NSTX-U

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Destabilization of counter-propagating TAEs by co-current, off-axis NBI

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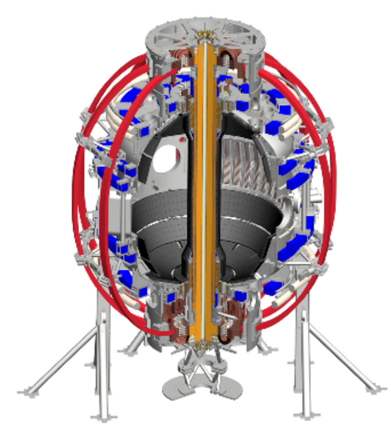

Abstract

Neutral Beam injection (NBI) is a common tool to heat the plasma and drive current non-inductively in fusion devices. Energetic particles (EP) resulting from NBI can drive instabilities that are detrimental for the performance and the predictability of plasma discharges. A broad NBI deposition profile, e.g. by off-axis injection aiming near the plasma mid-radius, is often assumed to limit those undesired effects by reducing the radial gradient of the EP density, thus reducing the "universal" drive for instabilities. However, this work presents new evidence that off-axis NBI can also lead to undesired effects such as the *destabilization* of Alfvénic instabilities, as observed in NSTX-U plasmas. Experimental observations indicate that counter propagating toroidal AEs are destabilized as the radial EP density profile becomes hollow as a result of off-axis NBI. Time-dependent analysis with the TRANSP code, augmented by a reduced fast ion transport model (known as *kick model*), indicates that instabilities are driven by a combination of radial and energy gradients in the EP distribution. Understanding the mechanisms for wave-particle interaction, revealed by the phase space resolved analysis, is the basis to identify strategies to mitigate or suppress the observed instabilities.

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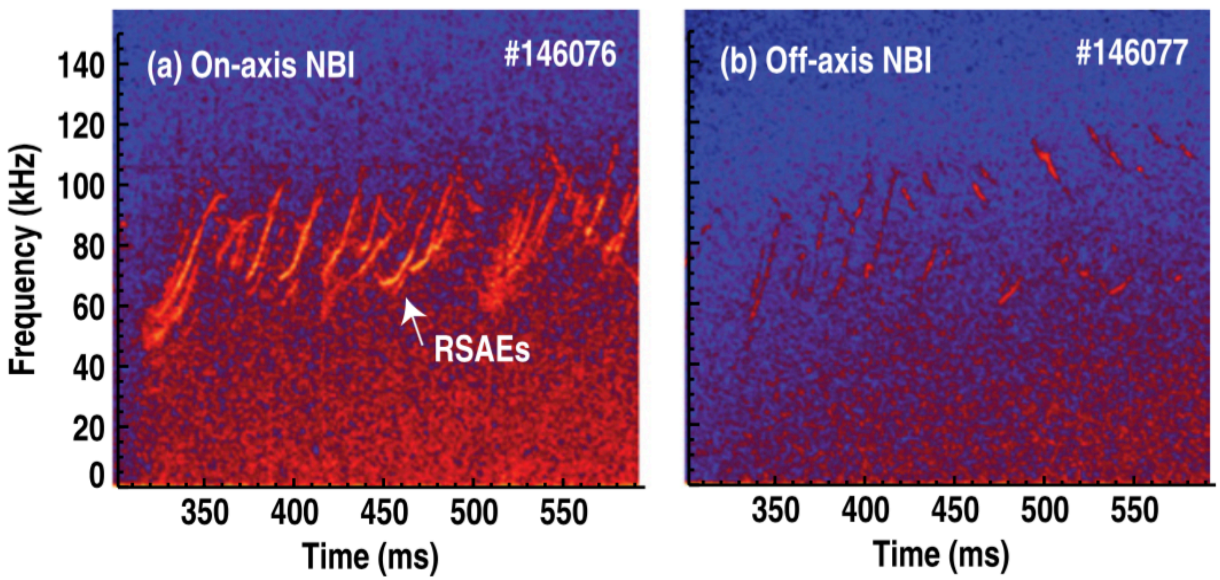
Off-axis NBI is generally assumed to be an effective tool to reduce *AE activity

- Broad pressure and current profiles
  - > good for MHD stability
- Broad *fast ion* density profile
  - > reduce gradients near peak of fast ion pressure -> reduce “universal drive” *[Kramer, NF 2017]*

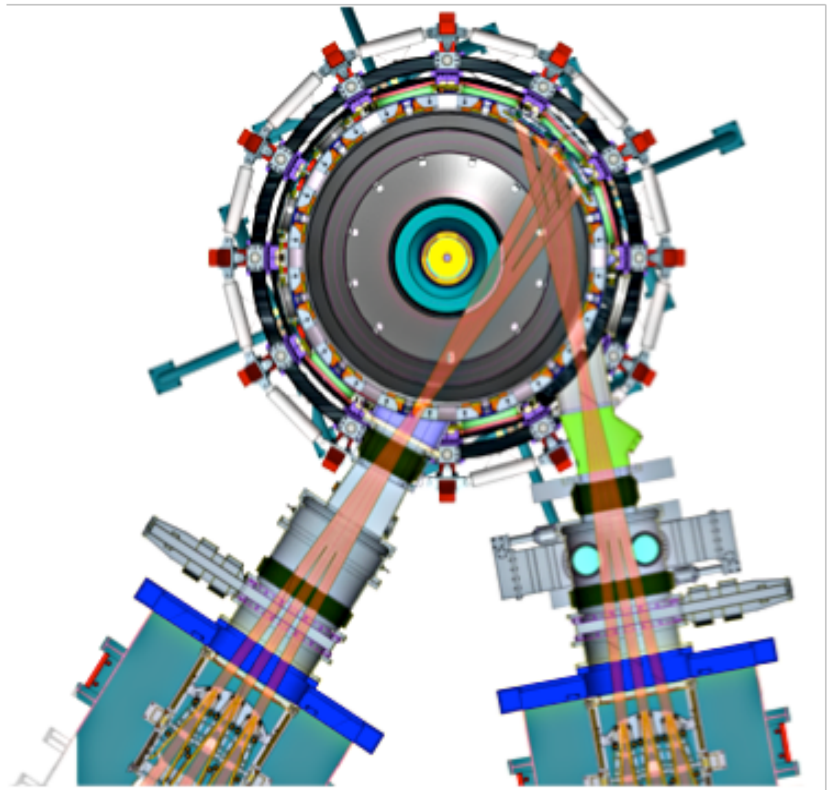


[Heidbrink, NF 2013]

Figure 5. Cross power of adjacent ECE channels that are located near $q_{\min}$ (at $R \simeq 195$ cm) during (*a*) on-axis and (*b*) off-axis injection. The same logarithmic colour scale is used in both figures. In the off-axis case, the mode activity at 400 and 500 ms coincides with brief diagnostic blips of the on-axis beams.

New off-axis NBI on NSTX-U enables exploration of AE stability vs NB geometry

Major radius	0.95 m
Aspect ratio	1.5
Elongation	2.7
Triangularity	0.8
Plasma current	<2 MA
Toroidal field	<1.0 T
Pulse length	~1-5 s
6 Neutral Beam sources:	
$P_{NBI} \leq 12$ MW, $E_{injection} \leq 95$ keV	



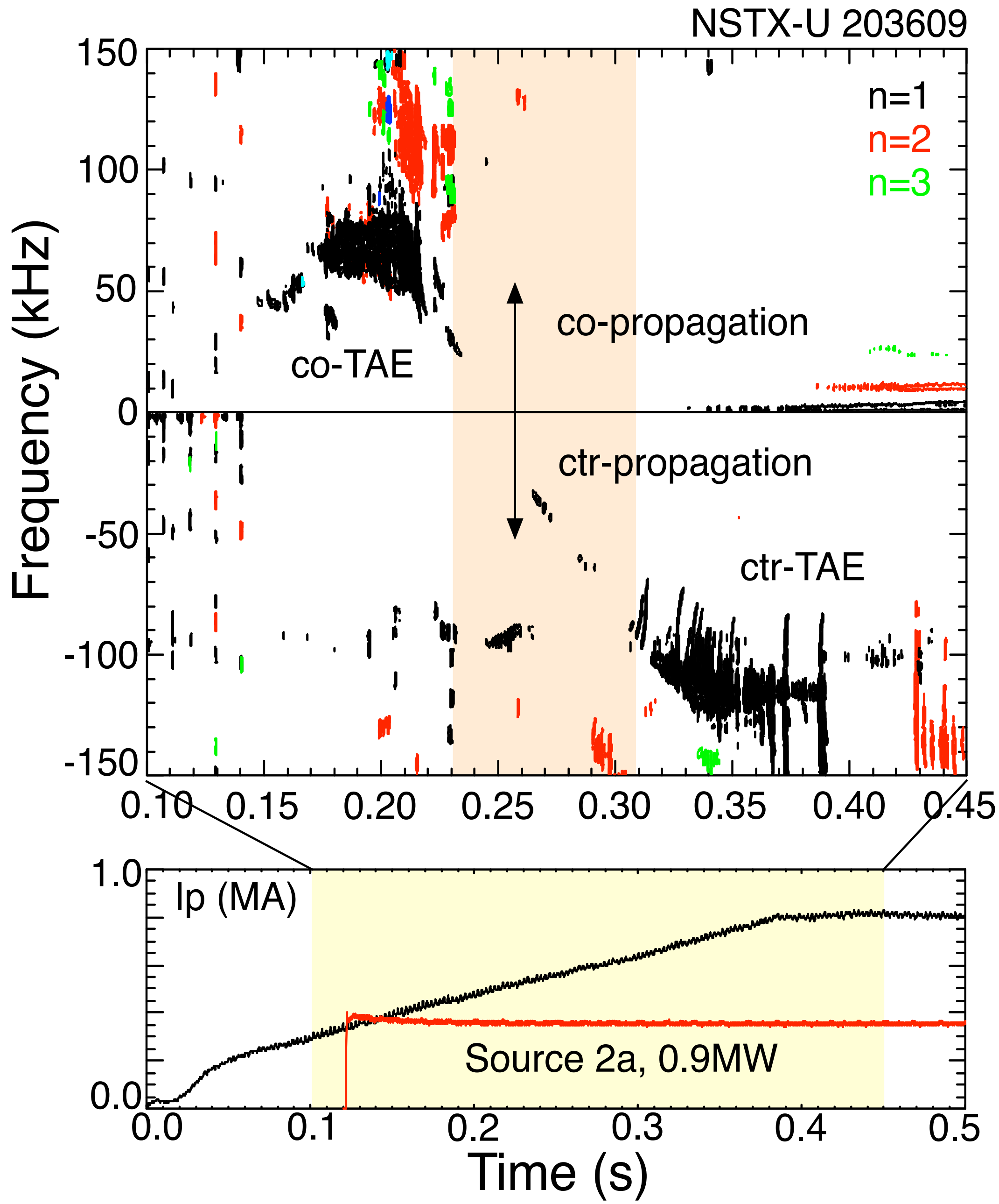
[Menard, NF 2012] *[Gerhardt, NF 2012]*

Complement previous studies in a small-aspect-ratio geometry with super-Alfvénic fast ions

