Reduced energetic particle transport models enable comprehensive time-dependent tokamak simulations

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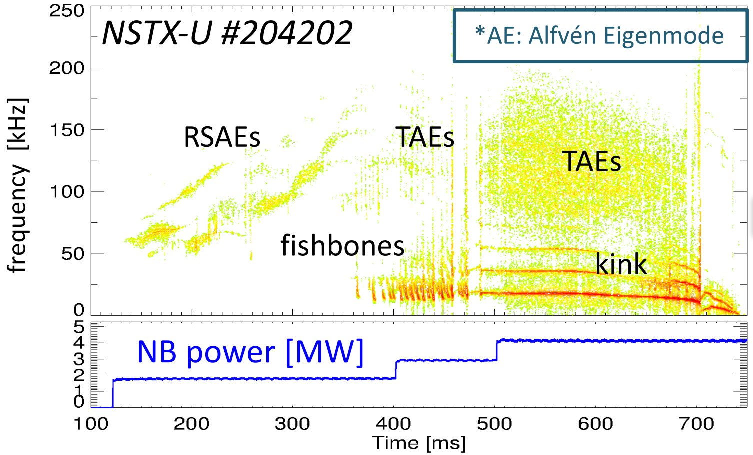
NSTX-U at Princeton Plasma Physics Laboratory and DIII-D at General Atomics are DOE Office of Science User Facilities

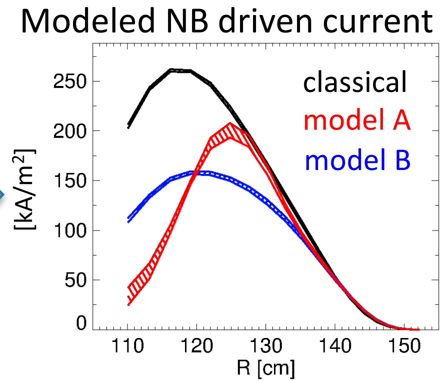
Verified, validated energetic particle (EP) models are required in integrated tokamak simulations

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

- But: EPs drive instabilities, instabilities affect EPs

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





Layout

- Overview of main modeling tools
- Summary of results
- Future work & conclusions

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- **Overview of main modeling tools**
- Summary of results
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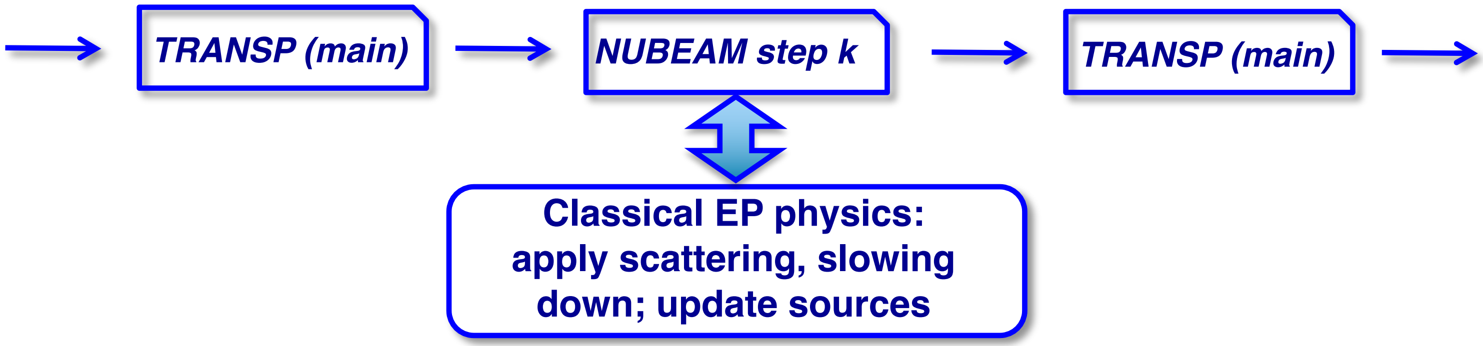
TRANSP code is the main platform for Integrated Simulations

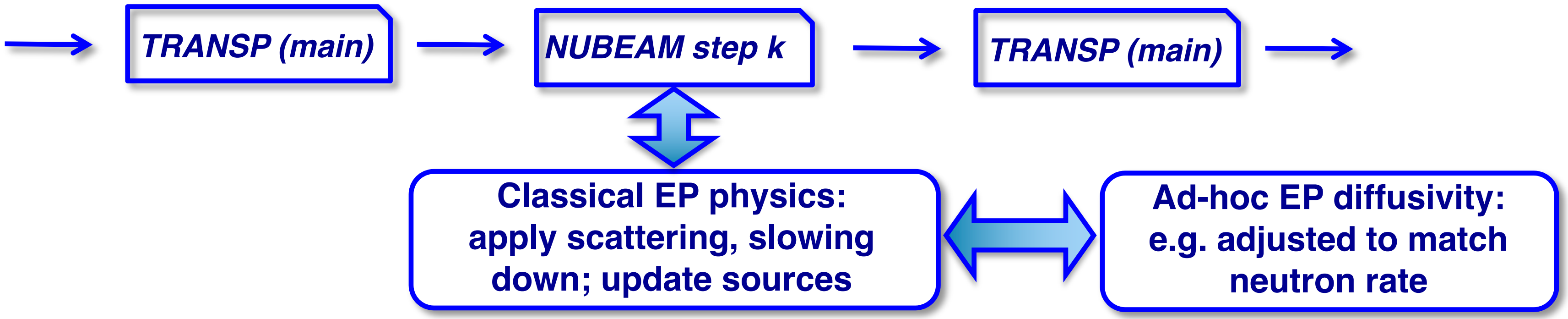
- NUBEAM module accounts for (neo)classical EP physics
  - Includes scattering, slowing down, atomic physics



