Reduced models of Energetic Particle (EP) transport for scenario modelling

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12th ITER International School

June 26-30, 2023 – Aix-en-Provence (France)

Work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under contract numbers DE-AC02-09CH11466

Acknowledgments

R.B. White[1], N.N. Gorelenkov[1], E. Bass[2], W.W. Heidbrink[3], C.S. Collins[4], L. Bardóczi[5], V. Duarte[1], E.D. Fredrickson[1], M. Gorelenkova[1], F.M. Poli[1], M.A. Van Zeeland[5], F. Zonca[6], P. J. Bonofiglo[1], J. Yang[1], A. A. Teplukhina[7], M. Vallar[8], M. Cecconello[9], A. Tinguely[10], M. Porkolab[10] and many others

ITPA-EP and SciDAC-EP groups

Experimental teams: NSTX, DIII-D, JET, ASDEX-Upgrade, KSTAR, TCV

[1]PPPL [2]UCSD [3]UCI [4]ORNL [5]General Atomics
[6]ENEA [7]CFS [8]SPC Lausanne [9]Uppsala U.
[10]MIT

Disclaimer

- I tried to be comprehensive, but I’m aware I inevitably focused on material I’m familiar with.

- I may have misrepresented work done by others – blame me!

- Feel free to reach out for comments, questions at mpodesta@pppl.gov

Layout

- Motivation – why *integrated* simulations, why *reduced* models
- Some definitions: “reduced models”; EP and mode representations
- Examples of reduced EP transport models
- Applications to integrated simulations
- A few words on model validation - what worked, what didn’t and why
- Future directions and summary

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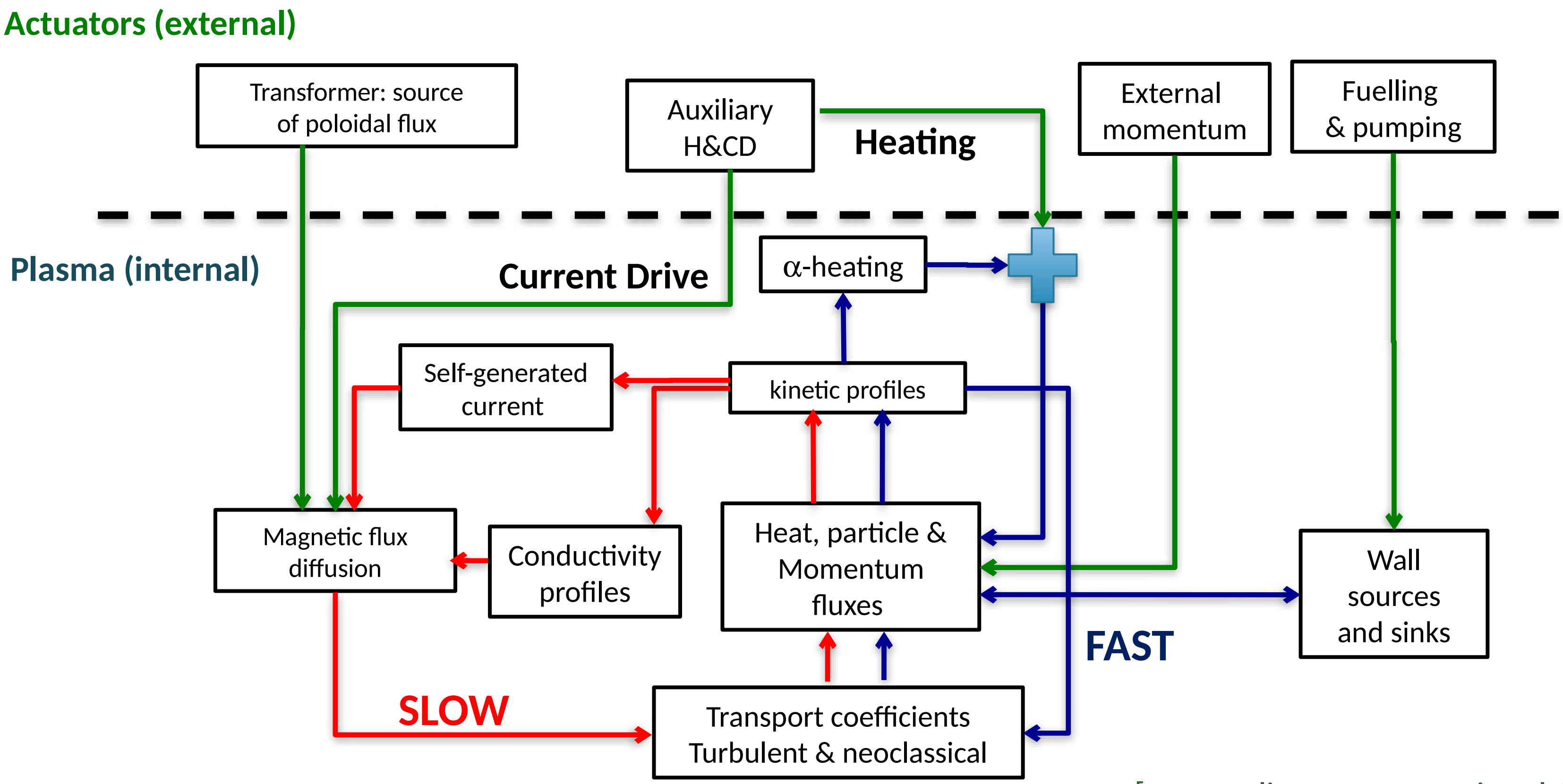
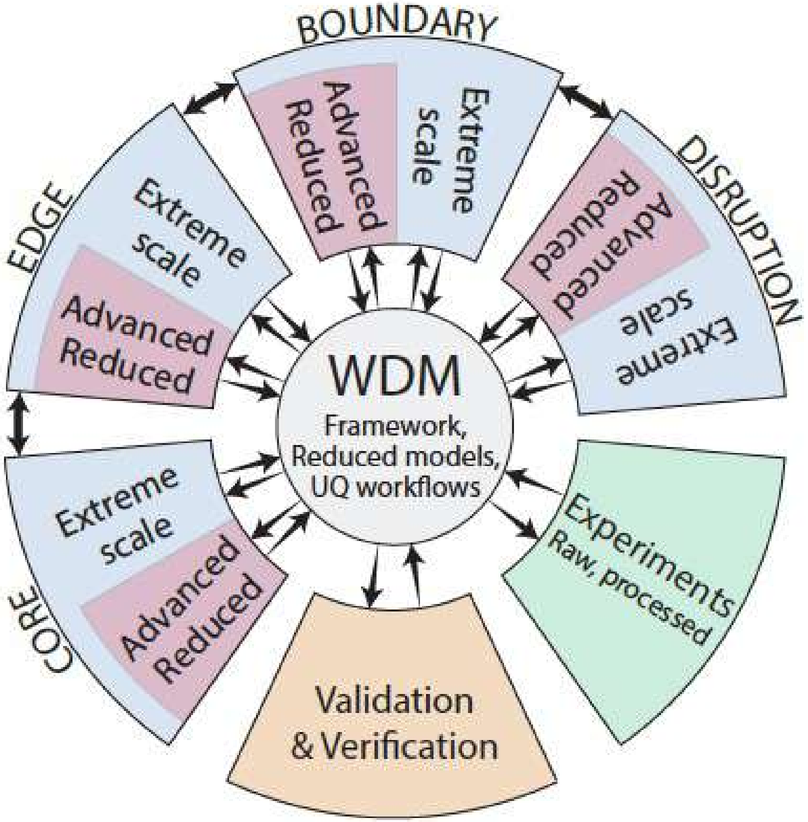
Tokamaks are complex systems

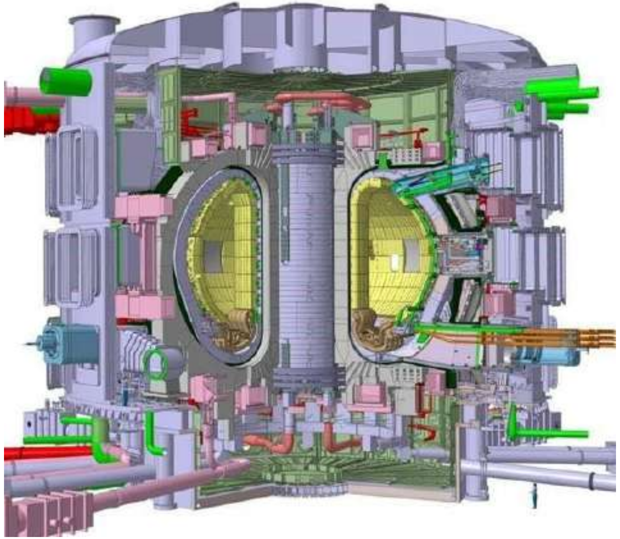


[F. M. Poli, ITER International School 2022]

Modeling whole device requires *integrated* simulation tools



engineering, technology



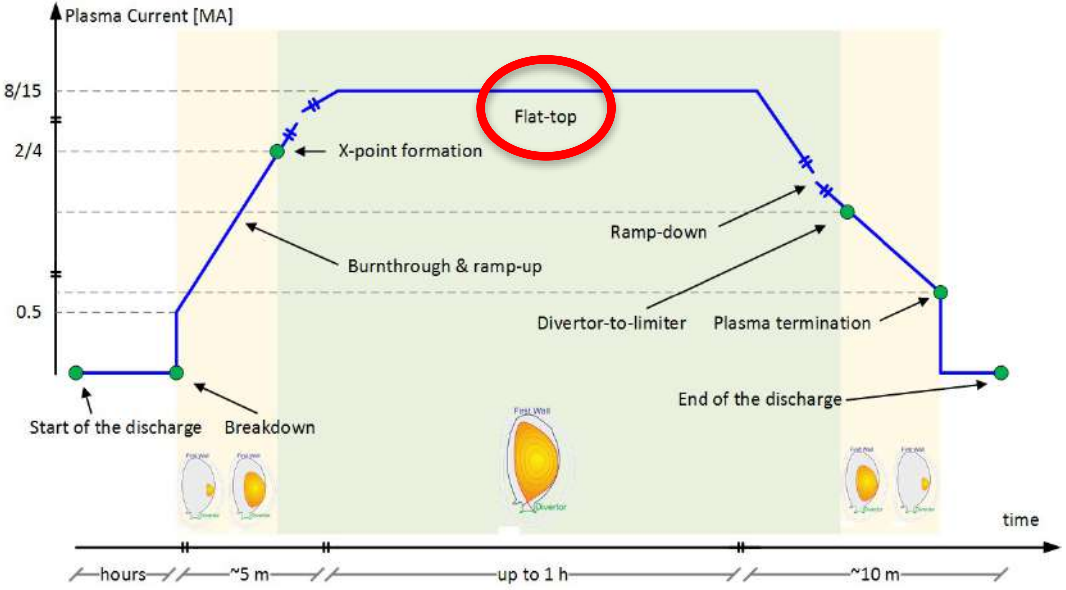
[FES *Integrated Modeling Workshop Report, 2015*]

Modeling discharge evolution requires *time dependent* simulations

- Steady-state is the ultimate goal for (most) fusion reactors…
- … but, first, we need to get there!
  - And have options to *safely* terminate a discharge

⇉ To design and optimize future reactors, time dependent capabilities are critical

- Includes evolution of plasma parameters (e.g. fast particle populations)
- Also includes engineering: power supplies, stresses, heat loads, transients, … – not covered here.

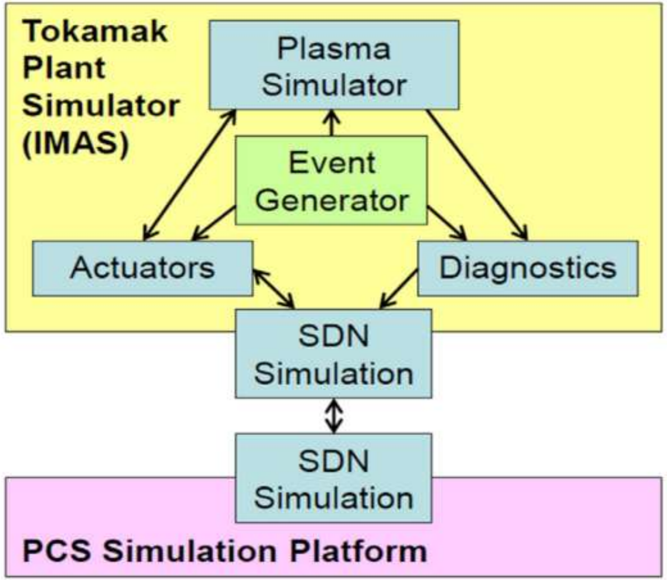


[G. De Tommasi, ITER International School 2022]

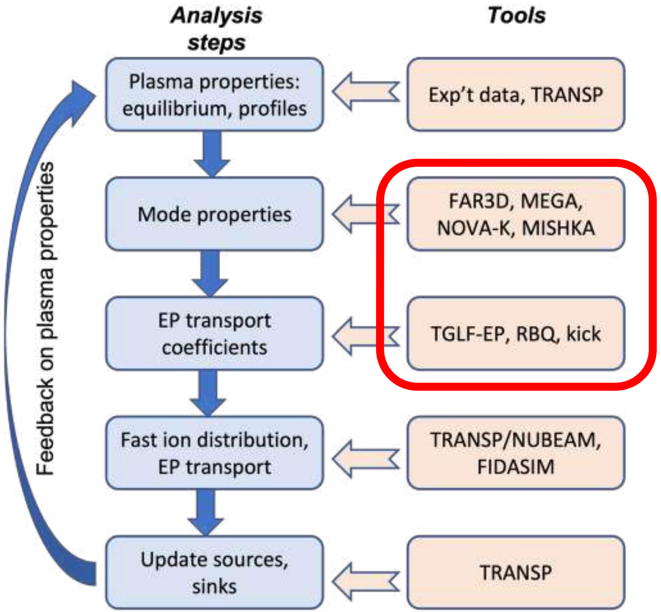
Commonly used frameworks: IMAS, TRANSP, TRIASSIC, …

IMAS already includes several modules for EP physics

→ See M. Schneider's presentation



TRANSP approach for interpretive and predictive runs involves external codes (at present)



[F. Imbeaux et al., NF 2015] [A. Mishchenko et al., PPCF 2023][J. Breslau et al., DOI: 10.11578/dc.20180627.4]
[A. Bécoulet et al., CPC 2007][G. Falchetto et al., NF 2014][C. Y. Lee et al., NF 2021]

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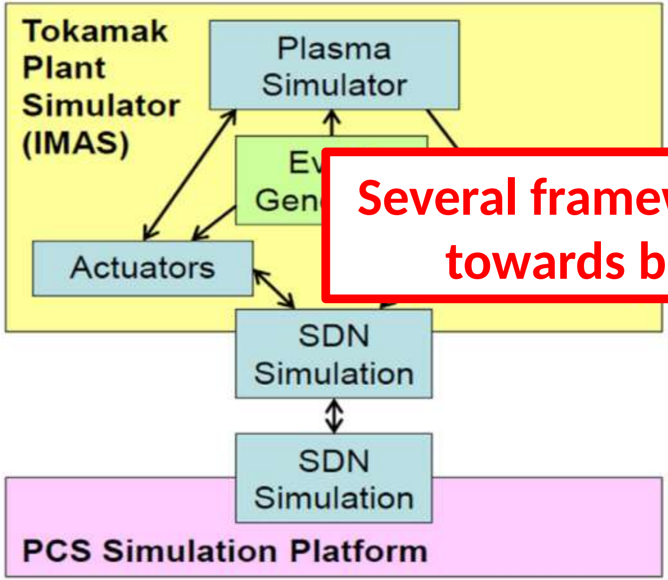

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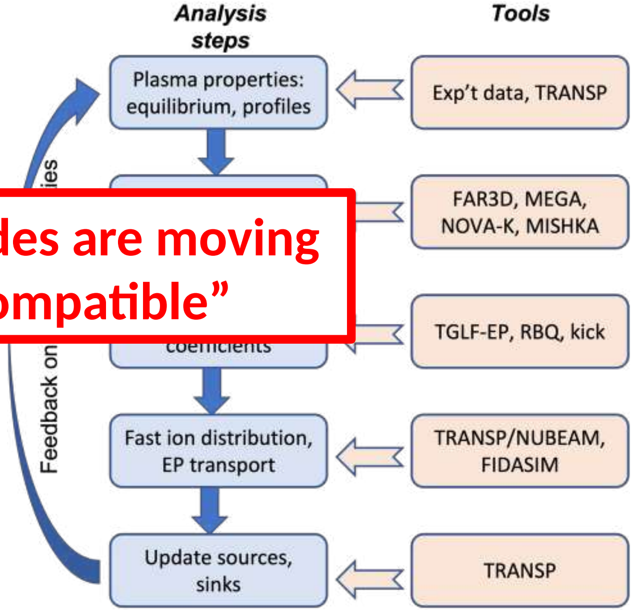

Several frameworks and codes are moving towards being "IMAS-compatible"

[F. Imbeaux et al., NF 2015] [A. Mishchenko et al., PPCF 2023][J. Breslau et al., DOI: 10.11578/dc.20180627.4]
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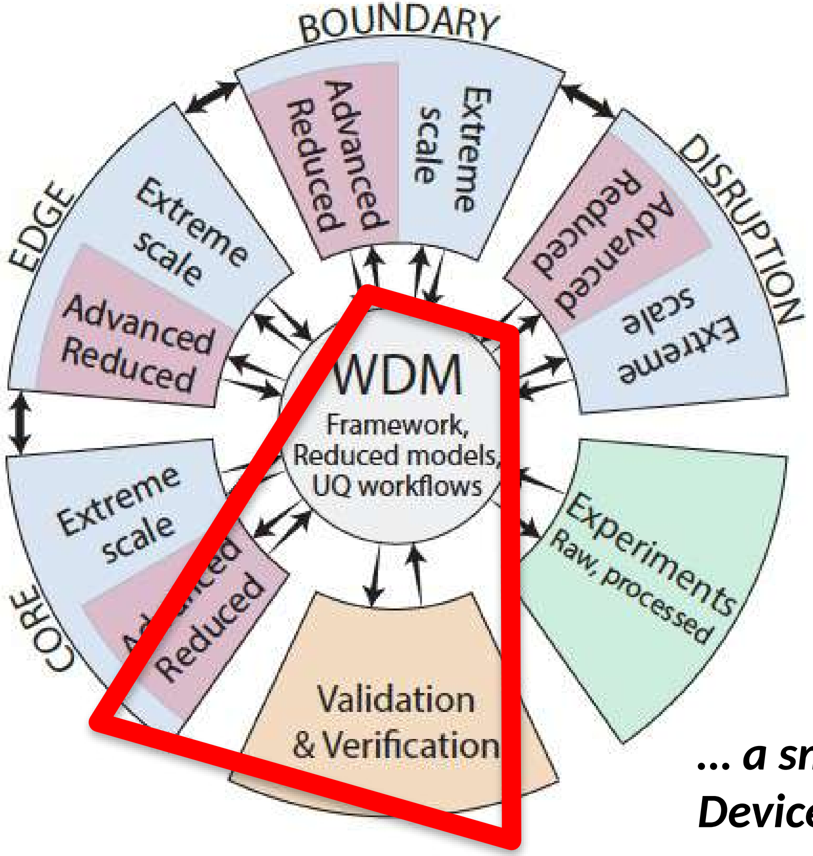
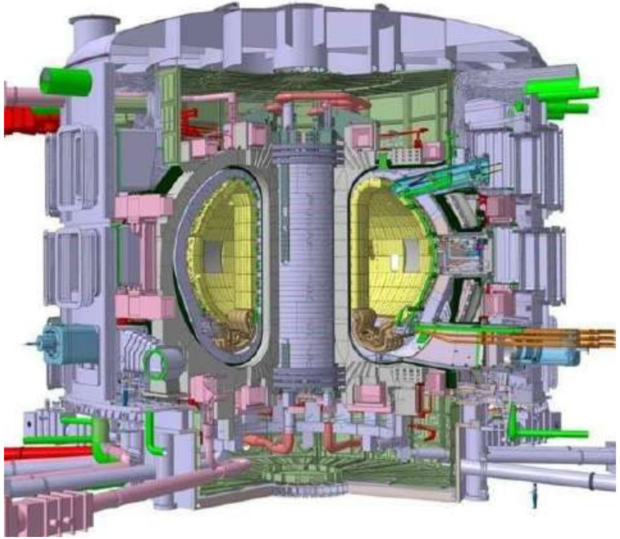
In the following slides, I'll focus on *EP modeling for integrated simulations*



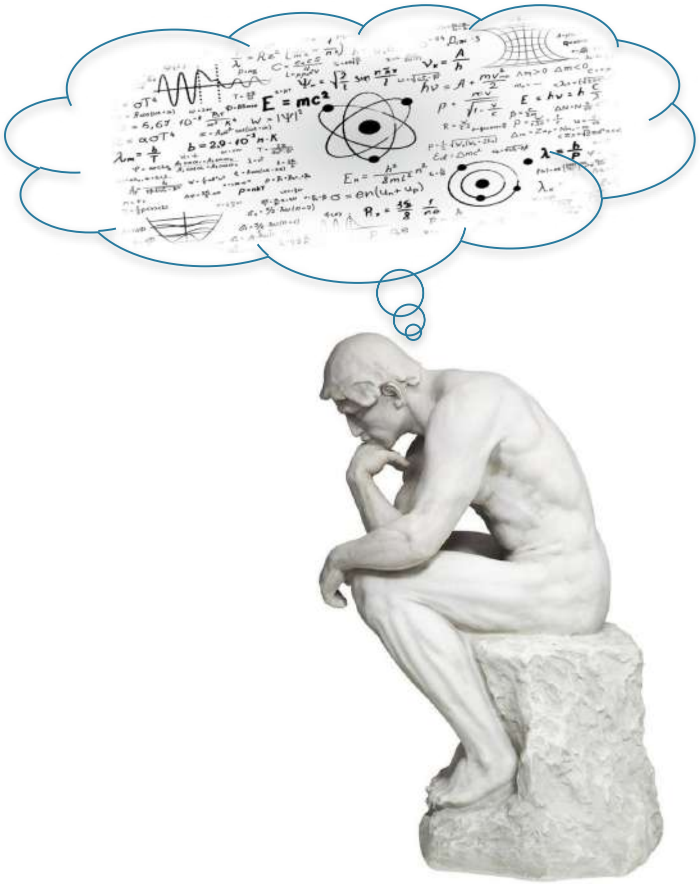
engineering, technology



... a small but fundamental part of Whole Device Modeling frameworks

I assume we all (mostly) agree on what Integrated Modeling means.

But what exactly do we mean by “reduced models”??



[A. Rodin, ca. 1884]

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How about this one? $dA(t)/dt = \gamma A(t)$

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How about this one? $dA(t)/dt = \gamma A(t)$

Let’s take another step…

$$\frac{dA(t)}{dt} = (\gamma_L - \gamma_d)\, A(t) - \int_0^{t/2} d\tau \int_0^{t-2\tau} d\tau_1 \tau^2 e^{-\hat{\nu}^3_{stoch}\tau^2(2\tau/3+\tau_1)+i\hat{\nu}^2_{drag}\tau(\tau+\tau_1)} \mathcal{O}\left(A^3\right)$$

stabilizing destabilizing

Berk, Breizman and Pekker, PRL 1996
Lilley, Breizman and Sharapov, PRL 2009

Is it still “reduced” or not?

Is this also “reduced”?

