NSTX-U

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Initial predictions of linear TAE stability in NSTX-U

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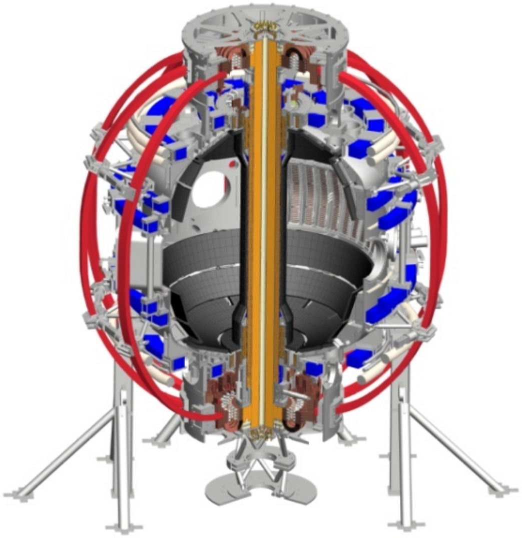

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Abstract

A second Neutral Beam (NB) injection line is being installed on the NSTX Upgrade device, resulting in six NB sources with different tangency radii available for NB heating and current drive. Optimization of NSTX-U discharges toward high performance requires an accurate knowledge of the NB driven current, especially when the behavior of the injected NB fast ions deviates from classical predictions. In particular, Toroidal Alfven Eigenmodes (TAE) destabilized by fast ions are known to affect NB driven current by inducing fast ion redistribution and loss. This work explores the linear stability of TAE modes for NSTX-U scenarios with various NB injection geometries, from more perpendicular to more tangential. Initial predictions, based on linear stability analysis through the ideal MHD code NOVA-K, are presented. For the scenarios considered in this work, TAE are marginally stable, with ion and electron Landau damping representing the dominant damping mechanism. Because of the higher magnetic field in NSTX-U (up to 1T) with respect to NSTX, the spectrum of less stable modes is likely to shift to higher toroidal mode numbers, peaking at n=5-8. Limitations of the model used for this study, such as an over-simplified treatment of plasma rotation, are also discussed.

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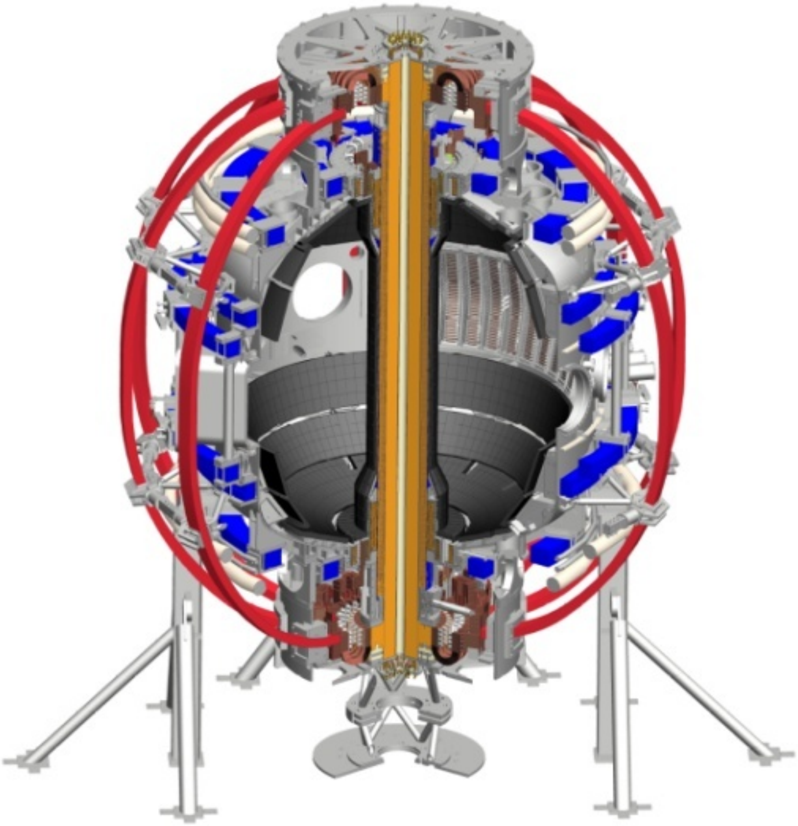
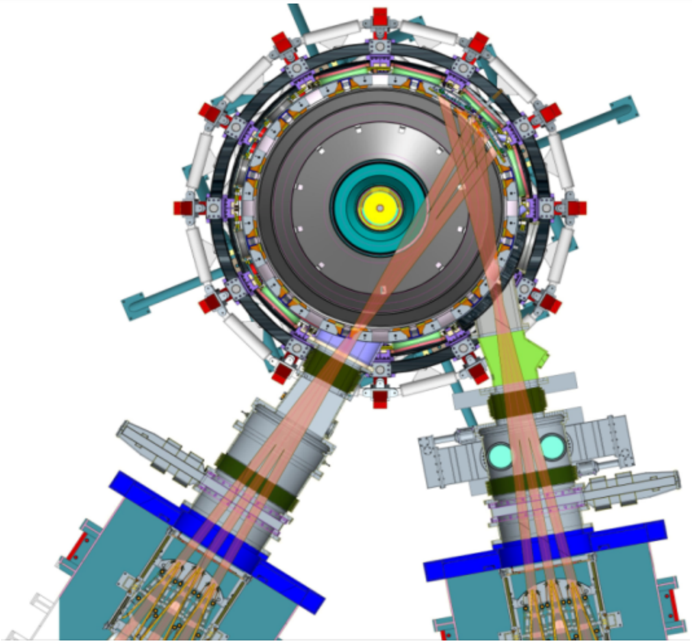
NSTX Upgrade : double plasma current, toroidal field & injected NB power; pulse length extended to ~5 sec.

Major radius [m]	0.85	0.9
Aspect ratio	1.3	1.5
I_{plasma} [MA]	<1.3	2
B_{tor} [T]	<0.55	1
Pulse length [s]	<2	5

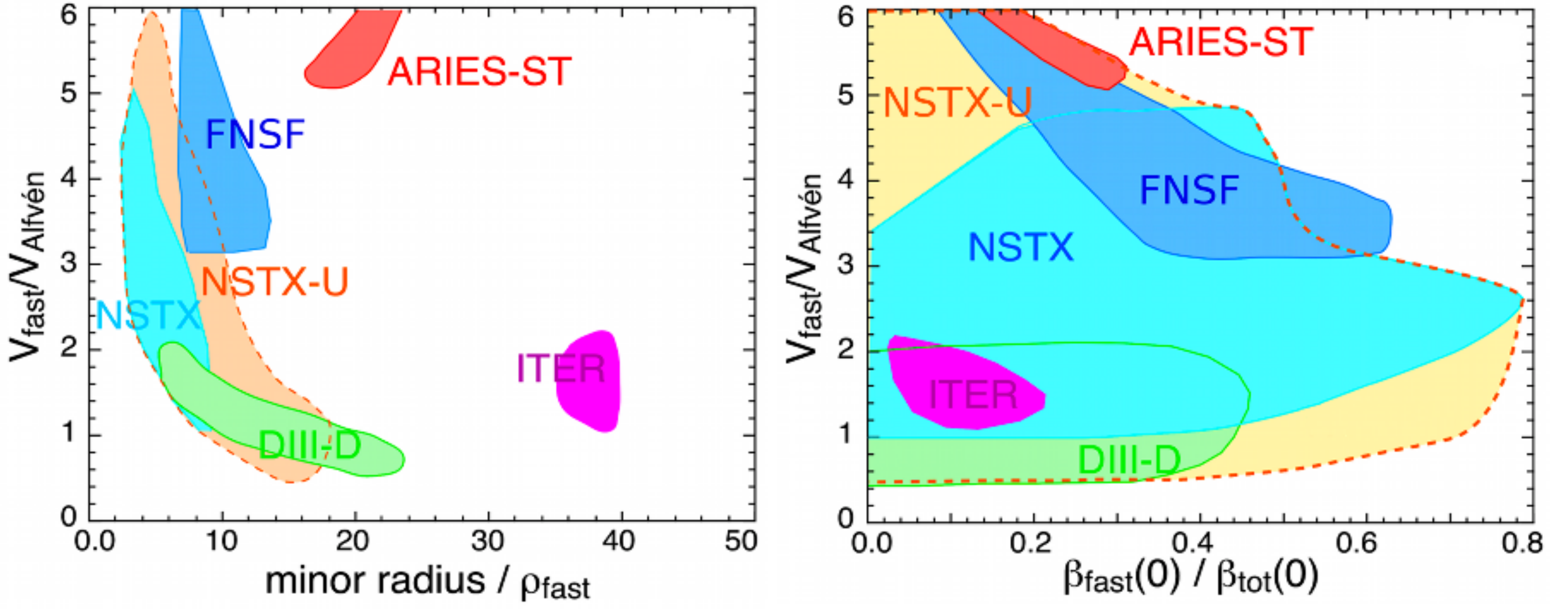


NB sources	3	6
P_{NBI} [MW]	≤ 7	≤ 14
$E_{injection}$ [keV]	≤ 95	
	$1 < v_{fast}/v_{Alfvén} < 5$	



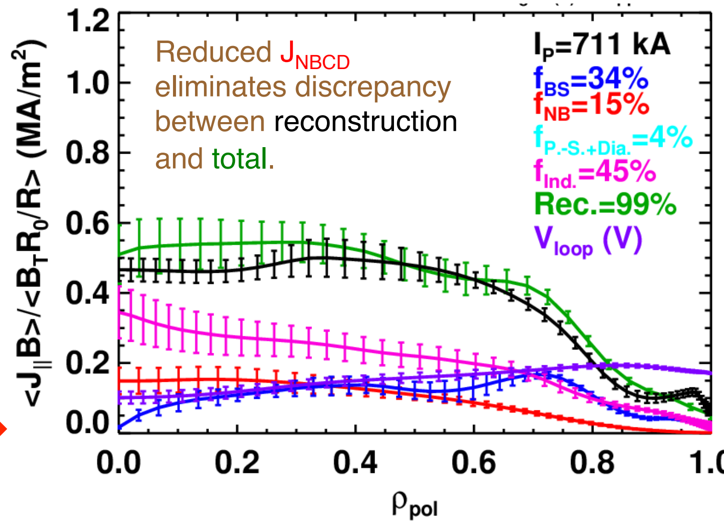
Present NBI New 2nd NBI

Parameter space for Energetic Particle Research on NSTX-U encompasses regimes relevant for ITER, FNSF



- Upgrade broadens achievable range of $v_{fast}/v_{Alfvén}$, ρ_{fast}/a, β_{fast}/β_{tot}
- TAE modes can be destabilized

> **Effect on NB driven current, overall performance?**



Reduced J_{NBCD} eliminates discrepancy between reconstruction and total.