- Large EP orbit width (mimic alphas in fusion reactor)
- Numerous AE resonances accessible by *super-Alfvénic* EP population

Counter-propagating TAEs are observed during co-NBI with deposition r/a~0.5

- Injection from NB source 2A, aimed at mid-radius (outboard)
- B_t~0.65T
- I_p~0.8MA (flat-top)
- $n_{e,i}$~2-3x$10^{19}$$m^{-3}$
- $T_{e,i}$~1keV
- P_{nb}<1MW
  - *Much lower than typical P_{nb} expected for routine NSTX-U operation*



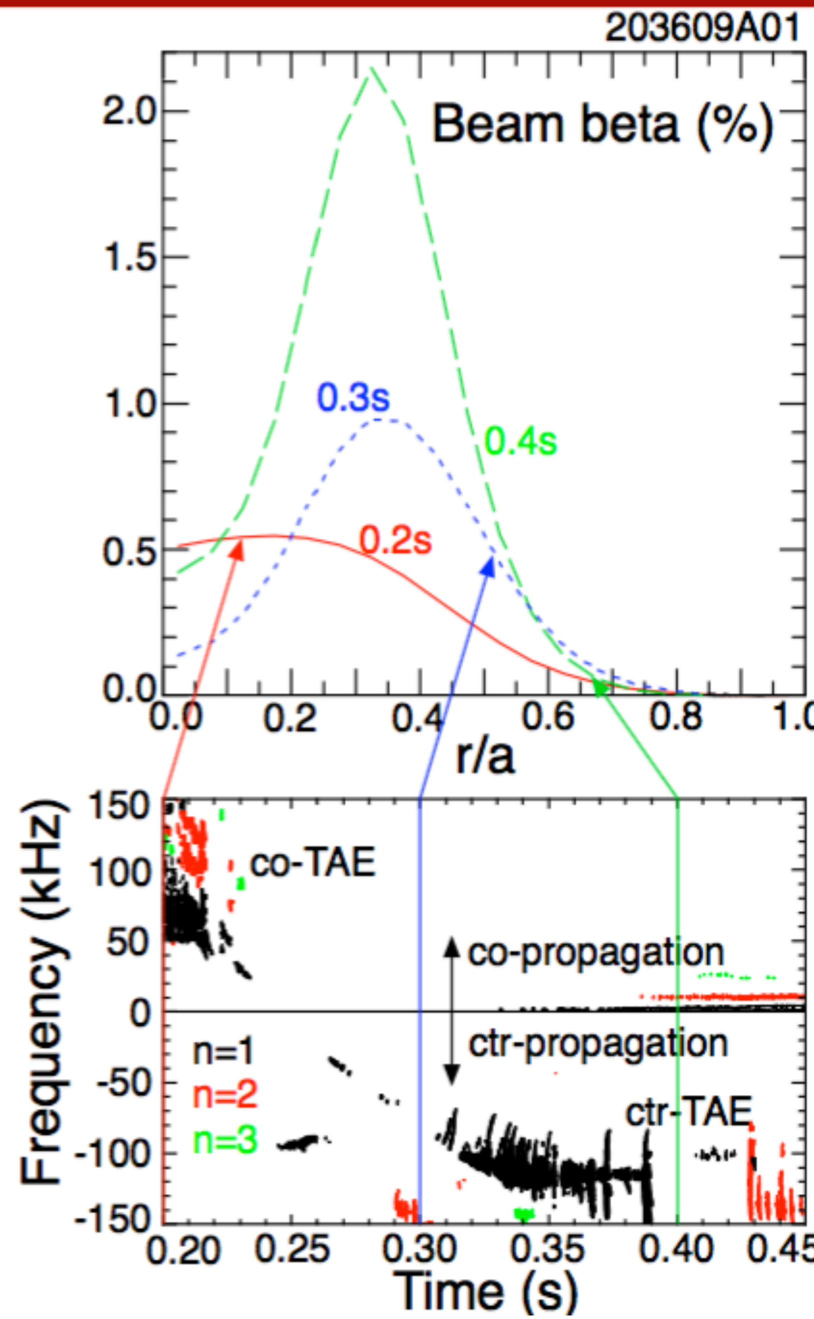
Simple explanation: cntr-TAEs correlate with hollow NB ion density profiles

- Reversed radial gradient of EP density favors drive of *cntr*-TAEs
- Similar effects predicted/ observed for inversion of *energy* gradient (NBI+RF)

[Wong, Phys. Lett. A 1999]
[Fredrickson, PoP 2000]

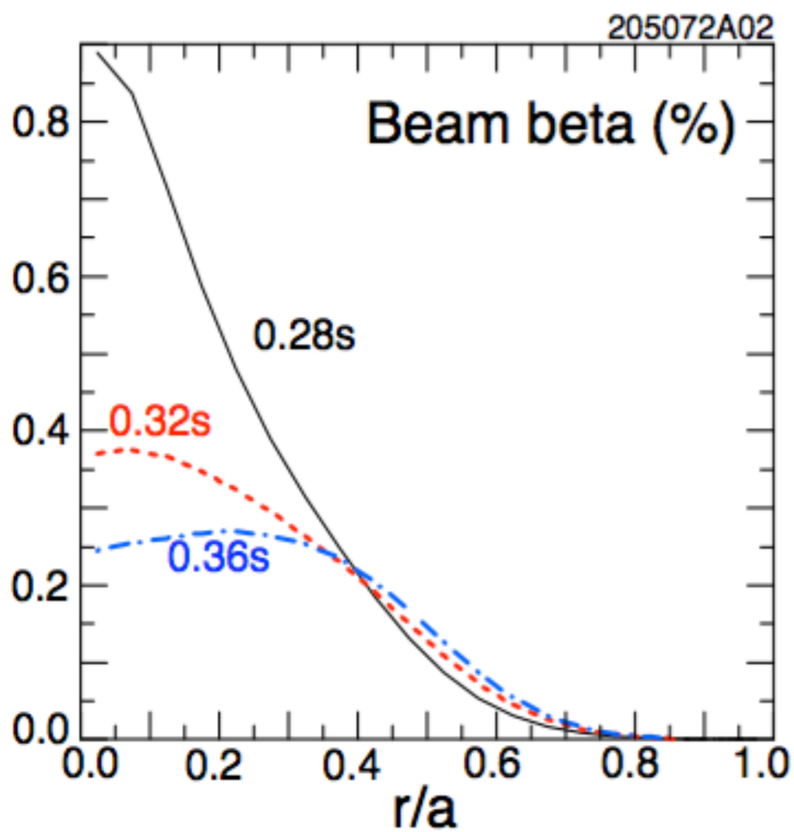
>*Is this the whole story?*

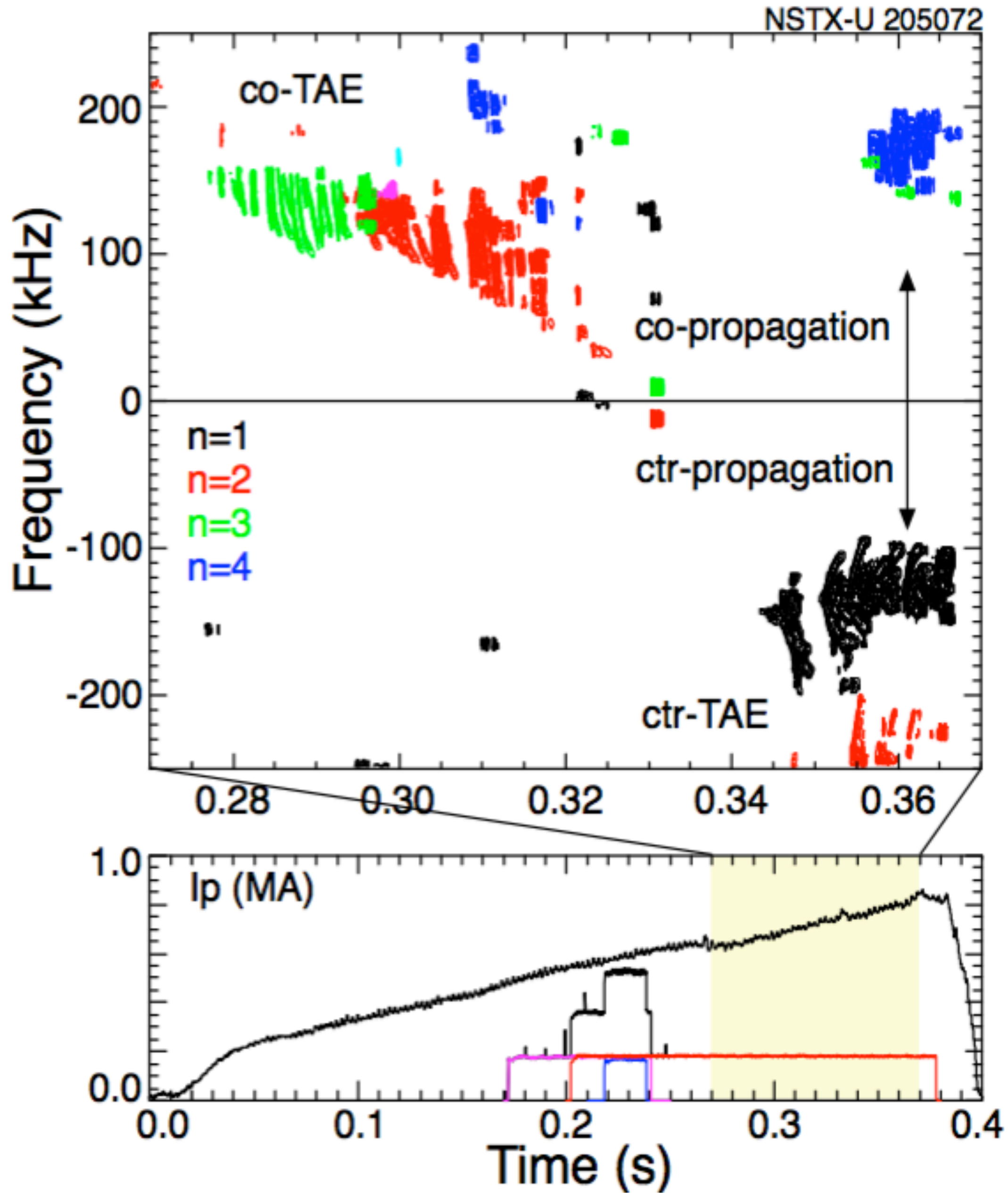
- *Cntr-TAEs also seen in NSTX-U discharges with ~flat central EP profiles!*



