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NSTX-U

Computation of AE stability and saturation through a reduced fast ion transport model in TRANSP

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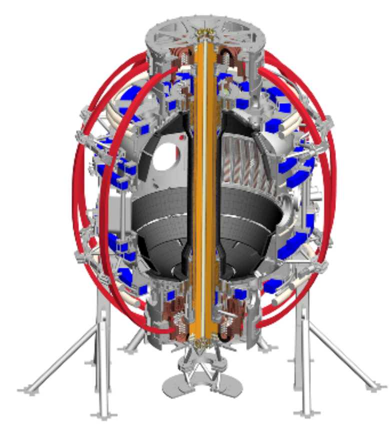
NSTX-U Monday Meeting
Room B318 - PPPL
01/09/2017

http://nstx.pppl.gov/DragNDrop/Draft_Paper_Review/MPodesta_kick_model_AEstability.pdf

PPPL



Including effects of Alfvénic modes (AEs) can be important for reliable time-dependent simulations

- NUBEAM/TRANSP now include a reduced, physics-based model for energetic particles (EP): *kick model*
  - Enables more accurate computation of NB heating, current-drive
  - Enables "numerical experiments" leveraging on TRANSP/ NUBEAM capabilities

- Analysis with TRANSP + kick model has been quite successful to interpret experimental data
  - Thermal profiles from exp't, mode properties from NOVA+exp't
  - Tested on a variety of NSTX/NSTX-U, DIII-D scenarios

> *Can the model be used for <u>predictive</u> AE+EP runs?*

> *What are the pros/cons of the kick model approach?*

> *What are the limitations?*

Some definitions…

- *Predictive*: all quantities are predicted, including thermal profiles, q-profile, unstable spectrum, etc.
- *Semi-predictive*
- *Semi-interpretive*

Typical range of kick model simulations

- *Interpretive*: all quantities are known (thermal profiles, mode spectrum vs time) -> how is EP population responding?

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Outline

- Methodology for interpretive *vs* predictive analysis
  - Inferring linear mode stability
  - Inferring mode saturation amplitude
- Example from NSTX #141711
  - Predictions of AE linear stability, saturation, EP behavior
  - Comparison with experiment
- Future work

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Power balance is the key for kick model analysis in NUBEAM/TRANSP

Consider evolution of mode energy, E_w

$$\frac{\partial E_w}{\partial t} = P_{EP} - 2\gamma_{damp} E_w$$

power from EPs to the mode

damping rate

Introduce 'growth rate' in analogy with damping rate:

$$\gamma_{gr}(E_w) \doteq \frac{P_{EP}(E_w)}{2E_w} \Rightarrow \frac{\partial E_w}{\partial t} = 2\left[\gamma_{gr} - \gamma_{damp}\right] E_w$$

- In the limit of vanishing mode amplitude (*linear* phase)

$$\gamma_{lin} \doteq lim_{E_w \to 0} \frac{P_{EP}(E_w)}{2E_w} \Longleftarrow$$ linear growth rate

- In the limit of vanishing dE_w/dt, finite E_w (*saturated* phase)

$$\gamma_{gr}(E_w) - \gamma_{damp} \to 0 \Rightarrow E_w \to E_w^{sat} \Longleftarrow$$ saturation amplitude

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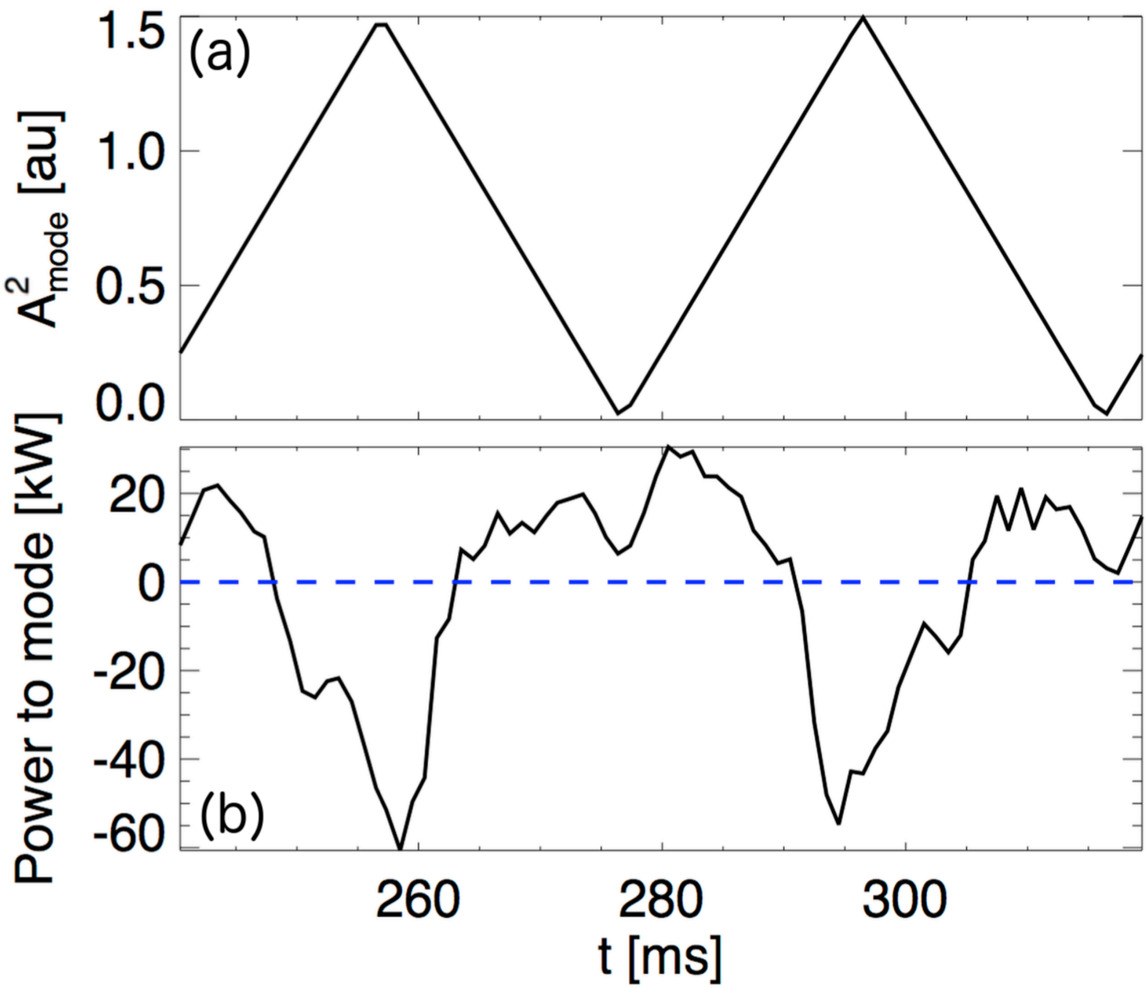
Linear growth rate and saturation amplitude can be inferred from $P_{EP}(E_w)$ characteristic

TRANSP run: sweep mode amplitude ~sqrt(E_w), record power from EPs to the mode



Build $P_{EP}(E_w)$ curve, infer γ_{lin} and saturation amplitude

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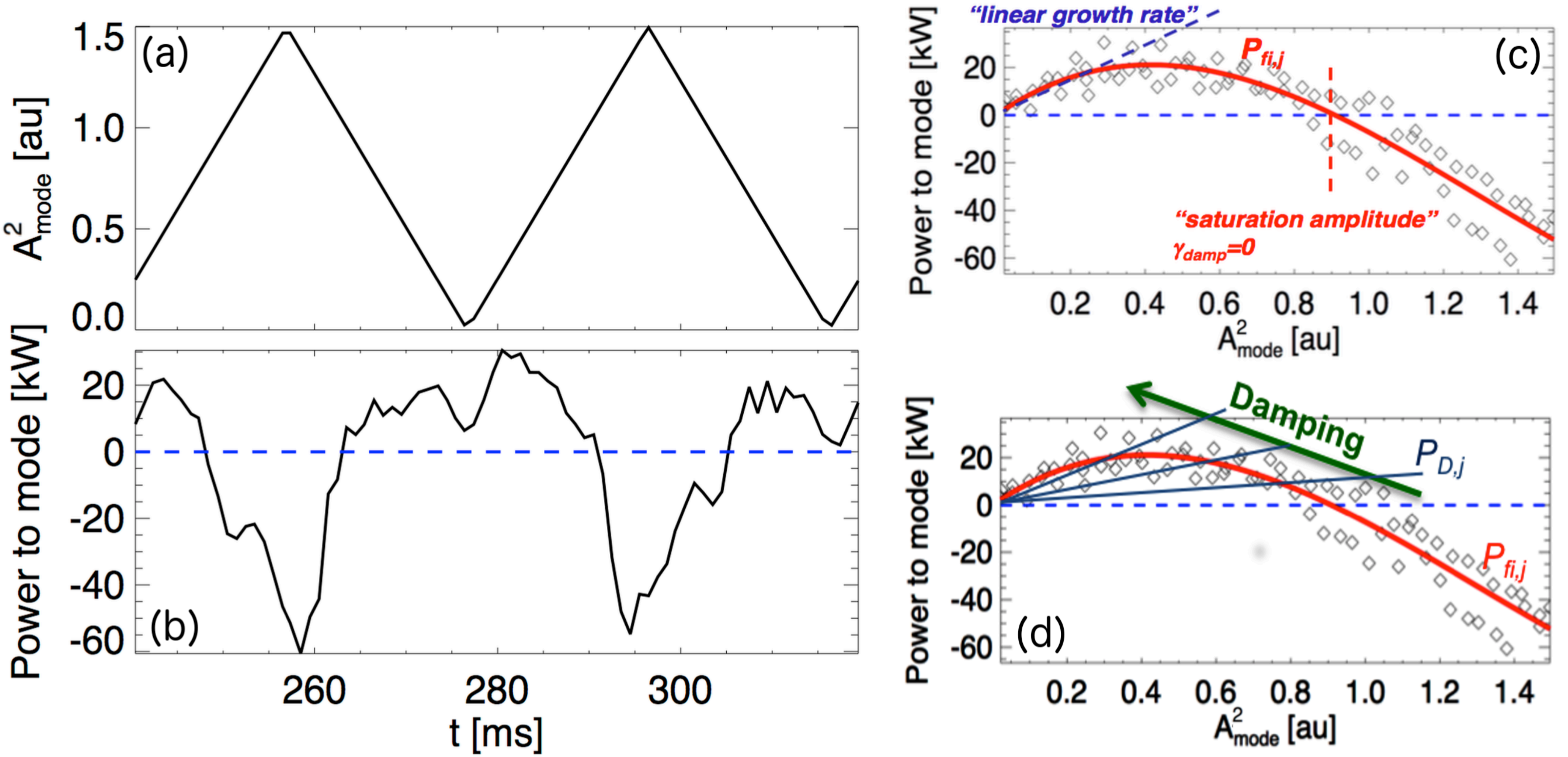

