NSTX

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Transient Energetic Charge Exchange Flux Enhancement Observed in NSTX Neutral-Beam-Heated H-mode Discharges

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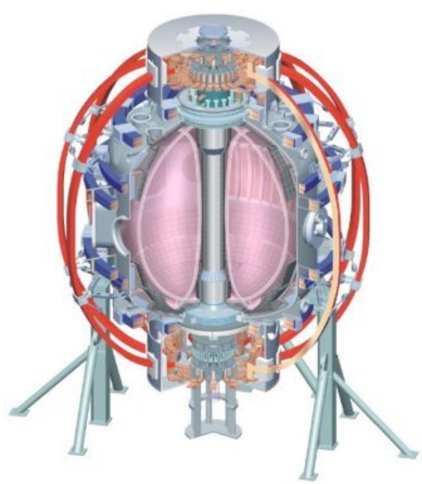


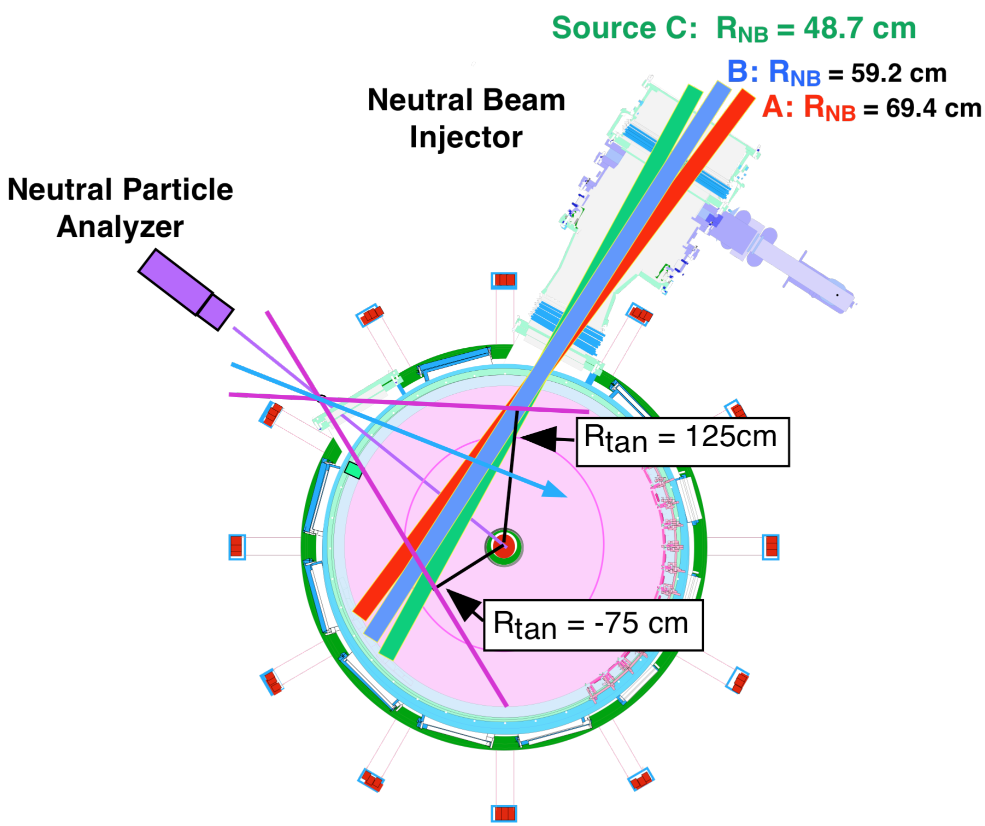
Abstract

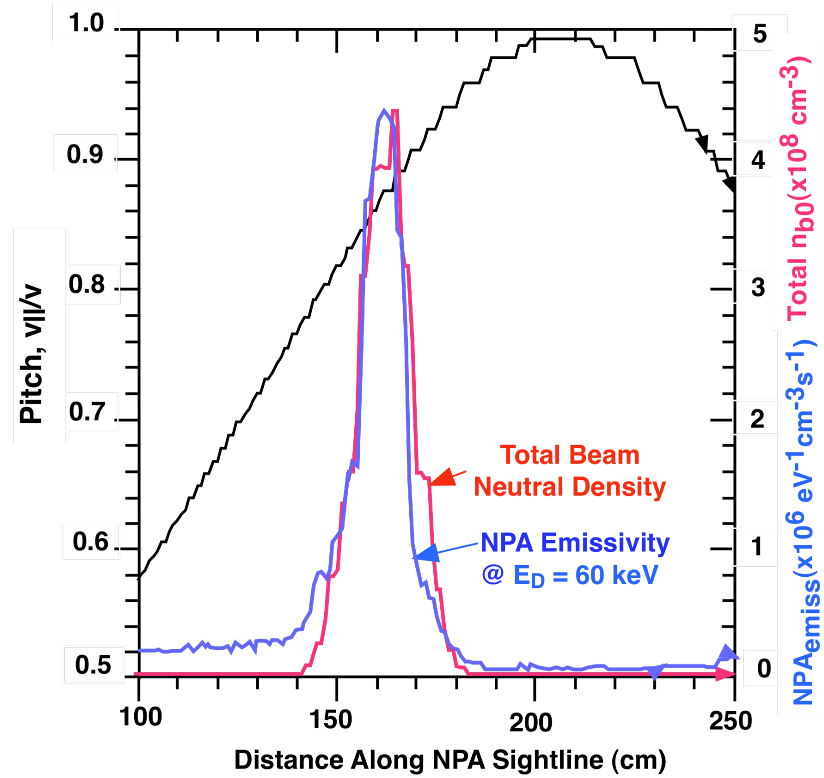
Transient energetic charge exchange flux enhancement observed in NSTX neutral-beam-heated H-mode discharges* S.S. Medley, G.J. Kramer, R.E. Bell, E. Belova, E.D. Fredrickson, S.P. Gerhardt, B.P. LeBlanc, M. Podestà, Y. Ren, A. L. Roquemore, PPPL N.A. Crocker, UCLA, and the NSTX Team, Large increases in the E||B Neutral Particle Analyzer (NPA) charge exchange neutral flux localized at the Neutral Beam Injection (NBI) full energy are observed in the National Spherical Torus Experiment (NSTX). Termed the High-Energy Feature (HEF), it appears only at the NBI full energy, exhibits growth times ~ 20-80 ms, seldom develops a slowing down distribution and arises only in discharges where NTM modes ($f < 30$ kHz) are absent, TAE activity ($f \sim 30$-150 kHz) is weak and GAE/CAE activity ($f \sim 400$-1200 kHz) is robust. The HEF occurs only in H-mode discharges with $P_b \geq 3$ MW and $v_{||}/v \sim 0.7$-0.9; i.e. only for passing ions. The HEF appears to be caused by a GAE wave-particle interaction that modifies of the NB fast ion distribution, $f_i(E,v_{||}/v,r)$. This proposed mechanism was studied using the SPIRAL code that imports a TRANSP-calculated $f_i(E,v_{||}/v,r)$ distribution and evolves it under drive from GAE wave-particle resonances. **Supported by U.S. DoE Contract Nos. DE-AC02-09CH11466 and DE-FG02-99ER54527.*

High-Energy Feature (HEF)

A strong increase (~ 4x) in the E||B NPA charge exchange flux that is narrowly localized around the NB full injection energy.