May be inaccurate if EP transport is enhanced by instabilities

With instabilities, additional physics is required for quantitative simulations

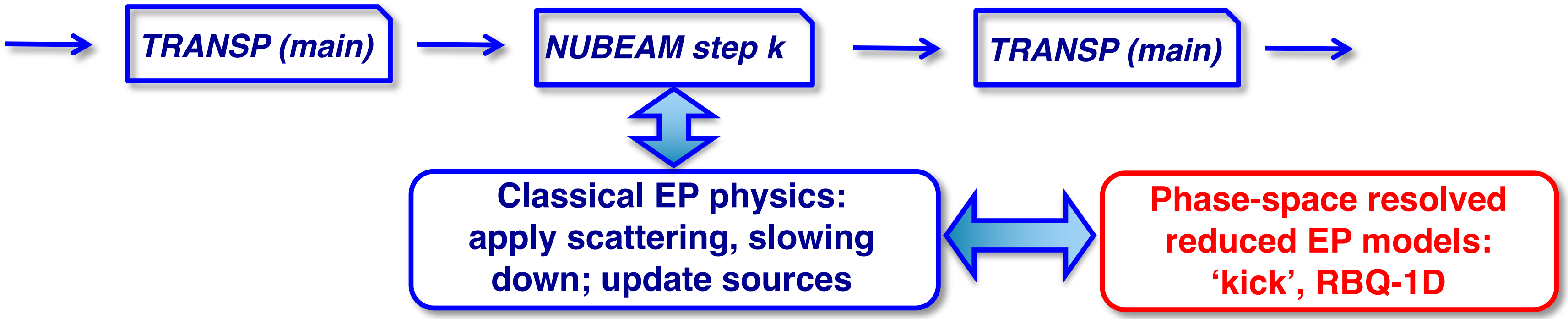
- NUBEAM module accounts for (neo)classical EP physics
  - Includes scattering, slowing down, atomic physics



Ad-hoc transport models: often unphysical -> no predictive capabilities!

Kick and *RBQ-1D* reduced models address EP transport in time-dependent integrated simulations

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



New physics-based models enable predictive capabilities

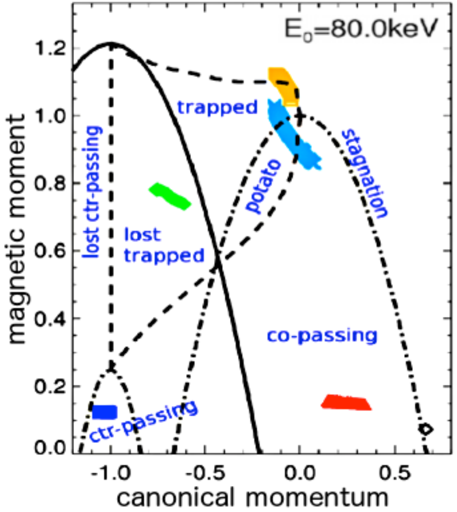
Podestà PPCF 2014, PPCF 2017; Gorelenkov NF 2018

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



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:

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

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

$\omega = 2\pi f$: mode frequency

n : toroidal mode number

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

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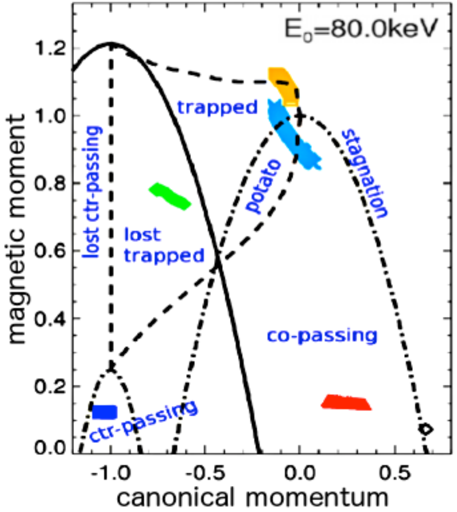

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Define ***transport matrix(es)*** for NUBEAM:

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

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

Podestà PPCF 2014, PPCF 2017

RBQ-1D and *kick* models distill physics of wave-particle interaction for its inclusion in $p(\Delta E,\Delta P_\zeta)$

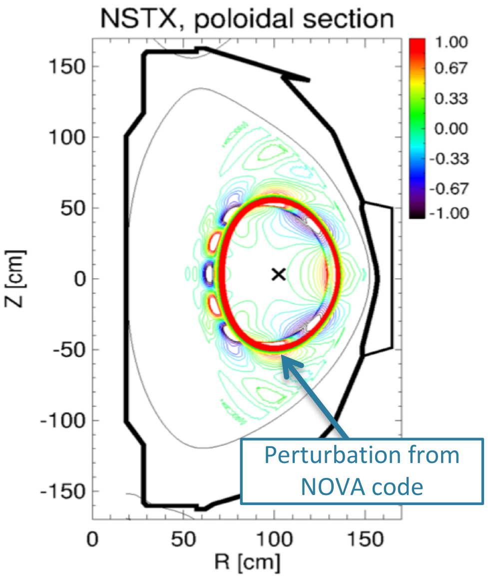
- Both models use mode structure, damping rate from MHD codes, e.g. NOVA/NOVA-K
  - Input: thermal profiles, equilibrium

- RBQ-1D based on resonance-broadened quasi-linear theory for wave-particle interaction:
  - Use "diffusive transport" approximation -> gaussian $p(\Delta P_\zeta | E,P_\zeta,\mu)$
  - 1D: transport along canonical momentum P_ζ dominates
  - Computationally efficient

