# Phase space effects on fast ion transport modeling in tokamaks

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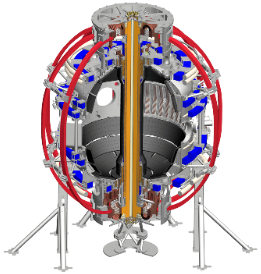
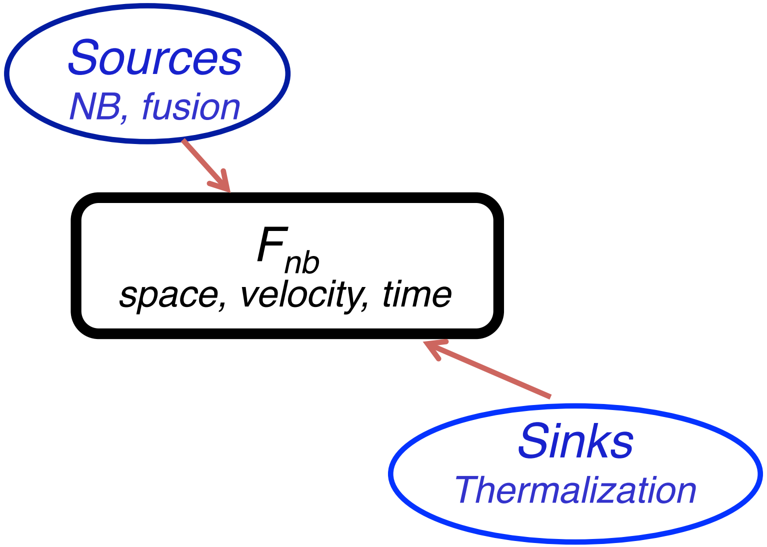


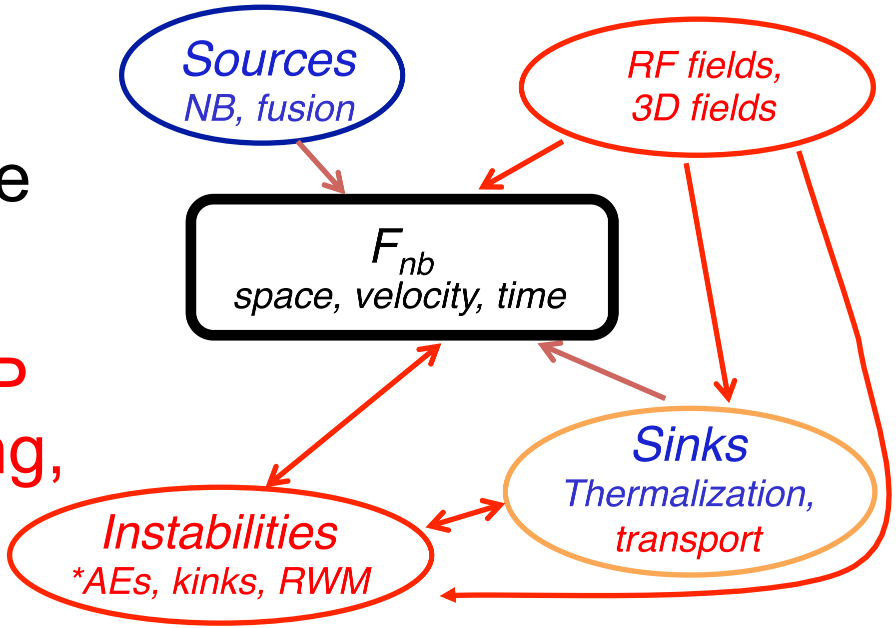
# Reliable & quantitative understanding of Energetic Particle (EP) dynamics is crucial for burning plasmas

- ‘Classical’ physics works
- *Except when it doesn’t...*



# Reliable & quantitative understanding of Energetic Particle (EP) dynamics is crucial for burning plasmas

- 'Classical' physics works
- EPs from Neutral Beam (NB) injection, alphas, RF tails drive instabilities
  - e.g. Alfvénic modes - AEs
- With instabilities, 'classical' EP predictions (e.g. for NB heating, current drive) can fail



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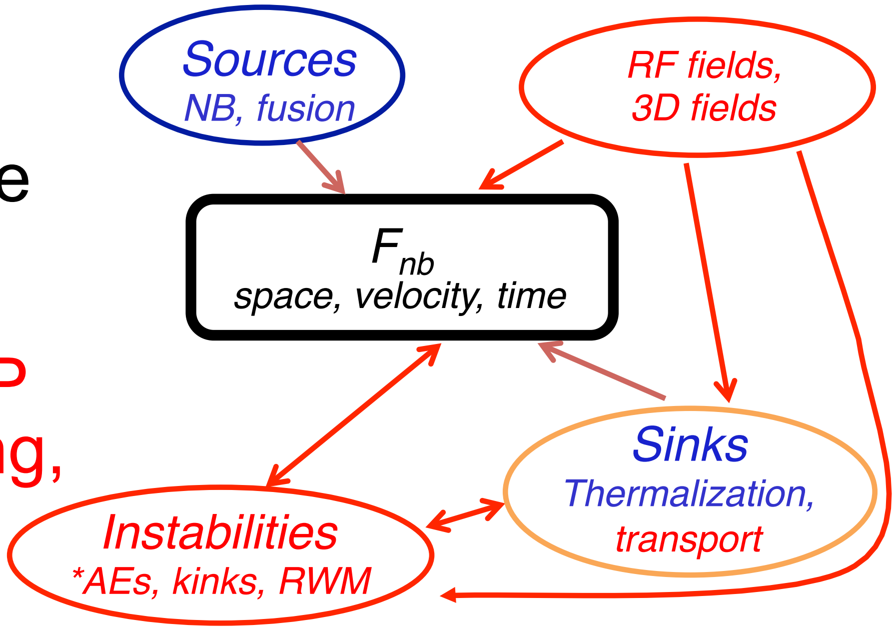


> *Predictive tools are being developed, validated for integrated modeling of these effects in present and future devices (ITER, Fusion Nuclear Science Facility - FNSF)*