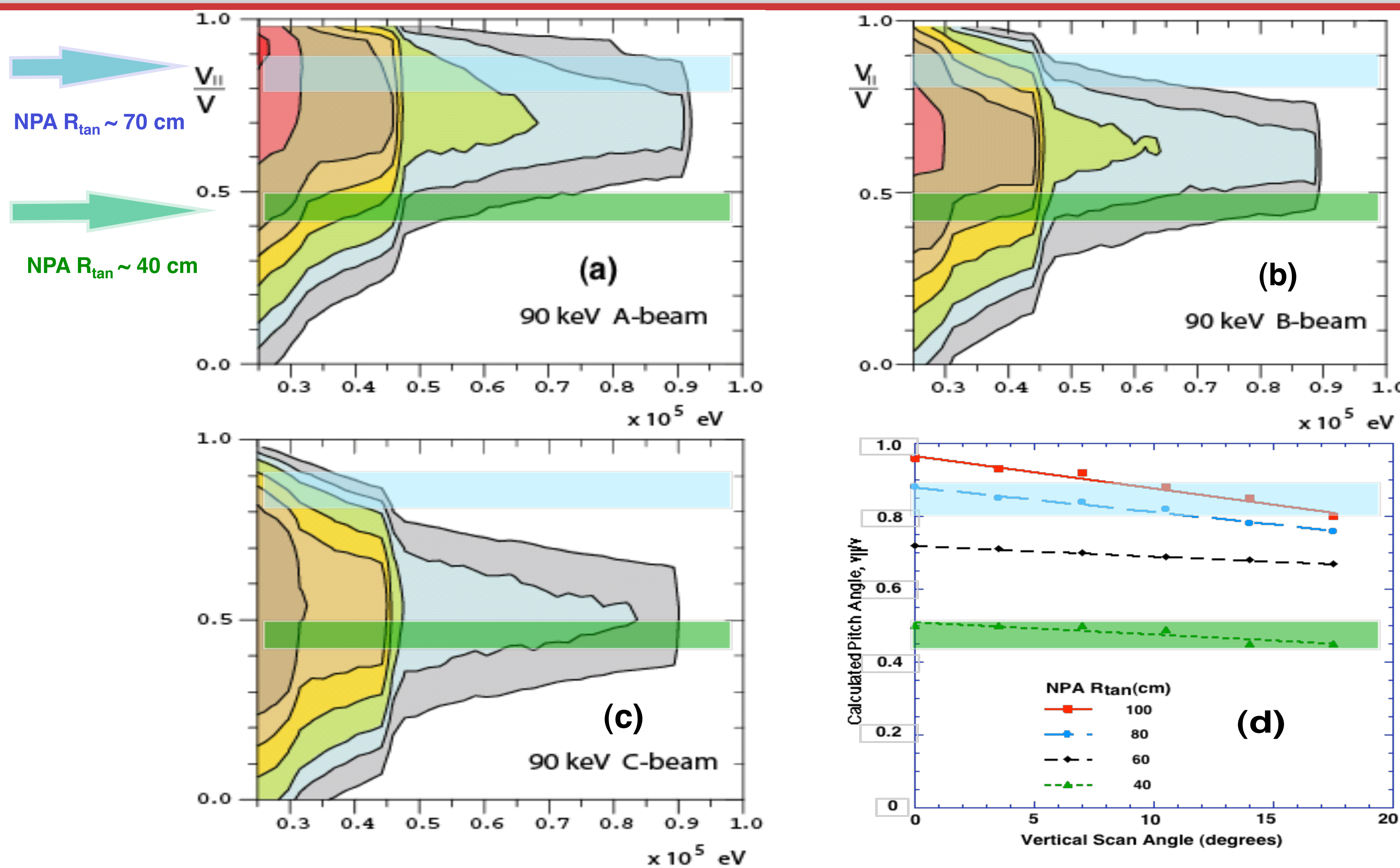
The EIIB Neutral Particle Analyzer (NPA) on NSTX Scans Horizontally on a Shot-to-Shot Basis





- Intersection of NPA sightline with the footprint of the beam neutrals localizes the charge exchange flux measurement in space with resolution of ΔR ~ 20 cm and ΔZ ~ 3 cm and in pitch angle with a resolution of $v_{\|}/v$ ~ 0.05.

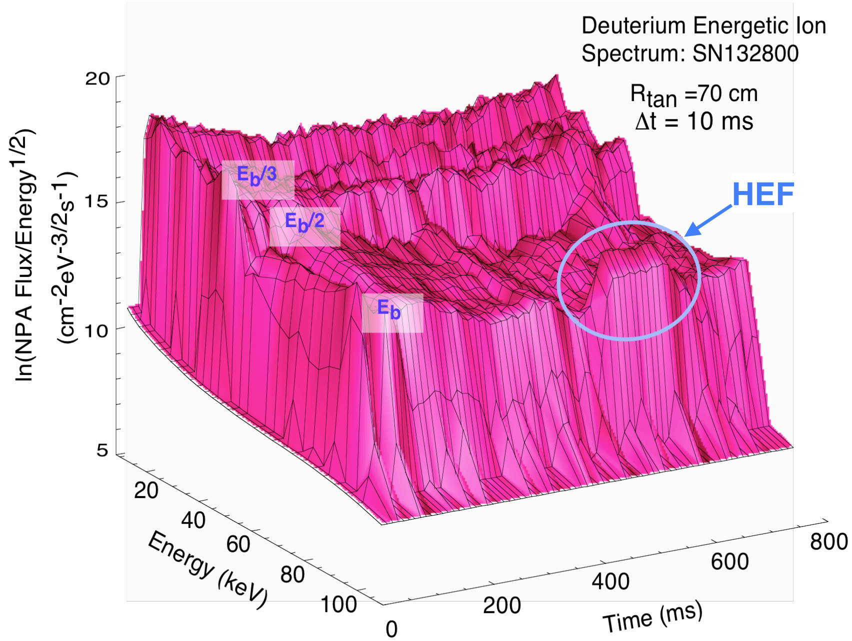
The Pitch Angle, $v_{||}/v$, Viewed by the NPA Depends on Both the Horizontal and Vertical Sightline Setting

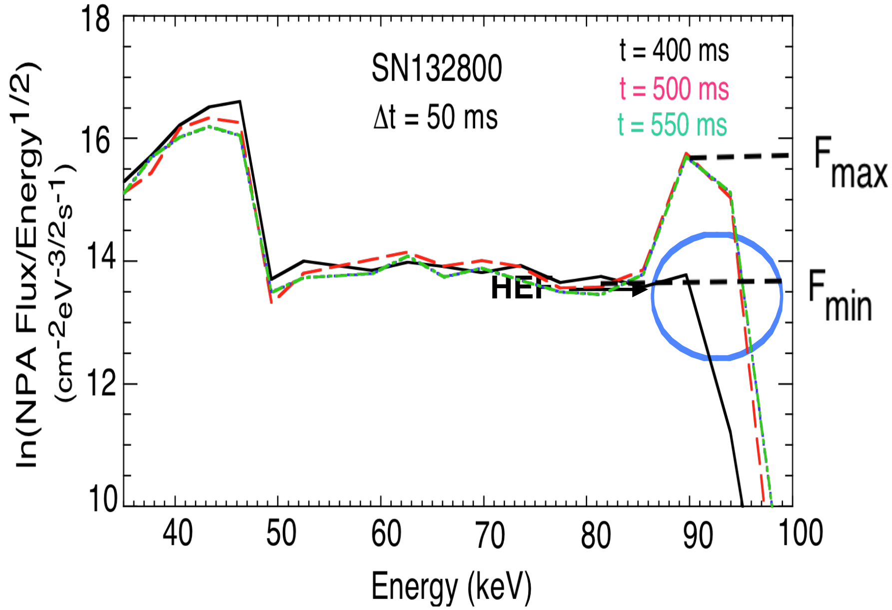


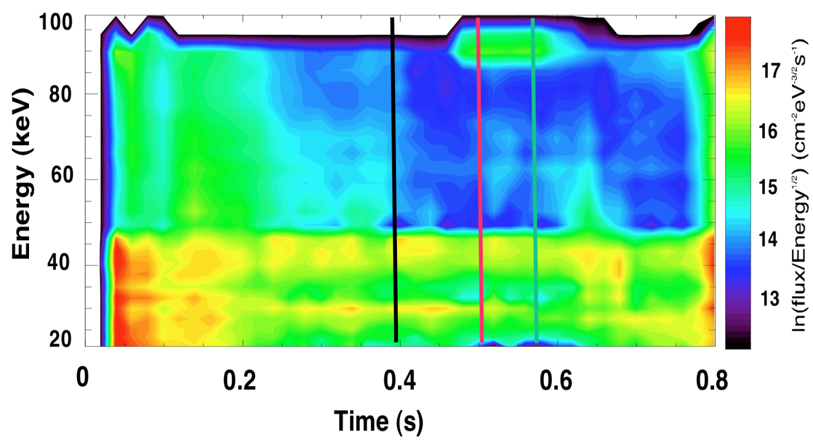
- For 'typical' R_{tan} ~ 70 - 80 cm, the NPA views passing ions with $v_{||}/v$ ~ 0.85 ± 0.05.

