EXTENSION OF THE REDUCED ENERGETIC PARTICLE TRANSPORT *KICK MODEL* TO LOW-FREQUENCY PERTURBATIONS

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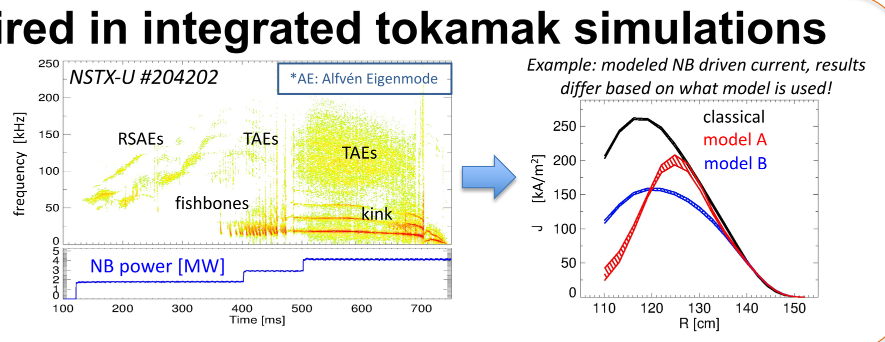
Verified, validated EP models are required in integrated tokamak simulations

- EPs (alphas, NB ions, RF tails) provide main source of heating, momentum, current drive in burning plasmas
- *But: EPs drive instabilities, instabilities affect EPs*

This work: reduced EP transport models being developed, validated for time-dependent predictive simulations



TRANSP is the main platform for testing EP models in Integrated Simulations

- NUBEAM module in TRANSP accounts for (neo)classical EP physics
- Includes scattering, slowing down, atomic physics (charge-exchange)

→ **TRANSP (main)** → **NUBEAM step k** → **TRANSP (main)** →

Ad-hoc EP diffusivity: e.g. adjusted to match neutron rate — *Ad-hoc transport models: -> often unphysical -> no predictive capabilities!*

Classical EP physics: apply scattering, slowing down; update sources — *NUBEAM can be inaccurate when EP transport is enhanced by instabilities*

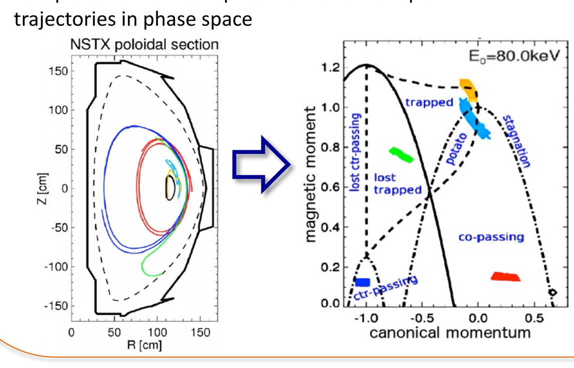
Phase-space resolved reduced EP models: kick, RBQ, … — *Physics-based models -> enable predictive capabilities*

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

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

Each **particle 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



Wave stability (drive):

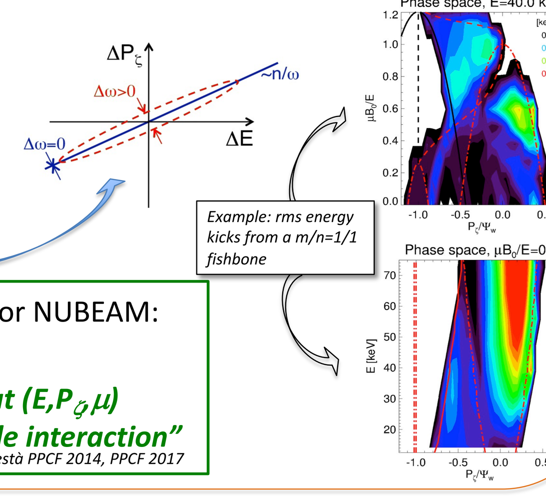
$$\gamma \propto \omega \frac{\partial F_{nb}}{\partial E} + n \frac{\partial F_{nb}}{\partial P_\zeta}$$