# How important are fast ion phase space modifications by instabilities for accurate integrated modeling?

- Fast ion driven instabilities (e.g. Alfvénic modes -AEs) tap energy from gradients of fast ion phase space
  – Phase space: energy, canonical toroidal momentum, magnetic moment $(E, P_\zeta, \mu)$
- As a result, phase space is modified by instabilities

> ***What is the effect of those modifications on integrated modeling results?***

  – *Relevant for analysis of present, NB-heated plasmas*

  – *Relevant for improving predictive tools for ITER, Fusion Nuclear Science Facility (FNSF) and beyond*

# Outline

- Modeling tools: developing ‘kick model’ in TRANSP
- Experimental scenario
- Modeling results:
  - Fast ion distribution function
  - Integrated quantities: NB driven current
  - Derived results: power balance & AE stability
- Summary & outlook

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# TRANSP code is used for time-dependent simulations including fast ion transport by instabilities

- NUBEAM module of TRANSP is the work-horse for simulations including fast ions (NB injection, alphas)
  - "Classical" physics is assumed for fast ion evolution (e.g. scattering, slowing down)
  - Additional modules can be used to mimic non-classical EP transport

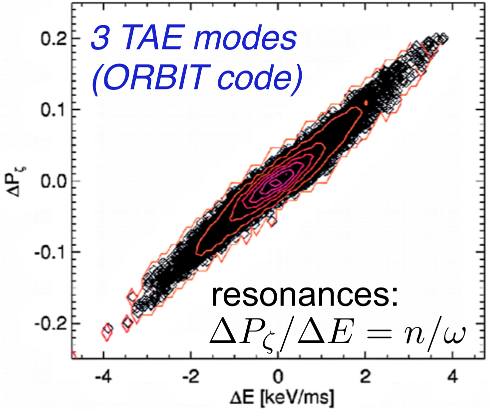
> Here we compare results from two models for enhanced fast ion transport by instabilities:
> - Simplest, ad-hoc diffusive model: $\Gamma_{fi} = -D_b \nabla n_b$
> - New physics-driven, *phase space resolved* "kick" model

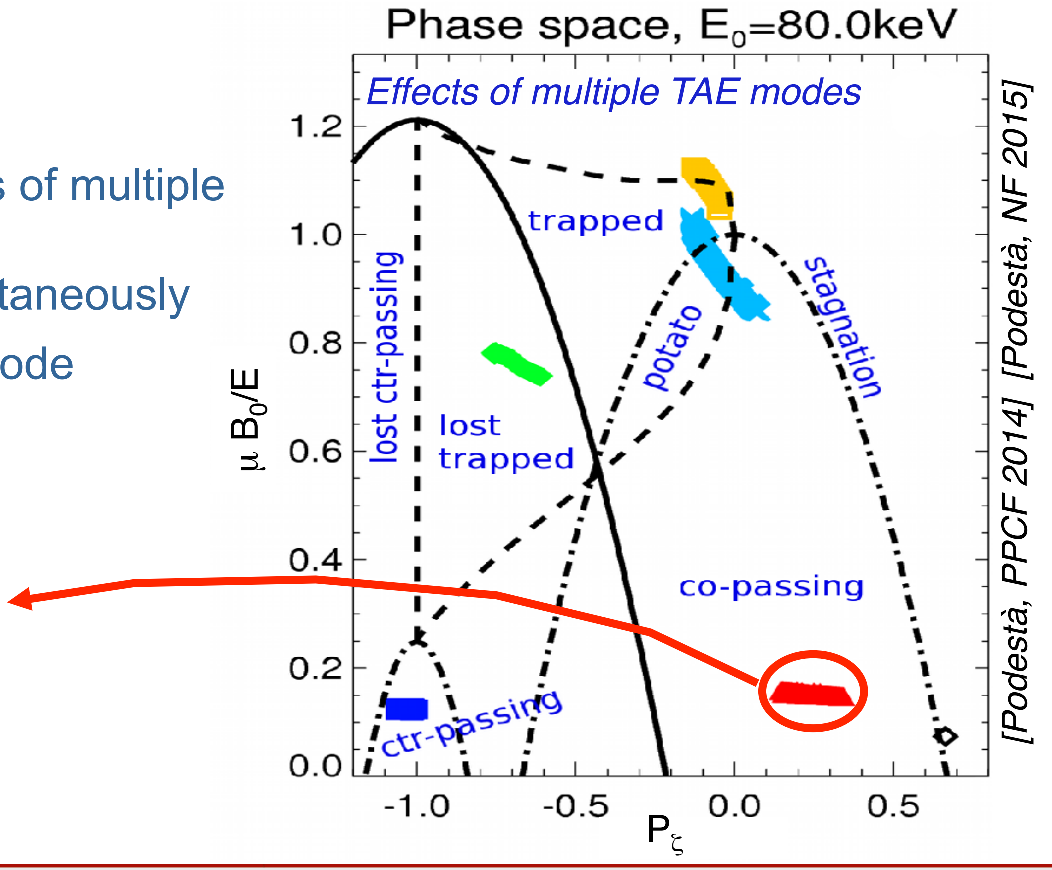
# New ‘kick model’in NUBEM uses a *probability distribution function* to describe transport in phase space $(E,P_\zeta,\mu)$

Kicks $\Delta E$, $\Delta P_\zeta$ are described by

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

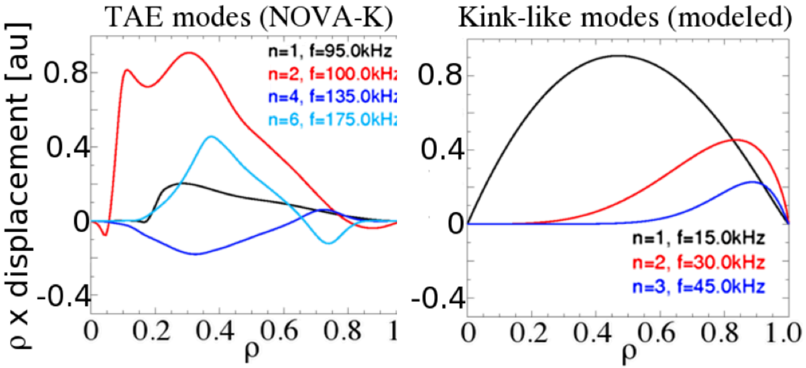
- Each $p(\Delta E,\Delta P_\zeta)$ can include the effects of multiple modes
- Up to 5 $p(\Delta E,\Delta P_\zeta)$’s can be used simultaneously
- Kicks assumed to be proportional to mode amplitude, A(t)

