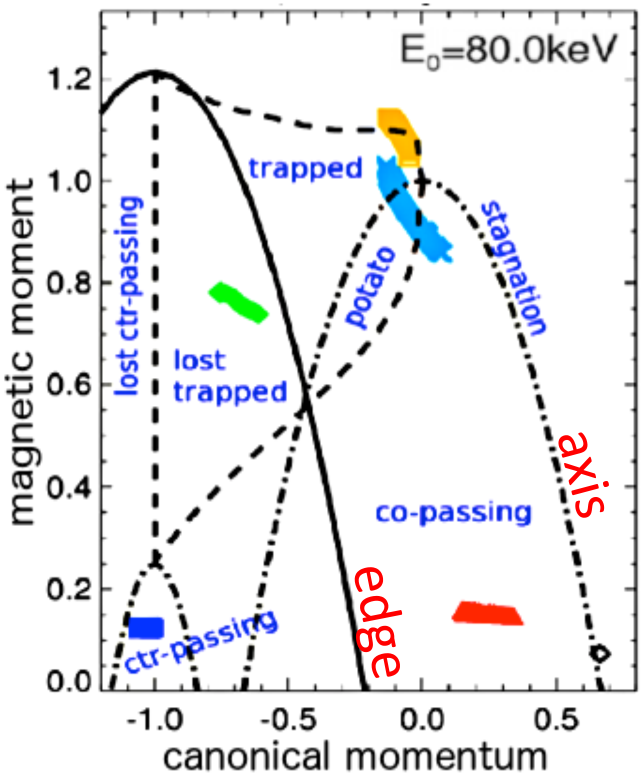
Each orbit characterized by:

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

Wave stability (drive):

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

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



- Resonant interactions obey simple rule:

$$\omega P_\zeta - nE = const.$$

$$\Downarrow$$

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

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

Define ***transport matrix*** for Monte-Carlo NUBEAM:

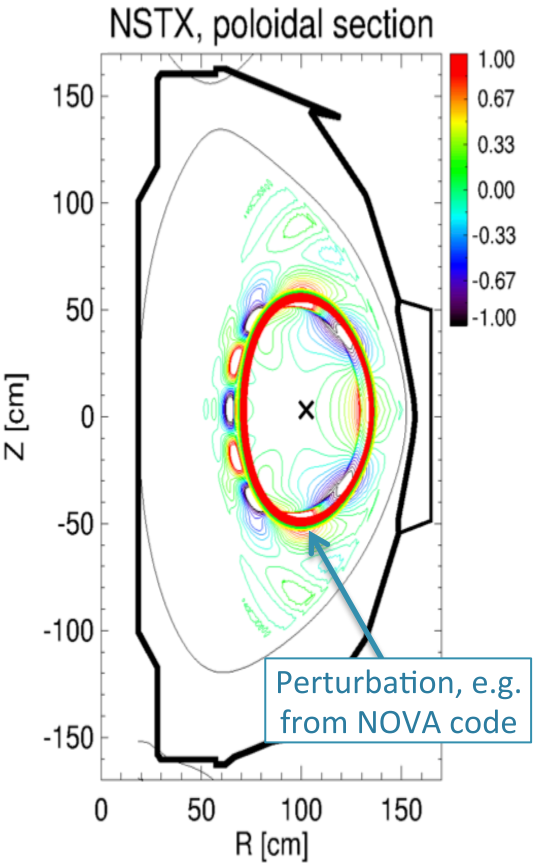
$$p(\Delta E, \Delta P_\zeta \mid E, P_\zeta, \mu)$$

"Conditional probability that a particle at (E, P_ζ, μ) receives kicks ΔE, ΔP_ζ from wave-particle interaction"

Podestà PPCF 2014, PPCF 2017

Kick model: particle-following ORBIT code used to infer transport matrix numerically

Initialize test particles uniformly in phase space

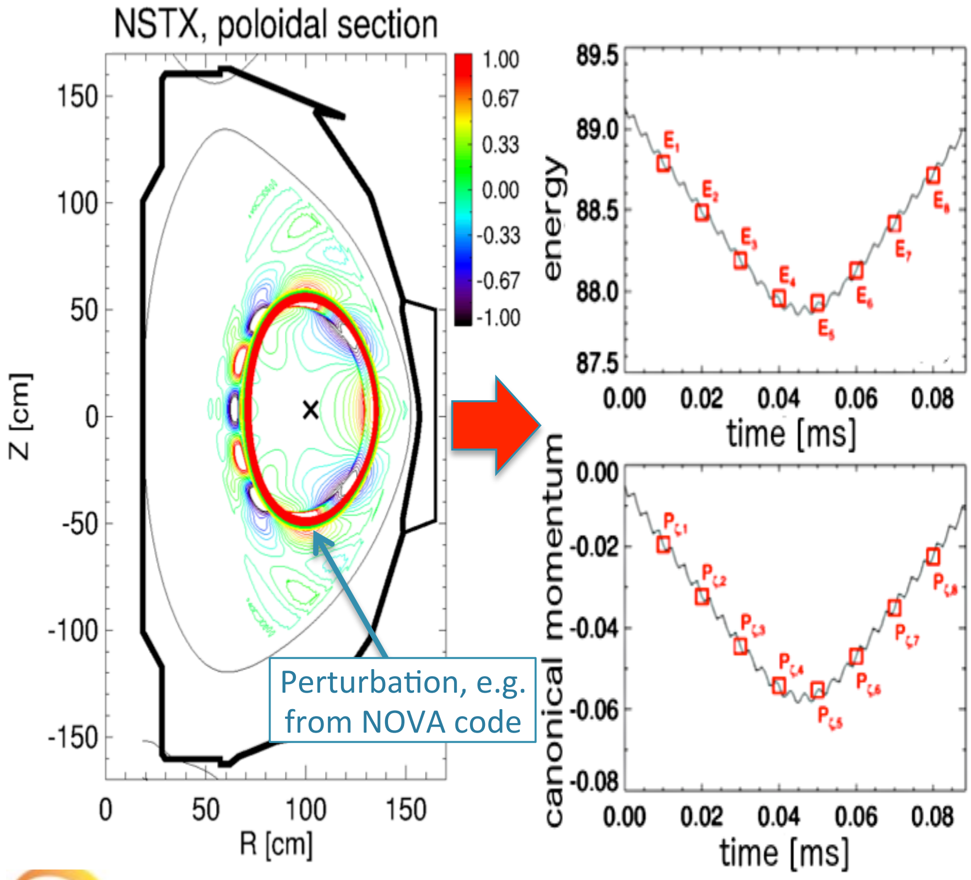


Podestà PPCF 2017

Kick model: particle-following ORBIT code used to infer transport matrix numerically