Resonant interactions obey simple rule:

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

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

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



Define ***transport probability matrix(es)*** for NUBEAM:

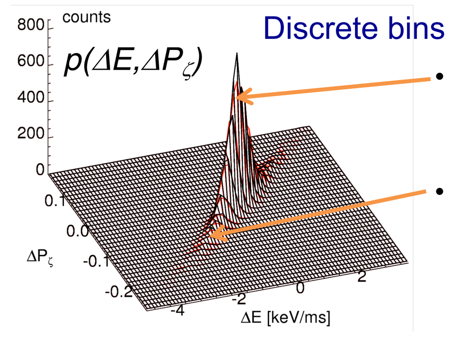
$$p(\Delta E, \Delta P_\zeta | E, P_\zeta, \mu)$$

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

Podestà PPCF 2014, PPCF 2017

Probability matrices describe enhanced transport in Monte Carlo module NUBEAM

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



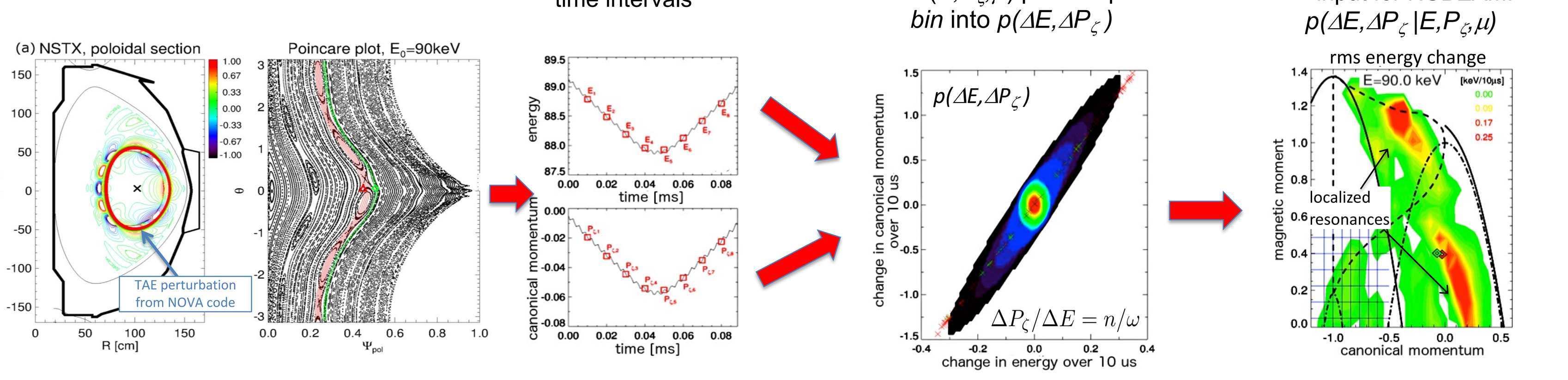
- 'Non-resonant' particles have small fluctuations around initial (E, P_ζ)
- 'Resonant' particles can experience large ΔE, ΔP_ζ variations

- Probability matrix approach not limited to "diffusive" transport
- Can account for convective transport
  - Skewed PDF
- Can be used to introduce different sources of EP transport
  - MHD instabilities
  - Microturbulence
  - 3D fields (not explored yet)

Kick model distills physics of wave-particle interaction for inclusion in $p(\Delta E, \Delta P_\zeta)$ transport matrix for NUBEAM

- AEs: use mode structure, damping rate from MHD codes, e.g. NOVA/NOVA-K
  - Input: thermal profiles, equilibrium
- Kinks, Tearing Modes: analytic expressions for mode structure; mode spectrum and frequency from experiments
  - Kinks: hat-like radial displacement
  - TMs: alpha(m,n,Psi) coefficients from simple gaussian at q=m/n or cylindrical model
- Particle-following code ORBIT 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 compute 5D matrix -> input for NUBEAM: $p(\Delta E, \Delta P_\zeta | E, P_\zeta, \mu)$