S. P. Gerhardt et al., NF (2011)

Linear MHD analysis is used for initial predictions of linear stability of TAE modes in NSTX-U

- NOVA code used to compute linear Toroidal Alfvén Eigenmodes for given plasma profiles
  - Profiles from TRANSP simulations
  - See S. P. Gerhardt et al., NF 2012 for details on NSTX-U scenarios
- Kinetic (-K) post-processor calculates stability terms for given fast ion distribution function
- Back-of-the-envelop estimates:

$$k_\perp \rho_f \sim 1 \Rightarrow \frac{nq}{a}\frac{v_f}{\omega_{cf}} \sim 1$$
$$\Rightarrow n \sim B \Rightarrow n = 2 - 10$$

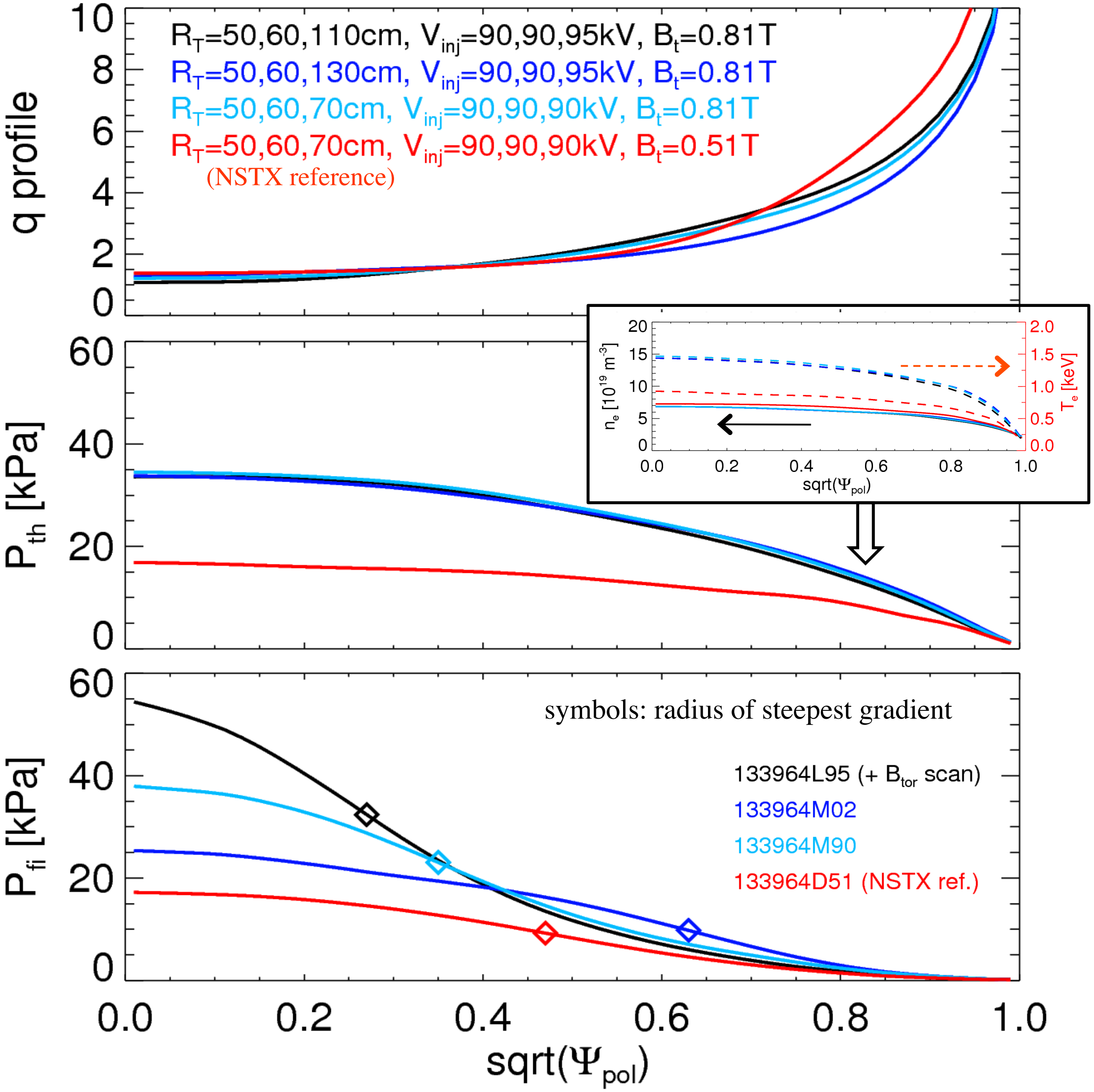
Expect up-shift of toroidal mode number with higher B_t
Broad spectrum possible because of large v_f

TRANSP code provides relaxed equilibria for NSTX-U; study scenarios with similar thermal profiles, different NBI parameters

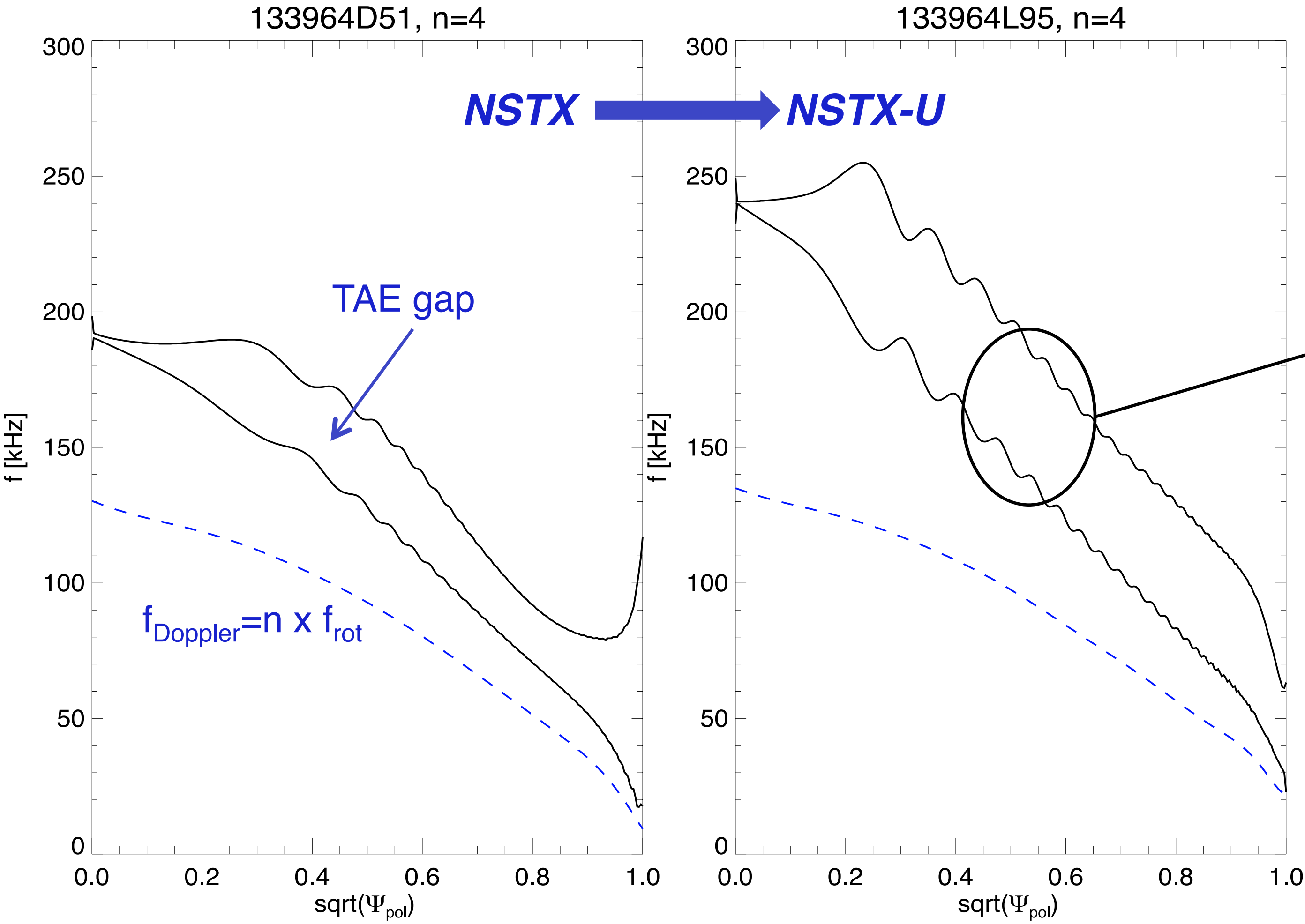
- Limit $B_t \leq 0.8$ T
  - First 2 years of NSTX-U operations
- Keep injection energy ~constant
- Vary NBI tangency radii combination

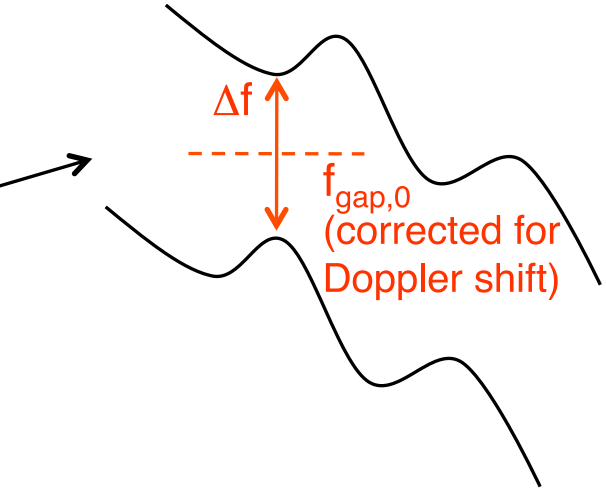
> Reasonable match for q(R), P_{th}

> Broad range of P_{fi} profiles



TAE gap is broader for NSTX-U scenarios, consistent with 0th-order scaling for gap frequency & width

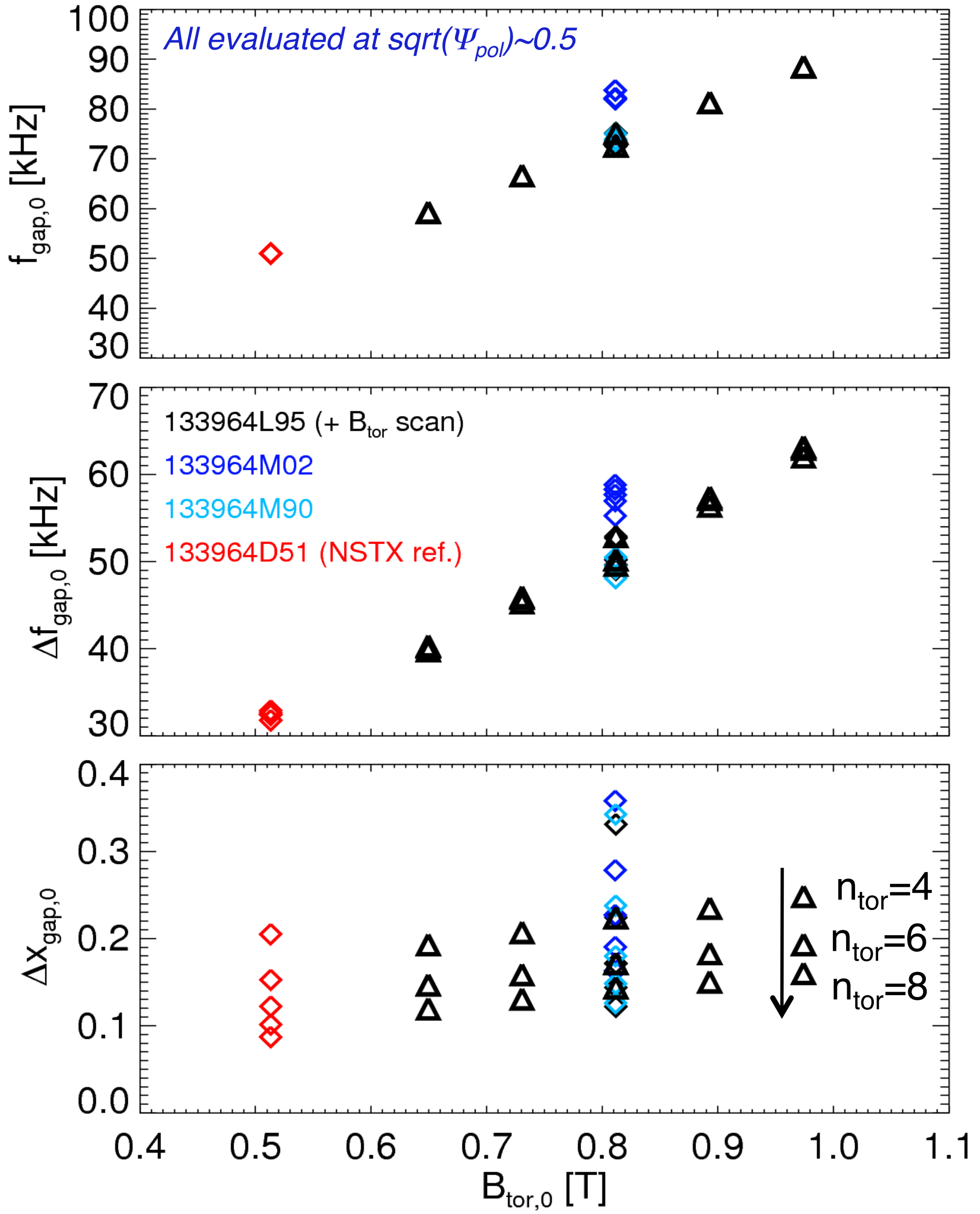


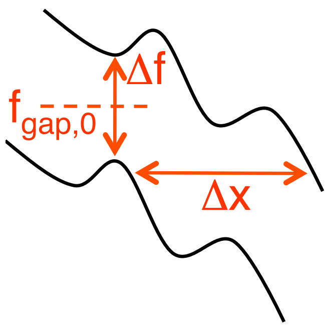


Higher B_{tor}, similar density:

- $f_{gap,0} \sim v_A/4\pi qR \sim B/n^{1/2}R$ ↗
- Δf/f~a/R (inv. aspect ratio) ↔

Scaling of TAE gap center frequency & width indicates higher mode frequencies as B_t is increased





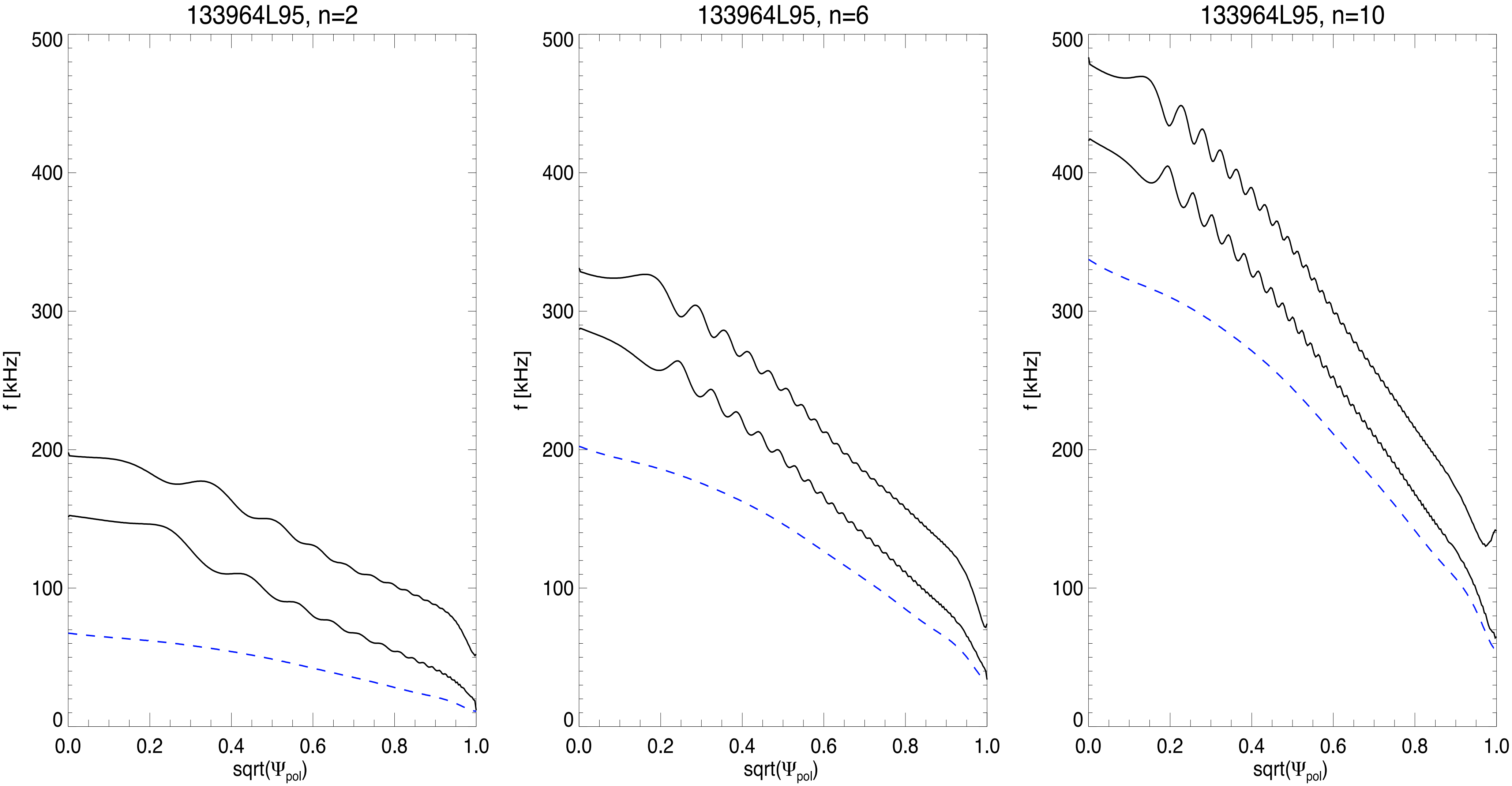
$f_{gap,0} \sim v_A/4\pi qR \sim B/n^{1/2}R$

$\Delta f_{gap,0}/f_{gap,0} \sim a/R$ (inv. aspect ratio)

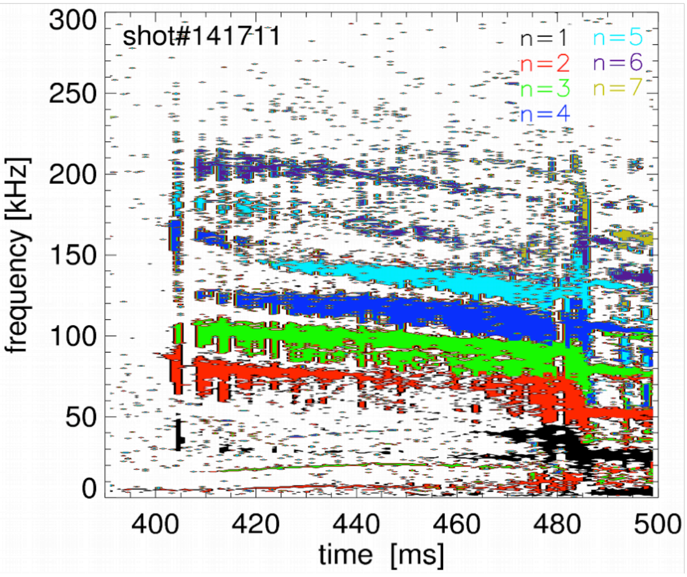
$\Delta x_{gap,0}$: radial "width"

- Look at f_{MHD} *in the plasma frame*
  - Correct for Doppler shift
- 40% increase in center gap frequency when B_t doubles
- Radial width of TAE gap also increases (slightly)
  - Broader mode structures?
  - Enhanced fast ion transport?

On average, Doppler shift alters the radial gap width: broader modes found as rotation decreases



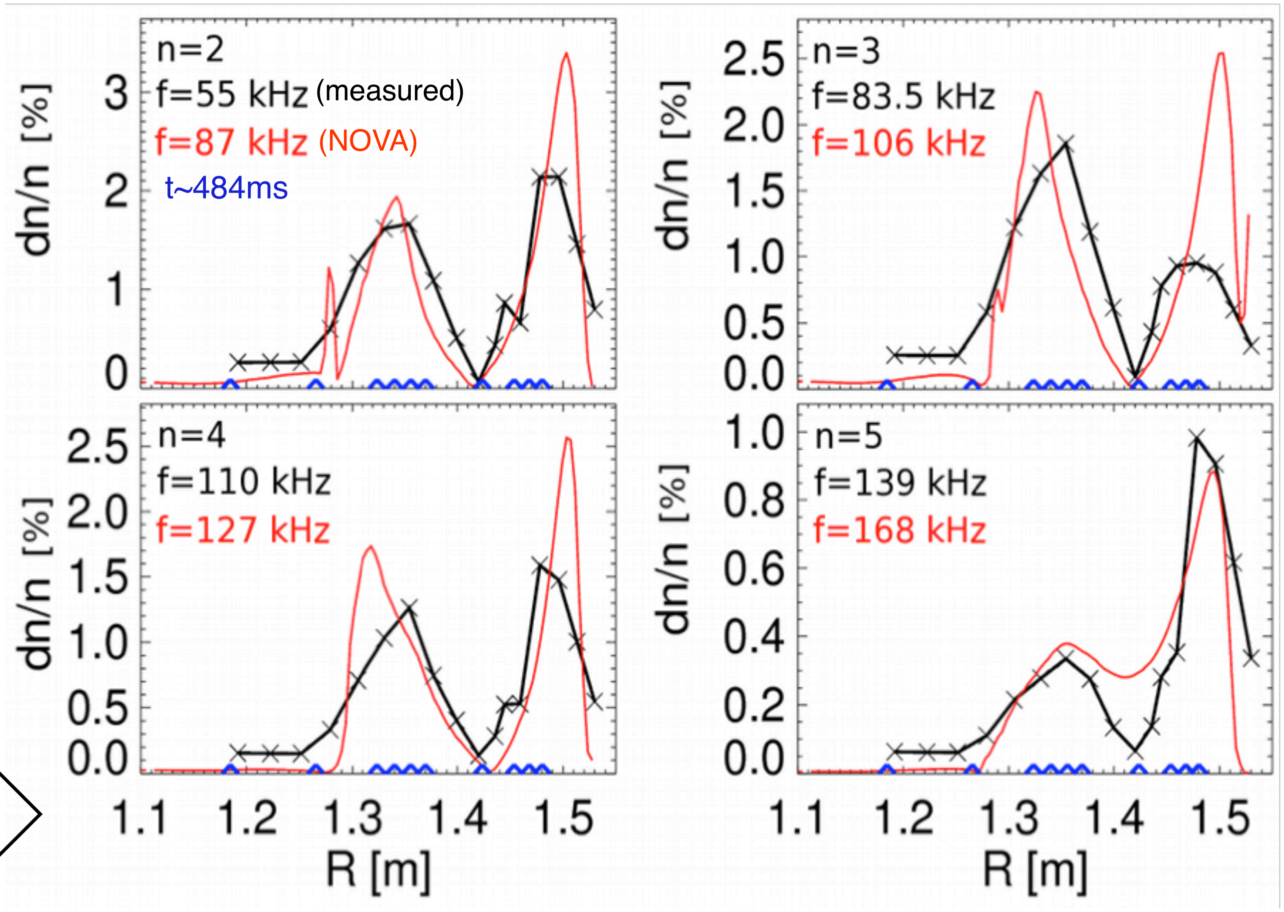
Mode structure analysis with NOVA has been validated against reflectometer data on NSTX



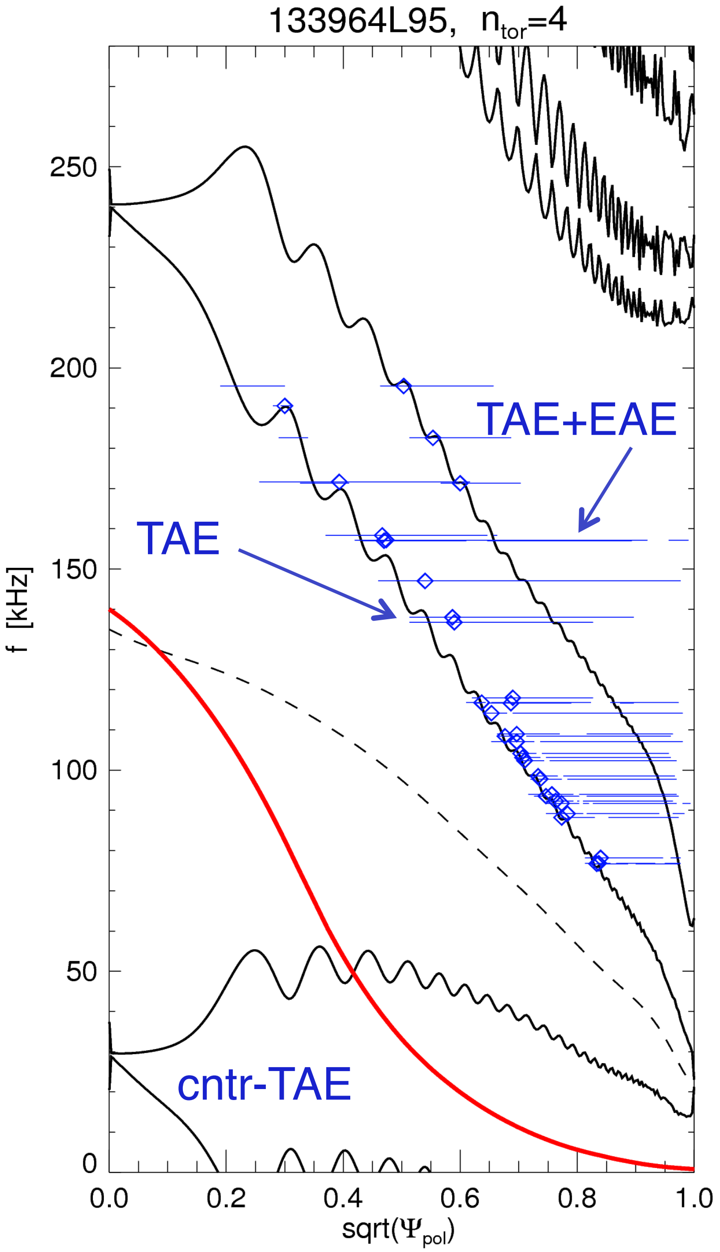
M. Podestà et al., NF (2012)

