Energy Channeling from Trapped to Passing Fast Ions Mediated by CAE/GAE Activity in NSTX

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and the NSTX Research Team

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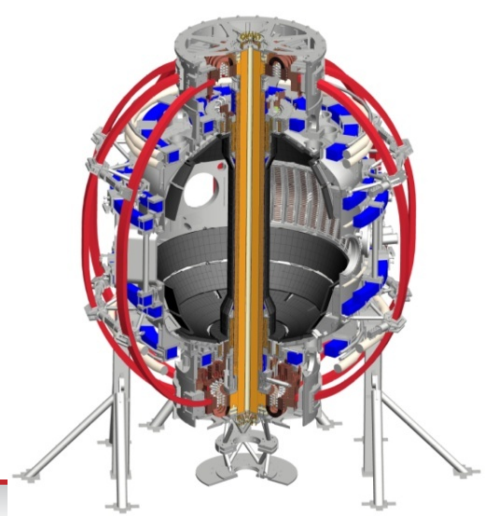

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Abstract

Energy channeling from trapped to passing fast ions mediated by GAE/CAE activity in NSTX S.S. Medley, E. Belova, G. Kramer, M. Podestà, *Princeton University* and D. Liu, *UC Irvine*

In the National Spherical Torus Experiment, an increased charge exchange neutral flux localized at the neutral beam full injection energy is measured by the EIIB Neutral Particle Analyzer. Termed the High-Energy Feature (HEF), it appears on the beam-injected energetic ion spectrum in discharges where NTM or kink modes ($f < 10$ kHz) are absent, TAE activity ($f \sim 10 - 150$ kHz) is weak and CAE/GAE activity ($f \sim$ 400 - 1200 kHz) is robust. The HEF exhibits a growth time of $t \sim 20 - 80$ ms and develops a slowing down distribution that continues to evolve over periods > 100 ms. HEFs are observed only in H-mode discharges with NB power $P_b \sim 4$ MW and in the pitch range $v_{||}/v$ 0.7 - 0.9. The HEF appears to be caused by a CAE/GAE wave-particle interaction that modifies the fast ion distribution, $f_i(E,v_{||}/v,r)$. This mechanism was studied using the SPIRAL code that evolves an initial TRANSP-calculated $f_i(E,v_{||}/v,r)$ distribution in the presence of background plasma profiles under drive from wave-particle resonances with CAE/GAE Alfven eigenmodes.

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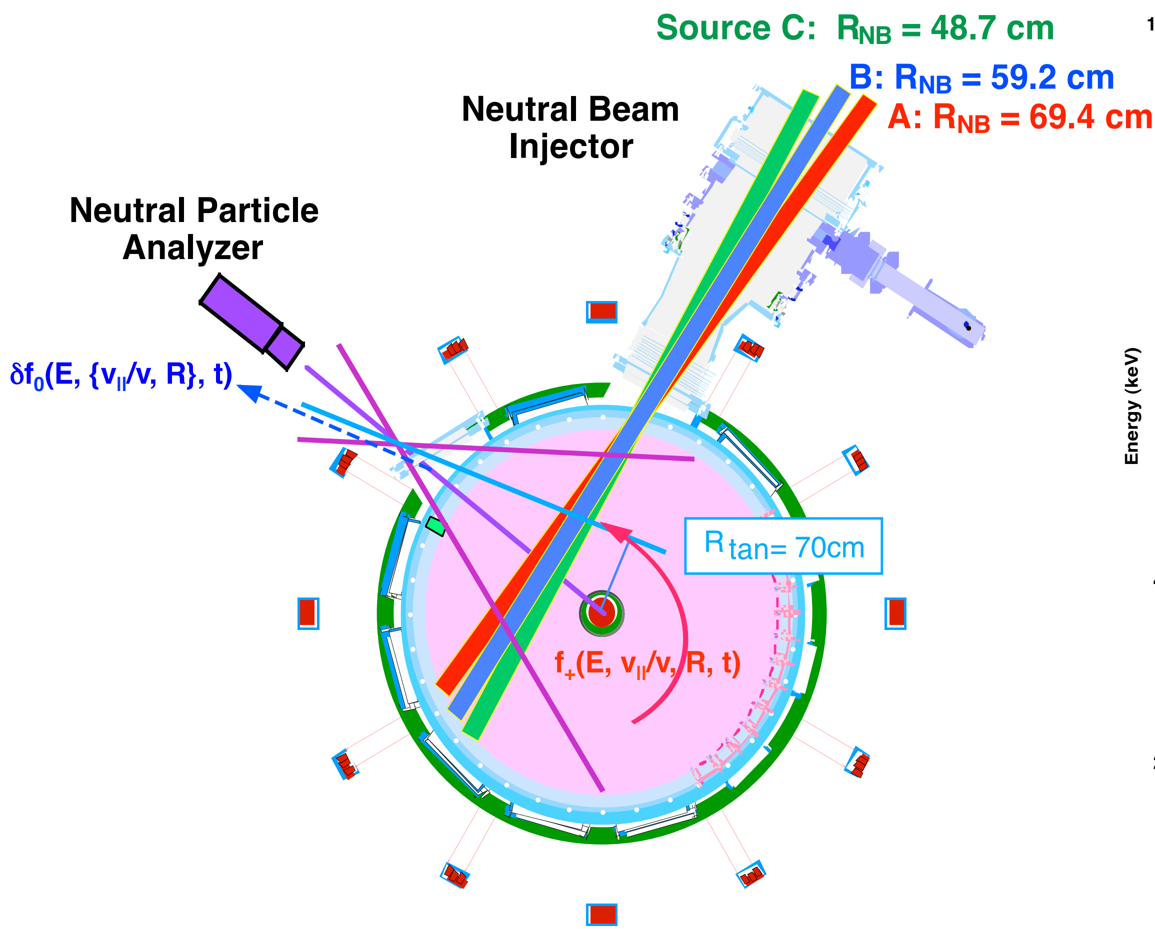
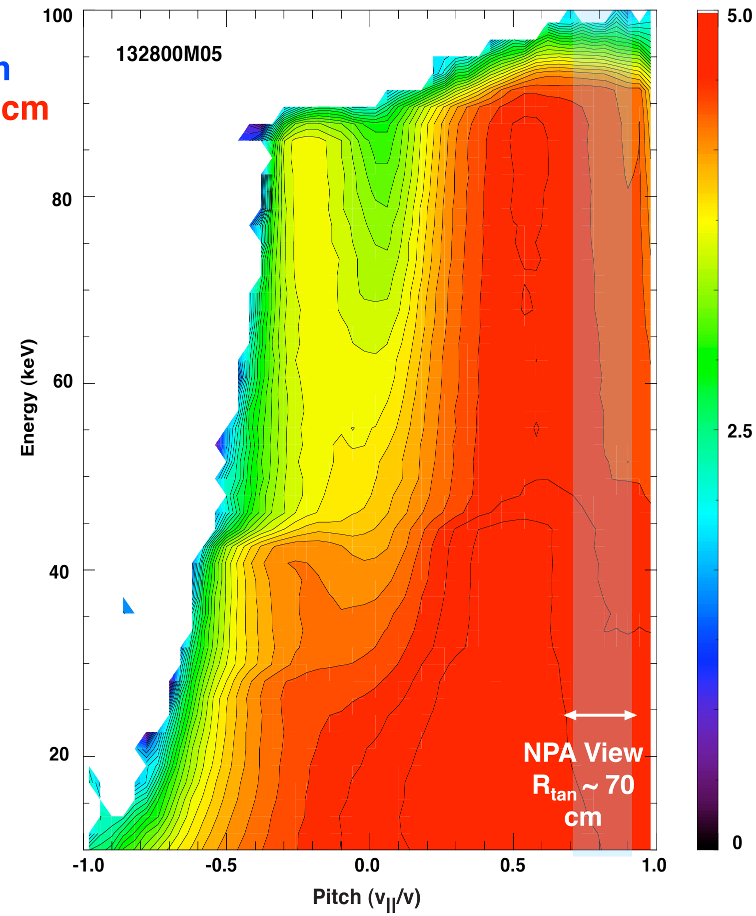
The EIIB Neutral Particle Analyzer (NPA) on NSTX

The NPA scanned horizontally on a shot-to-shot basis over a range $-75 < R_{tan}(\text{cm}) < 125$