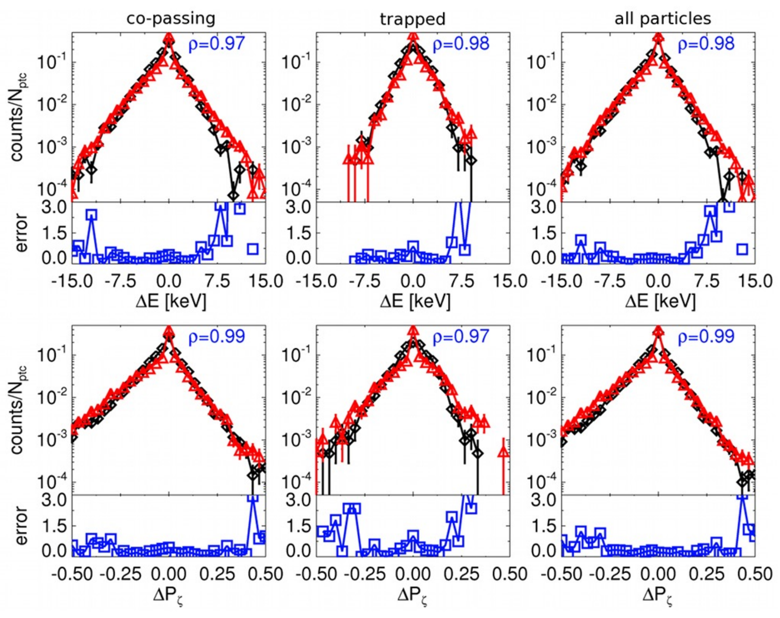
Podestà PPCF 2014, 2017

Kick model approach has been verified with ORBIT code

White PF-B 1984

- Evolve initial particle distribution
- Kick model: apply transport matrix to modify energy, canonical toroidal momentum
- ORBIT: apply perturbation to evolve orbits
- Good agreement with ORBIT observed when evolving F_{nb} over 5 ms, typical time step of NUBEAM

Good reconstruction over 3 orders of magnitude for co-, trapped (, counter- not present in *this* input F_{nb}) particles



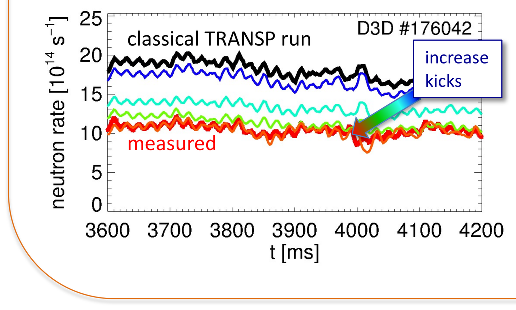
black: ORBIT
red: Kick Model
ρ: correlation coefficient
error: (ORBIT-model)/ORBIT

Podestà PPCF 2014, PPCF 2017, NF 2018

Model can be used for both *interpretive* and *predictive* simulations

- Focus on energetic particle evolution, stability of EP-driven instabilities (e.g. Alfvén Eigenmodes), EP transport by instabilities

Interpretive runs: *reduced input from experiment*
- *To validate EP models, analyze actual discharges*
- Use experimental info to set ΔE, ΔP_ζ
  - E.g. based on neutron rate, internal measurements of mode amplitude



