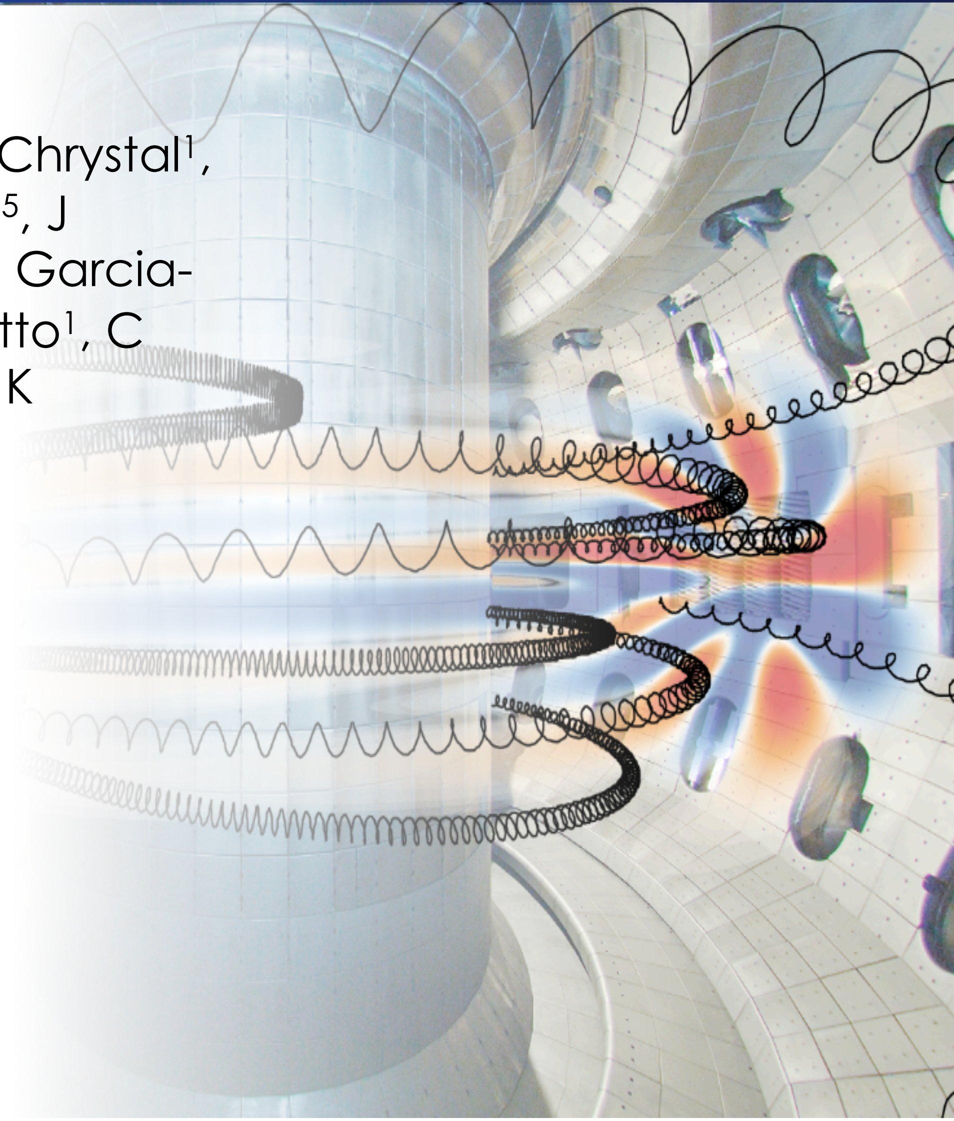
Modification of Alfvén Eigenmode Drive and Nonlinear Saturation Through Variation of Beam Modulation in DIII-D

MA Van Zeeland[1]
WW Heidbrink[2], M Austin[3], L Bardoczi[1], C Chrystal[1], CS Collins[1], N Crocker[4], XD Du[1], V Duarte[5], J Gonzalez-Martin[6], R Hong[4], G McKee[7], M Garcia-Munoz[6], N Gorelenkov[5], Z Lin[2], S. Munaretto[1], C Petty[1], M Podesta[5], T Rhodes[4], D Spong[8], K Thome[1],Y Todo[9], Z. Yan[7], G. Yu[10], Y Zhu[10]

[1]General Atomics, San Diego, CA USA
[2]University of California Irvine, CA USA
[3]University of Texas Austin, TX USA
[4]University of California Los Angeles, CA USA
[5]Princeton Plasma Physics Laboratory, NJ USA
[6]Universidad de Sevilla, Sevilla, Spain
[7]University of Wisconsin Madison, WI USA
[8]Oak Ridge National Laboratory, TN USA
[9]National Institute for Fusion Science, Japan
[10]University of California Davis, CA USA



Presented at the
16th IAEA TM on Energetic Particles in Magnetic Confinement Systems
Shizuoka, Japan,
Sept. 3-6, 2019

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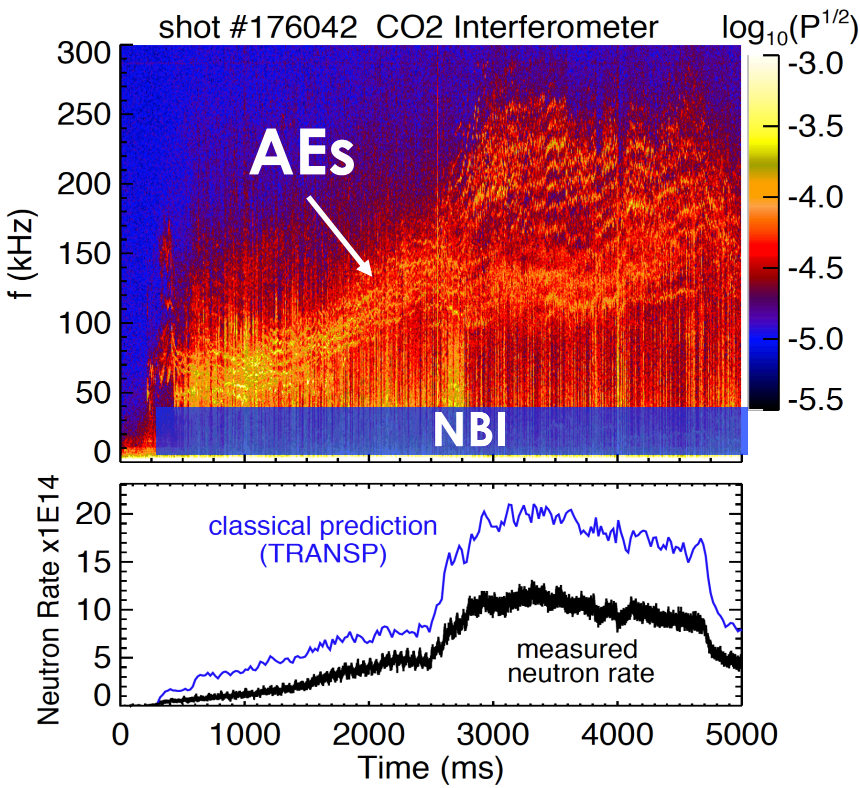
GENERAL ATOMICS

Background

- **Alfvén Eigenmodes (AEs) are driven unstable by ~80kV beams in DIII-D**
- **They cause fast ion transport and reductions in performance**
- **Goal is to understand:**
  - Modes
  - Mode drive
  - Saturation (how amplitude is set)
  - Impact on fast ion profile
  - How to control



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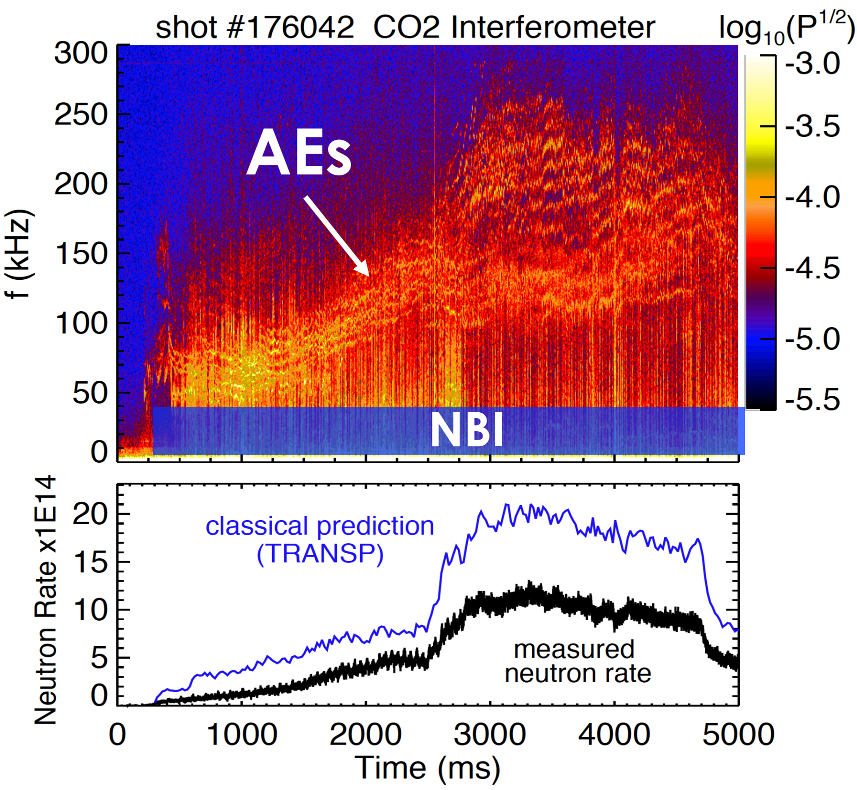

A lot of effort over the last 10 years has been focused on these

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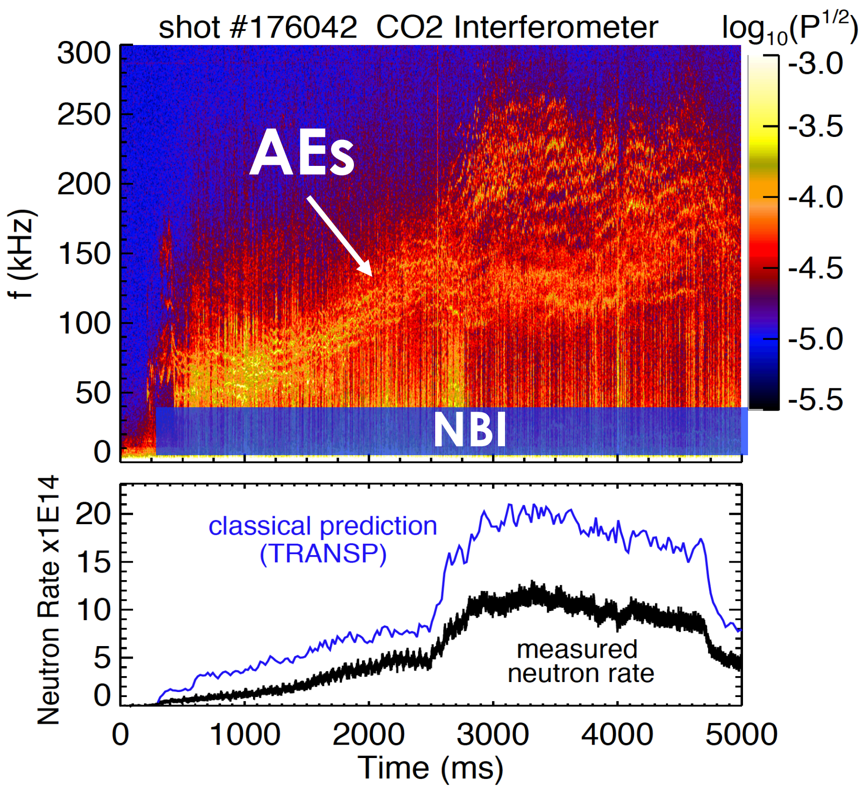

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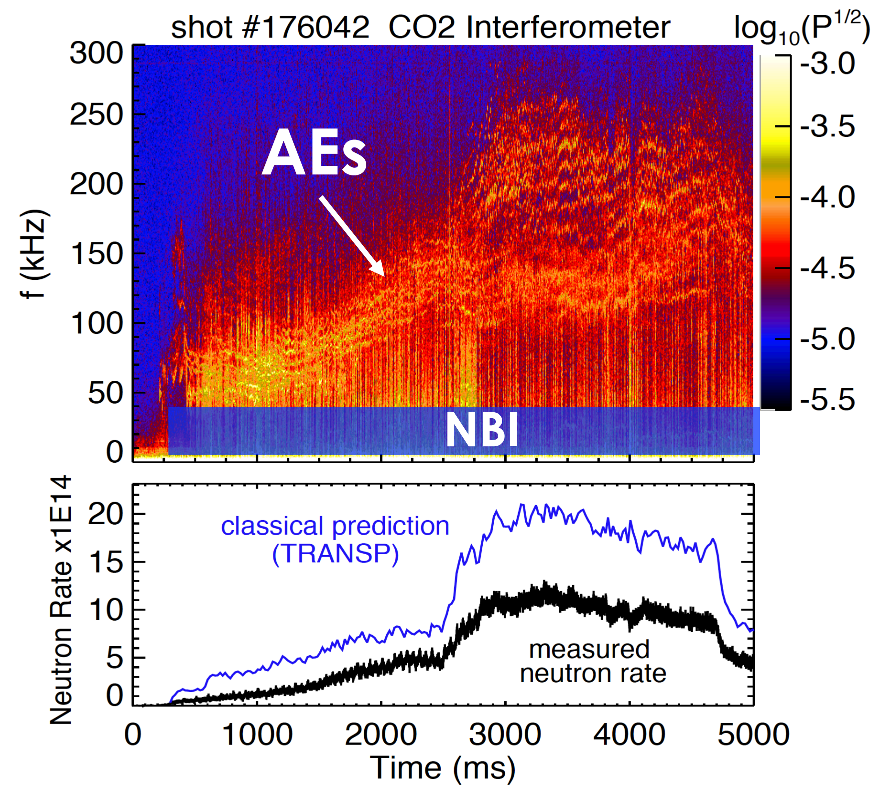
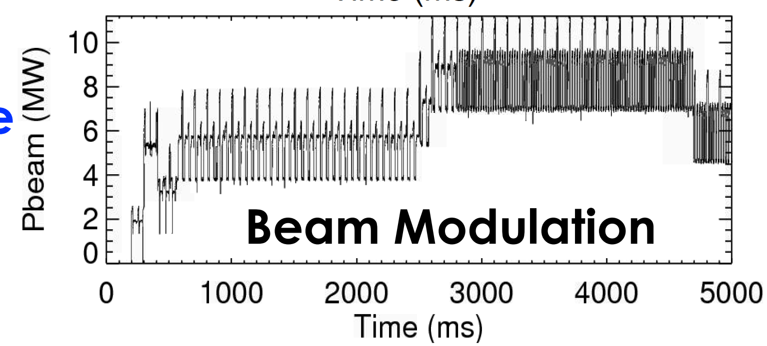
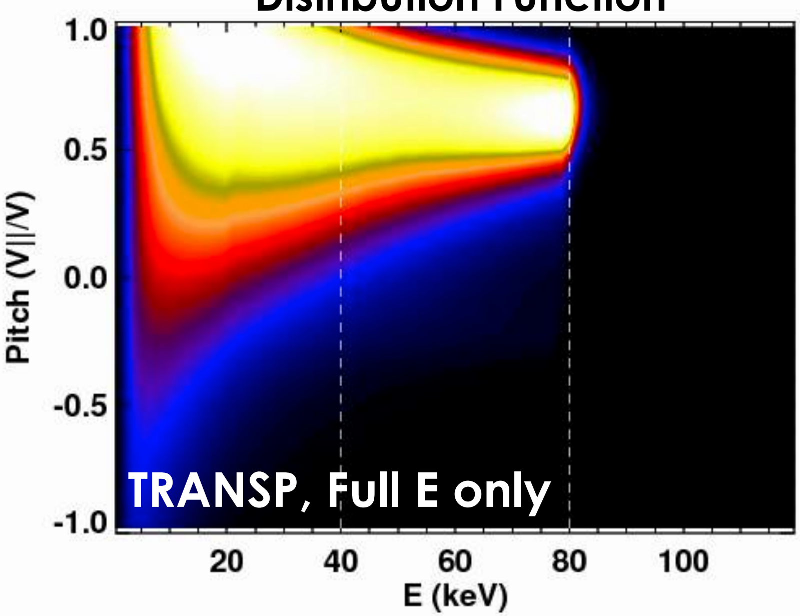


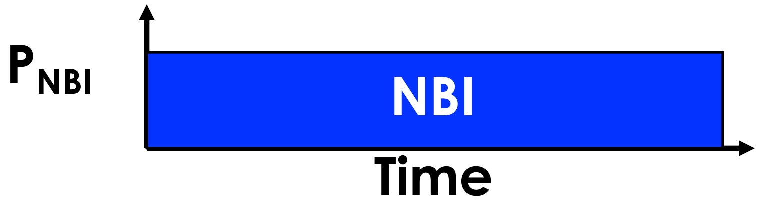


Beam Modulation Can Have Significant Implications for AE Drive[1,2]

- **Constant beams have nice slowing down distribution function**
  - This is or Maxwellian is often assumed in theory