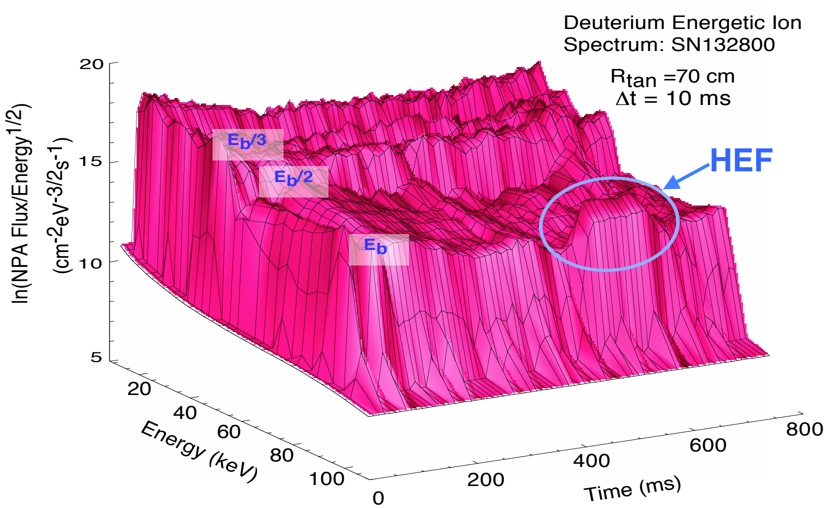


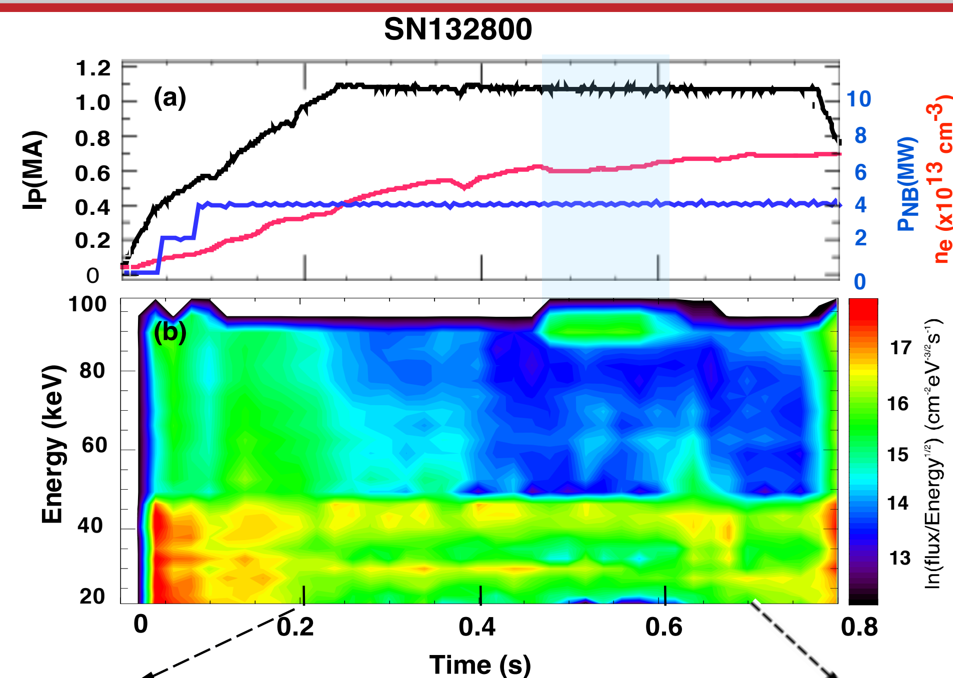


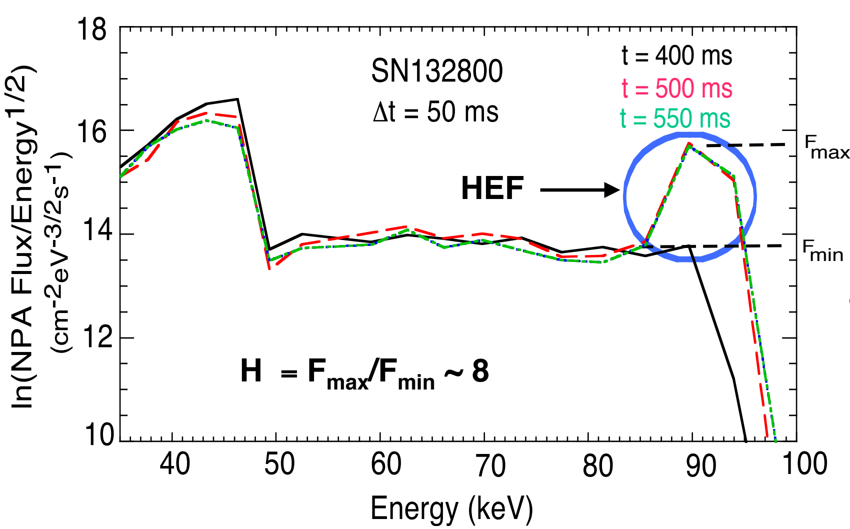
•NPA flux, $\delta f_0(E, \{v_{||}/v, R\}, t)$, is localized to charge exchange of the circulating fast ions, $f_+(E, v_{||}/v, R, t)$, at the sightline intersection with the beam (and halo) neutral footprint. For $R_{tan} \sim 70$ cm, $R_{int} \sim 80 \pm 10$ cm.

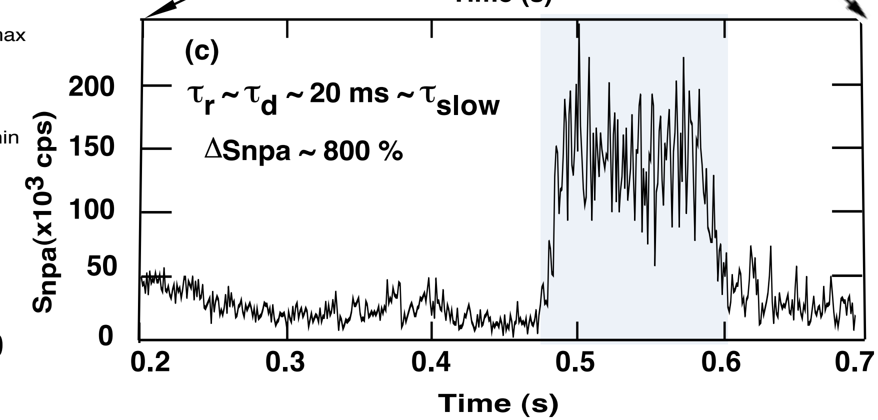
From the NPA simulator in TRANSP, for 'typical' $R_{tan} \sim 70$ cm, the NPA views passing ions with $v_{||}/v \sim 0.8 \pm 0.1$.

The High-Energy Feature (HEF) is a Large Increase in the NPA Charge Exchange Flux Localized Around E ~ E_b





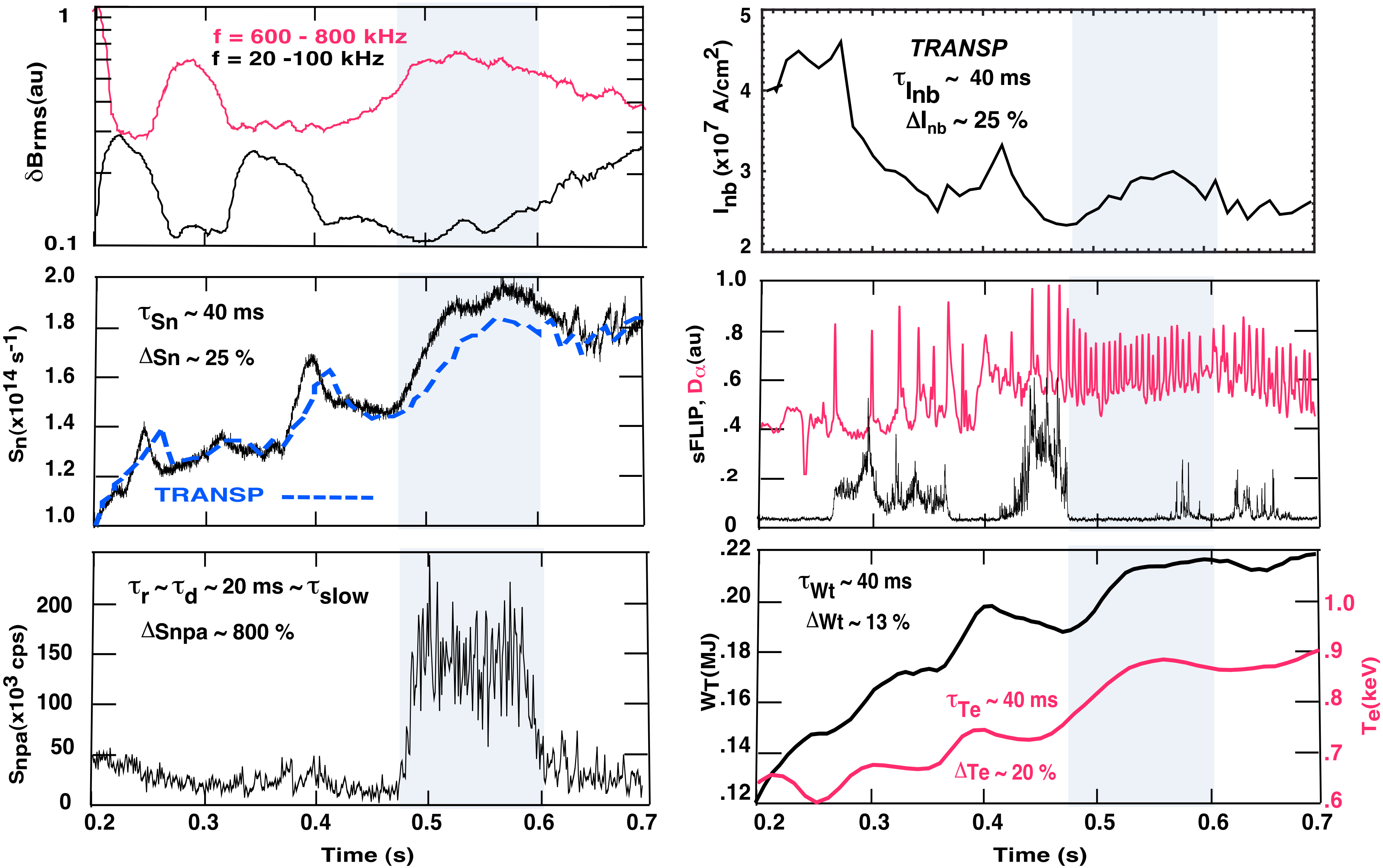




- The HEF evolves as a ***CX flux enhancement*** above the normal slowing down distribution.

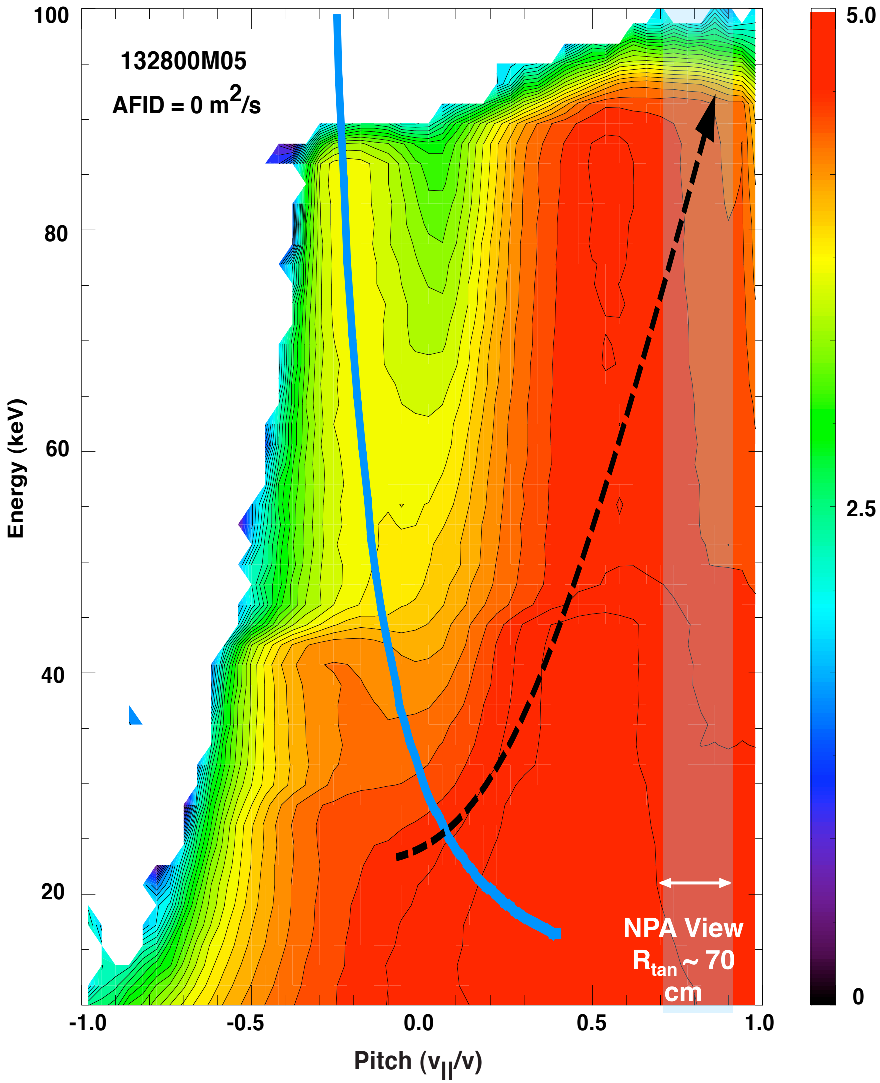
HEF Activity "Drives" NSTX Plasma Parameter Enhancements