Experiments suggest a more complicated interpretation

Hollow EP density profile not always observed when cntr-TAEs are destabilized





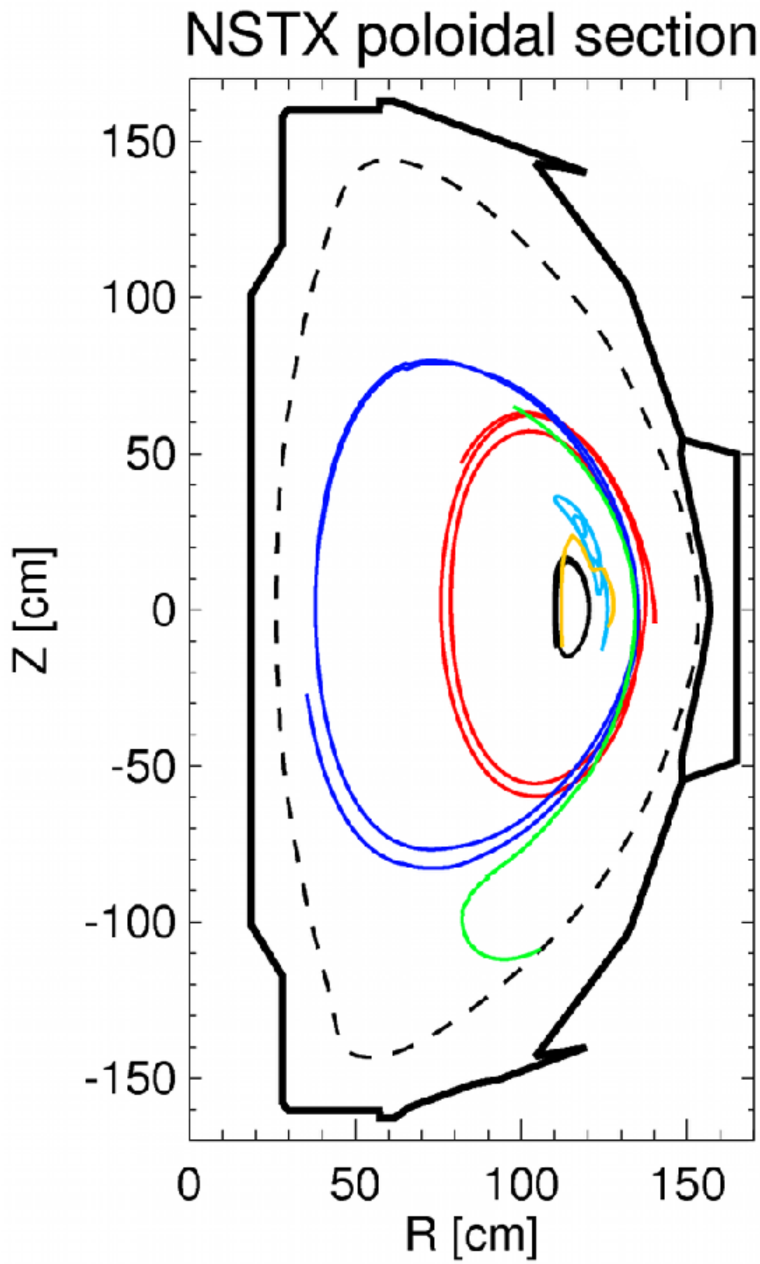
Conditions for destabilization of cntr-TAEs are explored via TRANSP analysis

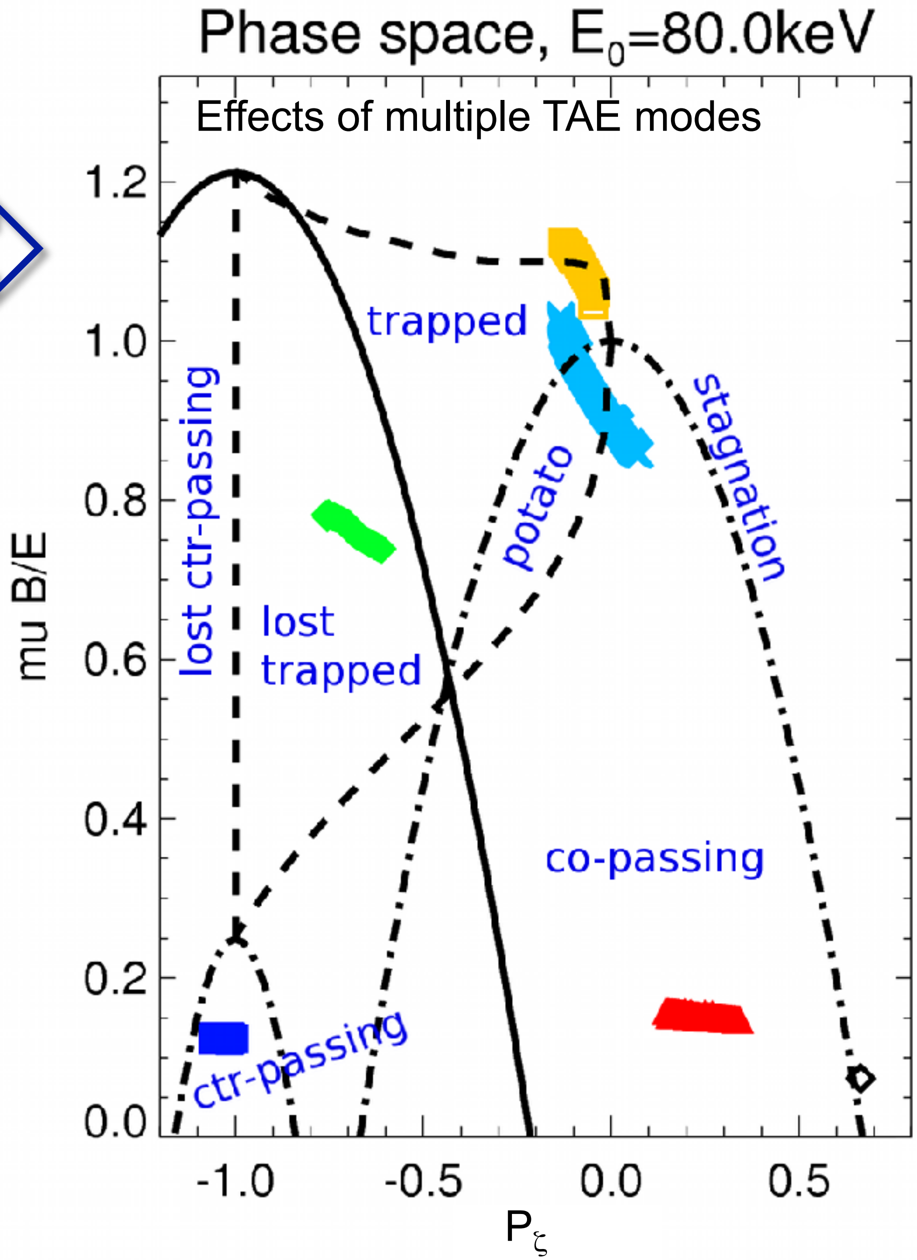
- TRANSP is a comprehensive code for integrated, time dependent simulations of tokamak discharges
- Its NUBEAM module is the work-horse for simulations including fast ions (NB injection, alphas)
  - "Classical" physics is assumed for fast ion evolution (e.g. scattering, slowing down)
- Additional modules can be invoked in NUBEAM to introduce non-classical fast ion transport

>Here we use the 'kick model' in NUBEAM to mimic enhanced fast ion transport by instabilities:

>Physics-driven, *phase space resolved* model

Constants of motion (E, P_ζ, μ) are the natural variables to describe wave-particle interaction





R. B. White, Theory of toroidally confined plasmas, Imperial College Press (2014)

ORBIT code used to infer "kick probability matrix" associated with each mode from NOVA

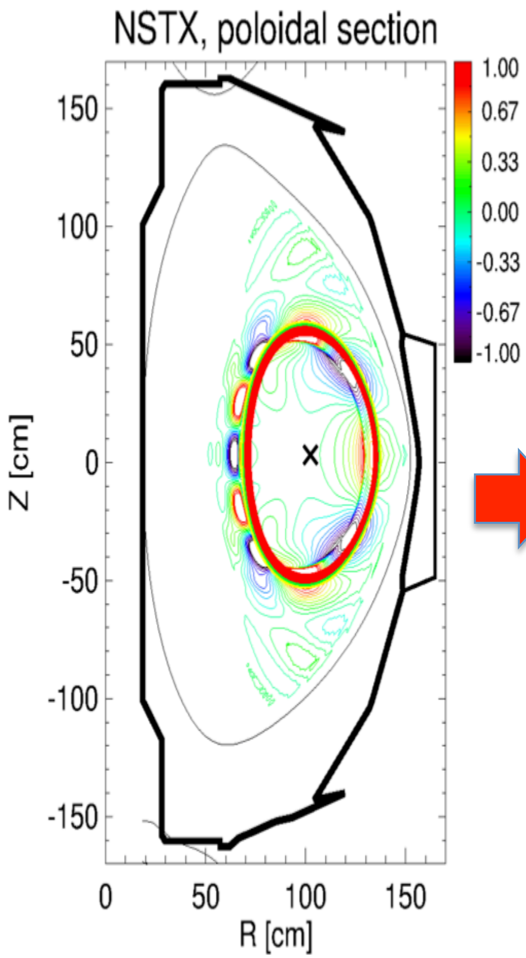
Initialize test particles uniformly in phase space