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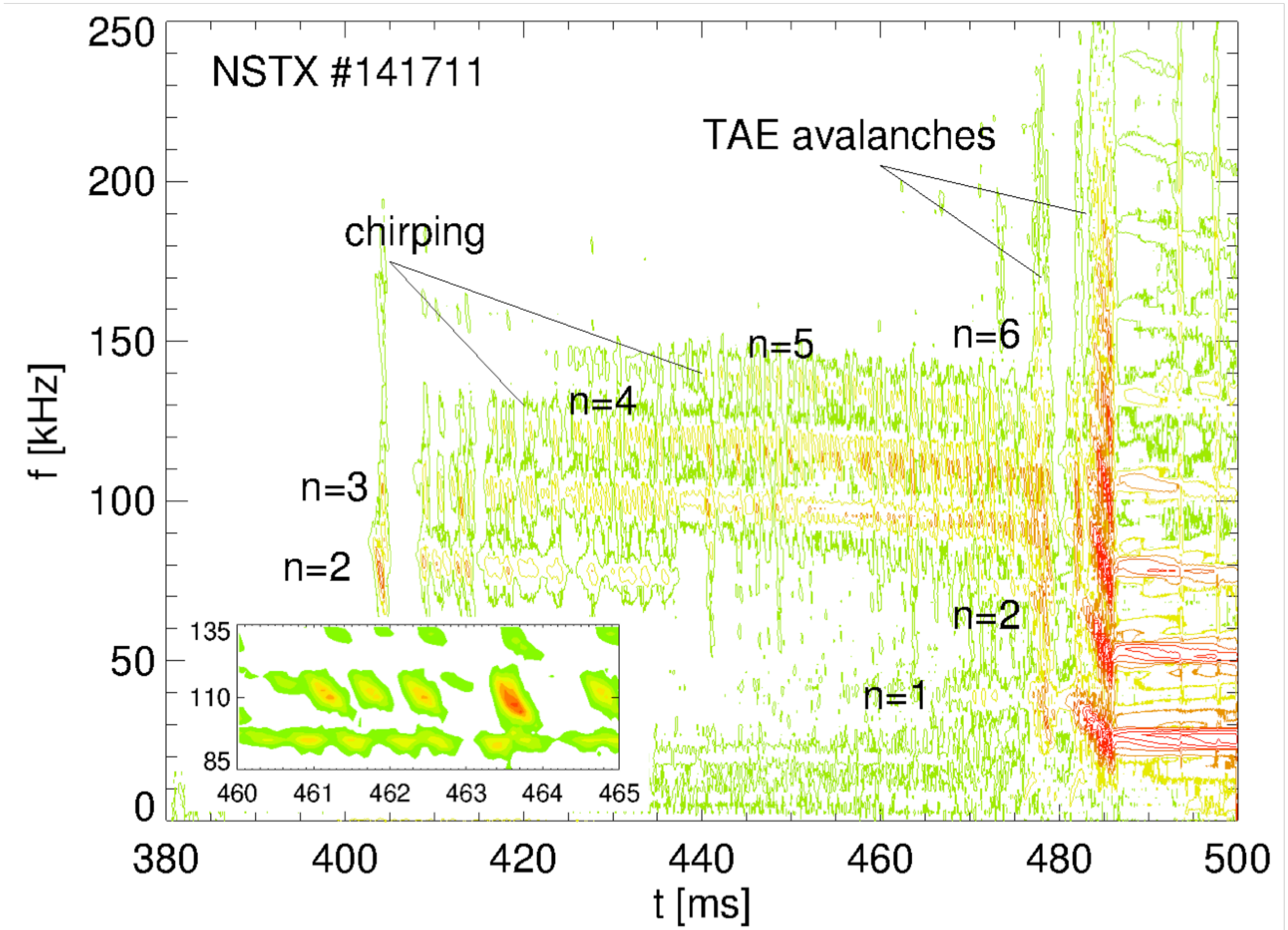
Target scenario: NSTX #141711

NB-heated L-mode featuring robust TAE activity

> *Neglect TAE avalanches in this work*



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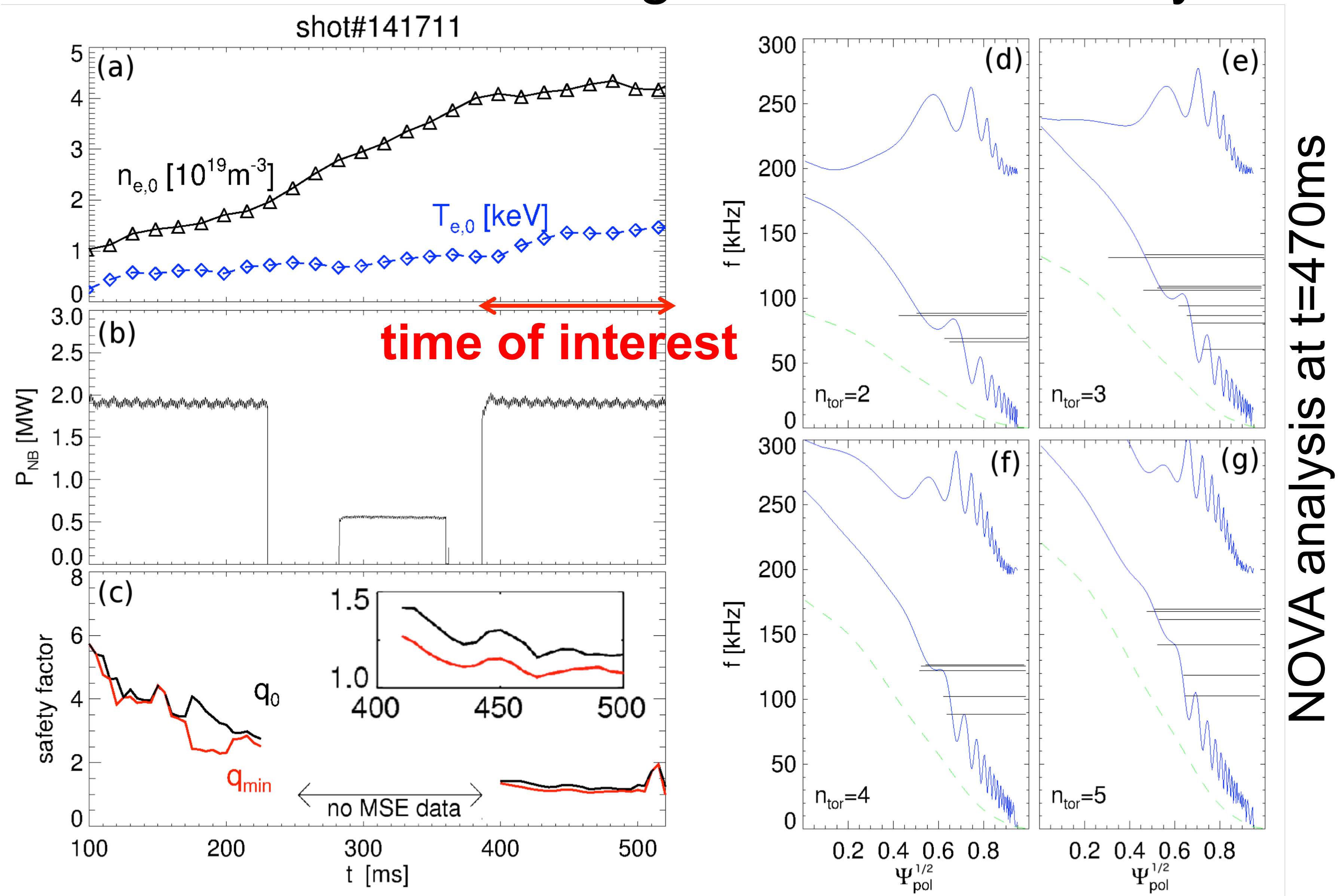
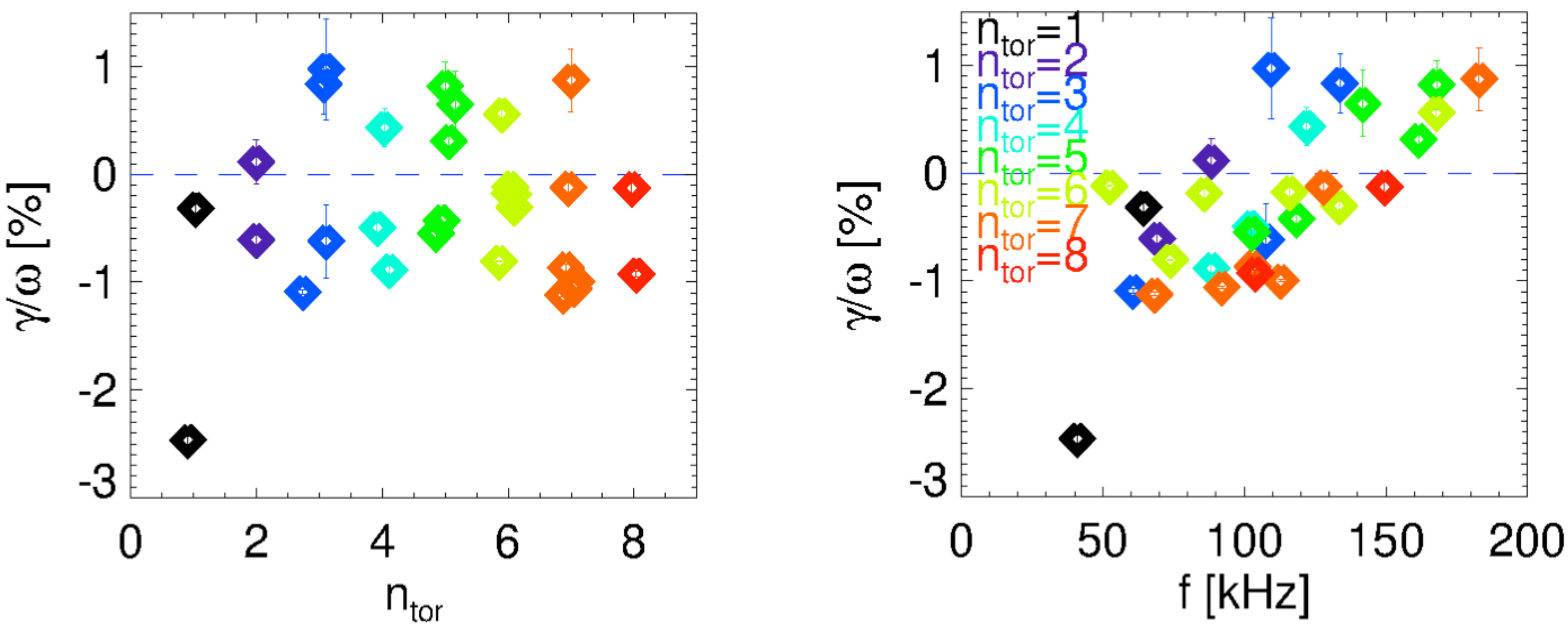