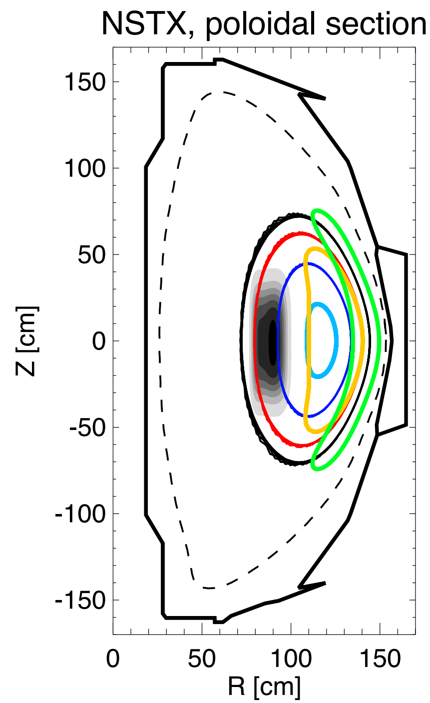
Plasma parameter excursions consistently follow HEF growth with a lag time of ~ 20 ms

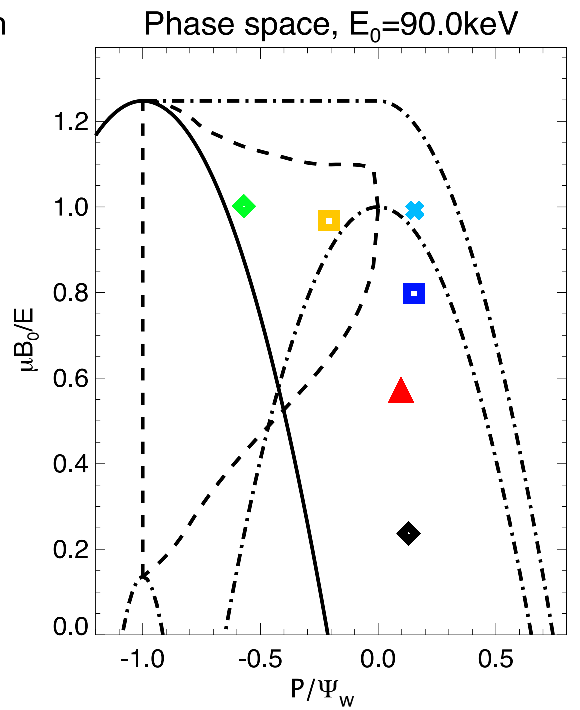


Phase and Configuration Space View of the HEF Mechanism

The NPA views a wide energy range but only a small portion of phase/configuration space

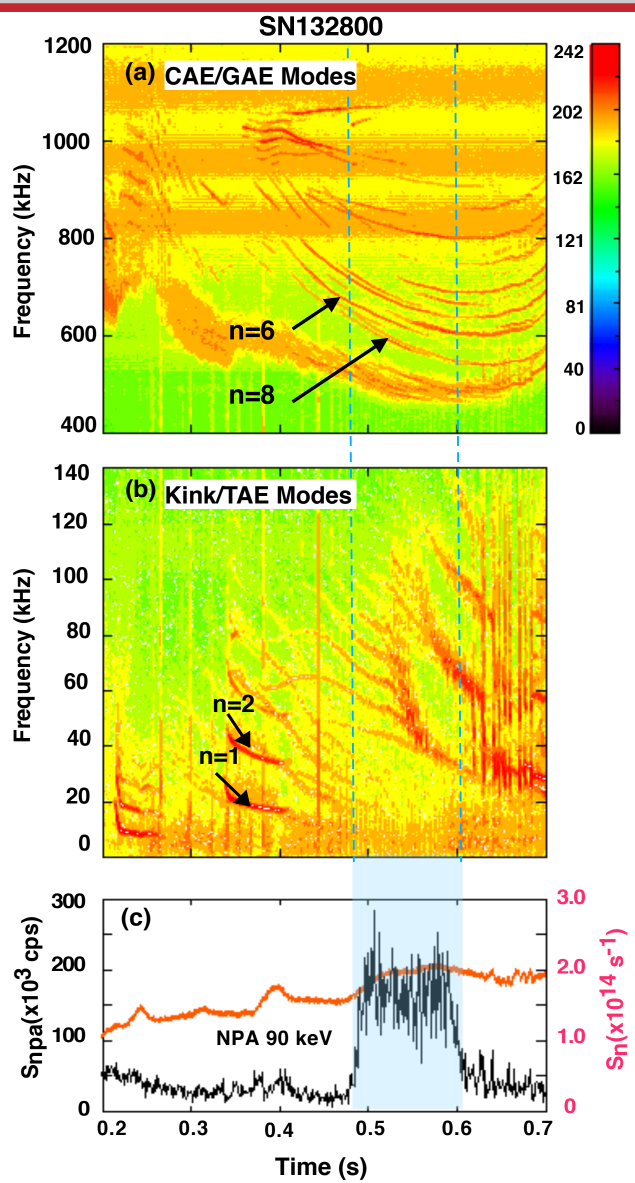


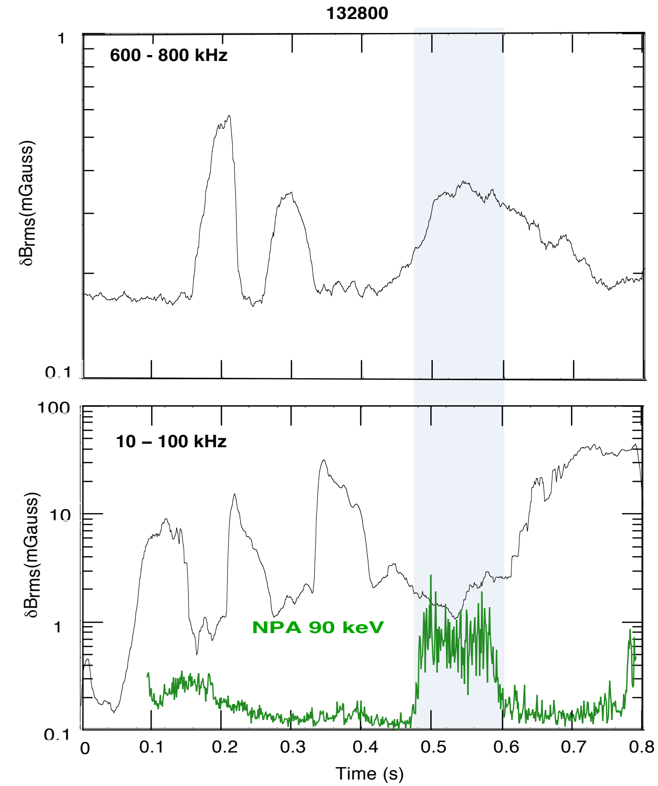




- Energetic ions drive waves
  Waves "pump" energetic ions
- Mechanism for energetic ion "pump"?
  – wave energy 'channeling' via resonant ion Landau damping
  – other damping mechanisms?

HEFs Occur when Kink/NTM Modes (f < 20 kHz) are Absent, TAEs (f ~ 20 -150 kHz) are Weak, and CAE/GAE Activity (f ~ 500-800 kHz) is Robust

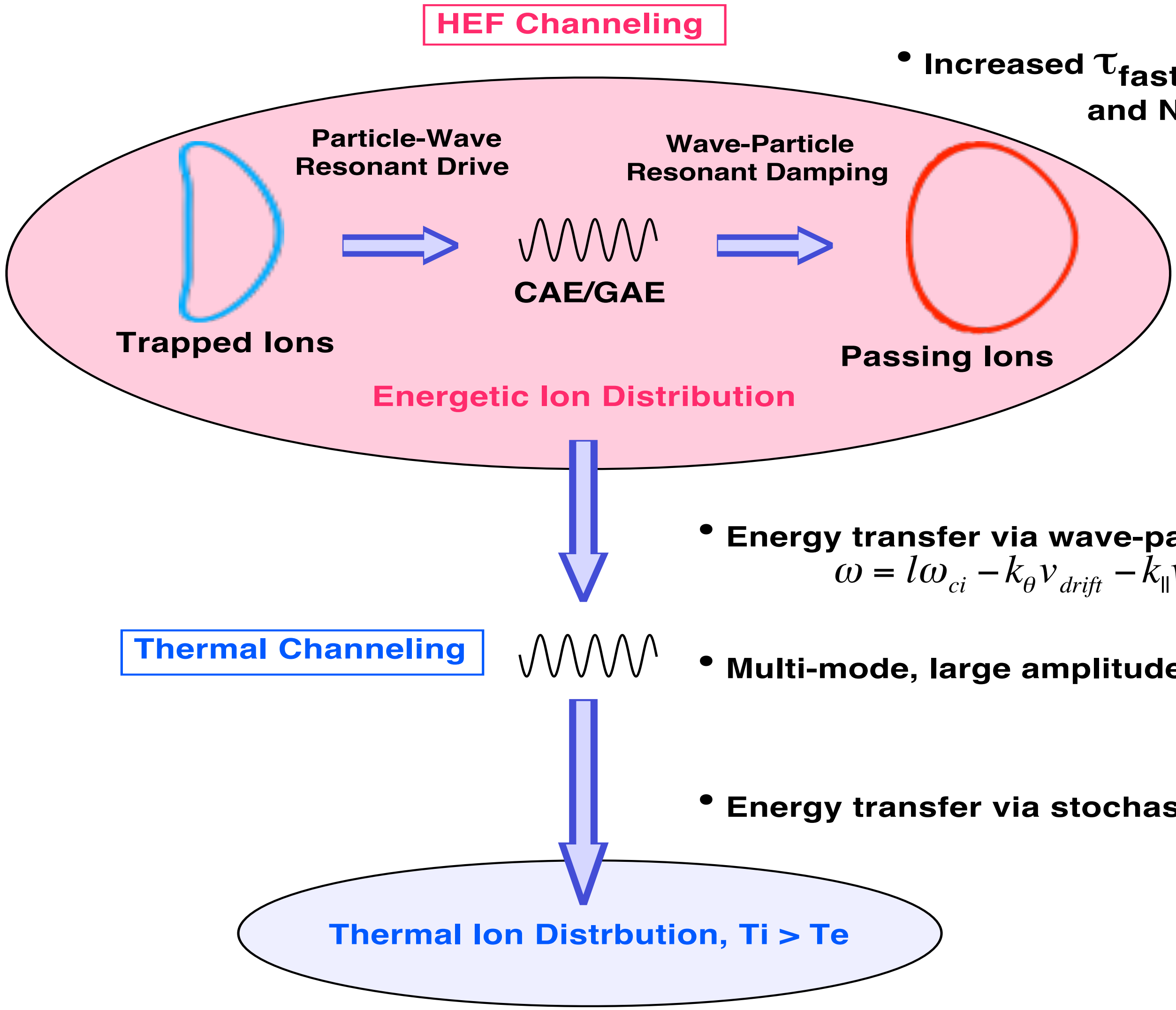




Two HEF drive mechanisms are being pursued:

1. CAE/GAE energy channeling (in this poster)
   - HEFs occur when CAE/GAE are robust
2. Effect of TAEs (future work)
   - HEFs occur when TAE is weak
   - do TAEs inhibit HEF formation?