Steady Tangential NBI Distribution Function





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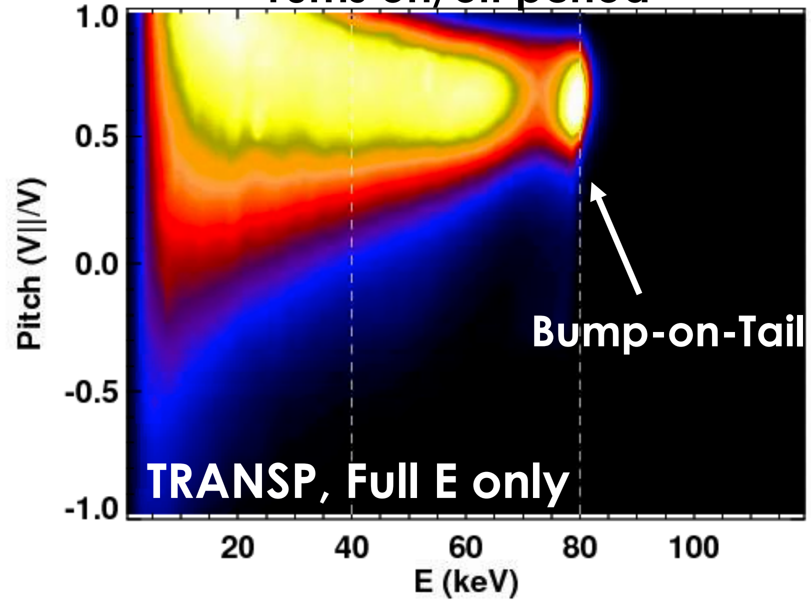
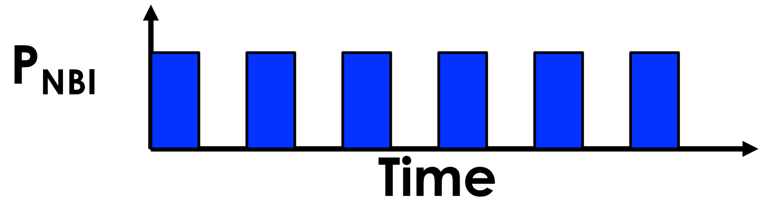
- **Modulation period changes bump-on-tail feature**
  - Often chosen arbitrarily or for diagnostics, NOT physics

2ms after Tangential NBI turn-on, 10ms on/off period





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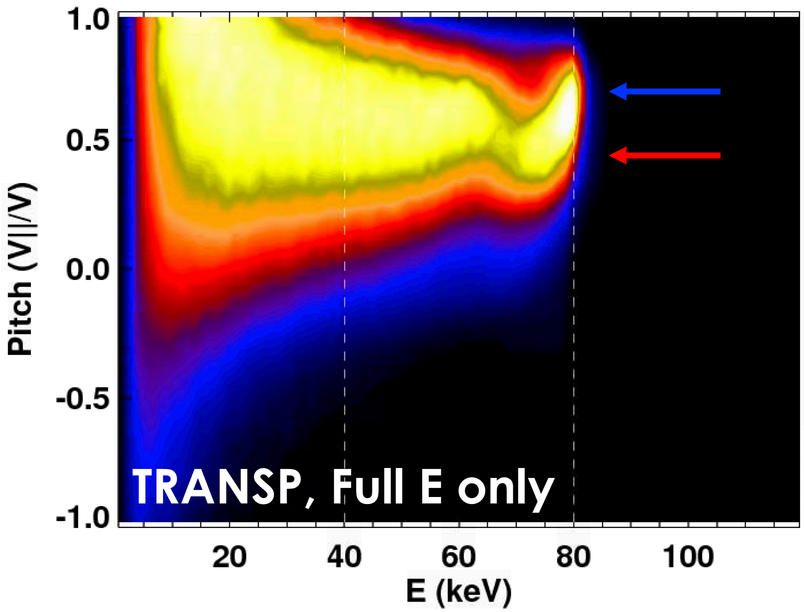
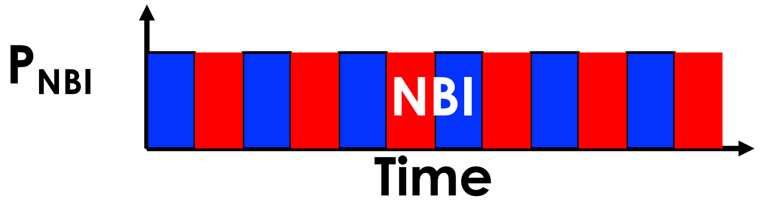
- **For Interleaved beams, the time-dependent beam mix depends on modulation period**
- **In this experiment, vary modulation period to investigate impact on AEs – *Do we see a change in drive from these effects?***

2ms after Tangential NBI turn-on, Tangential and Perp NBI Interleaved 10ms on/off period





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- **Analysis of the bump-on-tail contribution to AE drive in expt.**
  - Imaging Neutral Particle Analyzer (INPA) measurements
  - TRANSP and Kick Modeling
  - MEGA Modeling
- **Measurements of TAE growth and saturation during individual beam pulses**
  - Large amplitude oscillations
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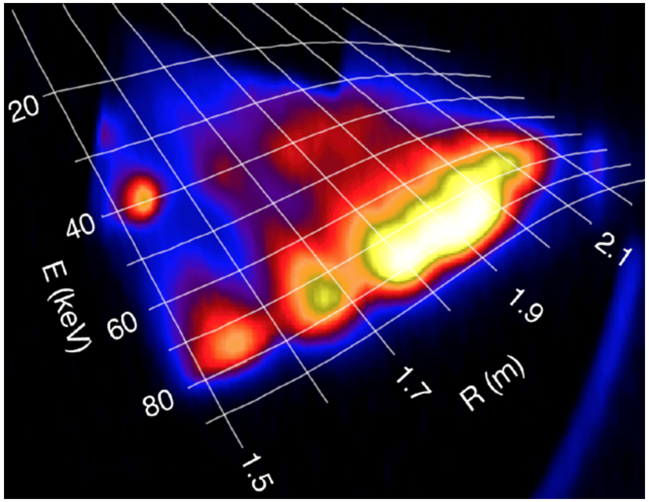

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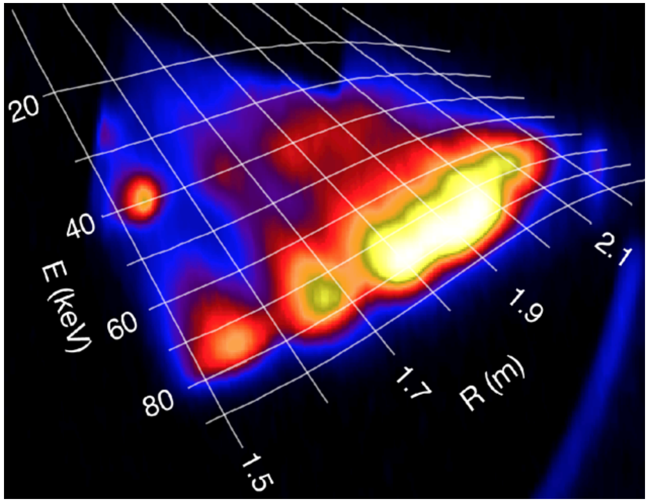
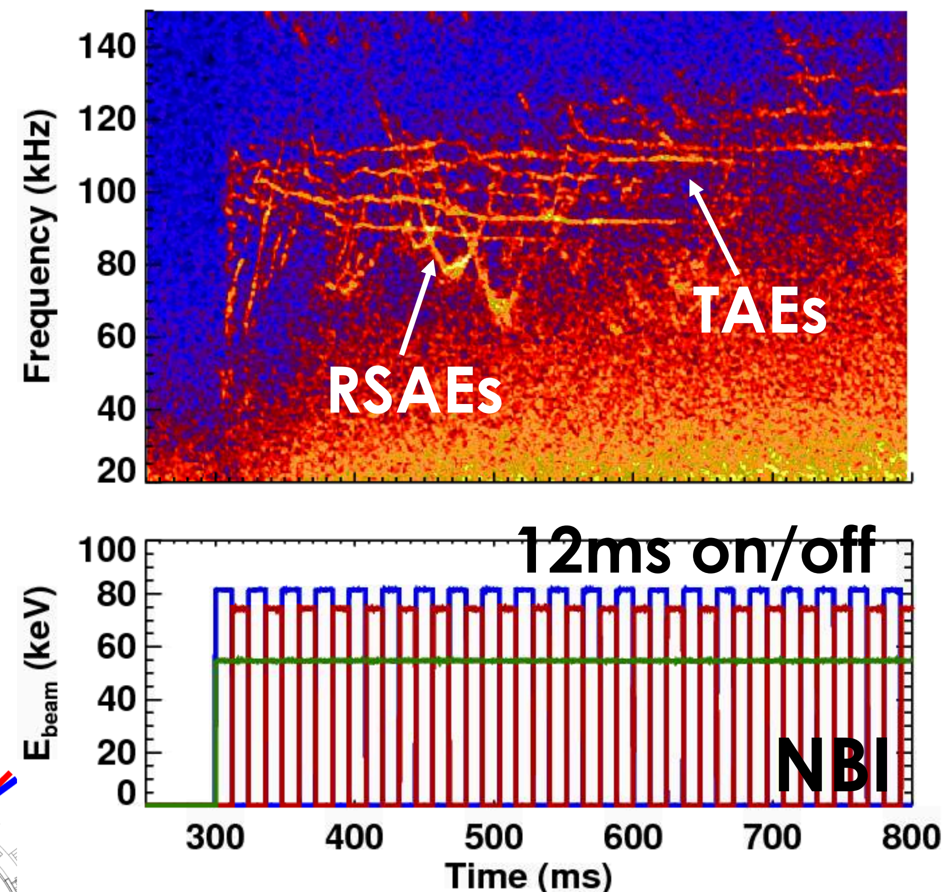
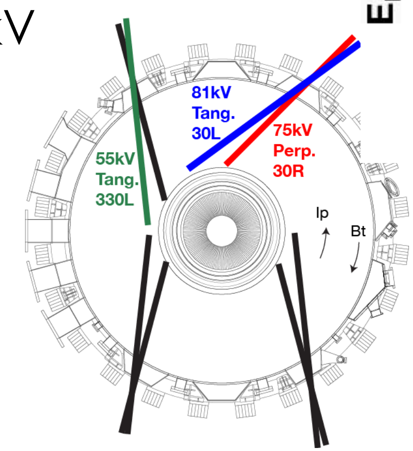


Experiment Scans Interleaved Beam Modulation Period to Investigate Impact on AEs

- **Standard L-mode DIII-D current ramp scenario**
  - Multiple AEs
- **Diagnostic beam fixed at 55kV**
- **80kV Tangential and 75kV Perpendicular beam modulated out of phase**
  - V_B/V_A ~ 0.3-0.4
- **Modulation period varied from 7ms on/off to 30 ms on/off then steady**
  - Typical slowing down time from 80kV to 50kV ~ 20ms
- **Impact on modes and fast ions documented**





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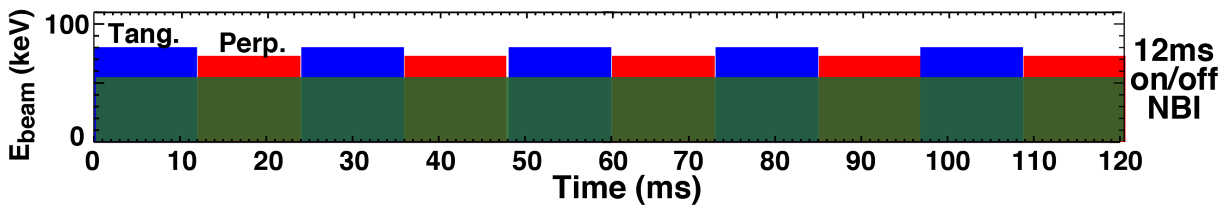
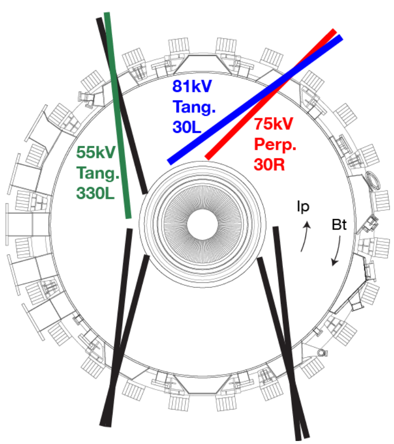
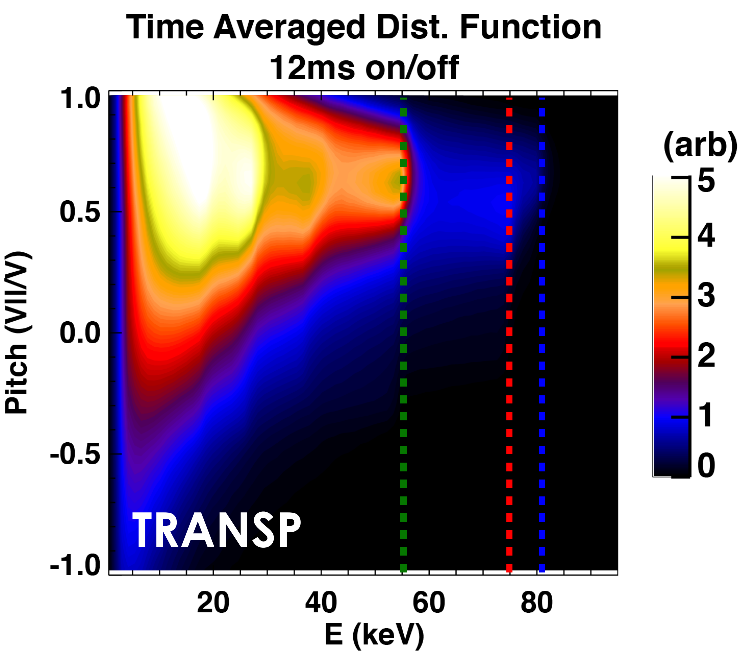
The Distribution Function Evolution Varies Significantly with Modulation Period

- **The overall time-averaged dist. function is similar for all modulation periods**







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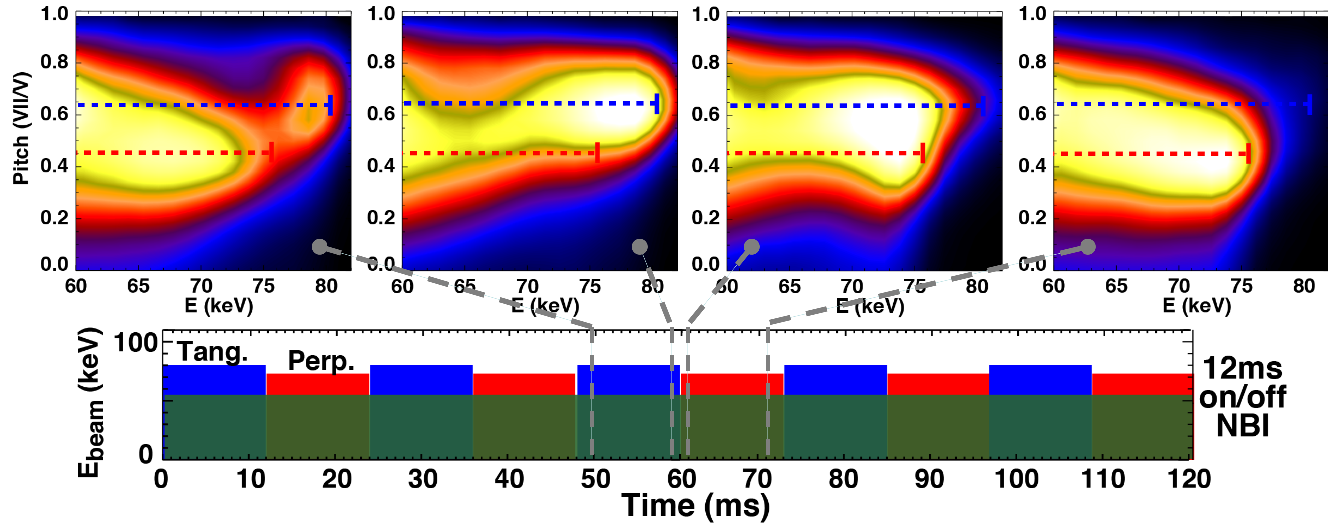
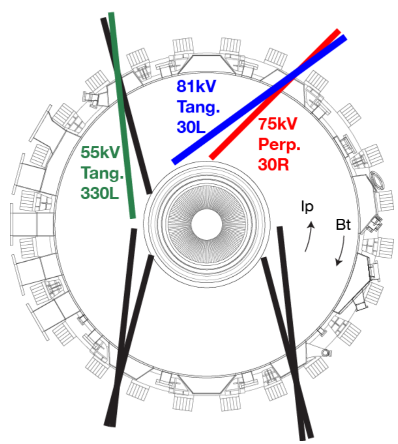
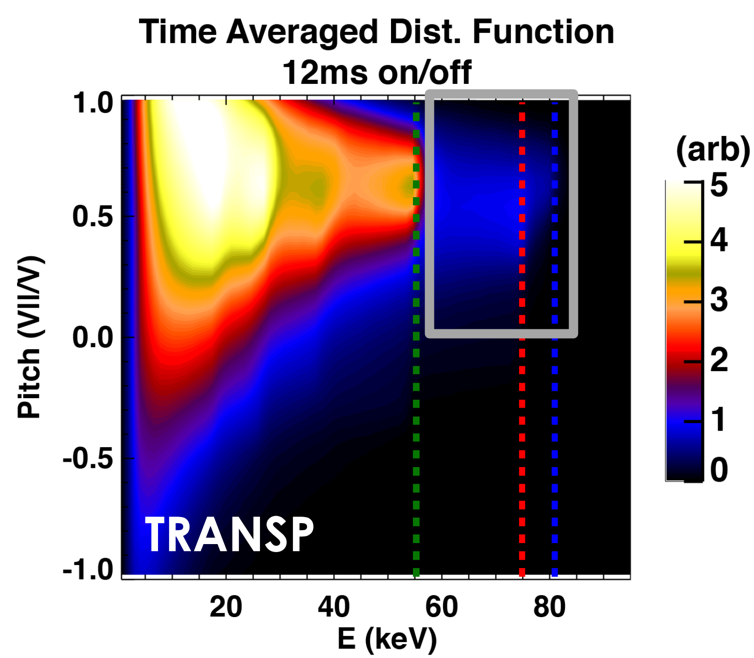
The Distribution Function Evolution Varies Significantly with Modulation Period