Illustration of a 'Brief' HEF: Duration ~ 100 ms

This HEF appears to evolve as an enhancement of CX flux near E_b = 90 keV



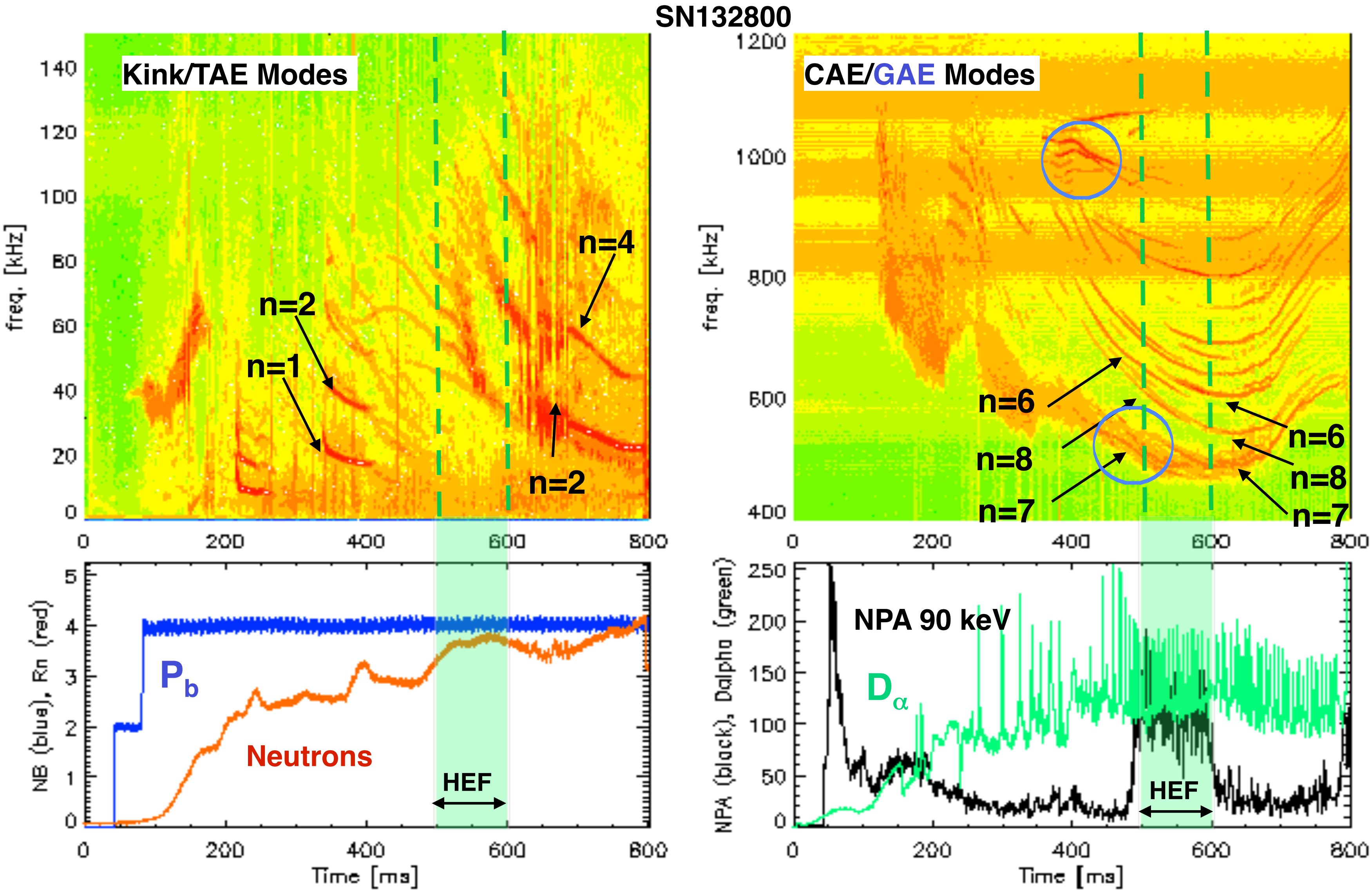




- The NPA charge exchange spectrum exhibits enhanced signal only near E ~ E_b (e.g. never at E_b/2 or E_b/3).
- HEF can be characterized by peak-to-base flux ratio H = F_{max}/F_{min} ~ 10.
- Lack of evolution of a slowing-down distribution below the HEF is a common (and not understood) feature.

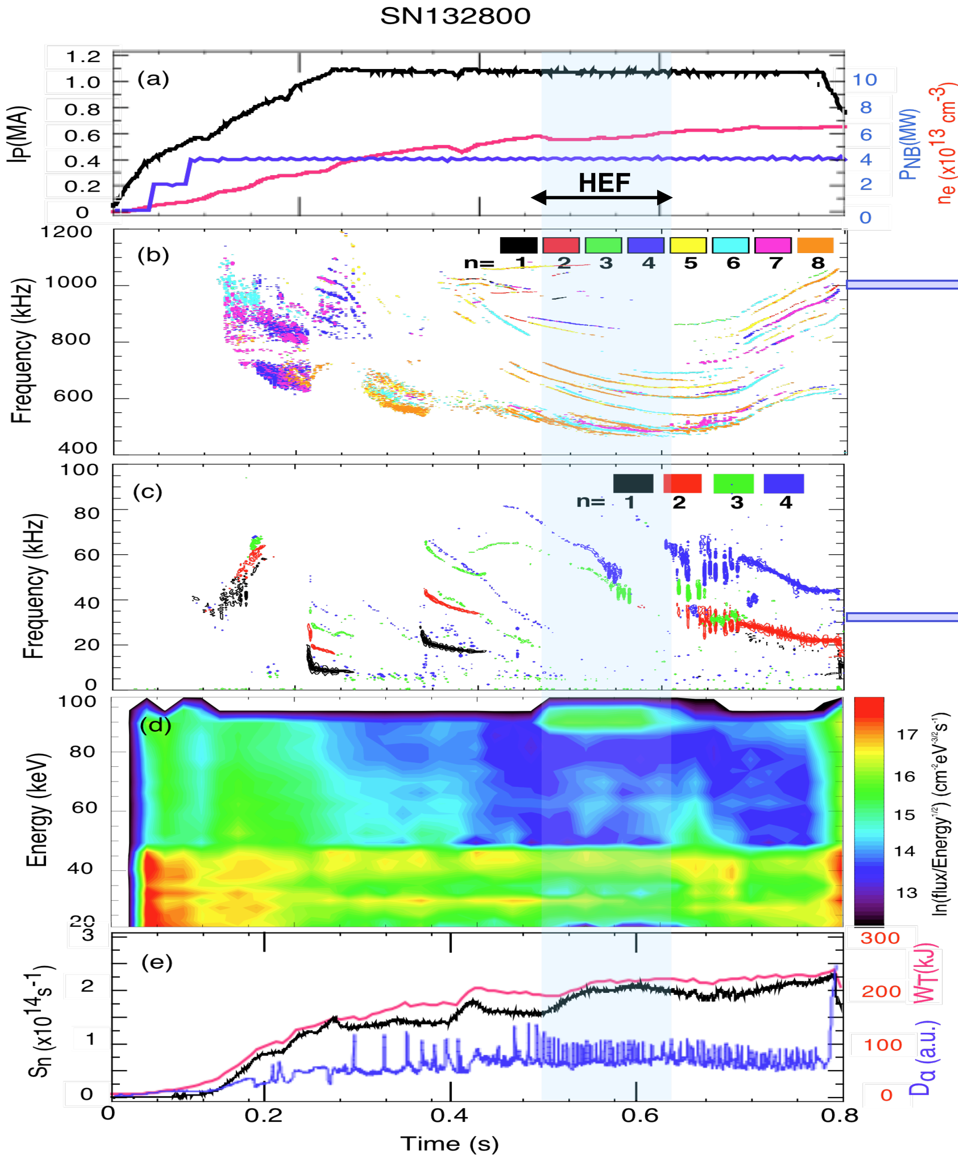
HEF Existence Requires No Kink and Weak TAE MHD Activity

No MHD ‘chirping’ is observed on Mirnov signals during the HEF interval

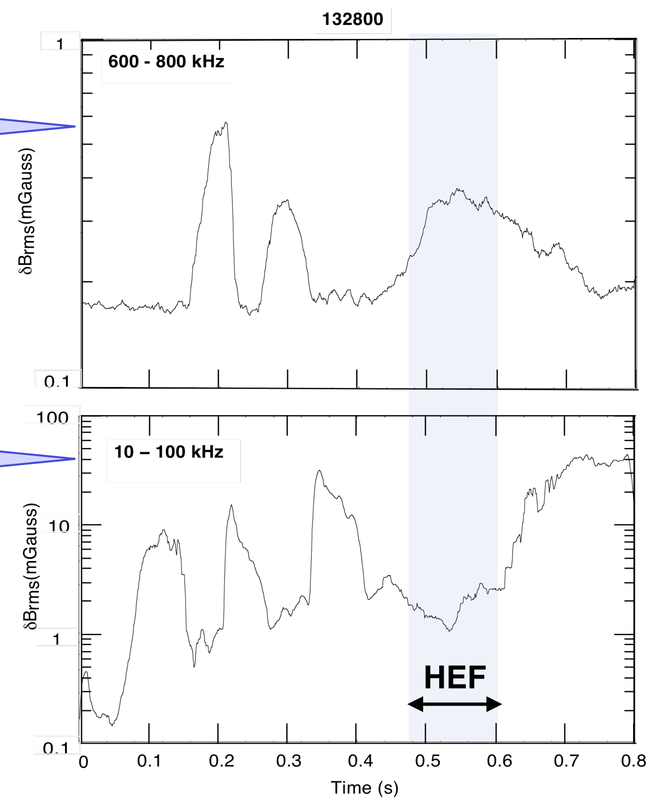


Discharge Data and Mirnov δB_{rms} Evolution for a 'Brief' HEF

Contour plot (d) shows the HEF affects CX flux only near the NBI full energy



- HEF occurrence requires $P_b \geq 4$ MW (e. g. sources A&B @ 90 keV) .