Overview: Energy Channeling from Trapped to Passing Fast Ions Mediated by CAE/GAE Activity

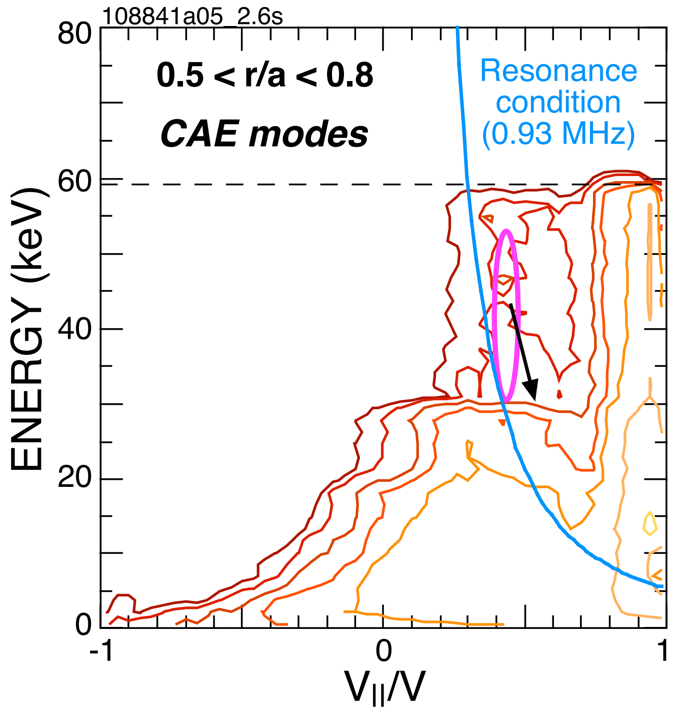


- Increased τ_{fast} ... S_n, T_e, W_T... and NB current drive
- Energy transfer via wave-particle resonance
  $$\omega = l\omega_{ci} - k_\theta v_{drift} - k_{\parallel} v_{\parallel}$$
- Multi-mode, large amplitude CAEs
- Energy transfer via stochastic heating

D.A. Gates, N. N. Gorelenkov, and R.B. White Phys. Rev. Lett. **87** 205003 (2001)

Energetic Ion Resonance Conditions for CAE/GAE Modes

As ion energy drops, parallel energy remains constant to satisfy the resonance condition, but the perpendicular energy can be lower resulting in higher pitch

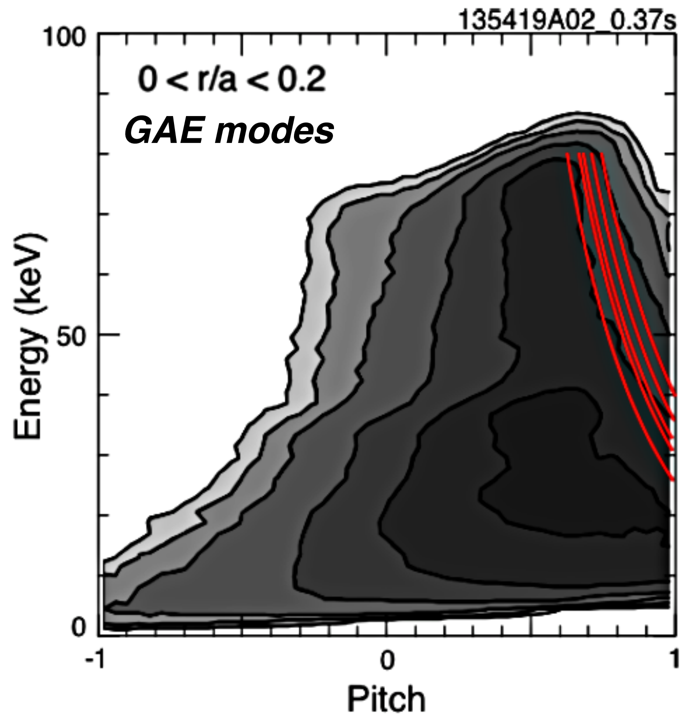


$$\omega = l\omega_{ci} - k_\theta v_{drift} - k_{||}v_{||}$$

$$\frac{v_{||}}{v_b} > \frac{\omega_{ci}R}{nv_b}\left(1 - \frac{\omega}{\omega_{Ci}} - \frac{k_\theta v_{Dr}}{\omega_{Ci}}\right)$$

$$k_{||} = (m - nq)/qR \quad k_\perp \rho_b > 1$$

Fredrickson.. 2004 Phys. Plasmas **11** 3653



$$\omega = \omega_{ci} - k_{||}v_{||}$$

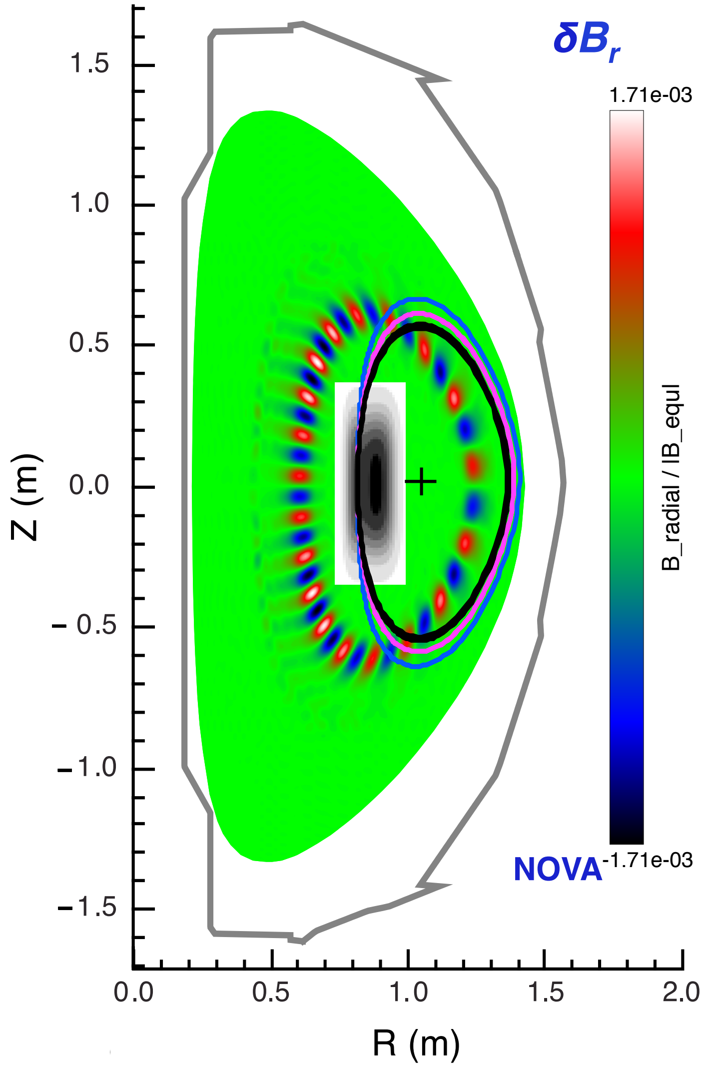
$$v_{||}/v_b = (\omega_{ci} - \omega)/\omega(V_{Alfven}/v_b)$$

Fredrickson.. 2012 NF **52** 043001

- **GAE always propagate counter to the NBI direction, but CAE can bi-propagate.**

SPIRAL Code Simulation

SPIRAL imports $f_i(E,v_{||}/v,r)$ from TRANSP and evolves it under *AE wave-particle interactions: GAE, 132800M03, f = 525 kHz, n/m=6/19, $\delta n/n \sim 0.1$ %