Initialize test particles uniformly in phase space

Track energy, momentum variations (*kicks*) at fixed time intervals



Perturbation, e.g. from NOVA code

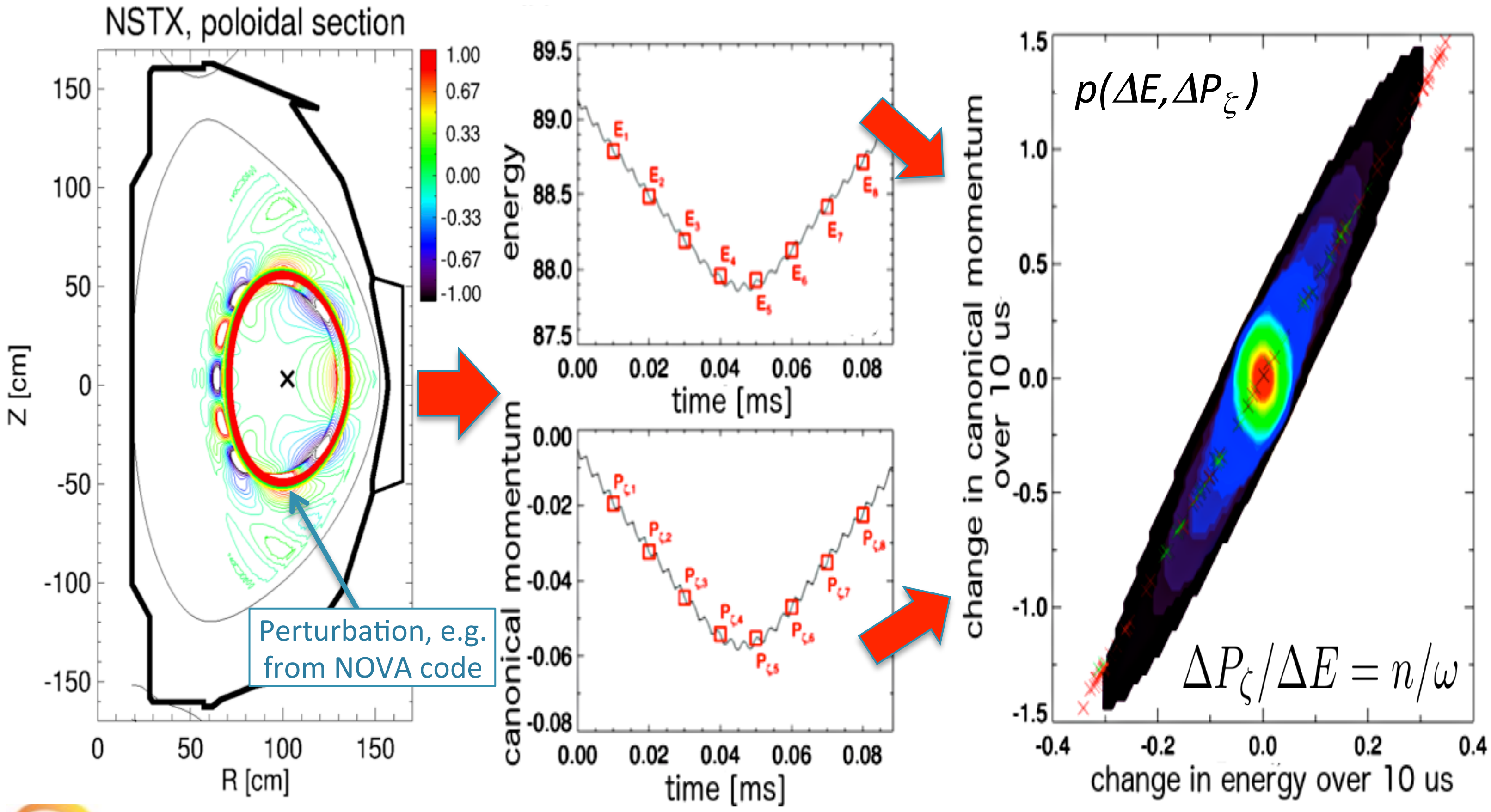
Podestà PPCF 2017

Kick model: particle-following ORBIT code used to infer transport matrix numerically

Initialize test particles uniformly in phase space

Track energy, momentum variations (*kicks*) at fixed time intervals

Combine ΔE, ΔP_ζ from same (E, P_ζ, μ) phase space *bin* into $p(\Delta E, \Delta P_\zeta)$



Podestà PPCF 2017

Kick model: particle-following ORBIT code used to infer transport matrix numerically

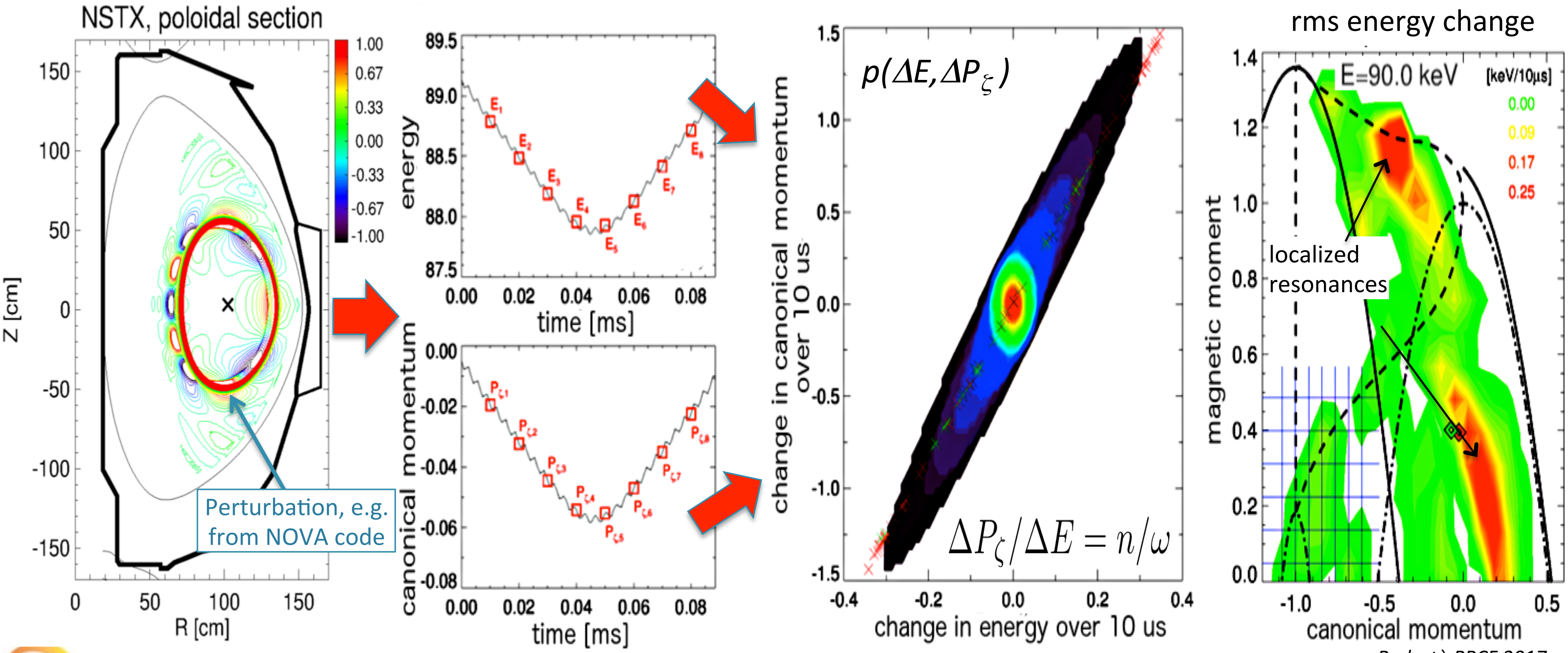
Initialize test particles uniformly in phase space

Track energy, momentum variations (*kicks*) at fixed time intervals

Combine ΔE, ΔP_ζ from same (E,P_ζ,μ) phase space *bin* into $p(\Delta E,\Delta P_\zeta)$

Repeat for all (E,P_ζ,μ) *bins* to infer 5D matrix

input for NUBEAM: $p(\Delta E,\Delta P_\zeta\,|E,P_\zeta,\mu)$

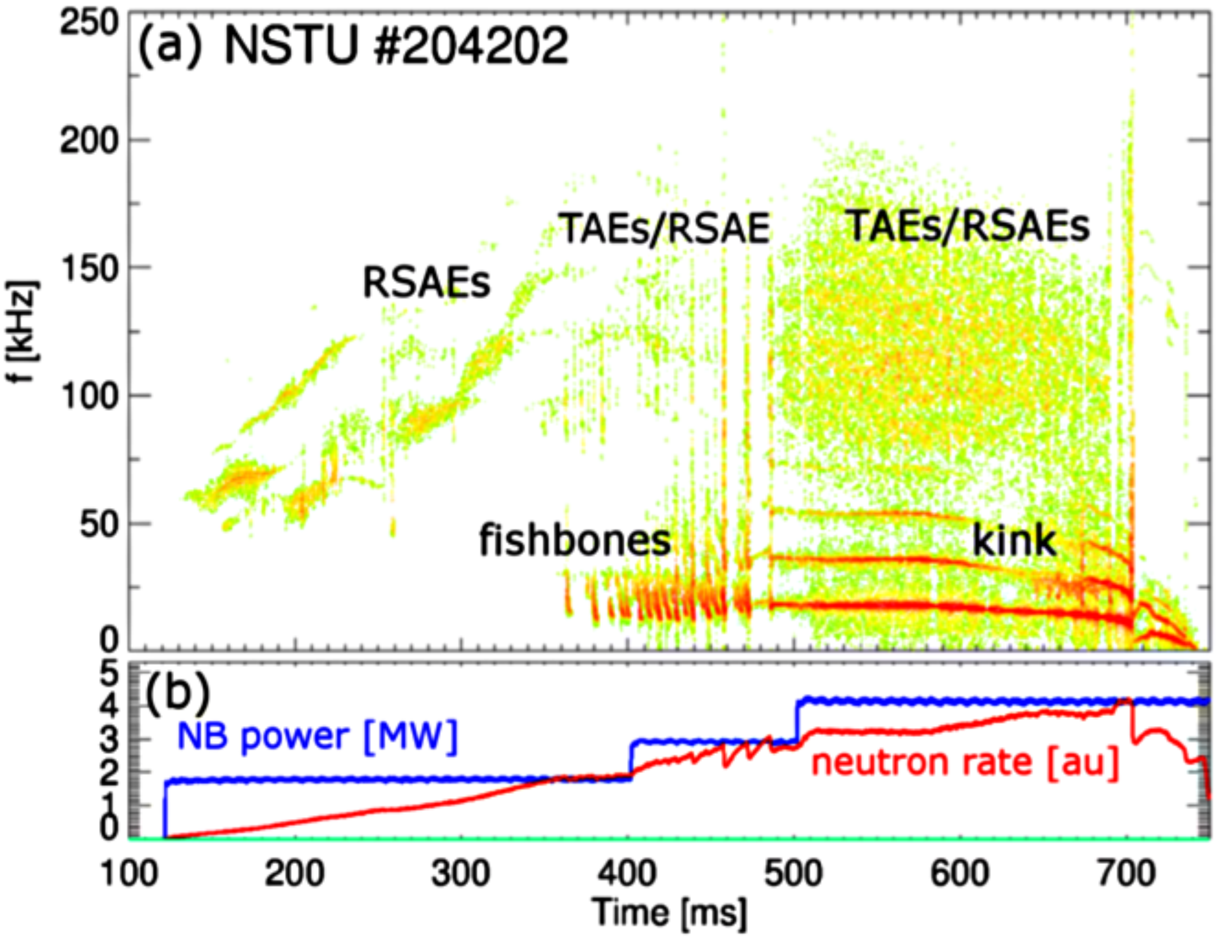


Podestà PPCF 2017

Layout

- Overview of analysis tools
- **Experimental scenario and TRANSP analysis**
- New insight from *stand-alone* analysis
- Conclusions & Future work