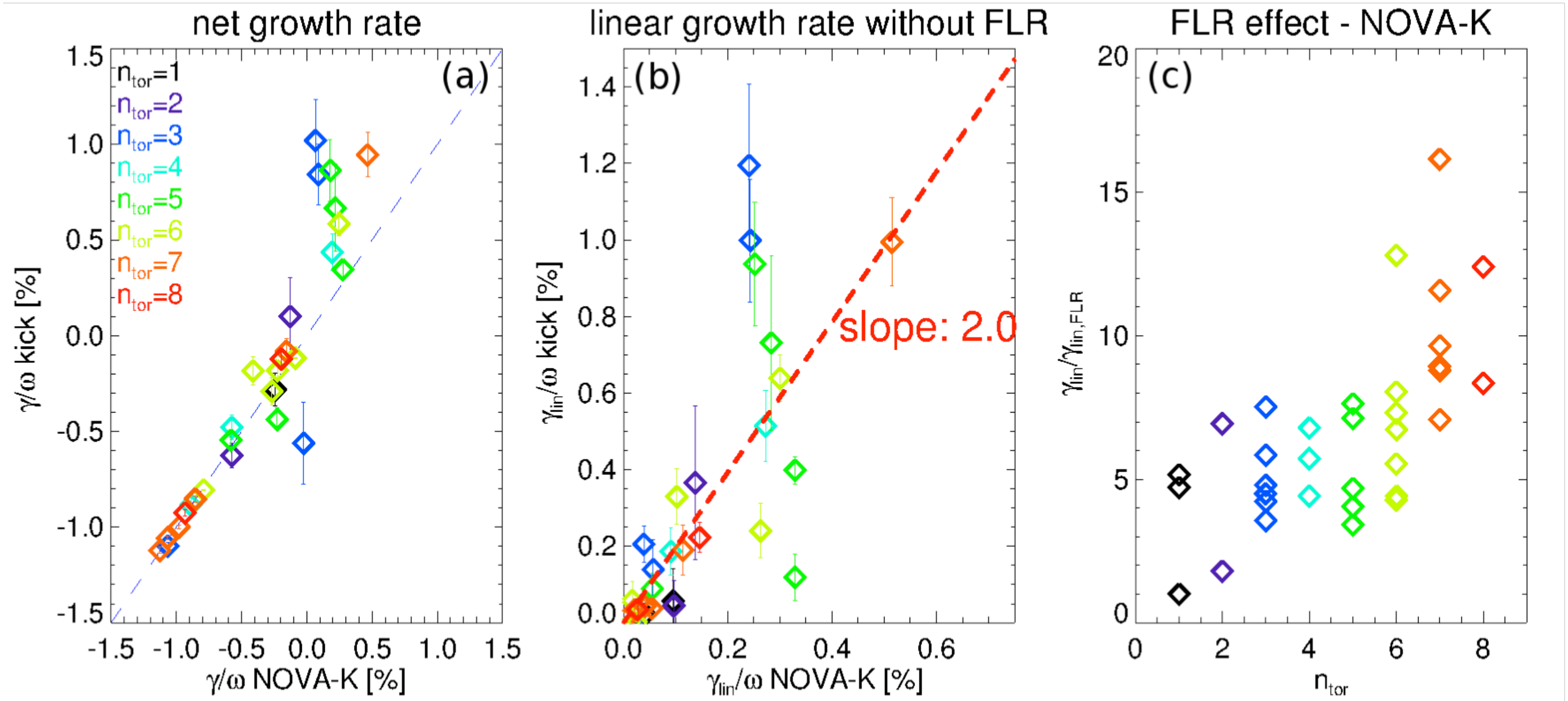
NOVA analysis provides ~50 candidate modes with toroidal mode numbers *n=1-8*

- NOVA finds *all* eigenmodes for given toroidal mode number/frequency range - regardless of their stability
- 'Linear' kick model analysis identifies 9 unstable modes with *n=2-7*

net growth rate including damping from NOVA



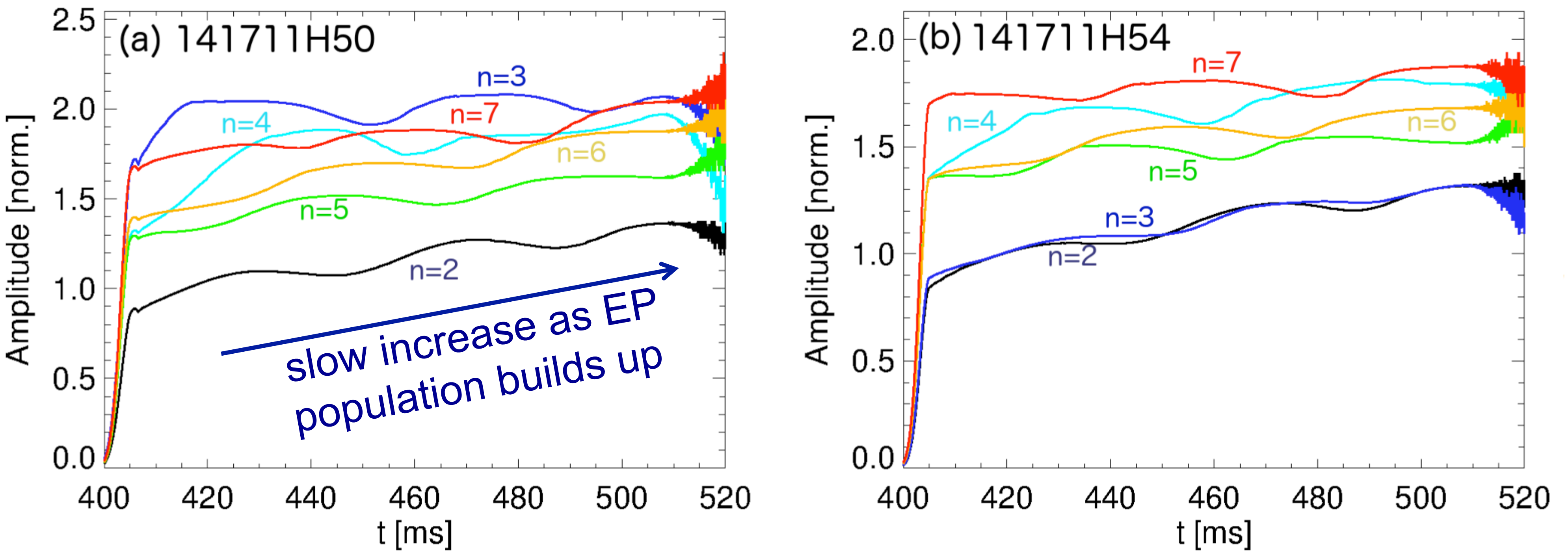
On average, kick model computes 2x larger γ_{lin} than NOVA-K



- Difference likely due to different fast ion distribution, lack of sources/sinks in NOVA-K
- FLR effects *not* included in ORBIT (-> kick model)
  - Inferred growth rates, saturation amplitudes are upper limit

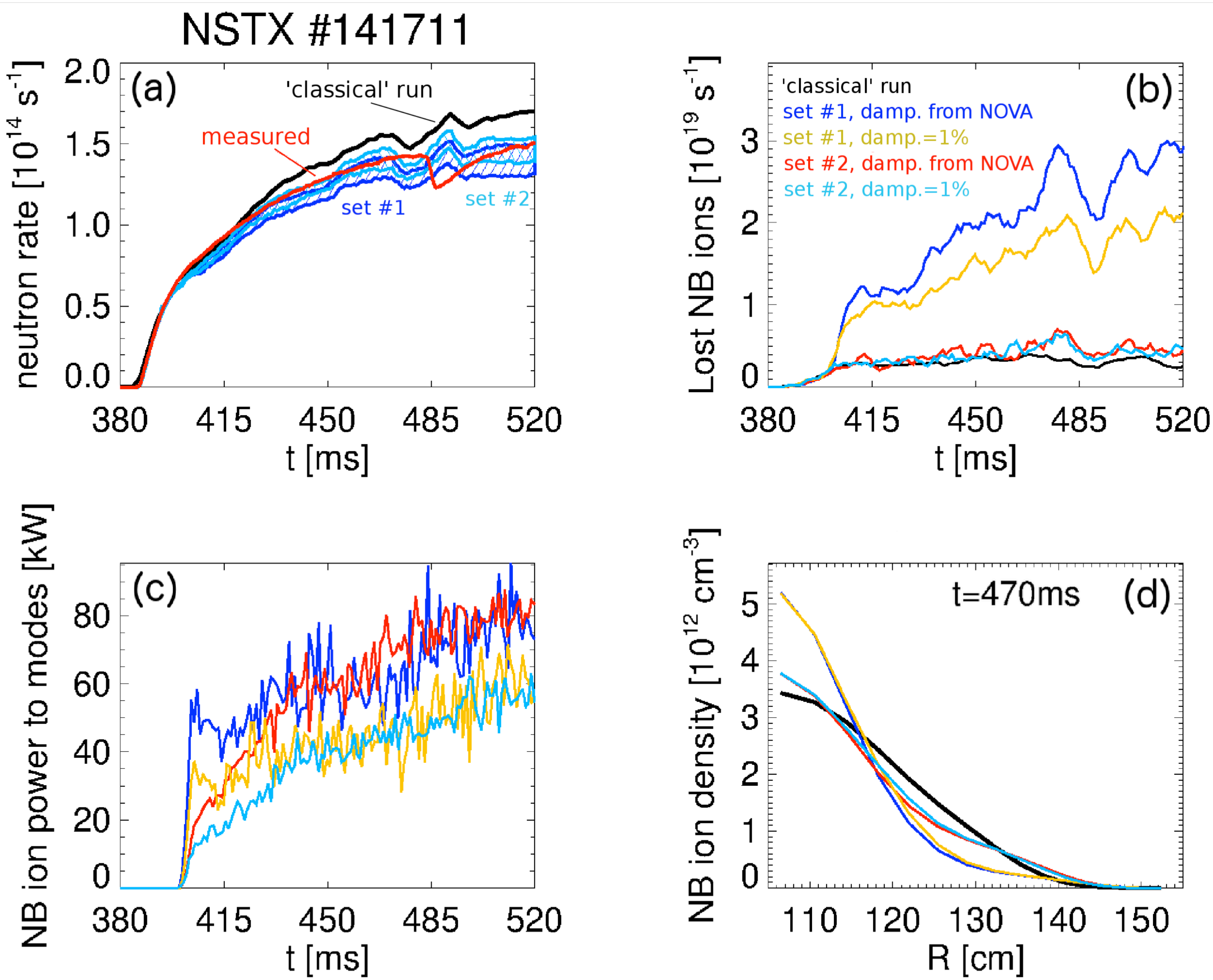
Saturation amplitudes are $\delta B_r/B \sim 10^{-4}$-$10^{-3}$ for weakly bursting/chirping phase

- Divide 9 unstable modes into two sets, n=2-7



- Amplitude =1 corresponds to $\delta B_r/B=5x10^{-4}$
- Inferred saturation amplitudes appear reasonable, based on previous analysis
  - $\delta n/n$ from UCLA reflectometer
- *Results can vary considerably if different damping rates are used*

TRANSP computes similar neutron deficit for the two sets of 'unstable' modes



Summary of *semi-predictive* kick model analysis

- Kick model *can* be used for semi-predictive analysis
  - Requires thermal profiles
  - Requires candidate modes (, damping rates) from NOVA/NOVA-K
- NUBEAM/TRANSP implementation has several advantages over single-time-slice analysis
  - Provides well-diagnosed time-dependent simulations
  - (Classical) sources, sinks are accurately simulated
  - Integrates non-classical EP effects into whole discharge simulation
- Main limitations:
  - Relies on other codes to infer mode structure, damping rates
  - Best suited for slowly varying background profiles (I_p, $q(r)$)
  - Requires additional analysis to “predict” bursting/chirping modes (cf. recent work by Duarte, Berk, Gorelenkov)