Plot Legend

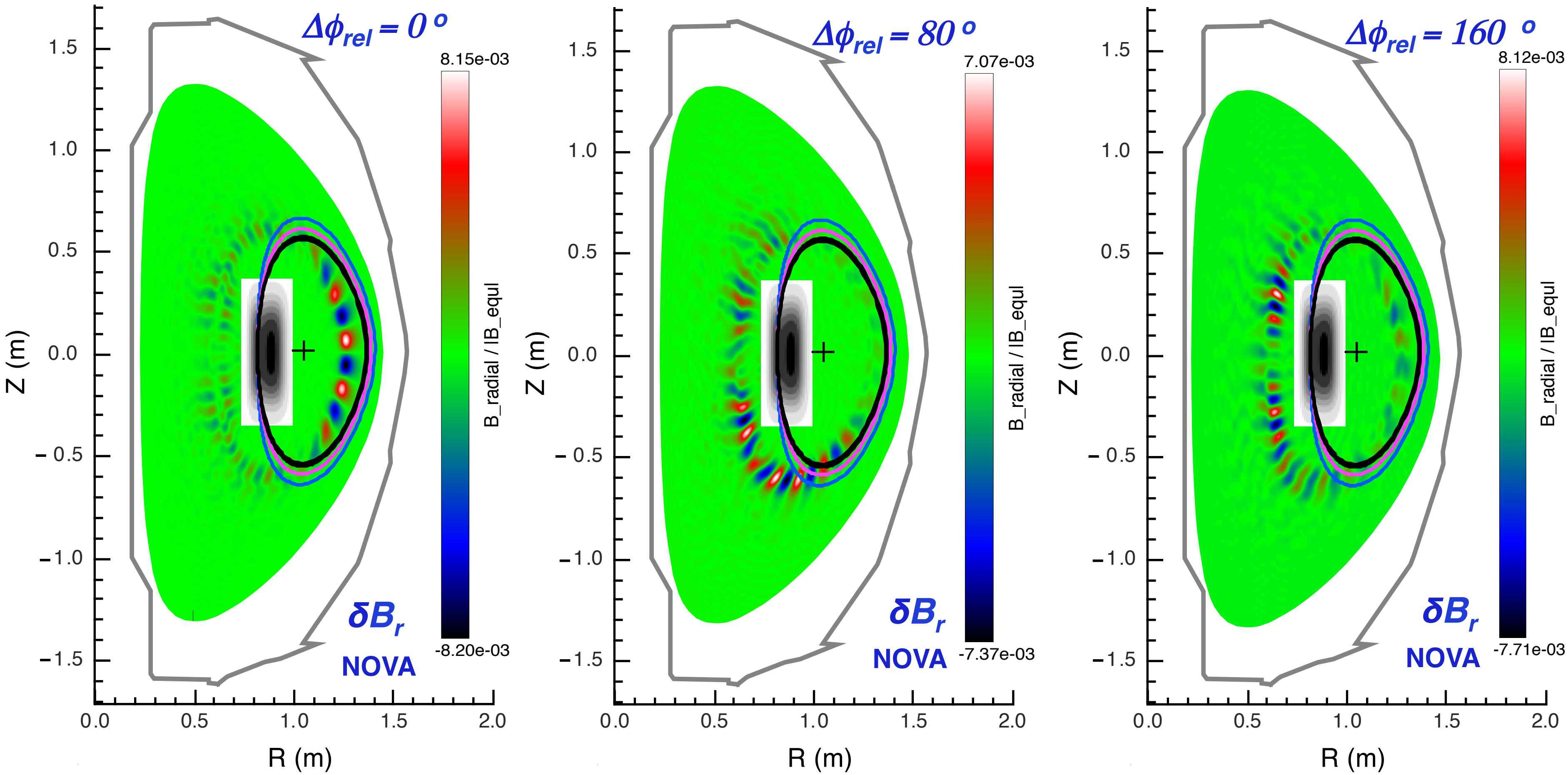
- NOVA n = 6, m = 19 mode structure (red/blue).
- Passing orbits: E_b = 90 keV, $v_{||}/v = 0.8 \pm 0.1$
- Footprint of NB primary neutrals (shaded box).

Analysis Process

- Construct equilibrium for HEF case
  – e.g. using EFIT, LRDFIT, HYM codes.
- Construct candidate Alfvén eigenmodes
  – e.g. using NOVA, HYM codes.
- Compute $\delta f_i(E,v_{||}/v,r)$ due to wave-particle interactions using SPIRAL.

Superimposed NOVA Mode Structures Evolve in Space

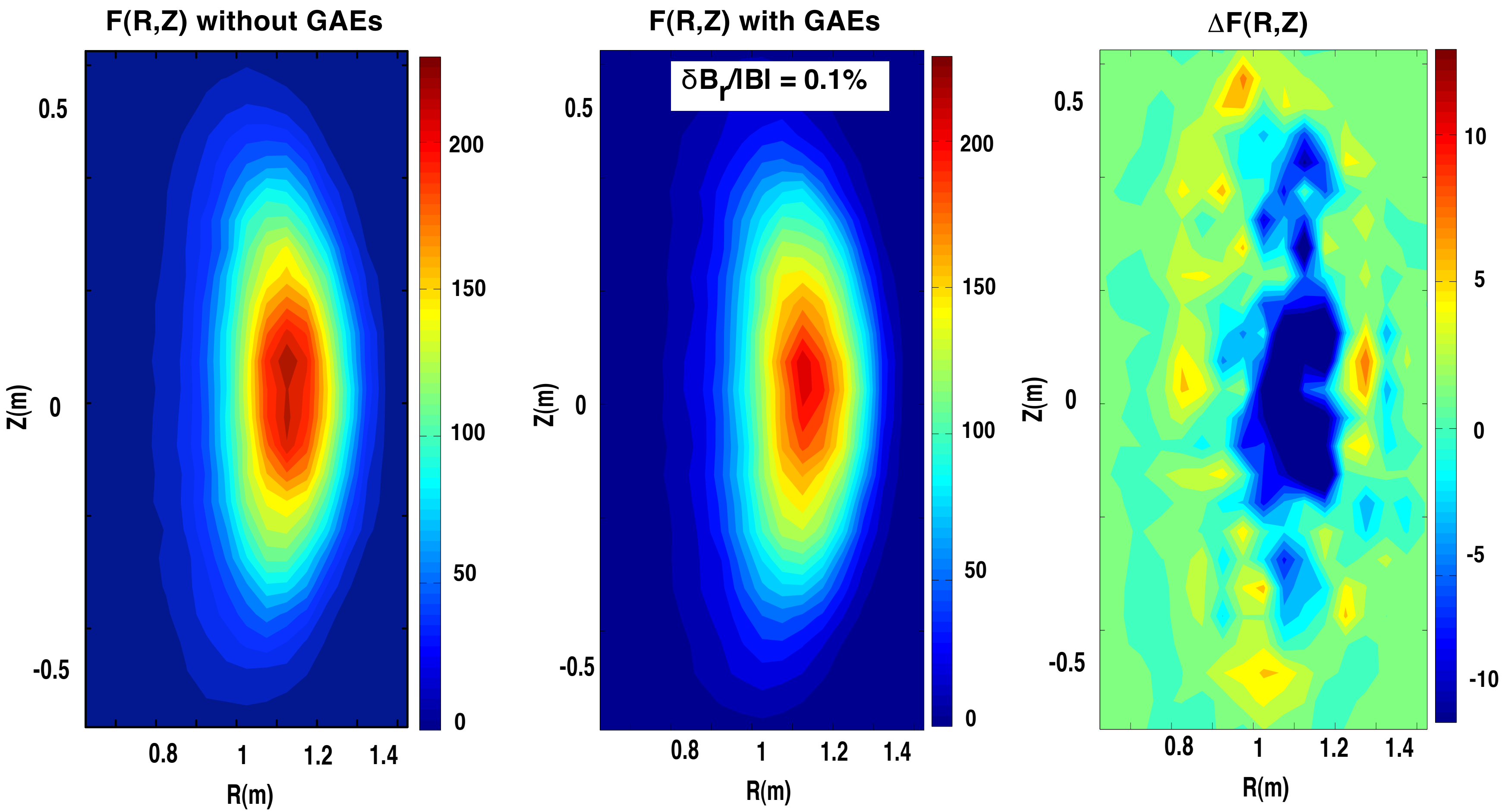
Superposition of 9 GAE modes with f = 525 - 872 kHz, n = 4-8, m = 17-24, $\delta n/n$ = 0.1 %



- **A shortcoming of NOVA mode structures (red/blue) is minimal spatial overlap with passing orbits: E_b = 90 keV, $v_{||}/v$ = 0.8 ± 0.1 and the footprint of NB primary neutrals (shaded box).**

SPIRAL Results with NOVA Mode Structures: I

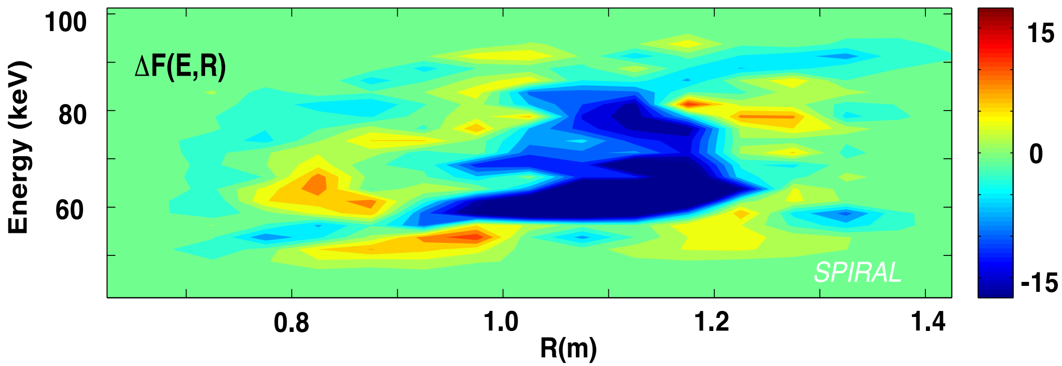
Superposition of 9 GAE modes with f = 525 - 872 kHz, n = 4-8, m = 17-24, $\delta B_r/B$ = 0.1 %



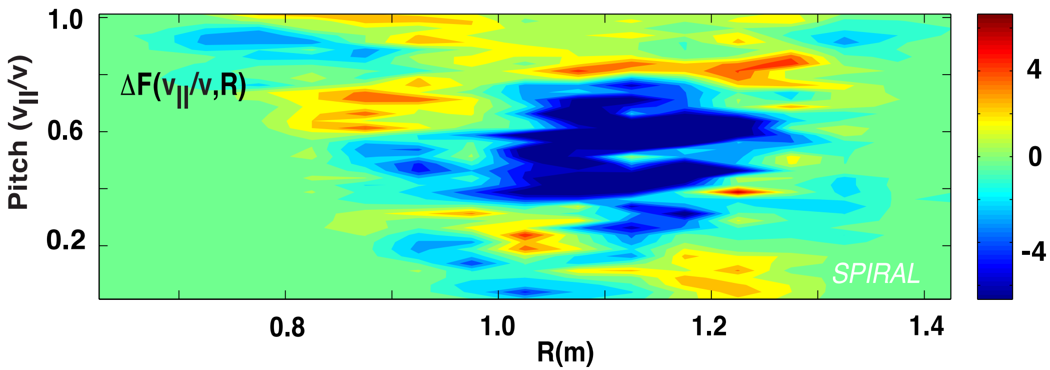
- NOVA GAE eigenmodes deplete energetic ion density in the core and spatially redistribute energetic ions into a peripheral ring as seen in ΔF(R,Z).

SPIRAL Results with NOVA Mode Structures: II

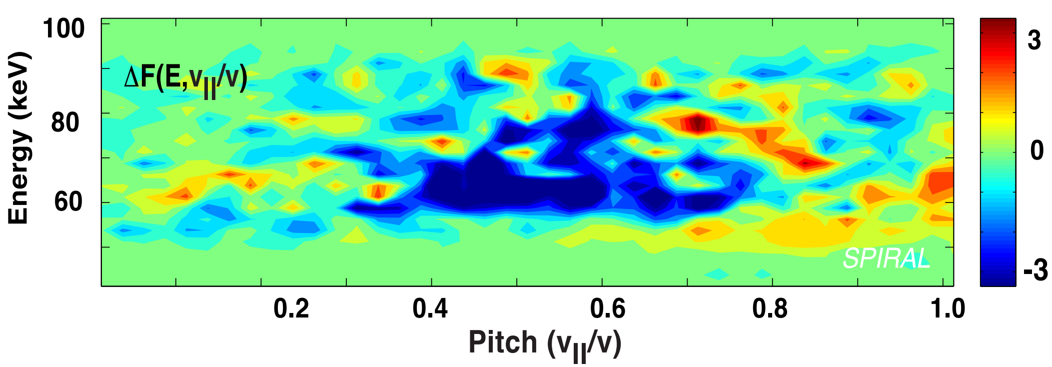
Superposition of 9 GAE modes with f = 525 - 872 kHz, n = 4-8, m = 17-24, $\delta B_r/B$ = 0.1 %



- GAE eigenmodes deplete the energetic ion distribution in the core and enhance the population in a peripheral ring.