Gorelenkov NF 2018

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

Initialize test particles uniformly in phase space

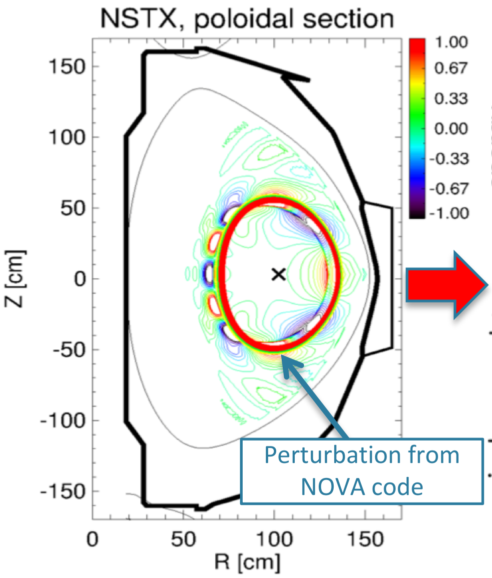


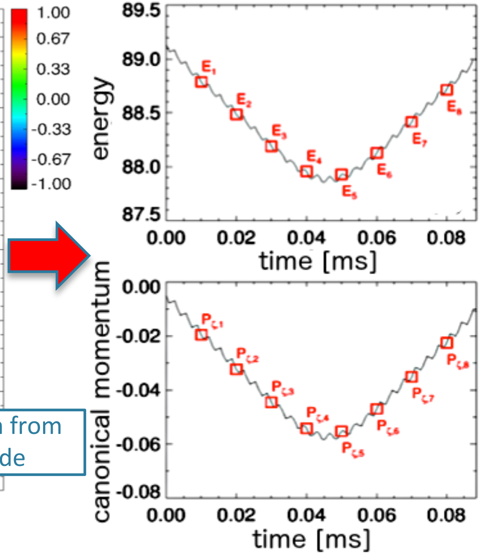
Podestà PPCF 2017

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





Podestà PPCF 2017

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

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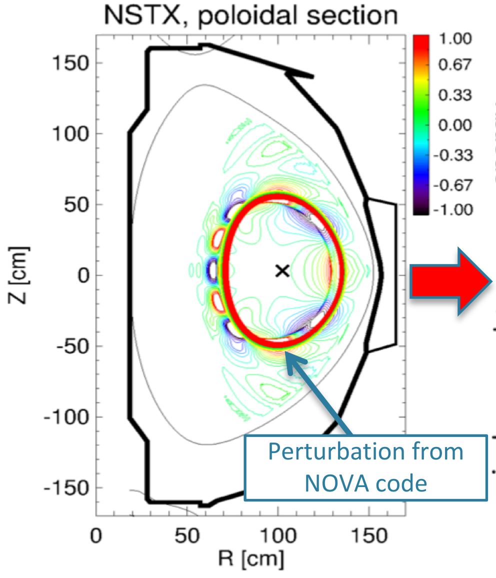
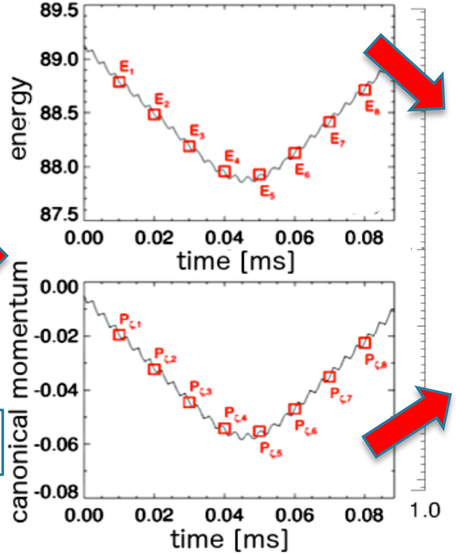
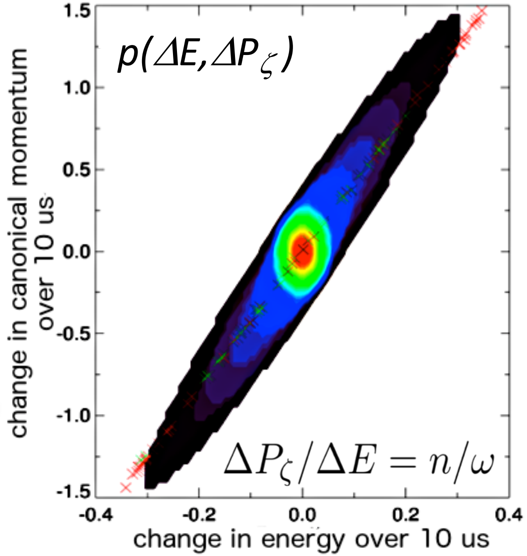
Track energy, momentum variations (*kicks*) at fixed time intervals

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







Podestà PPCF 2017

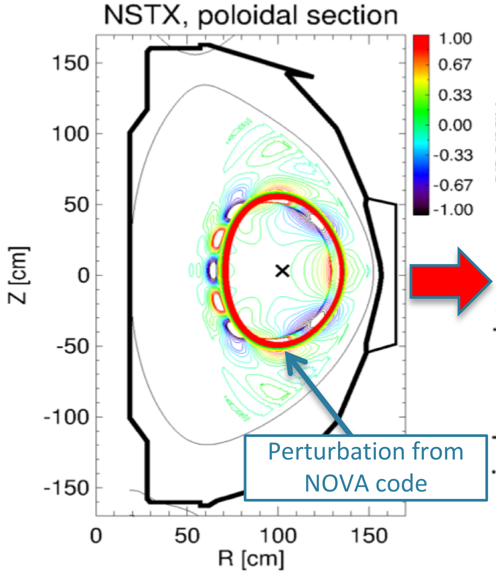
Kick model: particle-following ORBIT code used to infer transport matrix numerically

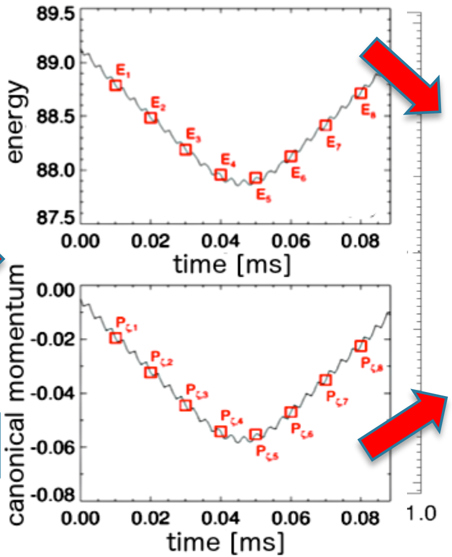
Initialize test particles uniformly in phase space

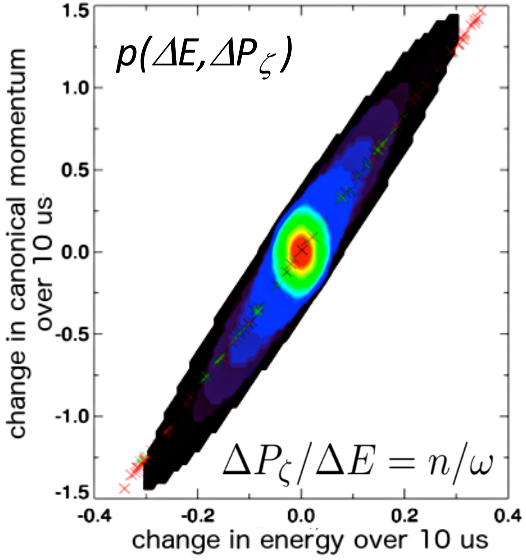
Track energy, momentum variations (*kicks*) at fixed time intervals

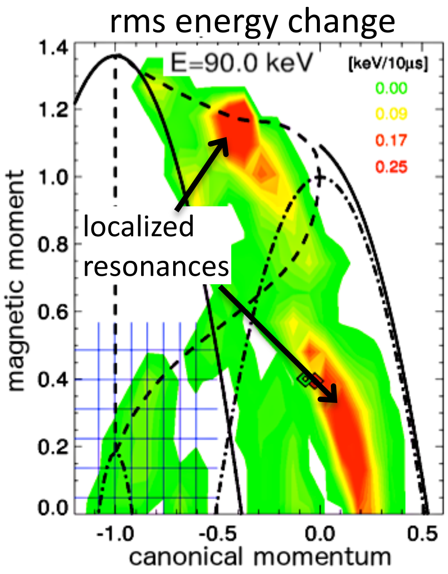
Combine ΔE, ΔP_ζ from same (E,P_ζ,μ) phase space *bin* into $p(\Delta E,\Delta P_\zeta)$