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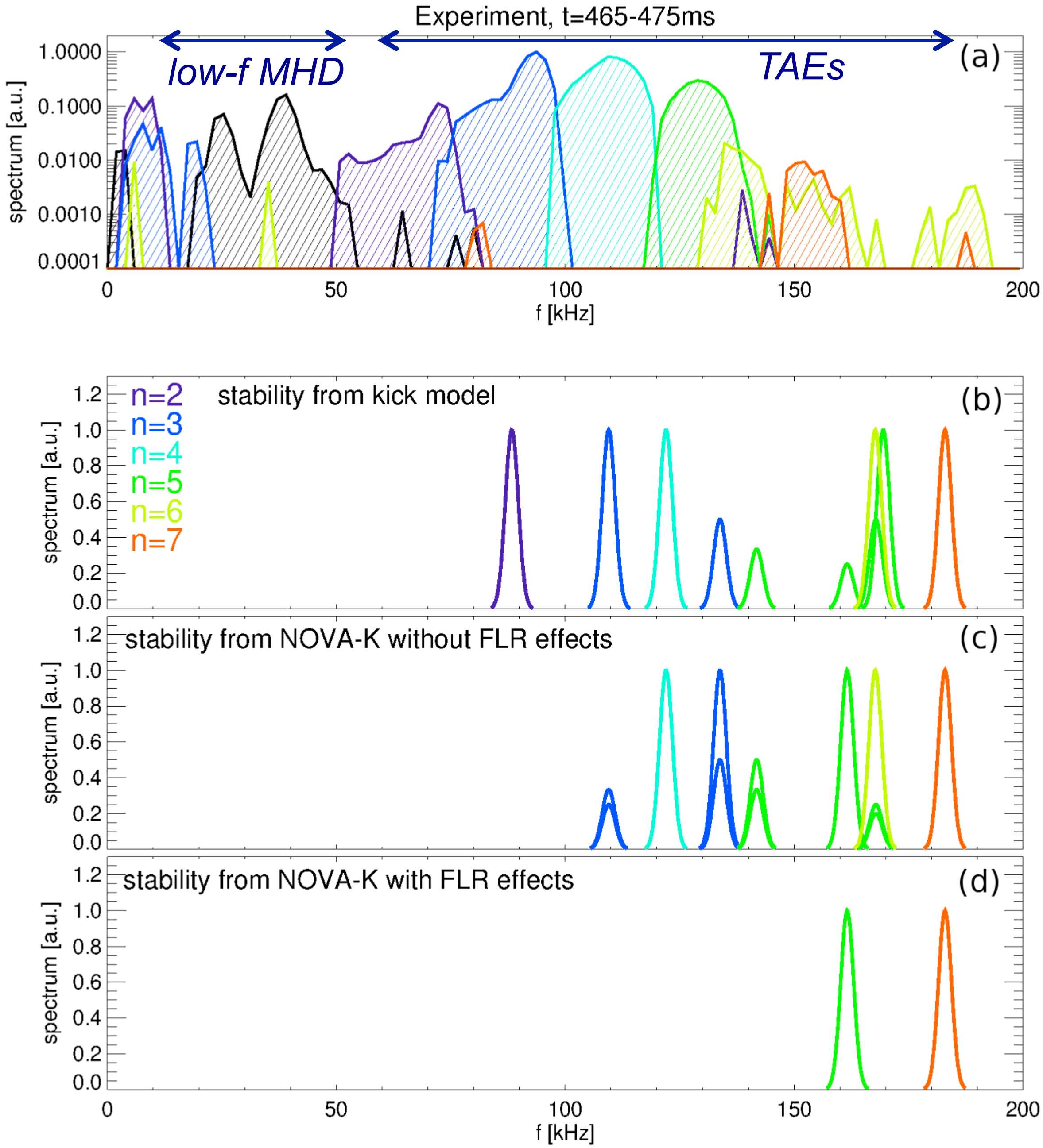
Predicted unstable spectrum is in reasonable agreement with measurements

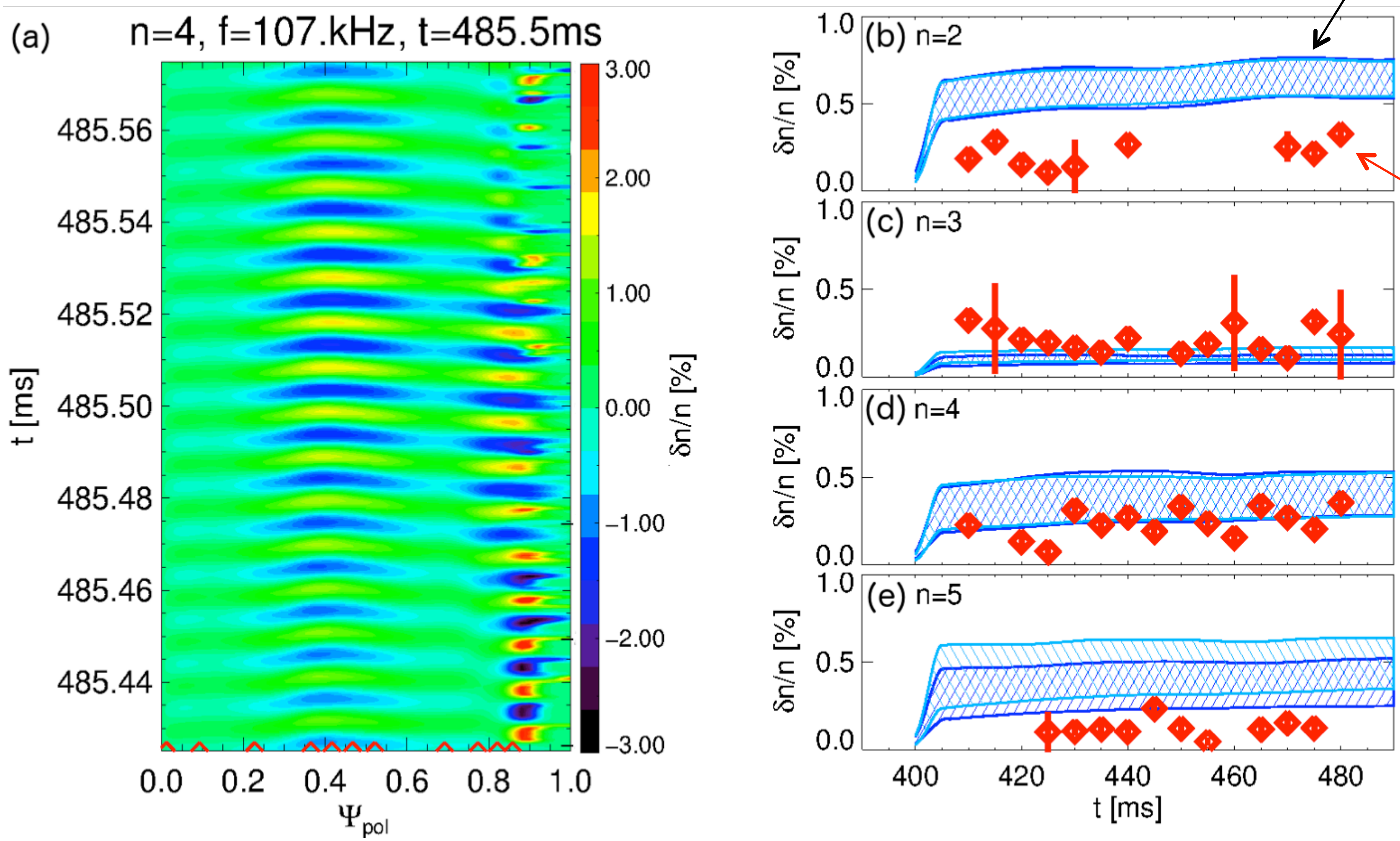


- Experiment shows a rich spectrum:
  - TAEs, low-f MHD (, EHO?)
- Predicted spectrum looks ~OK
- Frequency (NOVA) shifted up by ~10-20kHz, probably due to choice of γ_{adiab}
- NOVA-K finds similar unstable spectrum *if FLR effects are neglected*
- NOVA-K seems to underestimate γ_{lin} when FLR effects are included

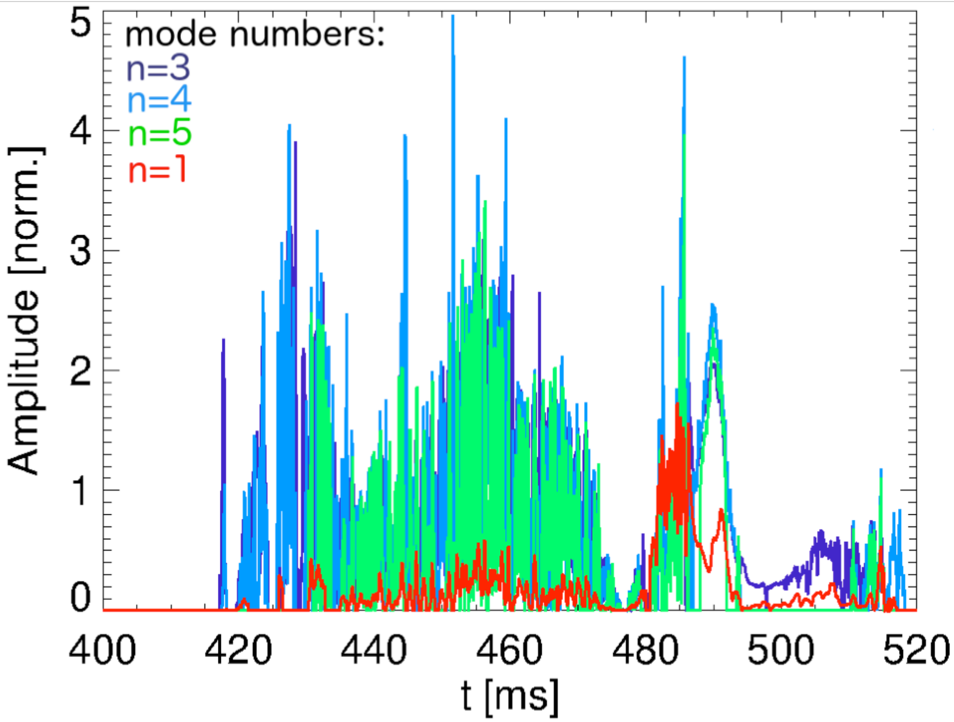
(Average) predicted saturation amplitude is within x2-3 from measurements