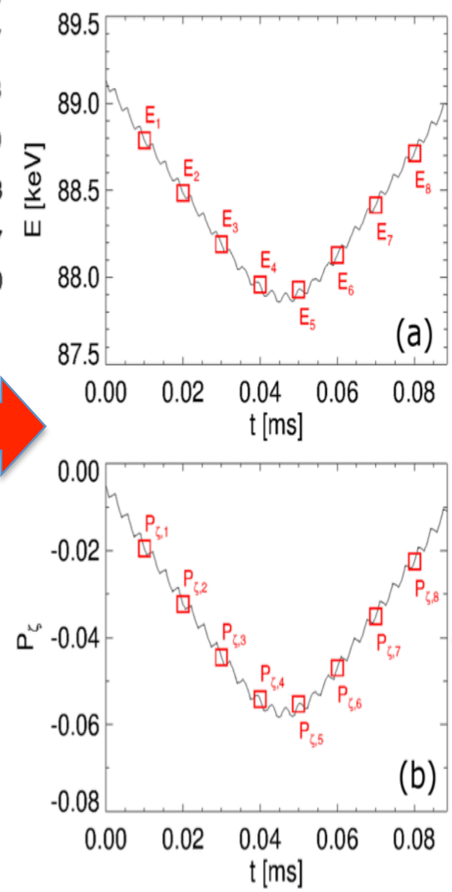
Record energy, P_ζ variations at fixed intervals

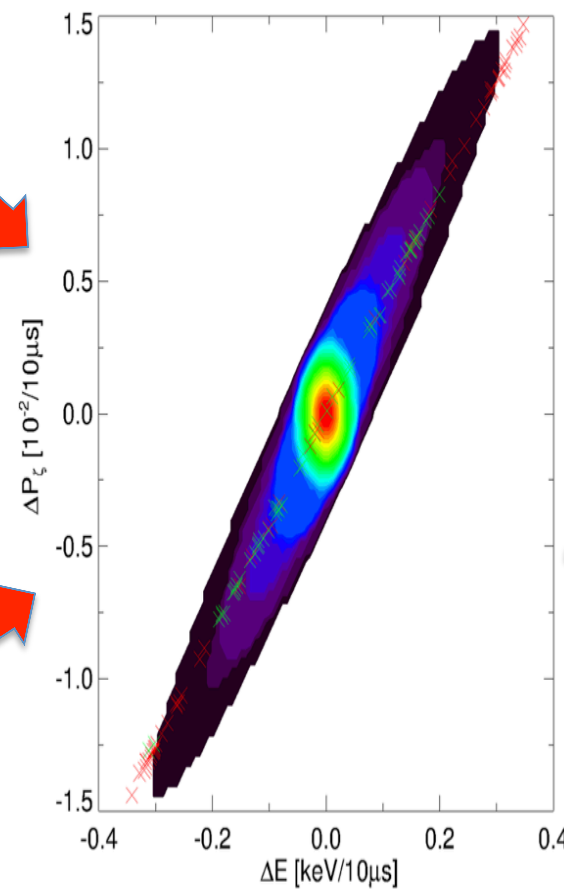
Combine E, P_ζ from same phase space *bin* into PDF

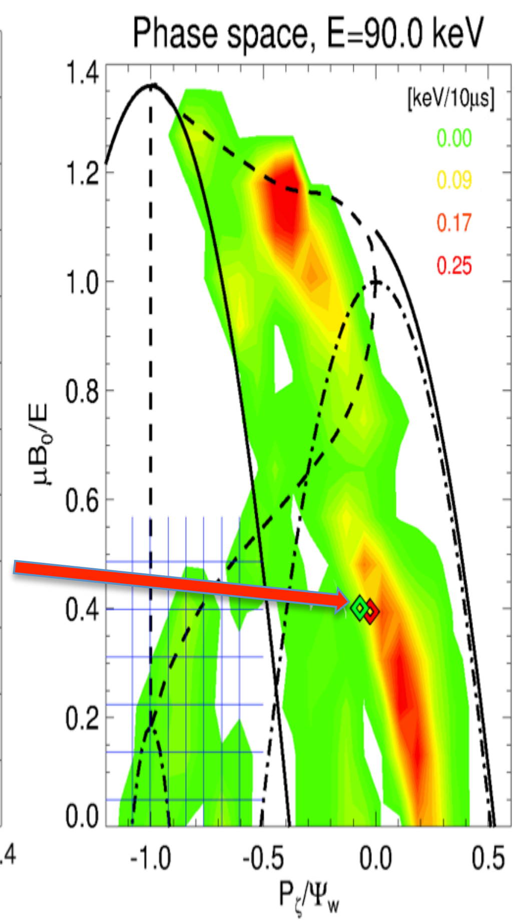
Repeat for all phase space *bins* to infer 5D matrix

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









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"

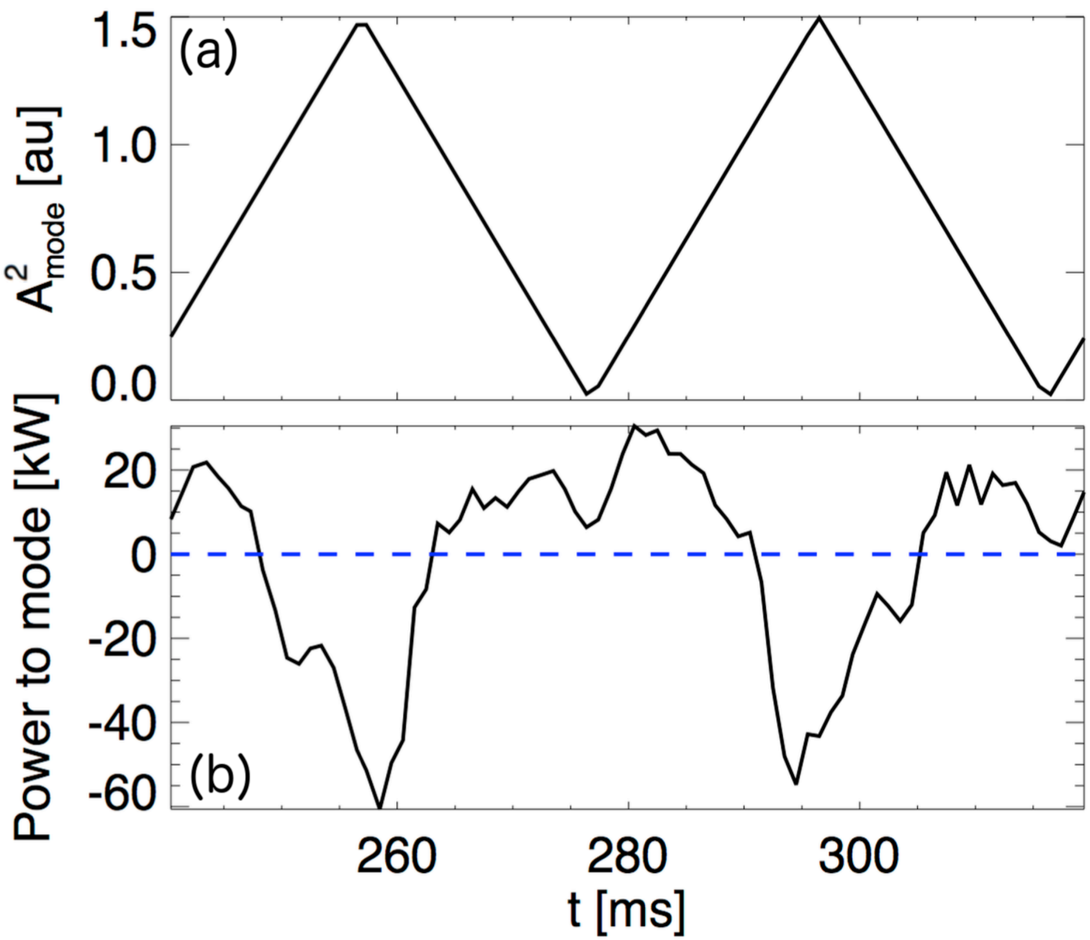
$$\Rightarrow \gamma_{eff,j} \approx 0\ ,\ P_{fi,j} \geq 0$$