- **The overall time-averaged dist. function is similar for all modulation periods**
- **Largest variation is at highest energies**
- **Injected pitch changes with beam**
- **For shorter mod. periods (~12ms), positive *dF/dE* is always present above 60kV**







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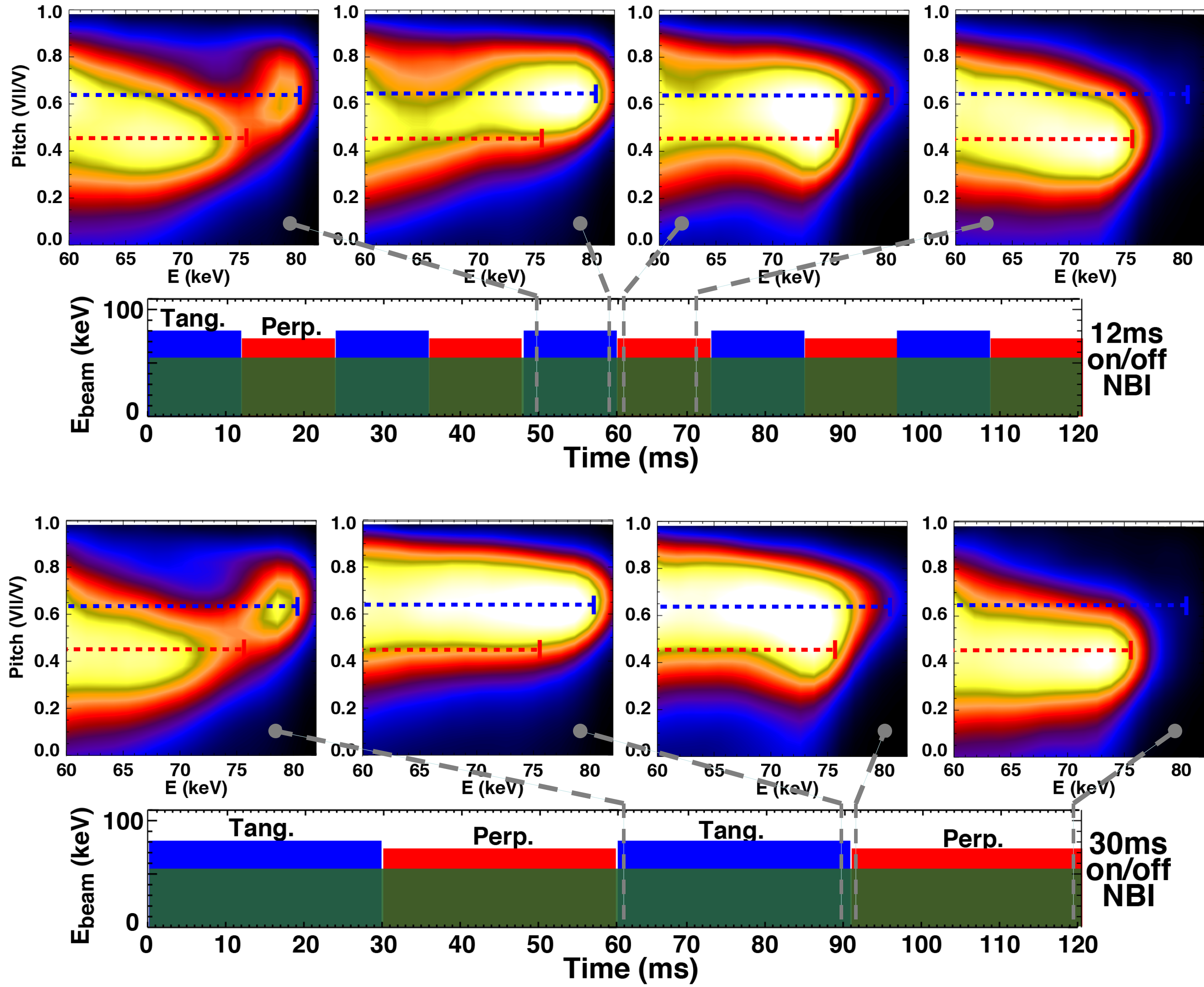
- For longer mod. periods (~30ms) becomes slowing down before end of pulse



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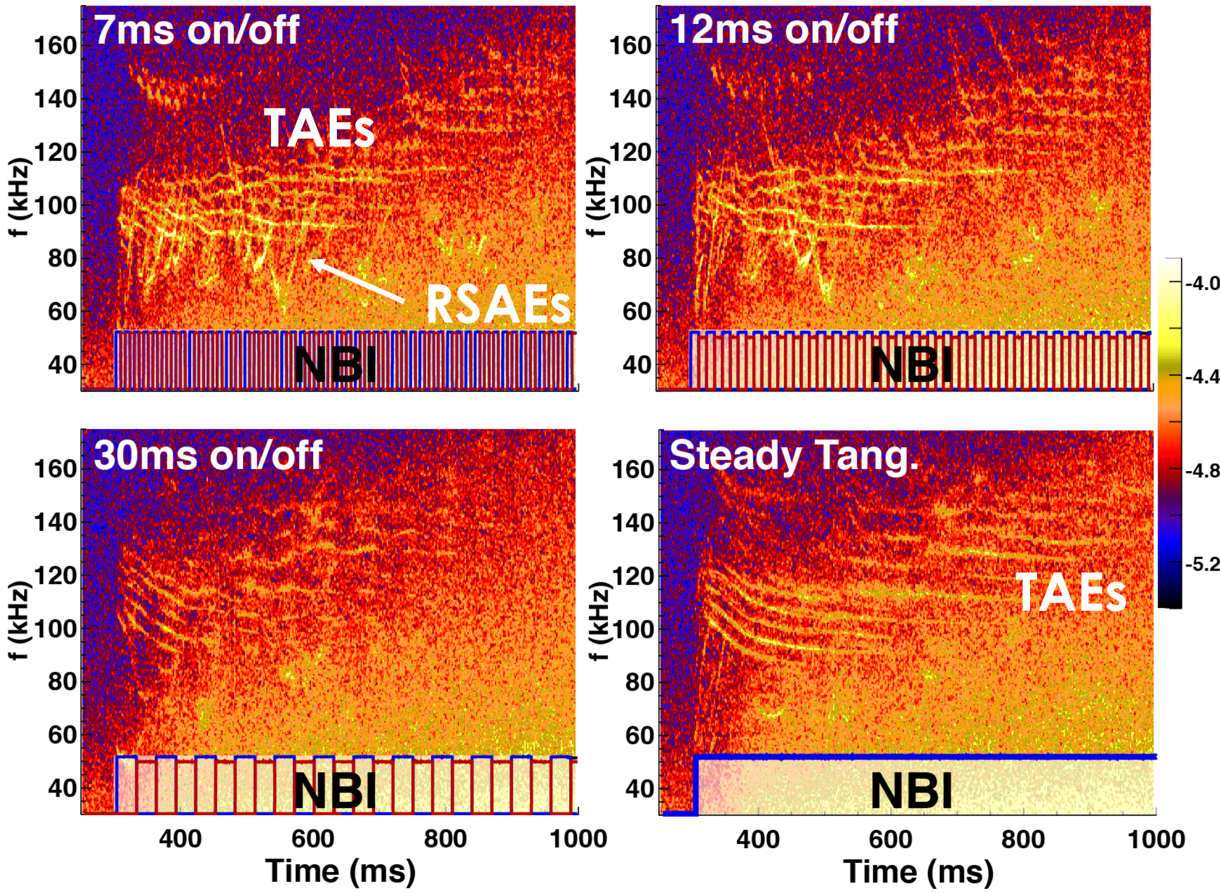
Unstable AE Spectra Changes With Modulation Period

- **Density and current profile evolution well-matched**
- **CO2 interferometers give broad overview of activity**
- **From 7ms to steady tangential beam, mix of RSAE and TAE changes to primarily TAE**
- **Same time averaged power for all *modulation* cases**

CO2 Interferometer



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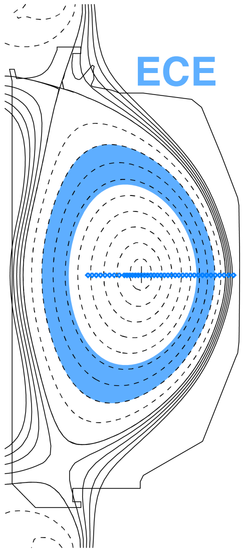
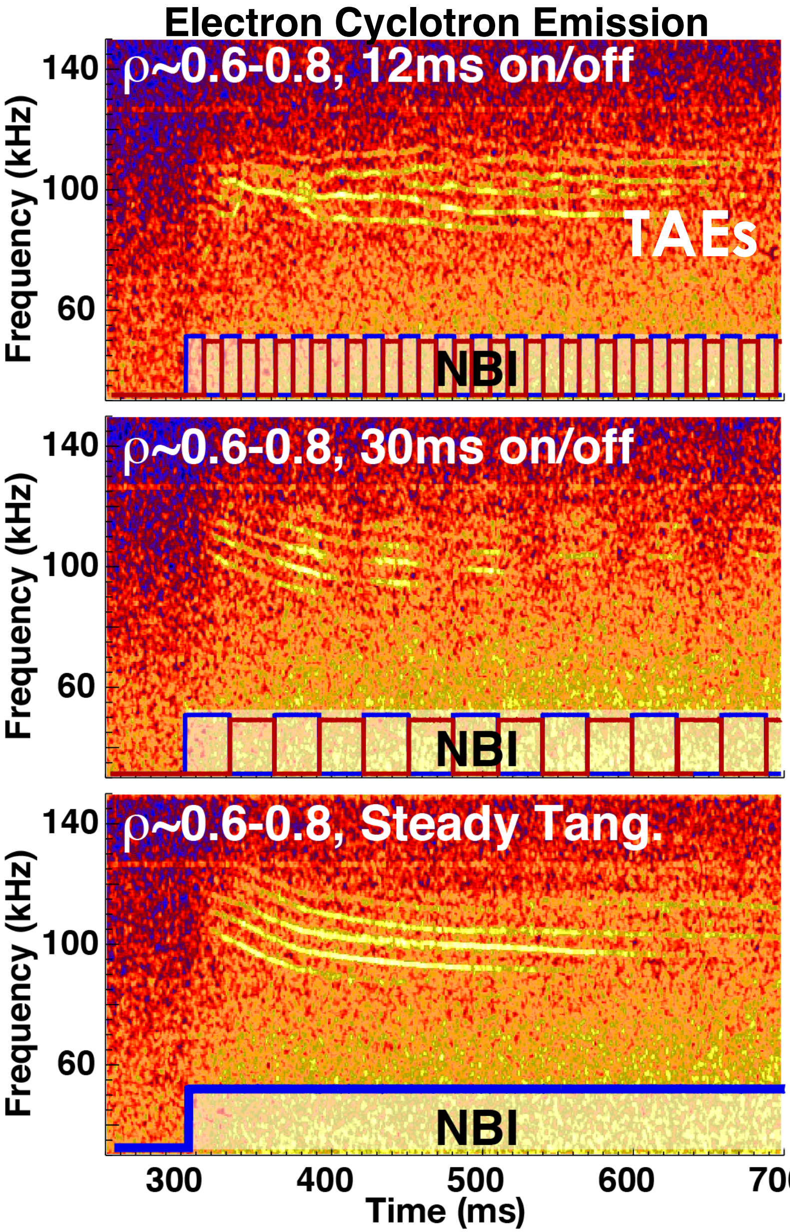
At Large Radii, TAEs are Dominant and Persistence Depends on Modulation Period

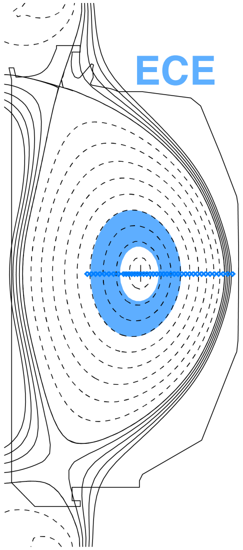
- **Multiple TAEs unstable in all cases**
  - n~3-5
- **TAEs persist in 12ms on/off and steady beam cases**
- **TAEs intermittent and weaker for 30ms on/off period**
- **TAEs strongest for steady tangential beam**
- **Modulated TAE and contributions to drive will be looked at in detail in next section of talk**

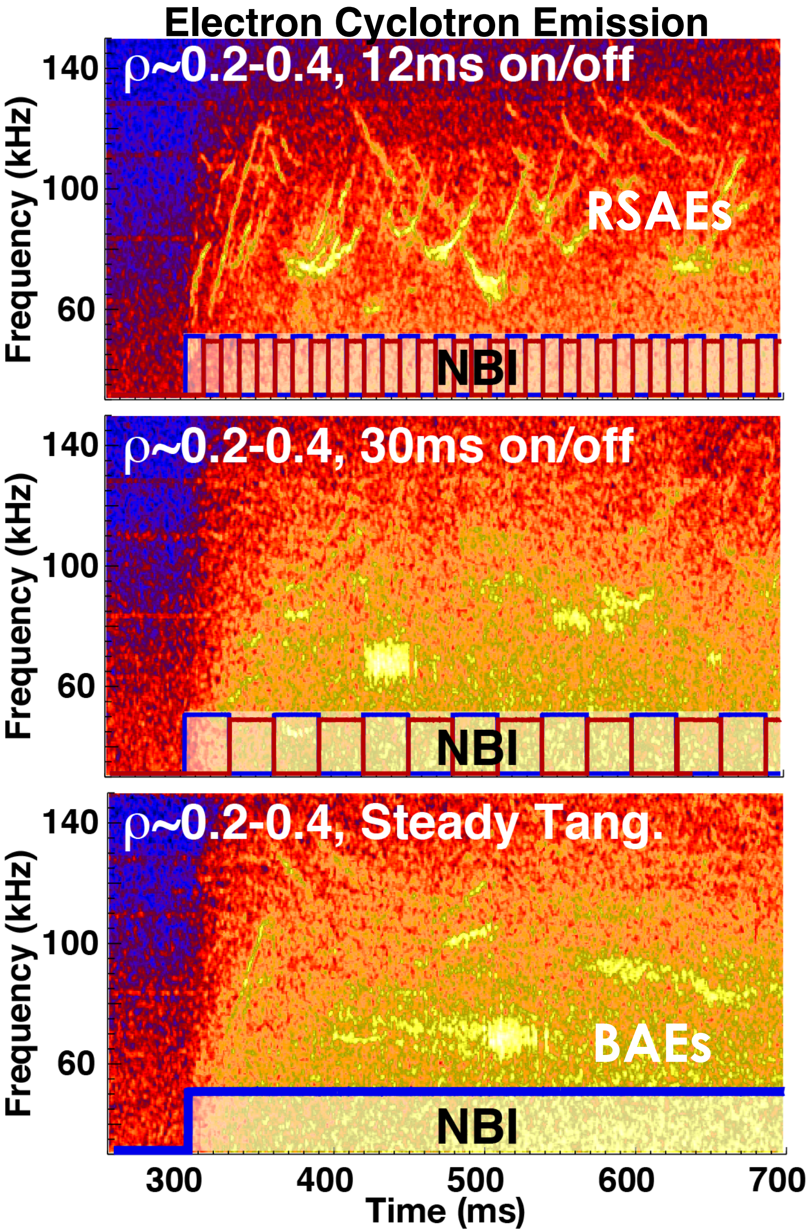




At Inner Radii, RSAEs Dominant for Short Modulation Periods But Shift to BAEs For Longer

- **12 ms on/off, multiple RSAEs and some indication of BAEs**
- **30 ms on/off and steady tangential beam case have weak RSAE and dominant BAE**
- **Shift in spectrum is *NOT* currently understood**
  - Matched density, current, etc.
  - Te higher in BAE cases
- **BAE dependence on beam and plasma parameters discussed in detail *this afternoon (Heidbrink, I-5)***
  - BAE favors tang. beam