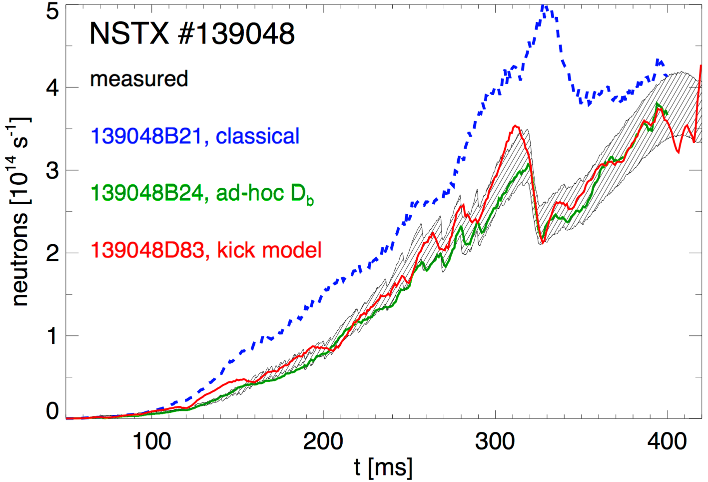


# Mode properties, temporal evolution are inferred from experiments; use models if no experimental data available

- Mode structure, frequency, $n_{tor}$ from experiments + NOVA, or from simple models
- Plug modes in particle-following code ORBIT to compute $p(\Delta E,\Delta P_\zeta)$
  - Repeat for each mode, or set of modes
- Initial amplitude A(t) from experiments
  - Can iterate to get better match with neutrons, $W_{MHD}$
- Use $p(\Delta E,\Delta P_\zeta)$, A(t) in NUBEAM/TRANSP for complete simulation
- *Ad-hoc $D_b$: adjust $D_b$ to match neutrons*




[Podestà, NF 2015]

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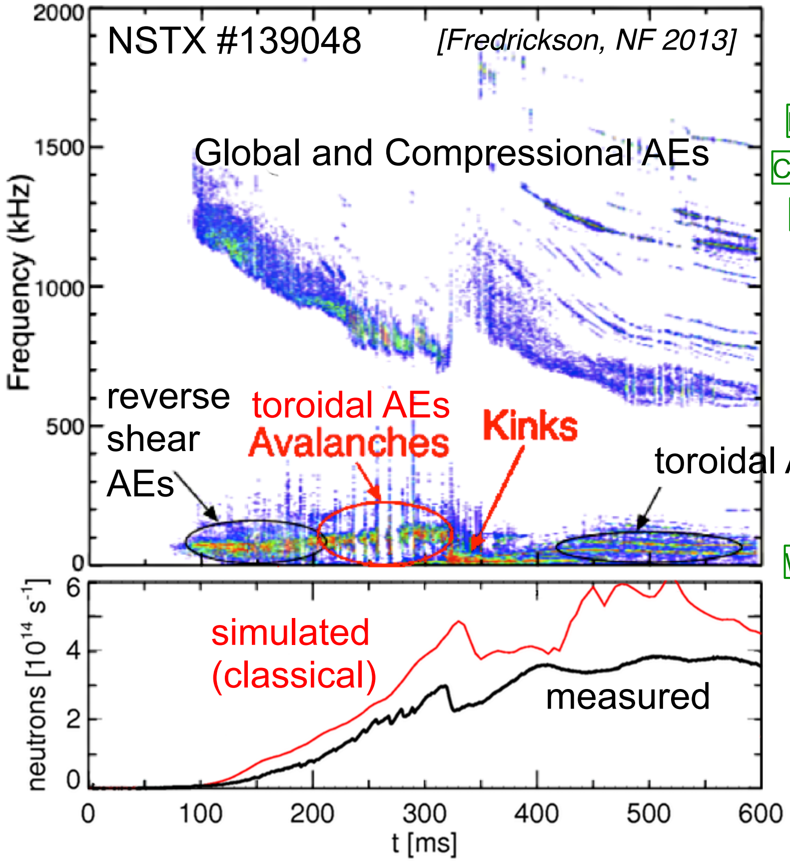
# Models are tested on a database from NSTX discharges featuring strong MHD activity

Analyze three NSTX discharges
#141711, #141719, **#139048**

- Discharges include L- and H-mode phases
- NB power: 2-4MW
- Focus on TAEs, low-f kink-like instabilities
  - *Neglect high-f Compressional and Global AEs*
- Mirnov coils mainly used to infer (normalized) mode amplitudes

*Database:*

- Simulation results binned every 10ms
- Error bars indicate variation within 10ms
- No systematic uncertainties included