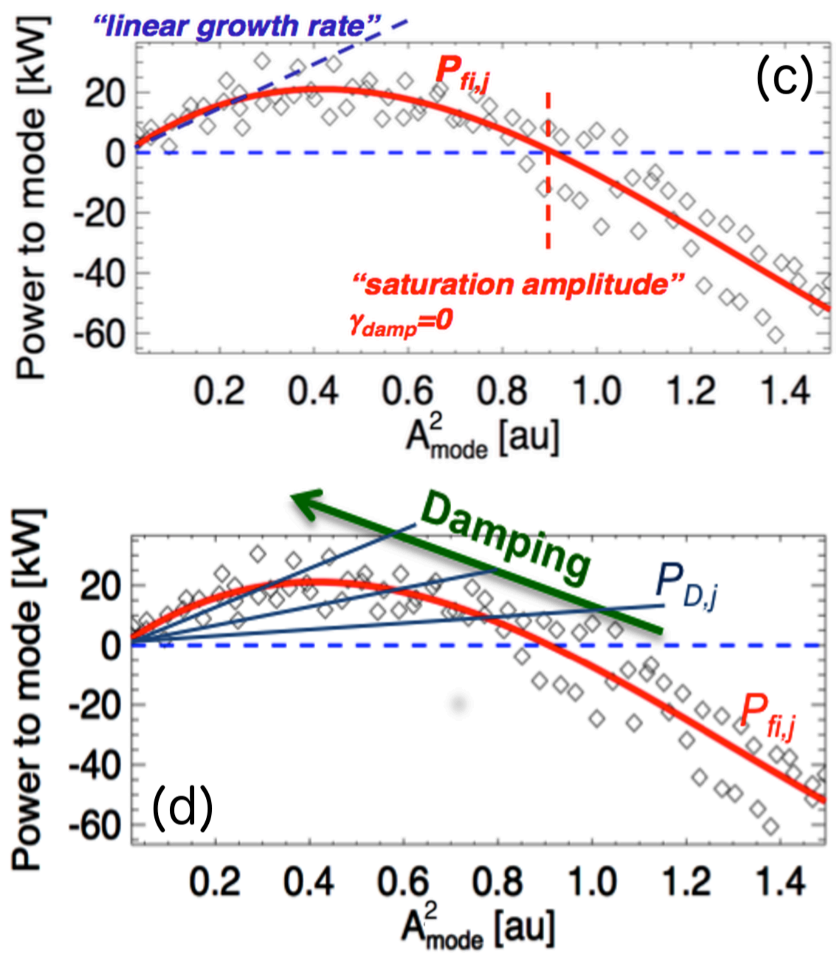
Condition at saturation

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

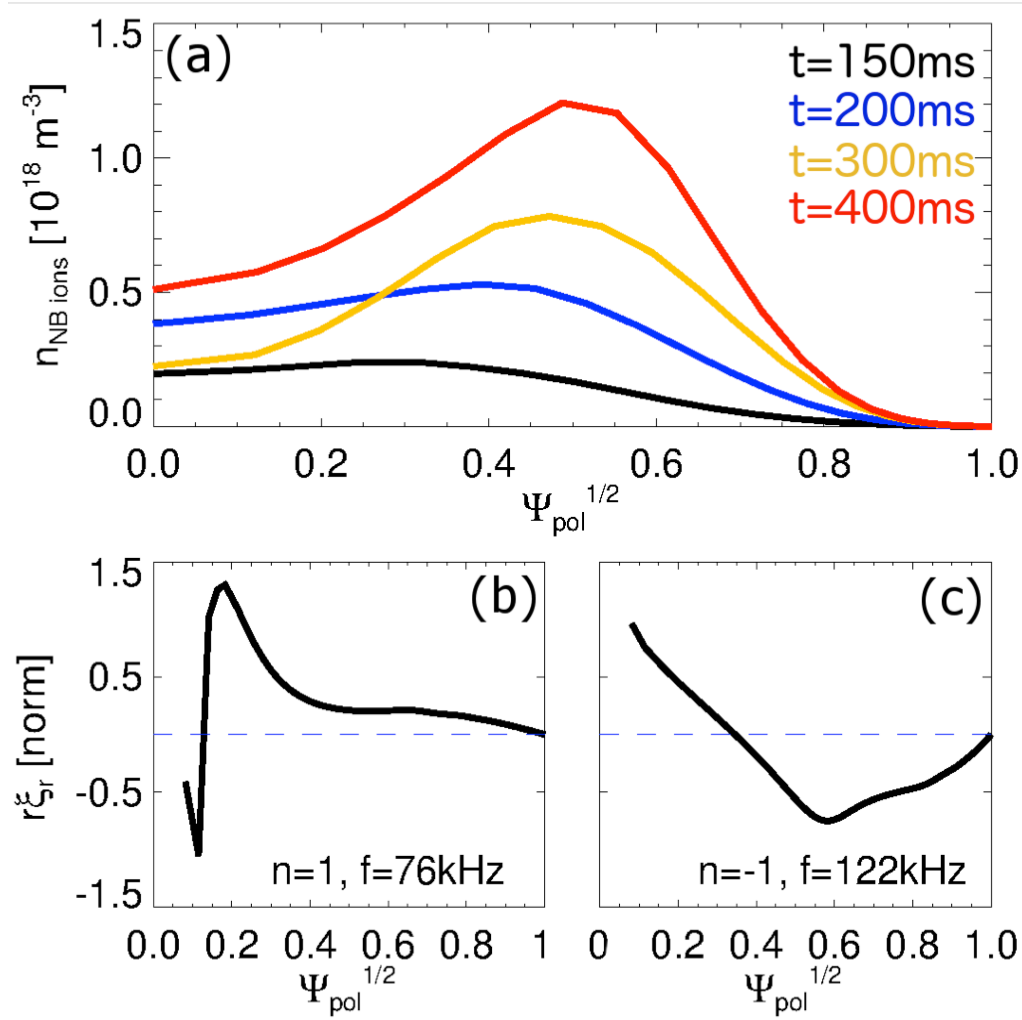
> infer "linear growth rate" & "saturated amplitude"



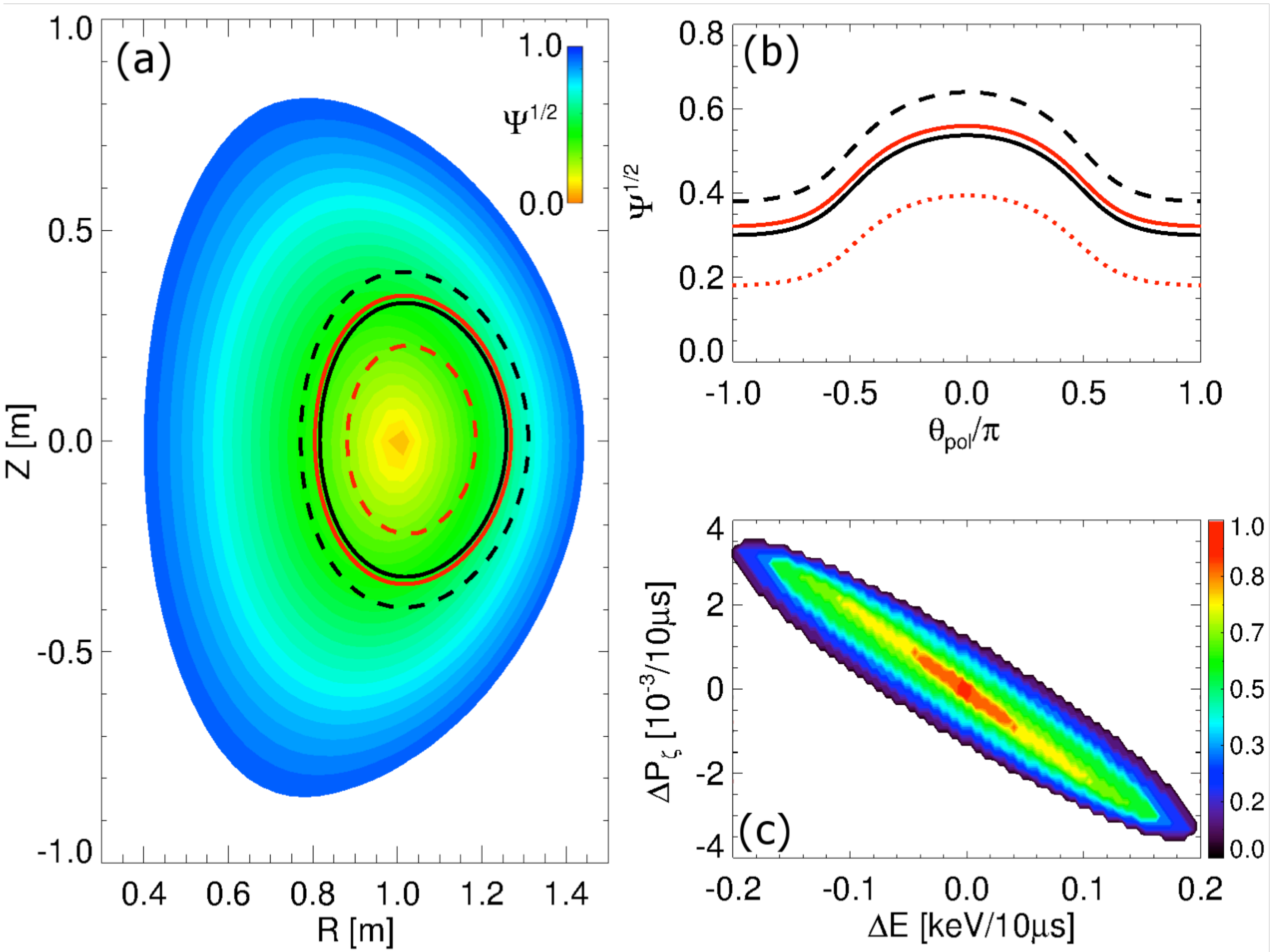


NOVA provides n=1 eigenmodes at two representative times (co- vs cntr-TAEs)

- First step: compute eigenmodes at time of max co- vs cntr-TAE activity
- Use ideal MHD code NOVA/NOVA-K
- Use experimental density, electron temperature profiles
- Assume $T_e \sim T_i$
- Assume rotation ~0 (!!)
  - No CHERS data available