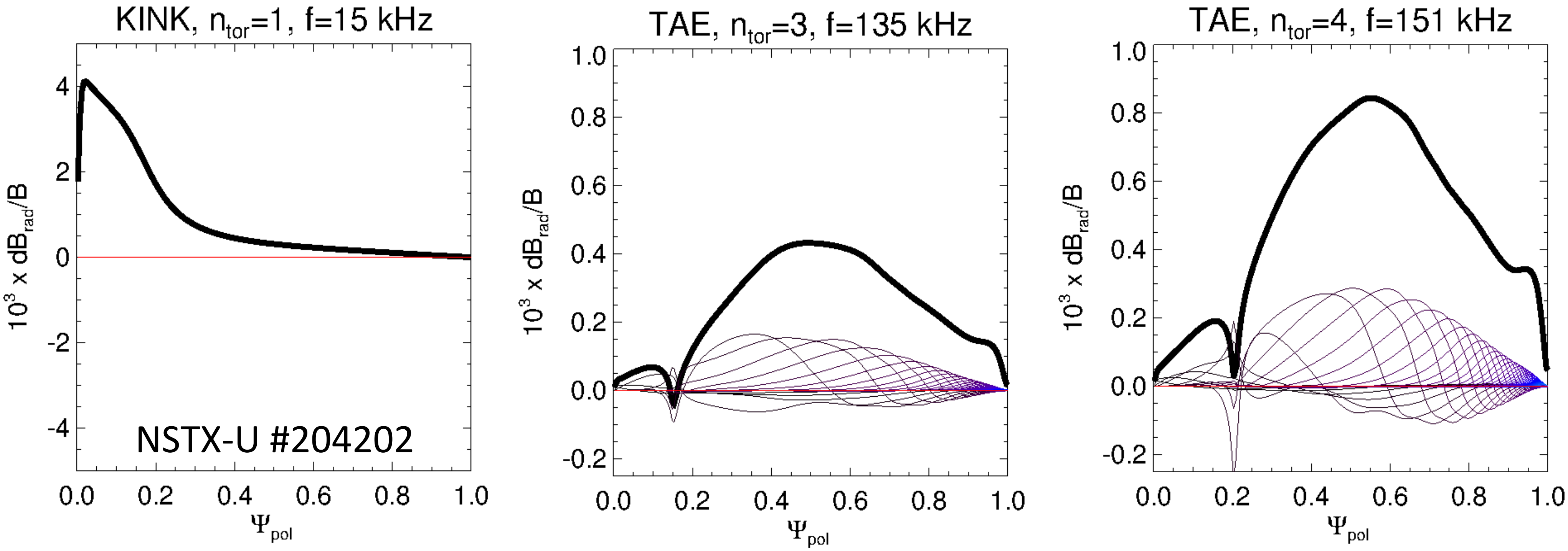
Target scenario: NSTX-U with Alfvénic and low-frequency instabilities



Podestà NF 2019

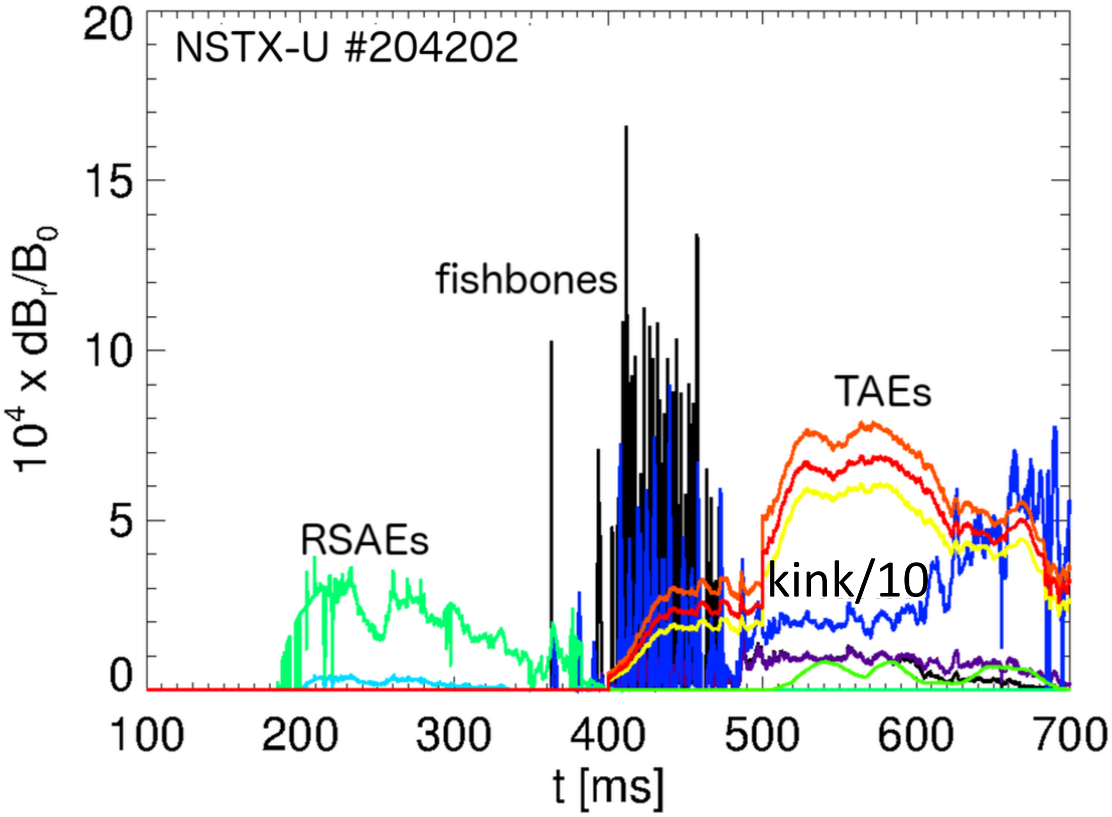
- NB power ramped up as discharge evolves
- q-profile relaxes towards q_{min}~1 -> fishbones, followed by kink
- Alfvénic modes observed throughout entire discharge

Kick model analysis based on AE mode structure from NOVA, analytical (m,n)=(1,1) kink/fishbone



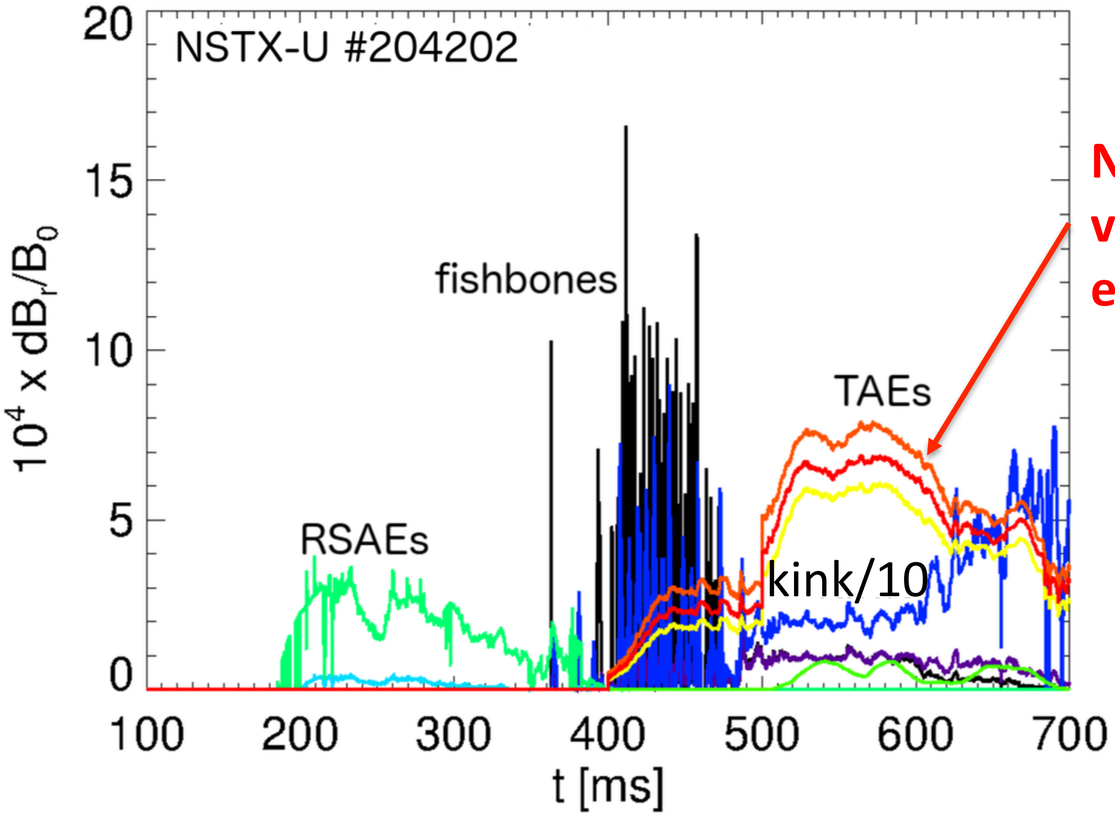
- AEs have n-2-5, f=75-200kHz, broad mode structure
- Hat-like radial displacement used for kink, fishbones