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\mathbf{v}) + \nu_n\Delta(\rho-\rho_{eq}), \quad (1)$$

$$\rho\frac{\partial}{\partial t}\mathbf{v}_{MHD} = -\rho\mathbf{v}\cdot\nabla\mathbf{v}_{MHD} + \rho\mathbf{v}_{pi}\cdot\nabla\left(v_\parallel\mathbf{b}\right) - \nabla p + (\mathbf{j}-\mathbf{j}_h')\times\mathbf{B}$$
$$+\frac{4}{3}\nabla(\nu\rho\nabla\cdot\mathbf{v}_{MHD}) - \nabla\times(\nu\rho\vec{\omega}), \quad (2)$$

$$\frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}, \quad (3)$$

$$\frac{\partial p}{\partial t} = -\nabla\cdot\left[p(\mathbf{v}_{MHD}+\mathbf{v}_{tor})\right] - (\gamma-1)p\nabla\cdot\left[(\mathbf{v}_{MHD}+\mathbf{v}_{tor})\right]$$
$$+(\gamma-1)[\nu\rho\omega^2 + \frac{4}{3}\nu\rho(\nabla\cdot\mathbf{v}_{MHD})^2 + \eta\mathbf{j}\cdot(\mathbf{j}-\mathbf{j}_{eq})] + \chi\Delta(p-p_{eq}), \quad (4)$$

$$\mathbf{E} = -\mathbf{v}_E\times\mathbf{B} - \mathbf{v}_{tor}\times(\mathbf{B}-\mathbf{B}_{eq}) + \eta(\mathbf{j}-\mathbf{j}_{eq}), \quad (5)$$

$$\mathbf{v} = \mathbf{v}_{MHD} + \mathbf{v}_{pi} + \mathbf{v}_{tor}, \quad \mathbf{v}_{pi} = -\frac{m_i}{2e_i\rho}\nabla\times\left(\frac{p\mathbf{b}}{B}\right), \quad (6)$$

$$v_\parallel = \mathbf{v}_{MHD}\cdot\mathbf{b}, \quad \mathbf{v}_E = \mathbf{v}_{MHD} - v_\parallel\mathbf{b}, \quad (7)$$

$$\mathbf{j} = \frac{1}{\mu_0}\nabla\times\mathbf{B}, \quad \vec{\omega} = \nabla\times\mathbf{v}_{MHD}, \quad \mathbf{b}=\mathbf{B}/B, \quad (8)$$

based on an extended MHD model given by Hazeltine and Meiss

EP effect

thermal ion diamagnetic drift

+

(equilibrium toroidal rotation =0)

$\nu=\eta/\mu_0=\nu_n=\chi=10^{-6}v_A R_0$

Main equations of the MEGA code

⇒ *see lecture by Y. Todo on Wednesday*

[Y. Todo, IAEA-TCM 2017]

Hierarchy of EP models: broad range of complexity (partial list)

Increasing complexity, physics fidelity, computational cost

Experiments

Critical gradient models

RBQ

Kick model
M. Podestá et al., PPCF **56**, 055003 (2014)

Todo model
Y. Todo et al., Nucl. Fusion **52**, 033003 (2012)

Fully nonlinear, first-principles transport model. Not yet successfully implemented.

Velocity space considered in integral (**1.5D**[1]), in reduced kinetics (**EPtran**[2]), or not at all (various versions of **Alpha**[3,4]).

[1]K. Ghantous et al., PoP **19**, 092512 (2012)
[2]He Sheng and R.E. Waltz, NF **56**, 056004 (2016)
[3]R.E. Waltz and E.M. Bass, NF **54**, 104006 (2014)
[4]He Sheng et al., PoP **24**, 072305 (2017)

Preserve (to varying degrees) details of velocity space: more physical resonance treatment, higher-fidelity validation (against FIDA).

[Courtesy E. Bass, UCSD]

My interpretation of “reduced EP models” for this lecture

- Let’s focus on what is relevant for <u>tokamak physics</u>
- Let’s further focus on what is relevant for <u>EP transport</u> in tokamaks
- Then reduce complexity to meet the needs of Integrated Simulations (time-dependent WDM).

➔ *In my view*, a “reduced” EP transport model should:

  - be computationally efficient, to be included in WDM frameworks,
  - neglect physics aspects that are not strictly relevant for the problem at hand – there’s always room for improvement,
  - include metrics for success and limits of applicability (validation!).

Representing instabilities for reduced EP models

see lectures by W. Heidbrink, S. Sharapov on Monday

- For a given toroidal mode number *n* and frequency $\omega = 2\pi f$:

  $$A_n(t) = \Sigma_m A_{m,n}(t) \times e^{i(n\zeta - m\theta - \omega t)}$$

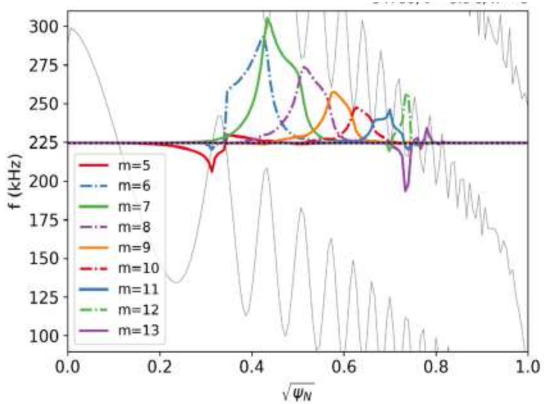
  summing over poloidal harmonics *m's*

Usually, the number of poloidal harmonics can be reduced to a sub-set of dominant harmonics

- Most reduced models rely on linear MHD
- Most reduced models neglect mode-mode coupling, non-linear mode physics (e.g. deformation of mode structure) etc.

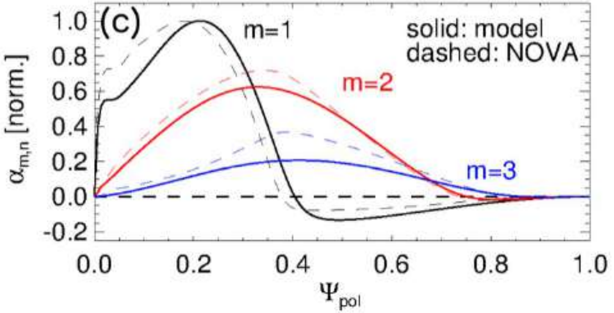
- Further simplification: analytic mode structure
  - Adequate for instabilities with one or few dominant harmonics: kinks, tearing modes, …

n=6 TAE mode from NOVA



[J. Gonzalez-Martin, U. Seville]

Kink from NOVA vs analytic



[M. Podestà et al., PPCF 2022]

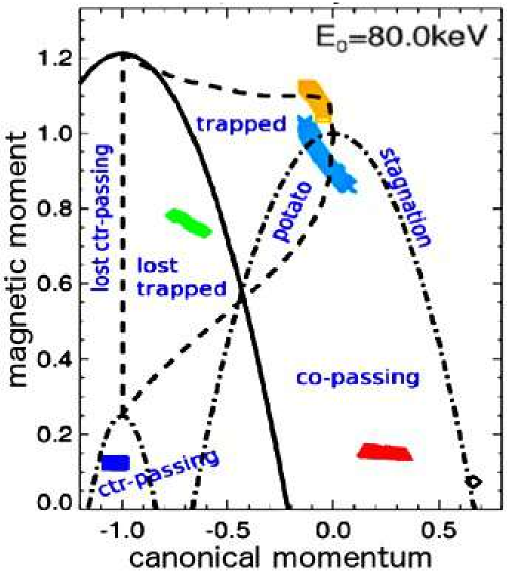
Constants of motion are convenient variables to describe EPs

- E, energy
- $P_\zeta \sim mRv_{par} - q\Psi$, canonical tor. 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:

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

ω=2πf : mode frequency
n : toroidal mode number

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

- Unperturbed orbits are points in the (E, P_ζ, μ) space
- Resonant orbits span space with well defined correlation E-P_ζ, related to wave parameters
  - Assume μ is conserved, $\omega \ll \omega_{ic}$

[R. B. White, Theory of toroidally confined plasmas, Imperial College Press (2001)]
see lectures by W. Heidbrink, L.G. Erickson, S. Sharapov, Y. Todo …

Goal of reduced models: provide transport coefficients for other codes

- Imagine you'd like to compute EP transport with your favorite code
  - What coefficient(s) would you need?
  - In which form?

- Imagine you'd like to compute EP transport with your favorite code
  - What coefficient(s) would you need?
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⇒ It depends on the transport model adopted!
  - From simple, ad-hoc models to phase-space resolved

General representation of EP transport through 5D matrix

- As discussed in previous lectures, resonances are main mechanism for EP transport

  ⇒ *see lectures by W. Heidbrink, S. Sharapov on Monday*

- But, in general, EP transport can be diffusive, convective, but also sub/super diffusive

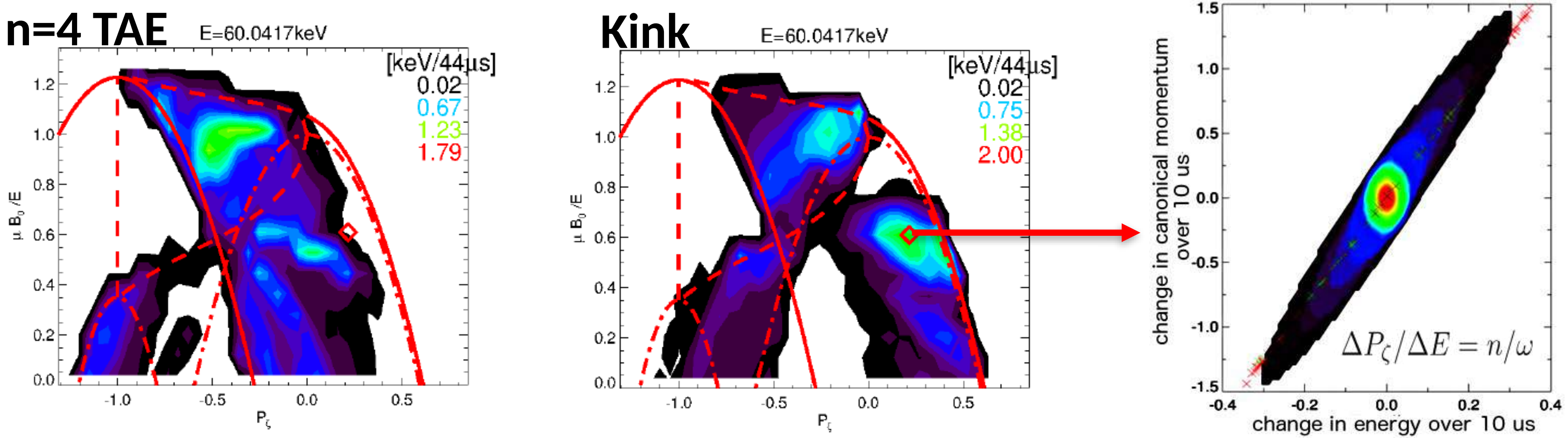
  [W. Heidbrink et al., PPCF 2012]
  [A. Bovet thesis, NF 2012]
  [K. Gustafson et al., PRL 2012]

⇒ A 5D matrix $p(\Delta E,\Delta P_\zeta\,|\,E,P_\zeta,\mu)$ can be introduced to describe the conditional probability that a particle at (E,P_ζ,μ) receives kicks ΔE, ΔP_ζ from wave-particle interaction.

  – “Kick matrix”

Example of kick matrices

- Maps of rms changes in energy, momentum provide quick look at location and strength of resonant interactions
- Details of $p(\Delta E,\Delta P_\zeta \mid E,P_\zeta,\mu)$ may vary from point to point in phase space
- *No assumptions need to be made on nature of transport*

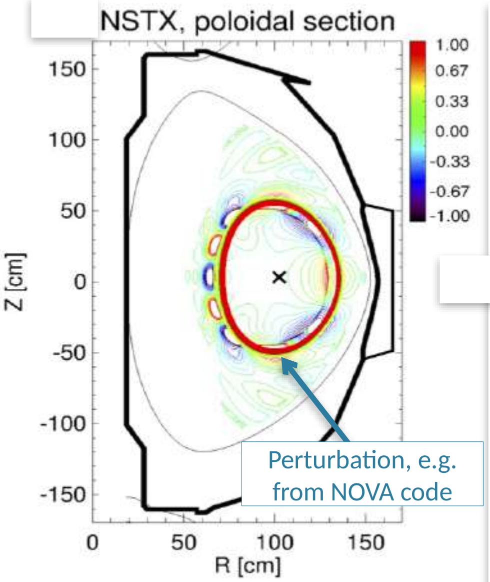


Advantage: can represent nearly ALL transport mechanisms!

[M. Podestà et al., NF 2019]

Kick matrices can be computed by orbit-following codes

Initialize test particles uniformly in phase space



[M. Podestà et al., PPCF 2017]

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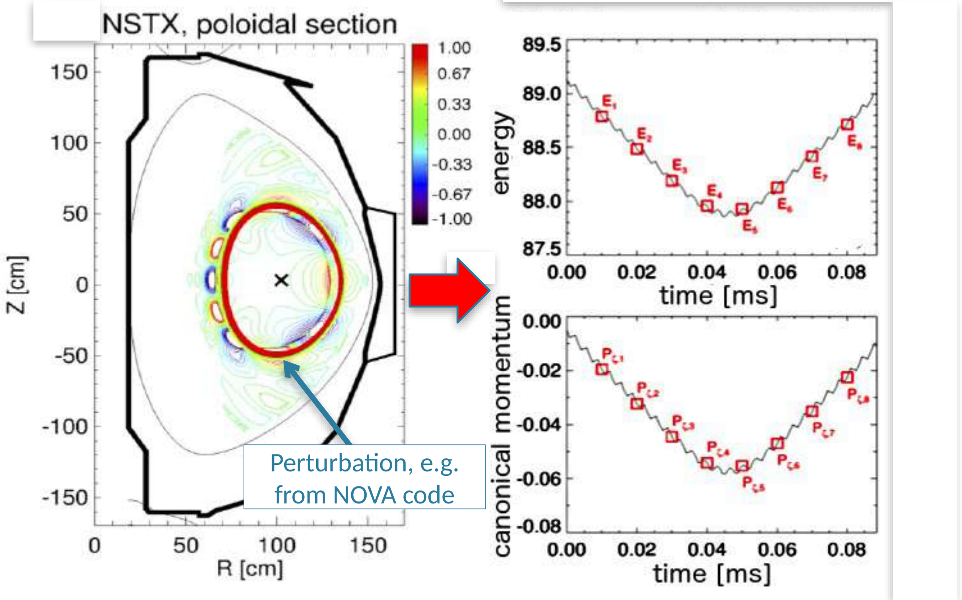

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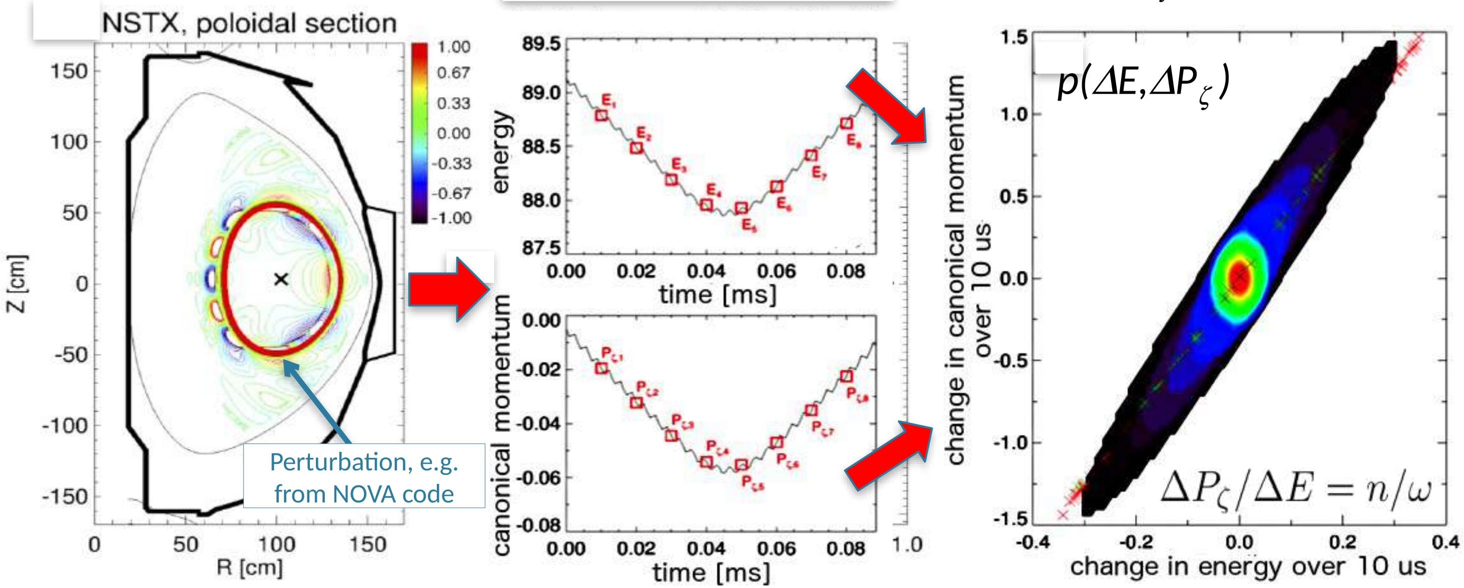
Initialize test particles uniformly in phase space

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

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



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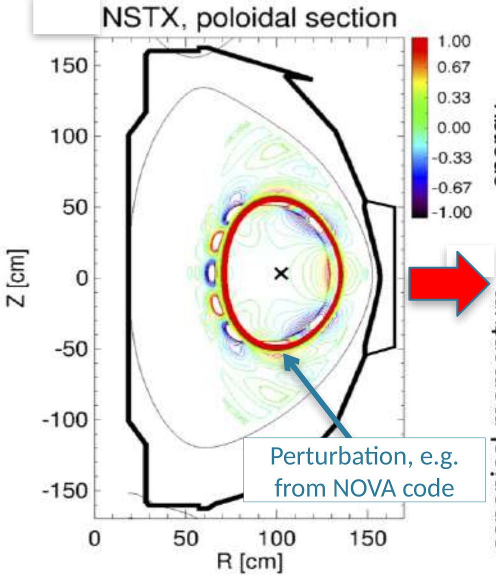
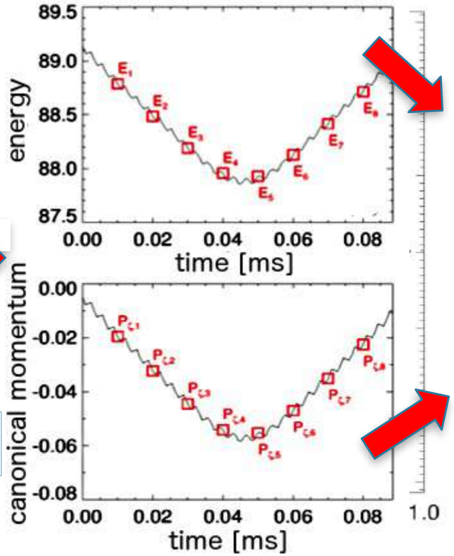
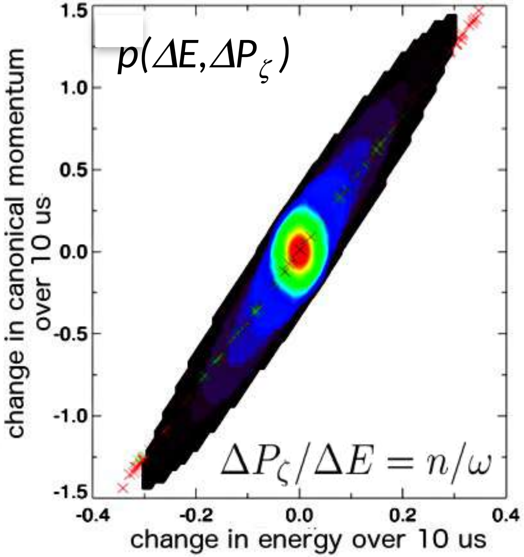
Track energy, momentum variations (*kicks*) at fixed time intervals

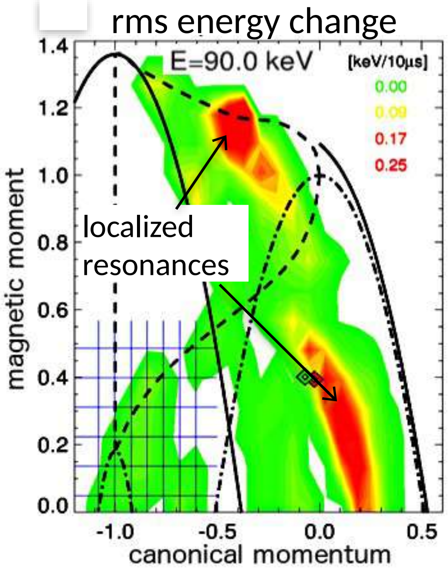
Combine ΔE, ΔP_ζ from same (E,P_ζ,μ) phase space *bin* into $p(\Delta E,\Delta P_\zeta)$

Repeat for all (E,P_ζ,μ) *bins* to infer $p(\Delta E,\Delta P_\zeta\,|E,P_\zeta,\mu)$









[M. Podestà et al., PPCF 2017]

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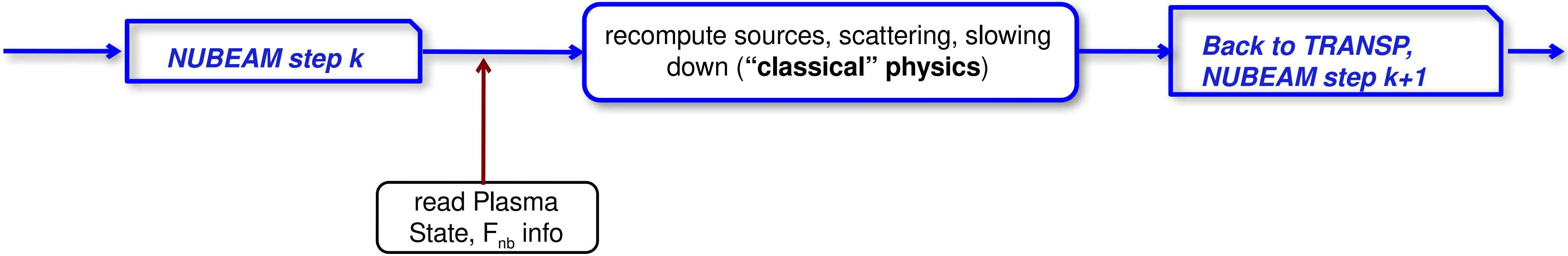
Integrating the 5D transport matrices in IM codes such as TRANSP



NUBEAM: Monte Carlo module of TRANSP that computes EP dynamic

[M. Podestà et al., PPCF 2014]
[M. Podestà et al., PPCF 2017]