Predictive runs:
- *To optimize/explore new scenarios*
- Use saturation condition to set ΔE, ΔP_ζ
  - Impose drive = damping vs time

$$\frac{\delta E_{wave}}{\delta t} = P_{EP} - 2\gamma_{damp} E_{wave} = 0$$

drive from NUBEAM or RBQ-1D; damping from NOVA-K

Main limitation:
- *Can be only as good as damping rate estimates!*

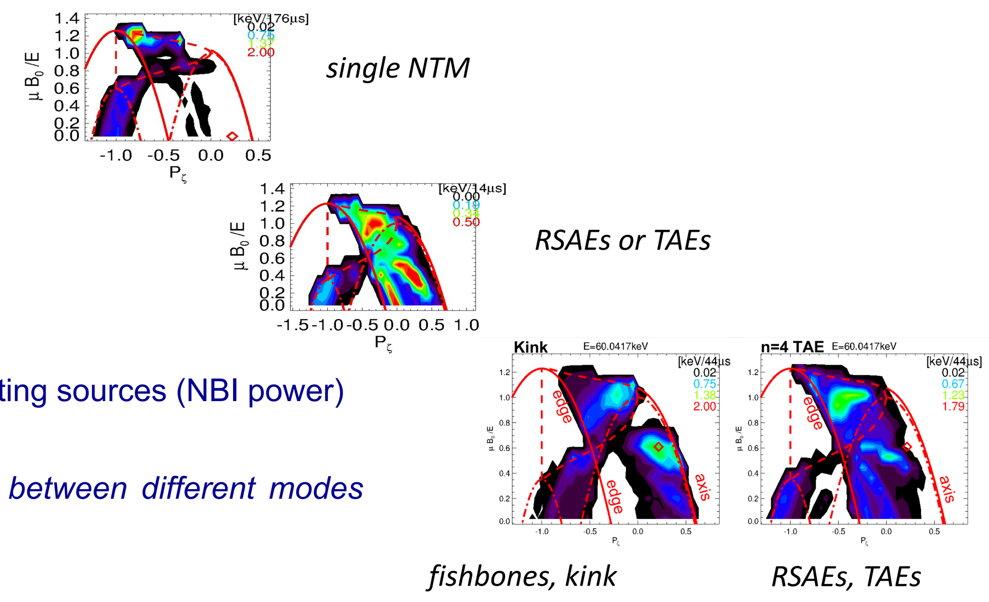
- **Many practical cases lie in between 'fully interpretive' & 'fully predictive'**
- For example, only *relative* mode amplitudes may be known from experiment
- Or: parameters for predictions are adjusted based on experimental information
  - e.g. limit frequency and mode number range
- Also: thermal profiles are assumed to be known in this work!
- *For truly predictive simulations, thermal profiles would need to be recomputed as sources change*

Podestà PPCF 2017

NSTX-U scenarios challenge models over broad set of conditions

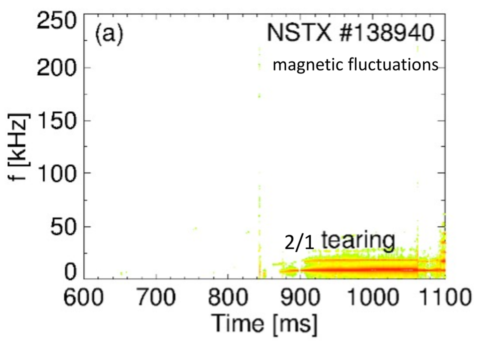
complexity

- NTM-only scenario
  - Single (dominant) instability
  - Limited number of resonances
- AEs-only scenario
  - Potentially large number of weaker AEs
  - "Sea" of resonances
- Multi-mode scenario
  - Variations in background plasma & heating sources (NBI power)
  - Multiple types of instabilities
  - *Need to account for possible synergy between different modes (e.g. fishbones + TAEs, kink + TAEs)*