Repeat for all (E,P_ζ,μ) *bins* to infer 5D matrix -> input for NUBEAM: $p(\Delta E,\Delta P_\zeta\,|E,P_\zeta,\mu)$







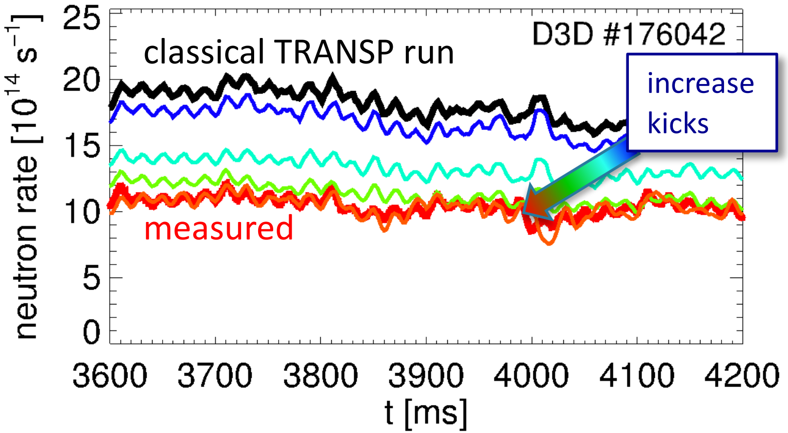


Podestà PPCF 2017

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

Interpretive runs:

- ➢ *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



Podestà PPCF 2017

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

Interpretive runs:

reduced input from experiment

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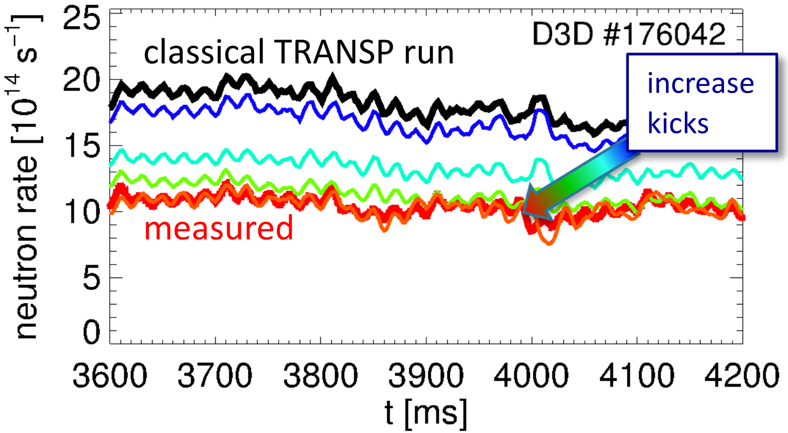


Predictive runs:

- ➢ *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'

Podestà PPCF 2017

Layout

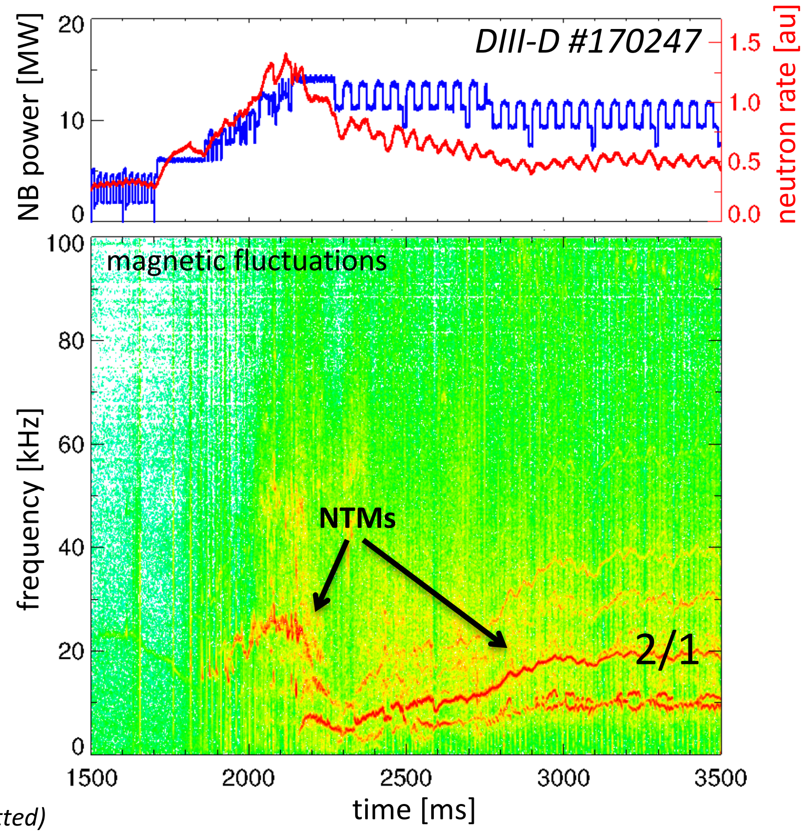
- Overview of main modeling tools
- **Summary of results: from validation/analysis to predictions**
  - Single-mode scenarios
    - NTM only: single dominant mode, few resonances in EP phase space
    - AEs only: many modes of same type, many resonances
  - Multi-mode scenarios
    - AEs + fishbones + kinks: multiple types of modes, many resonances
  - Example of predictive capabilities