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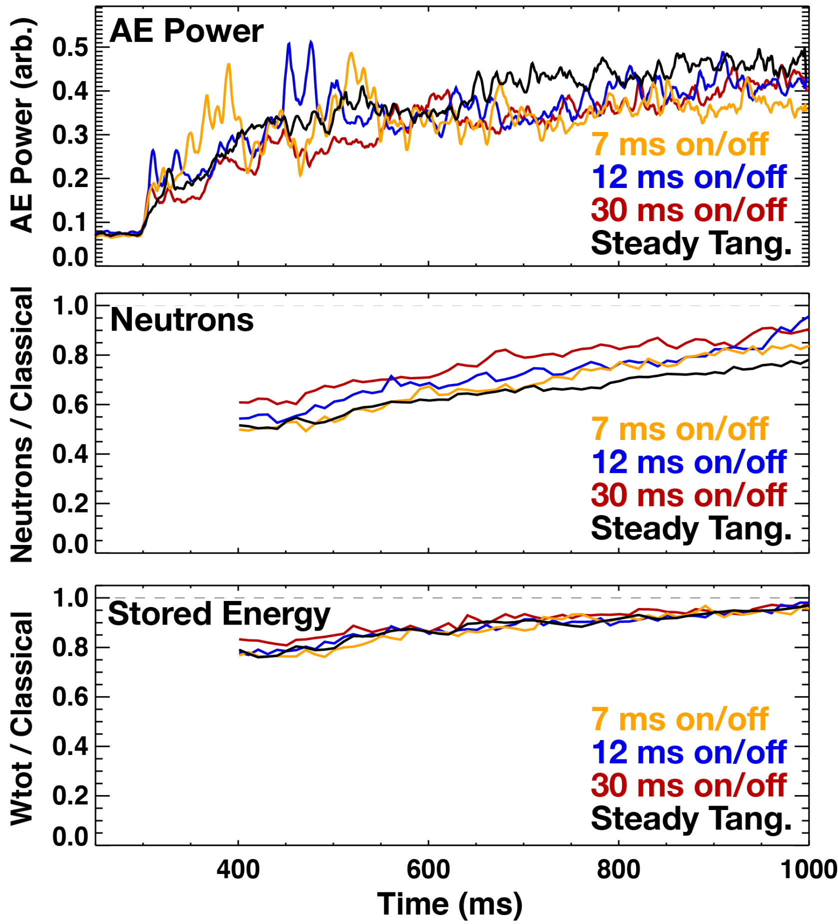
AE Impact on Fast Ion Confinement Also Depends on Modulation Period

- **AE amplitude is integrated power in AE freq. band**
  - 30 ms on/off has lowest overall amplitudes
- **Neutron emission and stored energy compared to classical TRANSP calculations**
  - A deficit indicates fast ion transport
- **All conditions have relatively large initial fast ion deficits then become classical by t=1100ms**
- **30 ms on/off has least fast ion transport**
- ***All pretty similar despite large difference in AEs = critical gradient-like behavior****



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*C.S. Collins, et.al. PRL, 116, 095001 (2016)

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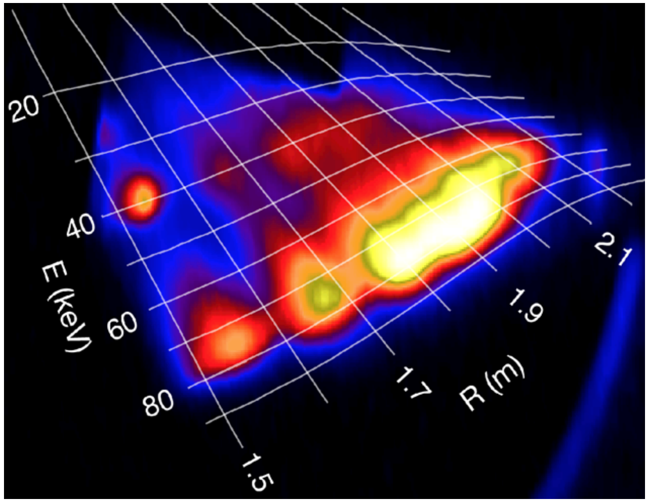

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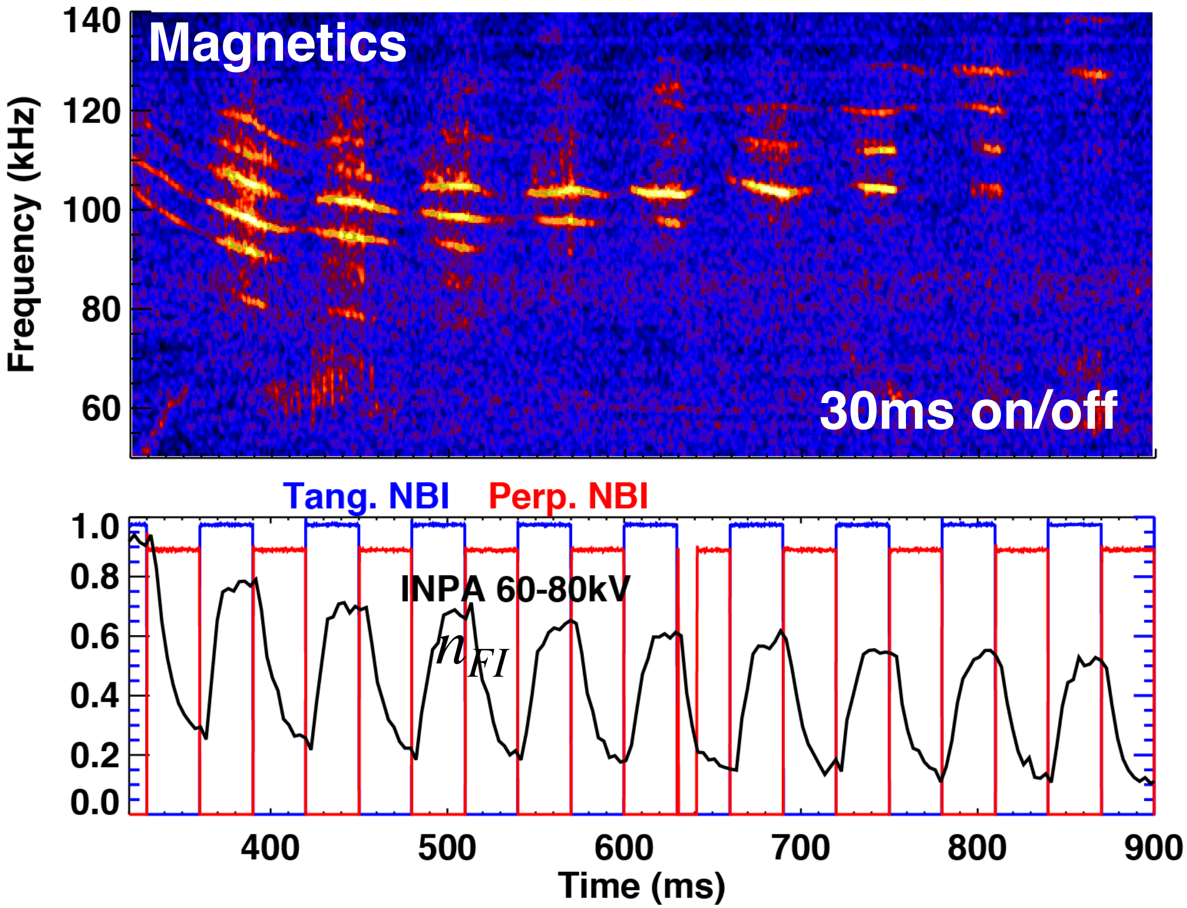
The TAEs At Large Radius Are Driven Preferentially During Tangential Beam Pulses



- **At each Tang. beam pulse, one or more TAEs unstable**
- **INPA probes local fast ion density (n_{FI}) near tangential beam pitch at TAE radius**
  - *Will use as proxy for radial gradient in local fast ion density*
  - ***Dedicated INPA talk Friday (X.D. Du, I-15)***

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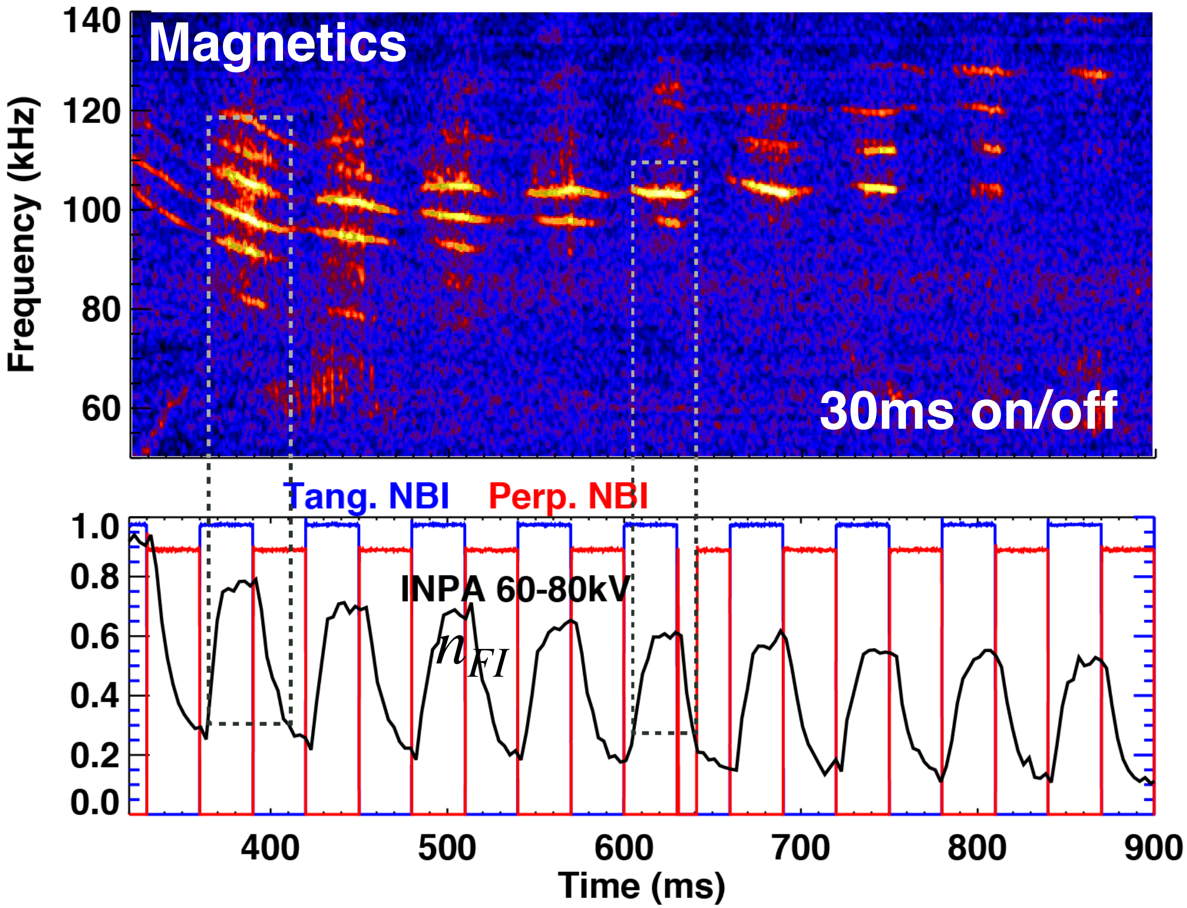

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- Modes driven unstable after beam turn-on once n_{EP} increases and stabilized when n_{EP} returns to that level
- As q_{min} drops,TAE is harder to drive and unstable at increasingly higher n_{EP}
  - Stability scan w/ qmin

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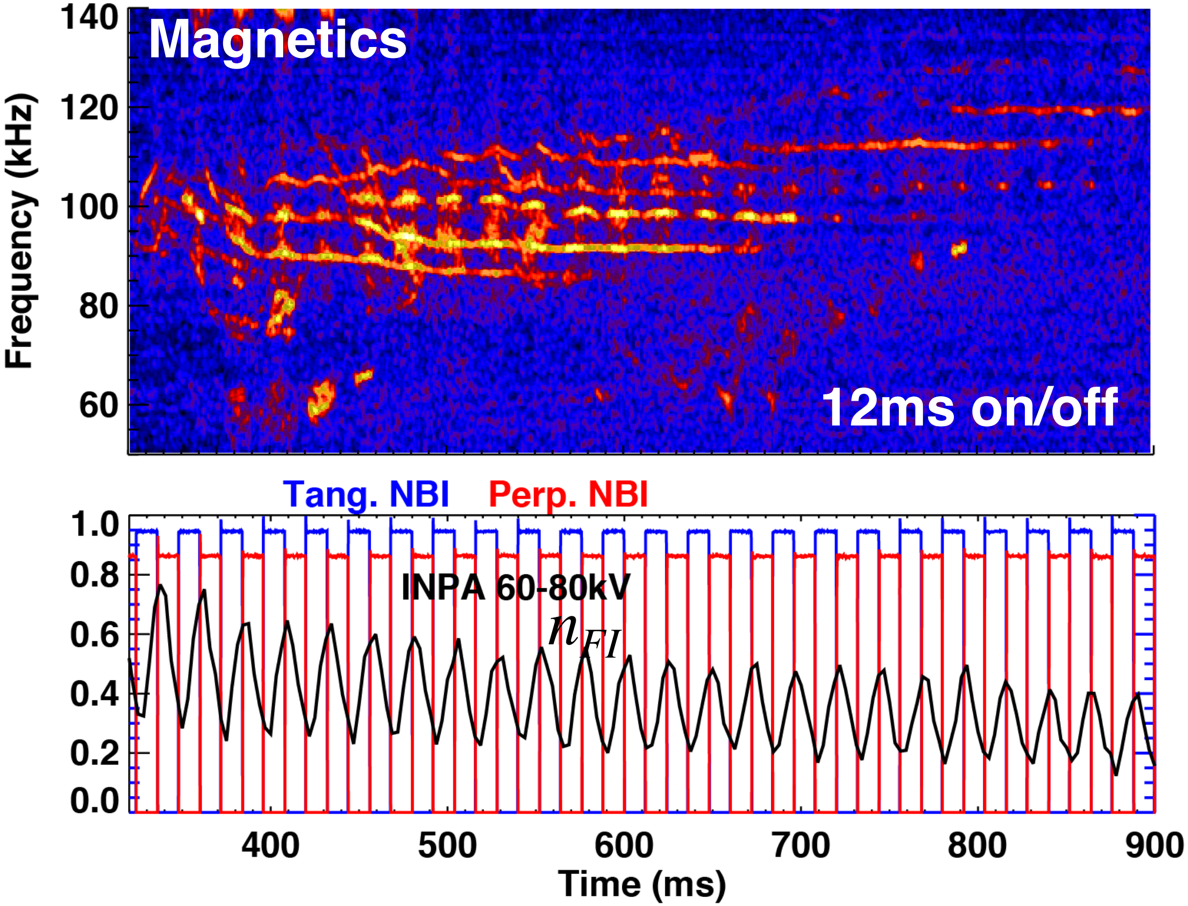
For Short Modulation Periods Majority of TAEs Remain Unstable Between Tangential Beam Pulses



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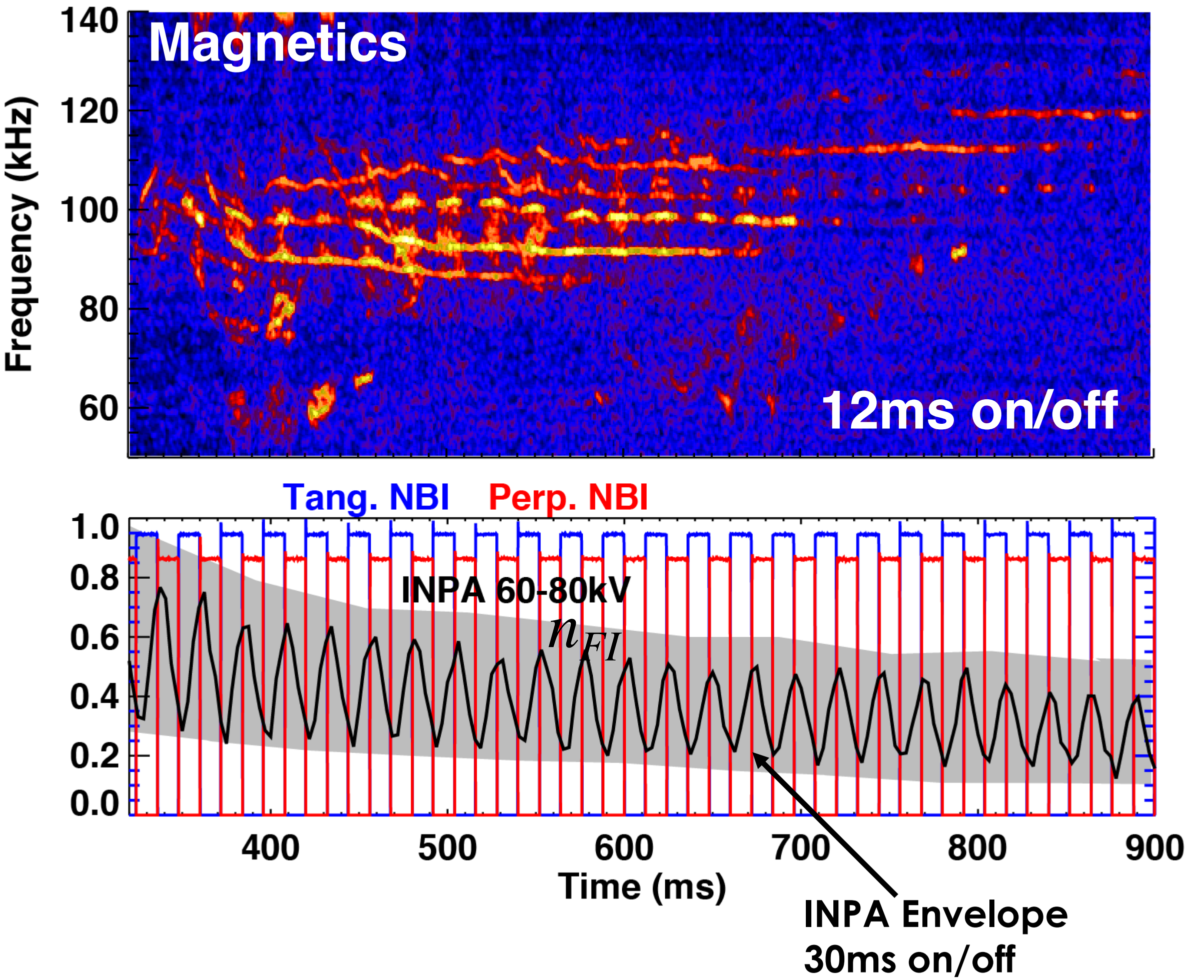