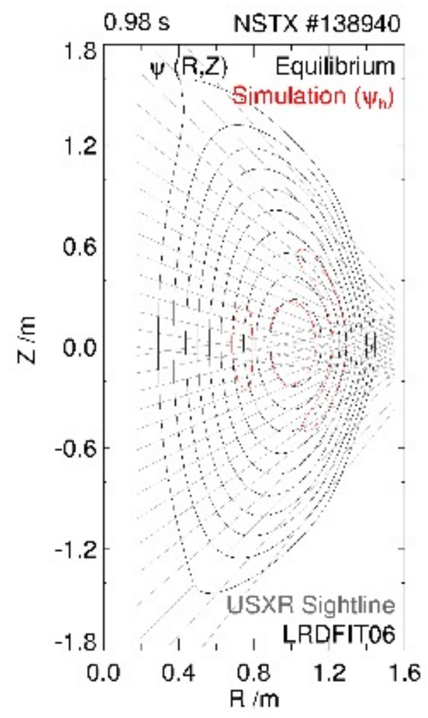


NSTX discharges with coupled kink and Tearing Mode

- NTM destabilized at end of discharge
  - Dominant 2/1 in this case
- No instabilities in the TAE frequency range observed during the time of interest
- Large TM amplitude causes EP confinement degradation
  - Clear drop in neutron rate

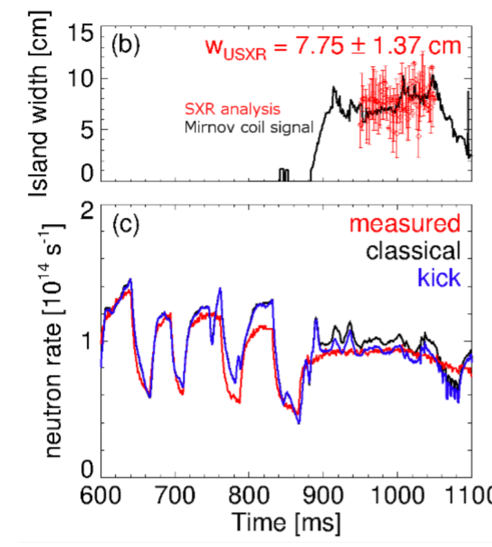


Yang PPCF 2021



- NTM island width is determined from forward modeling of perturbed emissivity from Soft X-Ray
- Need to include a 1/1 kink "non-resonant" component to achieve good fit
- Kink and TM are locked in phase

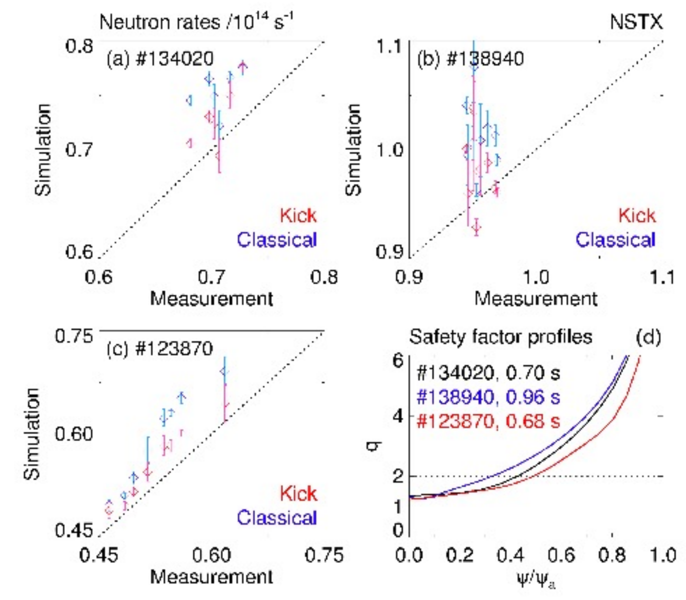
Yang PPCF 2021
Fredrickson PoP 2002



- NTM island width from Mirnov coils is rescaled based on absolute value from SXR fit
- Kick model matrix computed for coupled kink+TM
- TRANSP + kick reproduces experimental drop in neutron rate