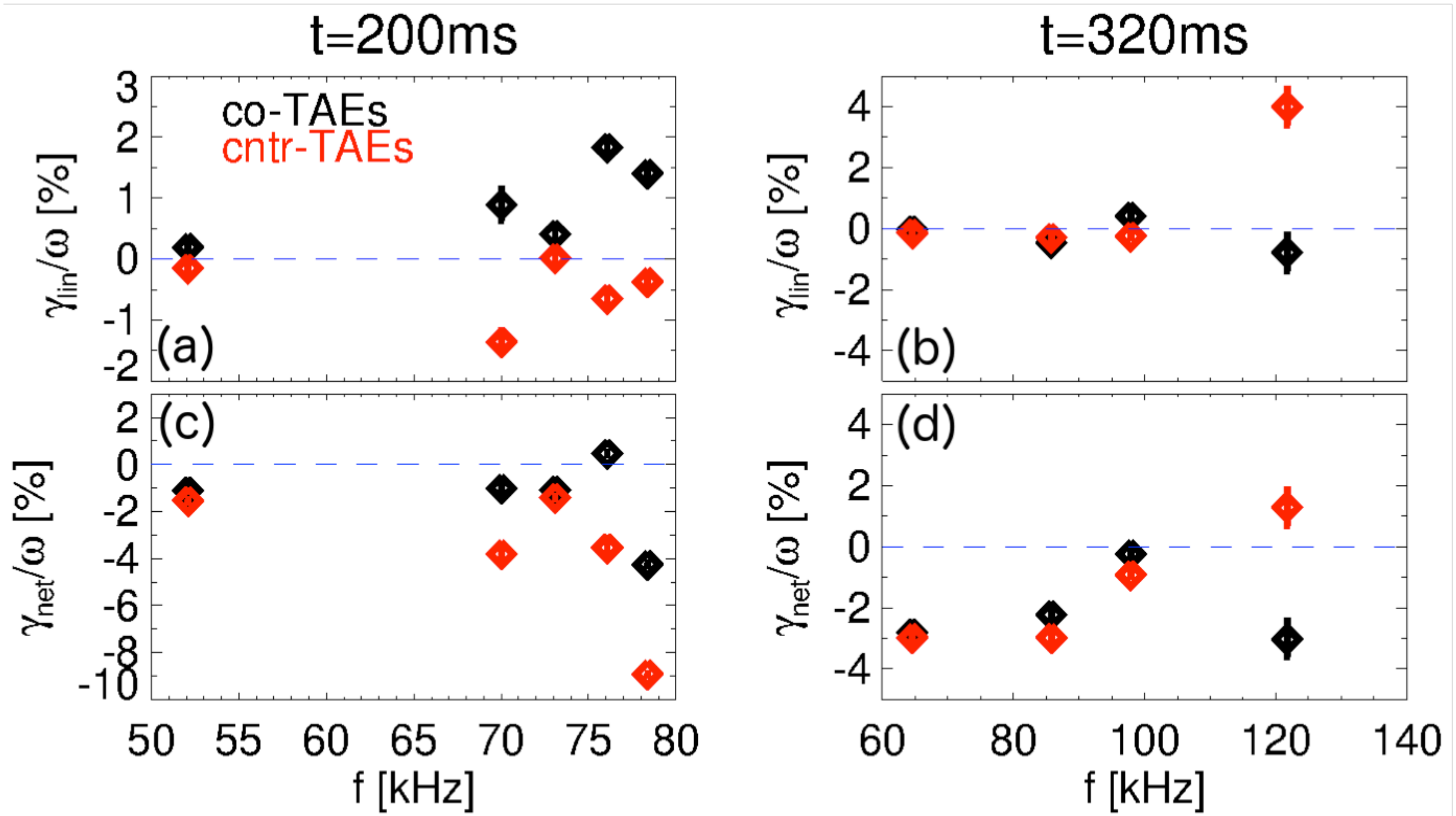
ORBIT code used to infer “kick probability matrix” associated with each mode from NOVA



- Account for large orbit width, small aspect ratio
- Mimic FLR corrections by averaging perturbation over $\Delta\rho \sim \rho_{L,i}$

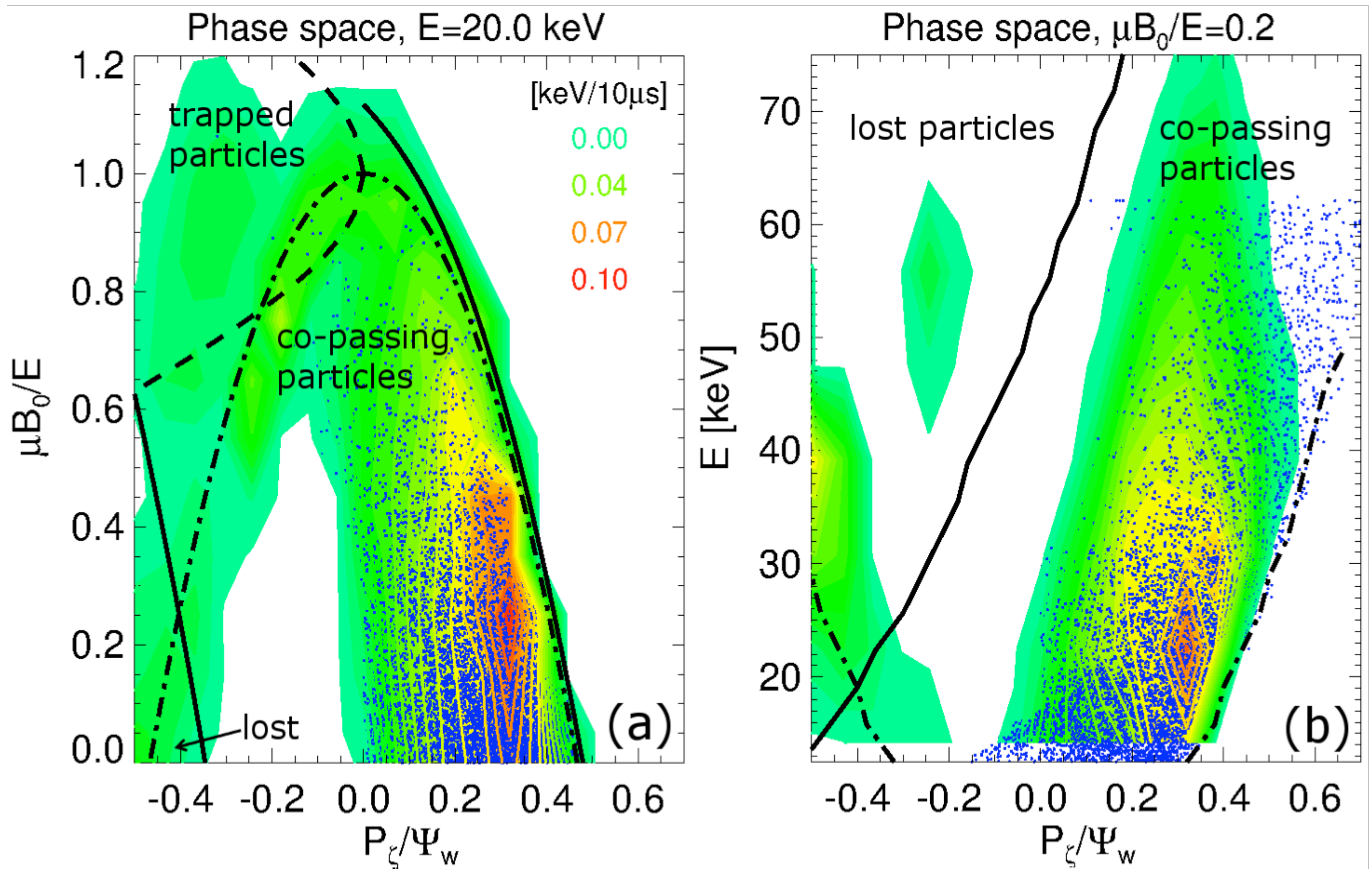
Kick model + damping rate from NOVA identifies two linearly unstable n=1 modes

- Run TRANSP + kick model with mode amplitude -> 0 to infer linear stability
  - *Use realistic EP distribution function, profile evolution*
  - Identify time range for validity of results based on evolution of "phase space boundaries"