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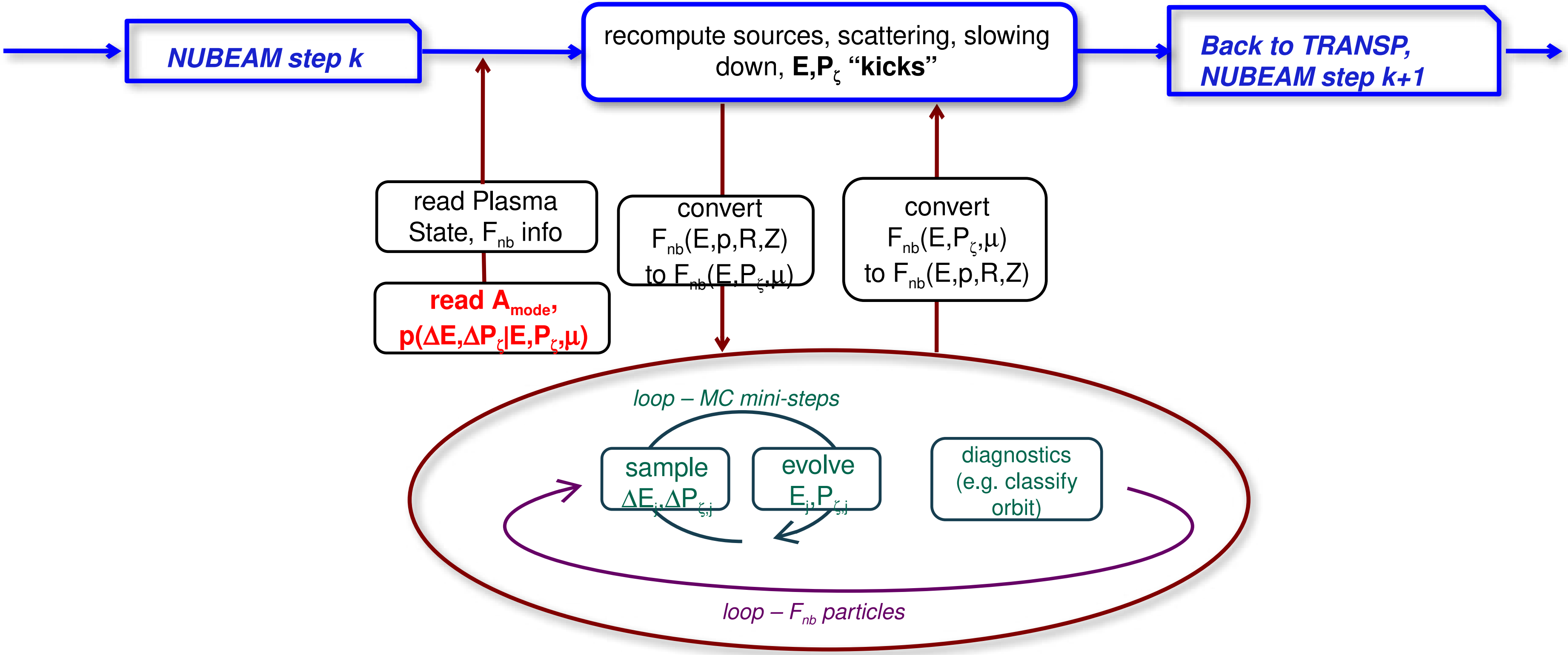
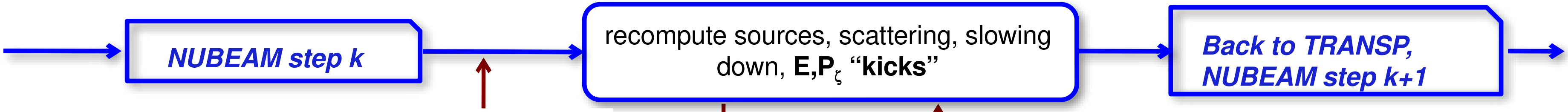


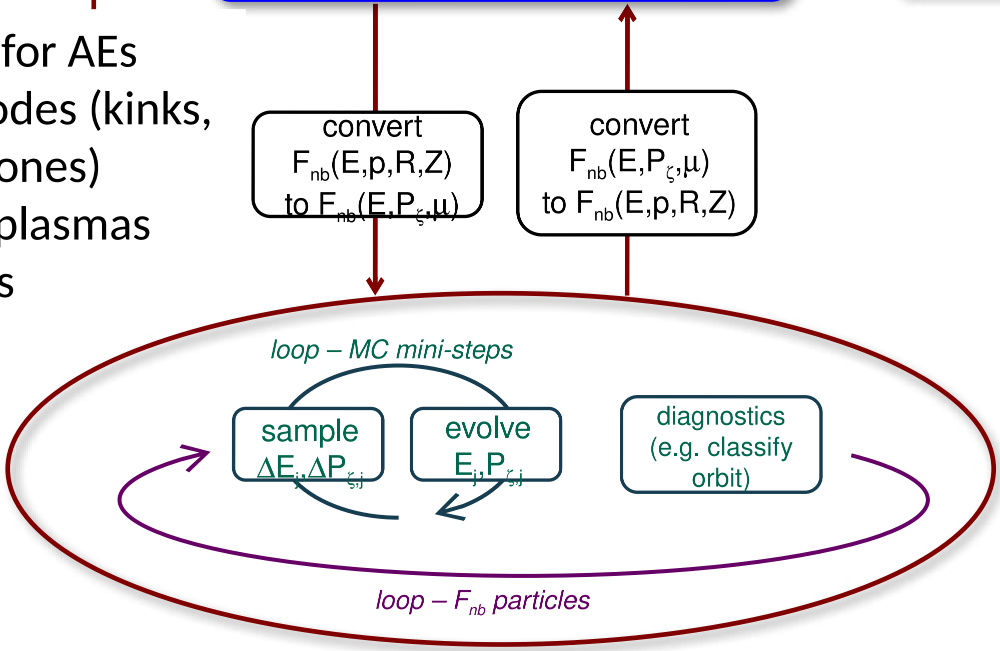
add "kicks" to F_{nb} variables

[M. Podestà et al., PPCF 2014]
[M. Podestà et al., PPCF 2017]

5D transport matrices are the essence of the *kick model* in TRANSP



- Originally developed for AEs
- Extended to low-f modes (kinks, TMs, sawteeth, fishbones)
- OK for multi-species plasmas
- Extending to 3D fields



[W. Heidbrink et al., PPCF 2018]
[L. Bardoczi et al., PPCF 2019]
[J. Yang et al., PPCF 2022, 2023]
[M. Podestà et al., PPCF 2022]
[P. Bonofiglo et al., NF 2022]
[M. Podestà et al., PPCF 2022]
[A. Teplukhina et al., NF 2023]

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RBQ model allows to reduce dimensionality of matrices to 3D

- Based on **R**esonance-**B**roadened **Q**uasi-linear theory
  - Take 5D transport matrix; assume diffusive transport → gaussian shape of probability → extract diffusion coefficients in E, P_ζ on (E, P_ζ, μ) grid.

$$p(\Delta E, \Delta P_\phi | P_\zeta, E, \mu, A_{kick}) = p_0\, e^{-\frac{1}{2(1-\rho)}\left[\frac{(\Delta E - \Delta E_0)^2}{\sigma_E^2} + \frac{(\Delta P_\phi - \Delta P_{\zeta 0})^2}{\sigma_{P_\phi}^2} - 2\rho\frac{(\Delta E - \Delta E_0)(\Delta P_\phi - \Delta P_{\zeta 0})}{\sigma_E\,\sigma_{P_\phi}}\right]}$$

with $\rho = \frac{<(\Delta E - \Delta E_0)(\Delta P_\phi - \Delta P_{\phi 0})>}{\sigma_E\,\sigma_{P_\phi}}$ and $\sigma_E^2 = 4\, D_E\, \delta t \quad ; \quad \sigma_{P_\phi}^2 = 4 D_{P_\phi} \delta t$

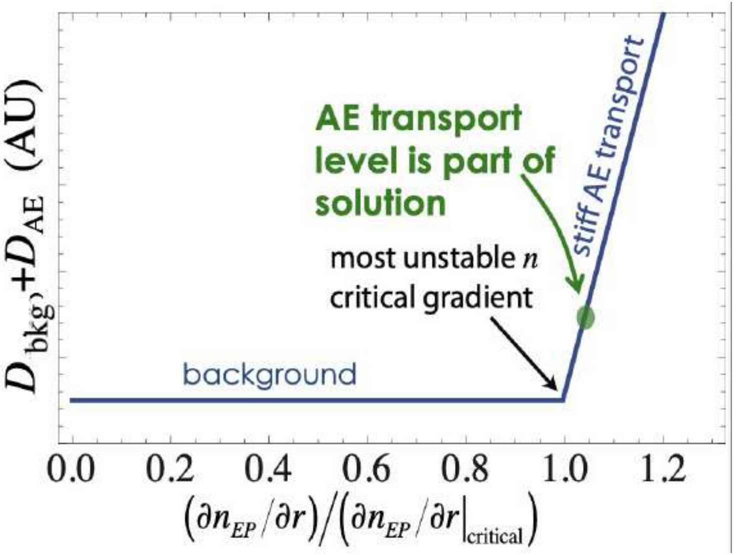
- Coefficients are computed numerically, e.g. using NOVA-K & RBQ2D.
- Reduced dimensionality → speed up computation.
- Similar to *kick model*, coefficients can be passed to TRANSP/NUBEAM.

→ *Developed specifically for Alfvénic modes*

[N. Gorelenkov et al., NF 2018]
[N. Gorelenkov et al., PLA 2021]
[V. Duarte et al., NF 2023]

Further reduction is possible by giving up phase space resolution

- TGLF-EP/Alpha assumes EP transport is near “critical gradient” for EP pressure
  - Provides worst-case scenario for time-averaged EP transport
    - *See lecture by W. Heidbrink on Monday*
- Near steady-state (on EP transport time-scale) provides radial diffusivity for EPs ⇒ input to TRANSP/NUBEAM
- Can include multiple EP species



- Only includes EP transport by Alfvénic modes
  - Plus contribution from microturbulence (usually small)

[E. Bass et al., PoP 2010]
[E. Bass et al., PoP 2017]
[H. Sheng et al., PoP 2017]

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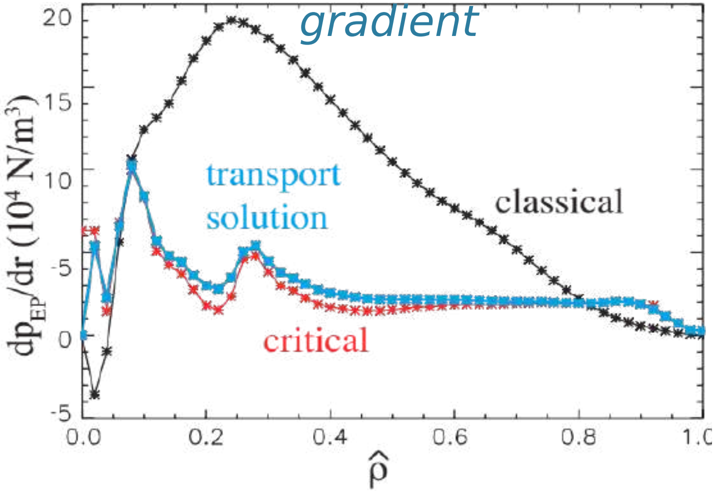
Driving fast ion pressure gradient



TGLF-EP/Alpha provides local critical gradient, from which fluxes and relaxed EP profile can be computed

[E. Bass et al., PoP 2010]
[E. Bass et al., PoP 2017]
[H. Sheng et al., PoP 2017]

Ad-hoc models are also widely used

- If detailed description of EP dynamic is not the primary goal, simple *ad-hoc* models are typically used

$$\Gamma_{EP} = -D_{EP}\, grad(n_{EP}) + n_{EP}\, v_{conv}$$

- Coefficients D_{EP} and v_{conv} are adjusted to match measured quantities such as neutron rate

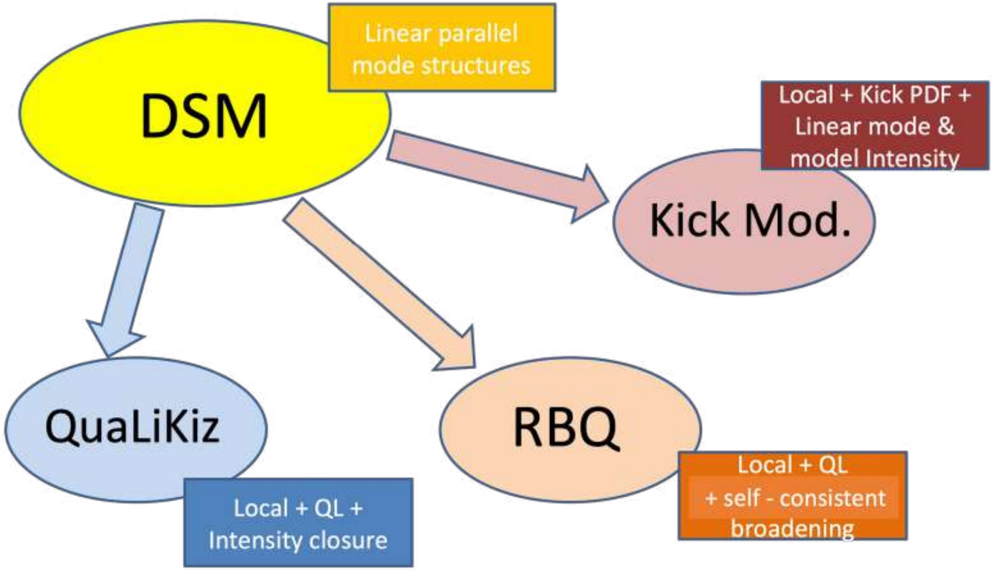
- In general, coefficients have little physical meaning!
- Nevertheless, they provide semi-quantitative information on overall EP transpor
  - Useful for quick scans, comparisons across multiple shots

Different reduced EP models can be unified under a single framework

- The models I just described have been developed independently, starting from different backgrounds

- Recent work indicates a route to unify those approaches starting from a common theoretical framework
  - Unified representation through Dyson Schroedinger Model, DSM (Zonca, Falessi et al.)

Recovering QL limit: … for a broad spectrum



[M. Falessi et al., PoP 2019] [F. Zonca et al., JoP 2021]
[F. Zonca, ISEP meeting, 2021] [M. Falessi et al., NJP 2023]

Let’s test our models!

This time, I’ll work my way up

from most reduced to phase-space resolved models

Layout

- Motivation – why *integrated* simulations, why *reduced* models
- Some definitions: “reduced models”; EP and mode representations
- Examples of reduced EP transport models
- **Applications to integrated simulations**
- A few words on model validation - what worked, what didn’t and why
- Future directions and summary

First, let’s define *Metrics for Success*: global vs local EP quantities

- How to judge whether a reduced model is doing a good job?

First, let's define *Metrics for Success*: global vs local EP quantities

- How to judge whether a reduced model is doing a good job?

- As EP and fluctuation diagnostics improve, there are more and more quantities that can be compared between experiments and simulations (more later)

- For simplicity, I will start by simply using *global* quantities
  - Neutron rate and stored energy are good candidates
    - Both are affected by EP transport, although in different ways
    - Both are typically available from experiments

Simple radial EP diffusivity D_{EP} provides quick tool for large scans

- Example from DIII-D NBI power scan investigating *stiff* EP transport

- TRANSP/NUBEAM simulations adjust uniform D_{EP} to match measured neutron rate

$$\Gamma_{EP} = -D_{EP}\, grad(n_{EP})$$

- AE mode amplitude inferred from ECE diagnostic

- Analysis clearly indicates increased EP transport vs. AE amplitude (i.e. increased NBI power)

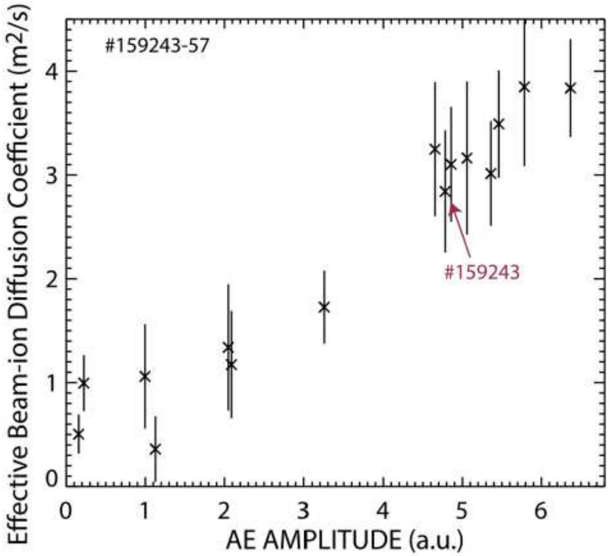


FIG. 5. Ad-hoc beam-ion diffusion coefficient D_B vs. average AE amplitude $\sum \delta T_e/T_e$ for the same scan as Fig. 3(b). D_B is found by matching the measured and calculated neutron rate as a function of time. The error bars represent the standard deviation of D_B between 516 and 897 ms. The discharge analyzed in detail in Secs. III–V is indicated.

[W. Heidbrink et al., PoP 2017]

Integrated Modeling accounts for effects of enhanced EP transport

- EPs are main source of heating for thermal plasma

- Simple EP transport models
  - Provide valuable info on trends as EP transport/loss vary
  - Enable separation between thermal and EP confinement effects

[G. Tardini et al., NF 2013]
[C. Holcomb et al., PoP 2015]

- Examples:
  - Thermal diffusivities from power balance
  - Neutral Beam current drive

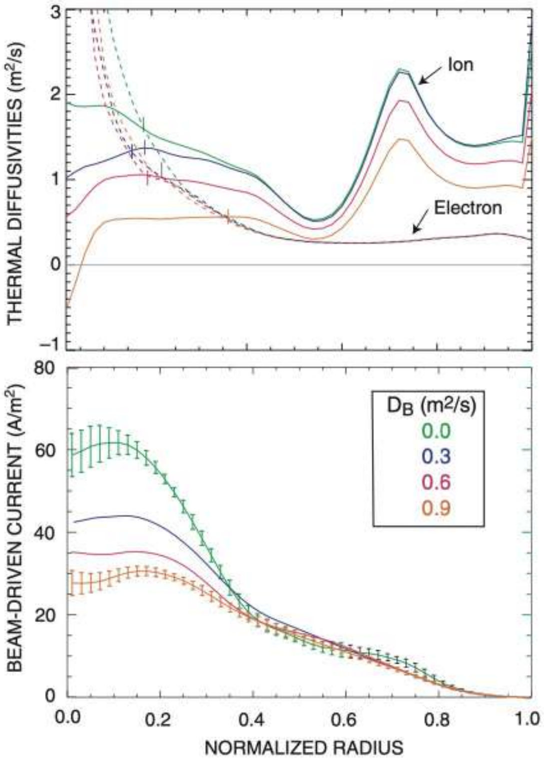
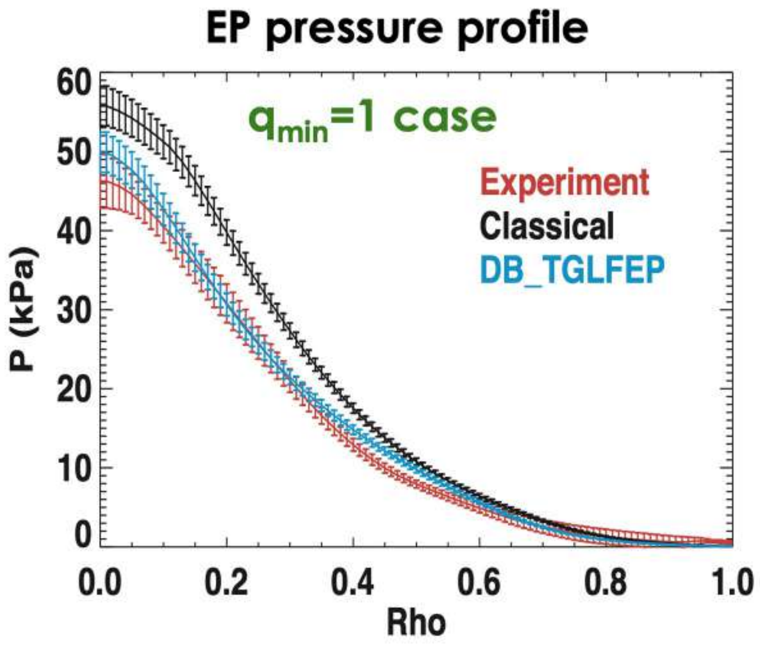


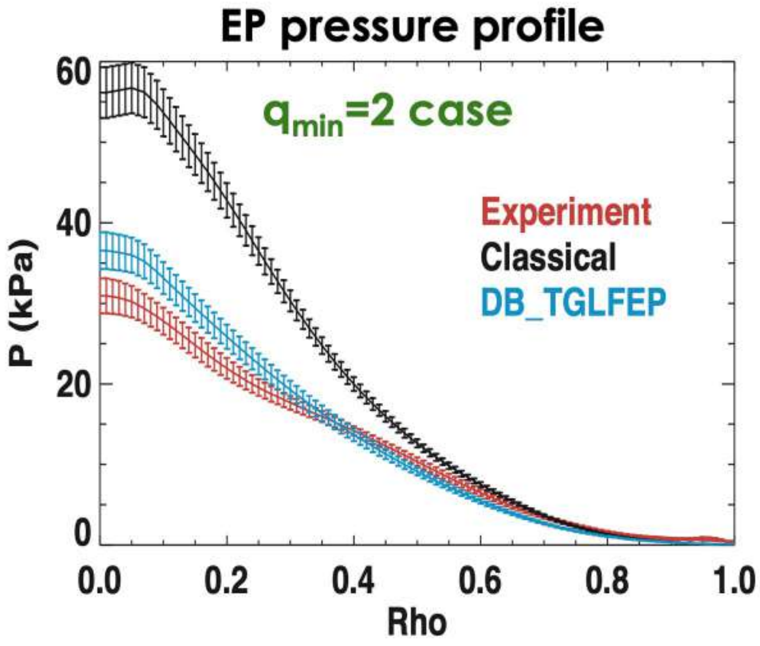
Figure 4. Sensitivity of the inferred (*a*) ion (——) and electron (- - - -) thermal diffusivities and the (*b*) beam-driven current density to the assumed value of beam-ion diffusion coefficient at 1.8 s in discharge #99411.