complexity

- Future work & conclusions

DIII-D discharge with large NTM provides a good test bed for EP transport models

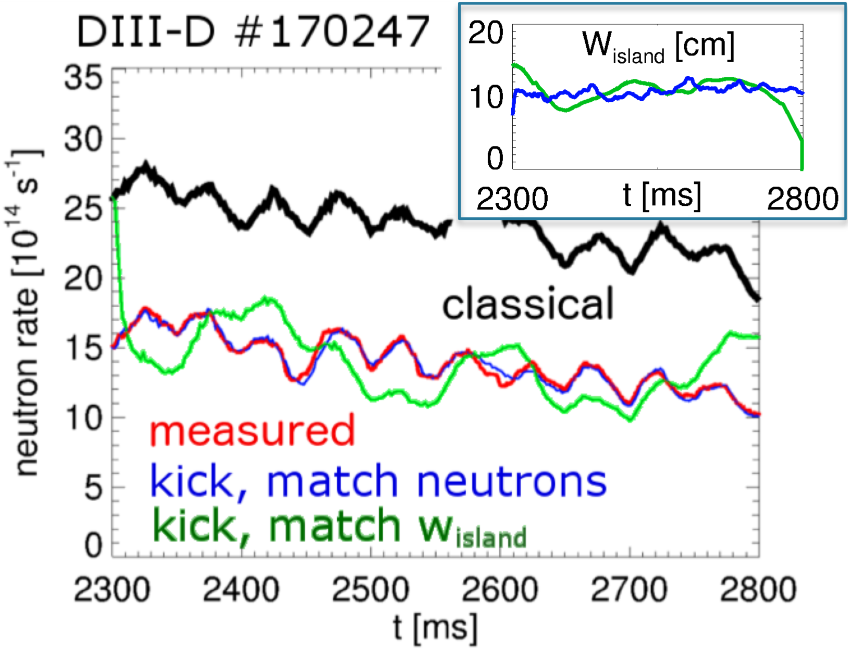
- NTMs destabilized by step-up in NB power
  - Dominant 2/1 in this case
- Large NTM amplitude causes EP confinement degradation
  - Clear drop in neutron rate



Heidbrink NF 2018 *Bardóczi PoP 2017* *Poli NF 2017* *Bardóczi PPCF 2018 (submitted)*

Interpretive analysis reproduces experiment, matches direct measurements of NTM island width

- Kick "interpretive" run:
  - Scale kicks to match measured neutrons
  - Mode amplitude related to w_{island}
- Inferred NTM island width agrees with measured w_{island} from ECE
  - *a posteriori* check, validation
  - Path towards 'predictive' simulations with w_{island} from Modified Rutherford Equation



Heidbrink NF 2018 *Bardóczi PPCF 2018 (submitted)*

Analysis gives reasonable agreement with phase-space resolved diagnostics

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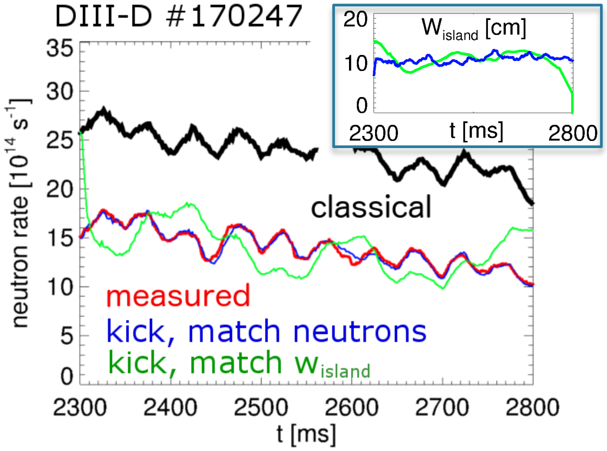
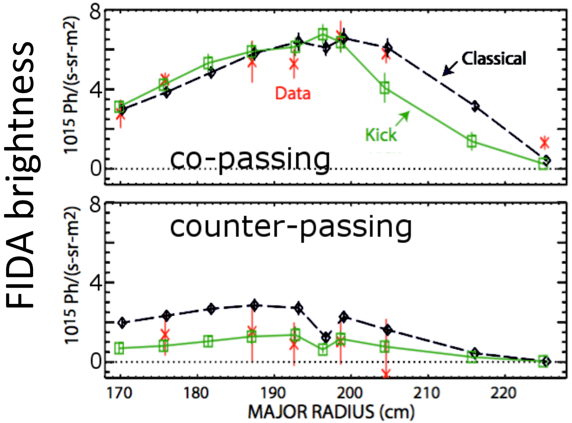


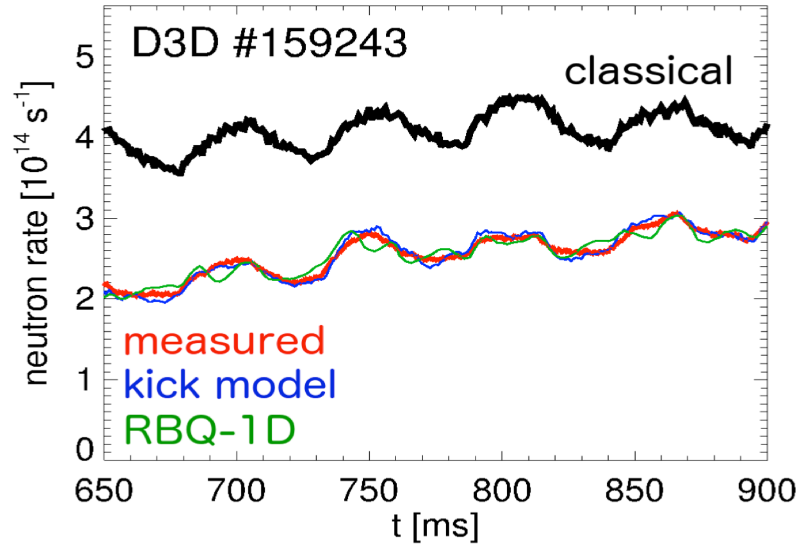
Bardóczi PPCF 2018 (submitted)

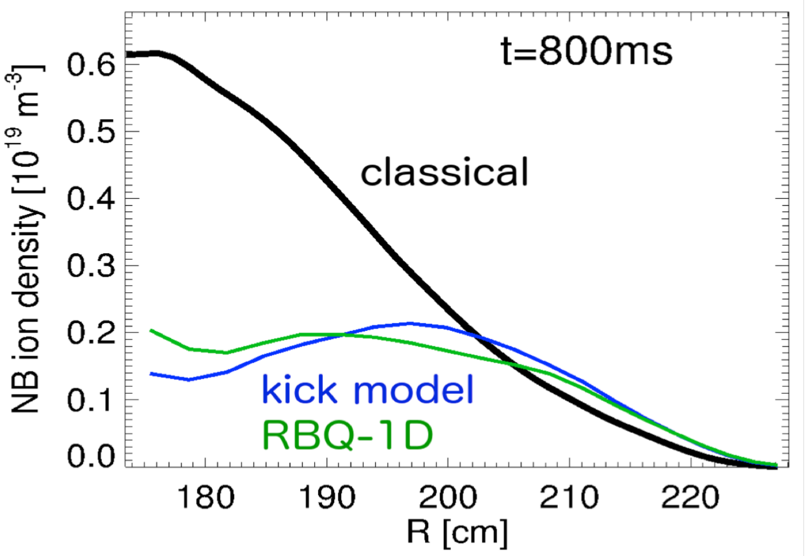
- Favorable comparison with phase-space resolved data (FIDA)
  - Acceptable for co-passing, good for counter-passing
  - ***Key exercise for model validation***
    - *Ad-hoc diffusion would give same drop for co/cntr*