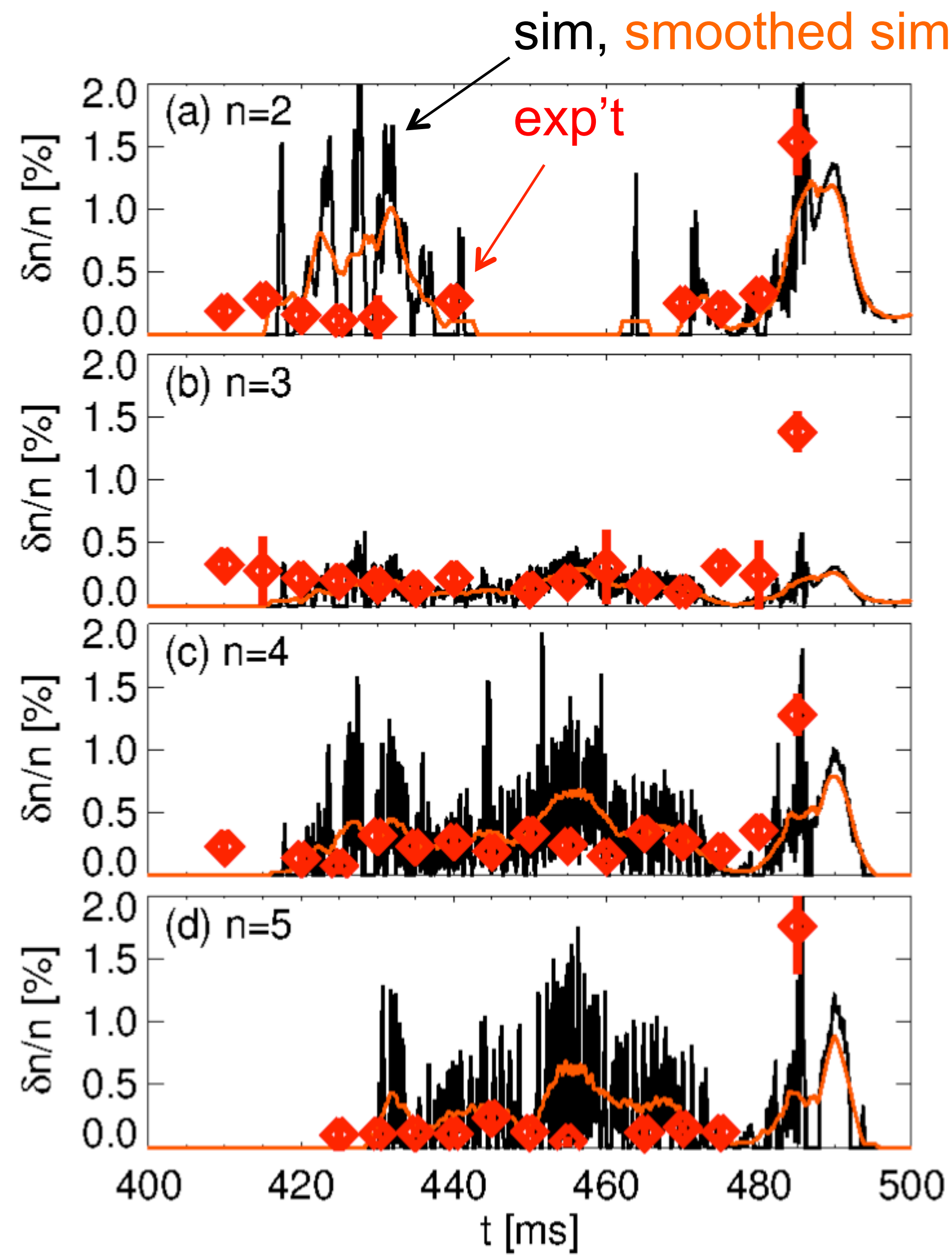
- δn/n from UCLA reflectometer
  - Average over TAE bursts every ~5ms

Colors: two sets of modes
Range: damping from NOVA/ NOVA-K vs γ_{damp}=1%



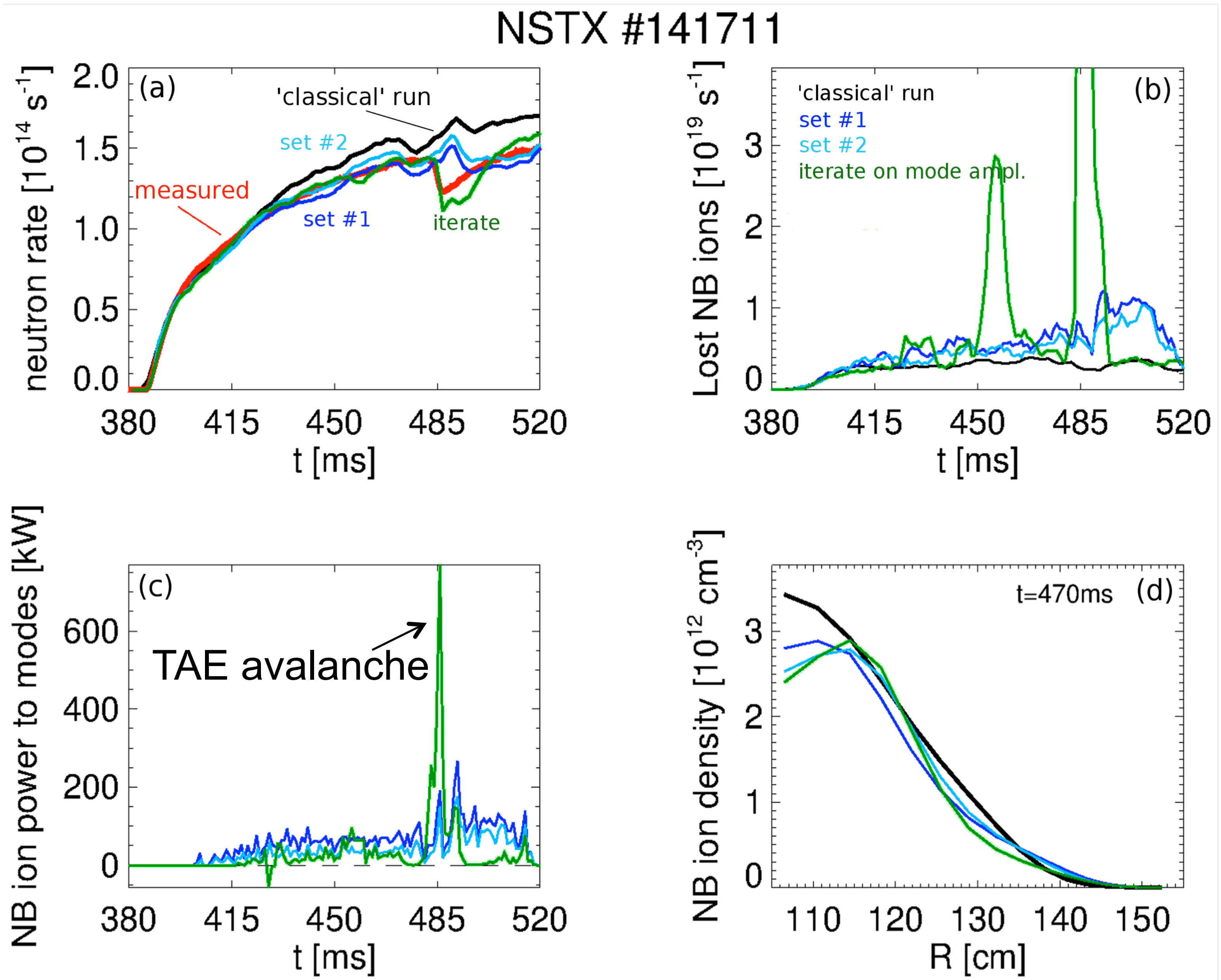
Including bursting behavior & iterating to match neutron rate brings δn/n closer to measurements





- Infer bursts from Mirnov coils
- Iterate TRANSP runs to match measured neutrons
- *Also include n=1 from mode-mode coupling (exp't evidence)*

Interpretive TRANSP runs lead to closer match with experiment



Summary of *(semi-)interpretive* kick model analysis

- Additional information from actual experiment greatly improves kick model results
- In most cases, actual analysis is a mix of prediction/ interpretation
  - E.g. mode amplitude(s) known at limited times, then 'extrapolate' based on match with neutrons
- Overall, semi-interpretive analysis works well for NSTX/NSTX-U, DIII-D scenarios
  - Promising results so far, including 'counter-TAE' case with off-axis NB2A (NSTX-U #203609)
  - Initial comparison with extended set of EP diagnostics (neutrons, FIDA, NPA, mode amplitudes) looks very promising (Heidbrink, PoP 2016 - submitted)

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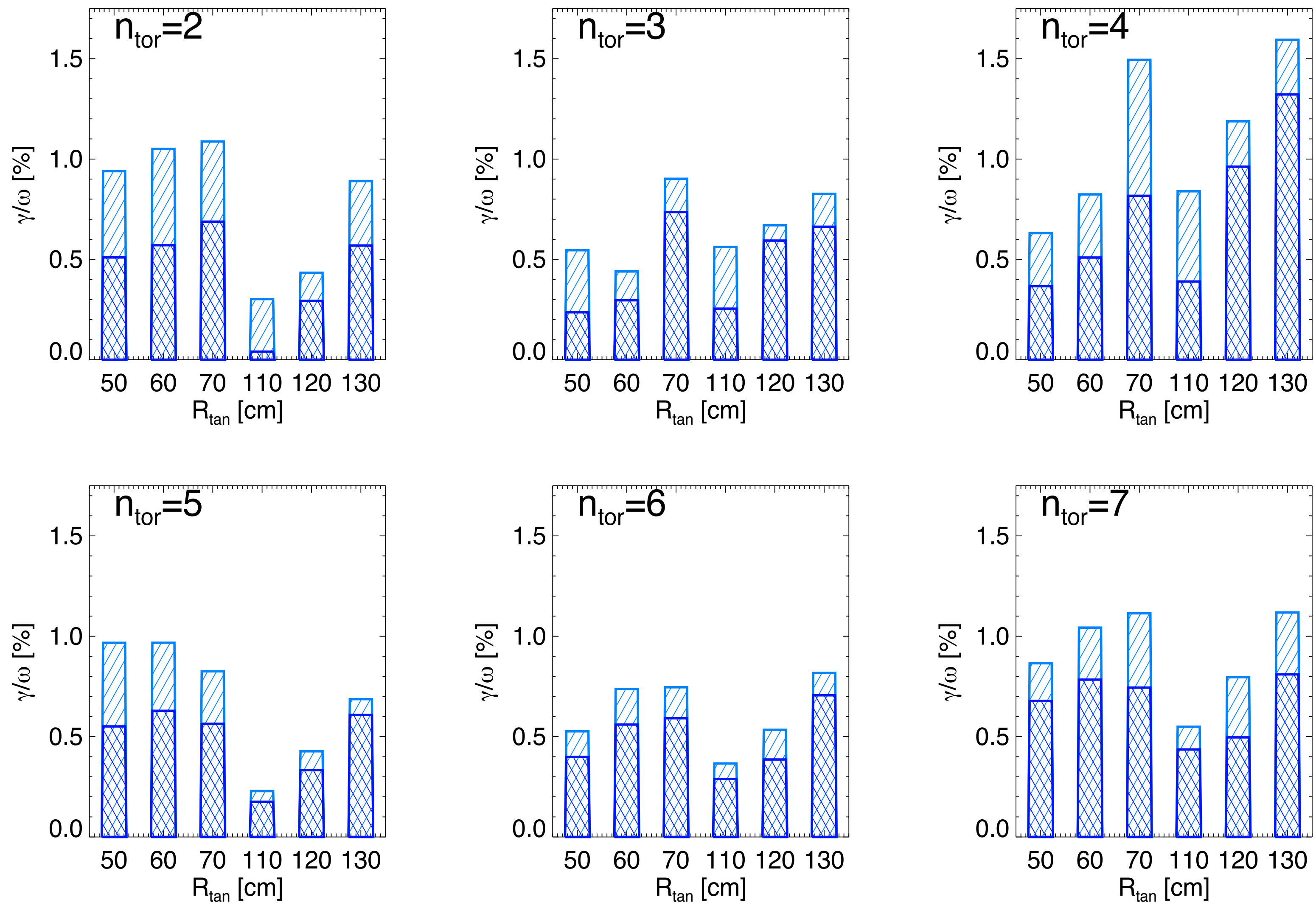
Outlook

- Analysis procedure has been established - moving on to more extensive validation
  – Target NSTX/NSTX-U and DIII-D scenarios to cover broad range of experimental conditions
  – Include comparison with FIDA, NPA, possibly sFLIP/FILD
- Mid-term: exploit kick model infrastructure in NUBEAM to implement CGM/RBQ model in TRANSP (Gorelenkov)
- Longer term developments:
  – Extend kick model to 3D-fields effects
    - May require some modifications to the code (NUBEAM)
    - Would enable time-dependent analysis with sources/sinks
  – Include gyro-averaging effects as ‘default’ (ORBIT)
  – Remove constraint on μ=const: extend to high-f CAEs/GAEs
  – Extend computation of kick probabilities to full-orbit codes (SPIRAL, others)