- HEFs are observed only in H-mode discharges: never in L-modes.

Plasma Profiles for a 'Brief' HEF: SN132800

Only significant T_e profile evolution is observed during the HEF phase

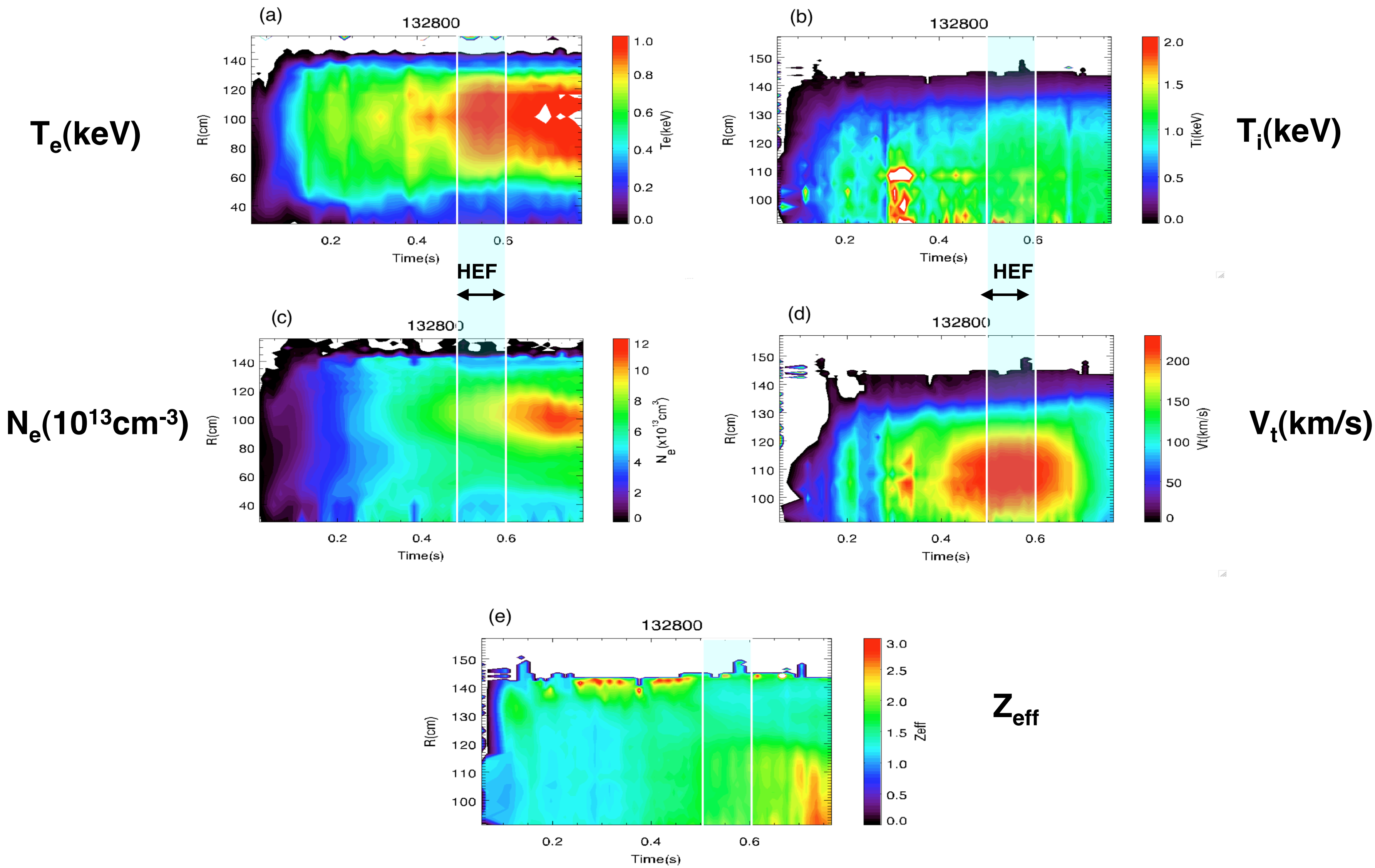
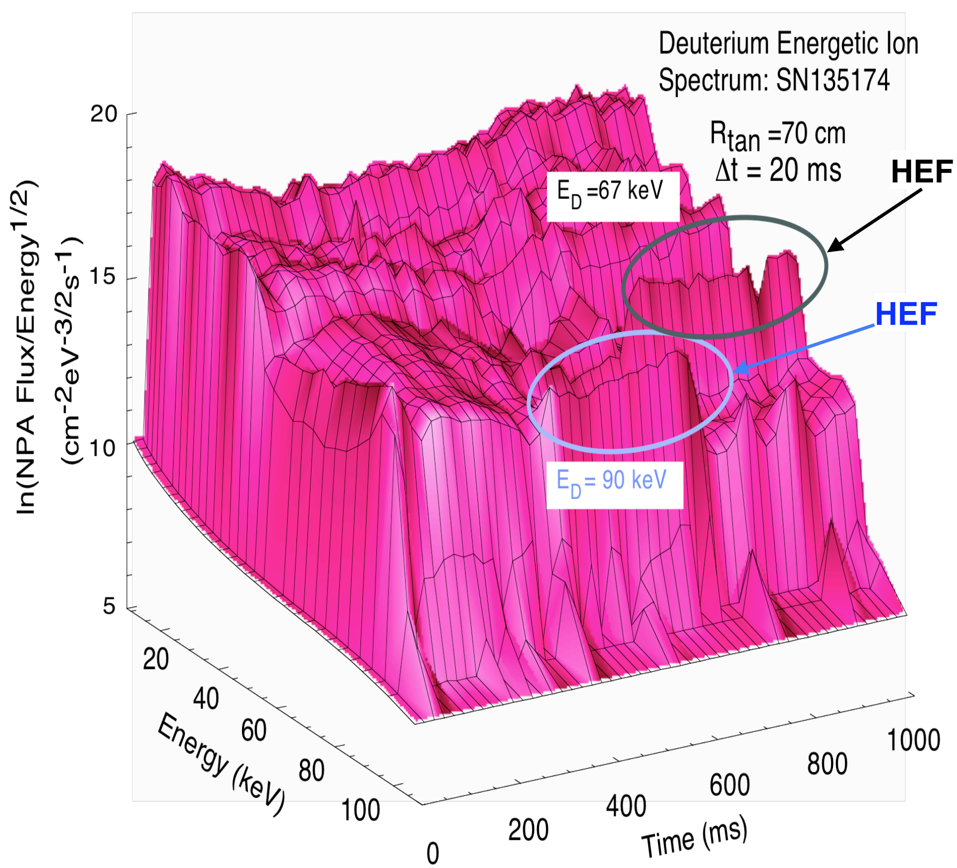
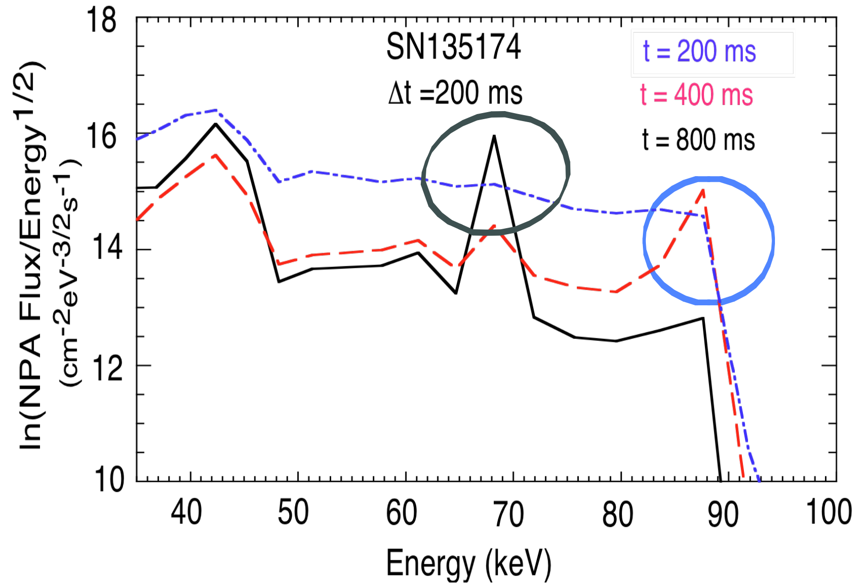