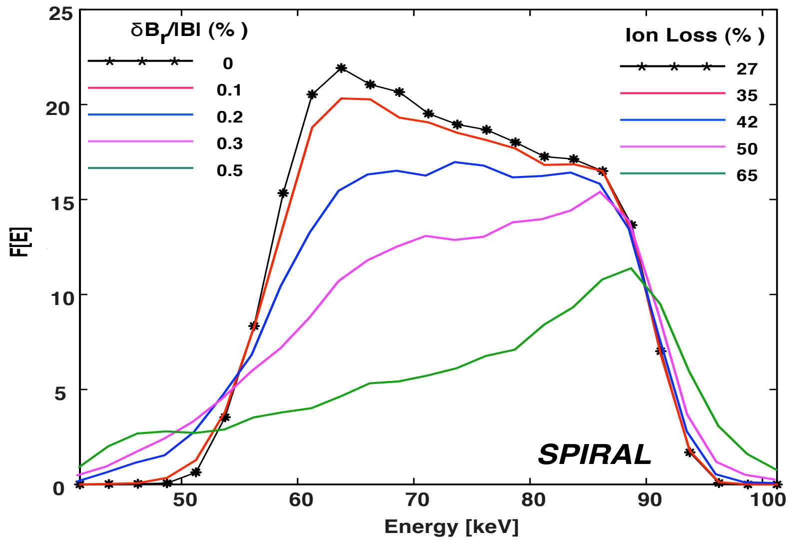


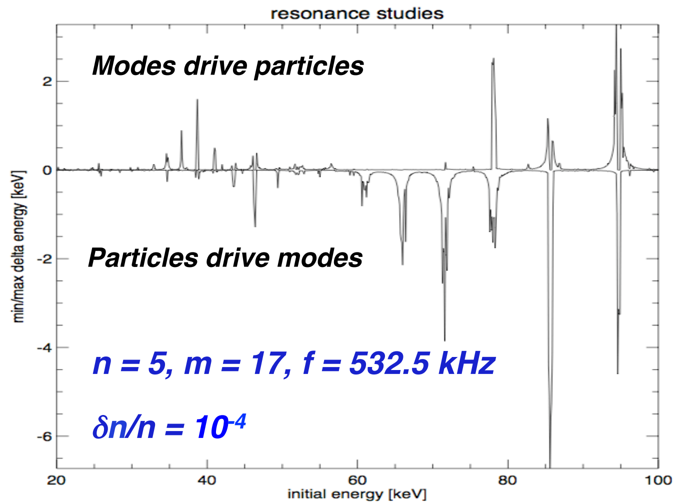
- GAE eigenmodes deplete the pitch distribution in the core and scatter ions to larger pitch.

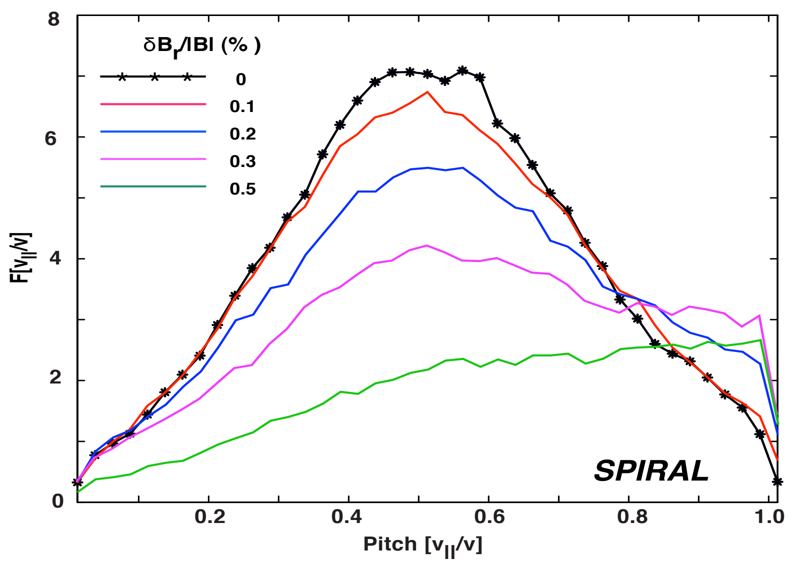


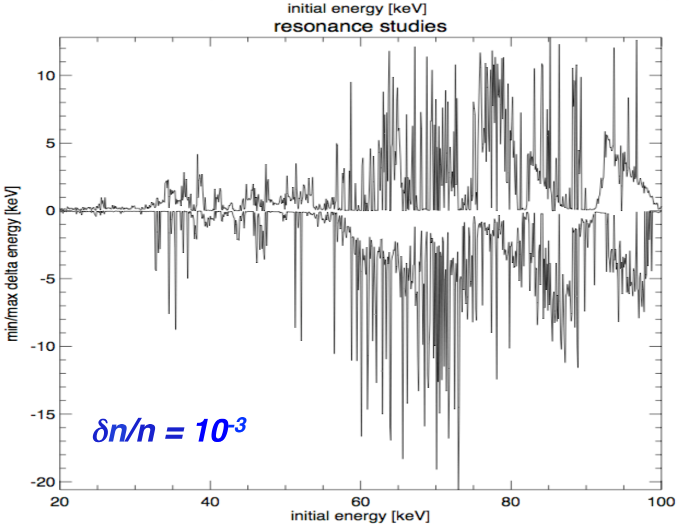
- GAE eigenmodes redistribute fast ions in both energy and pitch.

Fast Ion Distributions are Depleted in Energy and Pitch with Increasing NOVA Mode Amplitude, $\delta B_r/|B| = 0.1 - 0.5$ %





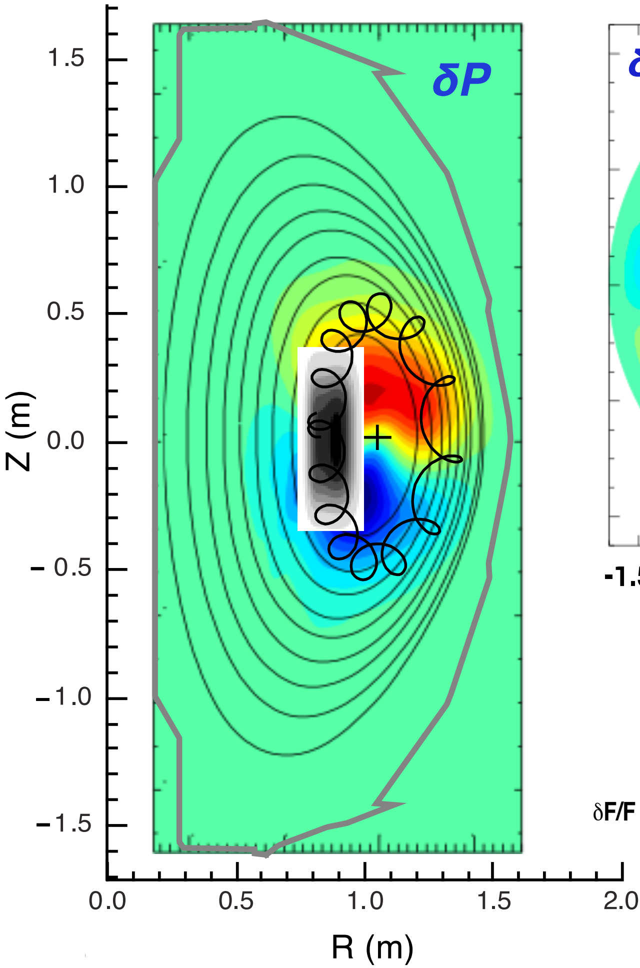




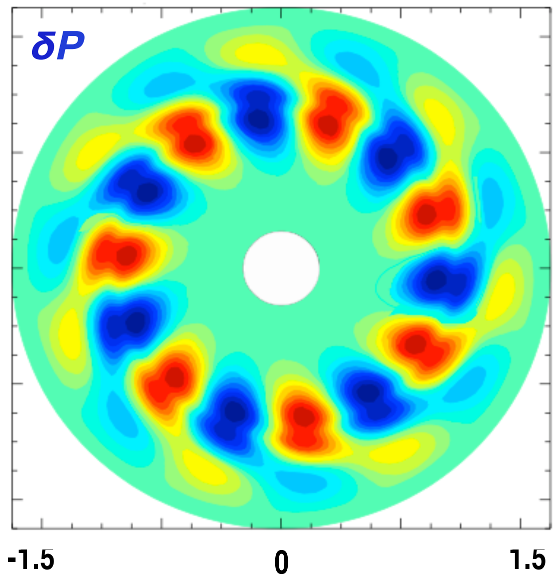
- Increasing mode amplitude leads to stochastic particle transport.