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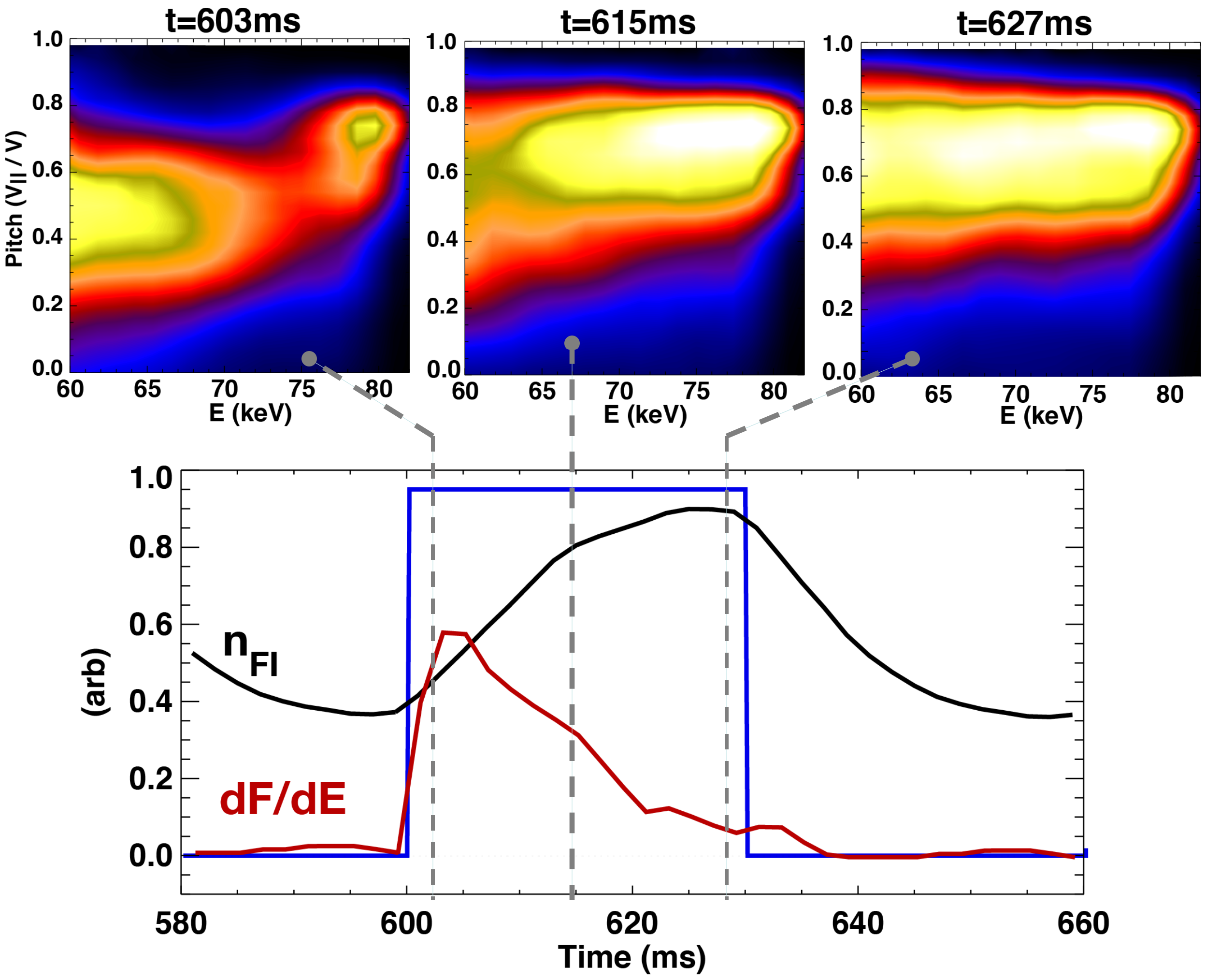
- **INPA measured 60-80kV tangential beam ion density doesn't plateau at each pulse like 30ms on/off**
- **Range of n_{FI} less than for long 30ms on/off**
- **Driving density doesn't decay enough between pulses to stabilize TAE**
- ***More persistent modes can lead to more transport***
  - *Even with same avg. injected power*

TAE Amplitude Evolution During a Tangential Beam Pulse Indicates Energy Gradient Not Primary Drive



- Distribution function evolution analyzed near TAE location
- n_{FI} = local fast ion density (60-80kV) in pitch range populated by tangential beam
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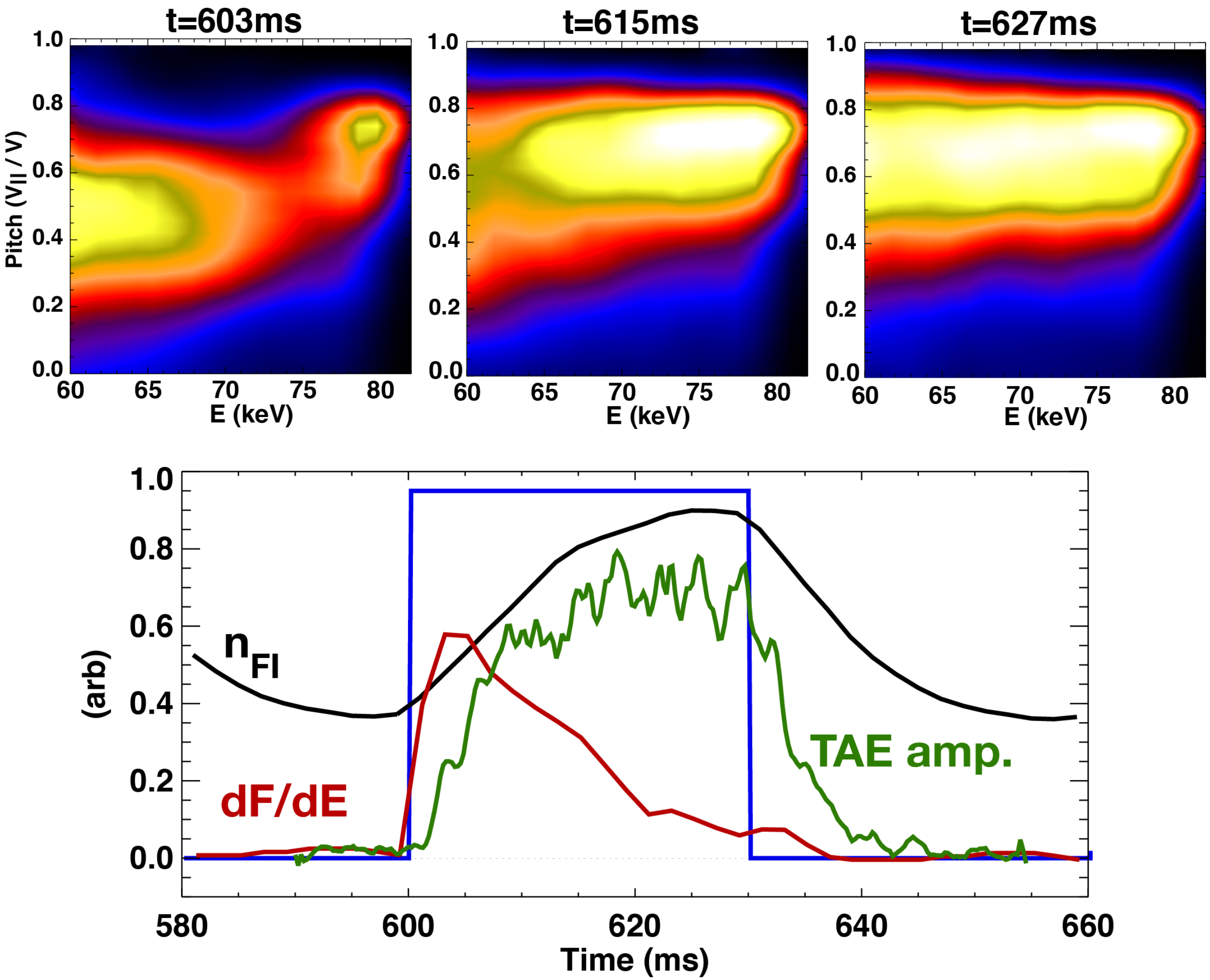

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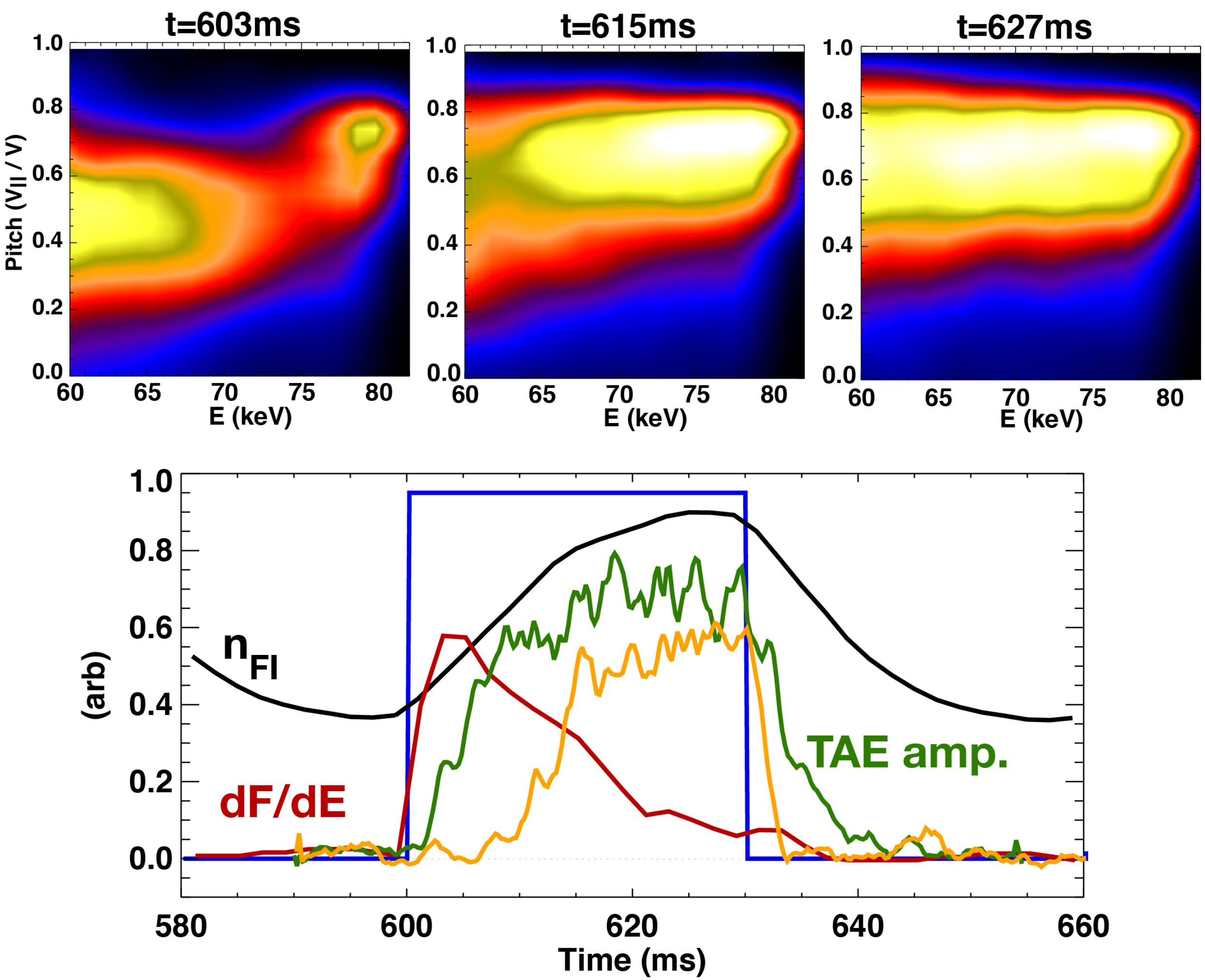

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  - Doesn't begin to decay until beam turn-off
- **TAE at later beam pulse is not unstable until after max dF/dE**

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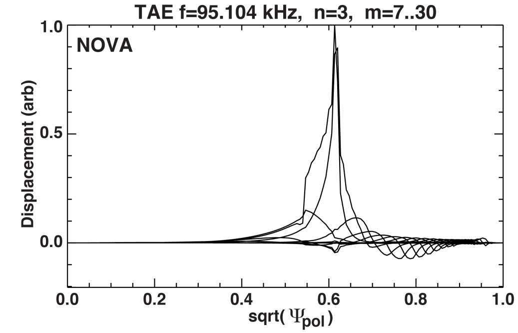
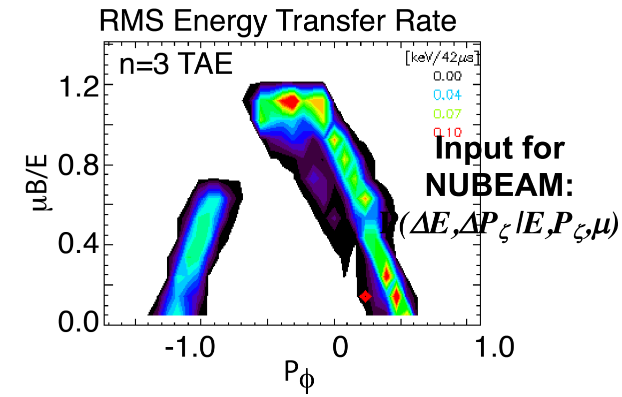
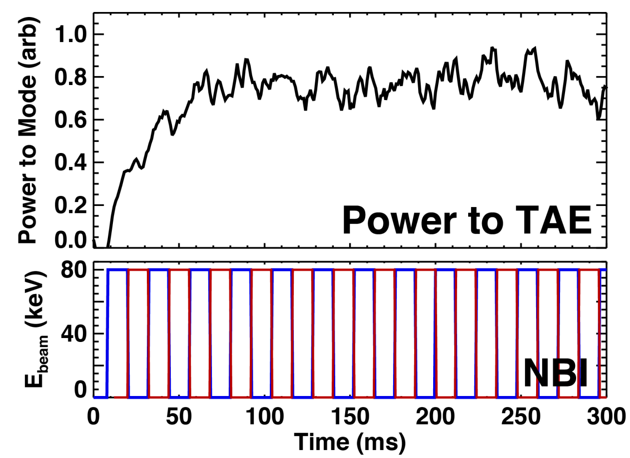
TRANSP Kick Model* Used to Calculate Energy Exchange With TAE For Different Beam Sequences

- **Eigenmodes calculated with NOVA**
  - n=3 TAE identified with localization and frequency similar to expt.
- **Kick probabilities (phase space dependent energy exchange) calculated with ORBIT**
- **Kick model in TRANSP follows beam ion energy exchange with mode in fixed equilibrium**
  - Mode set to low amplitude
- **Beam programming varied:**
  - Steady tangential beam
  - Steady perpendicular beam
  - Interleaved 12ms on/off
  - Interleaved 30ms on/off



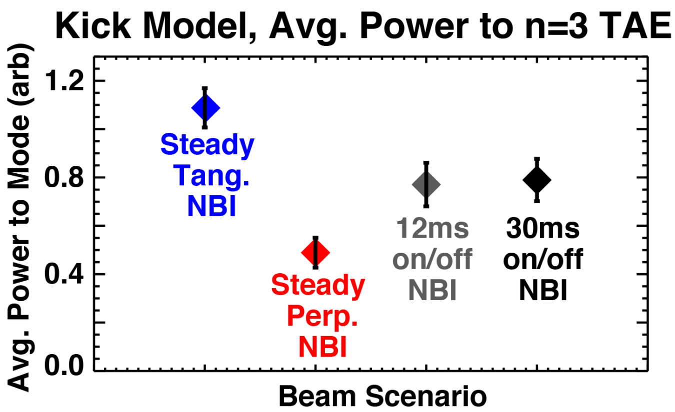




*Podesta, I-11, Kick Modeling, Thursday

Kick Model Calculations Show Variation In Power Transfer To TAE For Different Beam Sequences

- Tangential beam significantly more drive than Perp. beam - *consistent with data*
- Time avg. power transfer for 12ms on/off and 30ms on/off same - *consistent with small dF/dE role*



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Kick Model Calculations Show Variation In Power Transfer To TAE For Different Beam Sequences