Mode amplitude in kick model: *predictive* for AEs, *interpretive* for low-f modes



- AEs: amplitude estimated <u>from power balance</u>
  - Balance drive and damping at saturation: $\frac{\delta E_{wave}}{\delta t} = P_{EP} - 2\gamma_{damp} E_{wave} = 0$
  - Requires “external” iterations through successive TRANSP runs
- Low-f: amplitude <u>adjusted</u> to match measured neutron rate (AEs included)
  - *Improved from NF 2019 paper: remap displacement on Ψ_{pol}, adjust cutoff location, ...*

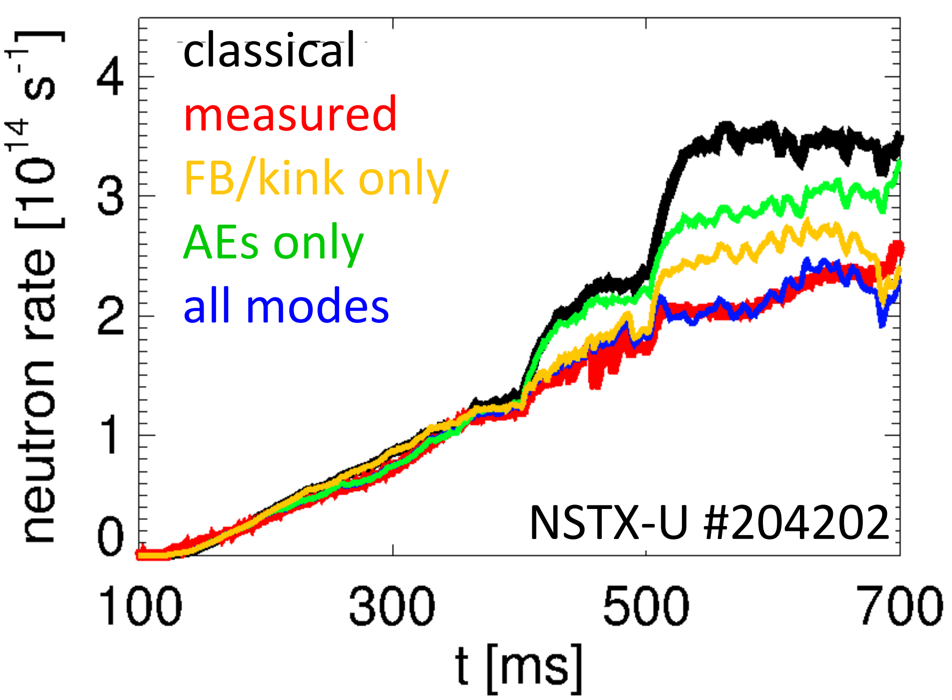
Mode amplitude in kick model: *predictive* for AEs, *interpretive* for low-f modes

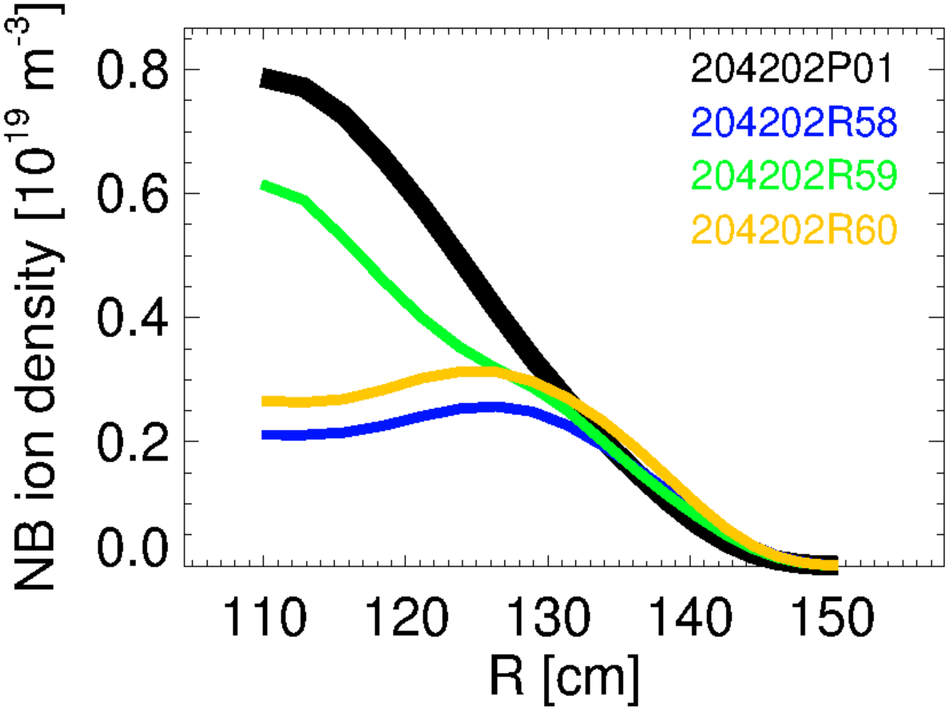


Note: steady amplitude vs bursting amplitudes in experiment

- AEs: amplitude estimated from power balance
  - Balance drive and damping at saturation: $\frac{\delta E_{wave}}{\delta t} = P_{EP} - 2\gamma_{damp}E_{wave} = 0$
  - Requires "external" iterations through successive TRANSP runs
- Low-f: amplitude adjusted to match measured neutron rate (AEs included)
  - *Improved from NF 2019 paper: remap displacement on Ψ_{pol}, adjust cutoff location, ...*

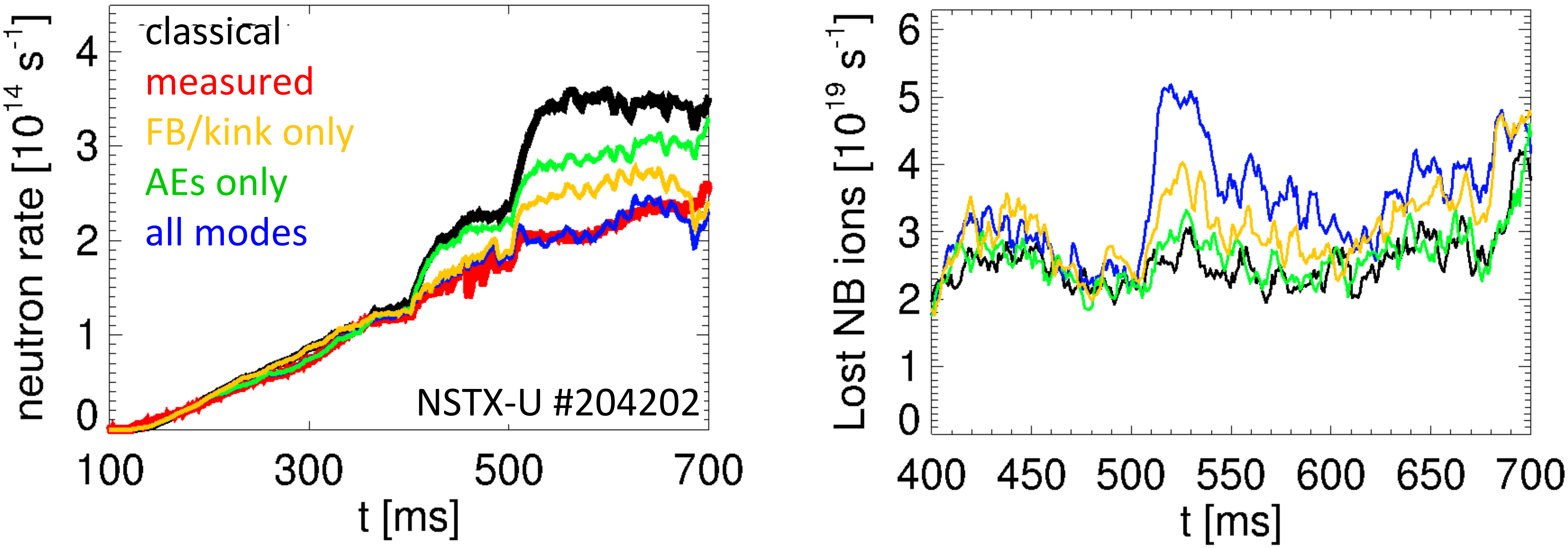
TRANSP + kick model analysis provides assessment of EP transport by different instabilities