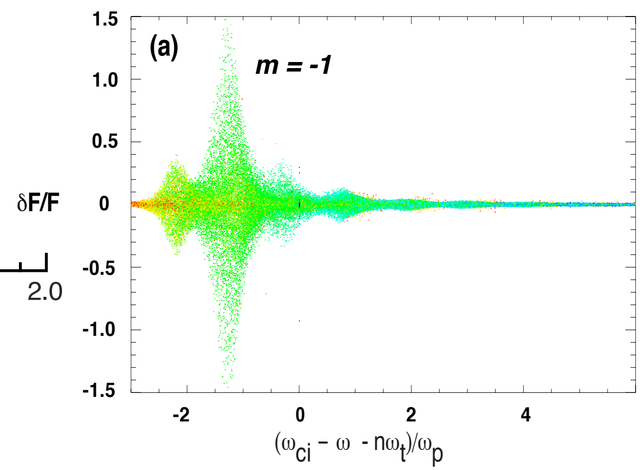
HYM Simulation of GAE Mode Structure for SN132800: n = 7, m = -1

H-mode with I_p = 1.0 MA, B_T = 4.5 kG, E_B = 90 keV, P_{NB} = 4 MW, $n_eL \sim 6\times10^{13}$ cm^{-2}



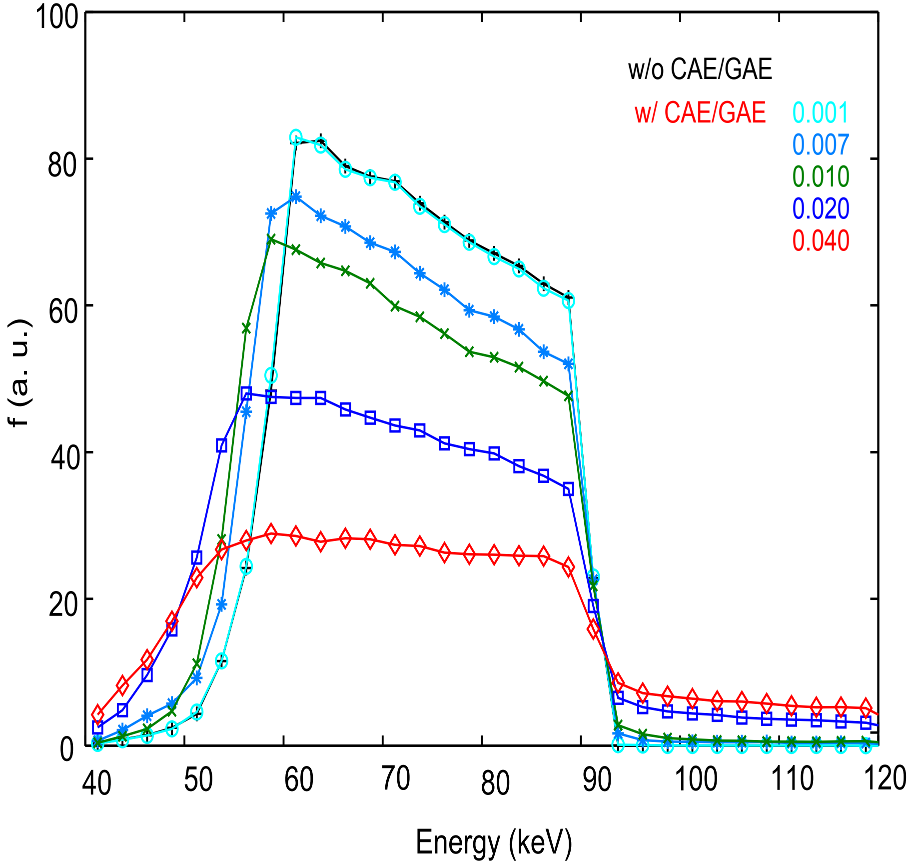
n = 7 (m = -1)
E_B = 90 keV, $v_{//}/v$ = 0.8

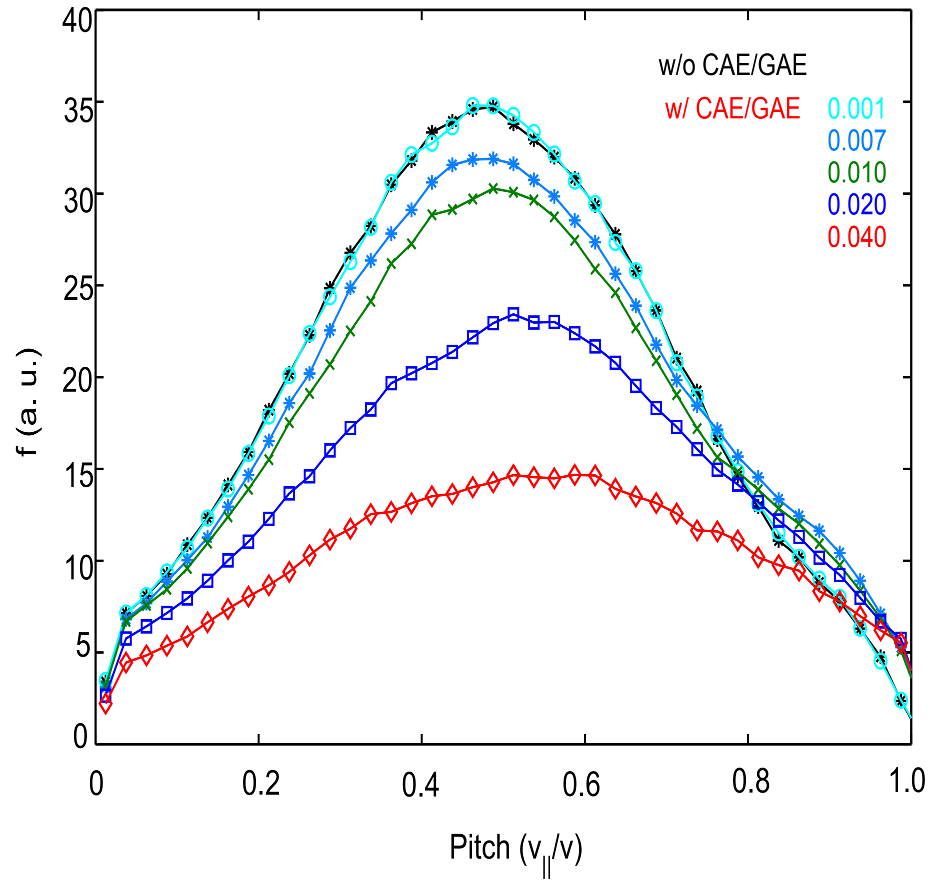




- *For $q_0 \sim 2$, simulations show unstable GAE for n ~ 6 – 9, consistent with Mirnov coil data.*
- *The n = 7, m = -1 GAE mode exhibits the largest growth rate with $\gamma/\omega \sim n_b/n_0 \sim$ 10%:*
- *$\gamma = 0.021\omega_{Ci0}$, $\omega = 0.21\omega_{Ci0}$ and $\omega_{Ci0} = 1.82\times10^7$ rad/s or f_{Ci0} = 2.9 MHz*
- *Lower-m modes have stronger particle resonant interaction due to their wider radial structure.*
- *(a) HYM mode spectrum for the n = 7 GAE mode.*

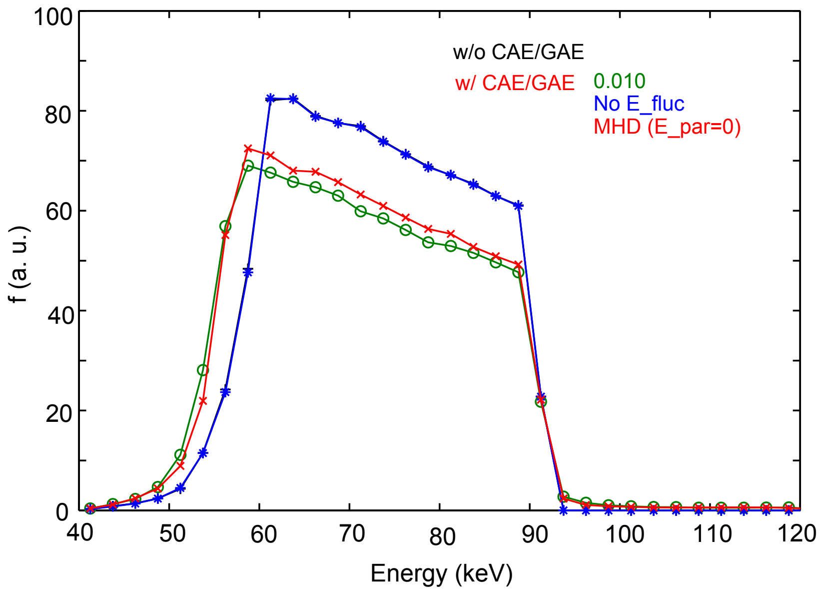
SPIRAL Simulations of $\delta f_i(E,v_{||}/v,r)$ for Various Amplitudes of the n= 7, m = -1 HYM GAE Mode for SN132800: Amp = 0.010 is measured amplitude

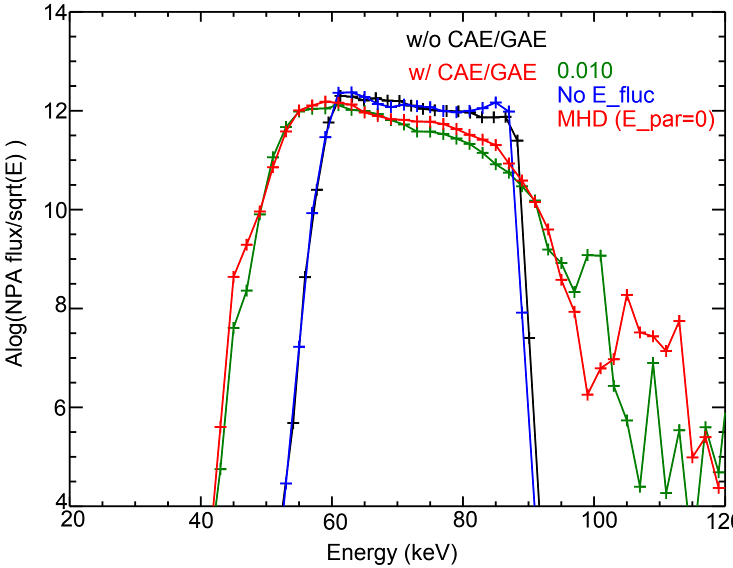


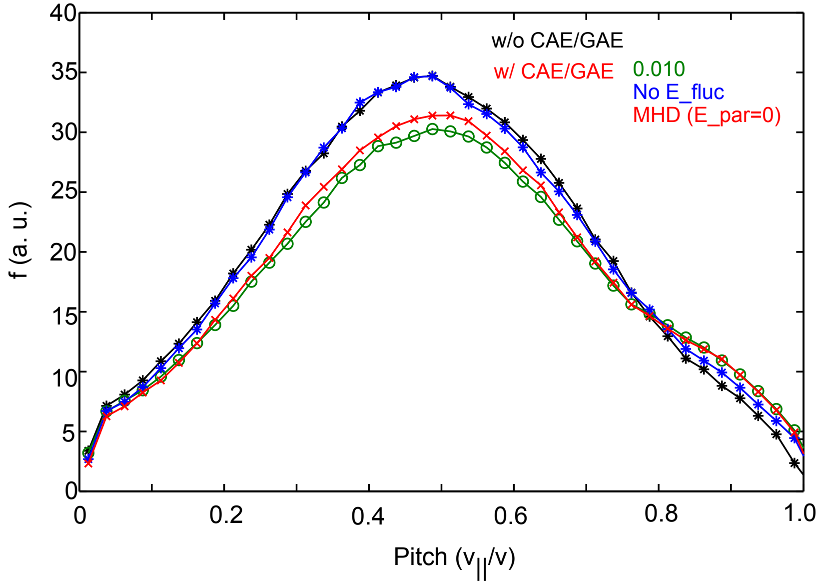


- ***The neutron rate calculated by SPIRAL decreases by ~ 20% as mode amplitude increases from 0 – 0.015 (contrary to the ~ 25% increase observed experimentally).***