- Tangential beam significantly more drive than Perp. beam - *consistent with data*
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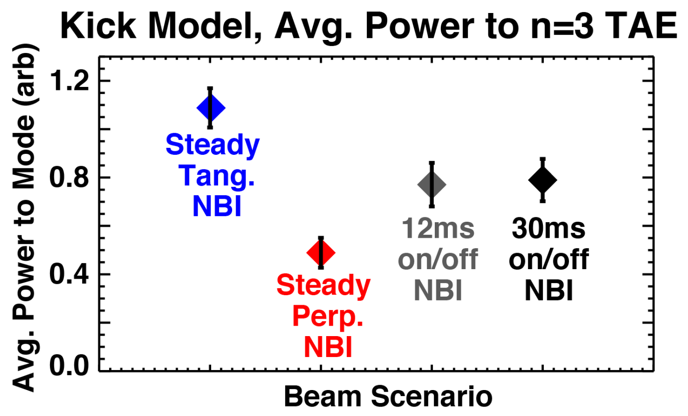

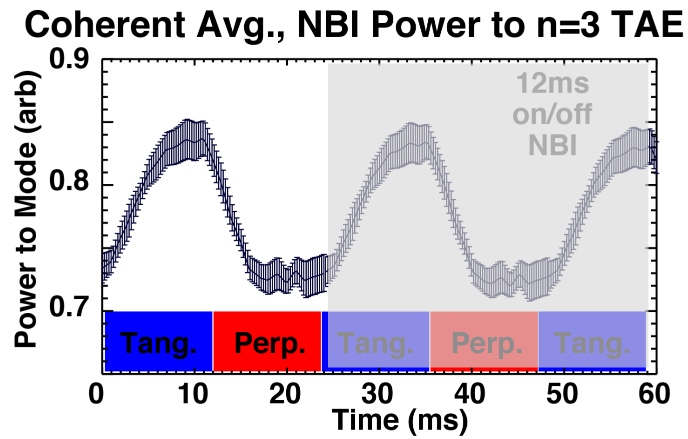

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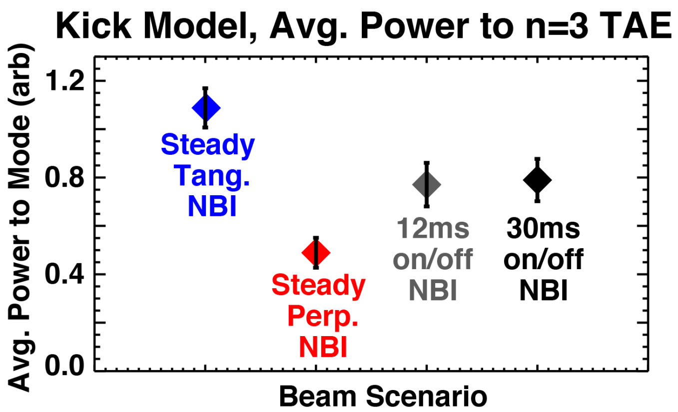

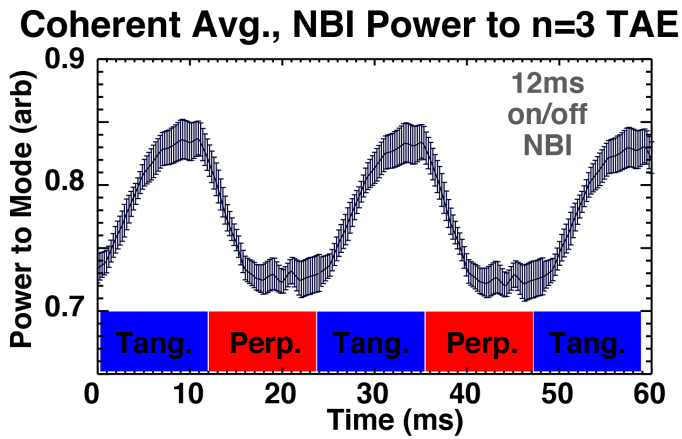

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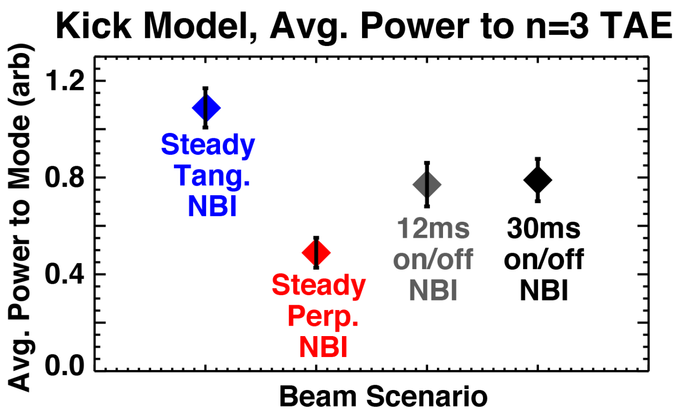
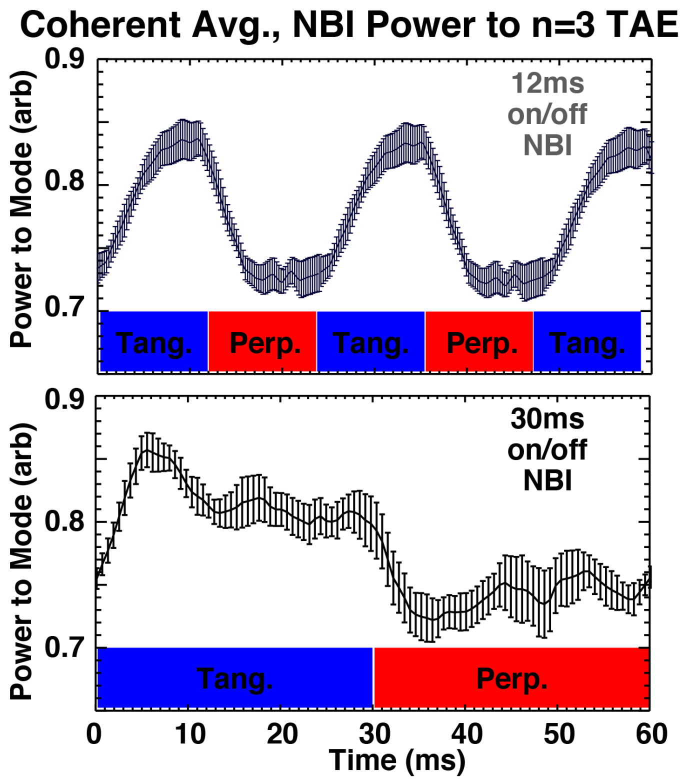
- **Power to mode coherently averaged over multiple beam pulses to reduce noise**
- **12ms on/off power to mode increases throughout tangential pulse then decays during perp. beam**
- **30ms on/off power to mode rises rapidly then decreases slightly (~5%) until steady state**
  - *Is small difference from peak representative of dF/dE effects?*





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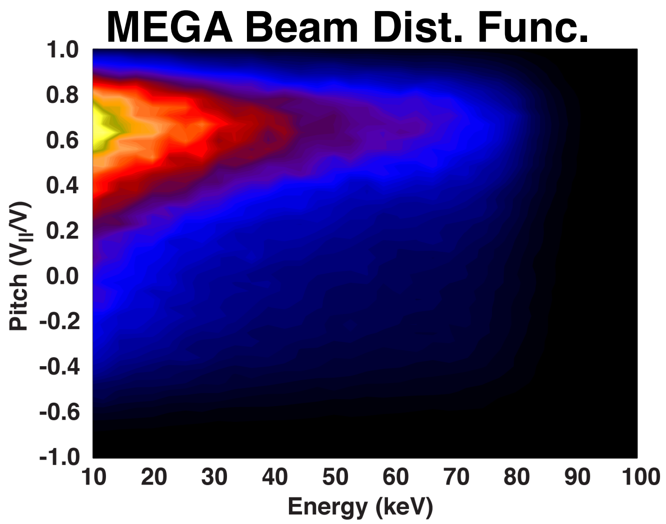
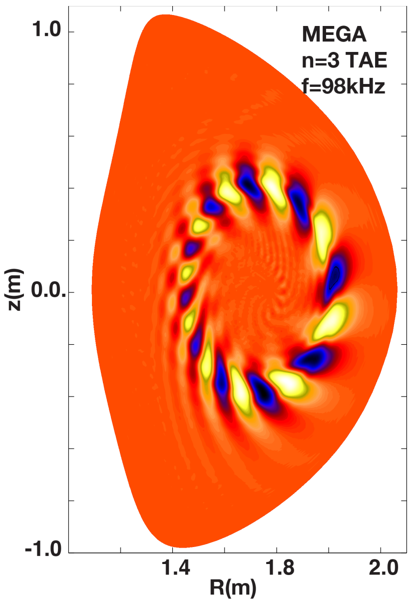
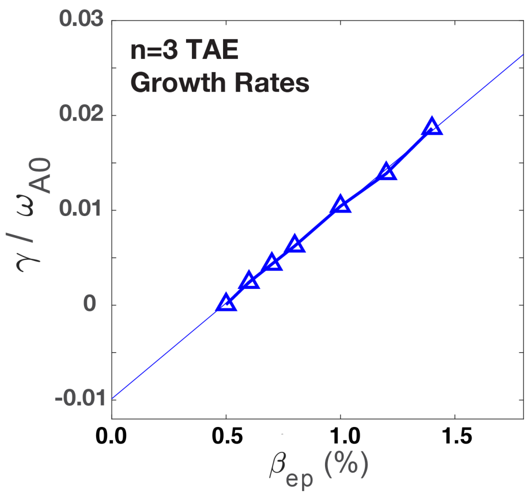
MEGA* Calculations With Realistic Beam Ion Distribution Function Find TAE Similar to Experiment

- **MEGA run in delta-F mode with functional form for beam-like distribution function**
- **n=3 TAE found at same location and frequency as expt.**
- **Mode is unstable at measured Beta-EP for *tangential* beam**
- **Consistent with expt., mode not found for *perpendicular* beam at 2X Beta-EP**







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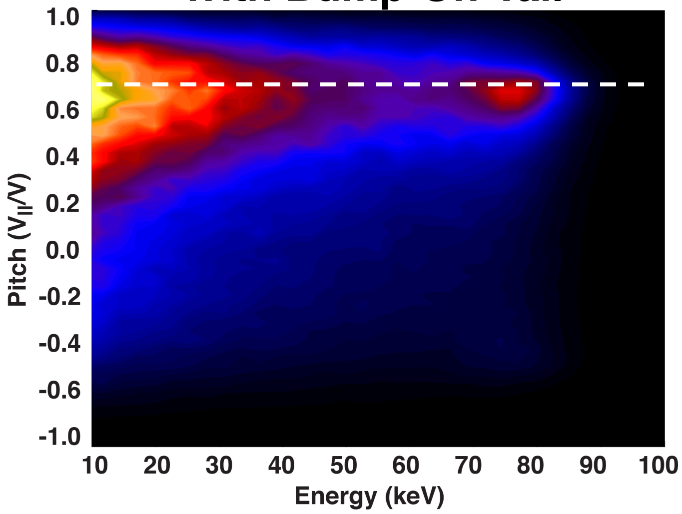
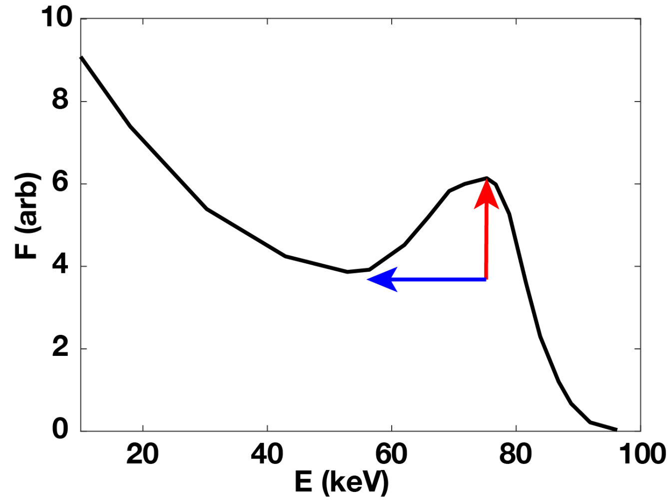
*Y. Todo, NF 54 (2014) 104012

MEGA Used To Model Bump-On-Tail Effects on AE Stability

- **Beam-like distribution modified to include Bump-on-Tail contribution**
- **Bump-on-Tail parameterized by energy gradient and peak on top of slowed down beam**
- **Mode stability calculated for range of Bump-on-Tail parameters**
  - Total fast ion pressure profile fixed

MEGA Beam Dist. Func. With Bump-On-Tail





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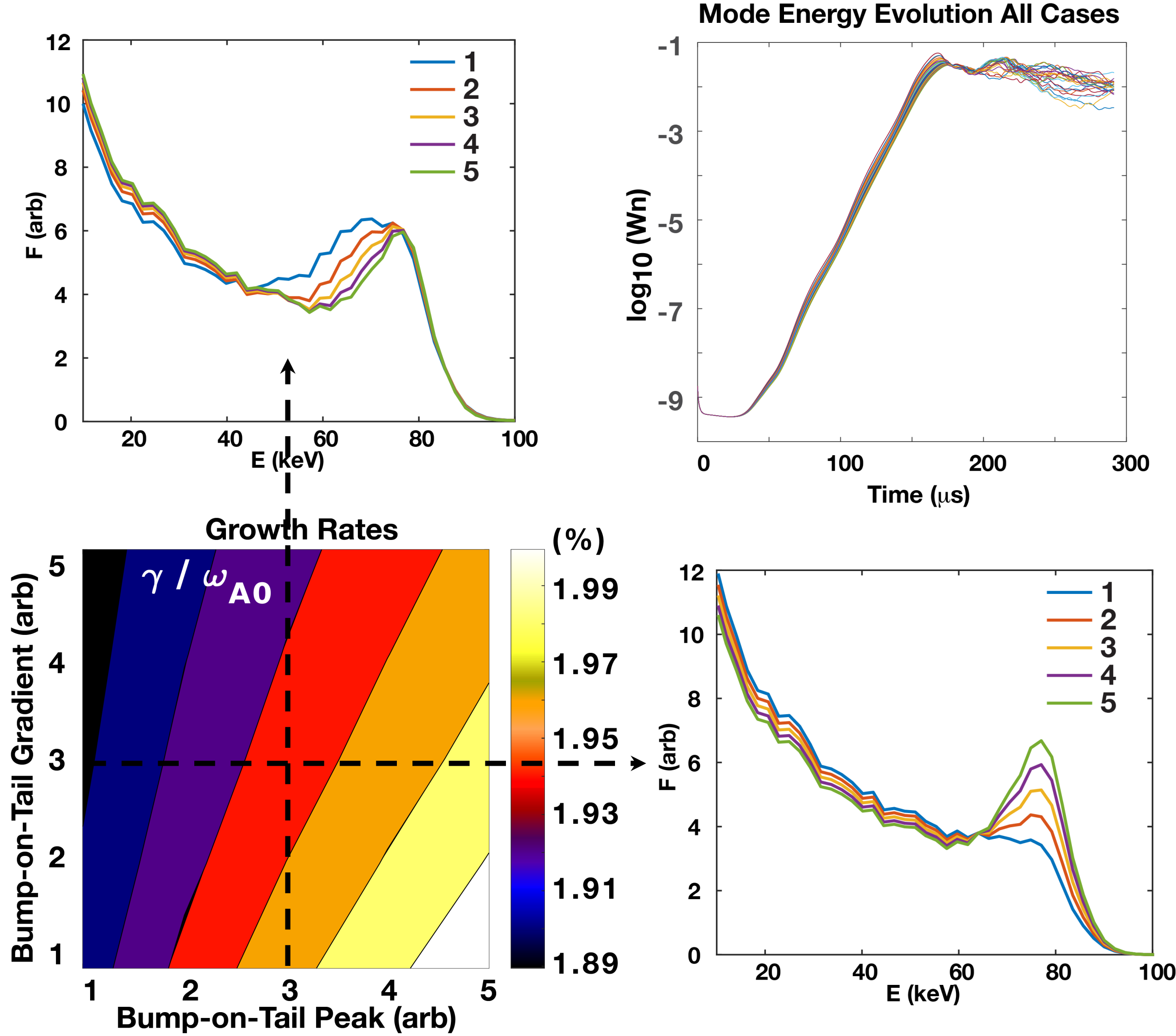
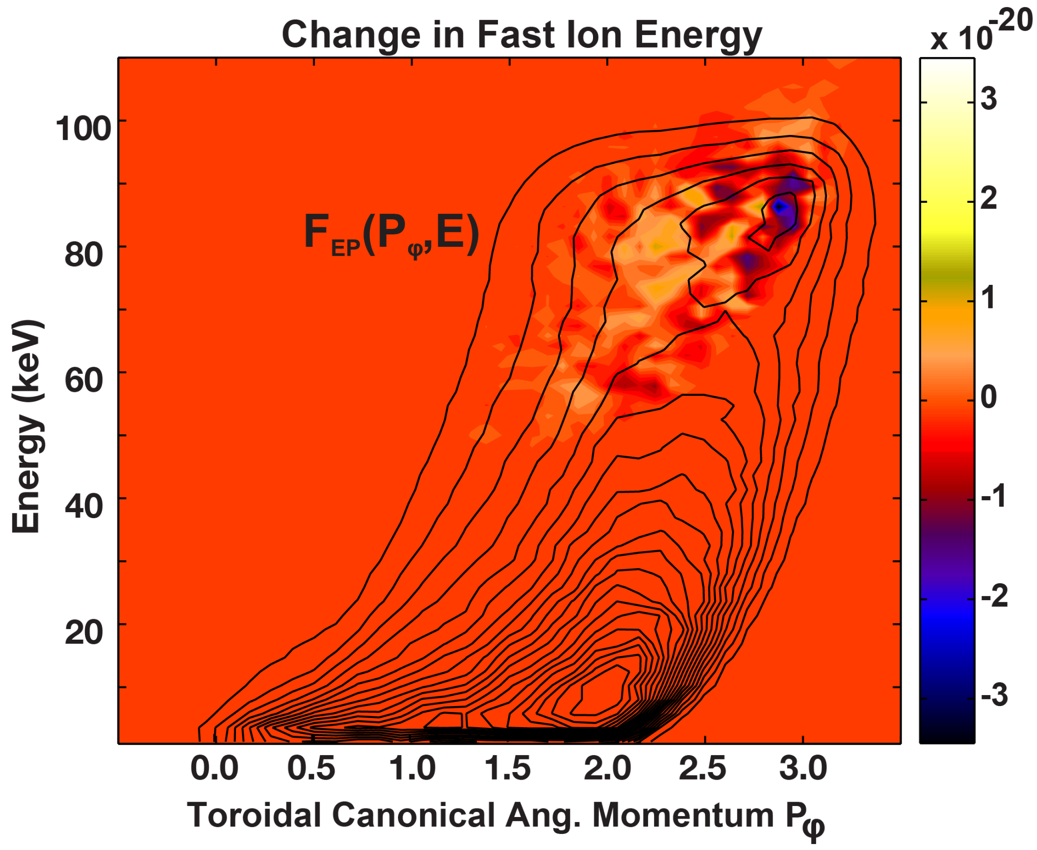
MEGA Shows Minor Impact Of Bump-on-Tail Feature On TAE Stability