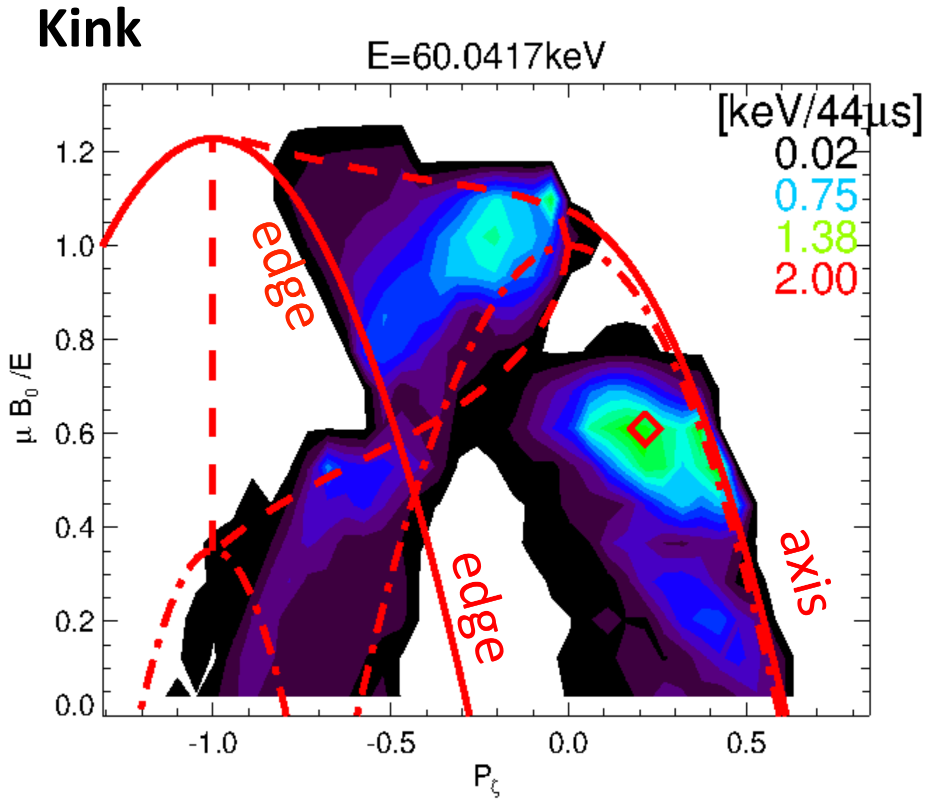
- AEs and fishbones/kinks cause comparable drop in neutrons
  - Fishbones, kinks are mostly responsible for NB ion density depletion
  - AEs have larger effect on NB ion energy redistribution

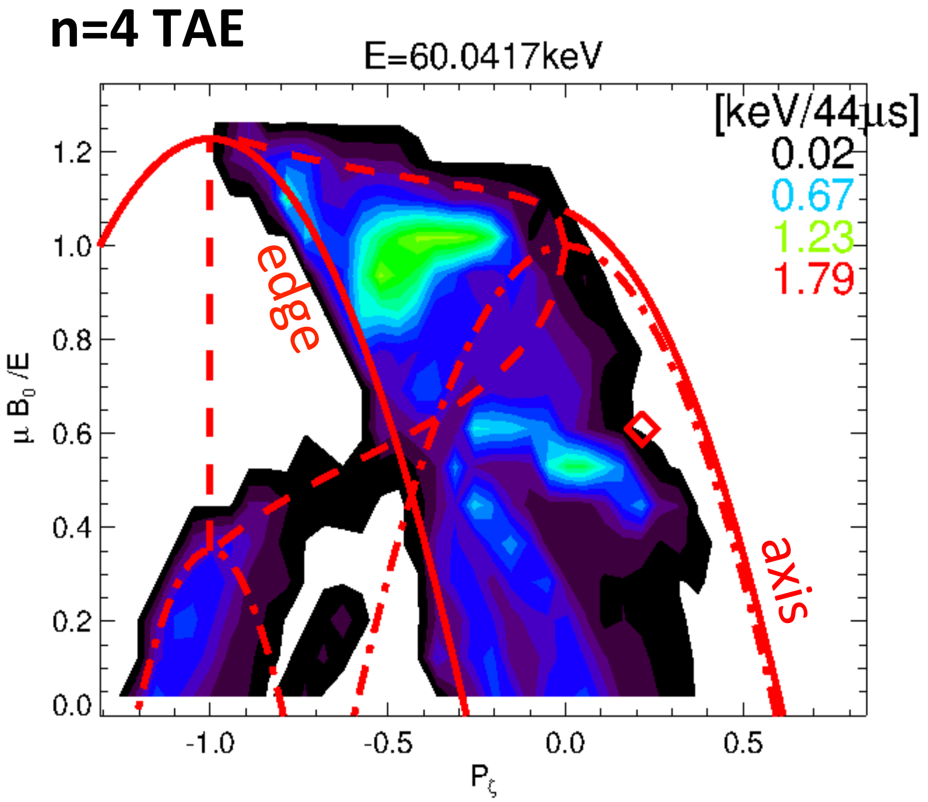
Synergy between AEs and low-f modes observed in calculated fast ion losses



- Little/no losses wrt classical in AE-only simulation
- Fishbones/kinks alone account for ½ total losses
- Total losses double when both types of instabilities are included

Synergy likely caused by phase space location of dominant resonances for different modes


Kink


n=4 TAE

- FBs/kinks push fast ions from core to mid-radius
- AEs mainly active from mid-radius outward
- *Together, AEs/low-f open channel from core to edge -> <u>losses</u>*

Can we reliably <u>model & predict</u> EP transport in scenarios with multiple instabilities?

- Previous work: *<u>interpretive</u>* results mostly consistent with measurements
  - Model guided by experimental data
  - Overall level of EP transport recovered, cf. neutron rate & fast ion diagnostics
  - "Right" spectrum of AE unstable modes: mode numbers, frequency range, evolution

Van Zeeland I-1, this meeting Podestà NF 2015, NF 2018, PPCF 2017
Heidbrink PoP 2017, NF 2018 Collins NF 2017
Kim NF 2018, NF 2019 Bardoczi PPCF 2019 *... and others*

- Conclusions for *<u>predictive</u>* modeling are more ambiguous
  - Mode evolution computed through "external" iterations
    - Steady AE amplitude (modeling) vs bursting amplitude (experiment)
  - No self-consistent model for fishbone/kink saturation yet

Can we reliably model & predict EP transport in scenarios with multiple instabilities?

- Previous work: *interpretive* results mostly consistent with measurements
  - Model guided by experimental data
  - Overall level of EP transport recovered, cf. neutron rate & fast ion diagnostics
  - "Right" spectrum of AE unstable modes: mode numbers, frequency range, evolution

Van Zeeland I-1, this meeting Podestà NF 2015, NF 2018, PPCF 2017
Heidbrink PoP 2017, NF 2018 Collins NF 2017
Kim NF 2018, NF 2019 Bardoczi PPCF 2019 *... and others*

- Conclusions for *predictive* modeling are more ambiguous
  - Mode evolution computed through "external" iterations
    - Steady AE amplitude (modeling) vs bursting amplitude (experiment)
  - No self-consistent model for fishbone/kink saturation yet

Is the lack of self-consistency in mode amplitude prediction an issue?

Layout

- Overview of analysis tools
- Experimental scenario and TRANSP analysis
- **New insight from *stand-alone* analysis**
- Conclusions & Future work

Check reliability of *interpretive* analysis to assess validity of *predictive* AE saturation results

- Use stand-alone NUBEAM as test-bed:
  - Freeze profiles and NB injection parameters @610ms
  - Keep kink amplitude constant, same as in reference TRANSP run
  - Start AEs at low amplitude, $\delta B_r/B \sim 10^{-6}$
  - Run NUBEAM with 100μs time-step
  - Update AE amplitude between steps based on power balance:

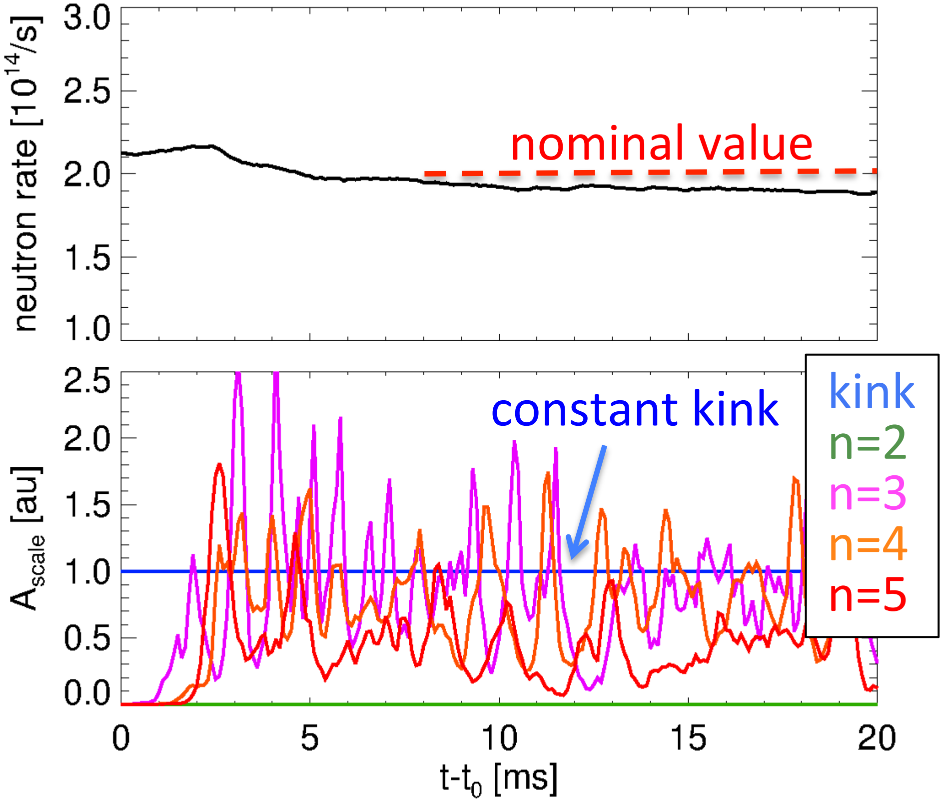
$$\frac{\delta E_{wave}}{\delta t} = P_{EP} - 2\gamma_{damp} E_{wave}$$