Illustration of 'Dual-Energy' HEFs at E_b = 90 keV & E_b = 65 keV

Dual-Energy HEFs can occur sequentially or overlapping in time



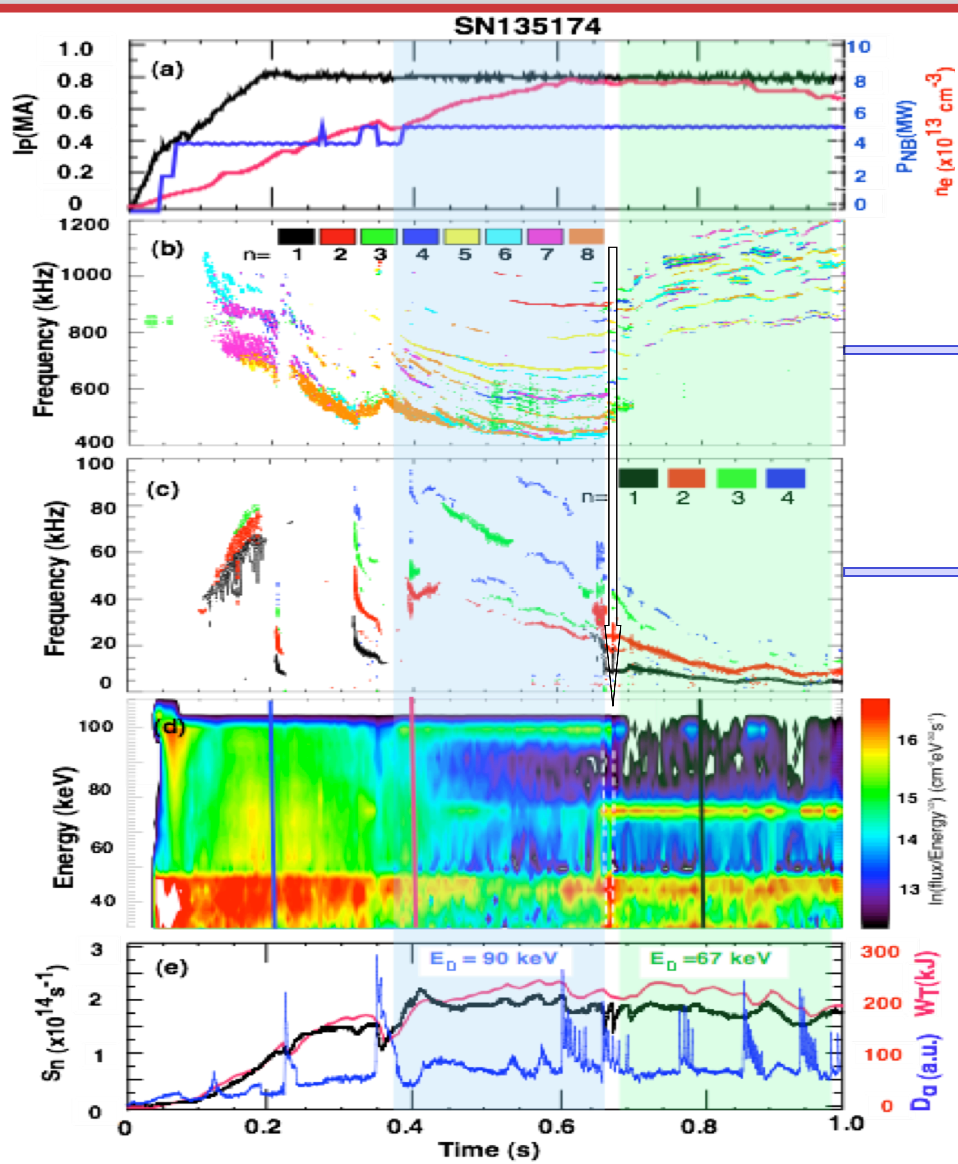


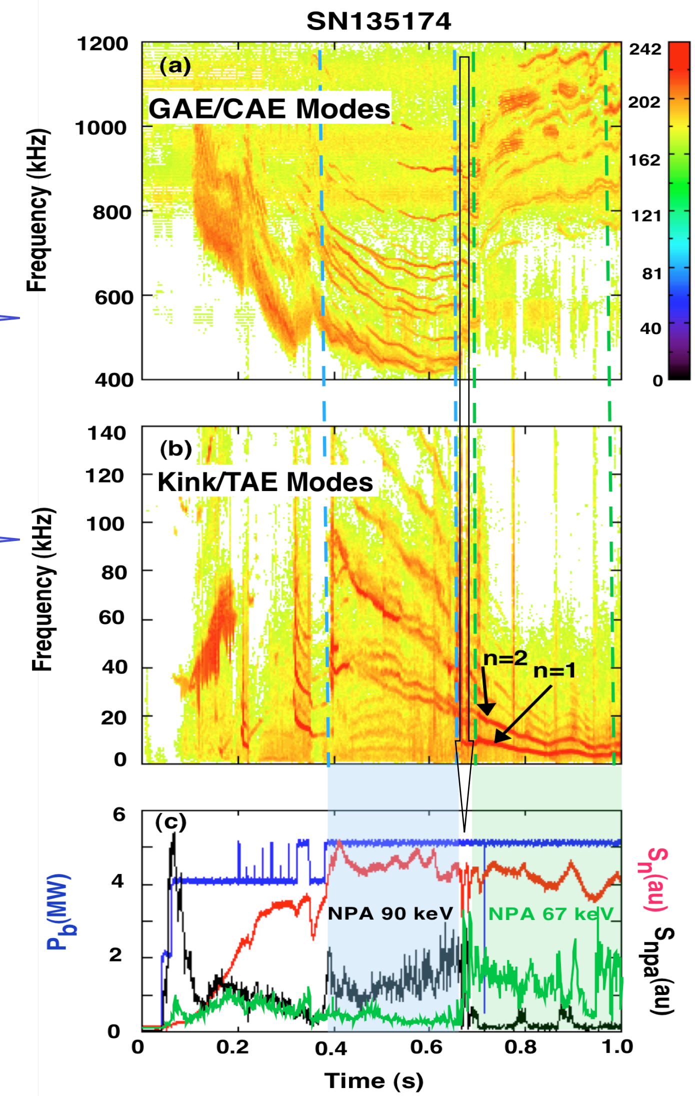
- The HEF at E_b = 90 keV appears to evolve as a *depletion* of CX flux in the region $E_b/2 < E < E_b$.

- The HEF at E_b = 65 keV appears to evolve as an *enhancement* of CX flux at the NB injection energy.