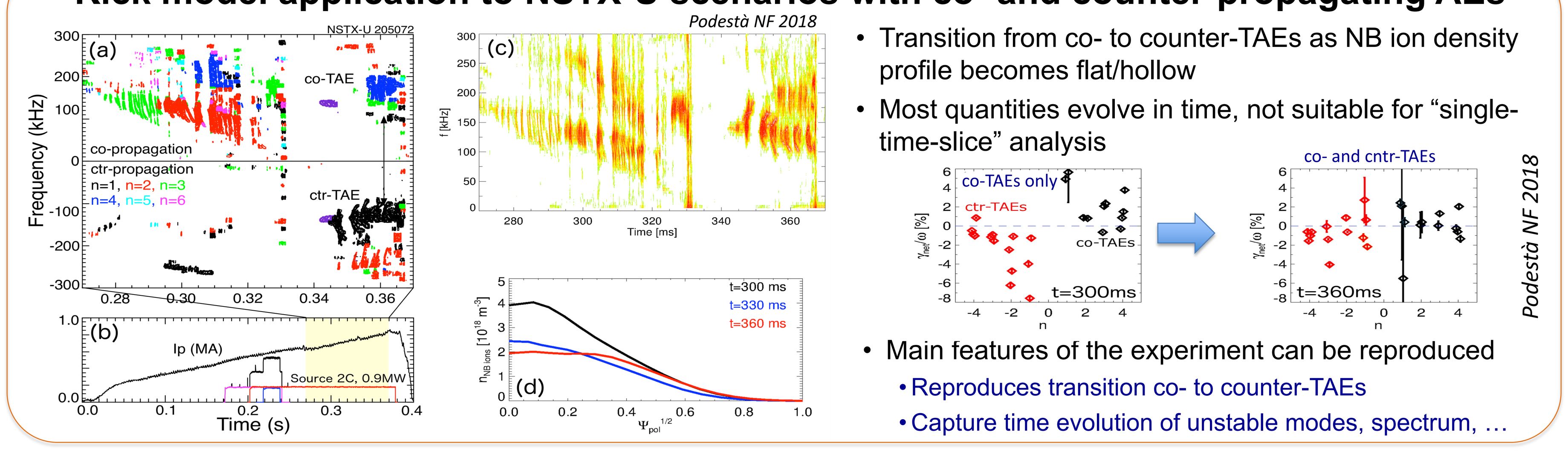
- Analysis from three NSTX discharges with different q-profile confirms validity of the approach
- *Drop in neutron rate (~10%) recovered with no free parameters*
- Extend previous work on DIII-D

Heidbrink NF 2018 *Bardoczi PPCF 2019*
Madsen NF 2020 *Liu NF 2020*



Kick model application to NSTX-U scenarios with co- and counter-propagating AEs

Podestà NF 2018



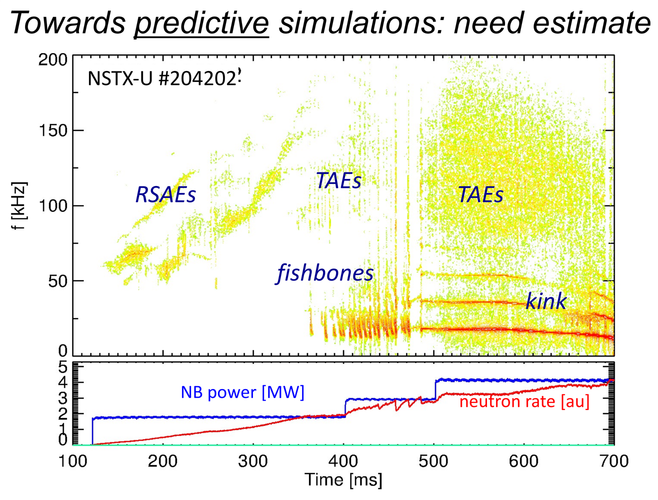
- Transition from co- to counter-TAEs as NB ion density profile becomes flat/hollow
- Most quantities evolve in time, not suitable for "single-time-slice" analysis
- Main features of the experiment can be reproduced
  - Reproduces transition co- to counter-TAEs
  - Capture time evolution of unstable modes, spectrum, …