Backup

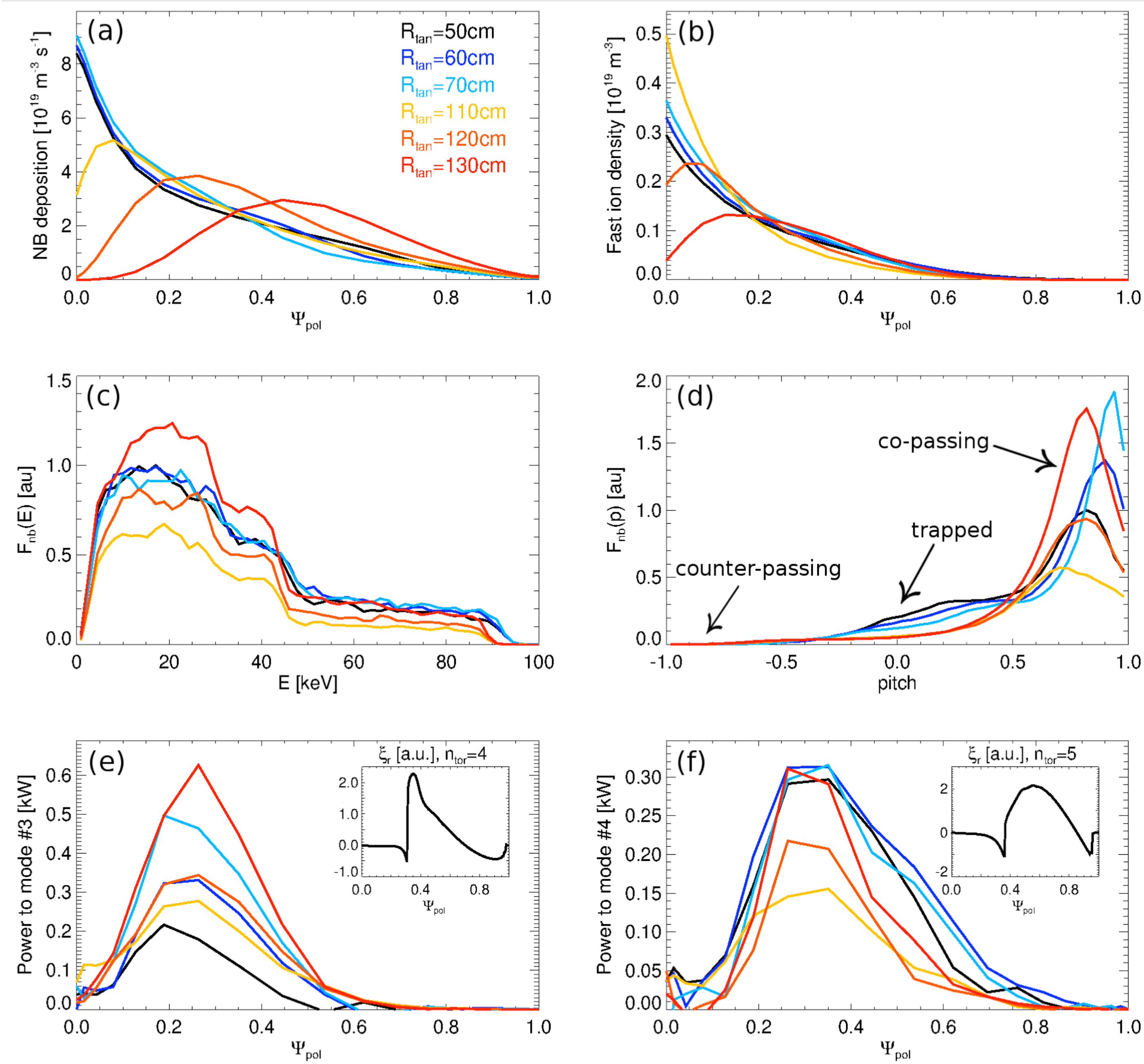
Kick model enables *numerical experiments* for scenario development, e.g. to optimize NB mix

- Computed growth rate varies with NB tangency radius

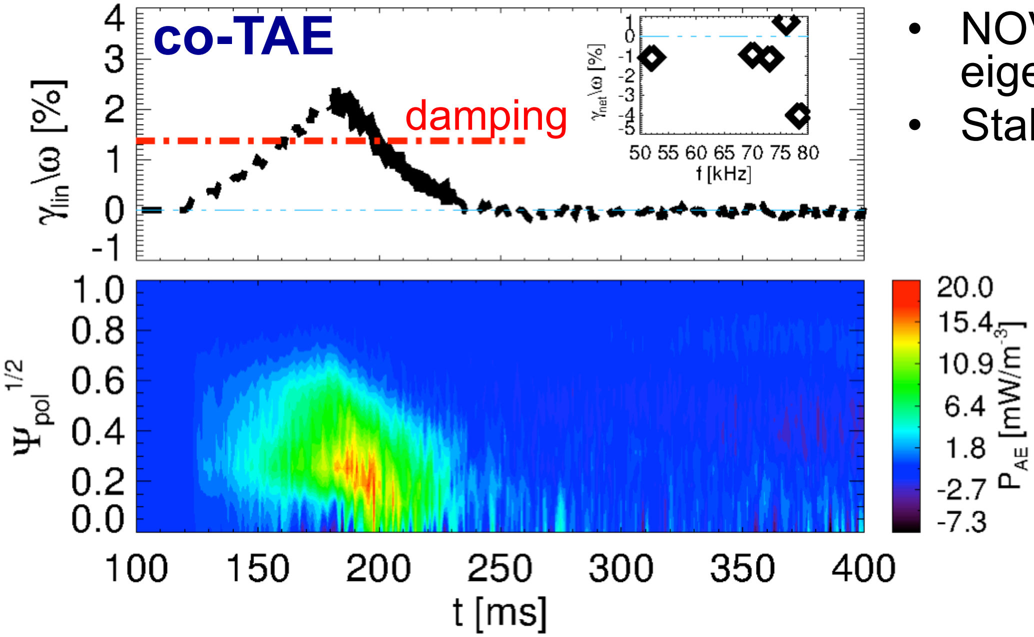


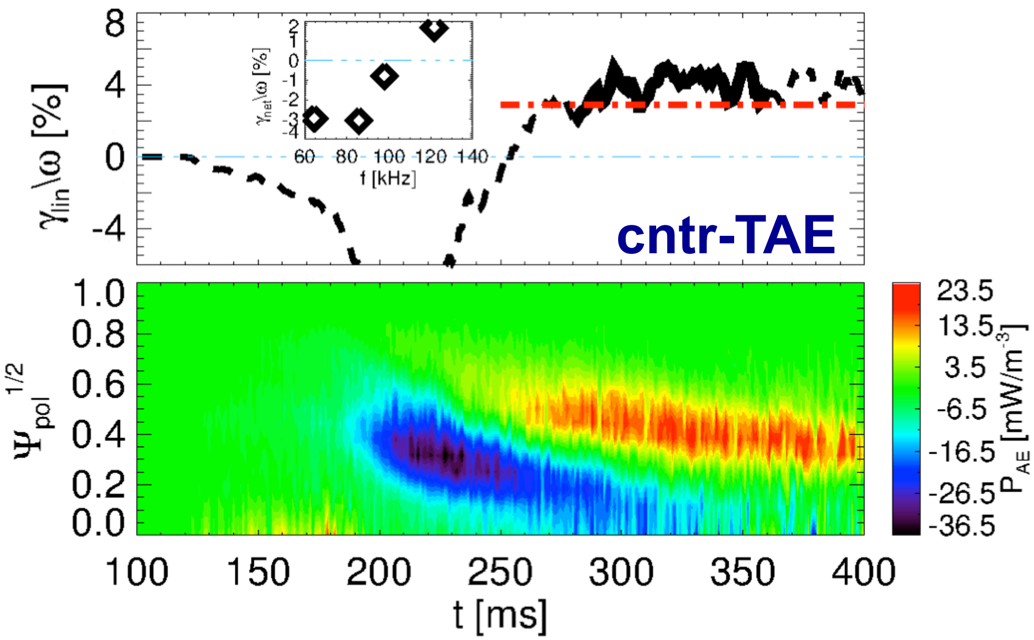
- No obvious correlation found…

Diagnostics in TRANSP are crucial to unfold complex dependence NBI <-> TAE stability

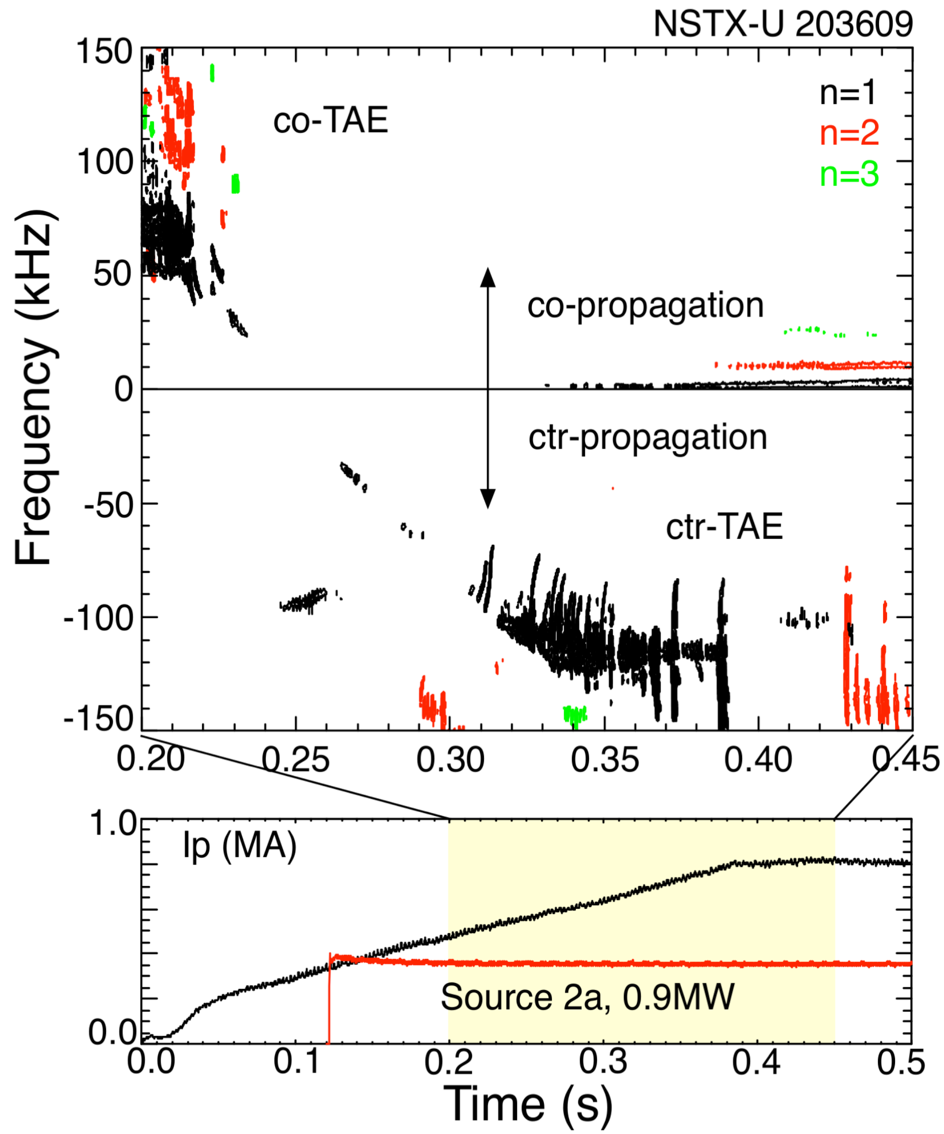


Kick model analysis recovers transition from co- to cntr-TAEs during off-axis NBI *(all preliminary!)*