Discharge Data and Mirnov Spectrograms for a 'Dual-Energy' HEF

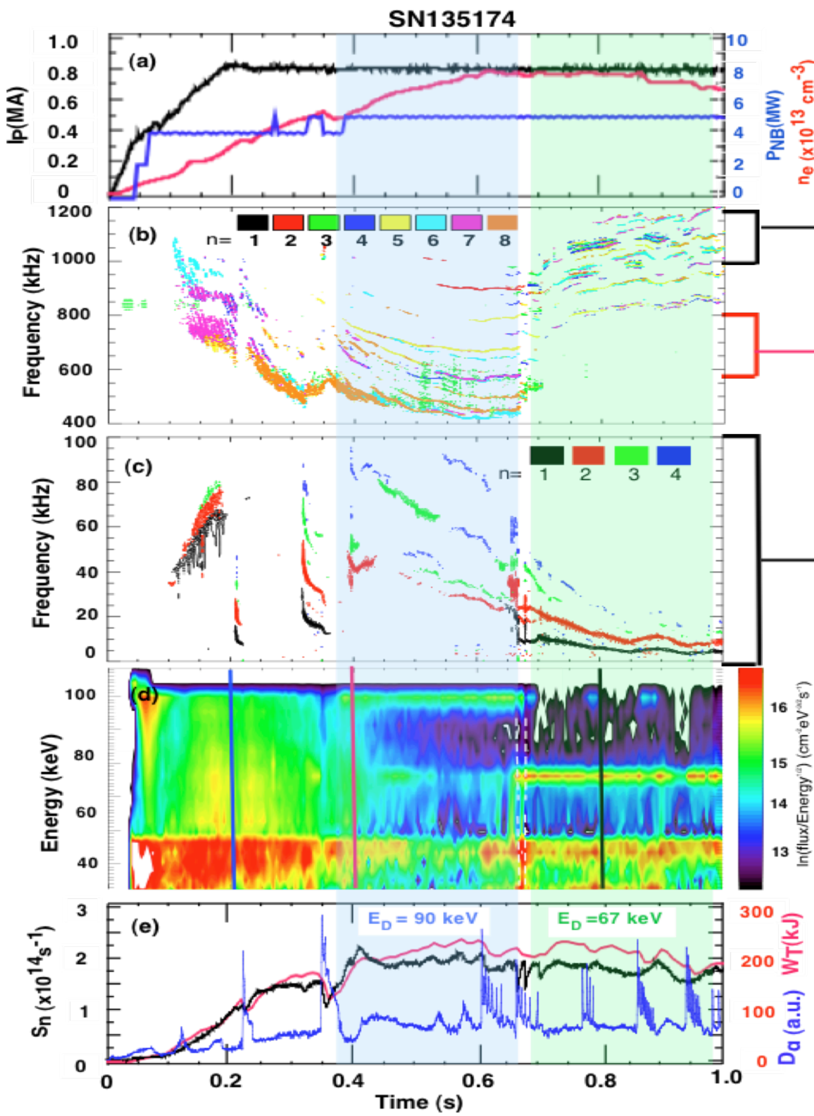
The E_b = 90 to 65 keV HEF transition coincides with abrupt MHD change (down arrow)

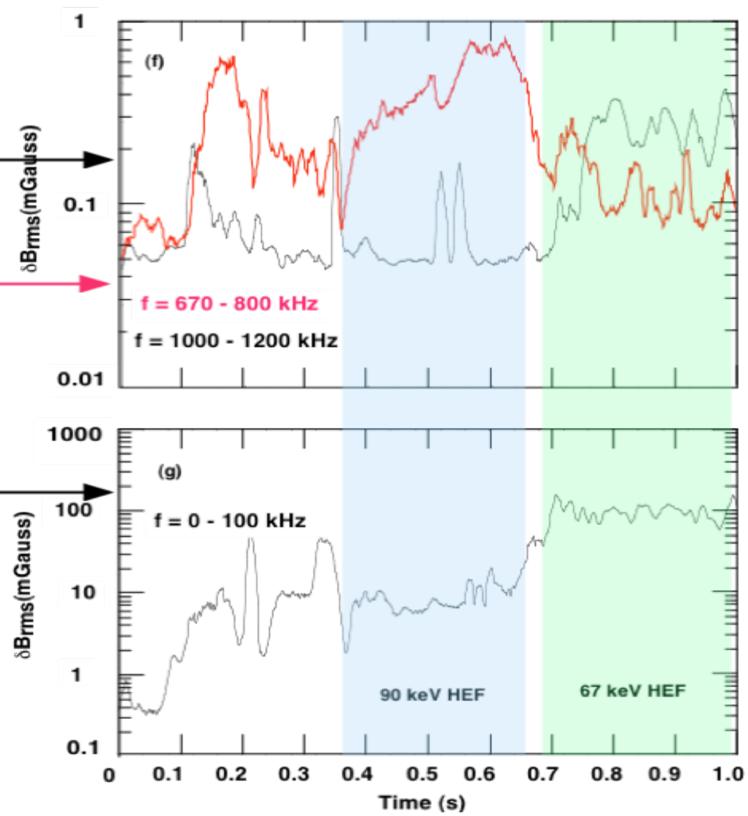




Mirnov Mode Amplitudes for a 'Dual-Energy' HEF

Mode amplitudes 'invert' at the E_b = 90 to 65 keV HEF transition

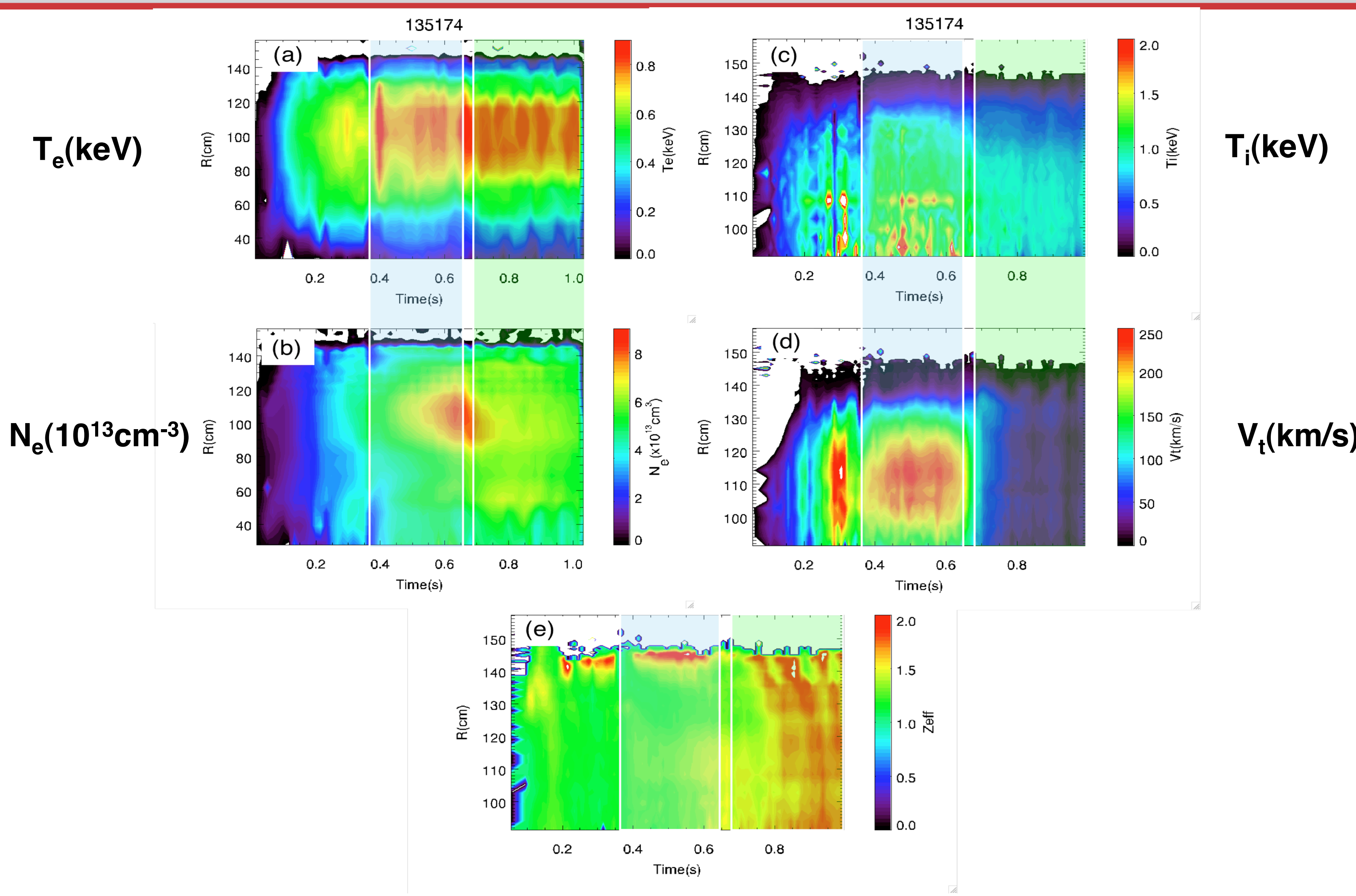




- Mode amplitude 'inversion' coincides with an abrupt collapse of toroidal rotation velocity (see next viewgraph).