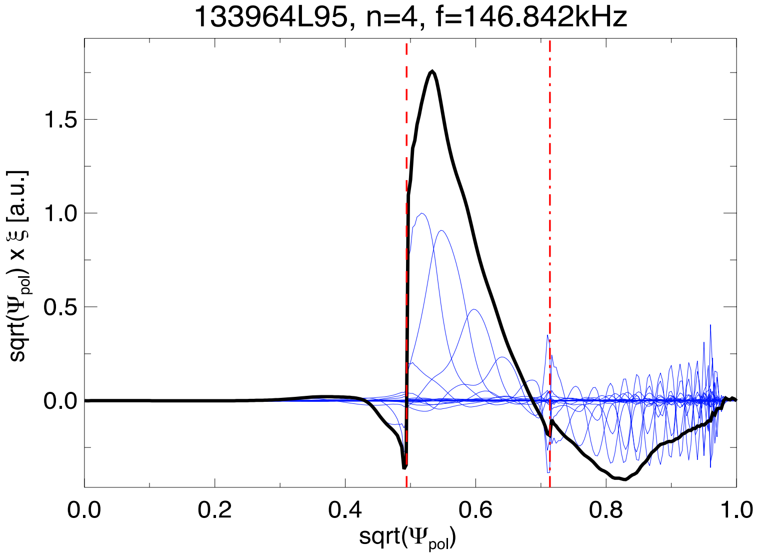
Example: discharge with multiple bursting TAE and TAE *avalanche*

- Simulate reflectometer's response to NOVA eigenmodes
- Look for best match with "reasonable" frequency agreement

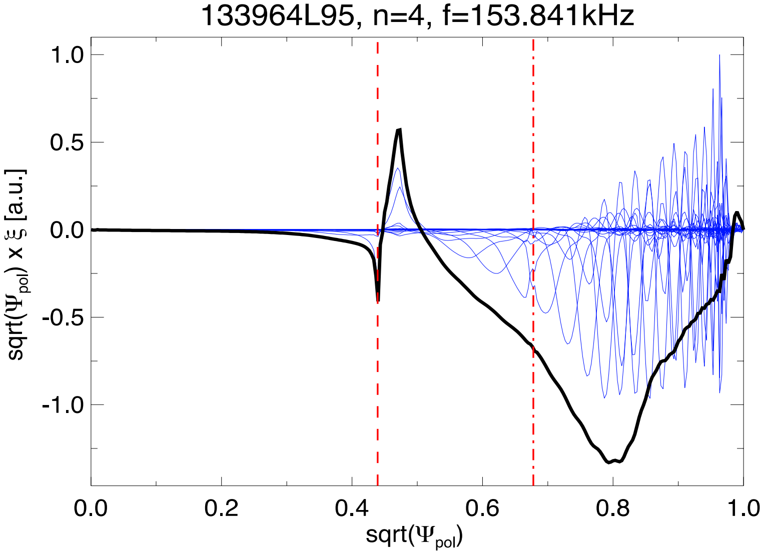


Modes classified into three types: TAE, Doppler shifted cntr-TAE, TAE+EAE





Some modes are well localized inside the TAE gap : proper TAEs (perhaps minor harmonics outside gap)

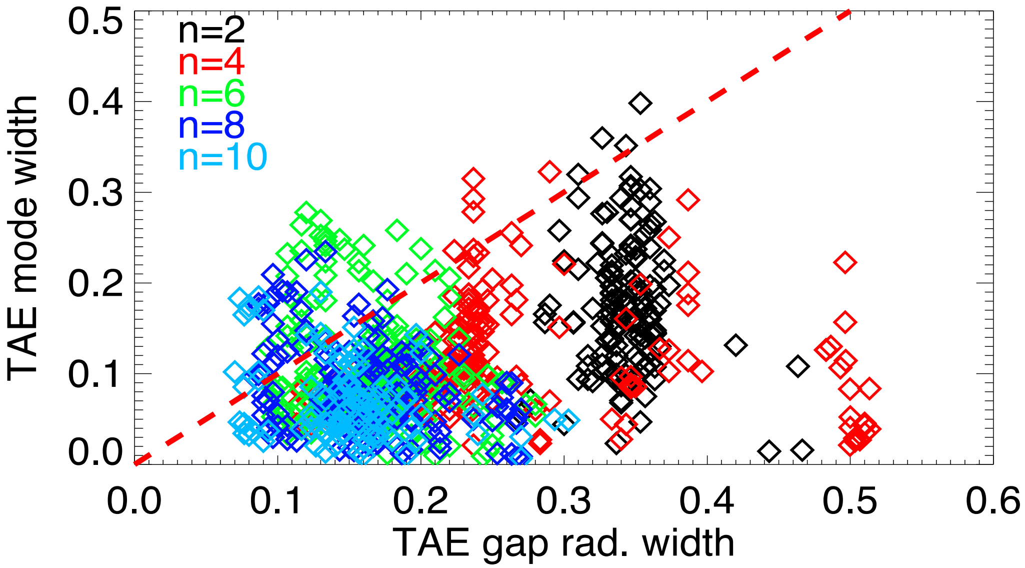


Other modes tunnel through upper continuum to match EAE dispersion relation: mixed TAE+EAE modes

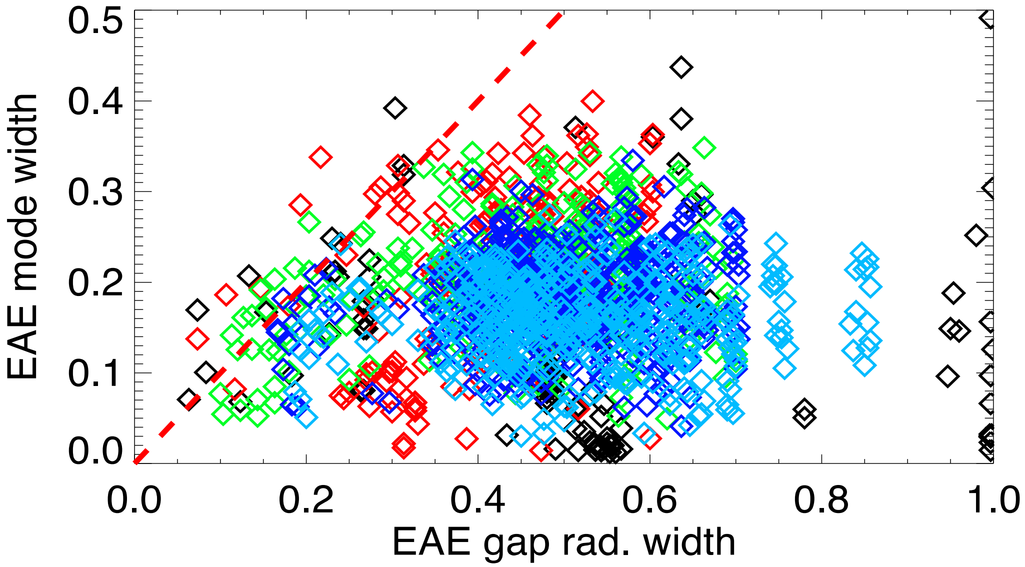
(Double-gap modes)

N. Gorelenkov, PRL (2005)

Mode width varies with n_{tor} & gap width for TAEs; no systematic variations for EAEs



- Radial width of TAEs slightly decreases for higher *n*'s
- Lower n's have width Δx_{mode}~.1–.3
  - Could drive substantial fast ion transport – if unstable

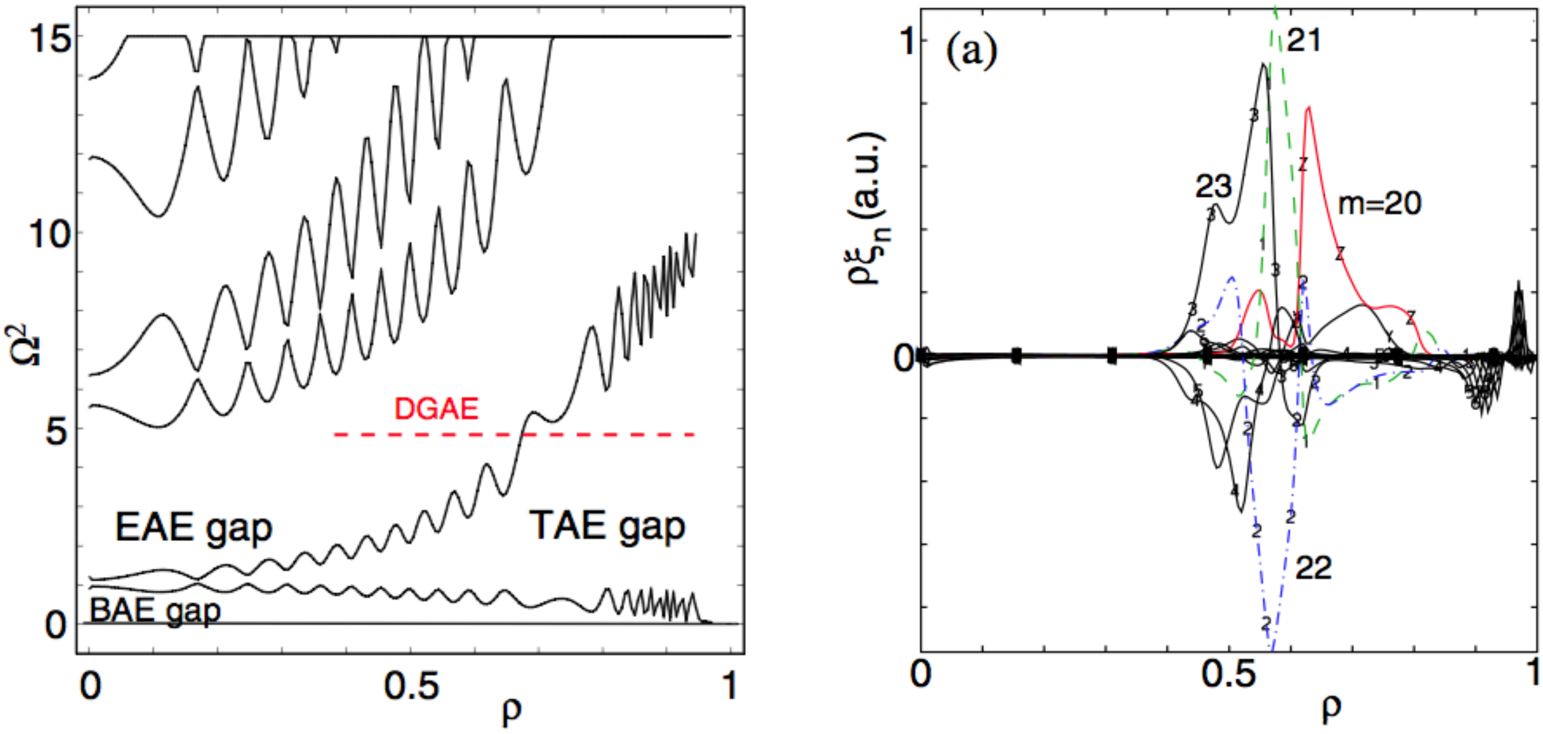


- EAE gap more radially extended
- Often reach plasma edge
- Mode width comparable to TAEs