Lestz GP12.70
Crocker GP12.83
Tang GP12.84
Fu GP12.68
Hao GP12.67
Wang GP12.69

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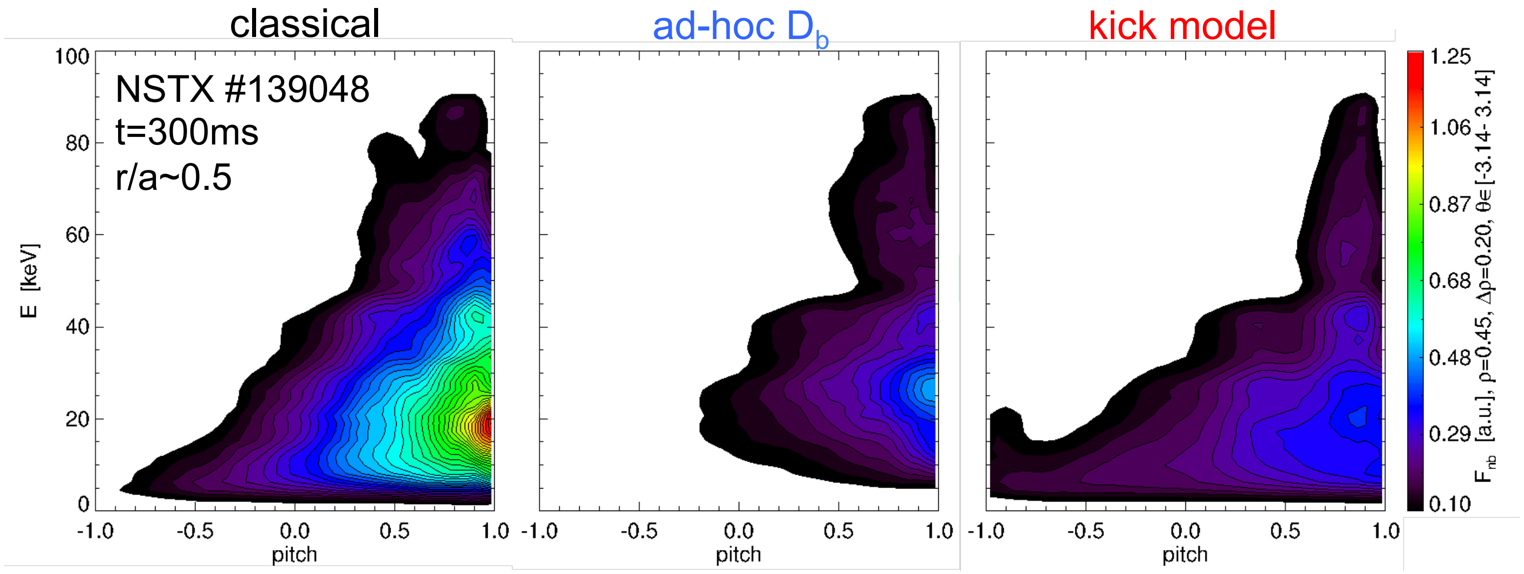
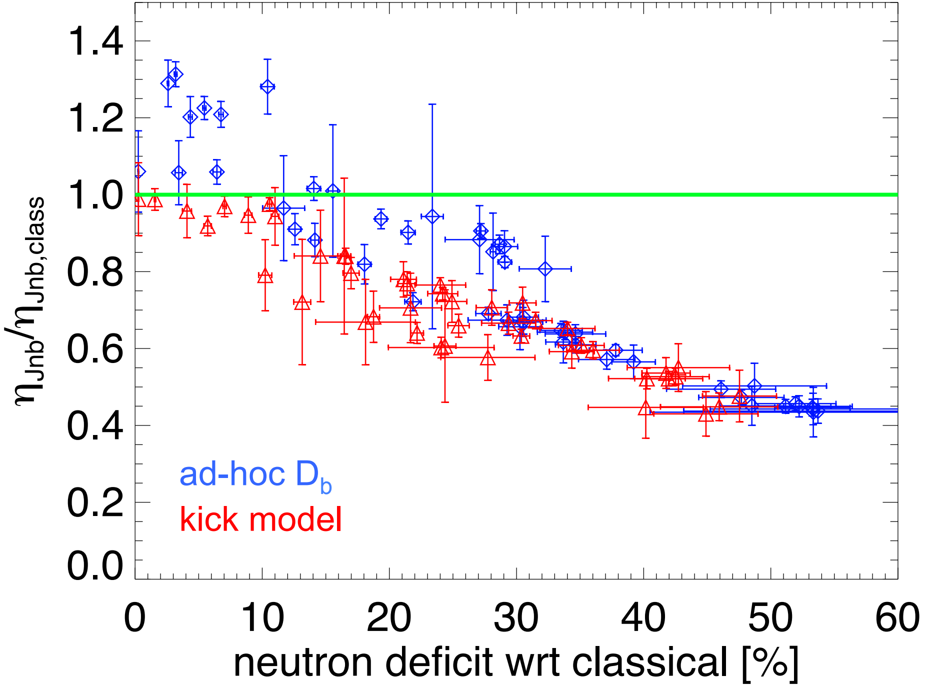
# Models result in considerably different fast ion distribution functions




- Ad-hoc $D_b$ model affects all $(E,P_\zeta,\mu)$ regions indiscriminately
- Kick model includes $(E,P_\zeta,\mu)$ selectivity:
  - AEs mainly affect higher-energy co-passing particles in this example
  - Lower energy, counter-passing particles (pitch<0) almost unaffected

> *Important when $F_{nb}$ is then used for AE stability calculations*

# NB-CD efficiency, fast ion density are greatly reduced by strong AE activity




NB-CD efficiency here defined as:

$$\eta_{Jnb} = \frac{\Sigma_{r/a} J_{nb}}{\Sigma_{r/a} J_{tot}} \frac{1}{P_{NB}}$$

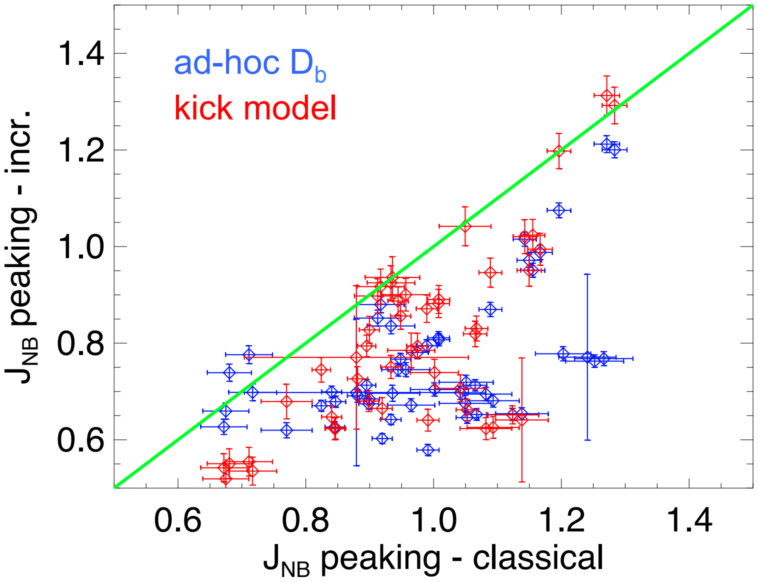
- Neutron deficit scales with AE virulence
  - Neutron deficit used as proxy for AE activity
- Up to 50% overall reduction in $\eta_{Jnb}$ is computed