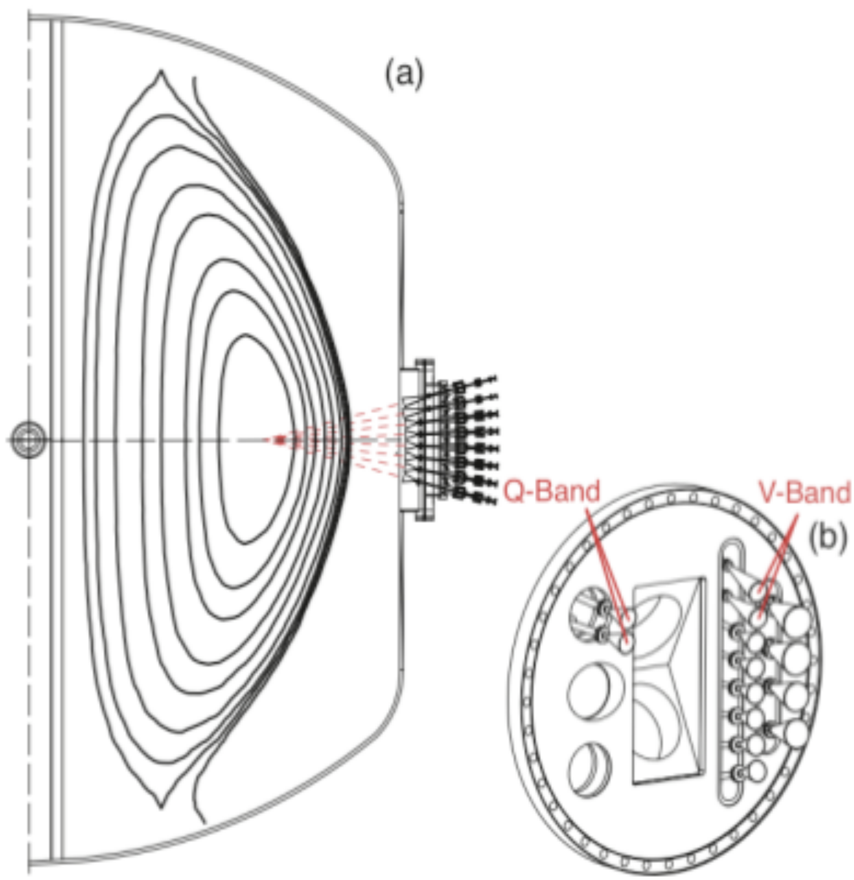
Plasma Profiles for a ‘Dual Energy’ HEF: SN135174

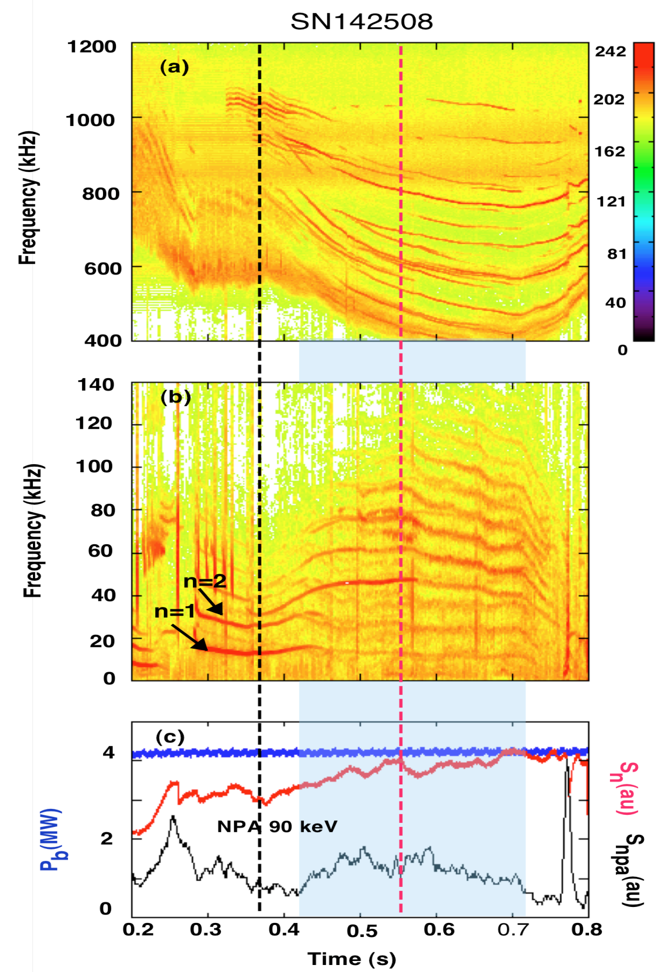
Significant plasma profile evolution is observed during the two HEF phases



Multichannel Reflectometer: I

Recent 16-channel upgrade extends cutoff density range to n_o = 1.1 - 6.9 x 10^{19} m^{-3}



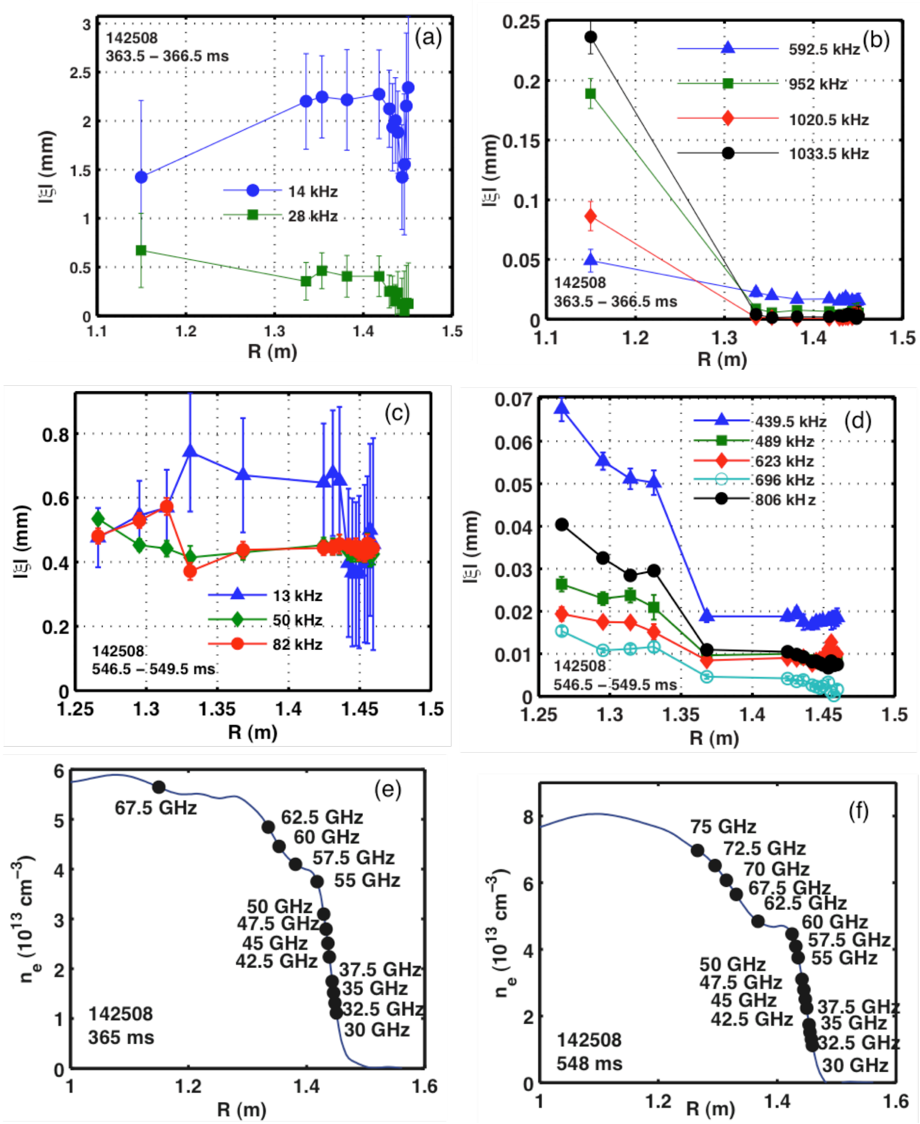


- Q-Band(30-50 GHz) and V-Band(55-75 GHz) are separated 10.2° toroidally at ΔZ ~ 13 cm.

- Reflectometer data analyzed before (black) and during (red) the HEF.