Podestà NF 2018

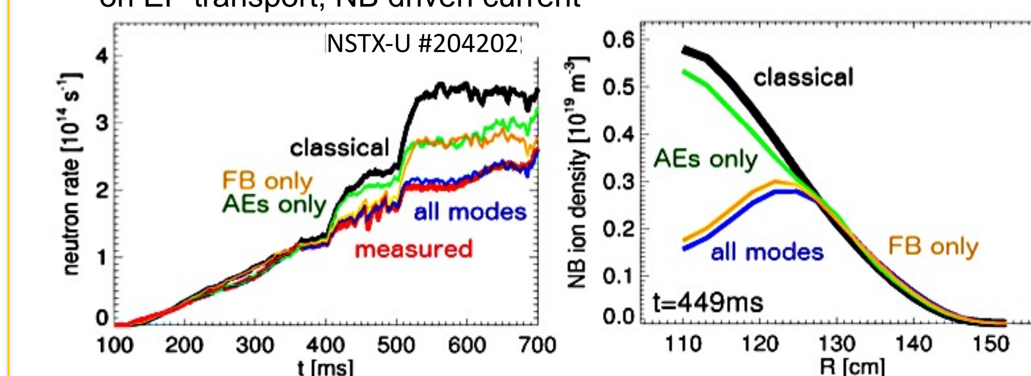
Kick model application to NSTX-U multi-mode scenario

Podestà NF 2019

Towards predictive simulations: need estimate of unstable spectrum, saturated amplitudes



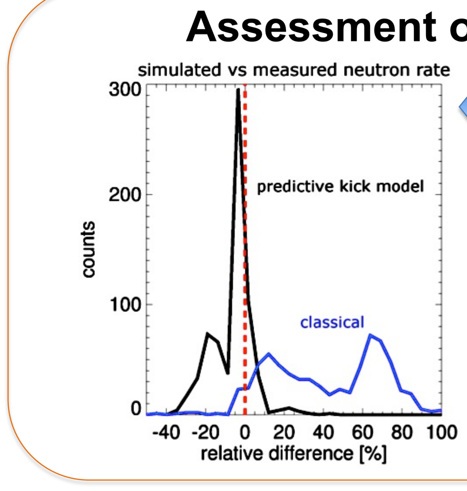
- Analysis provides assessment of role of different instabilities on EP transport, NB driven current



- Initial estimate for relative AE amplitudes:
  - Use saturation condition (drive=damping) to infer AE amplitudes vs time
- Then, rescale amplitude of fishbone & kink to match measured neutron rate
  - No damping available

- AEs and fishbones/kinks cause comparable drop in neutrons
  - Fishbones, kinks are mostly responsible for NB ion density depletion near the plasma core
  - AEs have larger effect on NB ion energy redistribution
- *Synergy between modes is observed*, e.g. in total EP losses

Assessment of *predictive* capabilities for AE-induced fast ion transport



Relative difference from interpretive simulations: NSTX, NSTX-U and DIII-D database

- *Predictive* analysis (AEs only) results generally agree within +/-15% with *interpretive* simulations
- However: in some cases, predictive runs fail to reproduce experiments!
  - Predicted AE spectrum differs from experiment
  - *Key role of damping rate from MHD codes*
    - Affects inferred AE saturation amplitude
- ***More validation is required to assess model limitations, missing physics***

Conclusions and future work

- Kick model extended to low-f instabilities, e.g. sawteeth, kink/fishbones, NTMs
- Model can reproduce experimental observations of fast ion transport
- Validation continues on several devices, including multi-species DT plasmas on JET

- Reduced models enable efficient simulations retaining (most of) the relevant EP physics
  - Including *predictive* capabilities (ITER & beyond)
- Phase-space resolution is required to move beyond *ad-hoc* models
  - Critical for heating, current drive, thermal transport
- ***Overall goal: develop framework to streamline TRANSP analysis including effects of instabilities on EPs***

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 U.S. DOE Office of Science User Facility