> *Slight differences between two transport models*

*Are differences also observed in radial profiles?*

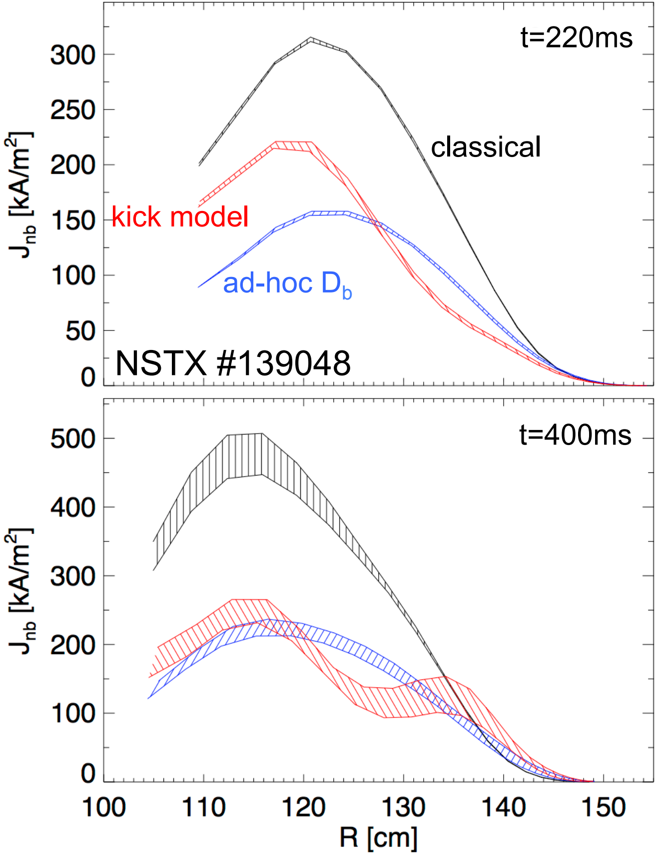
- *Critical info to develop current, q-profile control*

# NB-driven current peaking is reduced; resulting $J_{nb}$ profile varies across models




Peaking is computed as ratio of central to average $J_{nb}$:

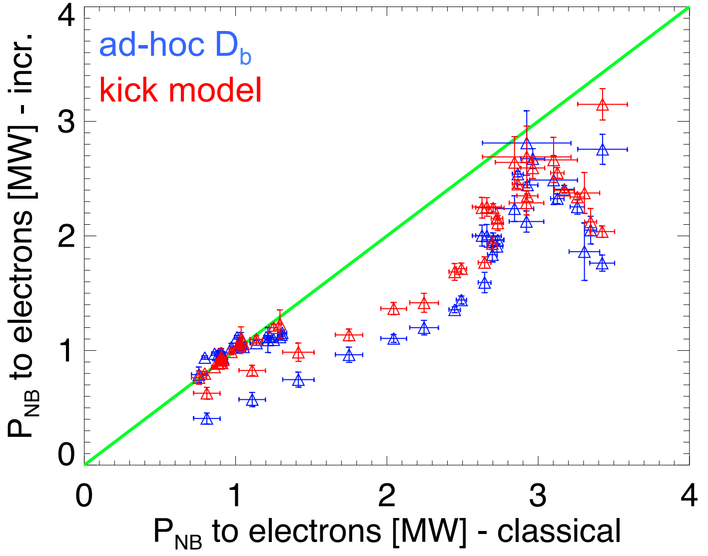
$$peaking = \frac{\Sigma_{r/a=0}^{r/a=0.2} J_{nb}}{< J_{nb} >_{0 \leq r/a \leq 1}}$$

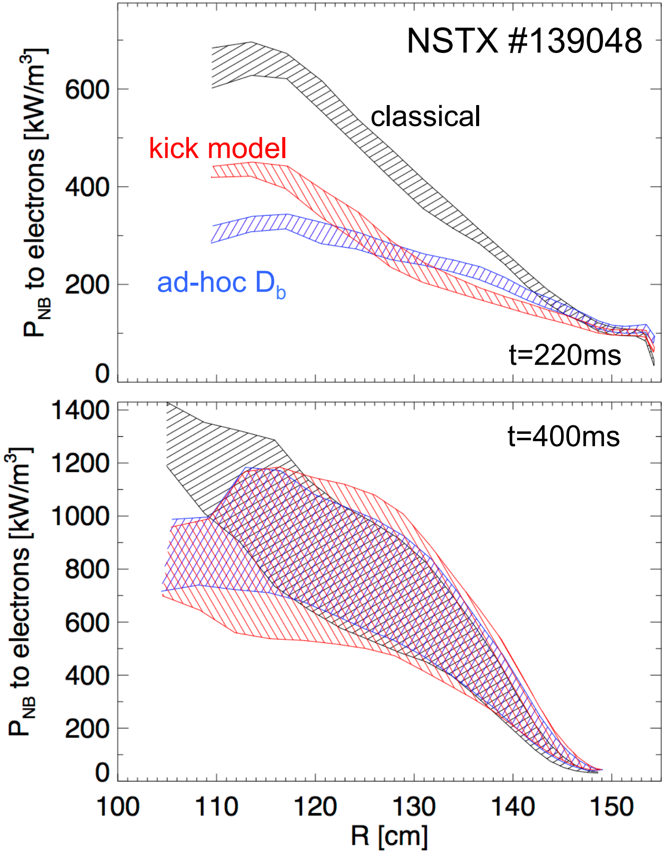



- Instabilities broaden NB-driven current
- Comparable broadening and reduction in peaking from both models

> *But: $J_{nb}$ profiles can be substantially different -> current profile control issues*

# NB power transferred to thermal plasma is reduced by similar amount for both models




- No substantial difference for volume-integral
- But: local power to thermal species can vary substantially