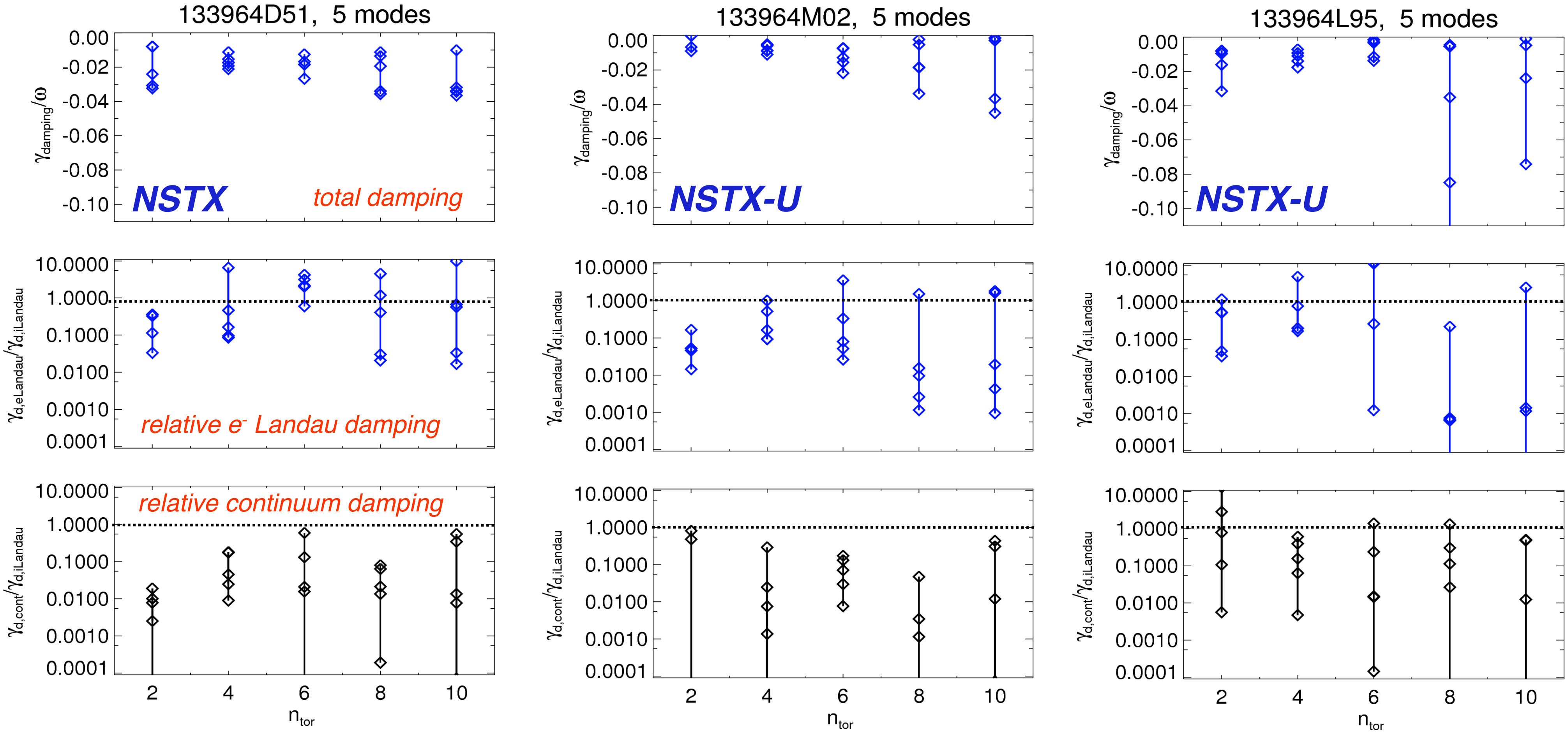
Coupling TAE+EAE may enable efficient coupling to core-localized modes through antenna at plasma edge

- “Double-gap” Alfvén eigenmodes can tunnel through upper TAE continuum
- Antenna could excited edge harmonics
  - Excitation propagates to inner plasma regions
- With good mode selectivity, may induce fast ion transport, control radial profile, help avoiding/minimizing instabilities

N. Gorelenkov, PRL (2005)

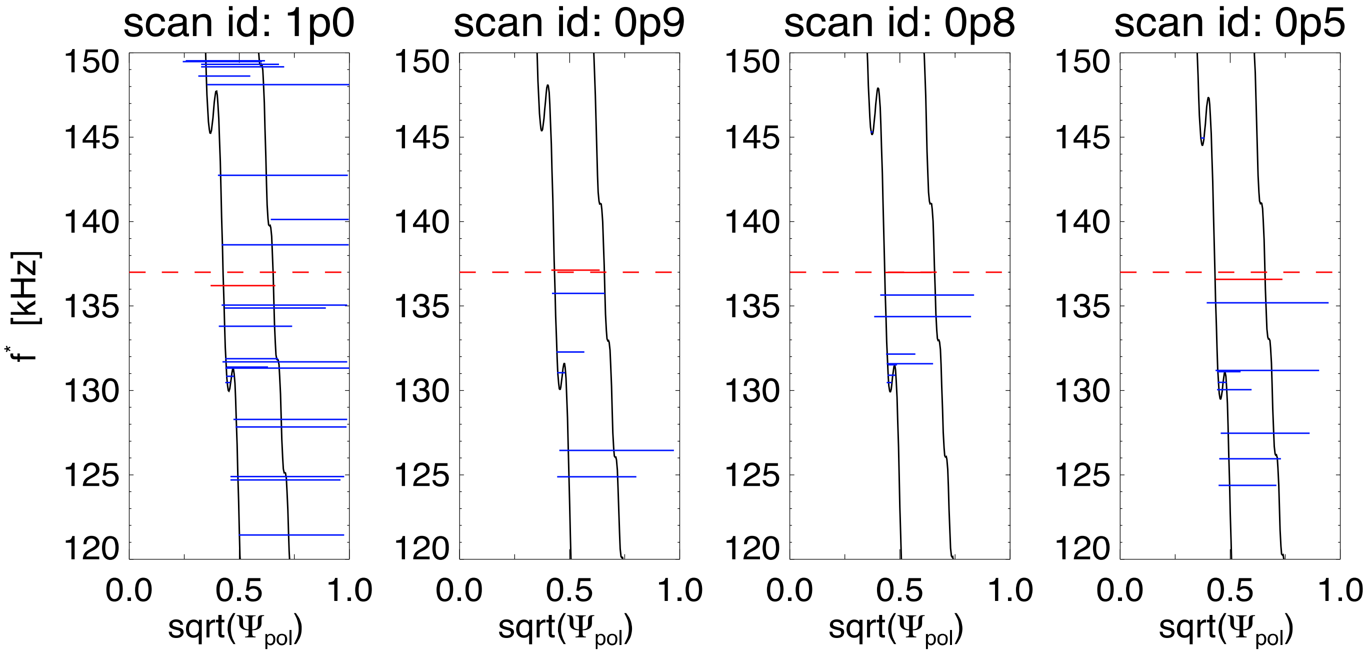


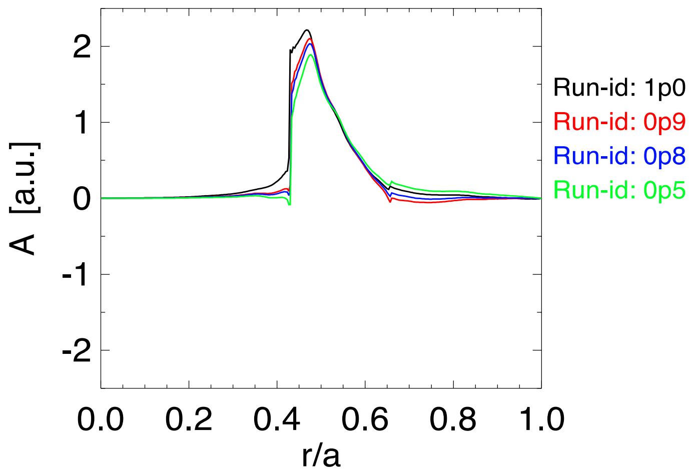
Three comparable damping mechanisms found; details change based on mode structure, frequency, …

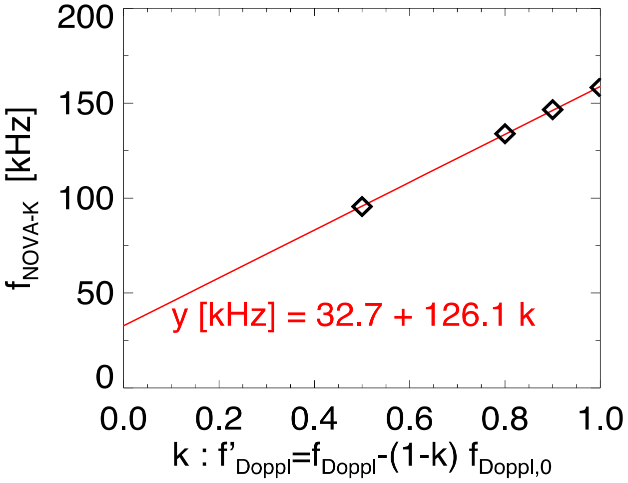


- 5 less stable modes shown
- Overall, damping rates are comparable w/ NSTX plasmas
- Continuum and e^-/i^+ Landau damping are comparable

More detailed analysis reveals missing physics in NOVA-K, makes stability calculations inaccurate





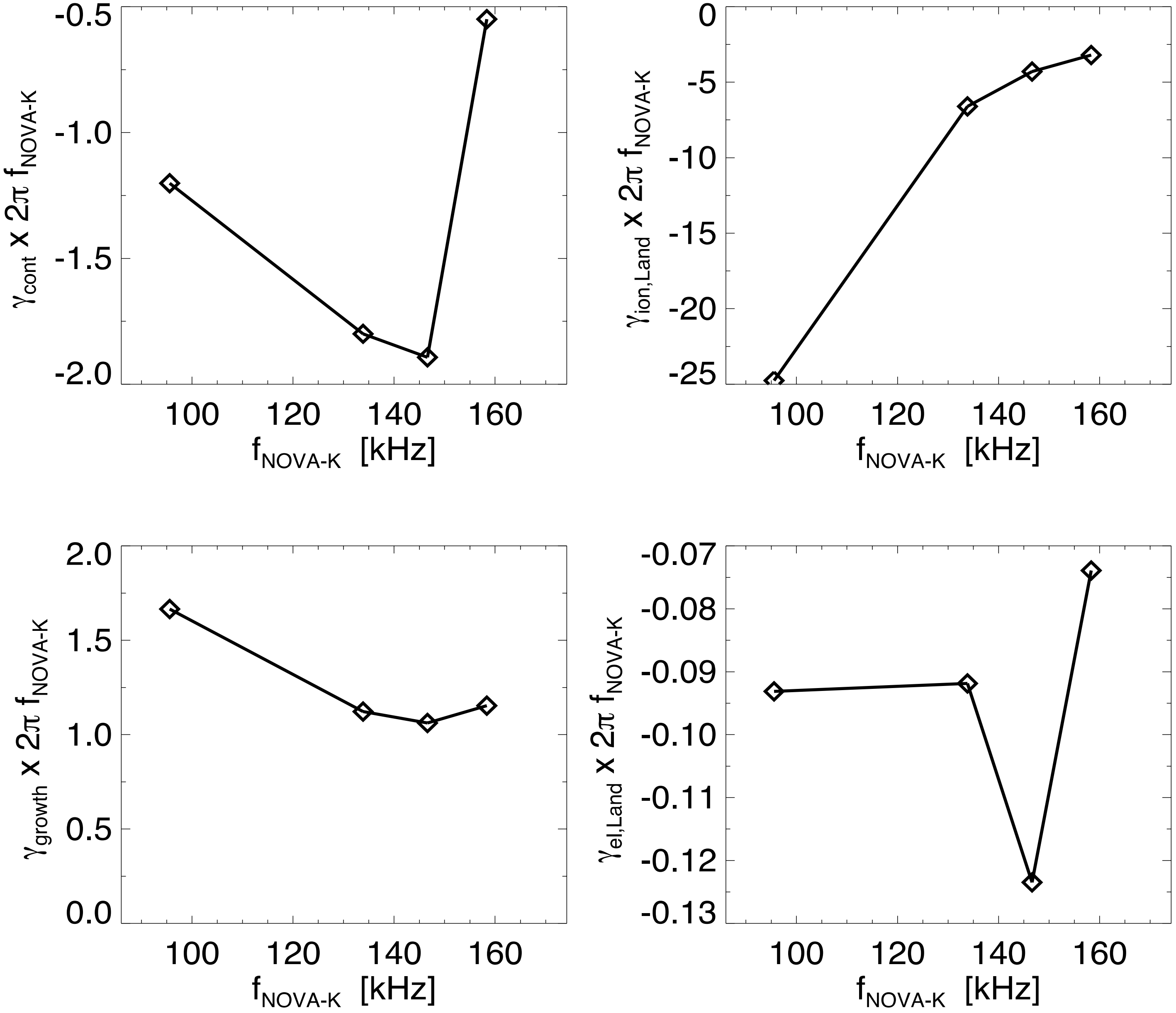


Example:

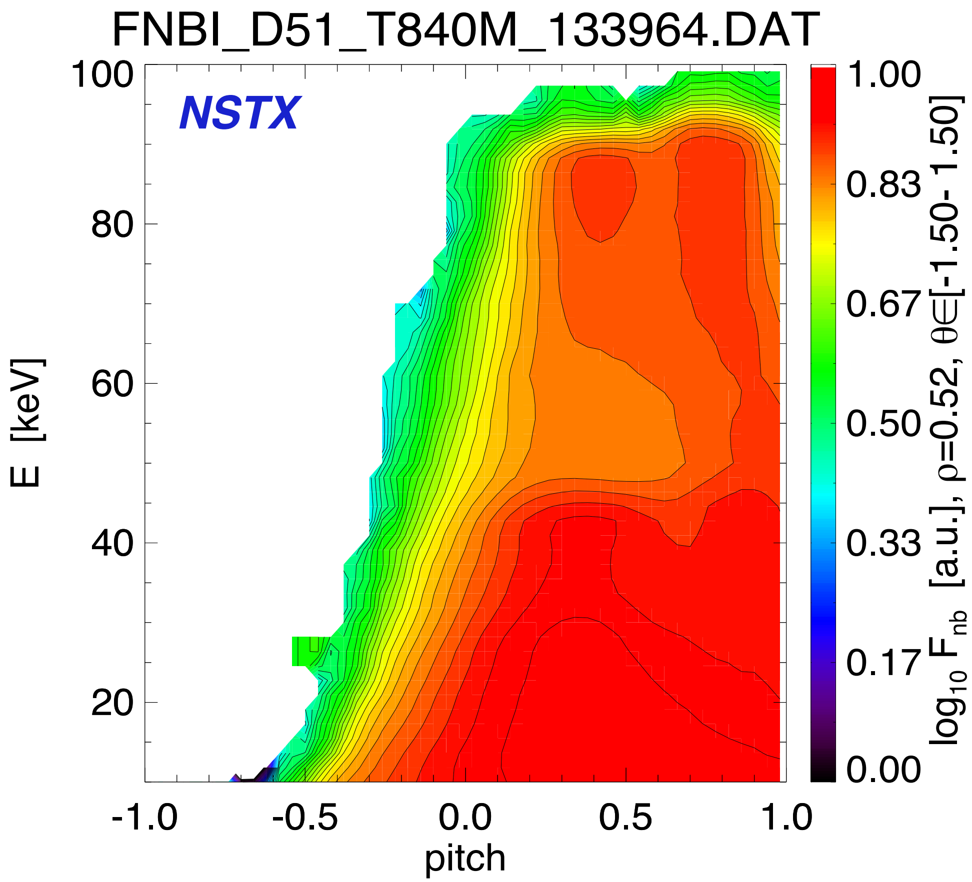
- Same scenario, rigid shift of rotation
- Follow “same” mode
- Compare damping rates

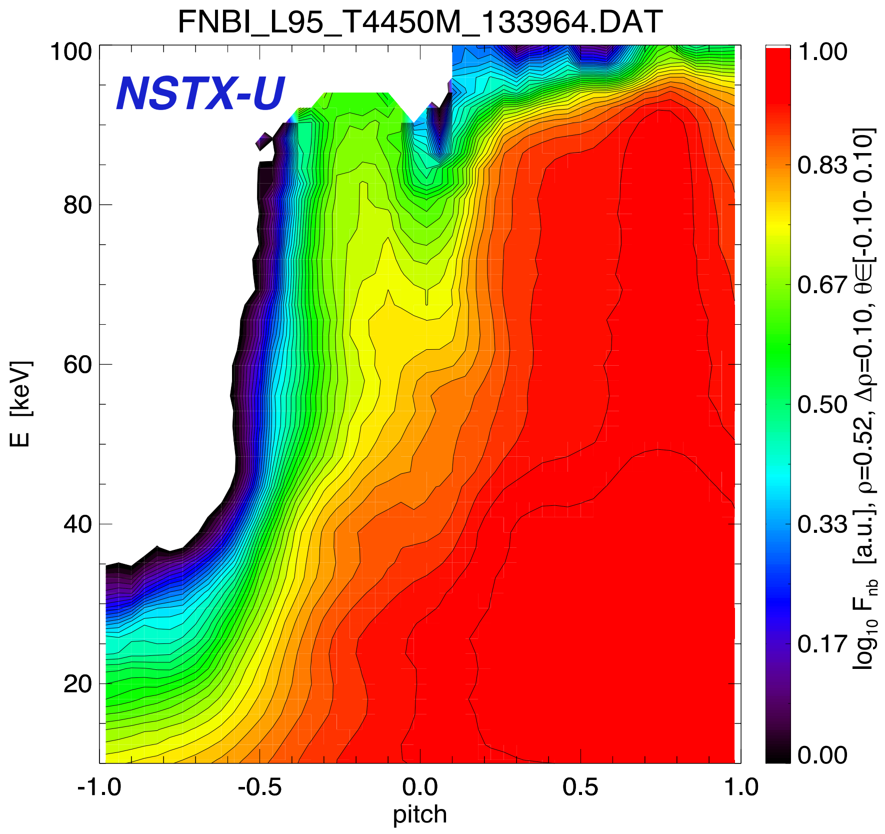
Contrary to expectations, damping rate varies with rigid shift of rotation – i.e., for unchanged plasma frame

Example for n=4 mode



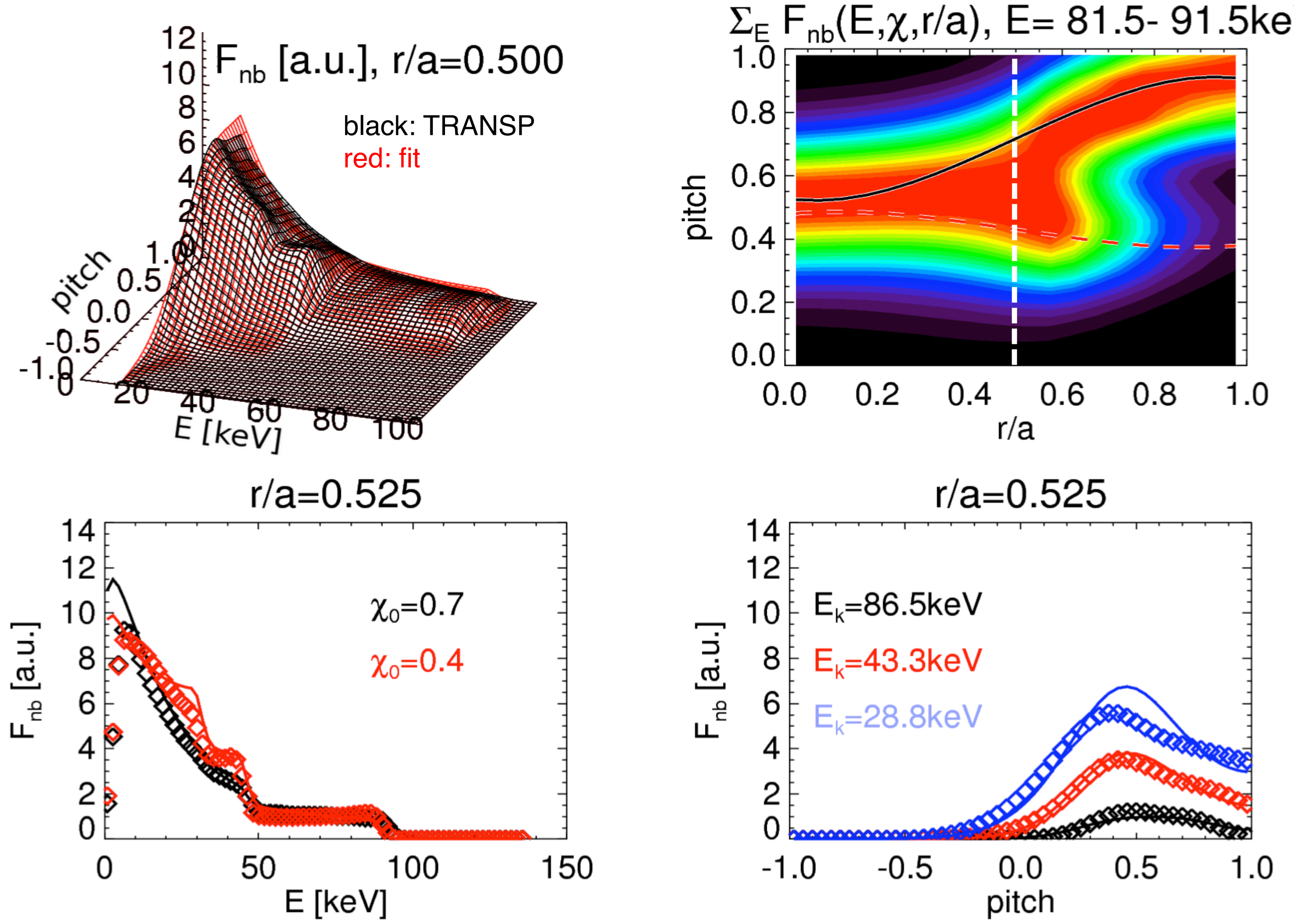
NB distribution function from TRANSP modeling used to compute TAE drive