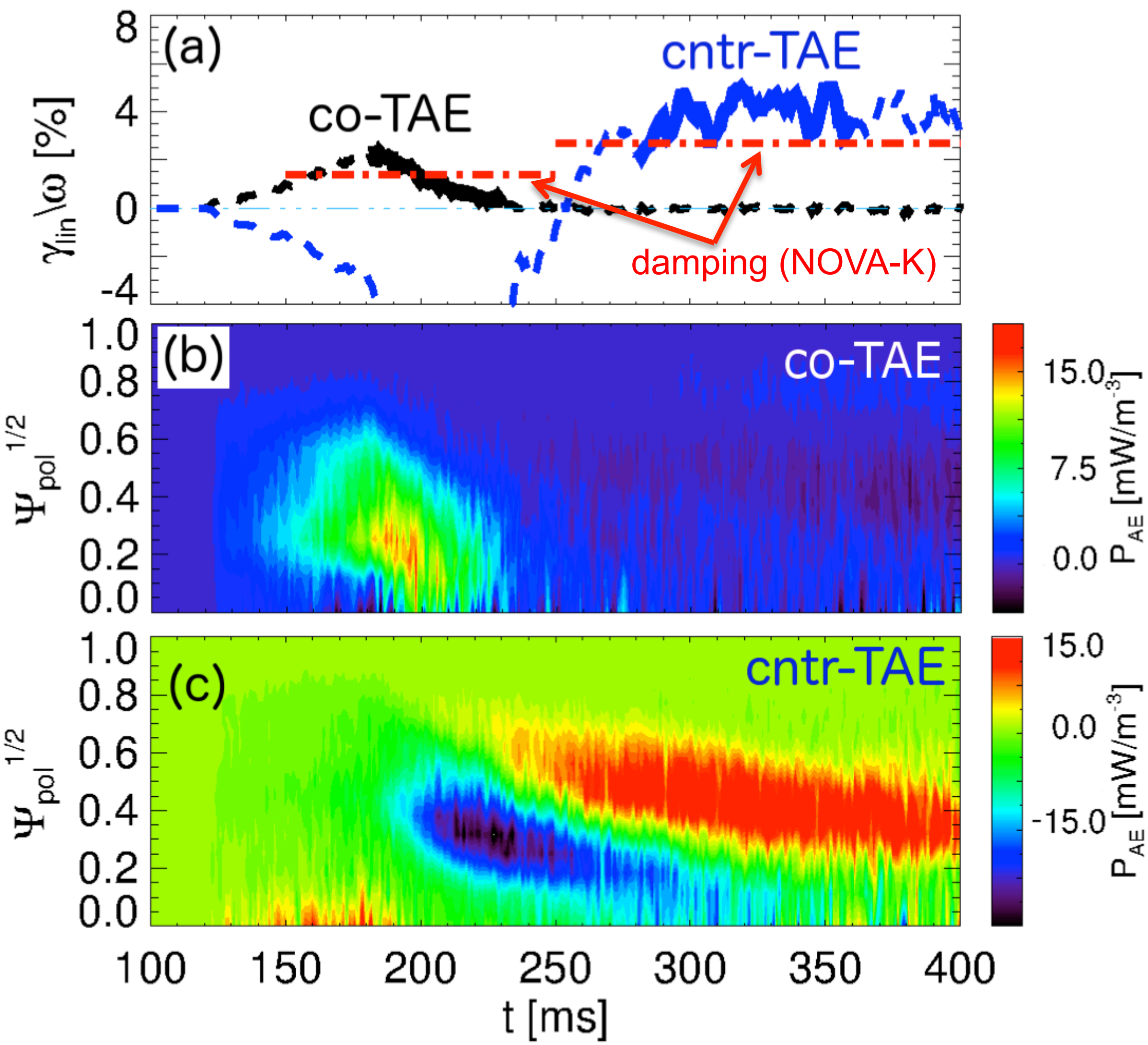


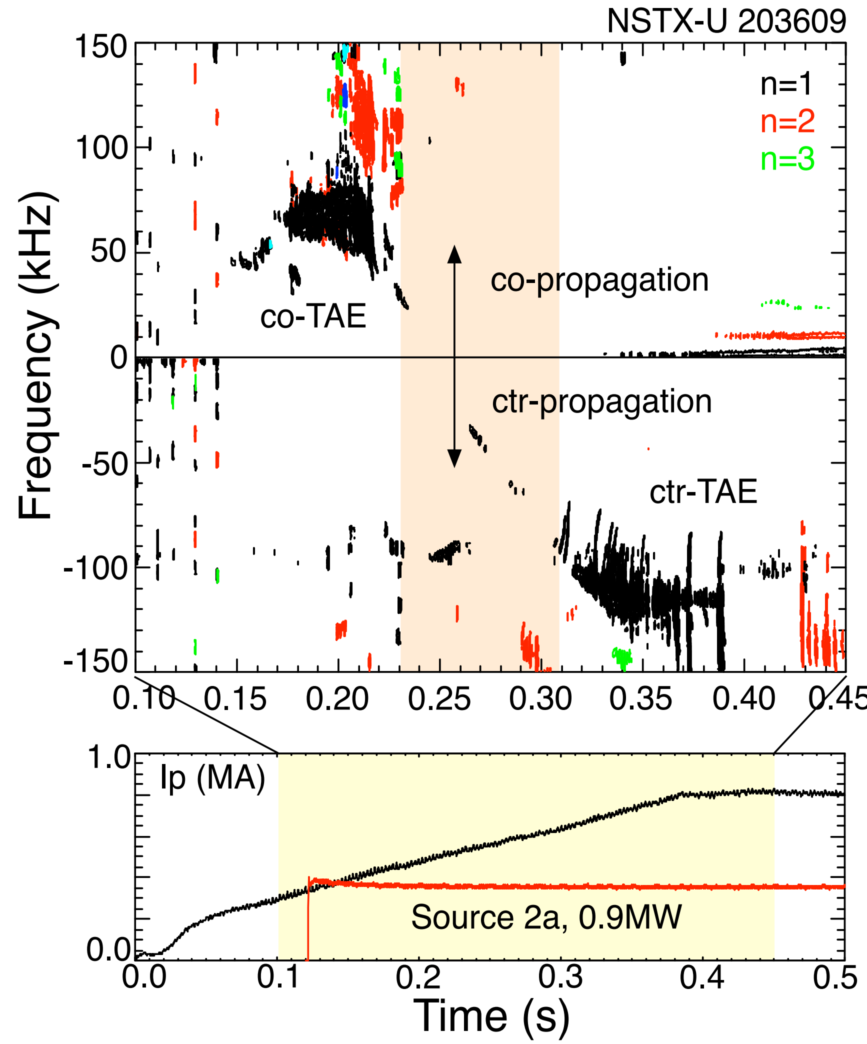
Unstable cntr-TAE has significant overlap with mode resonances for realistic F_{nb}

- EP distribution function from NUBEAM
  - Large variations of AE-induced EP transport in phase space



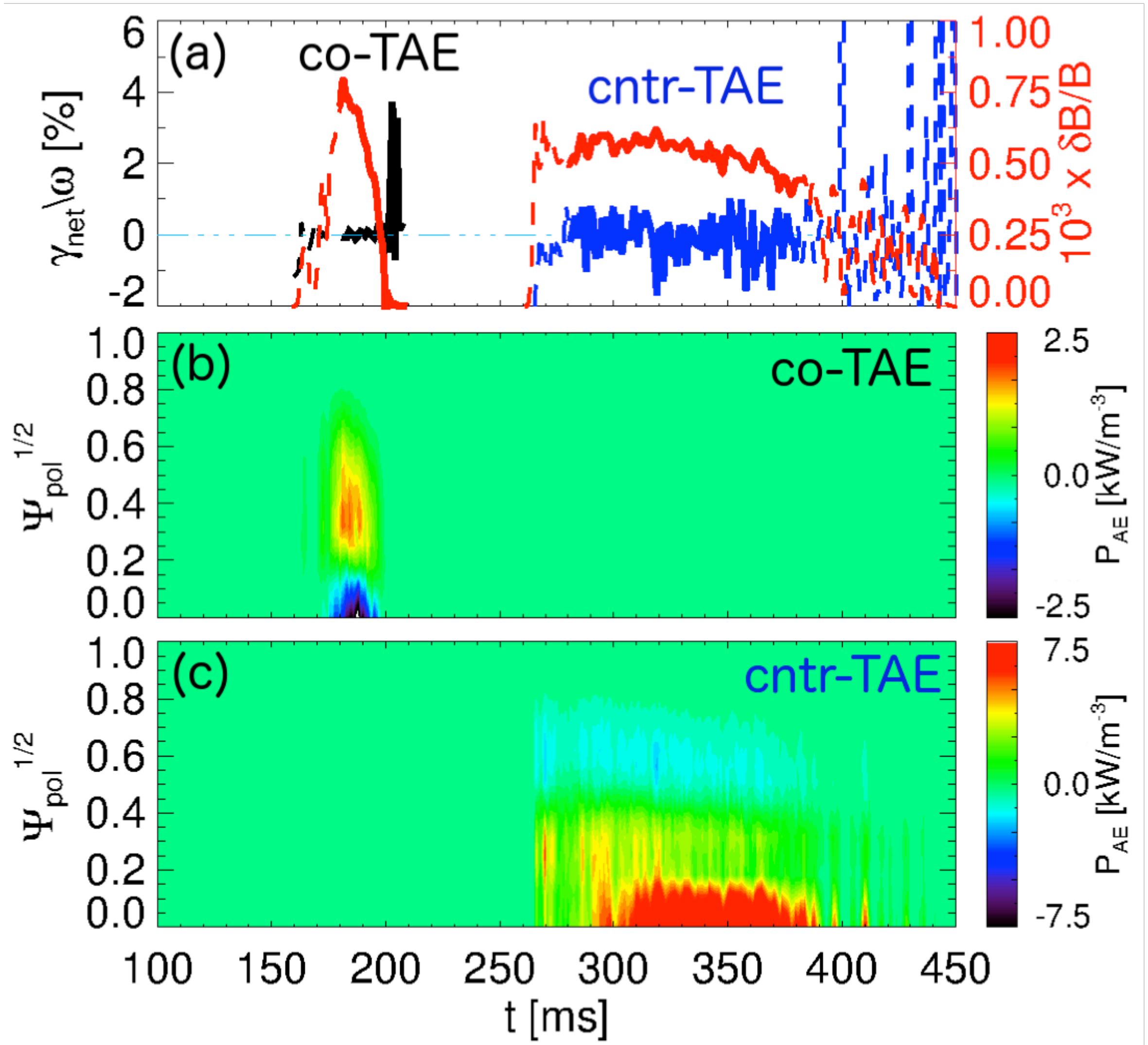
Linear stability vs time from kick model is roughly consistent with experiment





- Timing of most unstable |n|=1 modes nearly OK
- *Keep in mind: large uncertainties in (continuum) damping rate from NOVA-K*

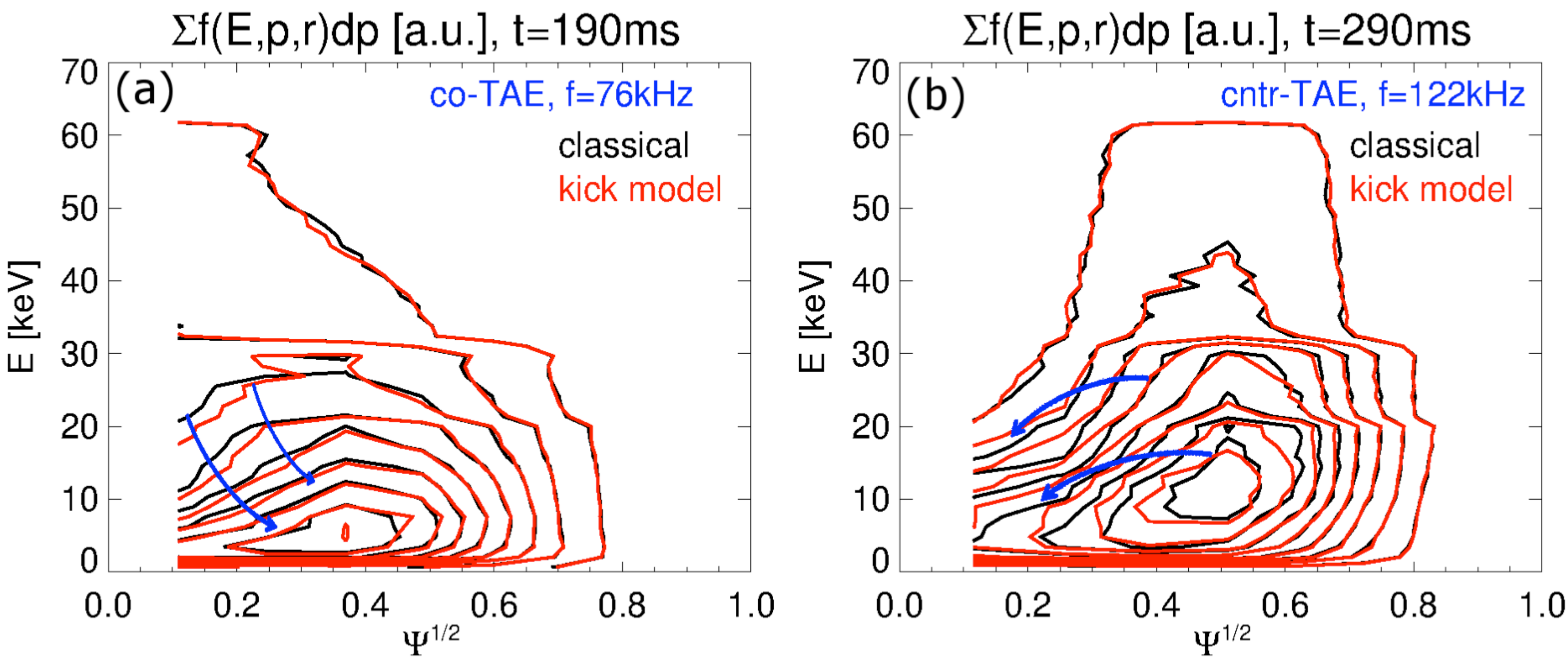
Saturation condition from kick model gives small amplitudes $\delta B/B<10^{-3}$