*> Important for local thermal transport analysis!*

*[Heidbrink, PPCF 2014] [Holcomb, PoP 2015] [Podestà, NF 2015]*

# Fast ion distribution modifications can strongly affect computation of AE mode stability

Kick model enables estimates of "mode stability":

$$\begin{cases} \dfrac{\partial E_{wav,j}}{\partial t} = P_{fi,j} - 2\gamma_{D,j} E_{wav,j} & \text{Wave energy evolution for } j\text{-th mode} \\ 2\gamma_{eff,j} E_{wav,j} \equiv P_{fi,j} - 2\gamma_{D,j} E_{wav,j} & \text{Effective growth rate, drive - damping} \\ \dfrac{\partial E_{wav,j}}{\partial t} = 2\gamma_{eff,j} E_{wav,j} & \end{cases}$$

$\Rightarrow \quad \gamma_{eff,j} \approx 0 \ , \ P_{fi,j} \geq 0$ **Condition at saturation**

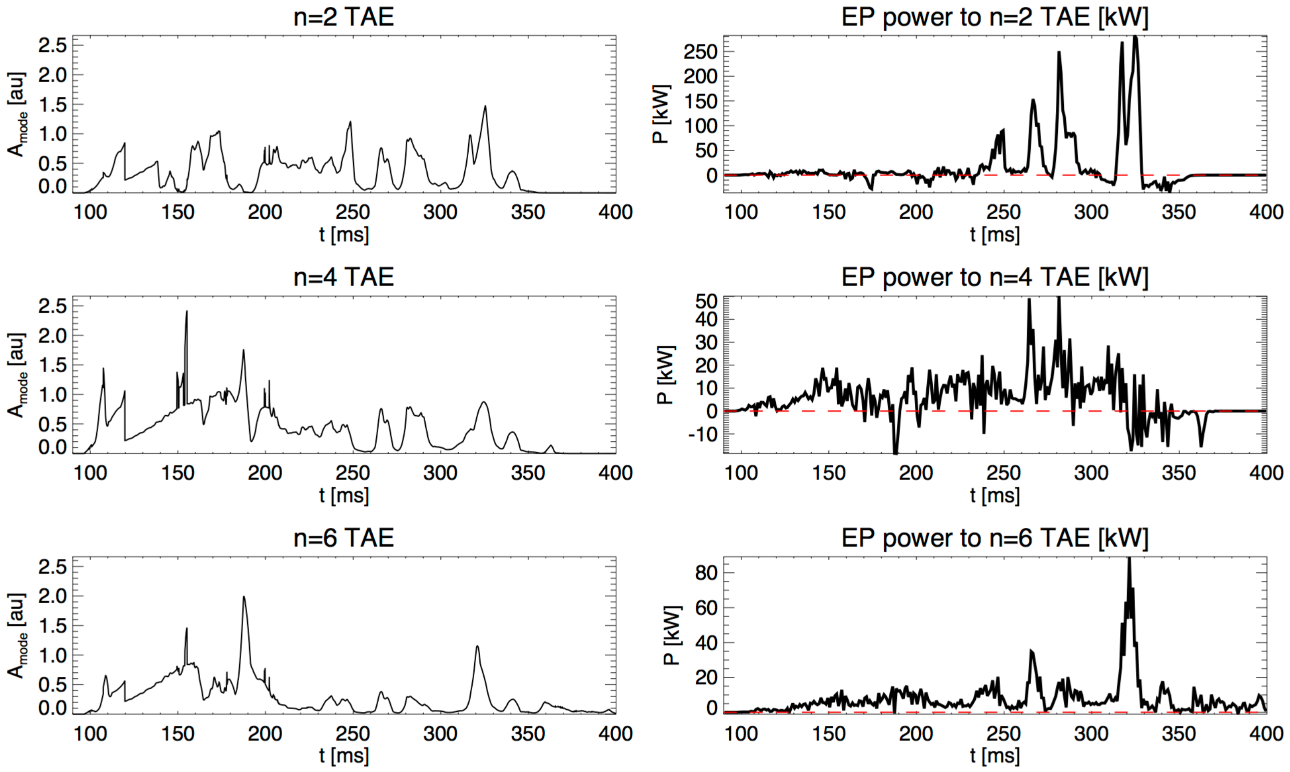
- Kick model computes $P_{fi,j}$ for each mode
- Amplitude $A_{wav,j} \sim E_{wav,j}^2$ imposed
- Worst case scenario: assume damping -> 0

> Need a positive $P_{fi,j}$ for a mode to be "unstable"

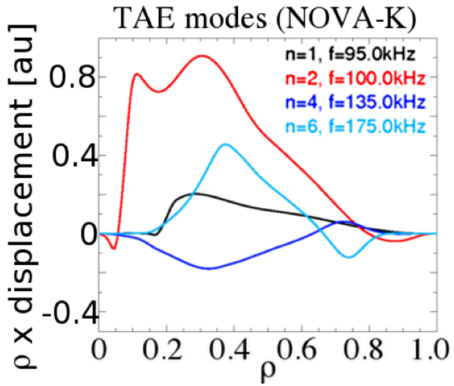
- Are $A_{wav,j}$ assumptions and $P_{fi,j}$ results energetically consistent?
- Can $A_{wav,j}$ be inferred from simulations (towards *predictive* capability)?