- **Very small (~5%) change in growth rates over entire parameter range scanned**
- ***TAE still most unstable mode for all cases***
  - *No RSAE or other core mode*



MEGA Shows Energy Exchange With TAE Occurs At Highest Energies

- **Most efficient energy exchange happens near injection energy**



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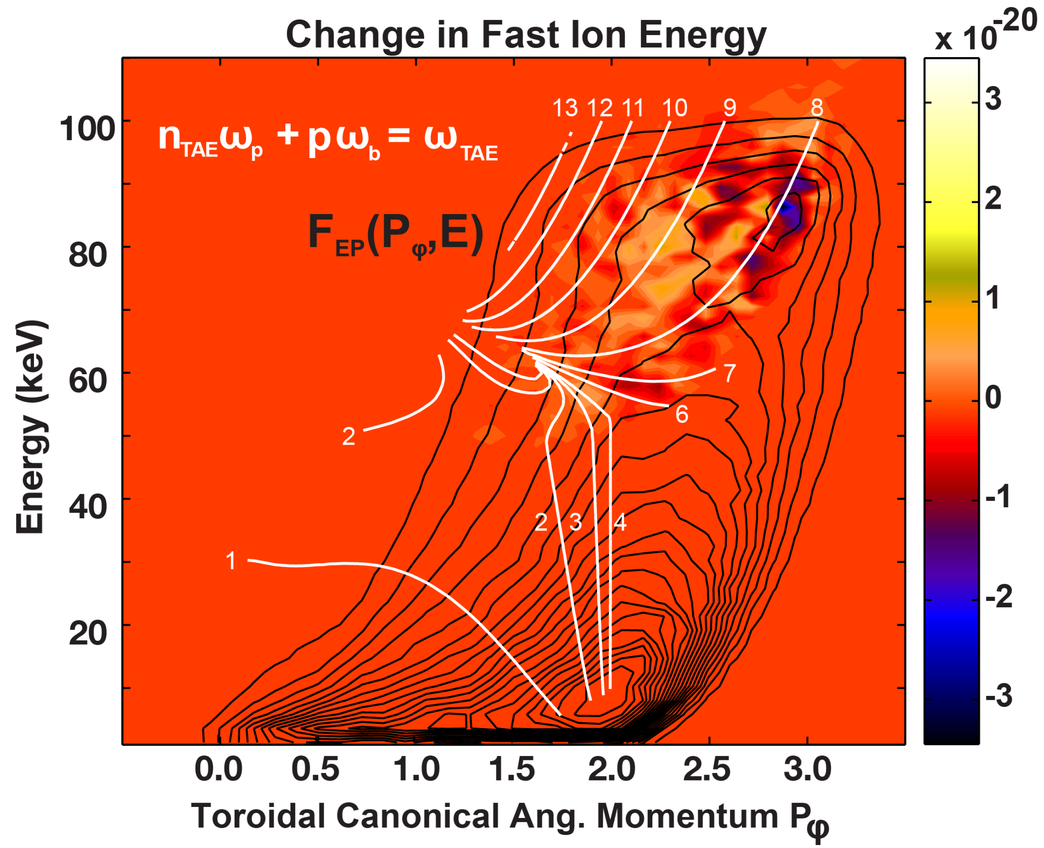
MEGA Shows Energy Exchange With TAE Occurs At Highest Energies

- **Most efficient energy exchange happens near injection energy**
- **Energy gain/loss occurs due to gradients across resonances**



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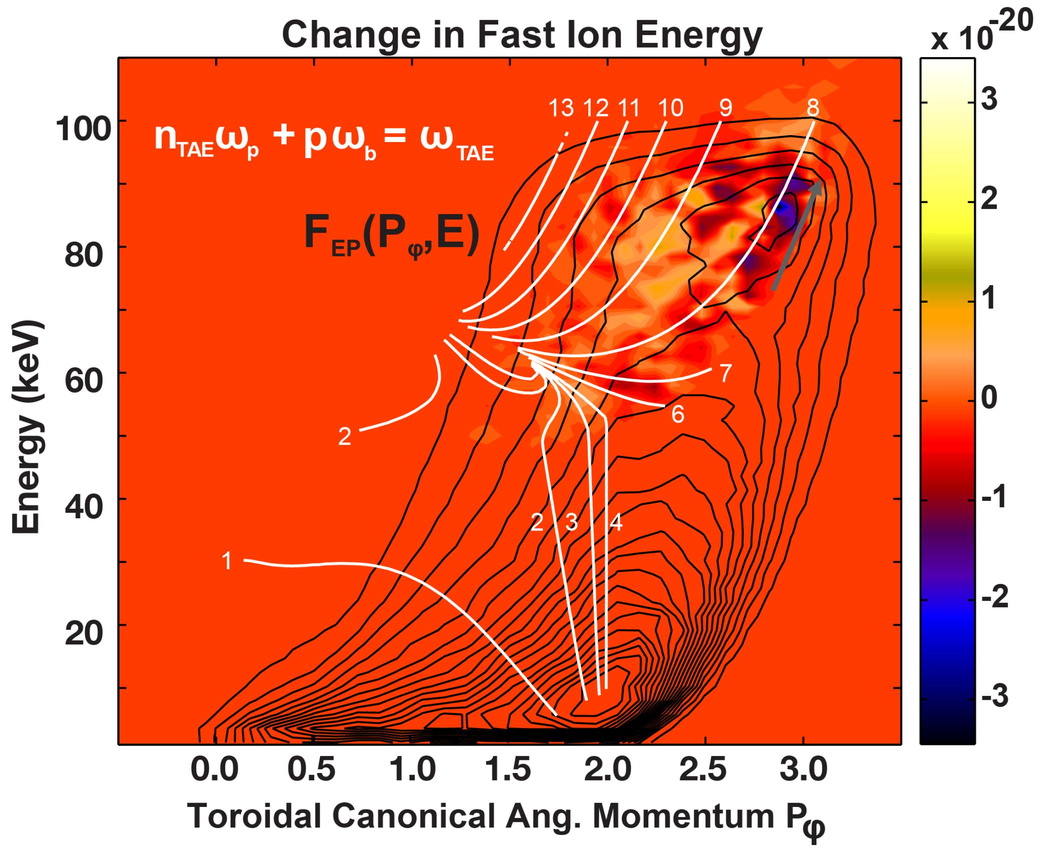
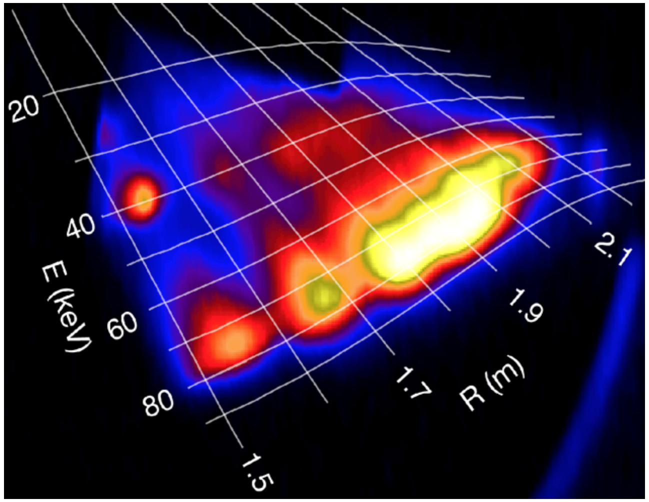
MEGA Shows Energy Exchange With TAE Occurs At Highest Energies

- **Most efficient energy exchange happens near injection energy**
- **Energy gain/loss occurs due to gradients across resonances**
- **Resonances near bump-on-tail are parallel to positive dF/dE gradient = *no energy exchange***
- **Energy exchange due primarily to dF/dPϕ**



Outline

- Experiment background and measurements of the impact of beam modulation period on AEs
- Analysis of the bump-on-tail contribution to AE drive in expt.
  - Imaging Neutral Particle Analyzer (INPA) measurements
  - TRANSP and Kick Modeling
  - MEGA Modeling
- **Measurements of TAE growth and saturation during individual beam pulses**
  - Large amplitude oscillations
  - Variation in saturation with drive and drag
  - Turbulence measurements during TAE saturation



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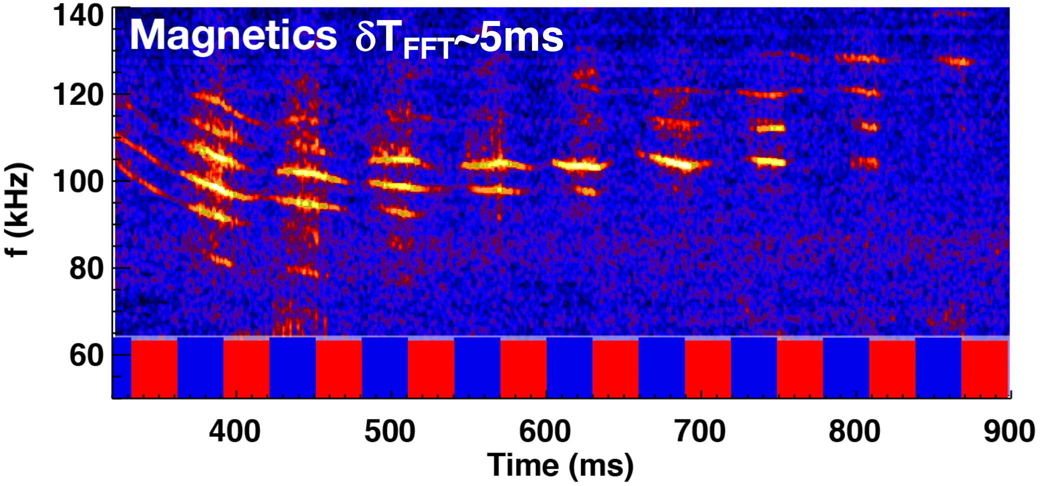
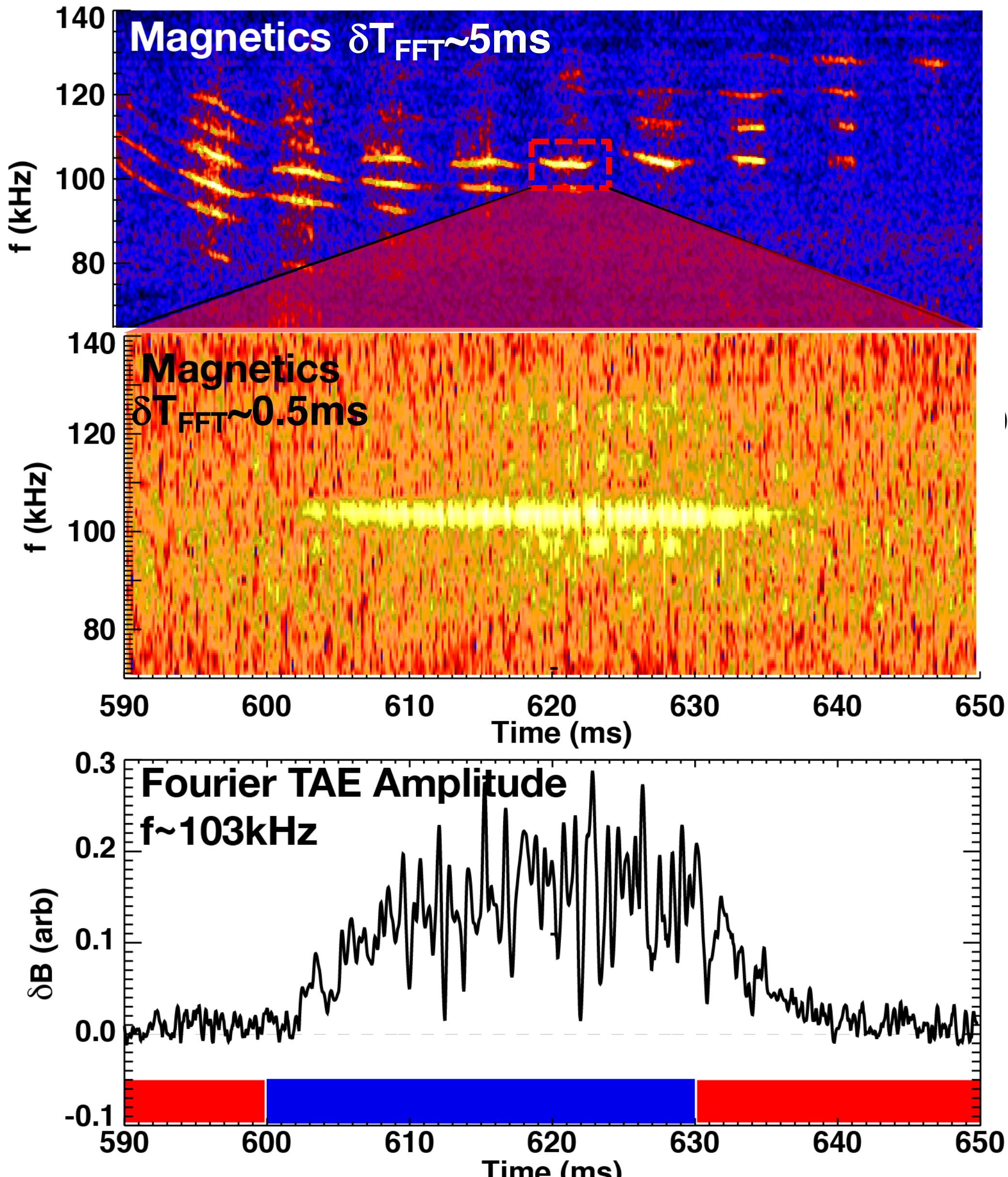
Individual Tangential Beam Pulse Shows Mode Growth and Saturation With Large Amplitude Oscillations

- **Typically large Fourier windows used (~5ms) to reduce noise**
  - ~500 waveperiods



Individual Tangential Beam Pulse Shows Mode Growth and Saturation With Large Amplitude Oscillations

- **Typically large Fourier windows used (~5ms) to reduce noise**
  - ~500 waveperiods
- **When Fourier window reduced (~0.5ms, 95% overlap) noise increases but growth and intermittent amplitude evolution become apparent**
  - Mode not visible in raw data
- **Large ($\delta A/A$~75%) intermittent amplitude oscillations**
  - Period ~ 10-100 waveperiods
- **Frequency relatively steady $\delta f/f$<2%**



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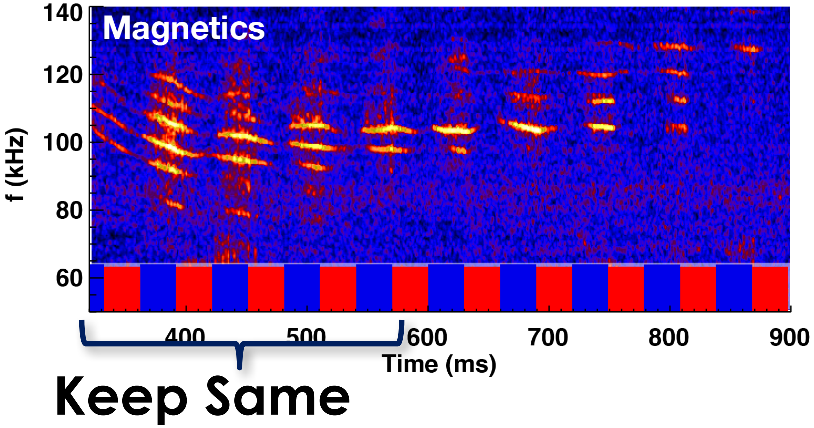
TAE Growth During Tangential Beam Pulse Exploited To Test Models for Mode Saturation