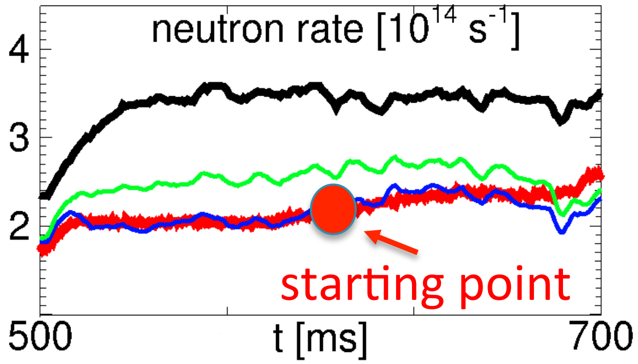
drive from NUBEAM + kick model

damping from NOVA-K

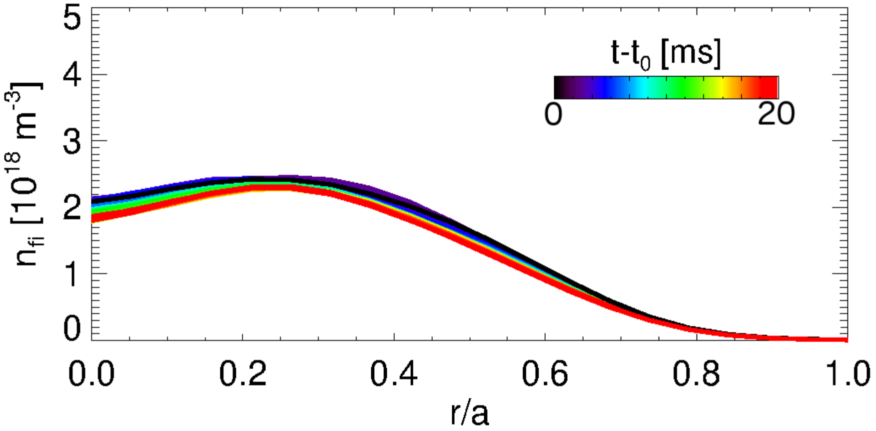
  - Repeat to cover 20ms, or approx ~1 slowing-down time
  - Modify initial conditions & repeat: ***do simulation results converge?***

Start from ref. TRANSP run: AEs and kink active before t_0=610ms, profiles already relaxed



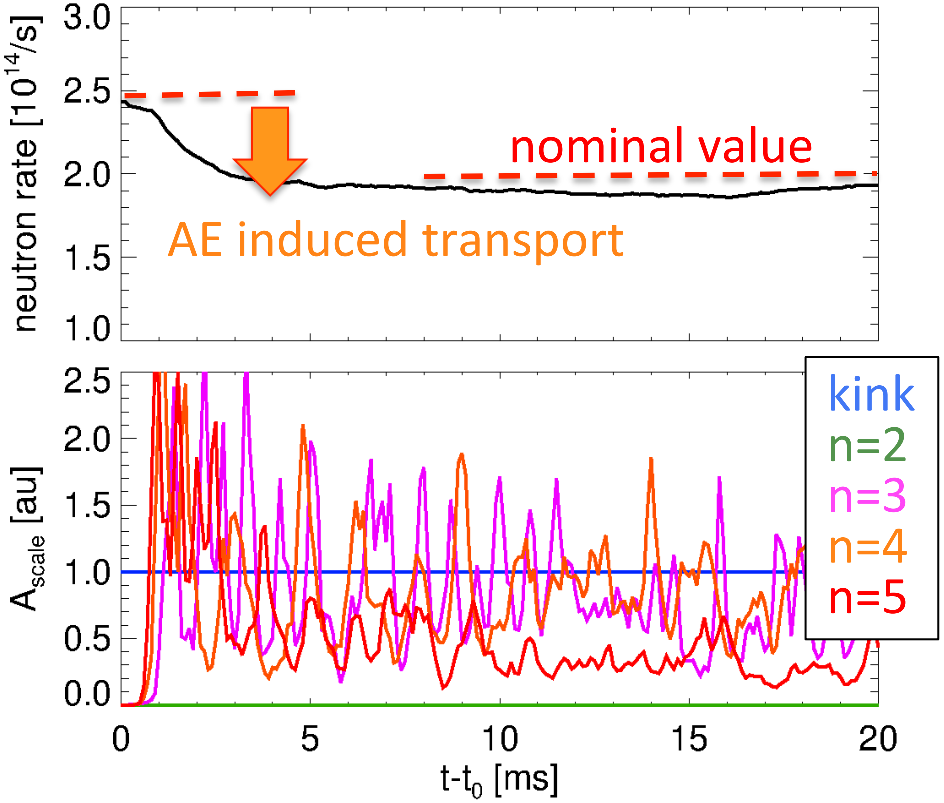


- Neutron rate remains roughly constant
- n=3-5 TAEs unstable, n=2 stable
- Modes show amplitude bursts
  - Consistent with experiment
  - *Same "predator-prey" physics as in Gorelenkov's talk? (see O-20, tomorrow)*



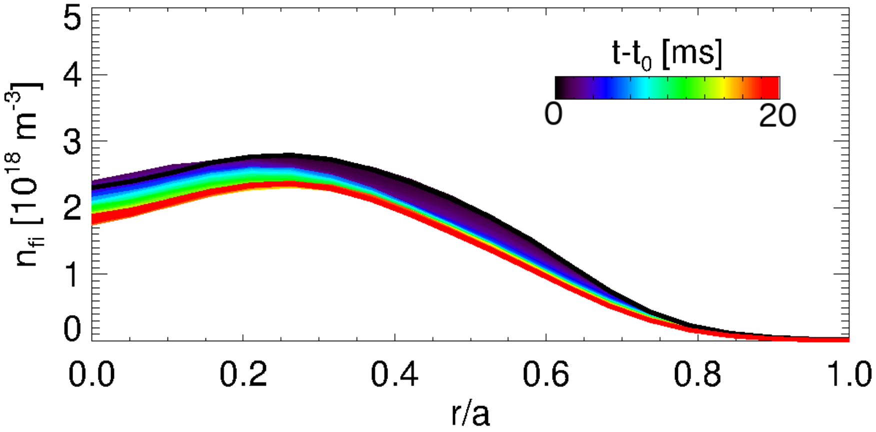
- NB ion density remains around nominal profile

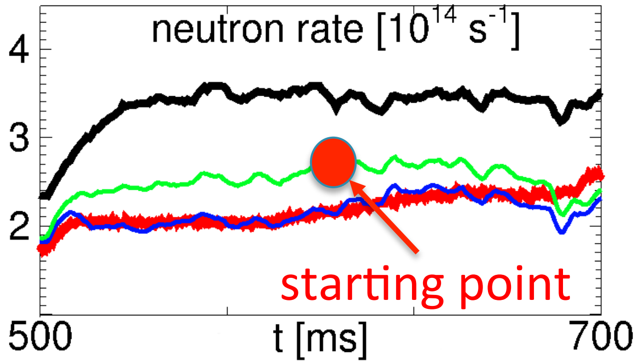
Start from run with low-f modes only: good convergence of simulation results