# Example: mode "saturation" can vary if multi-mode effects are taken into account

$\gamma_{eff,j} \approx 0\ ,\ P_{fi,j} \geq 0$ Condition at saturation

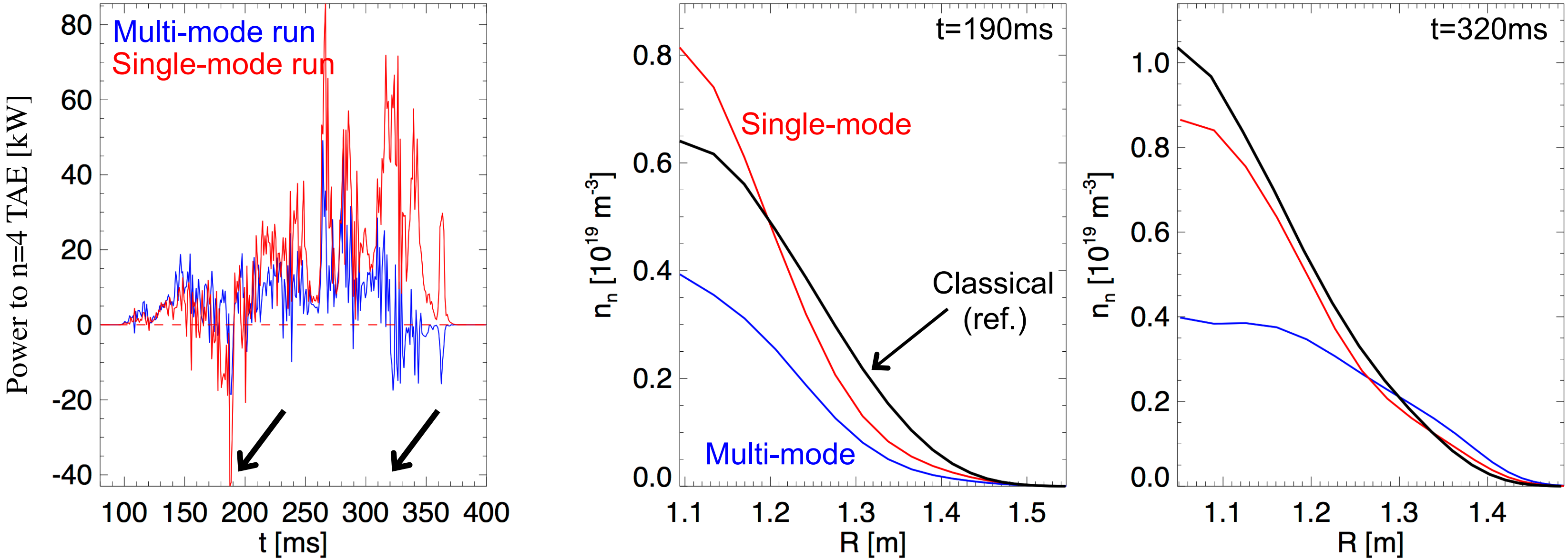



Focus on dominant n=2,4,6 TAEs



# Additional modes modify phase space, can affect estimates of saturation

$\gamma_{eff,j} \approx 0 \; , \; P_{fi,j} \geq 0$ Condition at saturation




- Use same mode amplitude for multi- and single-mode runs
- Power to mode also depends on presence of other modes
- Radial fast ion profile varies substantially

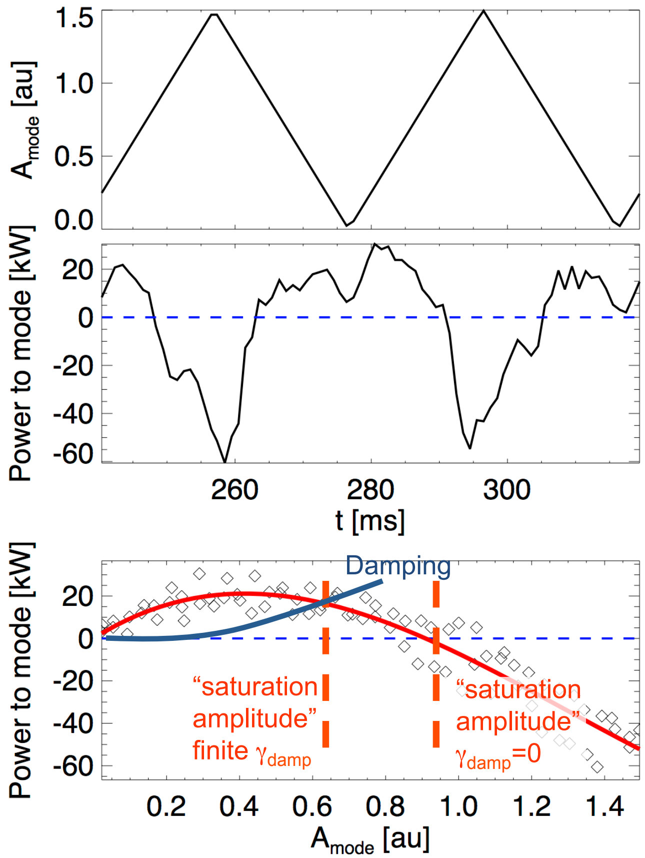
# Work in progress: developing a procedure to infer mode amplitudes based on energetics

*For a given scenario:*

- Compute ideal mode structures (e.g. with NOVA)
- Compute kick probability for each mode (e.g. with ORBIT)
- Plug probabilities in TRANSP, use modulated mode amplitude to probe "mode stability"
- Analyze power transferred to modes vs. mode amplitude

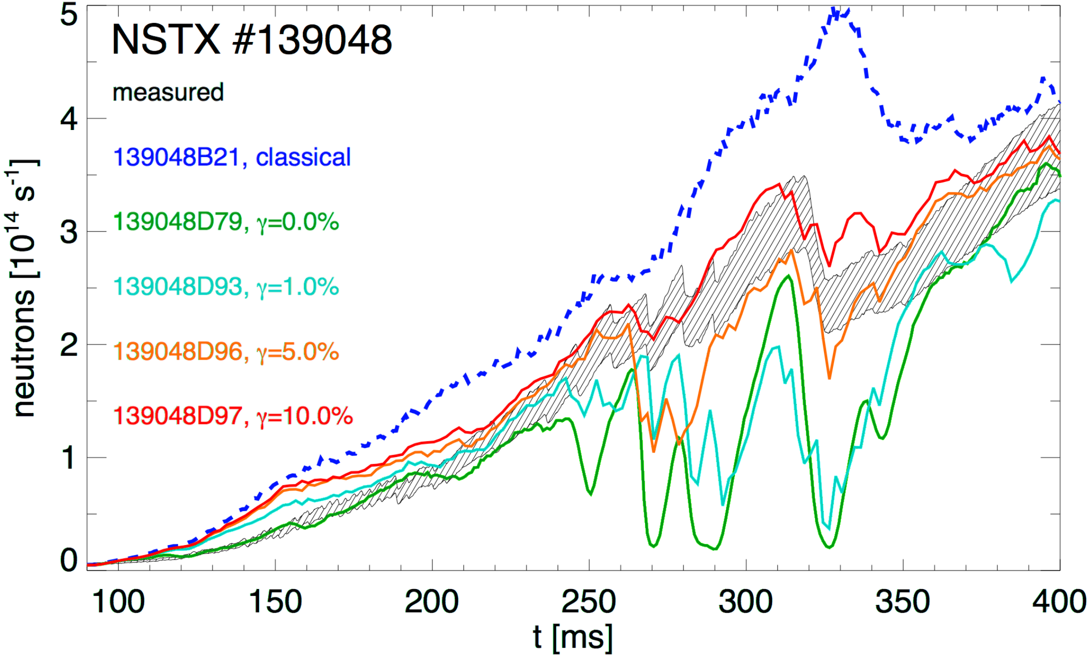
>Infer average "saturation amplitude"