- NOVA modeling at t=200ms and t=320ms provides n=1 eigenmodes
- Stability analysis used to select co- and cntr n=1 modes



Comparison of some reduced models used for EP transport

		ad-hoc D_{fi}	CGM model (*)	'kick' model
physics-based		no	yes	yes
required input		$D_{fi}(\rho,t)$	growth/damping rates	probability, mode amplitude
applicability				
	multi-mode	indirectly	multiple AEs	AEs, kinks, NTMs. Fishbones/ EPMs?
	steady-state	yes	yes	yes
	transients	yes	OK for $\tau>\tau_{relax}$	yes
phase-space selectivity		modest	no(t yet)	yes
predictive runs		requires guess D_{fi}	requires mode spectrum: growth/damping	requires mode spectrum, damping
improvements		none planned	extend to 2D in velocity space	remove μ conservation

(*) CGM – Critical Gradient Model, see IAEA-FEC 2014:
Gorelenkov TH/P1-2, Heidbrink EX/10-1

Kick model vs Critical Gradient model

Start from the evolution of mode energy: $\frac{\partial E_w}{\partial t} = P_{EP} - 2\gamma_{damp} E_w$

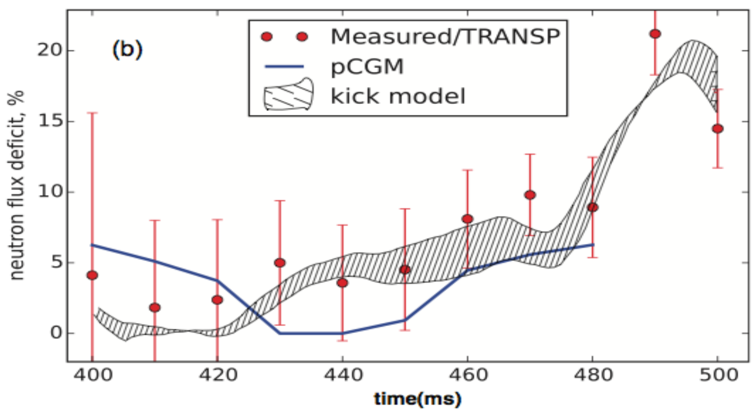
Introduce 'growth rate': $\gamma_{gr}(E_w) \doteq \frac{P_{EP}(E_w)}{2E_w} \Rightarrow \frac{\partial E_w}{\partial t} = 2\left[\gamma_{gr} - \gamma_{damp}\right] E_w$

CGM

- Assume γ_{damp} is known (NOVA)
- Assume $\gamma_{gr} \sim d\beta(r,E_w)/dr$
- Compute local $\beta(r,E_w)$ from 'saturation':

$$\gamma_{gr}(E_w) - \gamma_{damp} \rightarrow 0 \;\Rightarrow\; E_w \rightarrow E_w^{sat}$$

- Infer EP density profile from $\beta(r,E_w)$ at saturation



Kick model

- Assume γ_{damp} is known (NOVA)
- Compute $P_{EP}(E_w)$ for each mode
- Set E_w^{sat} from saturation:

$$\gamma_{gr}(E_w) - \gamma_{damp} \rightarrow 0 \;\Rightarrow\; E_w \rightarrow E_w^{sat}$$

- Infer EP density profile from TRANSP run
- *OR:* compute E_w by matching neutrons (, FIDA, NPA, …), verify γ_{damp} values
- *OR:* get E_w from experiment, verify saturation condition, γ_{damp} values

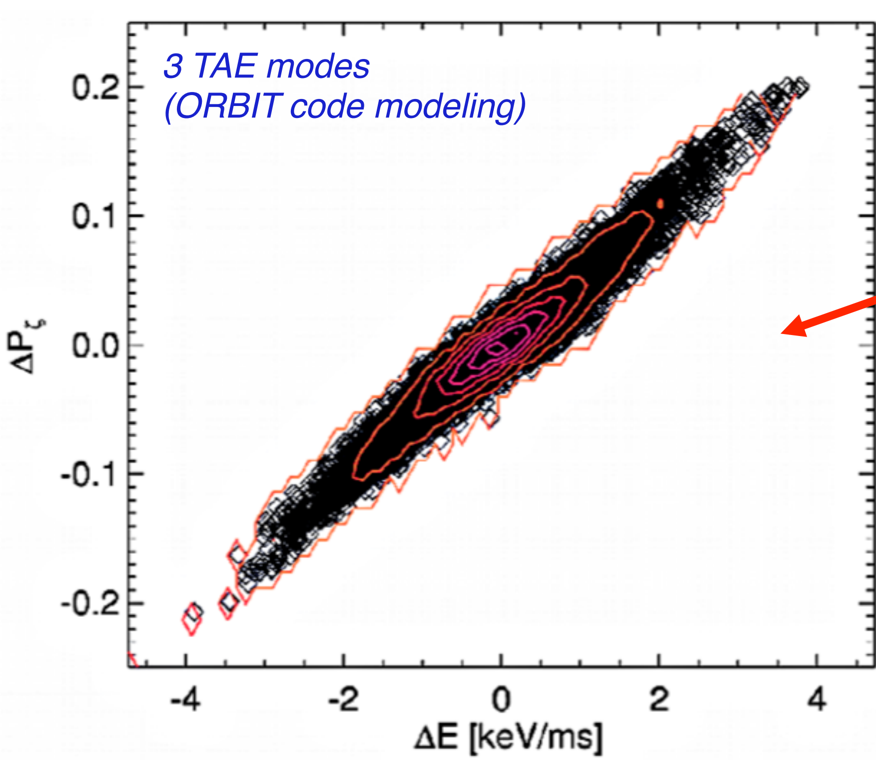
New 'kick model' uses a *probability distribution function* to describe particle transport in (E,P_ζ,μ) space

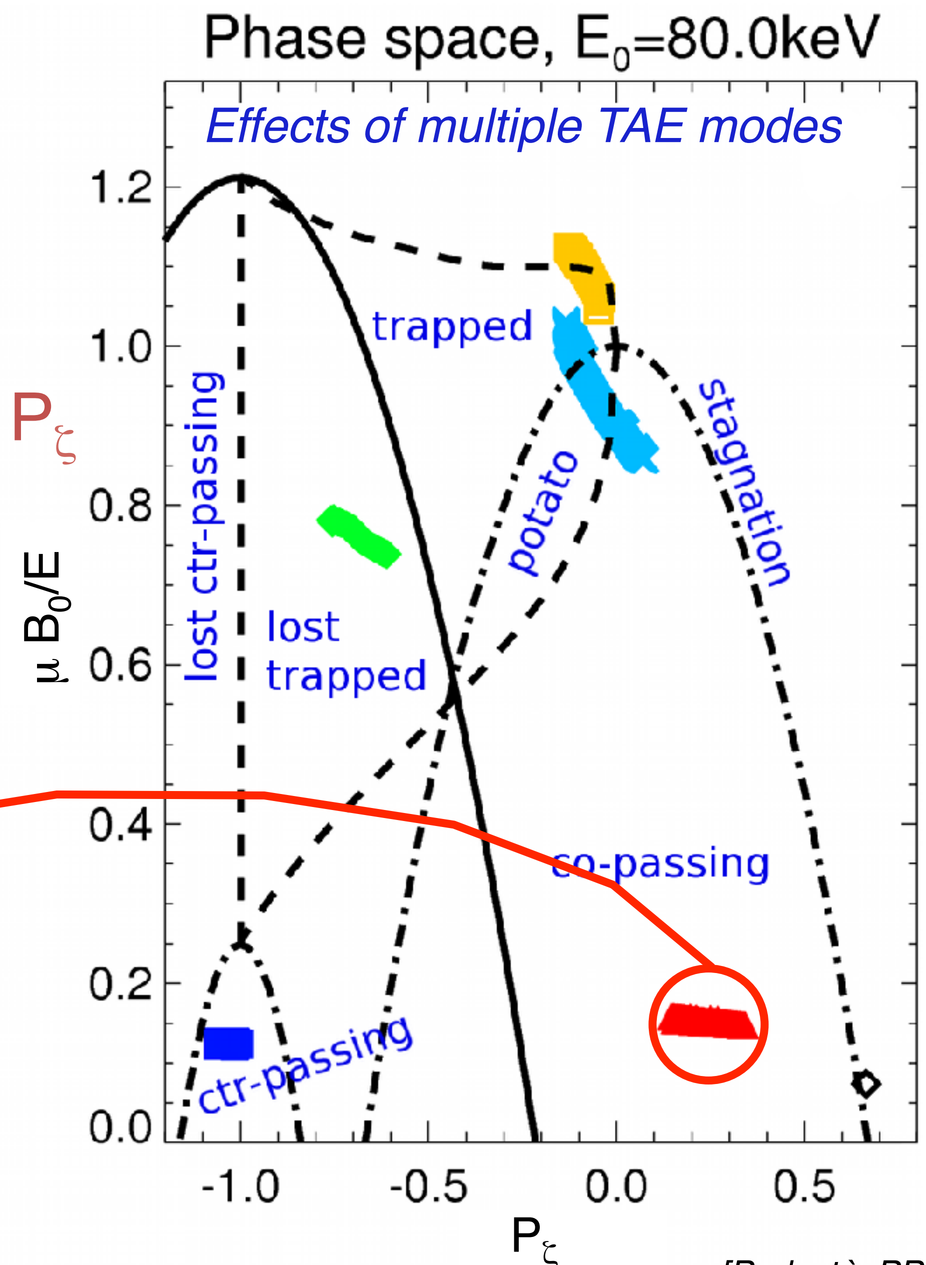
Kicks ΔE, ΔP_ζ are described by

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

which includes the effects of <u>multiple</u> modes, resonances.