nominal value

AE induced transport

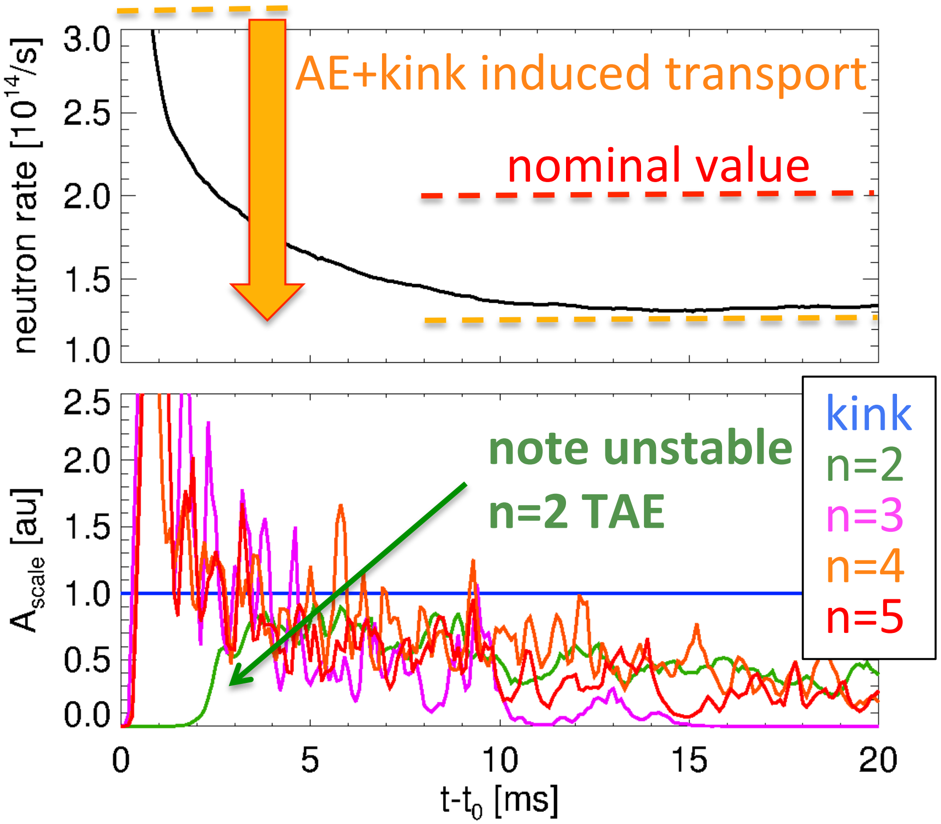


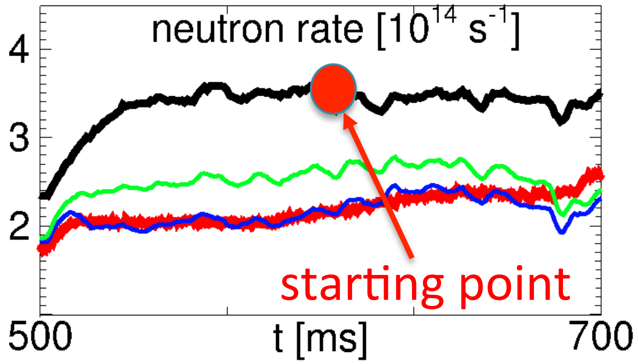


starting point

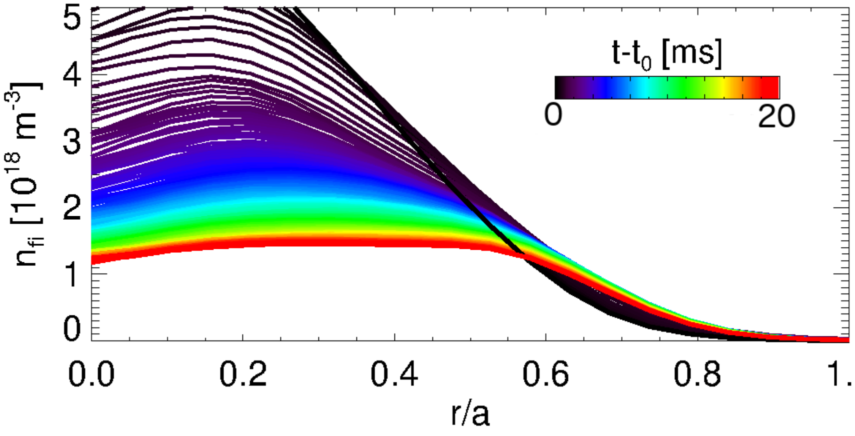
- Neutron rate drops to nominal value as AE amplitude “saturates”
- After transient, AEs show similar dynamic as in previous case
  - Bursting amplitude, similar level
- NB ion density relaxes to nominal profile

Start from 'classical' run, no prior effects of AEs & low-f modes: *converge to a different state*





- Larger drop in neutron rate
- AEs show different evolution than in previous cases
  - Large initial spike, bursts reduced
  - n=2 TAE now destabilized, unlike in previous cases



- NB ion density profile flatter, reduced to <70% than in previous cases

- ***Simulation converges to a different state as initial conditions are varied considerably***

Layout

- Overview of analysis tools
- Experimental scenario and TRANSP analysis
- New insight from *stand-alone* analysis
- **Conclusions & Future work**

NSTX-U simulations via reduced EP transport model: promising results, but more work needed for reliable predictive runs

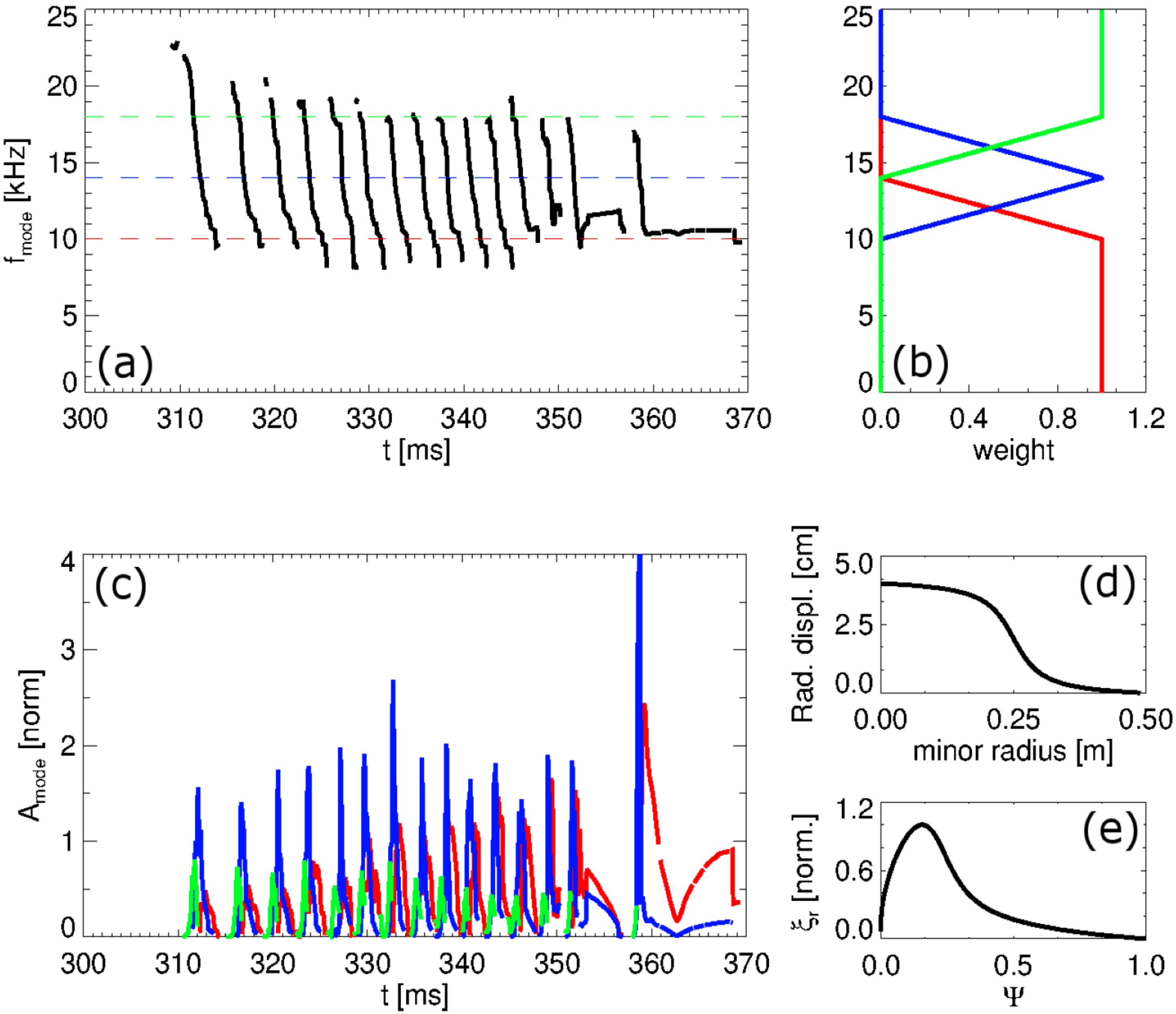
- Scenarios with AEs and low-f instabilities offer stringent test-bed for EP transport model validation

- Different instabilities can interact strongly, e.g. via modification of EP distribution
  - Observed synergy between modes -> enhanced losses
  - Important to compute self-consistent mode saturation
  - Other, possibly important mechanisms are neglected – e.g., mode-mode coupling
  - *Implication: all instabilities need to be included in simulations for consistent results*
  - Also implies that time-dependent simulations are required: previous history matters

- Future work on kick model in TRANSP: continue validation, improve predictive simulation capabilities
  - Improve model to infer saturation for kinks, fishbones, sawteeth, NTMs, ...
  - Implement EP transport by ripple, 3D fields, micro-turbulence (ongoing)
  - *Assess requirements to implement MHD module in TRANSP*