- *Net power to mode must vanish*
- *Not applicable to rapidly (<1ms) chirping modes*

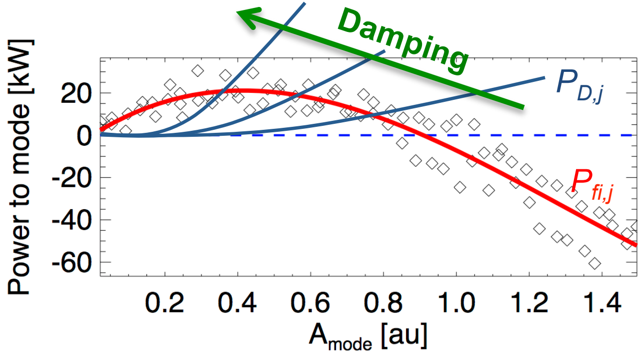


# Power balance between fast ions & modes can be used to *predict* mode amplitudes vs time for multi-mode scenarios

First tests to infer $A_{wave}$ from power balance:




- Damping rate is varied, $0<\gamma_{damp,j}<10\%$
- Conditions for 'acceptable' values:
  - Neutron rate matches experimental value
  - $P_{fi,j}\sim 0$ satisfied for all modes




> Required $\gamma_{damp,j}$ appear 'reasonable', $\gamma_{damp,j}<10\%$

> *To be done:* compare with damping rates from NOVA-K

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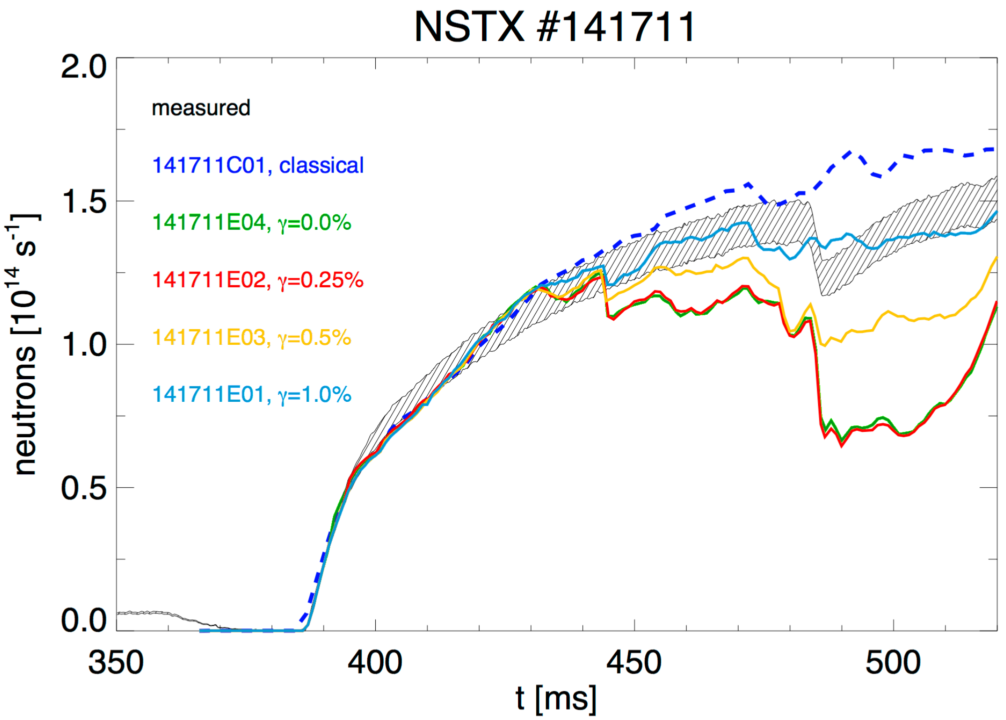
# Summary & outlook

- Two models compared for EP transport in integrated simulations:
  - Simple, ad-hoc diffusion model
  - Phase space resolved "kick" model – testing on NSTX, DIII-D    Kramer C06.10
  - *Comparison with physics-based "Critical Gradient Model" (N. Gorelenkov, IAEA-TM 2015) in progress*
- Ad-hoc model OK for global quantities (e.g. neutrons, $W_{MHD}$)
- But: substantial differences observed for profiles, fast ion distribution function & their temporal evolution
  - *Important for development of q-profile, current control (NSTX-U goals)*    Boyer GP12.76

- Future work:
  - Further validate kick model vs. phase space resolved measurements
    - e.g. from FIDA, ssNPA    Ruskov GP12.66
  - Investigate kick model performance for predictive simulations:
    - Main challenge is to predict mode amplitude evolution *consistently* (e.g. from energetics)

# Backup slides

# Power balance between fast ions & modes can be used to *predict* mode amplitudes vs time for multi-mode scenarios




- First tests to infer $A_{wave}$
- Here damping rate is varied based on
  - Neutron rate (match experimental value)
  - Satisfy $P_{fi,j}$~0 for all modes
- Required $\gamma_{damp,j}$ appear reasonable, $\gamma_{damp,j}$<10%