⇨ correlated random walk in E, P_ζ

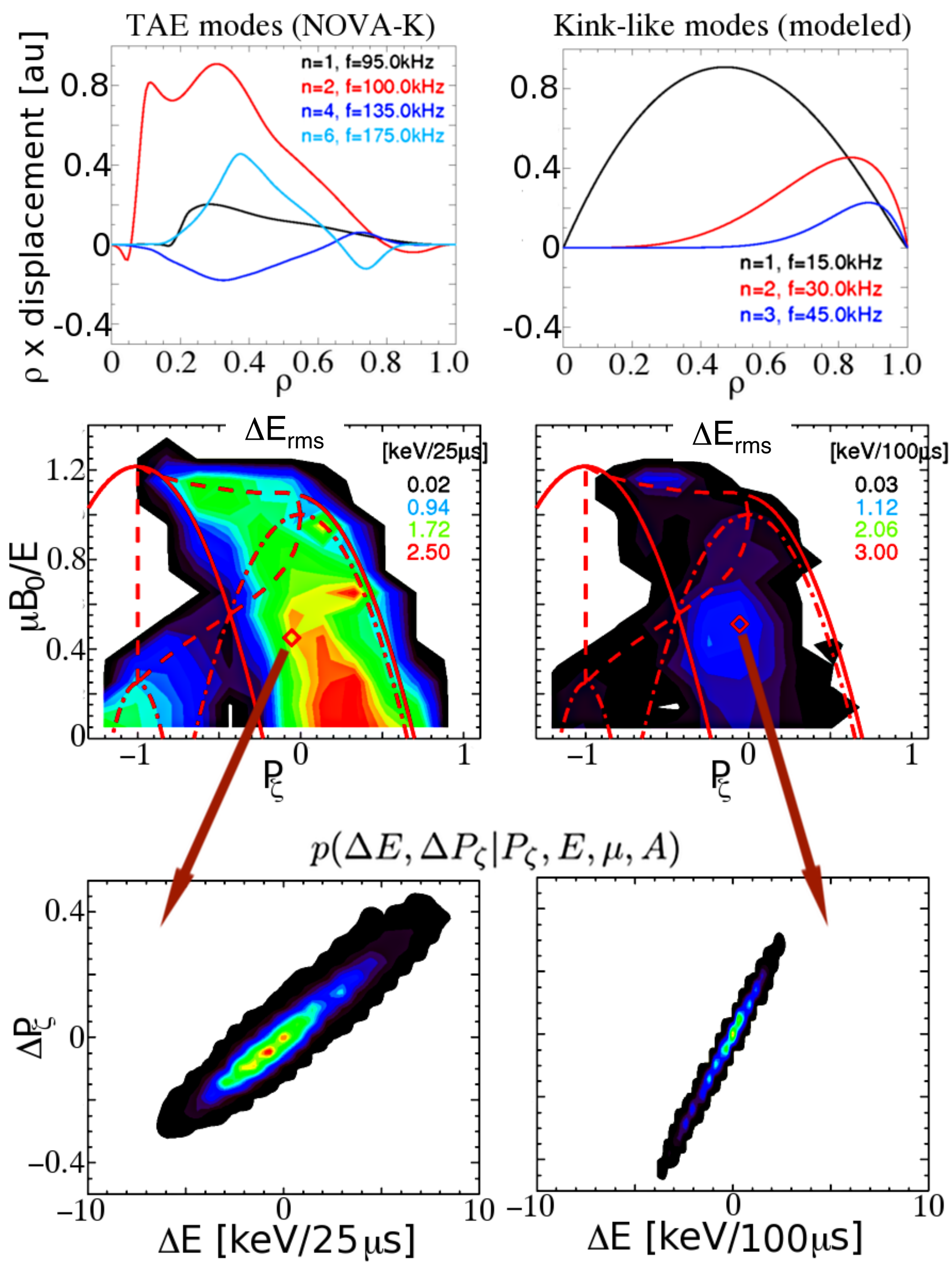




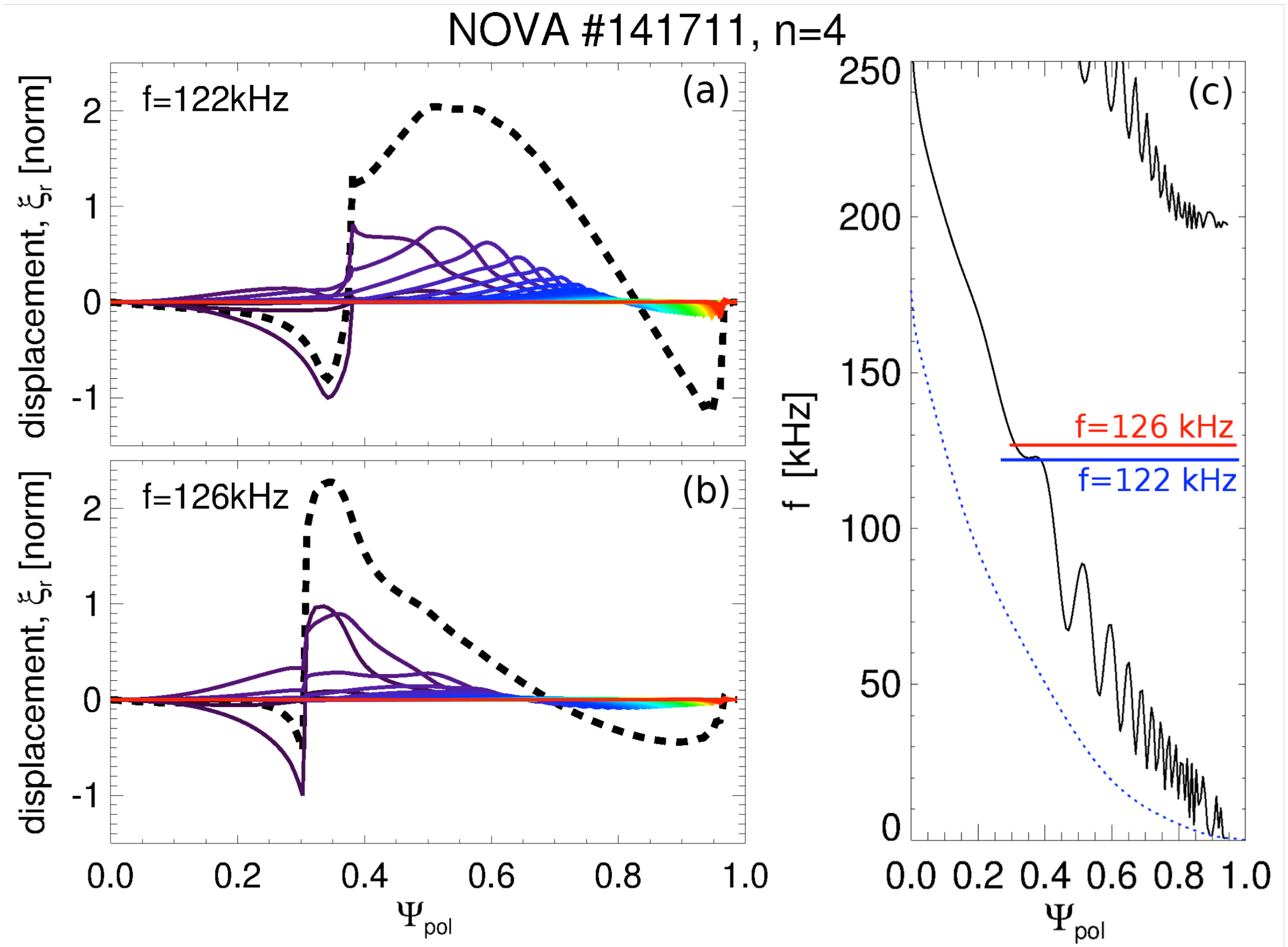
[Podestà, PPCF 2014]

$p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu)$ and a time-dependent 'mode amplitude scaling factor' enable multi-mode simulations

- Example: toroidal AEs (TAEs) and low-frequency kink
- $p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu)$ from particle-following code ORBIT
- Each type of mode has separate $p(\Delta E, \Delta P_\zeta)$, $A_{mode}(t)$
- TAEs and kinks act on different portions of phase space
- Amplitude vs. time can differ, too
- Effects on EPs differ
  - > TAEs: large ΔE, ΔP_ζ
  - > kinks: small ΔE, large ΔP_ζ

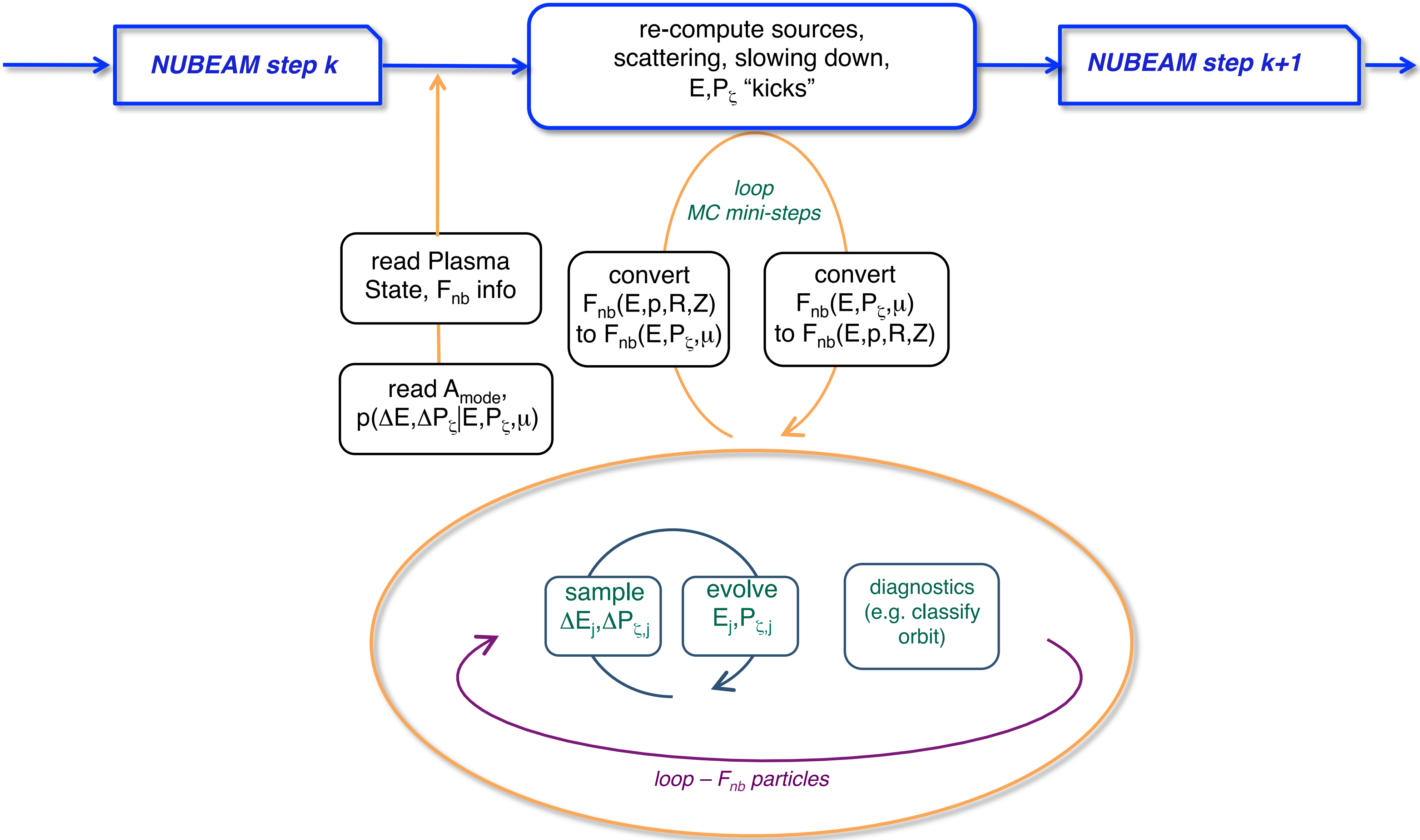


Accurate computation of mode structure is critical for reliable kick model analysis



- Main source of uncertainty in kick model runs comes from selection of candidate modes
- Example: ideal MHD doesn't resolve intersection with AE continuum
- Discontinuity in mode structure propagates to kick probability, e.m. energy associated with the mode

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



add "kicks" to F_{nb} variables