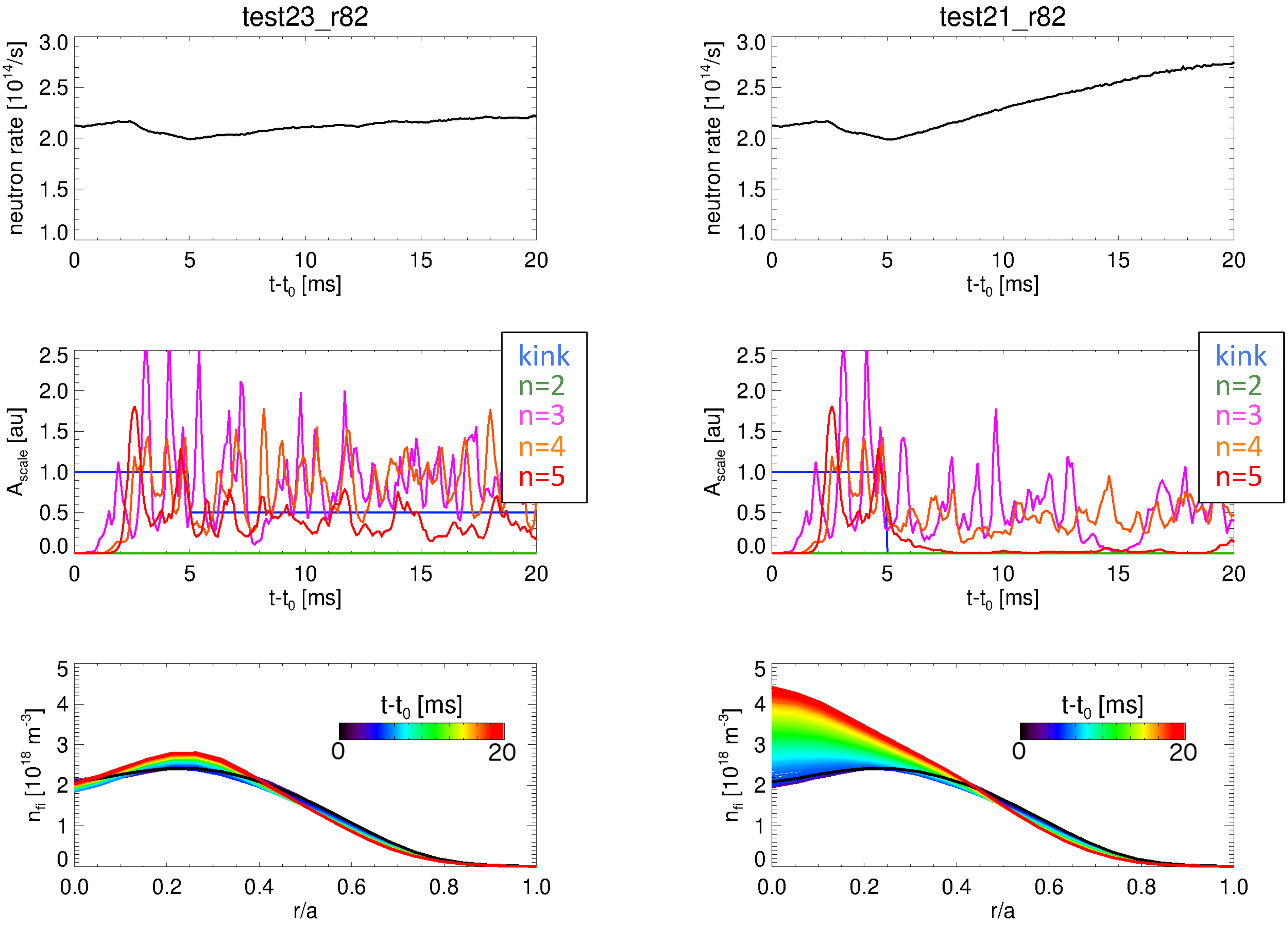
Backup

Fishbone modeled as superposition of three "sub-modes" to mimic frequency sweep

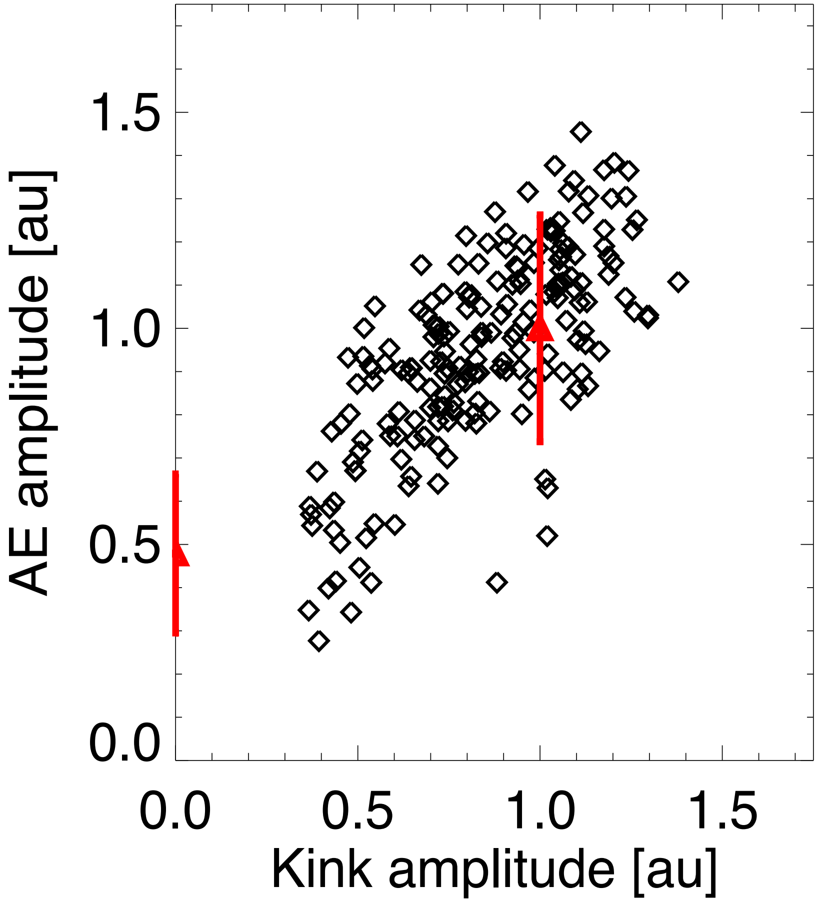


Podestà NF 2019

Test: decrease kink amplitude, look at changes in TAE behavior & saturation level

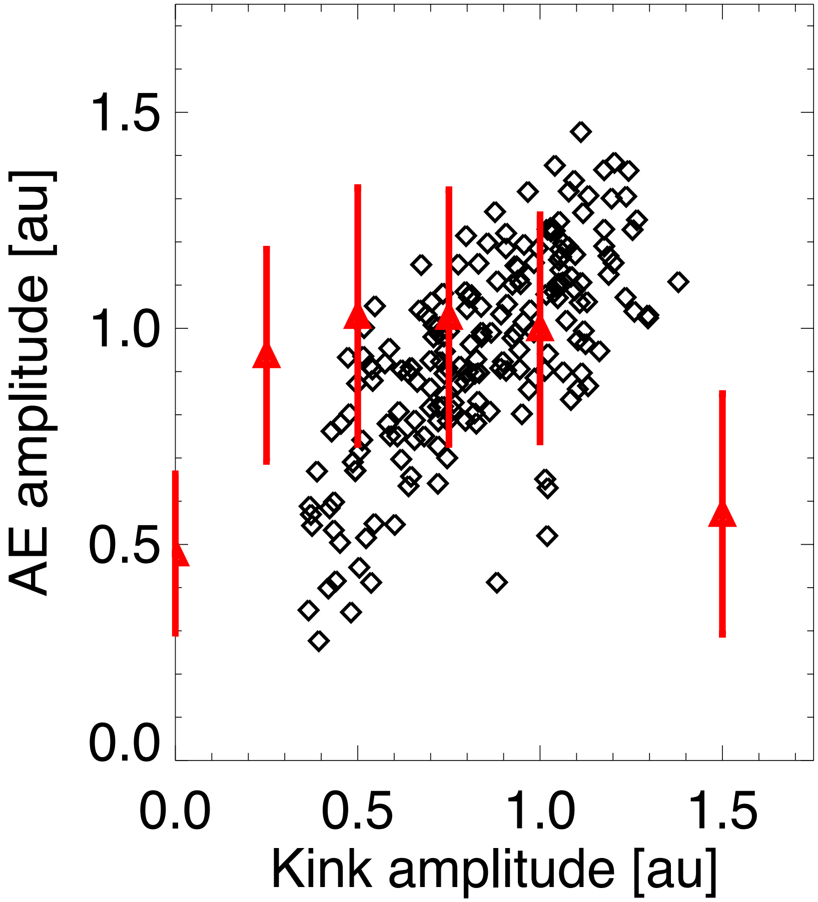


Vary kink amplitude during "stationary phase", look at changes in TAE dynamic and saturation



- Black: experimental amplitudes, normalized to average
- Red: results from modeling, vary kink amplitude

Vary kink amplitude during “stationary phase”, look at changes in TAE dynamic and saturation



- Black: experimental amplitudes, normalized to average
- Red: results from modeling, vary kink amplitude

- *Clear discrepancy in AE vs kink amplitude*
  - Forcing kink amplitude here
  - Not accounting for self-consistent mode saturation
  - Not accounting for possible effects on background profiles