[W. Heidbrink et al., NF 2002]

TGLF-EP can provide *physics-based* radial D_{EP} as input for IM codes

- TGLF-EP successfully recovers different levels of EP transport caused by AE instabilities on DIII-D

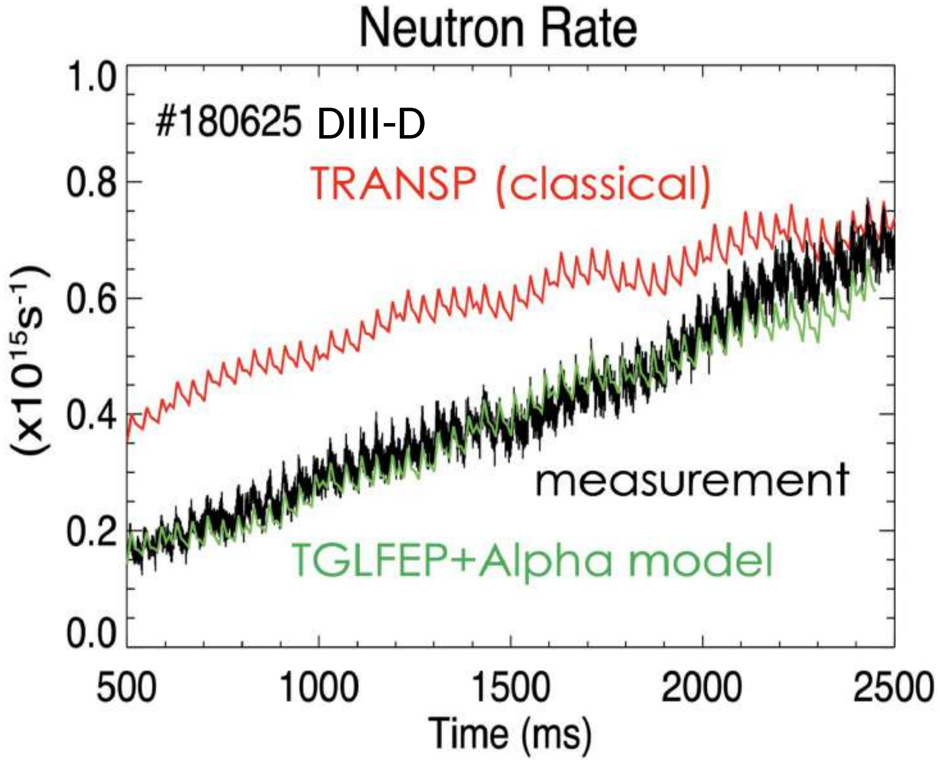




[E. Bass et al., IAEA-TCM EP 2017]

TGLF-EP can provide *physics-based* radial D_{EP} as input for IM codes

- TGLF-EP can be extended to time-dependent simulations



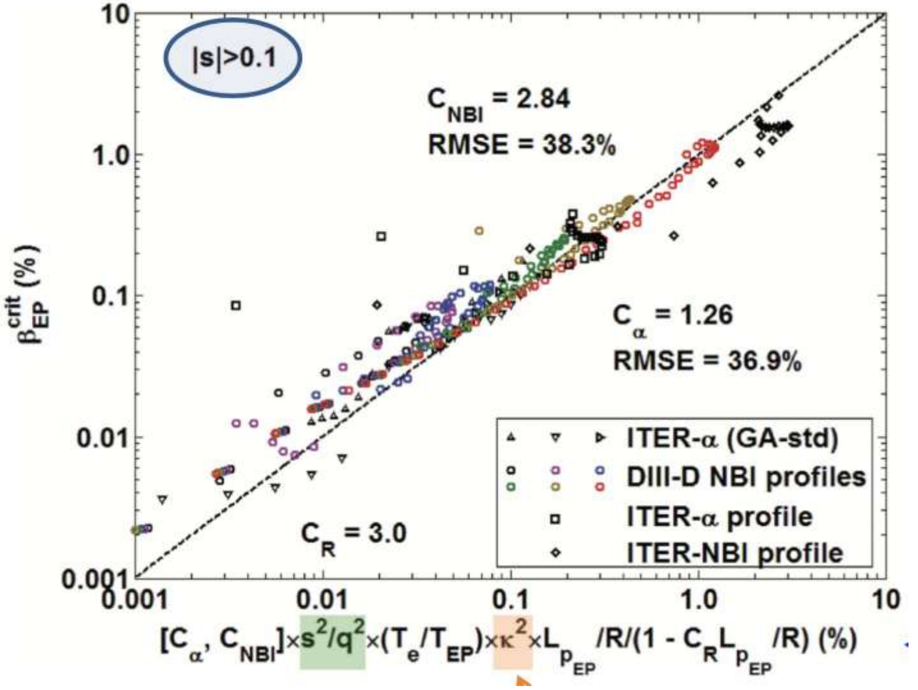
[E. Bass, 2023]

TGLF-EP computational efficiency enables large scans, predictions

- Ability to test several cases is critical to build databases

- From there, scaling laws can be inferred
  – E.g. to project trends to ITER and beyond
  – … and neural networks can be trained!

Inferred scaling low for critical EP pressure gradient



[E. Bass et al., IAEA-TCM EP 2017]

Global quantities provide reasonable estimate of success

- Neutron rate and stored energy
  - Both are affected by EP transport, although in different ways
  - Both are typically available from experiments

- However, they often don't ensure that the solution is unique

⇒ Looking at EP phase space response to instabilities provides much tighter constraint

Different diagnostics look at different EP phase space regions

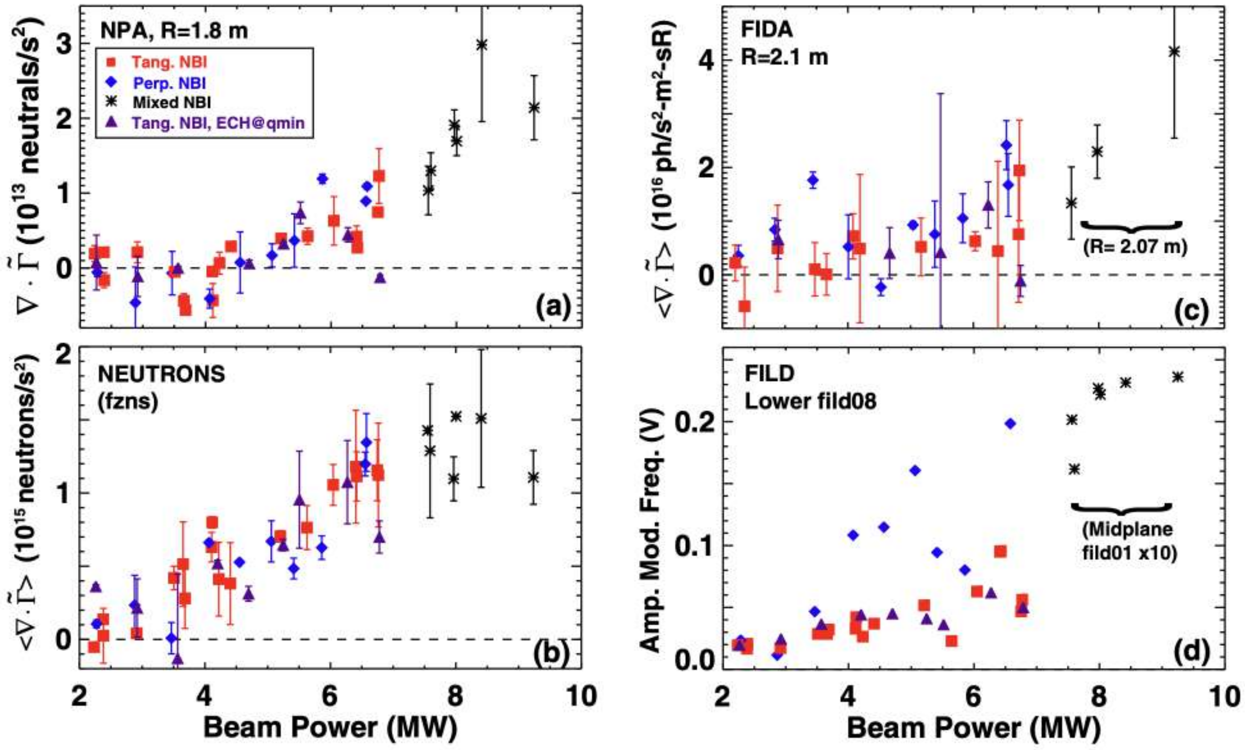


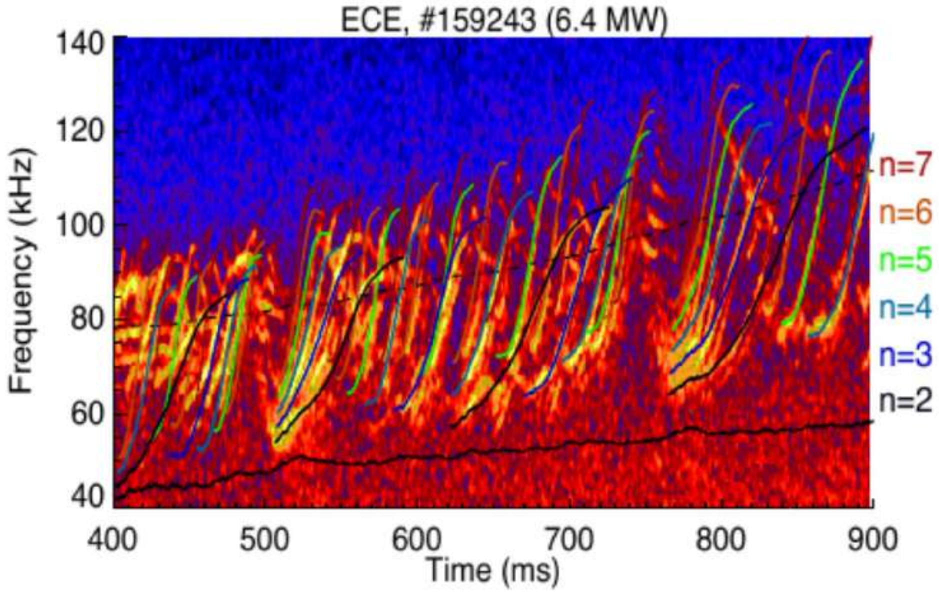
Figure 7. Time-averaged divergence of modulated flux (transport) versus total beam power for (*a*) NPA, (*b*) neutron, (*c*) FIDA diagnostics. In (*d*), the amplitude of the modulated beam particle losses recorded by the midplane and lower FILD detectors is plotted versus beam power.

DIII-D data

[C. Collins et al., PRL 2016]
[W. Heidbrink et al., PoP 2017]
[C. Collins et al., NF 2017]

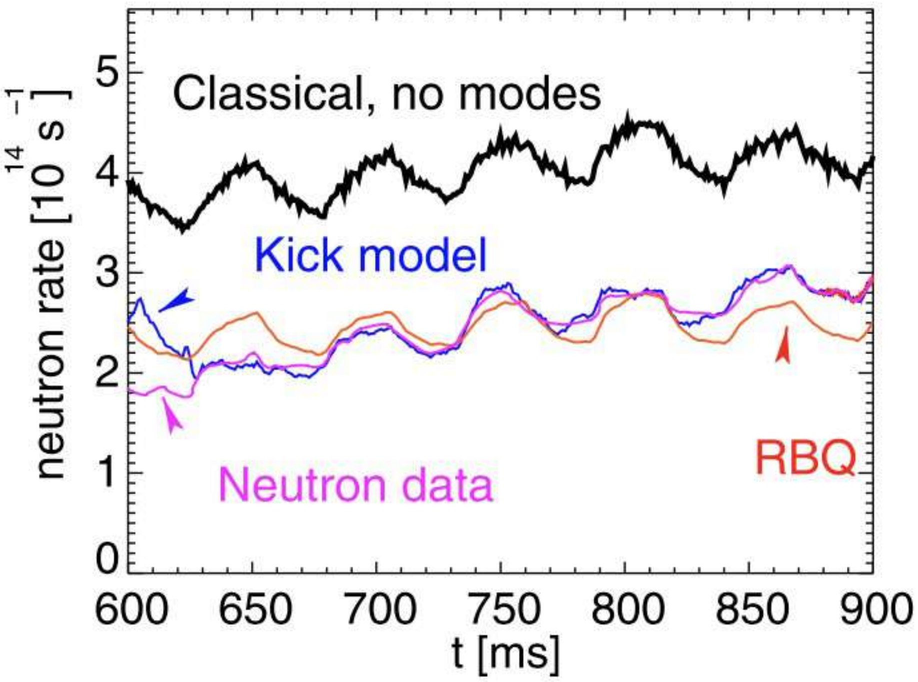
DIII-D #159243 has been widely used to test EP models

- Current ramp-up scenario
- High NBI power
- Strongly driven AE modes
  - Well above “critical gradient”
- Good diagnostic coverage
  - EPs, instabilities



[C. Collins et al., PRL 2016]
[W. Heidbrink et al., PoP 2017]
[C. Collins et al., NF 2017]

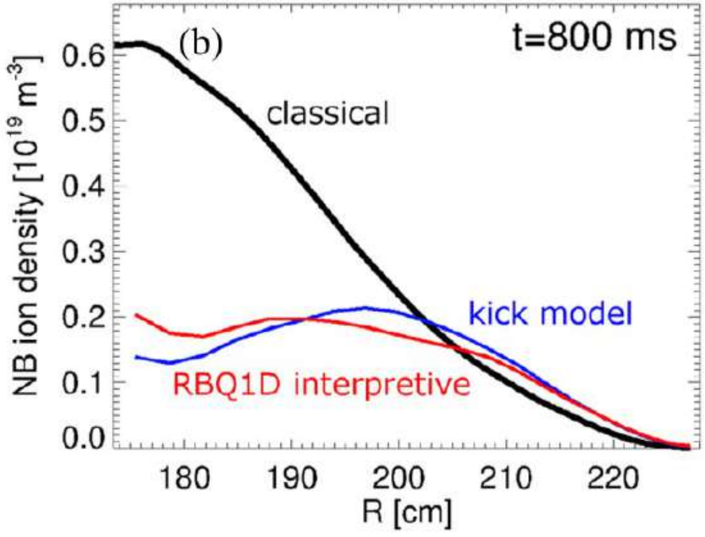
- AE modes calculated by NOVA/-K
  - Radial structure, frequency, damping rate
- AE amplitude inferred from ECE
- RBQ, kick compute EP transport coefficients
- TRANSP/NUBEAM computes EP evolution

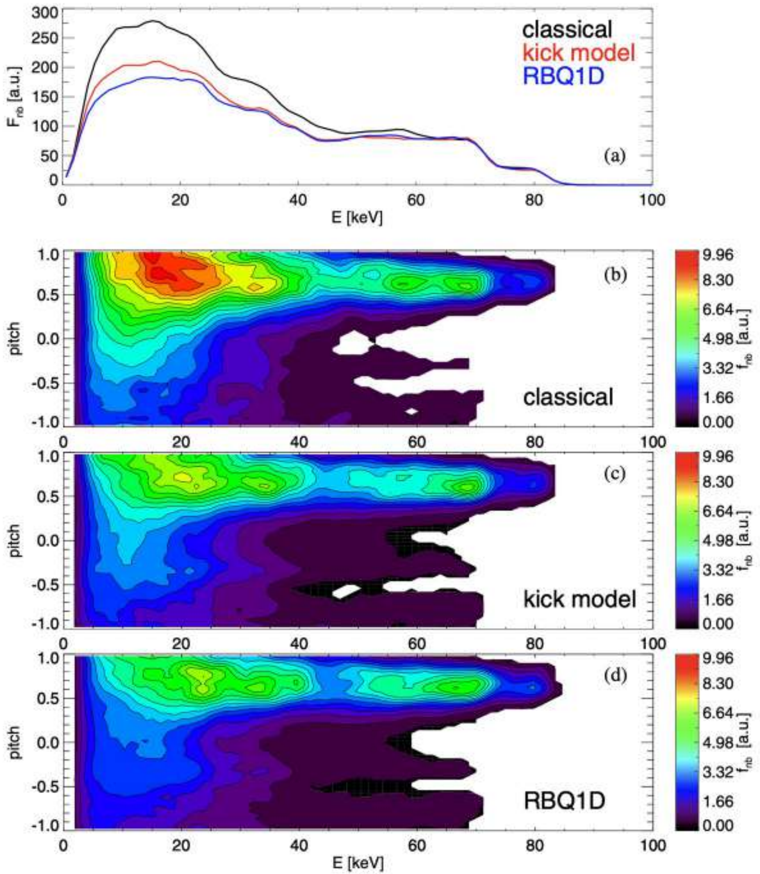


[W. Heidbrink et al., PoP 2017]
[N. Gorelenkov et al., PoP 2017]
[N. Gorelenkov et al., NF 2018]

Through NUBEAM, both models provide details on resulting EP distribution

- For the given inputs, both models provide a similar answer for n_{EP}
- EP distributions also look very similar
  - Same for other EP-related quantities: thermalization power, NB-CD, …



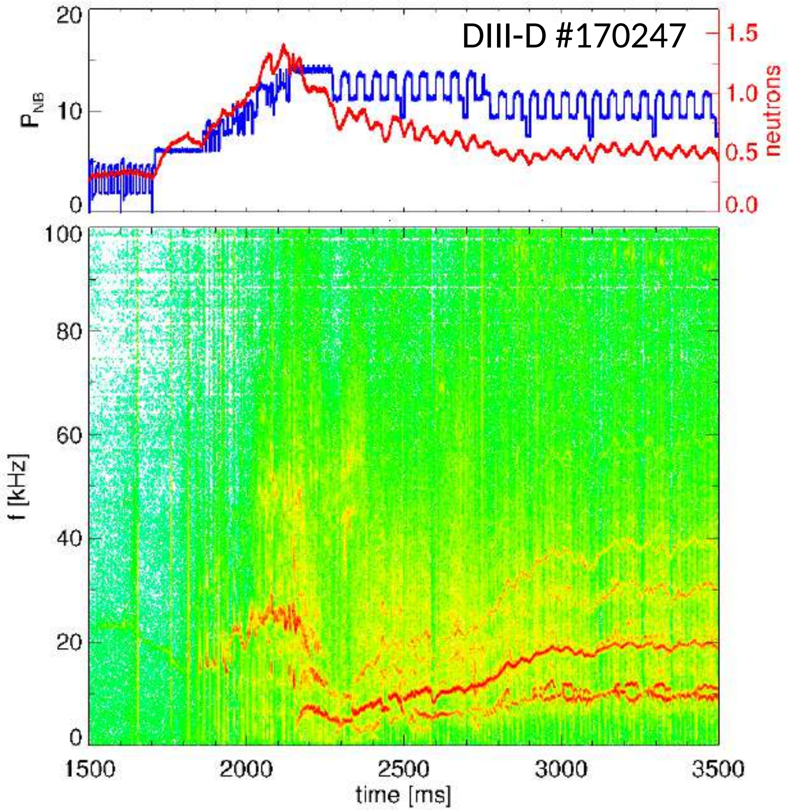


[N. Gorelenkov et al., PoP 2017] [N. Gorelenkov et al., NF 2018]

Kick matrix "agnostic" approach enables extension beyond AEs

- Required to include modes other than AEs in Integrated Modeling

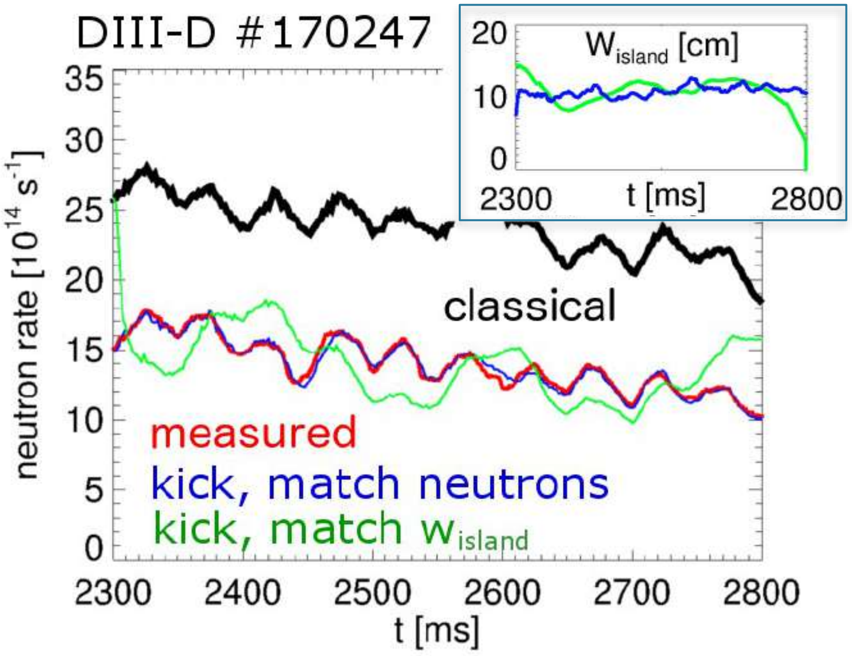
- Test case: DIII-D with unstable 2/1 Tearing Mode (TM)



[W. Heidbrink et al., PPCF 2018][L. Bardoczi et al., PPCF 2019]

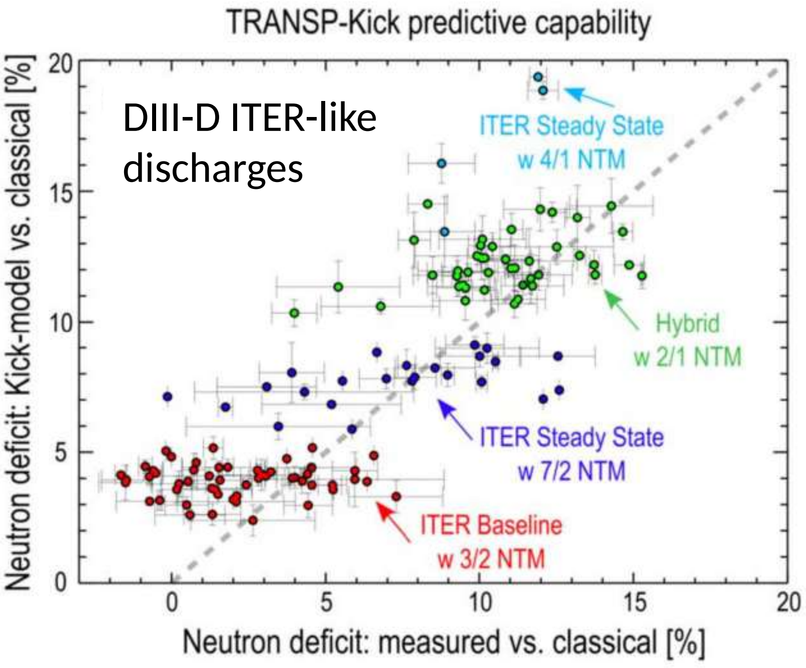
Interpretive kick model recovers measured neutrons, TM island width

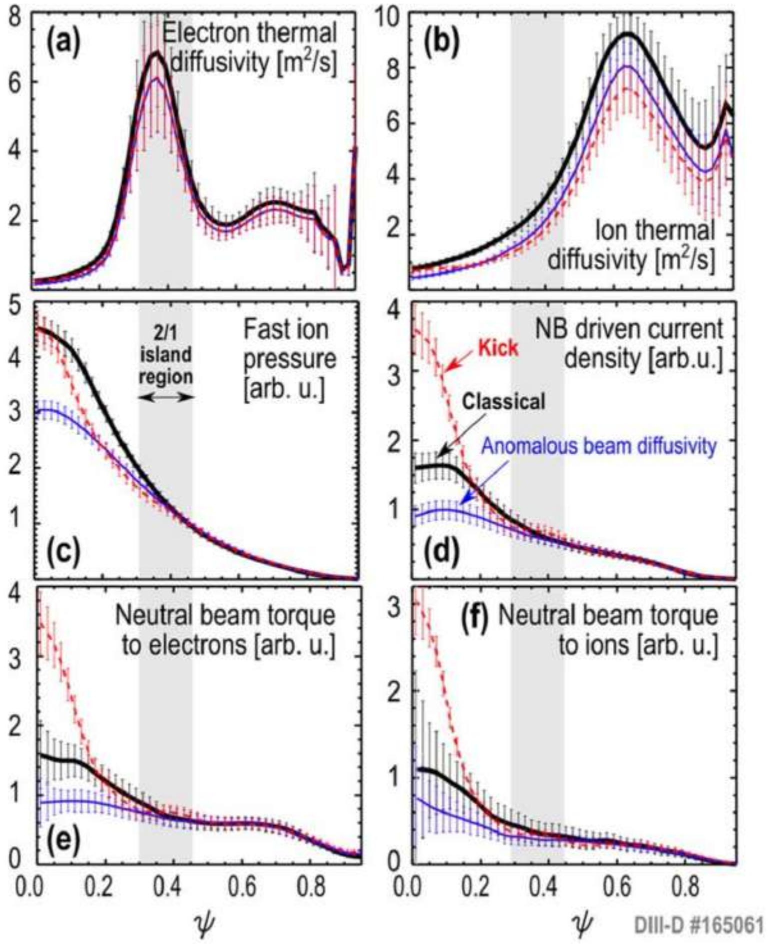
- Two approaches explored:
  - Match measured neutrons, infer TM island width
  - Use measured island width from ECE, compare neutrons
- For this shot, both approaches converge to similar results
- Validation of modeling results vs. EP diagnostics satisfactory (following slides)



[W. Heidbrink et al., PPCF 2018][L. Bardoczi et al., PPCF 2019]
[M. Podestà et al., NF 2019]