- Consistent with low injected NB power
- No direct measurements of mode amplitude available

TRANSP computes substantially different effects from co- vs cntr-TAEs

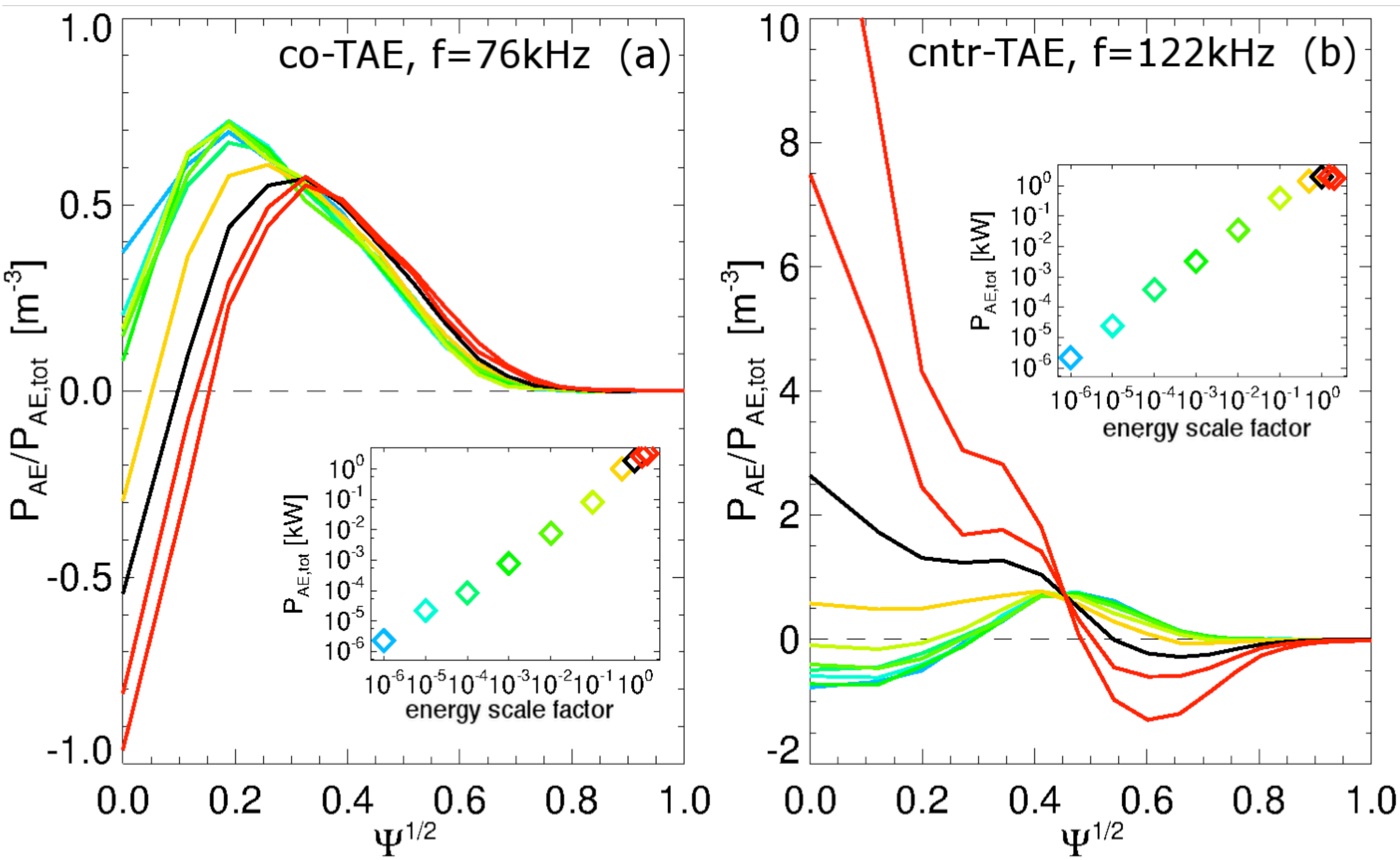
- Co-TAE: flatten EP density profile, move particles outward
- Cntr-TAE: flatten EP density profile, move particles *inward*



Wave-particle interaction near saturation differs considerably from "linear" phase

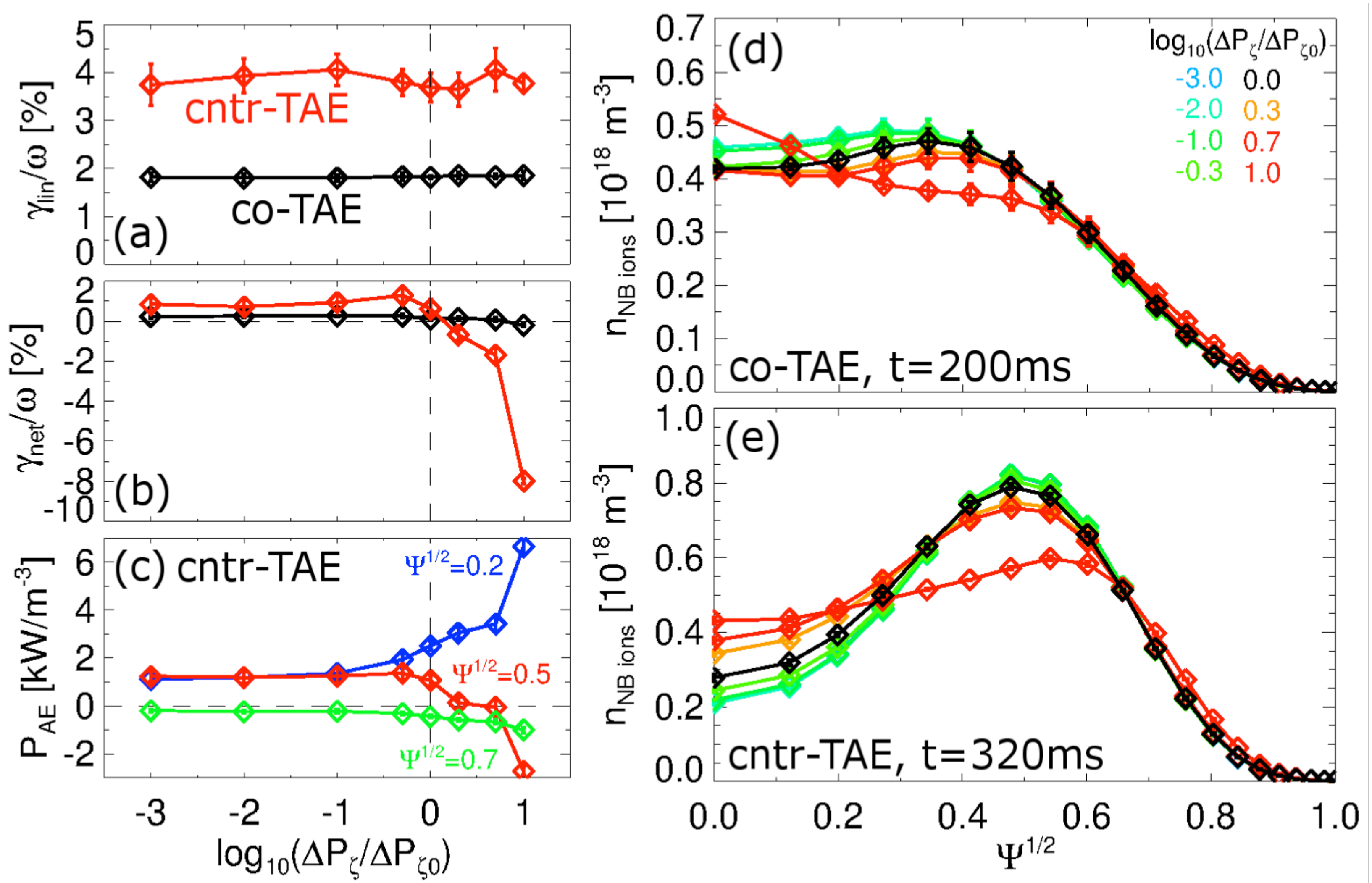
- "Linear" phase not representative of what modes will do once they grow to finite amplitude

> *Can't use linear growth rates to estimate/project transport in saturated phase*



TRANSP + kick model shows competition between gradients in EP phase space

- EP distribution from NB injection has complex phase space dependency
  > Both P_ζ (~"radial") and energy gradients are important to assess mode's linear stability & saturation amplitude



Summary

- Counter-propagating TAEs can be *destabilized* by co-injected, off-axis NBI
- TRANSP + kick model analysis recovers main experimental observations
  - Transition from co- to cntr-TAEs during current ramp
- TAE drive is a combination of phase space gradients
  - Drive may be enhanced by combined NBI+RF (e.g., ITER)
  - Instability already observed at low P_{nb}~1MW
  - Relevant for scenarios with limited flexibility in NBI deposition (e.g. ITER)
  - Relevant for current ramp-up scenarios assisted by NB-CD
  - Points to limitations of reduced models solely based on "universal drive" by EP density gradient