Heidbrink NF 2018

Kick & RBQ-1D successfully benchmarked for scenario with multiple unstable AEs





- AEs selected based on experimental data from ECE, Mirnov coils
- Amplitudes inferred around t=800ms
  - Adjusted vs time to match measured neutron rate

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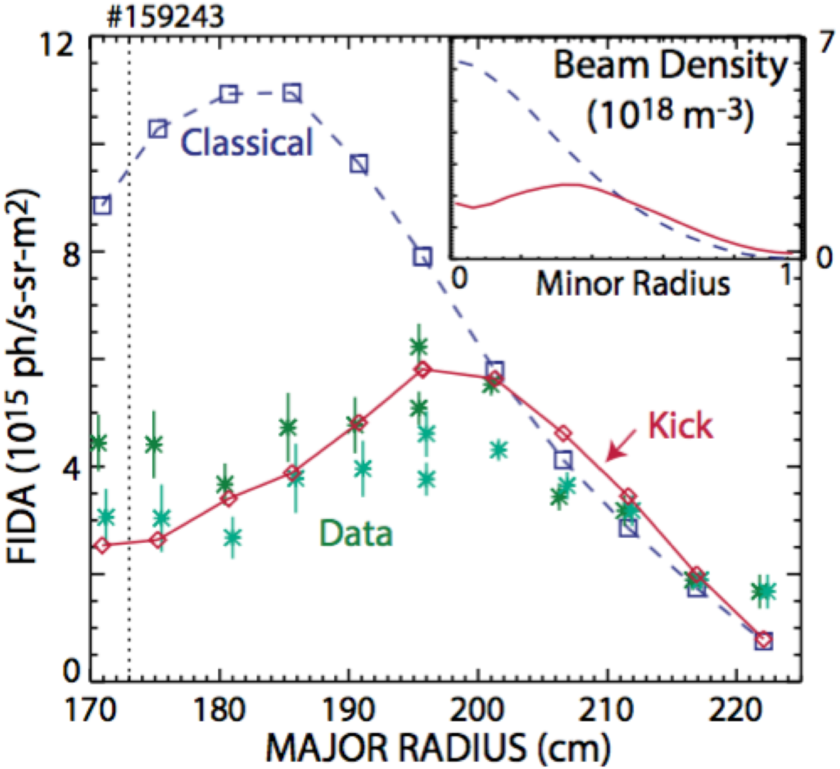
Successful comparison with phase-space resolved data (FIDA, NPA) validates models

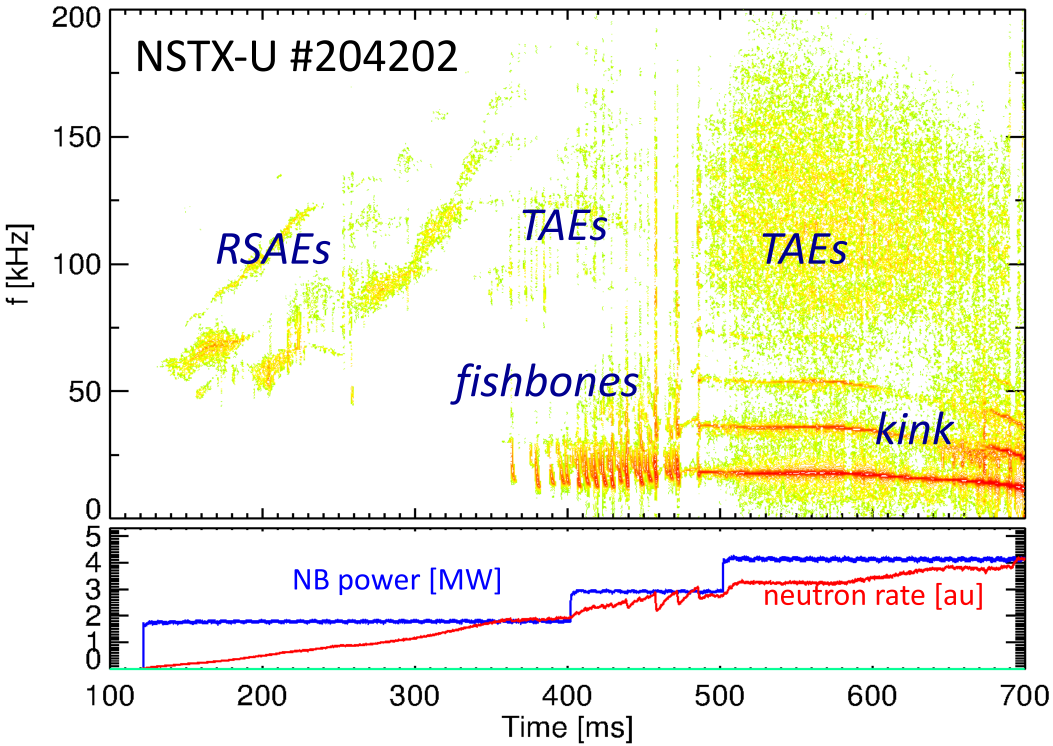


- Simulation can also reproduce dynamic response to NB modulation
- Less favorable comparison with FIDA using updated calibration
  - *Need to work closely with experimentalists*