Expt. Approach

- **Fix beginning phase until t=600ms pulse**



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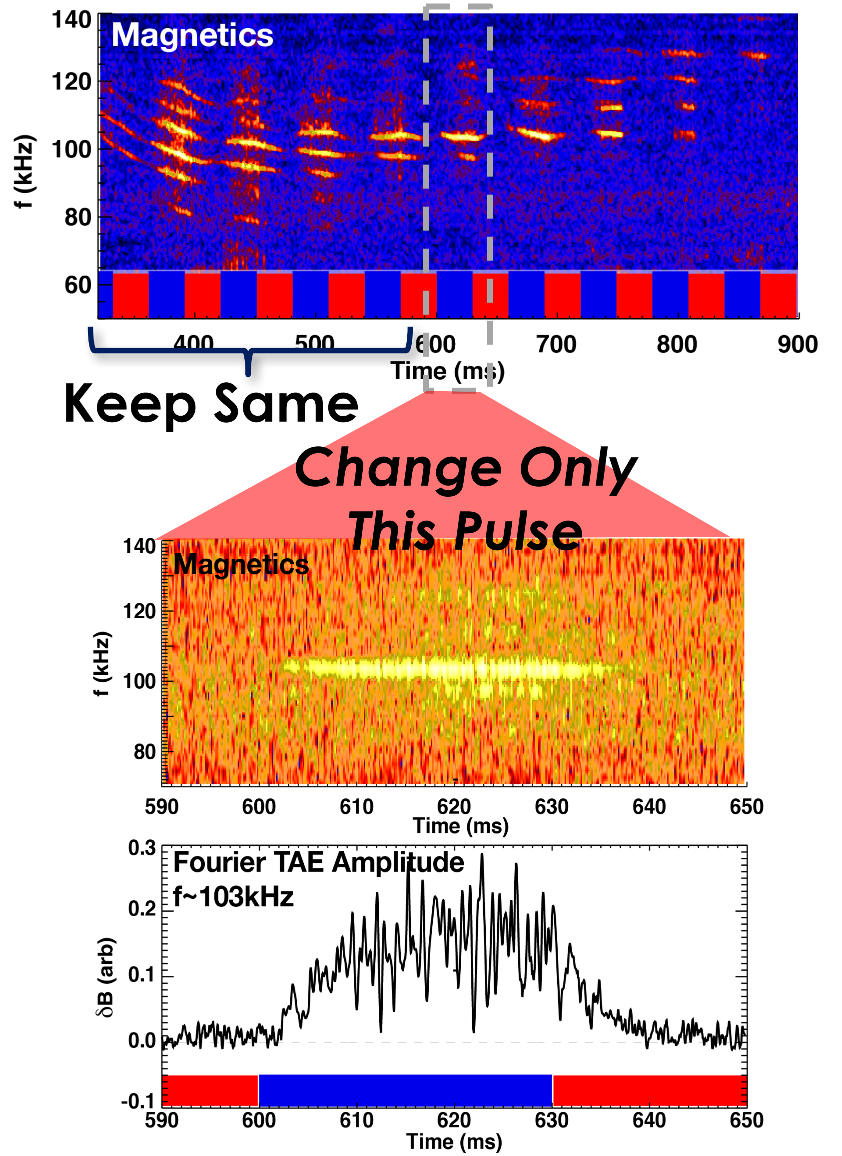
TAE Growth During Tangential Beam Pulse Exploited To Test Models for Mode Saturation

Expt. Approach

- **Fix beginning phase until t=600ms pulse**
- **At single pulse, scan parameters expected to modify mode saturation (Drive, drag, scattering)**
  - Drive: Add/Remove beam power
  - Drag: Add ECH at mode location
- **Test if mode can be varied over range of saturation scenarios**
  - *Steady-freq. & no amp. Oscillations*
  - *Steady-freq. & large amp. oscill.*
  - *Chirping*
- **Look changes in turbulence at mode location**



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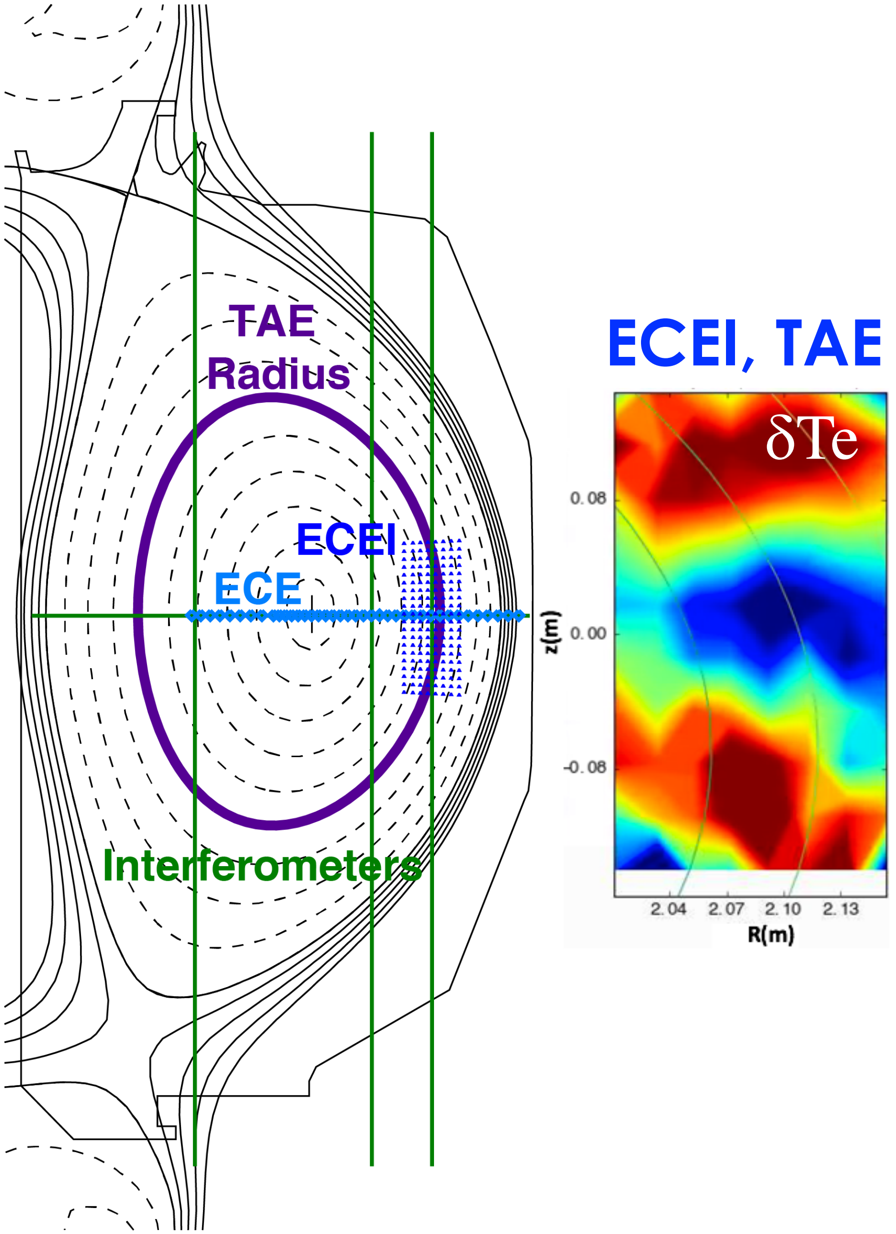
Multiple MHD and Turbulence Diagnostics Were Positioned Exactly at TAE Location

- **TAE mode structure and evolution from: Electron Cyclotron Emission (ECE), ECE Imaging (ECEI)**



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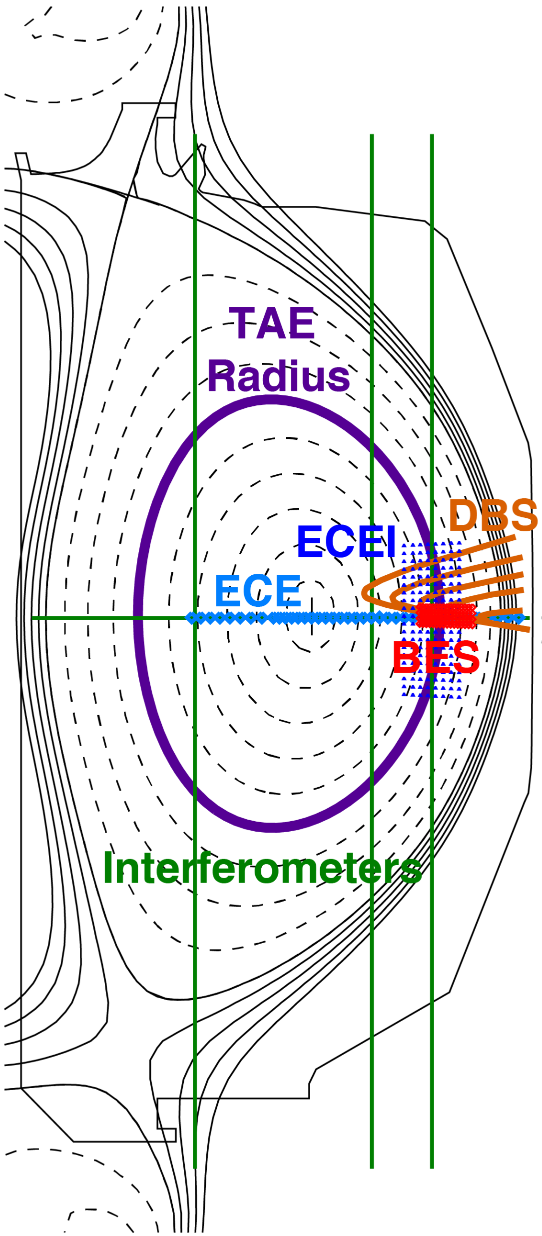
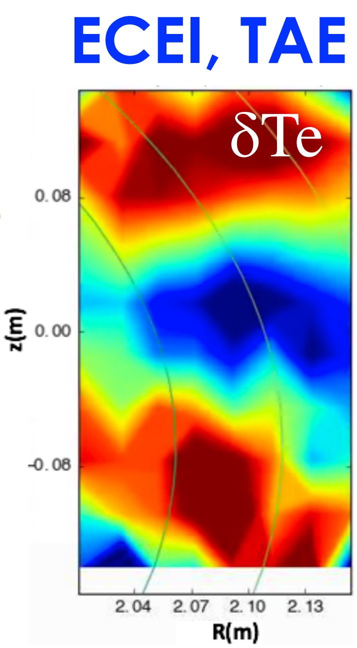
Multiple MHD and Turbulence Diagnostics Were Positioned Exactly at TAE Location

- TAE mode structure and evolution from: Electron Cyclotron Emission (ECE), ECE Imaging (ECEI)

- Turbulence variation during TAE saturation from: Beam Emission Spectroscopy (BES) , Doppler Backscattering (DBS) and Correlation ECE (CECE)





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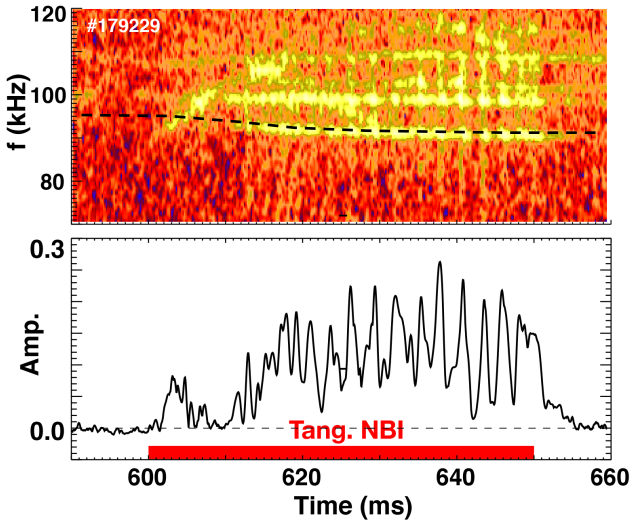
Varying Drive and Scattering Leads to Different TAE Saturation Behavior



- ***Ref. Case:*** **Larger amp. oscillations ($\delta A/A$) than target and multiple TAEs**

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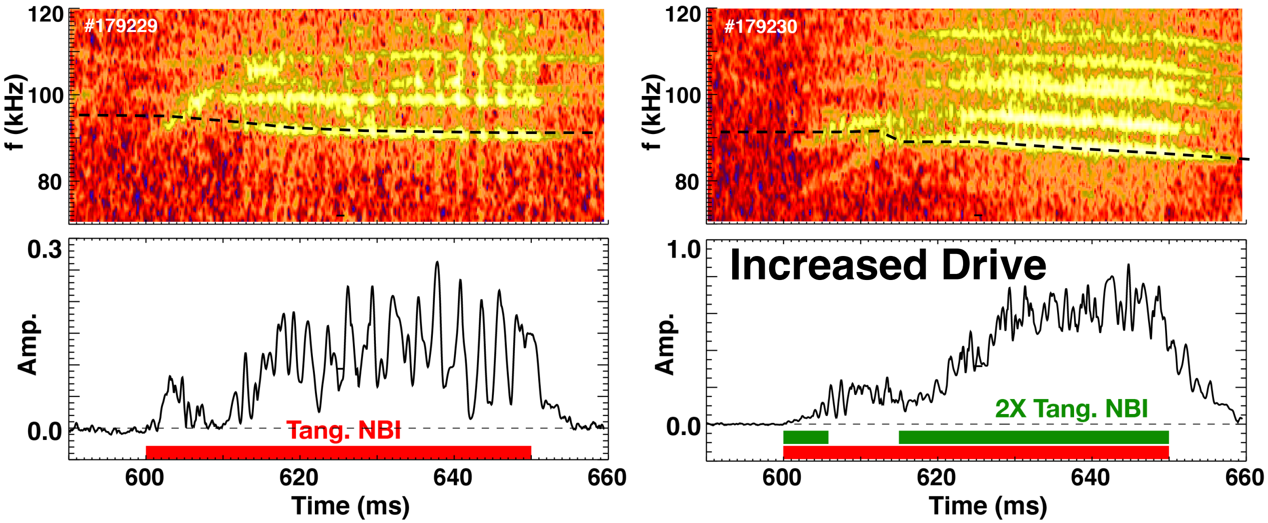

- ***Ref. Case:*** **Larger amp. oscillations (δA/A) than target and multiple TAEs**
- ***Increased Drive (added 2nd Tang. NBI):*** **Higher amplitude and smaller δA/A, also, more frequent osc.**

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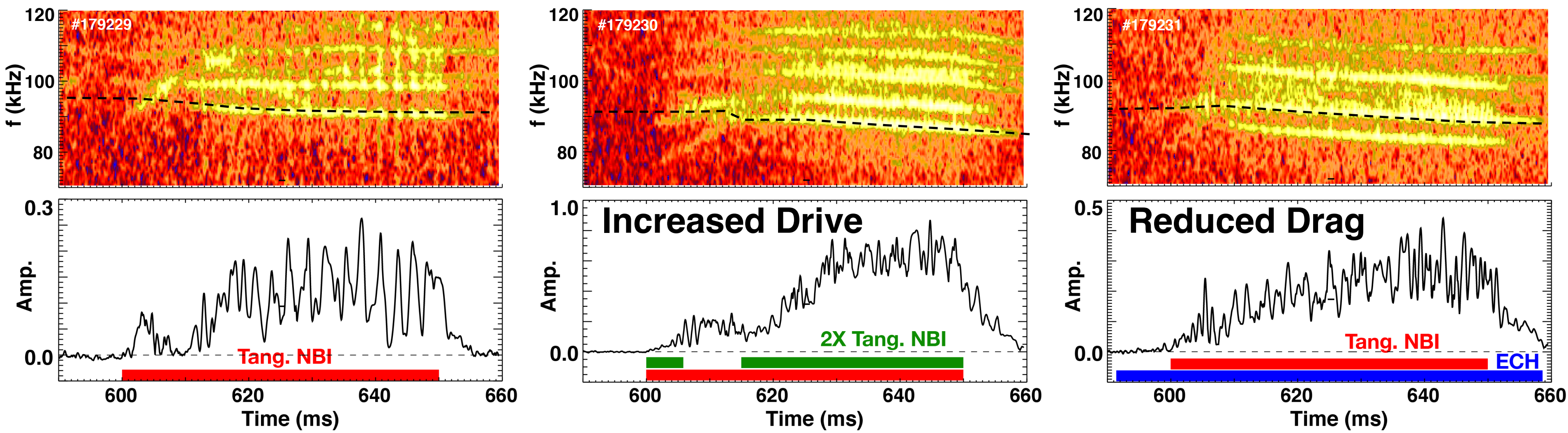

- ***Ref. Case:*** **Larger amp. oscillations (δA/A) than target and multiple TAEs**
- ***Increased Drive (added 2nd Tang. NBI):*** **Higher amplitude and smaller δA/A, also, more frequent osc.**
- ***Reduced Drag (added ECH):*** **Amplitude and δA/A between other cases and more frequent oscillations than ref. case**
- **Change in behavior can be directly compared to modeling for validation**

Conclusions

- **Short beam modulation periods relative to the slowing down time can create a persistent bump-on-tail feature**

- **A DIII-D experiment which varied modulation period of different geometry beams found significant differences in AE activity and EP transport for the same time-averaged injected power**

- **Detailed analysis of an individual TAE using TRANSP, Kick Modeling and MEGA found**
  - No strong role of energy gradient drive
  - TAE modulation with interleaved beams likely pitch dependence combined with slowing down of tangential beam between pulses

- **At saturation, modulated TAEs were found to exhibit large ($\delta A/A$~75%) intermittent amplitude oscillations with a periods ~ 10-100 waveperiods and little or no chirping**

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