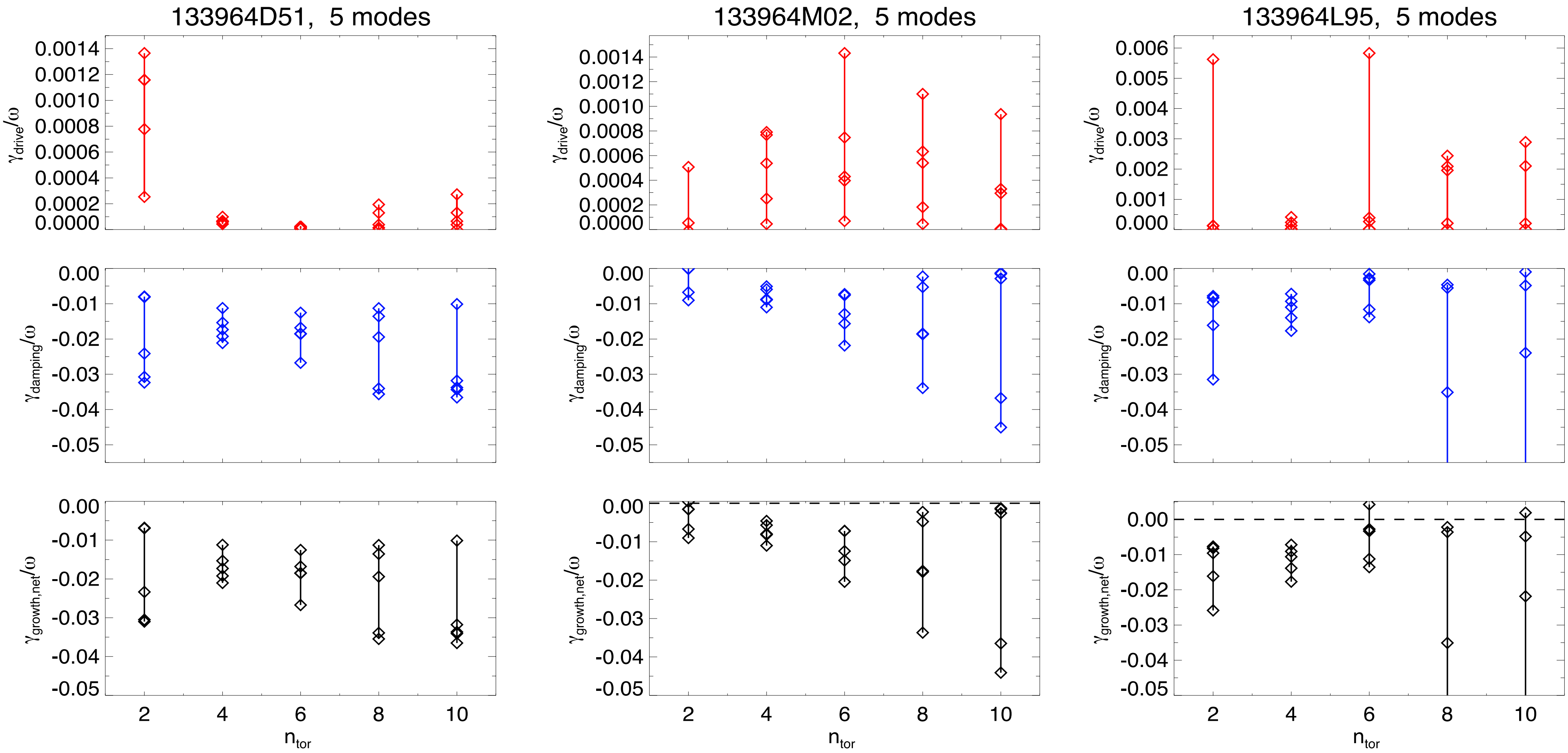
- F_{nb} from TRANSP/NUBEAM predictions with realistic NB injection geometry

NOVA-K input derived from a fit of TRANSP F_{nb} at one selected radius, taken at max $|grad(F_{nb}(r))|$



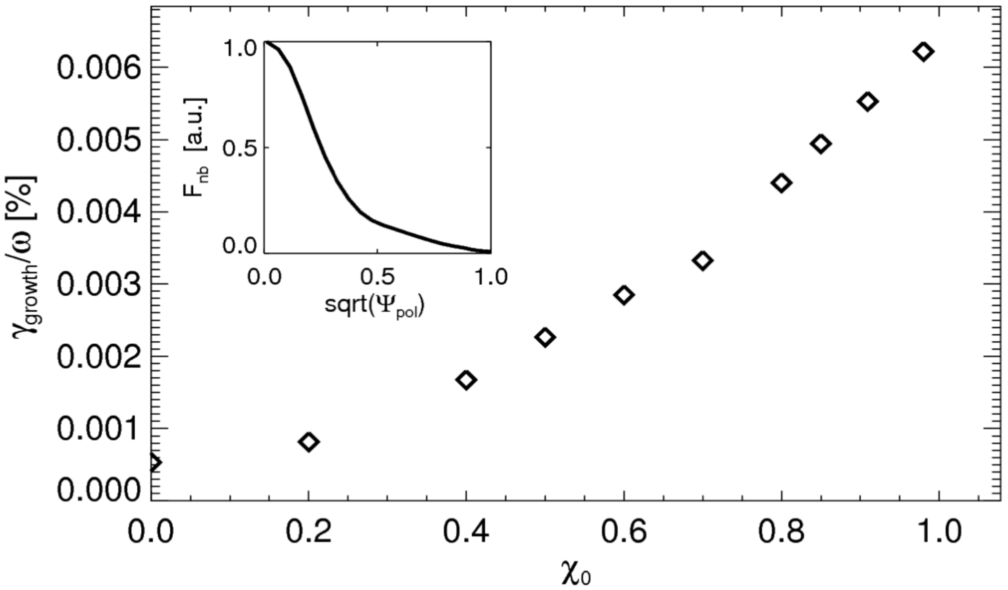
- Use 4 NB components: 2 energies, 2 deposition pitch χ_0
- Add drive from the 4 separate runs to get total drive

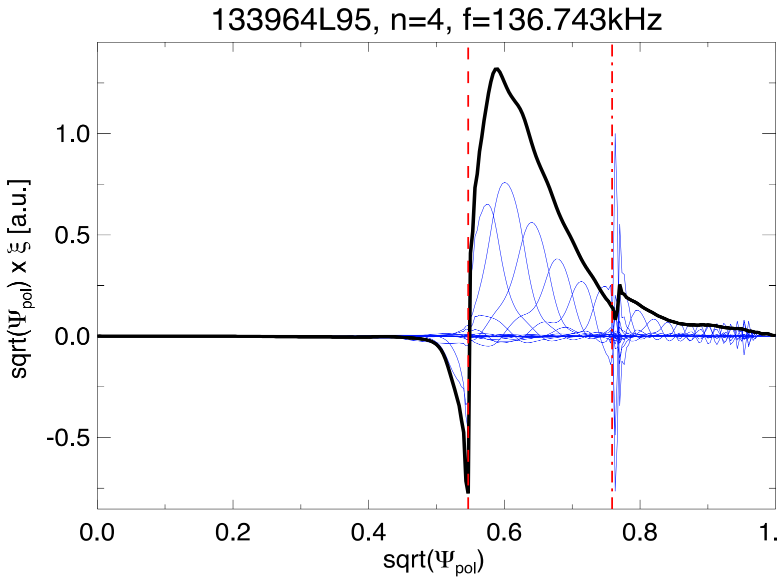
Overview of drive dependence on NB injection geometry. Qualitative study for “zero-rotation” case.

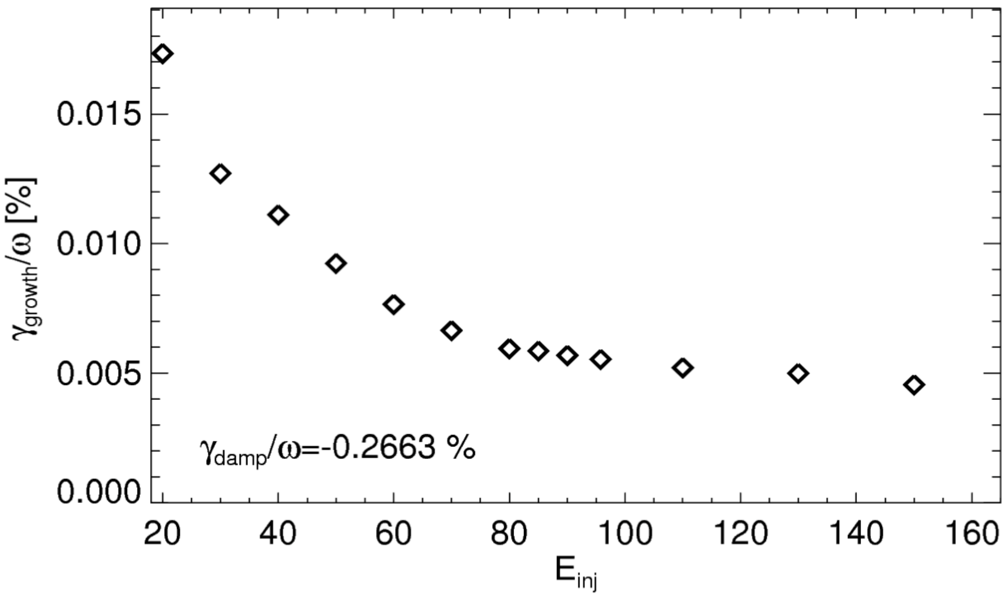


- Consider 5 most unstable modes
- NSTX-U scenarios look more unstable – drive is small

Drive dependence on NB injection geometry: vary injection pitch, energy for a given mode

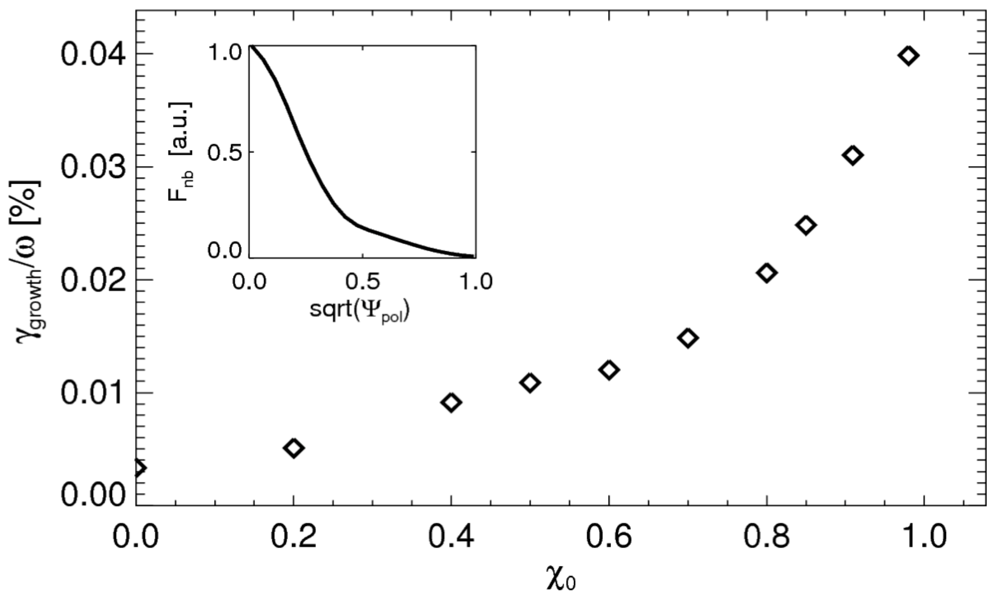


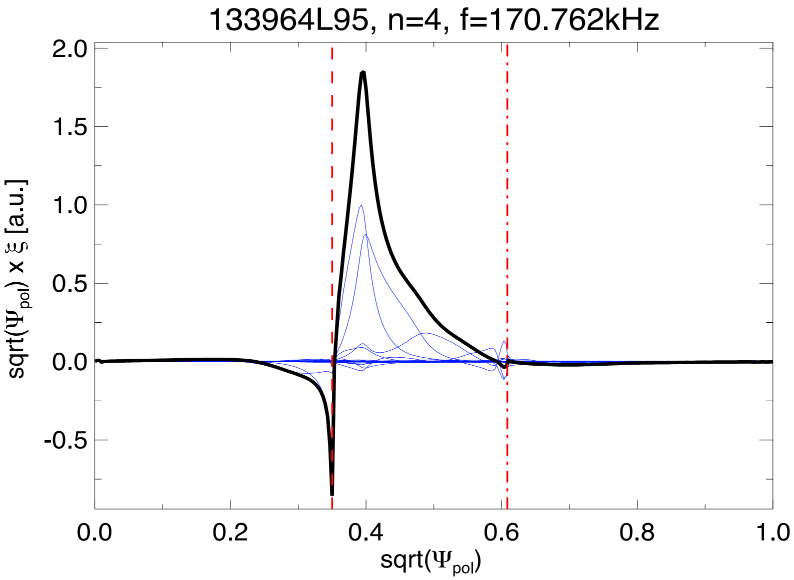


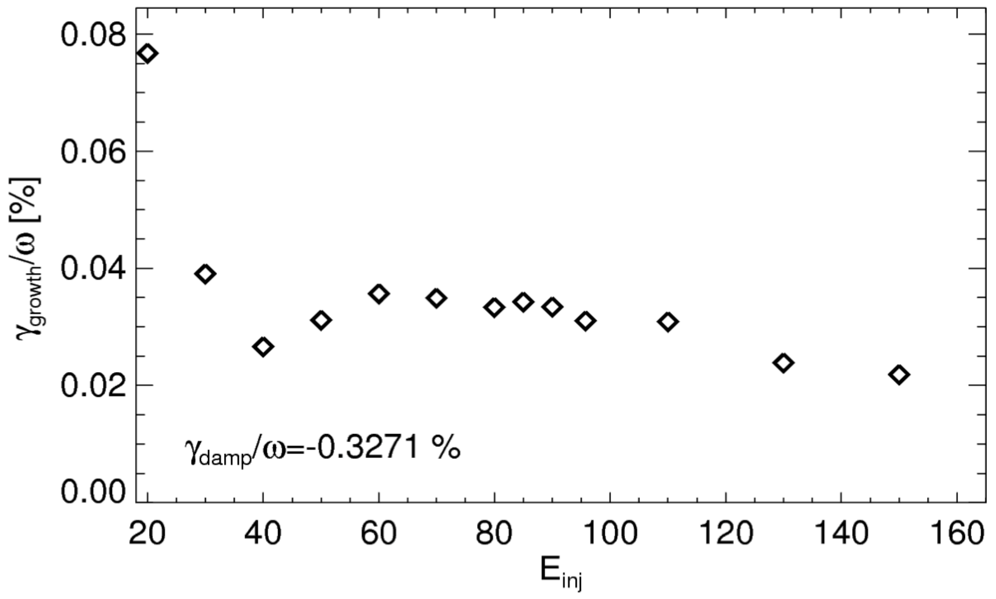


- Drive increases for more parallel injection
- Lower energies (E<60 keV) more efficient at driving mode
  - > Larger β_{fast} for regions where resonances are more effective?