- *Retaining phase space resolution is critical for validation*

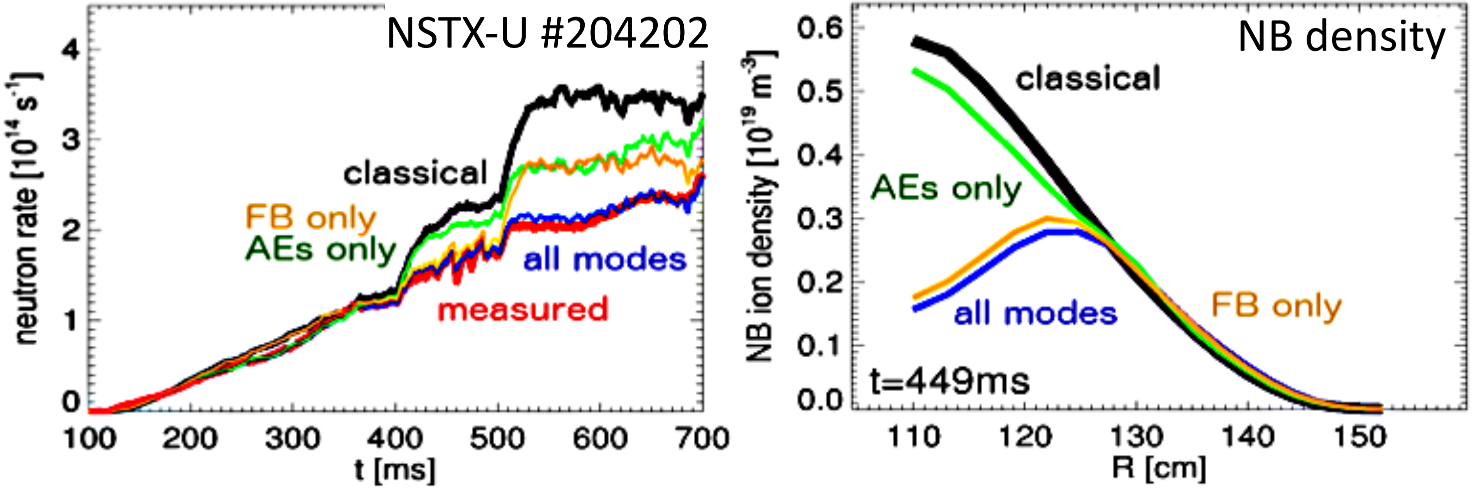
Heidbrink PoP 2016

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



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

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



- 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 modes is observed*, e.g. in total EP losses

Layout

- Overview of main modeling tools
- Summary of results
- **Future work & conclusions**

Reduced-physics EP transport models enable quantitative, time-dependent tokamak simulations

- Verification & Validation being extended for kick & RBQ-1D
- Extend RBQ to 2D (canonical momentum & energy)

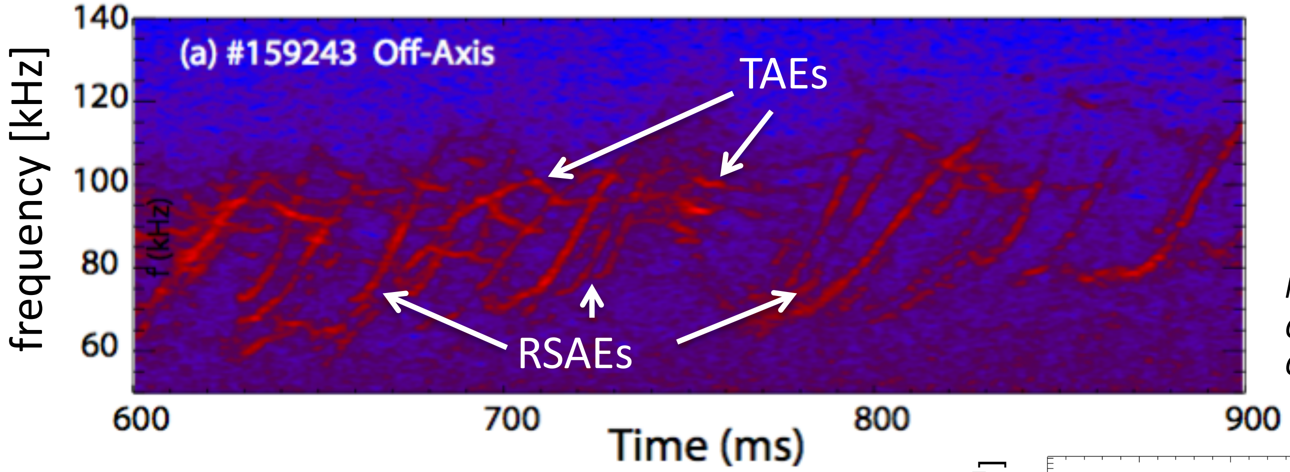
- Reduced models enable efficient simulations retaining (most of) the relevant EP physics
  - Including *predictive* capabilities (ITER & beyond)

- Phase-space resolution is required to move beyond *ad-hoc* models
  - Critical for heating, current drive, thermal transport

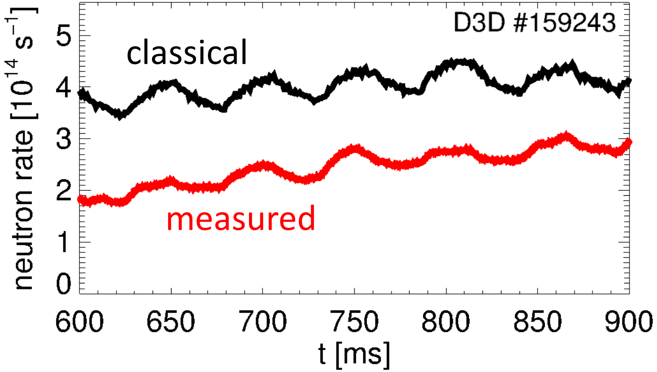
- ***Goal: develop framework to streamline TRANSP analysis including effects of instabilities on EPs***

Backup

Reasonable agreement also found for scenario with multiple unstable Alfvén Eigenmodes



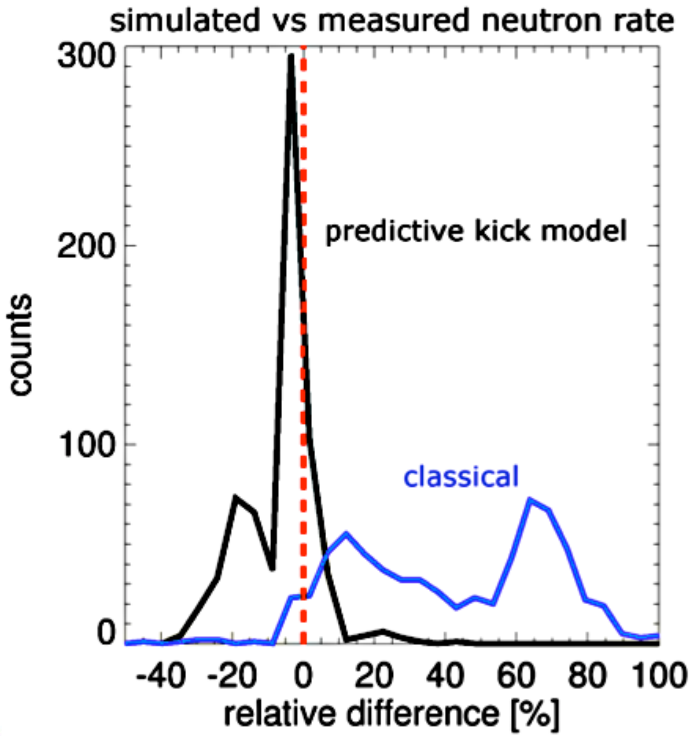
Heidbrink PoP 2016
Collins PRL 2016
Collins NF 2017