Validated modeling tools extended to IM simulations





- EP-induced EP transport and effects on IM results for DIII-D ITER-like discharges

[L. Bardoczi et al., PPCF 2019]

Validation is a necessary step
in developing (reduced) EP models

Layout

- Motivation – why *integrated* simulations, why *reduced* models
- Some definitions: “reduced models”; EP and mode representations
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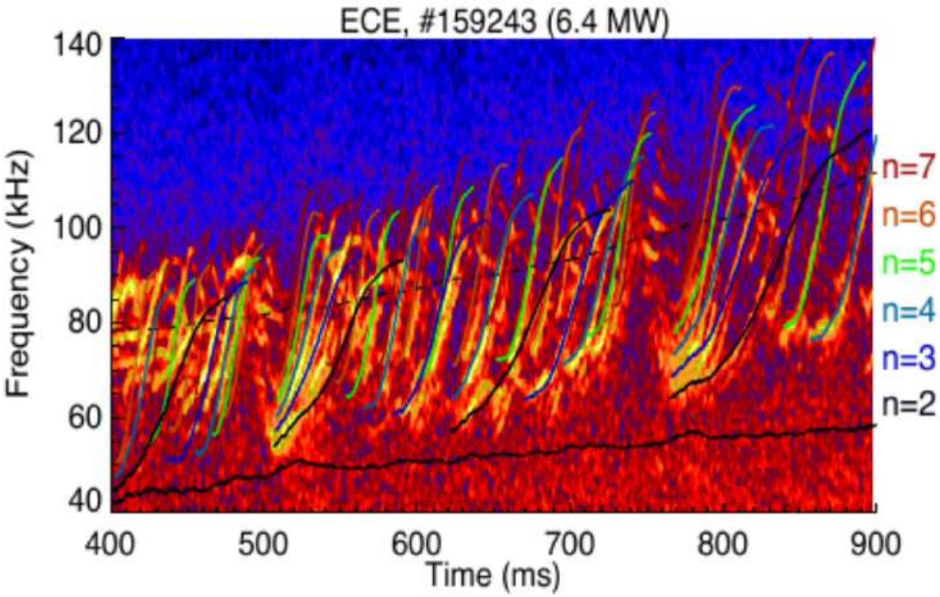
- Future directions and summary

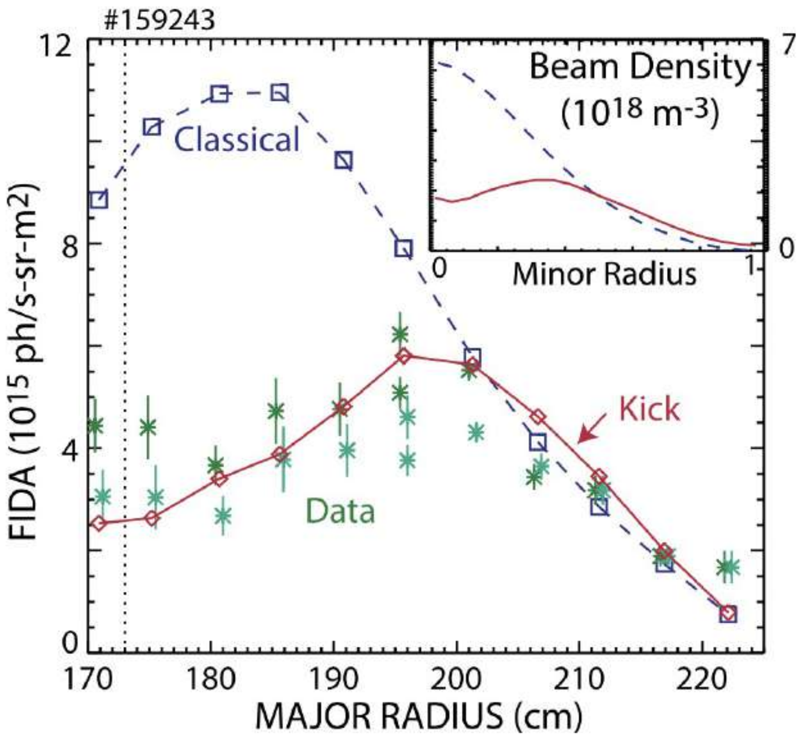
Back to well-diagnosed DIII-D #159243

- Several EP and fluctuation diagnostics available
  - FIDA, NPA, neutrons
  - Mode number, structure, amplitude



[C. Collins et al., PRL 2016]
[W. Heidbrink et al., PoP 2017]
[C. Collins et al., NF 2017]

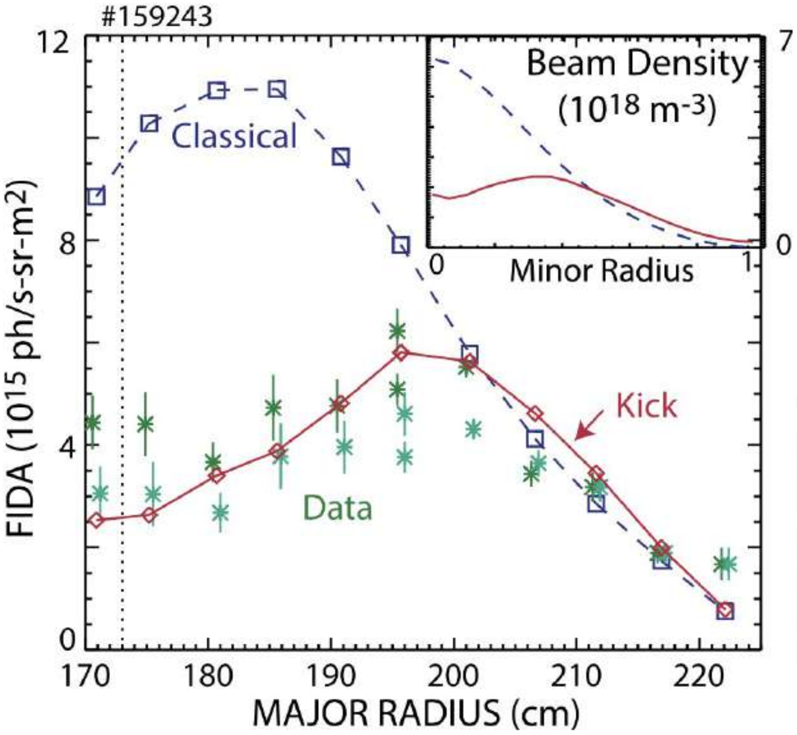
FIDA brightness from kick model in good agreement with experiment



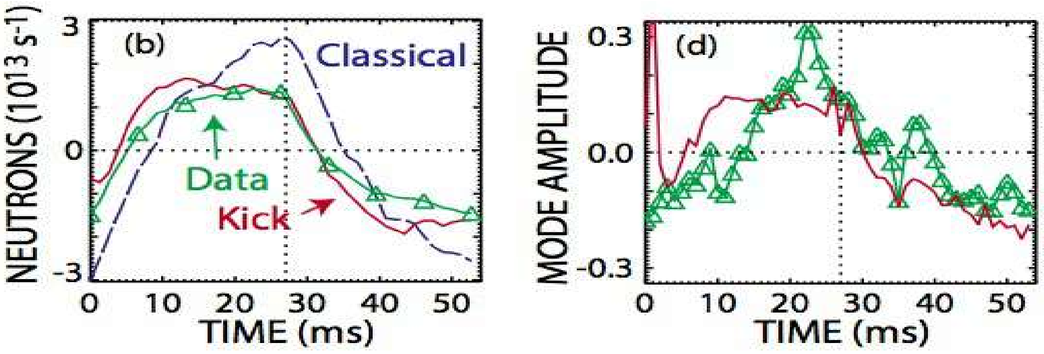
- Kick model applied for EP transport
- Synthetic FIDA brightness computed through FIDASim
  - Use fast ion distribution from NUBEAM

[W. Heidbrink et al., CCP 2011]
[B. Geiger et al., PPCF 2020]
[W. Heidbrink et al., PoP 2017]

EP response to NB modulation also in good agreement



- Kick model improves agreement of simulated vs measured modulated neutron rate
- Modulated mode amplitude from kick also in reasonable agreement with experiment

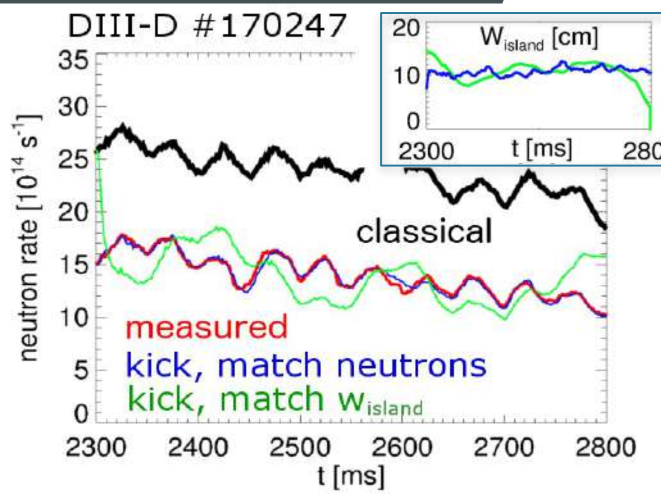


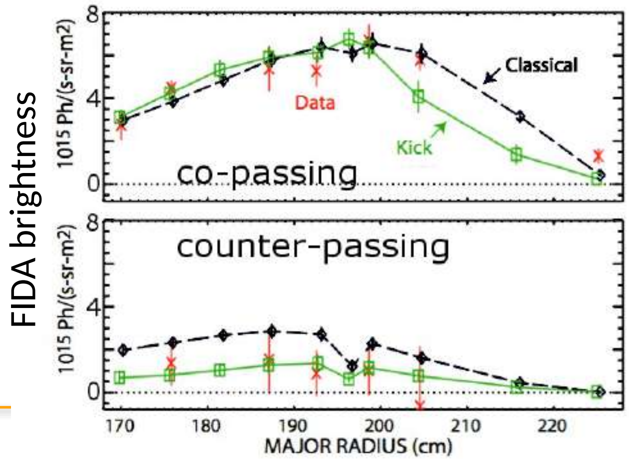
[W. Heidbrink et al., PoP 2017]

Reasonable agreement found for discharge with NTM

- FIDA: for co-passing NB ions, kick model overestimate transport
- For counter-passing, the agreement is better than using the classical TRANSP results

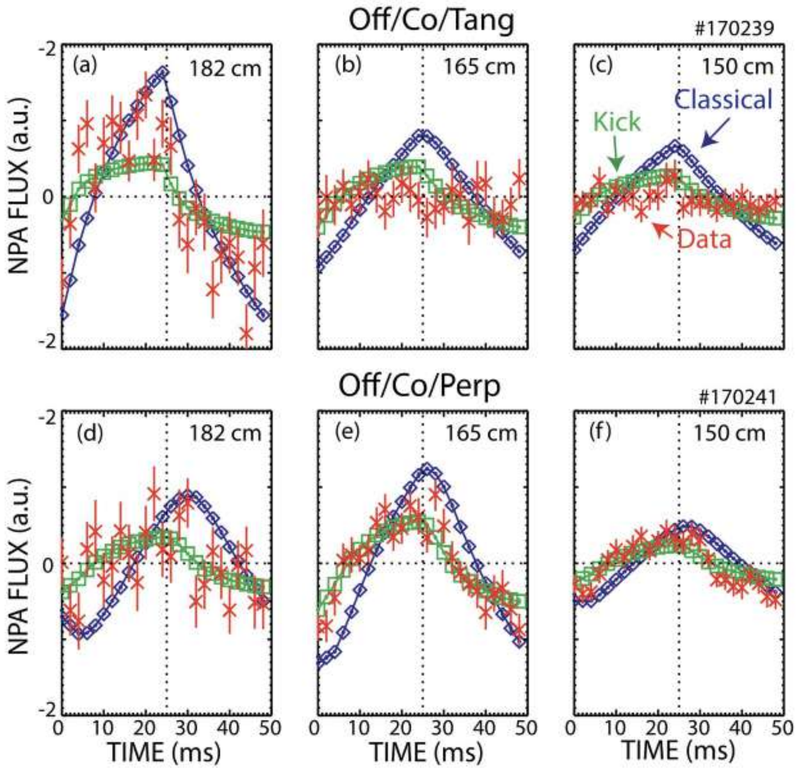
[W. Heidbrink et al., NF 2018]
[M. Podestà et al., NF 2019]





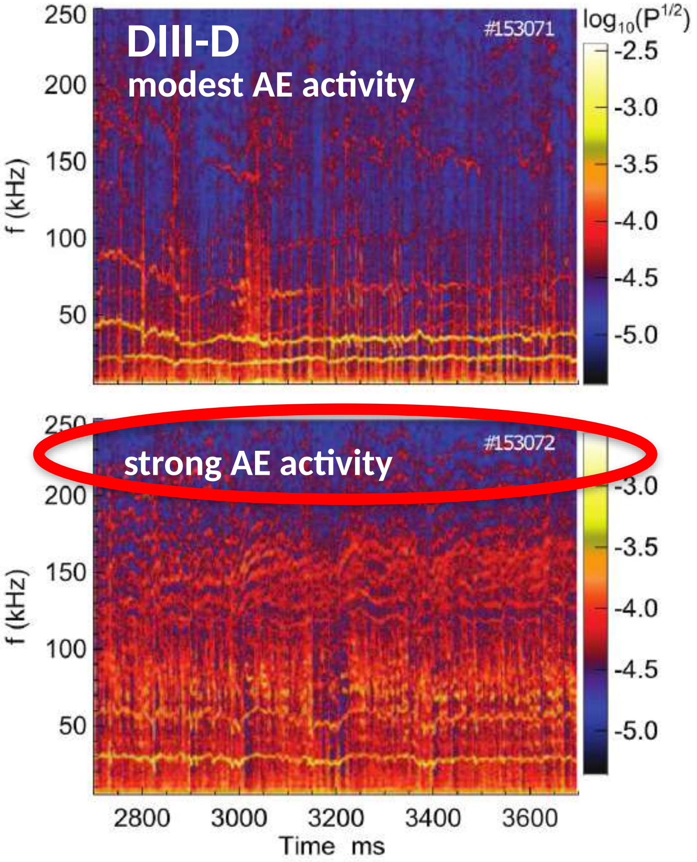
Reasonable agreement found for discharge with NTM

- FIDA: for co-passing NB ions, kick model overestimate transport
- For counter-passing, the agreement is better than using the classical TRANSP results
- Agreement with NPA data improves for kick run

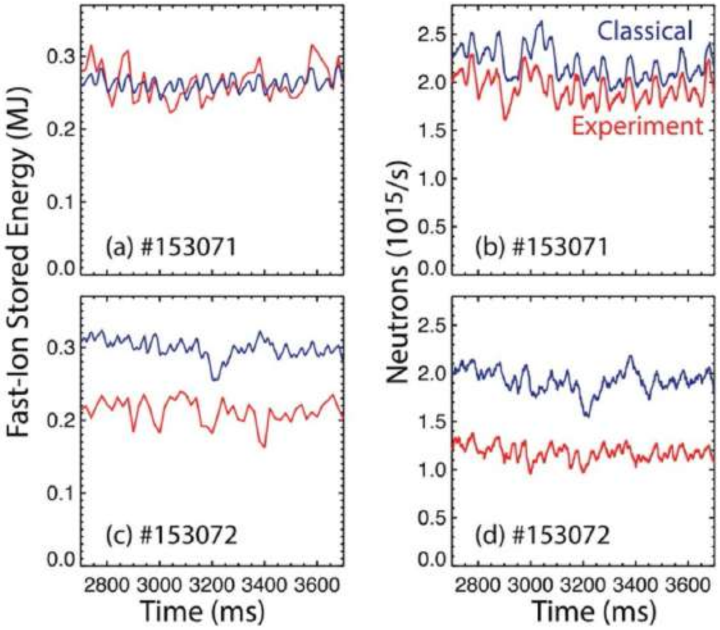


[W. Heidbrink et al., NF 2018]
[M. Podestà et al., NF 2019]

More advanced validation possible through EP tomography

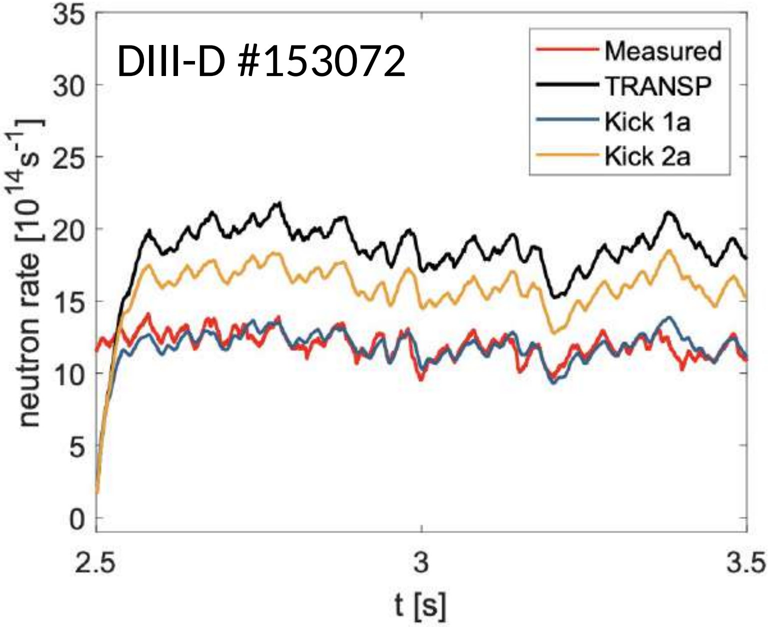


See M. Salewski's lecture on Tuesday



[B. Madsen et al., PPCF 2020]

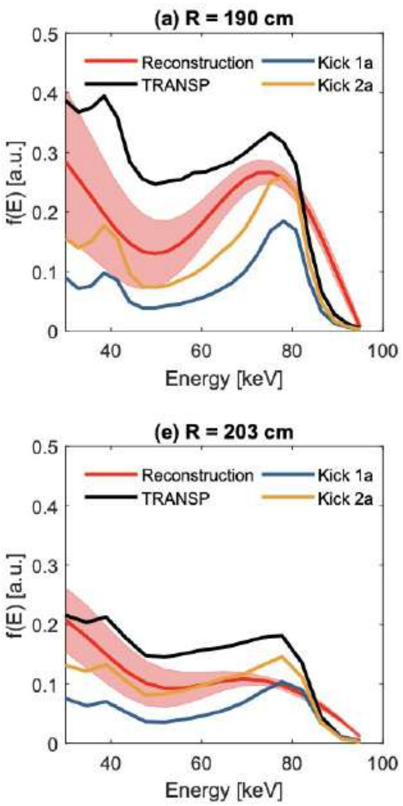
In this case, mode properties are NOT very well known…



- Approach:
  - Vary mode properties used for kick runs
  - Obtain NB ion distributions from NUBEAM
  - Run FIDASim
  - Compare TRANSP/NUBEAM results with results to tomography

[B. Madsen et al., PPCF 2020]

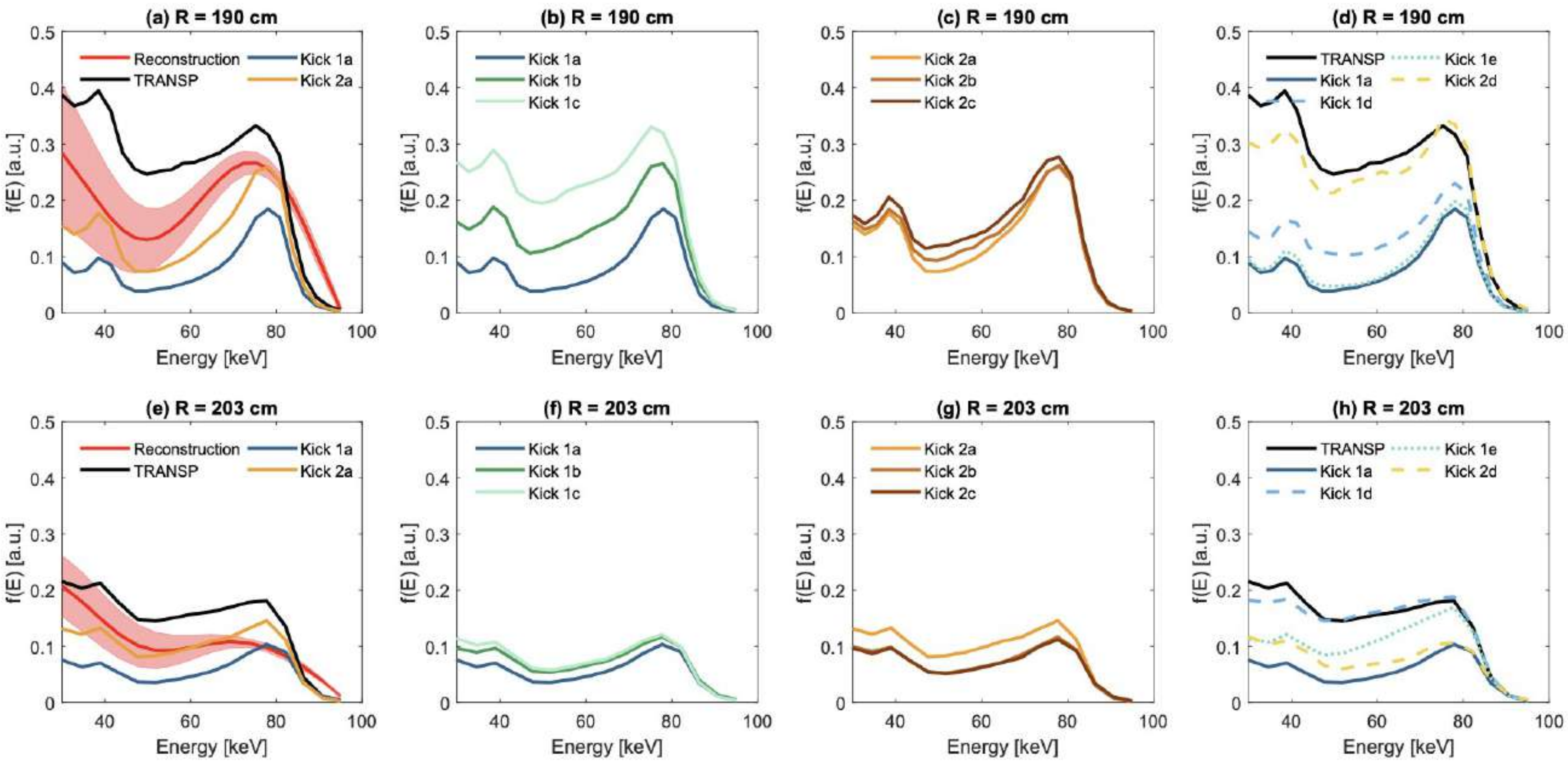
Tomography provides "measured" EP distribution for validation



- Focus on co-passing region of NB ion distribution from FIDA
- Kick run matching neutron rate (kick 1a) overestimates transport
- Run with 30% reduction in mode amplitude (kick 2a) is a better match

[B. Madsen et al., PPCF 2020] [See M. Salewski's lecture on Tuesday]

With several instabilities, model is very sensitive to input parameters



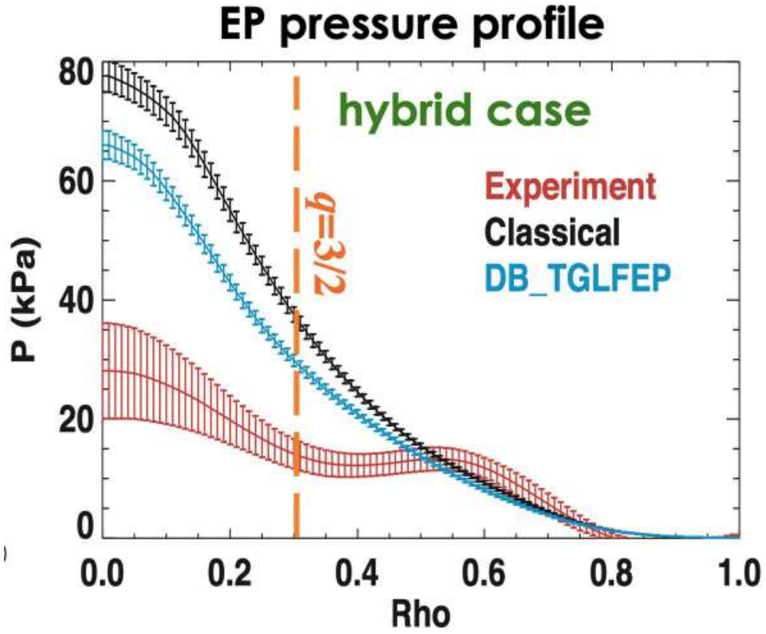
[B. Madsen et al., PPCF 2020] [See M. Salewski's lecture on Tuesday]

There are cases for which the models clearly fail.