Details of drive dependence on NBI geometry vary for each mode; strong(er) drive for passing ions is common feature

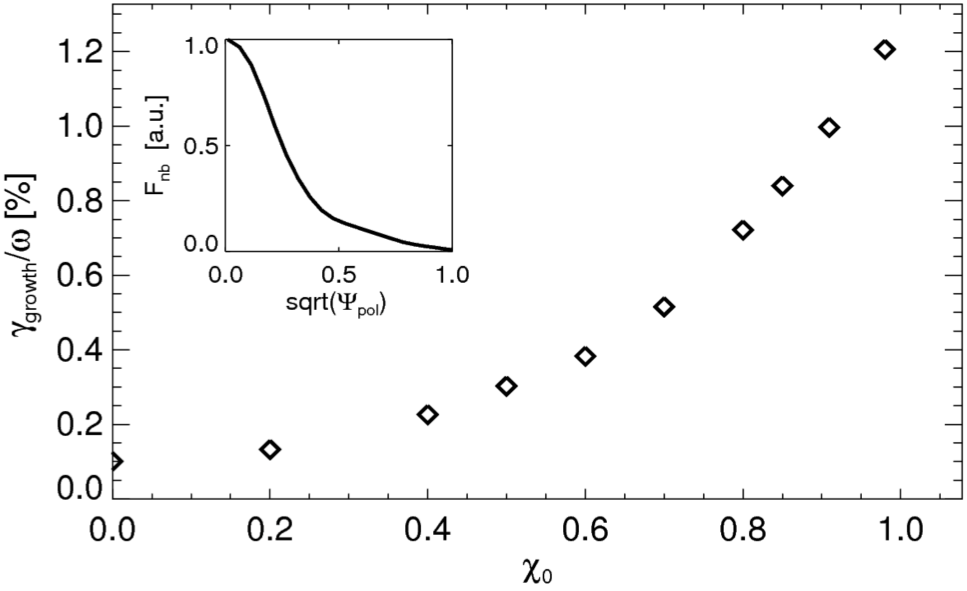


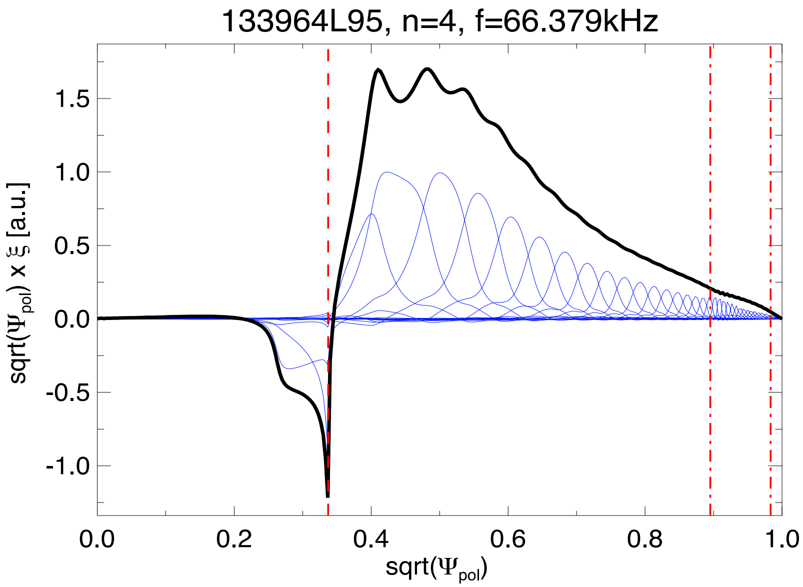


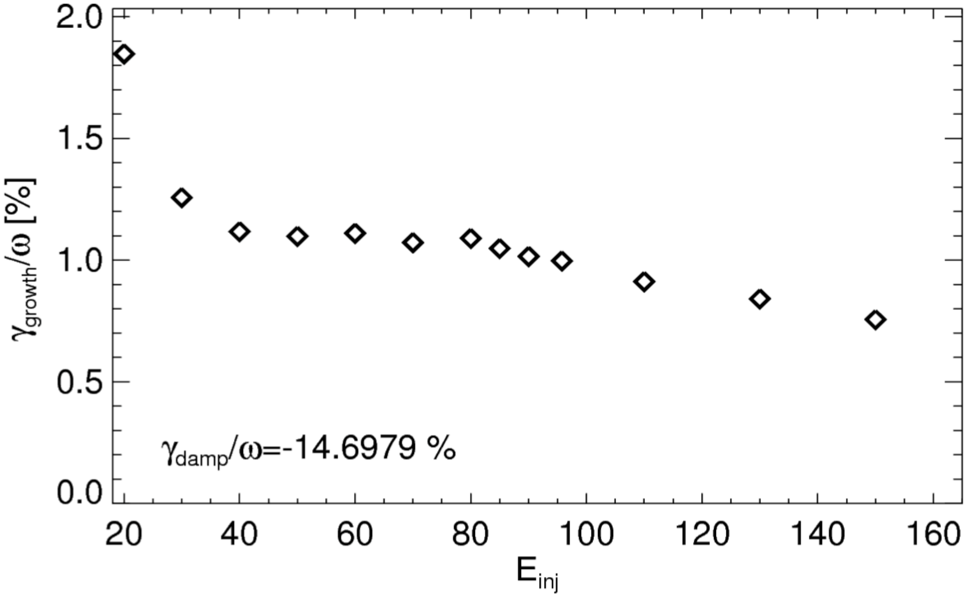


- Different mode structure
- Interaction with continuum also changes
- Mode more core-localized
  - > Stronger drive, larger fast ion population

Zero rotation case shows x100 larger drive, closer to expected values of ~1%

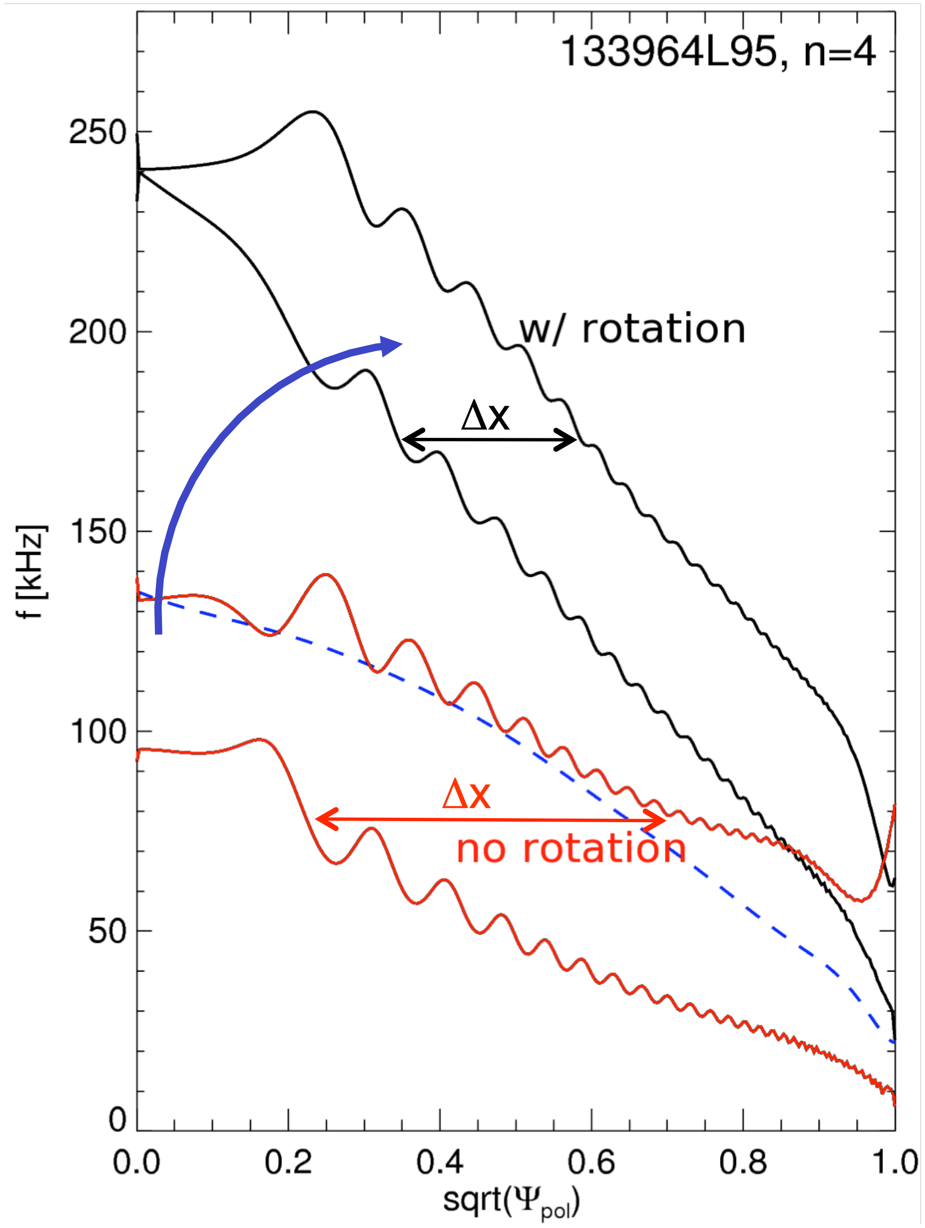






- Trends qualitatively similar to cases w/ rotation
- Much larger drive
- Much broader mode structure for no rotation case

Consistent treatment of rotation is crucial for correct computation of both damping and drive terms



- f_{rot} defines the relationship between plasma & lab frame
  - Affects drive
    - Modes and F_{nb} are “defined” in two different reference frames!
  - Does not affect damping such as Landau (thermal plasma & modes rotate w/ same f_{rot})
    - If properly accounted for…
- Modifies TAE gap
  - Gap narrows at higher f_{rot}
- But: rotation shear does not seem to have effects
  - Deduced from experiments

Summary and future work

- TAE modes might be more unstable in NSTX-U than in NSTX (including H-mode plasmas)
  - Based on linear analysis & comparison with NSTX scenarios
- Higher field results in broader *n* wavenumber spectrum, wider radial gap

> Analysis reveals limitations of NOVA-K code for plasmas with large rotation (e.g. Spherical Torii)

  - Role of rotation still non quantifiable with present code

Future work:

> Improve treatment of finite rotation in NOVA-K; e.g., lab frame:

  - Eigenmodes: f_{MHD}+n f_{rot} (modes)
  - Damping: f_{MHD}+ f_{rot} (modes); $v_{th}+2\pi$ R f_{rot} (thermal plasma)
  - Drive: f_{MHD}+ f_{rot} (modes) ; v_{fast} (fast ions)

> Improve model for fast ion distribution function?

  - Example: code to import F_{nb} from TRANSP/NUBEAM in M3D-K code under development
  - Can the same code/definitions be used for NOVA-K?