Effect of Electric Field Perturbations on the SPIRAL simulation of $\delta f_i(E, v_{||}/v, r)$ for n= 7, m = -1 HYM GAE mode: Amp = 0.010





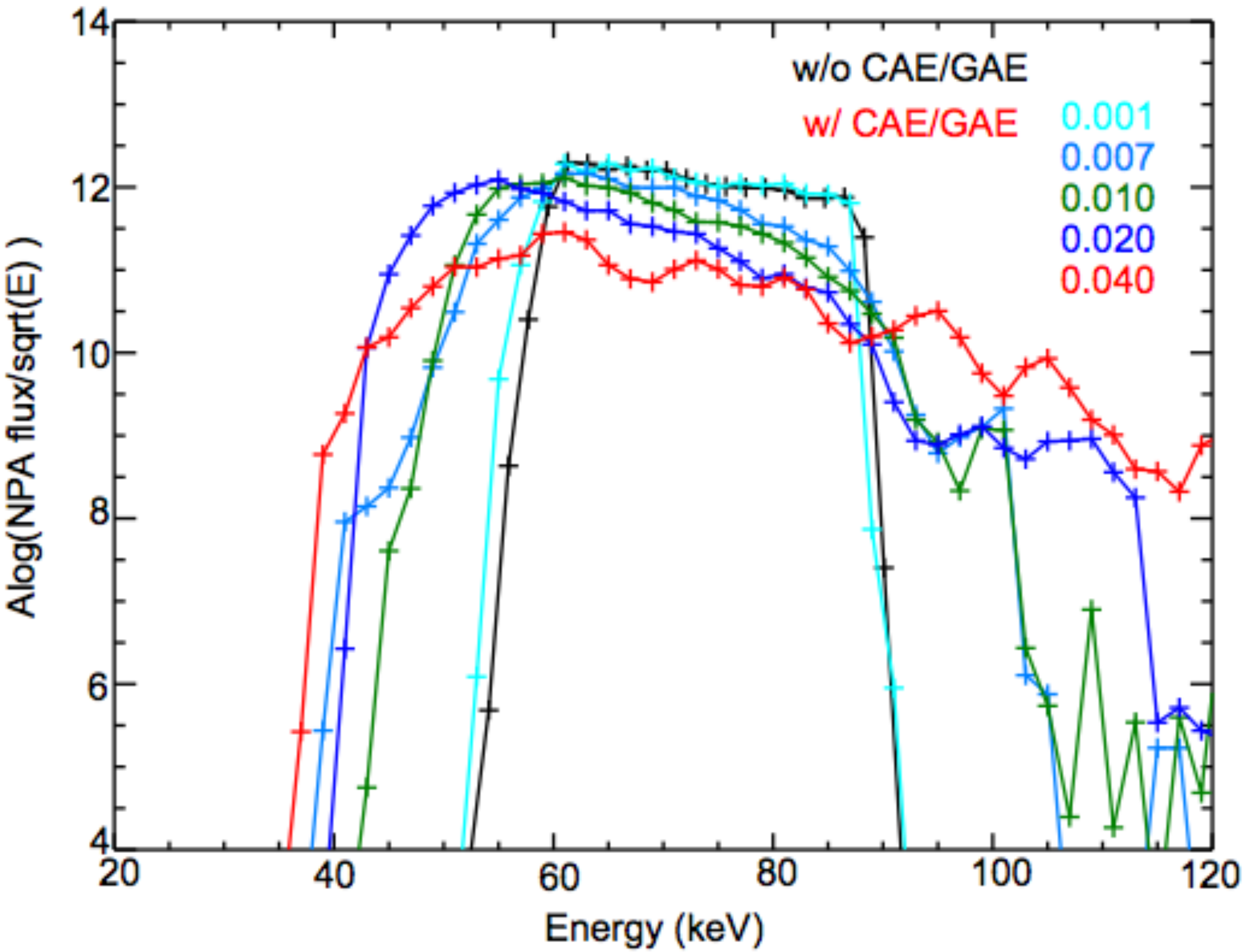


- **Perturbations of the SPIRAL simulation for $\delta f_i(E, v_{||}/v, r)$ are relaxed slightly for $\delta E_{||} = 0$ (red) but significantly for all $\delta E = 0$ (blue).**

- **For the all $\delta E = 0$ case, the NPA flux is virtually identical to the spectrum w/o the CAE/GAE perturbation (black) : i.e. δB perturbations alone have little effect on the NPA.**

FIDASIM NPA Simulation using HYM GAE Mode for SN132800

H-mode with I_p = 1.0 MA, B_T = 4.5 kG, E_B = 90 keV, P_{NB} = 4 MW, n_eL ~ $6x10^{13}$ cm^{-2}



δB, δE values for the AMP = 0.010 case

δB_R	1.9	7.6
δB_Φ	0.6	2.4
δB_Z	2.2	9.1
δE_R	2.4	9.6
δE_Φ	0.7	3.0
δE_Z	2.2	8.9

B(gauss), E(V/cm)

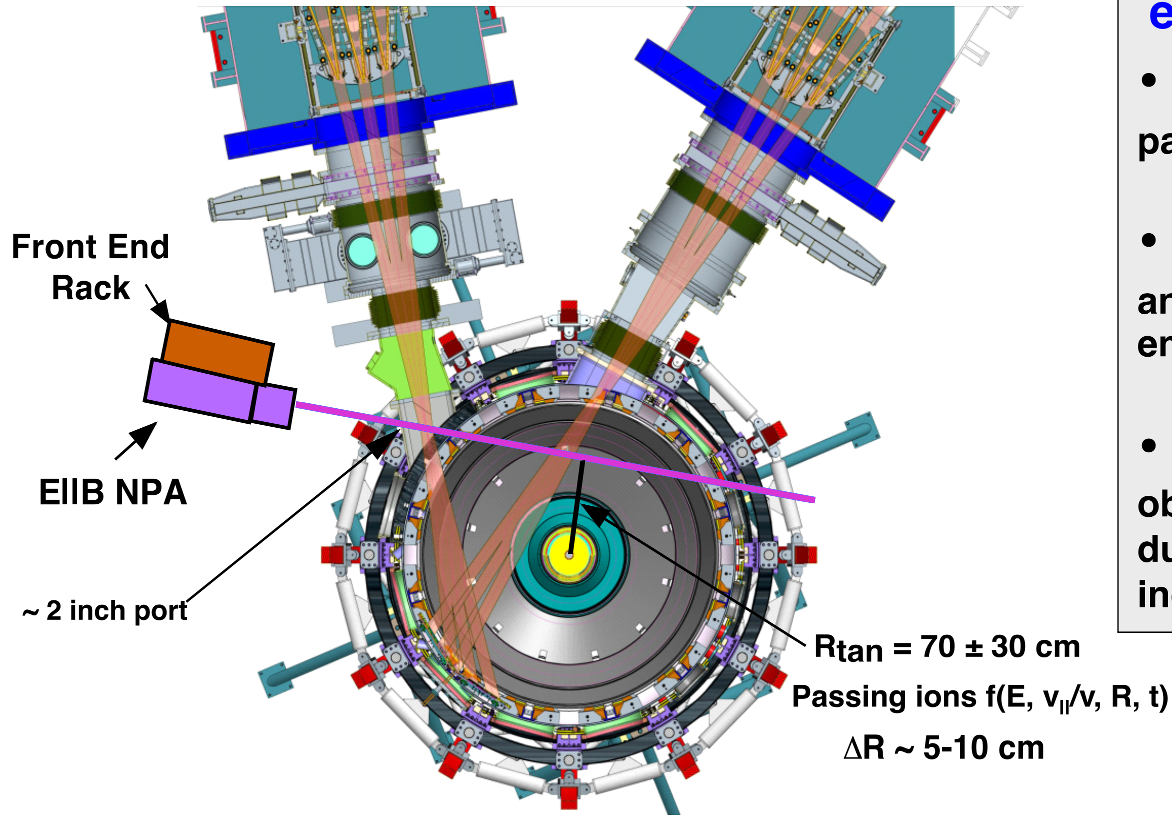
- ***FIDASIM NPA simulation using SPIRAL computed $\delta f_i(E,v_{//}/v,r)$ for various amplitudes of n= 7, m = -1 HYM GAE mode: Amp = 0.010 is measured amplitude.***

Concept for a Fixed Sightline E||B Neutral Particle Analyzer on NSTX-U

Energetic ion spectrum, $f(E, v_{||}, R, t)$, is core-localized to sightline intersection with 1st NBI

New 2nd NBI (R_{TAN}=110, 120, 130cm)

Present NBI (R_{TAN} = 50, 60, 70cm)



- E_D = 10–300 keV, $\Delta E/E$ ~ 2-5%, $v_{||}/v$ ~ 0.8 ± 0.1, Δt ~ 0.1 ms.

The HEF phenomenon could enhance NSTX-U performance

- Energy channeling from trapped to passing fast ions leads to…
- Increased fast ion confinement, τ_{fast}, and hence to increased S_n, T_e, W_T…and enhanced NB current drive.
- Sustained HEFs up to 600 ms were observed on NSTX. HEF strength and duration appear to increase with increasing NB power.

S. P. Gerhardt, *et al* Nucl. Fus. **52** 083020 (2012)

- The E||B NPA diagnostic has a unique capability for *definitive HEF identification*.

Summary of the High Energy Feature Phenomenology

HEFs lead to improved plasma performance through enhanced τ_{fast} … S_n, T_e, W_T…

- **Observed as enhanced CX flux near the NB full energy E_b ~ 90 keV, never at $E_b/2$ or $E_b/3$ and only in H-modes with P_b > 3 MW (never in L-mode discharges).**
- **Arise only in discharges where kink/NTM modes (f < 30 kHz) are absent, TAE activity (f ~ 30-150 kHz) is weak and GAE/CAE activity (f ~ 400-1200 kHz) is robust.**
- **Can 'turn-on' and 'turn-off' multiple times during a discharge, exhibit growth/ decay times of ~ 20 - 80 ms and can persist for ~100 - 600 ms.**
- **Have been observed for mid-plane NPA sightlines in the range R_{tan}~ 55 - 90 cm corresponding to $v_{||}/v$ ~ 0.7 - 0.9.**
- **Are modulated by ELMs and suppressed by robust lithiumization (e.g. > 200 mg/shot)**
- **Are corroborated by multiple NSTX diagnostic observations: e.g. sFLIP, BES, MPTS, FIReTIP, High-k Microwave Scattering, Neutrons, Multichannel Reflectometer.**

Conclusion: The CAE/GAE energy channeling mechanism yielded ion acceleration above the beam injection energy, but not the sought after High Energy Feature.