Those are the cases we should learn from!

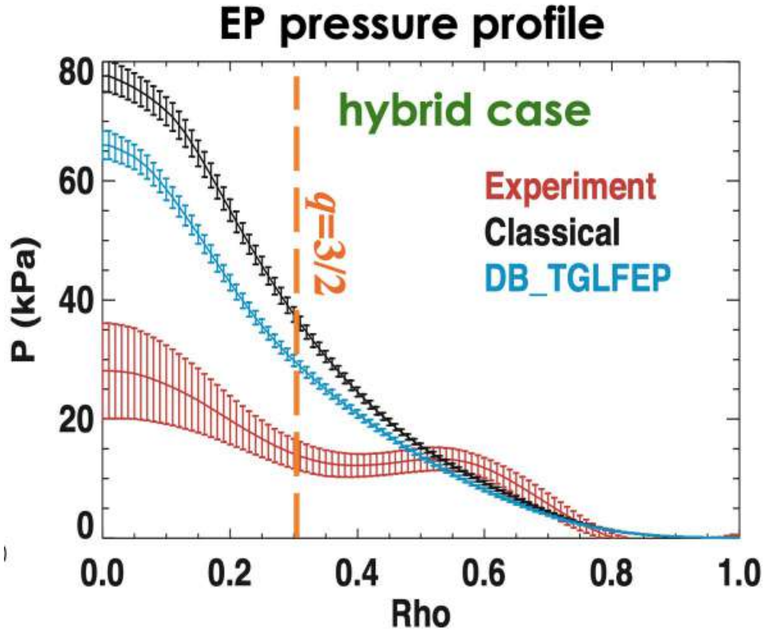
Example from TGLF-EP

- The model predict very little EP transport, inconsistent with experiment

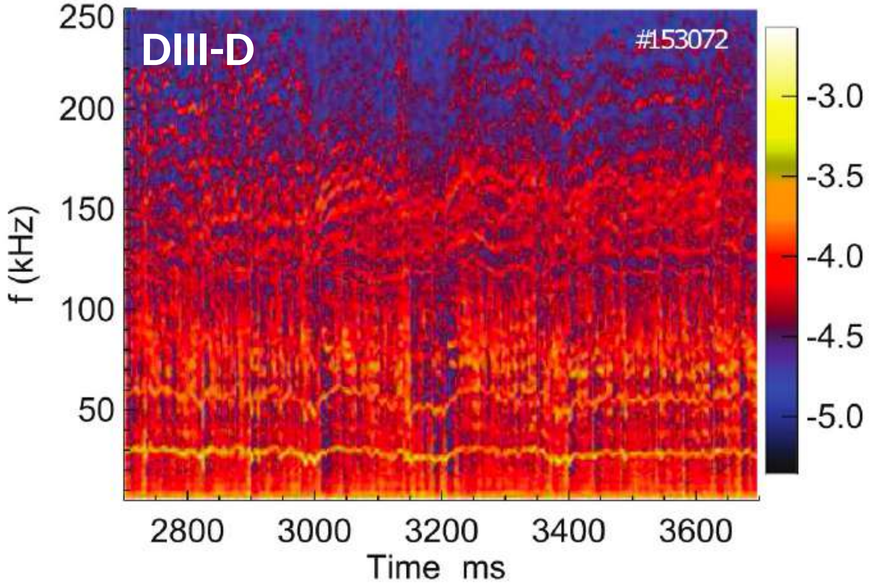


This discharge features a rich spectrum of instabilities

- The model predict very little EP transport

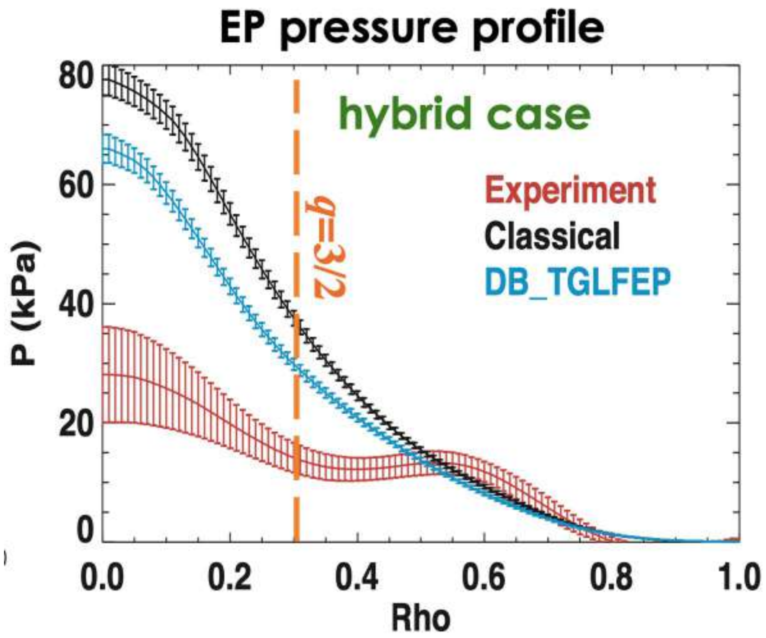


same DIII-D case used for EP tomography

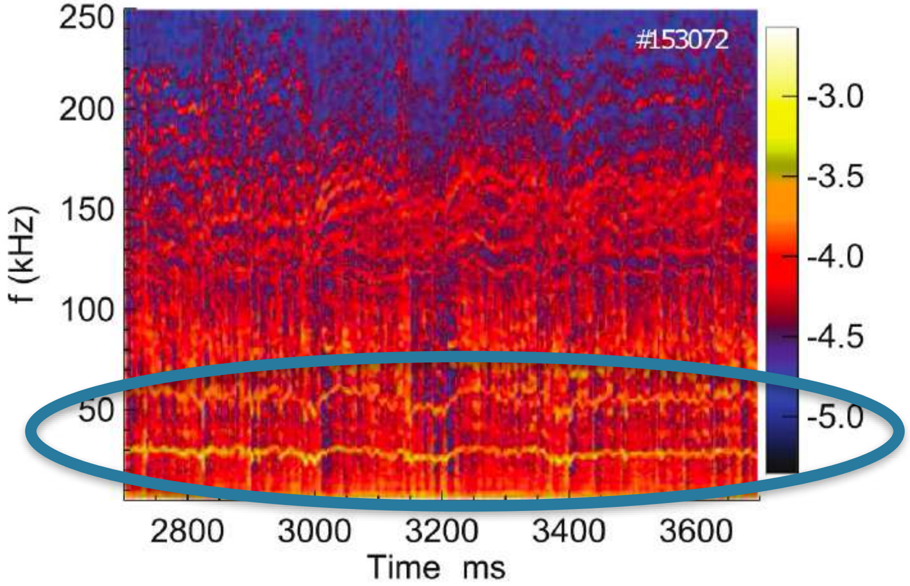


Missing physics results in inaccurate results

- The model predict very little EP transport

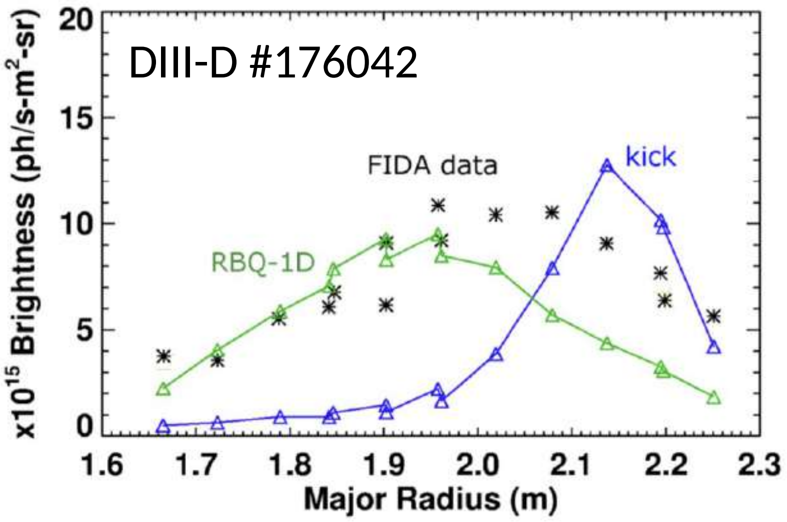


same DIII-D case used for EP tomography

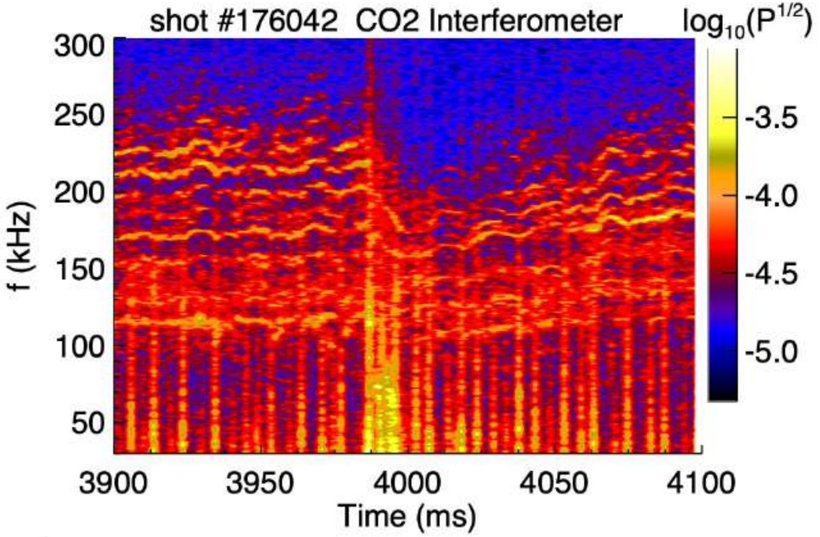


TGLF-EP doesn't include NTMs!

Example of failure from kick & RBQ models

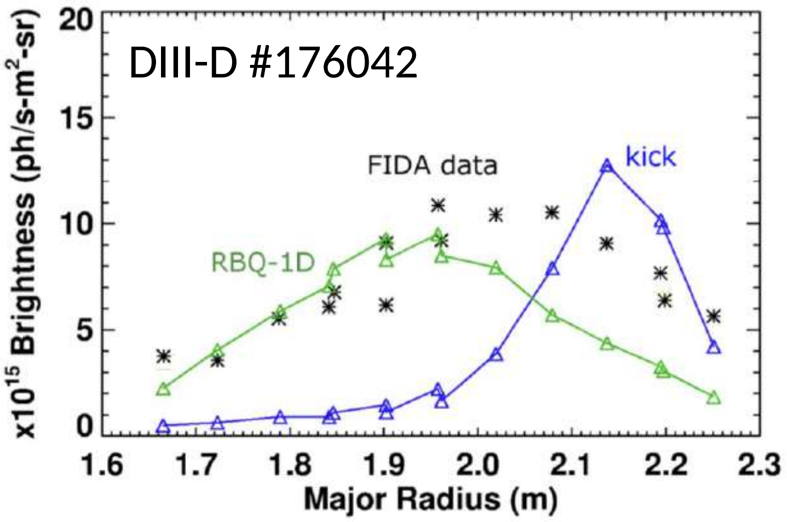


- Both kick and RBQ fail to recover FIDA results
- *Worse, the two models provide very different answers!*



[M. Podestà et al., FES Joint Research Target 2018]

Example of failure from kick & RBQ models



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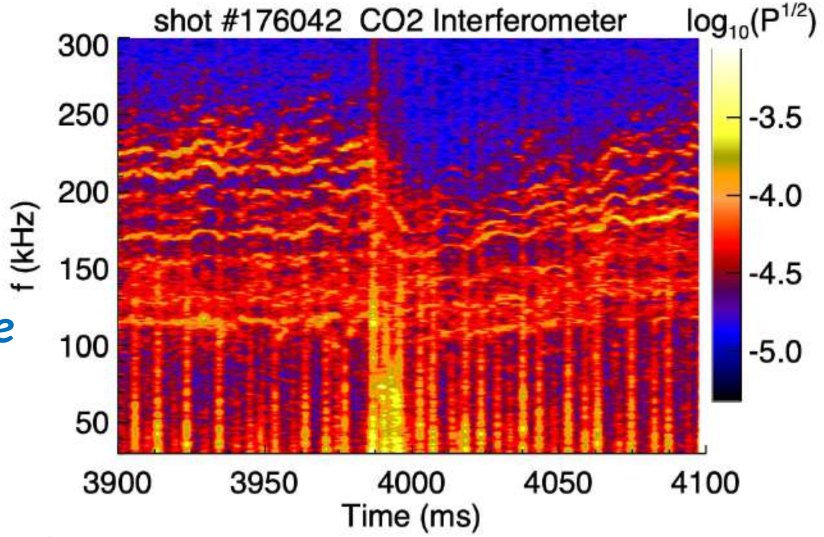
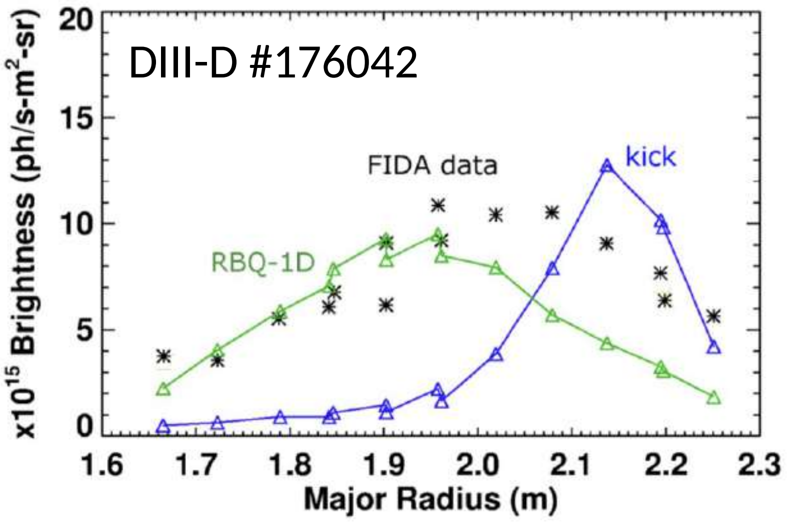


- **Here we tested both models in *predictive* mode:**
  - **Predict AE unstable spectrum**
  - **Predict saturation amplitudes**
- ***Probably too much at that time (2018)***

[M. Podestà et al., FES Joint Research Target 2018]

Example of failure from kick & RBQ models



- Both kick and RBQ fail to recover FIDA results
- *Worse, the two models provide very different answers!*
  - Models used different simplifications
    - kick neglected FLR effects
    - RBQ was only 1D in P_ζ
    - Rotation, stability, mode selection treated differently
  - Comparison improved when "same physics" was adopted
- *And yet: couldn't satisfactory recover FIDA results*
  - *Any volunteer??*

[M. Podestà et al., FES Joint Research Target 2018]

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Future directions for ITER and beyond

Some suggestions:

- Keep exploiting available facilities for validation of EP models (recent JET DT data are excellent example)
- Keep adding new physics – *but only when required*
- Be aware of purpose of “reduced models”, and its synergy with first-principles codes
- Adopt IMAS IDS more broadly for communication across models

Summary

- Reduced EP transport models are suitable for being included in Integrated Modeling frameworks: TRANSP ▭ IMAS

- *Interpretive* simulations on existing devices can reveal what needs to be improved & range of validity of each model

- *Predictive* simulations stress test the models. We need more!

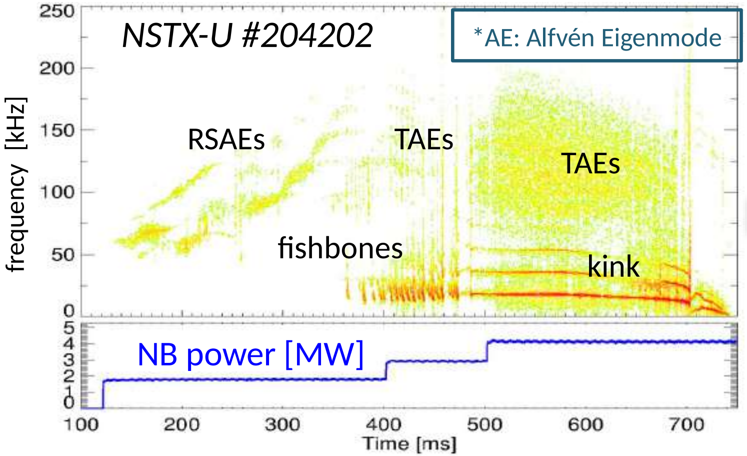
- *Reduced and first-principles EP models can – and should! – work together to develop truly predictive capabilities for ITER and beyond*

Backup slides

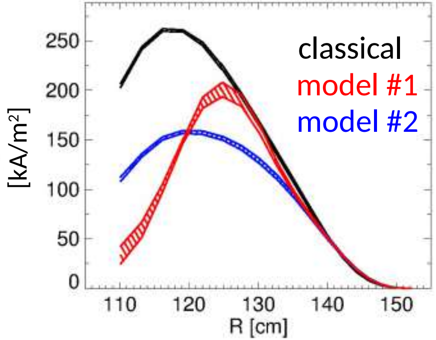
EPs (alphas, NB ions, RF tails) provide main source of heating, momentum, and NI current drive in burning plasmas

- But: EPs drive instabilities ⇄ instabilities affect EPs

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



Modeled NB driven current



Kick model implementation includes estimate of energy exchanged between EPs and waves

- Kick model computes $P_{fi,j}$ for each mode j as sum of energy "kicks" during orbiting time steps δt
- Once $P_{fi,j}$ is known, use simple equation for amplitude vs time:

$$\begin{cases} \dfrac{\partial E_{wav,j}}{\partial t} = P_{fi,j} - 2\gamma_{D,j} E_{wav,j} \\ 2\gamma_{eff,j} E_{wav,j} \equiv P_{fi,j} - 2\gamma_{D,j} E_{wav,j} \\ \dfrac{\partial E_{wav,j}}{\partial t} = 2\gamma_{eff,j} E_{wav,j} \end{cases}$$

Wave energy evolution for *j-th* mode

Effective growth rate, drive - damping

- Amplitude $A_{wav,j} \sim E_{wav,j}^2$
- Damping rates from NOVA-K

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

- Check: are $A_{wav,j}$ assumptions and $P_{fi,j}$ results energetically consistent?
- $A_{wav,j}(Pf_{i,j})$ can be used to infer "saturation amplitude"

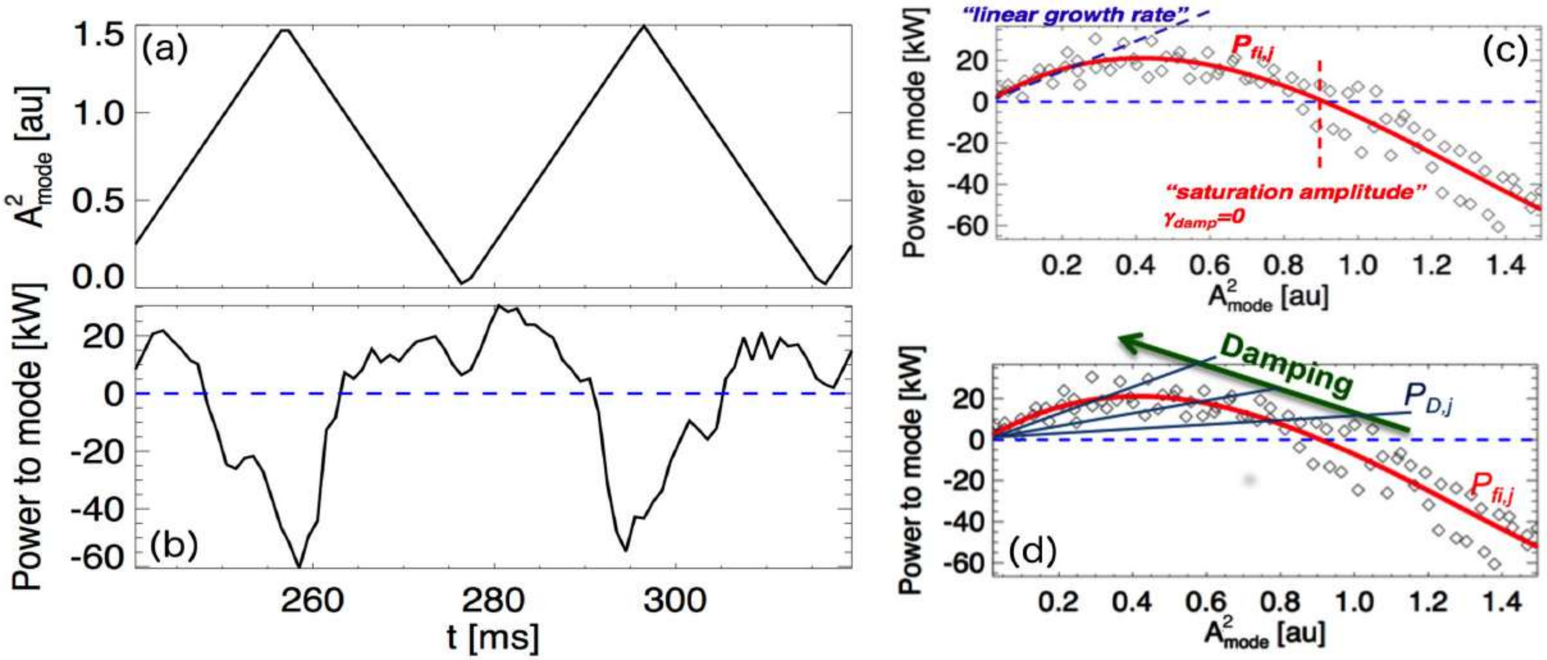
$$\Rightarrow \gamma_{eff,j} \approx 0 \ , \ P_{fi,j} \geq 0$$

Condition at saturation

Time-dependent mode stability properties can be obtained from kick model

Method: probe EP response to modes at different amplitude level through power balance analysis