- Mix of Toroidal and Reversed-shear AEs observed
- Large neutron deficit indicates substantial fast ion transport

Predictive analysis (AEs) results generally agree within +/-15% with *interpretive* simulations

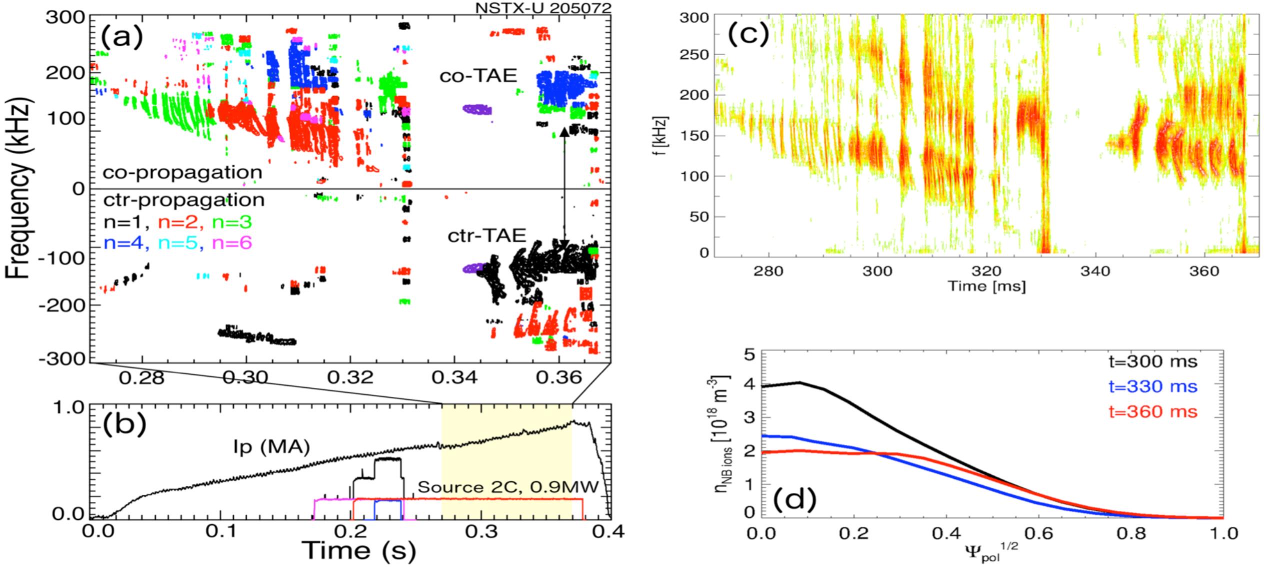
Relative difference from interpretive simulations: NSTX, NSTX-U and DIII-D database



- 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***

Predictive analysis: test kick model on challenging NSTX-U discharge

- Examples from NSTX-U scenario
  - Transition from co- to counter-TAEs as NB ion density profile becomes flat or hollow
  - Complex scenario, simulations are challenging
    - Most quantities evolve in time, not suitable for “single-time-slice” analysis



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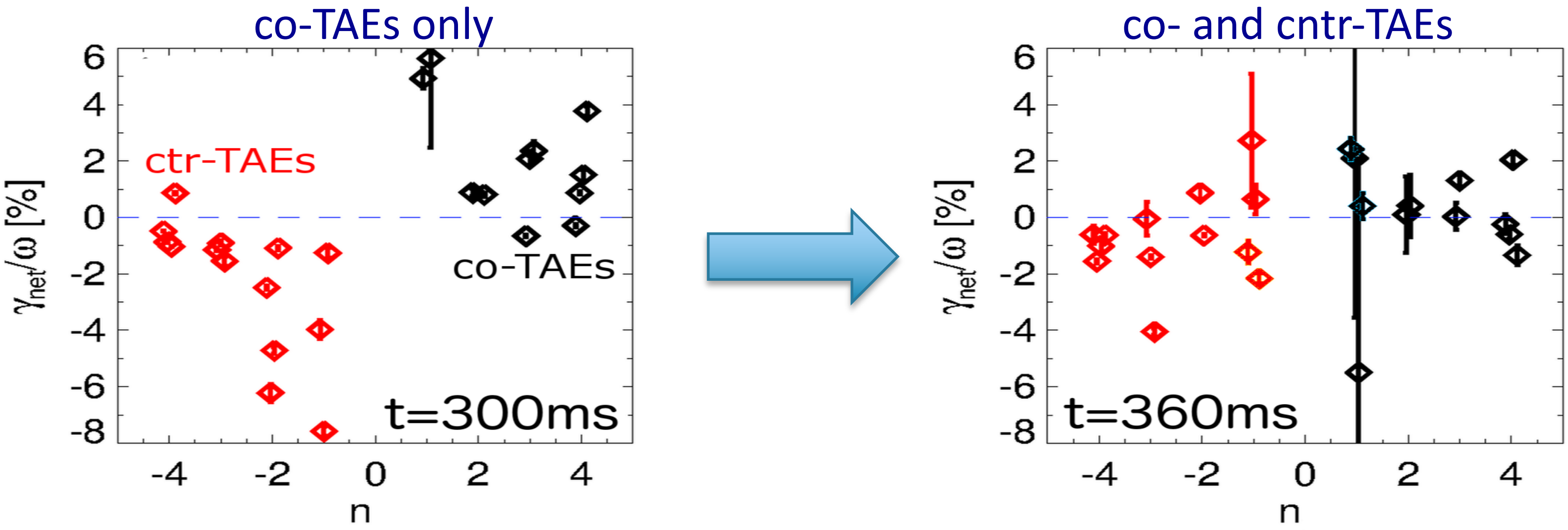
Predictive analysis recovers overall properties of measured instabilities

– Reproduces main features of the experiment
– Reproduces transition co- to counter-TAEs
– Capture time evolution of unstable modes, spectrum, …



Successful comparison with phase-space resolved data (FIDA, NPA)

- Retaining phase space resolution is important
  - Localized resonances result in “fine structures” in fast ion distribution, profiles
    - Comparison with FIDA: phase space resolution crucial for validation

Agreement extends to response to NB modulation