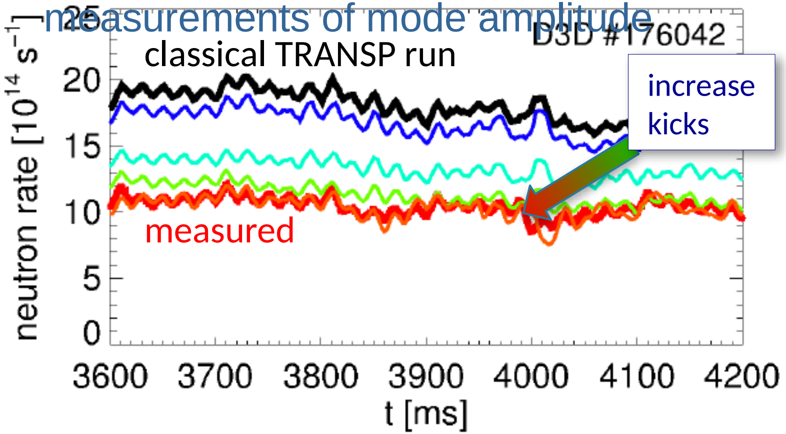
> infer “linear growth rate” & “saturated amplitude”



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

reduce input from experiment

Interpretive runs:

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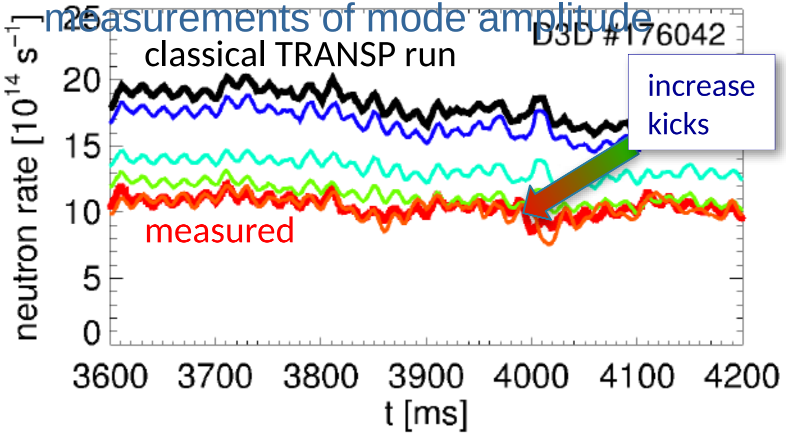


Predictive runs:

➢ *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

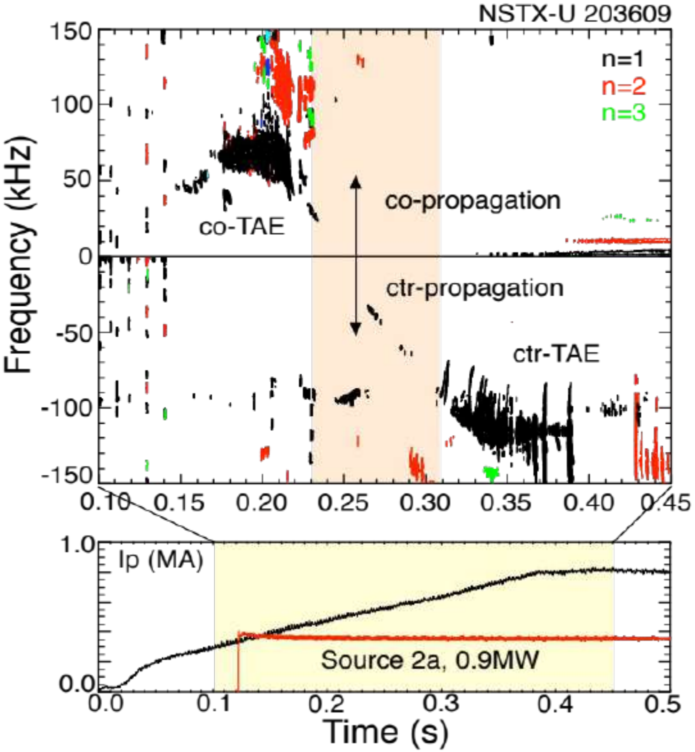
Main limitation:

- *Can be only as good as damping rate estimates!*

Podestà PPCF 2017

A challenging case: co- vs cntr-TAEs on NSTX-U

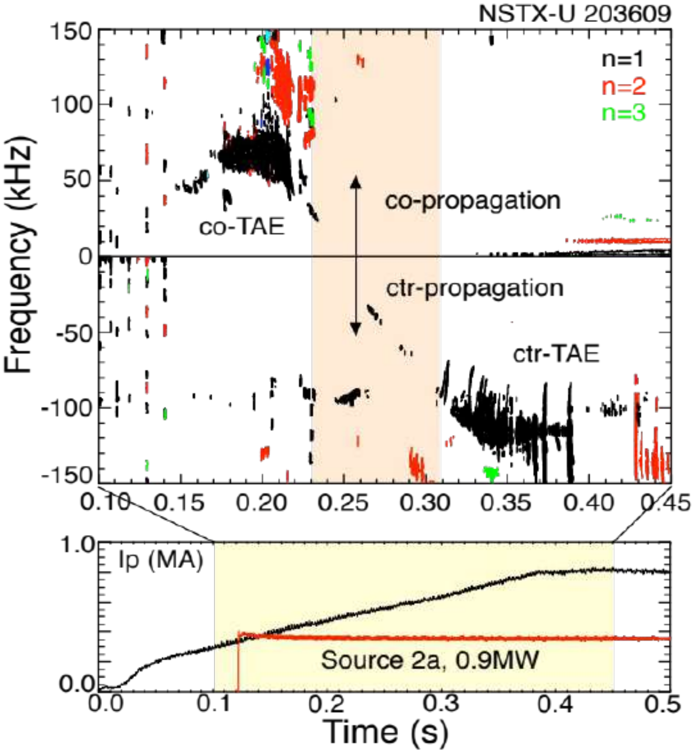
- An unexpected observations from NSTX-U with new, off-axis NBI…

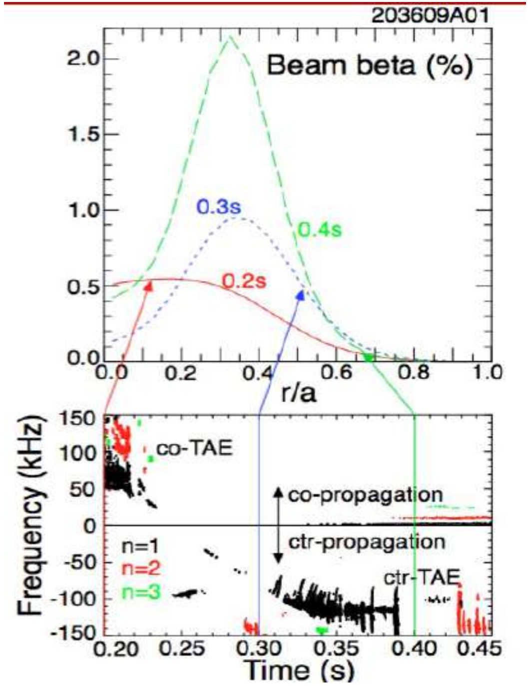


[M. Podestà et al., NF 2018]

Kick model is stress-tested to recover transition vs. time

- Highly transient conditions with evolving density, temperature and EP parameters



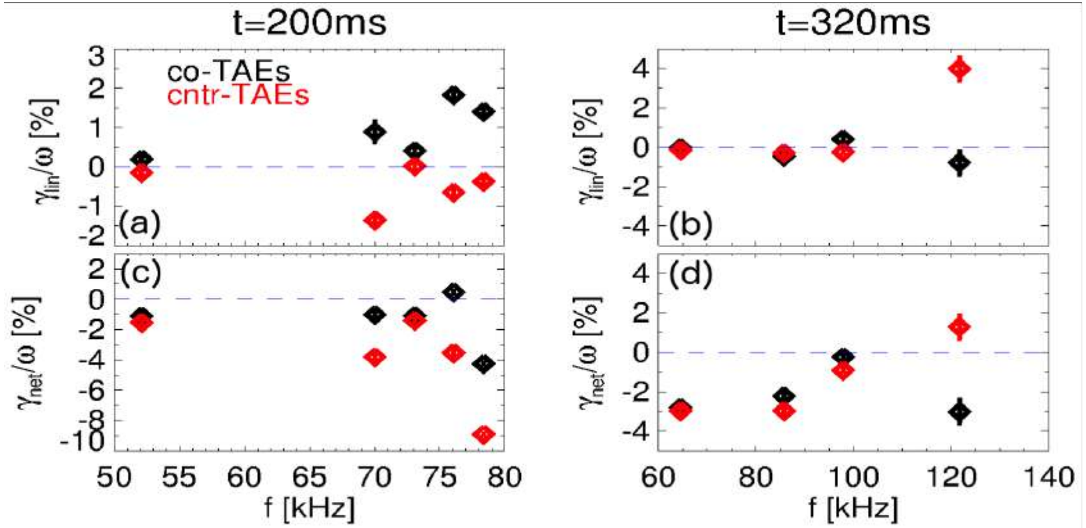


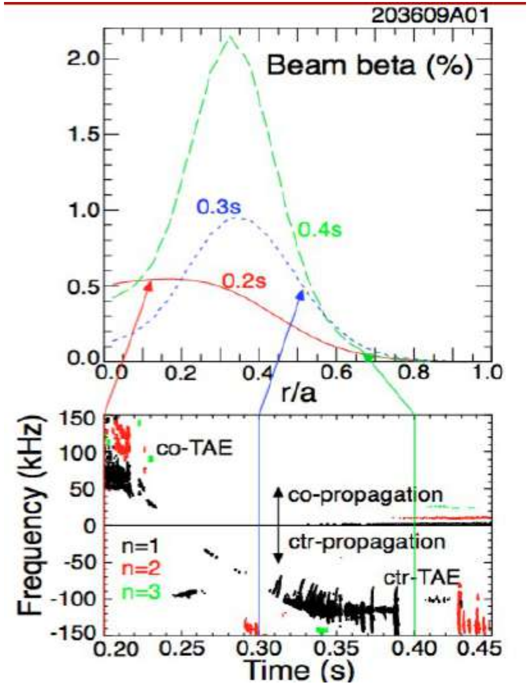
[M. Podestà et al., NF 2018]

Kick model identifies two linearly unstable n=1 modes, co ᄇ cntr

- Test AEs n=1 structures and damping rates from NOVA/-K
- AE drive by NB ions from kick model

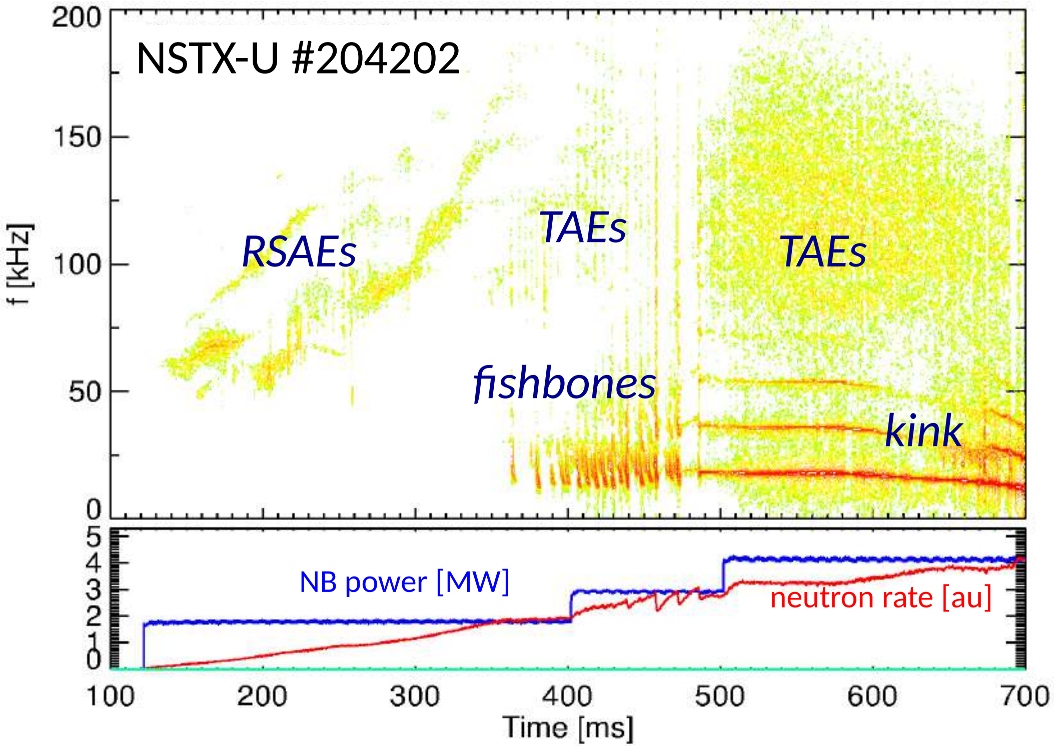
ᄑ Model recovers co- to cntr- transition, overall stability for *n=1* TAE





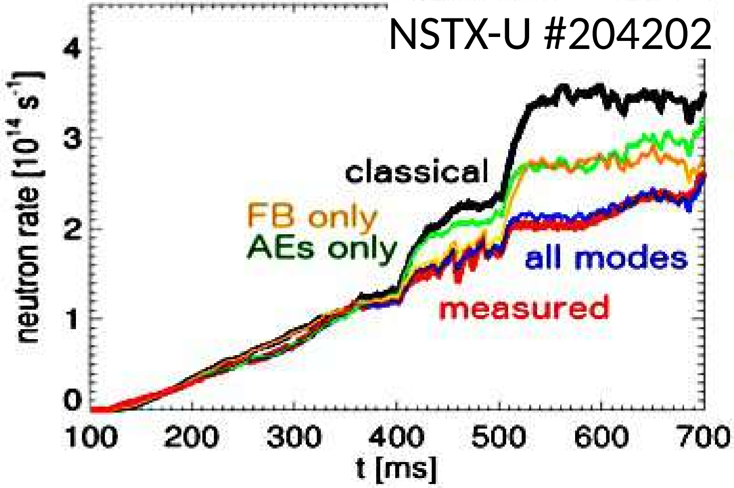
[M. Podestà et al., NF 2018]

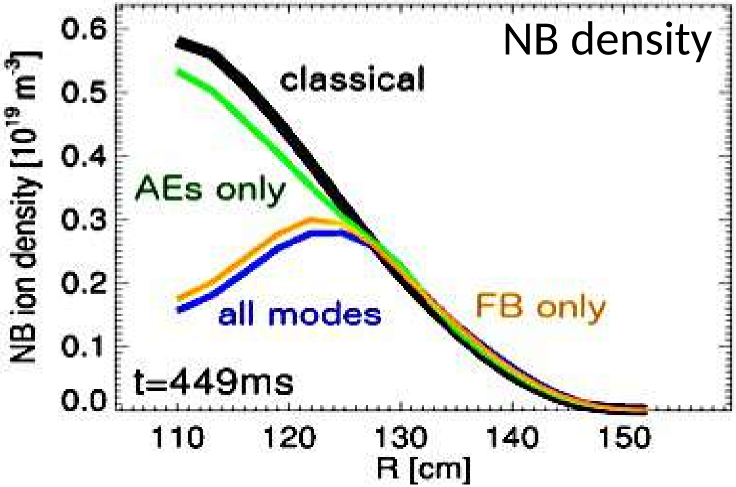
Towards *predictive* simulations: need estimate of unstable spectrum, saturated amplitudes



- 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

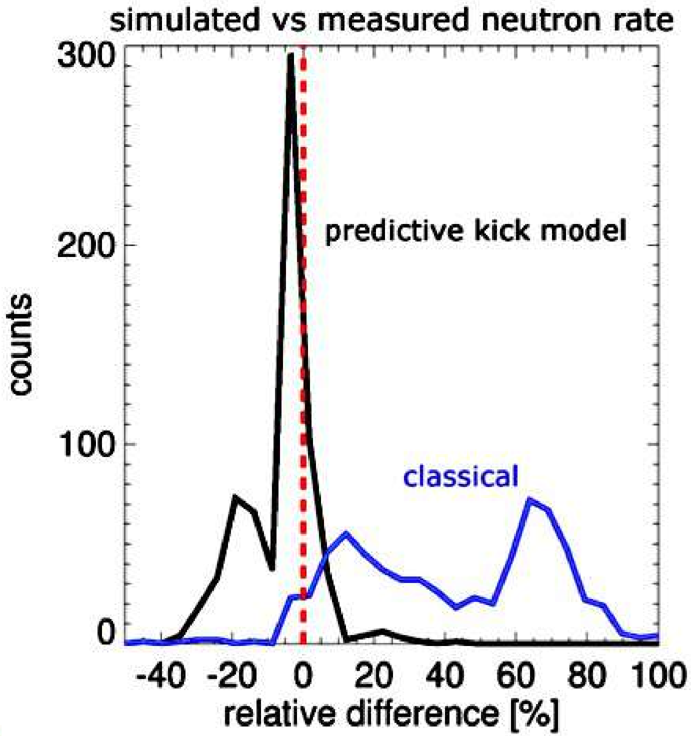




- AEs and fishbones/kinks cause comparable drop in neutrons
  - Fishbones, kinks are mostly responsible for NB ion density depletion
  - AEs have larger effect on NB ion energy redistribution
- *Synergy between modes is observed*, e.g. in total EP losses

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

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

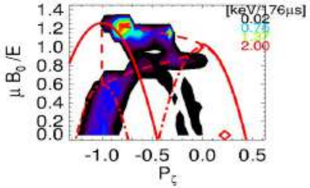


- However: in some cases, predictive runs fail to reproduce experiments!
  - Predicted AE spectrum differs from experiment
  - *Key role of damping rate from MHD codes*
    - Affects inferred AE saturation amplitude

NSTX-U and DIII-D scenarios challenge models over broad set of conditions

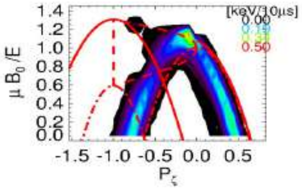
complexity

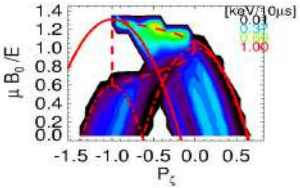
- DIII-D: NTM-only scenario
  - Single (dominant) instability
  - Limited number of resonances
- DIII-D: AEs-only scenario
  - Large number of weaker AEs
  - “Sea” of resonances
- NSTX-U: multi-mode scenario
  - Transient scenario, variations in background plasma & heating sources
  - Multiple types of instabilities
  - *Need to account for possible synergy between different modes*
    - *e.g. fishbones + TAEs + kink*

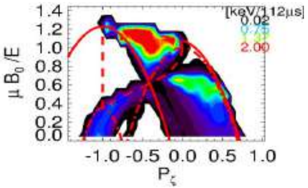


NTM

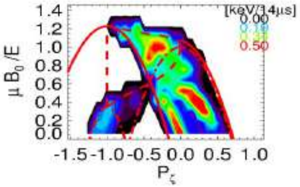
11x RSAEs and TAEs







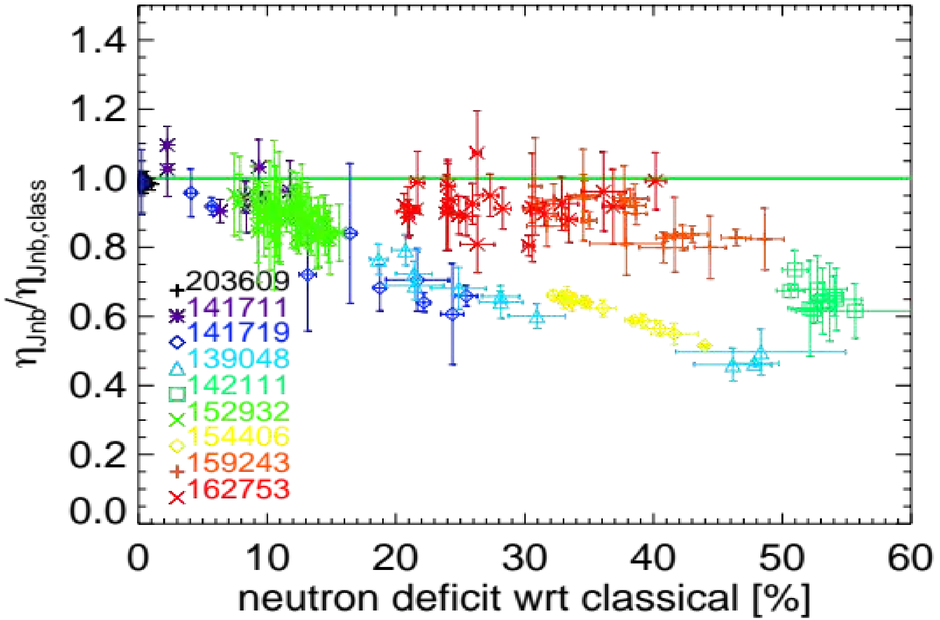
fishbones, kink



3x RSAEs
4x TAEs

NSTX/NSTX-U/DIII-D database

- Large variability across shots observed
  - Related to L/H-phase, profile peaking
  - Uncorrelated with device - i.e. aspect ratio, $v_{fast}/v_{Alfvén}$, etc

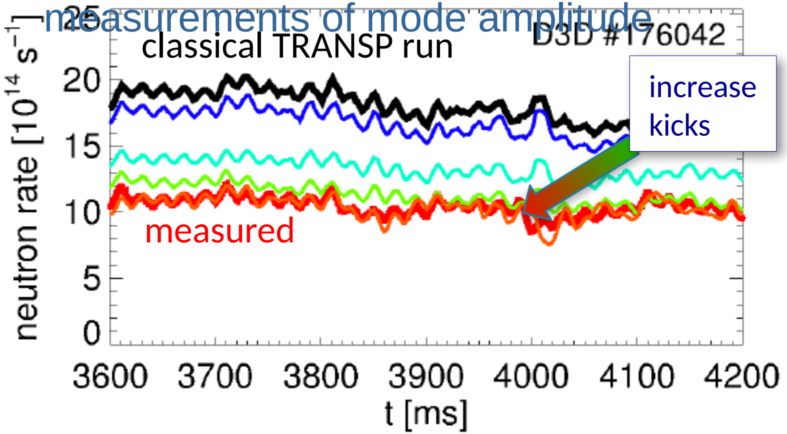


Interpretive vs. predictive analysis

Interpretive runs: *reduced input from experiment* Predictive 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



➢*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 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

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:

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

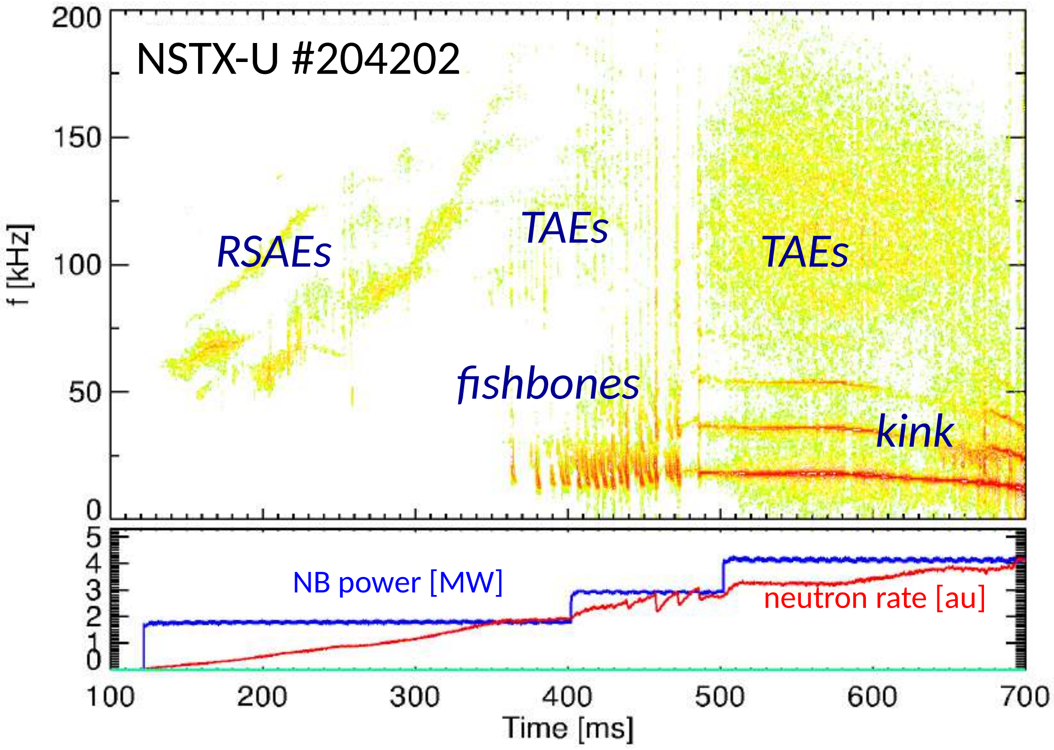
drive from NUBEAM + kick model

damping from NOVA-K

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

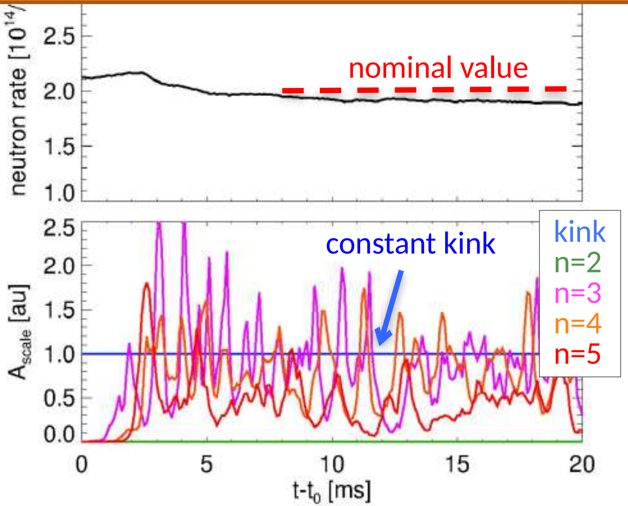
Synergy between TAEs and kink observed on NSTX-U

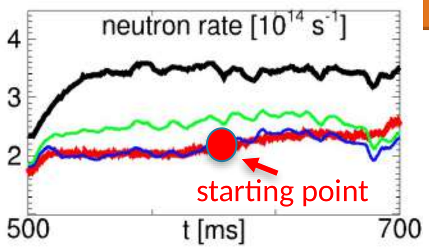
Podestà NF 2019



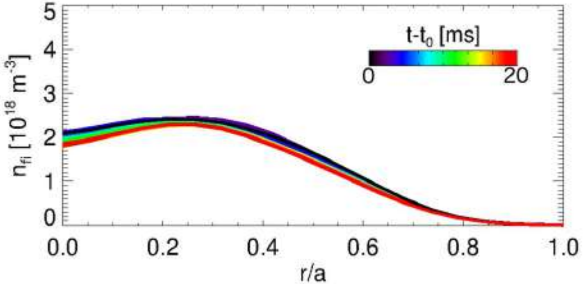
- TAE mode structures and damping from NOVA-K
- Need estimate for relative AE amplitudes:
  - Use saturation condition (drive=damping) to infer AE amplitudes vs time
- Then, rescale fishbone & kink amplitudes to match measured neutron rate
  - Use analytic expression for FB, kink mode structure
  - No damping info available (yet)

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



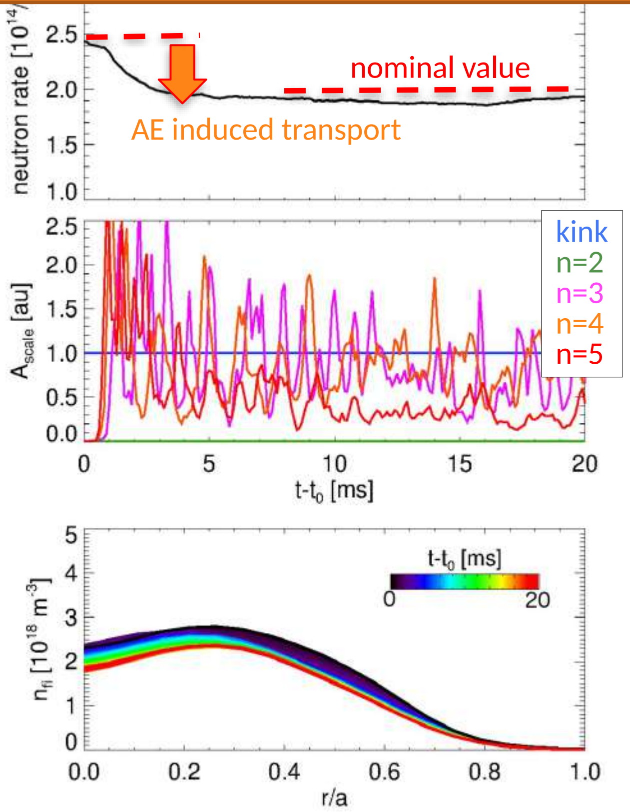


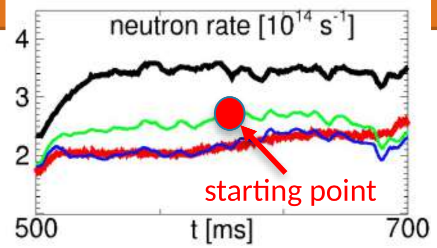
- Neutron rate remains roughly constant
- n=3-5 TAEs unstable, n=2 stable
- Modes show amplitude bursts
  - Consistent with experiment
  - *Same "predator-prey" physics as in Gorelenkov's talk? (see O-20, tomorrow)*



- NB ion density remains around nominal profile

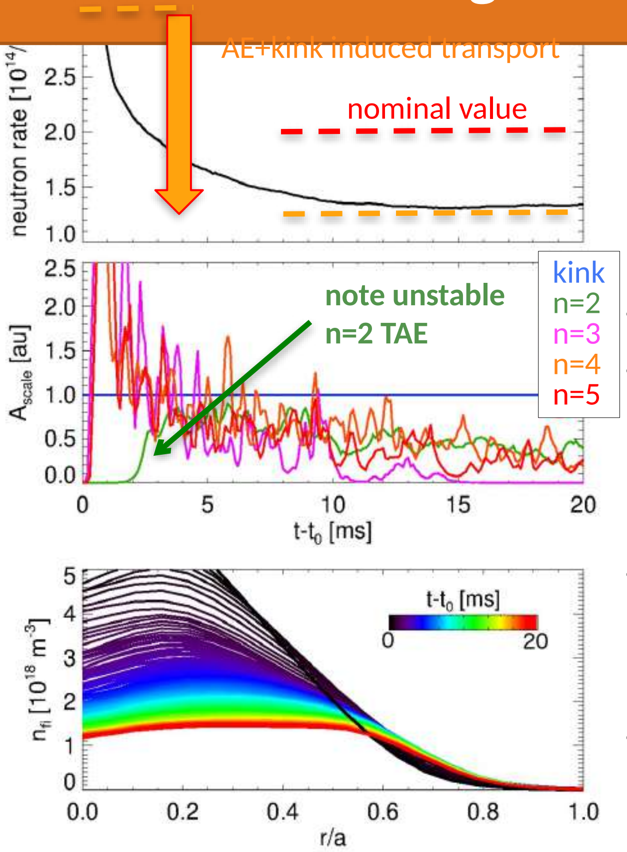
Start from run with low-f modes only: good convergence of simulation results

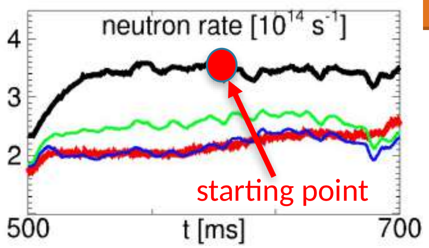




- Neutron rate drops to nominal value as AE amplitude "saturates"
- After transient, AEs show similar dynamic as in previous case
  - Bursting amplitude, similar level
- NB ion density relaxes to nominal profile

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

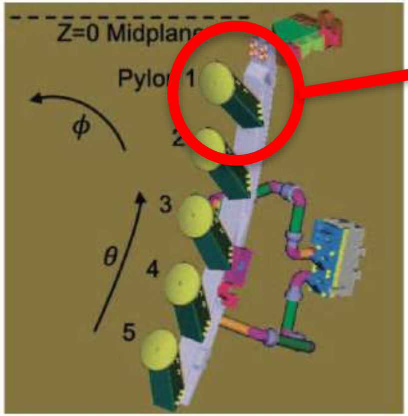


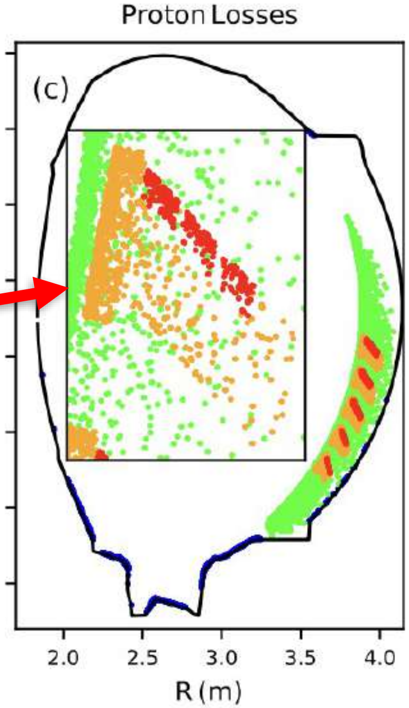


- Larger drop in neutron rate
- AEs show different evolution than in previous cases
  - Large initial spike, bursts reduced
  - n=2 TAE now destabilized, unlike in previous cases
- NB ion density profile flatter, reduced to <70% than in previous cases
- ***Simulation converges to a different state as initial conditions are varied considerably***

Recent developments: deal with vacuum region for EPs losses

- Example from Faraday Cups array installed on JET (aka KA2)
  - Measure fast ion lost
    - Mostly sensitive to high-energy D, T, p, alphas with E>500k
- Extended ORBIT to vacuum region
  - Implemented synthetic KA2
  - Validating against JET D, T, DT experim
- Species-dependent Kick Transport Matrices can be used in NUBEAM
  - Presently under test (previous slide)





DIII-D: investigate drive/damping mechanisms as NBI parameters are varied for single TAE

Van Zeeland NF 2021

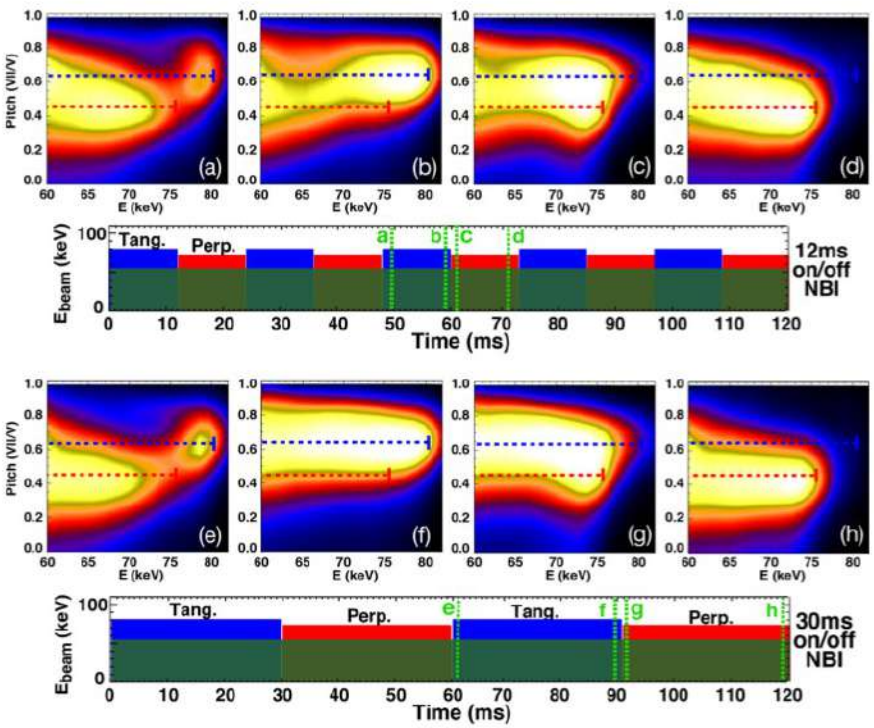
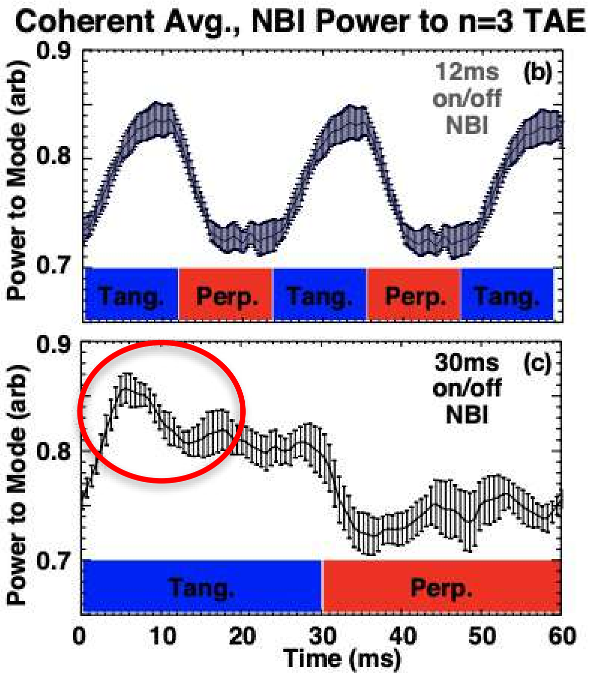


Figure 4. TRANSP calculated temporal evolution of the volume-averaged fast ion distribution function for: (a)-(d) 12 ms on/off interleaving and (e)-(h) 30 ms on/off interleaving of the 81 kV tangential and 75 kV perpendicular beams shown in Figure 3. The timing of the distribution function snapshots relative to the beam modulation are shown as dashed vertical lines overlayed on beam voltage waveforms.

DIII-D: investigate drive/damping mechanisms as NBI parameters are varied for single TAE

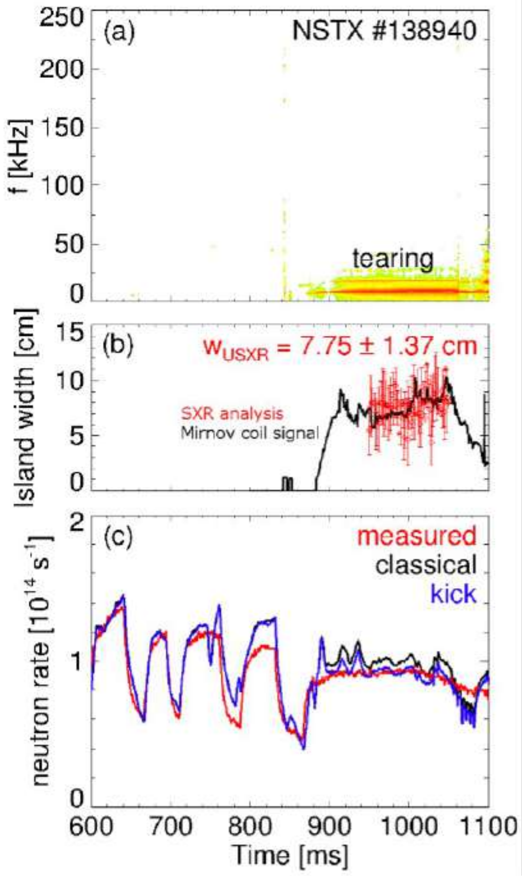


Van Zeeland NF 2021

Figure 15. Kick model calculations. (a) Time averaged power to the TAE for four different beam scenarios. (b) & (c) power to mode obtained by coherent average of several beam cycles for 12 ms and 30 ms on/off interleaving.

- Single n=3 TAE
- Kick + NUBEAM: compute power from NB ions to mode as NB is modulated
  - Low amplitude kept constant
  - "Linear" analysis
- Note initial spike for 30ms modulation
  - Associated with bump-on-tail
- Small extra 5% contribution to mode drive overall
- Helps to understand role of Pz vs. Energy gradients for mode stability
  - Comparison with MEGA

NSTX: study EP transport by coupled kink + NTM

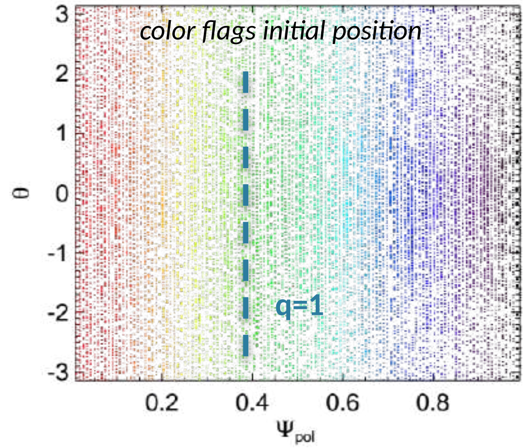


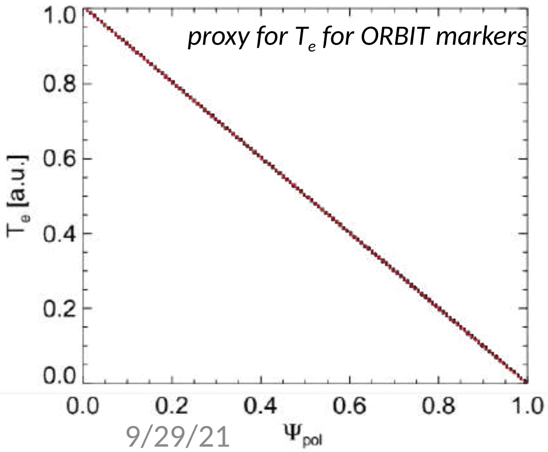
Yang PPCF 2021

- SXR data used to infer island width for 2/1 TM
  - Then rescale Mirnov coil data for time dependent amplitude
- Core kink also detected
- Modes are phase-locked
  - Need to be accounted for in kick model: single transport matrix including effect of both modes
  - Important to obtain neutron rate drop from TRANSP consistent with experiment
- Ongoing: comparison with M3D-C1k (C. Liu)
- Also see D. Liu's work on low-f instabilities in DIII-D

Liu NF 2021

NSTX-U: sawteeth revisited



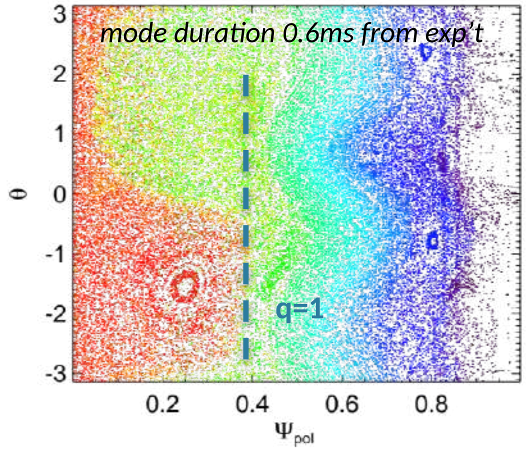


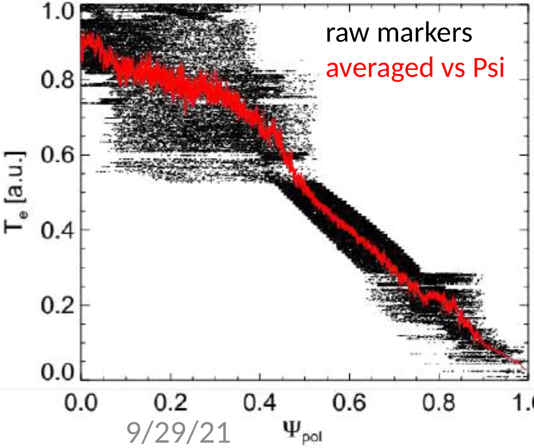
- Largely based on ORBIT work by White et al. *Zhao PoP 1997*
- Extend previous work on NSTX-U *Kim NF 2019*

- Streamline analysis with ORBIT
  - On-the fly estimate of (1,1) amplitude based on "mixing" of thermal electron markers
  - Input/output consistent with NUBEAM output
    - Can use directly in FIDASIM
  - Also produces kick matrix for TRANSP (tests ongoing)

- Data from experiment used to set duration of the SW crash, relative growth/crash fraction
  - Analytic model for mode structure: n=1, m=1(,2,3,…)

NSTX-U: sawteeth revisited





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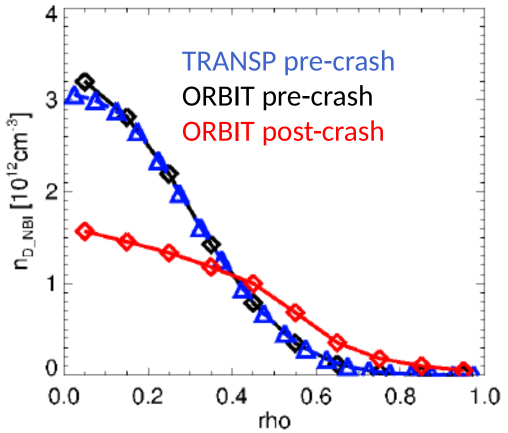
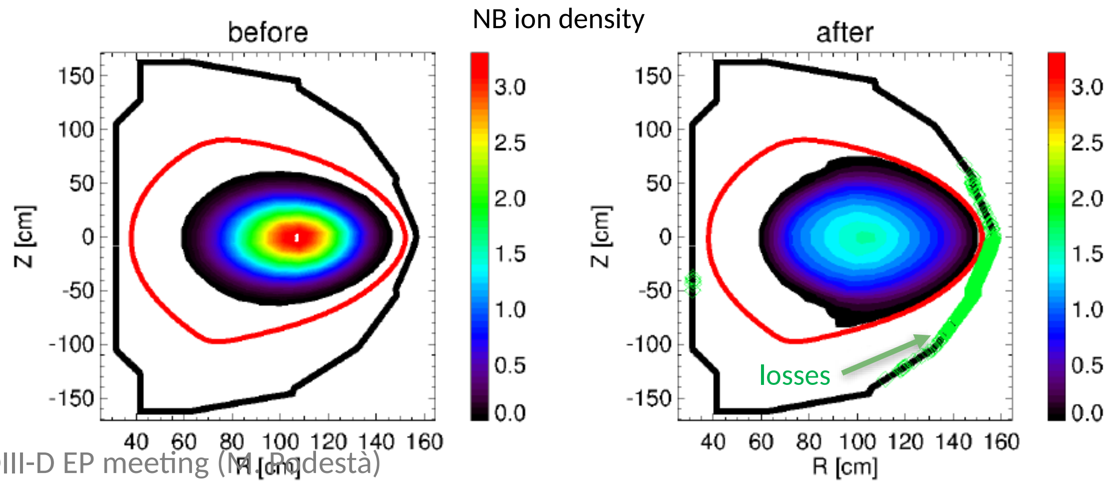
NSTX-U #204083: large redistribution of NB ions by sawteeth

- Assume “full reconnection”, include n=1, m=1,2,3

- Also available: losses to the wall, *including vacuum region* from LCFS to wall
  - Work by R. White
  - Useful for diagnostic optimization, analysis





NSTX-U #204083: large redistribution of NB ions by sawteeth

- Info on 2D fast ion distribution in R,Z vs energy, pitch available for comparison with fast ion diagnostics
  - E.g. FIDA, NPA through FIDASIM
- Can break down runs based on orbit type (co/cntr, trapped, ...)