Multichannel Reflectometer: II

Mode analysis suggests HEFs are driven by GAE wave-particle interactions



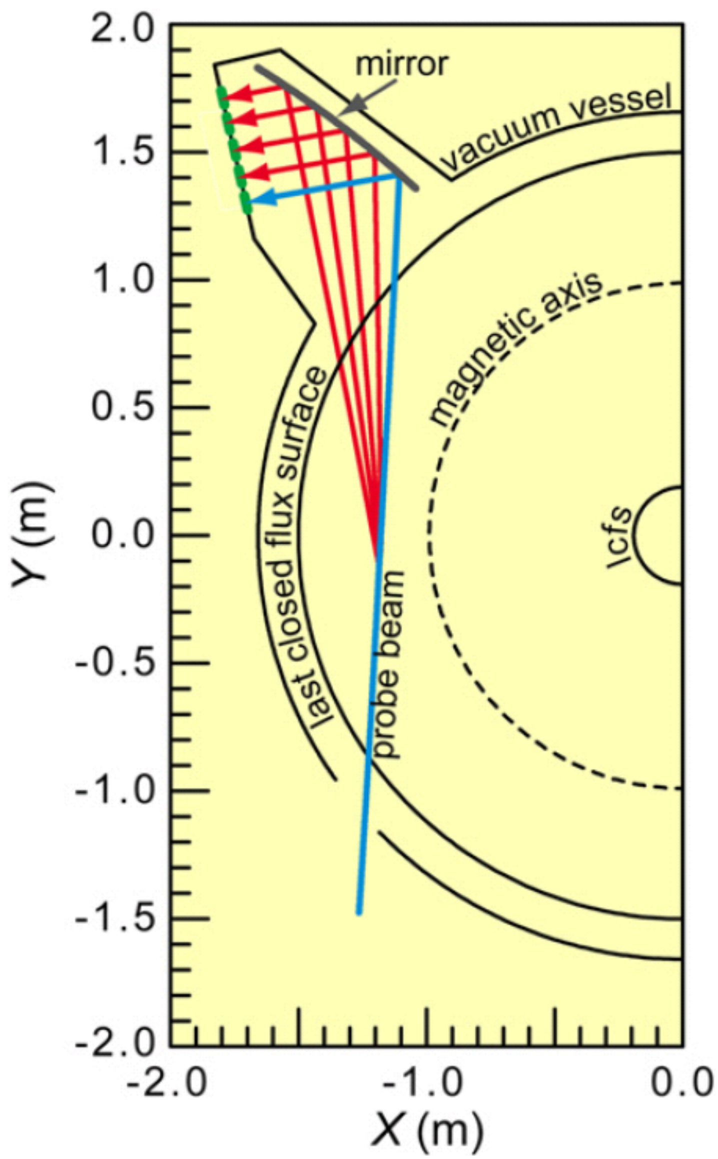
- The effective radial displacement, |ξ|, defined as half the path length fluctuation, is a good approximation of the cutoff surface displacement for global coherent density perturbations with large radial extent.

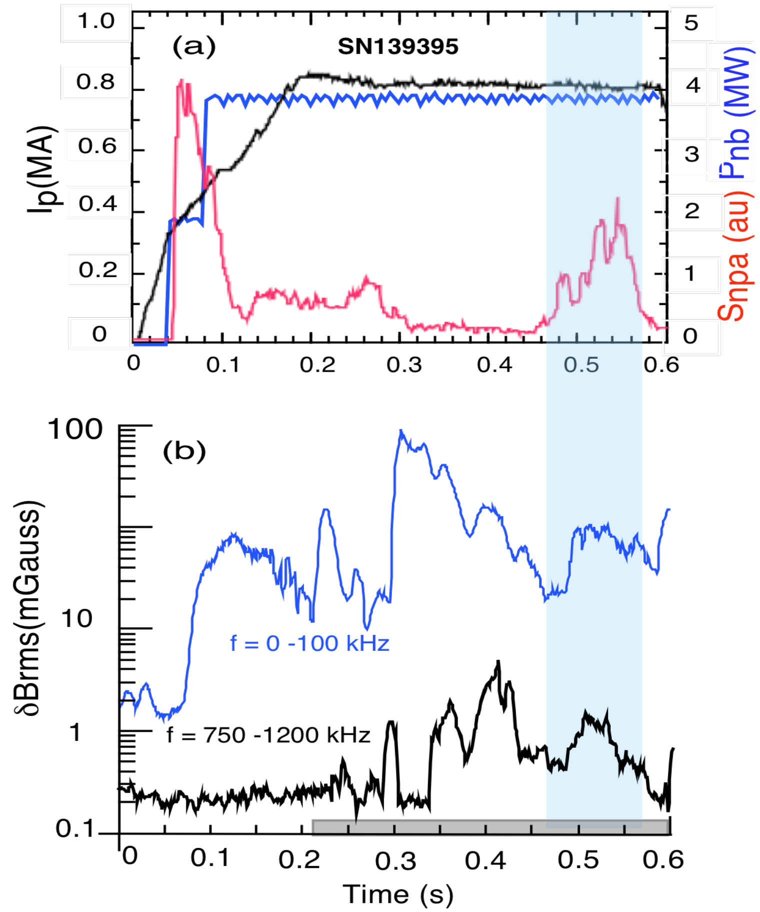
- Prior to the HEF, f = 14 kHz kink (panel a) and f ~ 1000 kHz CAE (panel b) modes are dominant with TAE modes being absent.

- During the HEF, residual kink and TAE modes are relatively weak (panel c) while robust f ~ 440 – 806 kHz GAE modes (panel d) are dominant towards the plasma inboard region: R ~ 1.25 – 1.35 m.

Tangential High-k Collective Microwave Scattering: I

As illustrated in the left panel, the high-k diagnostic can operate in both scattering and interferometric modes

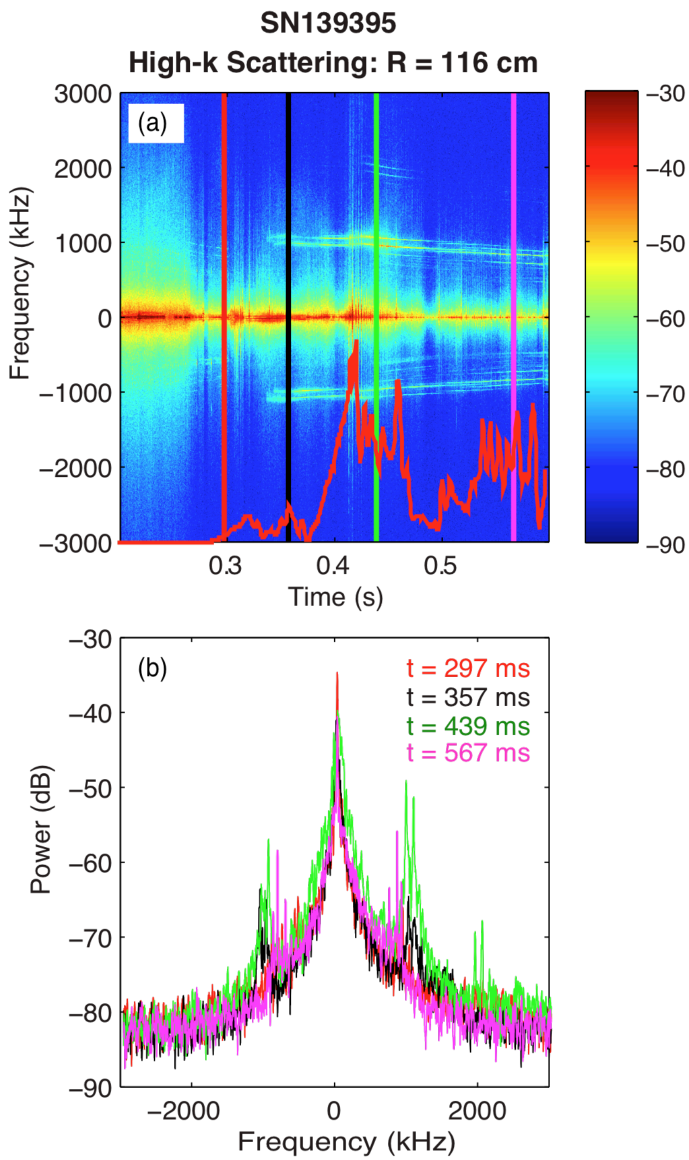




- **The HEF interval, t ~ 0.46 – 0.57 s, is demarked by the shaded vertical band and the red curve in panel (a) shows the NPA signal at E = 90 keV.**

Tangential High-k Collective Microwave Scattering: II

Measures δn_e at electron scale wave numbers ($k_\perp \rho_e < 0.6$ and $k_\perp < 20\ cm^{-1}$)



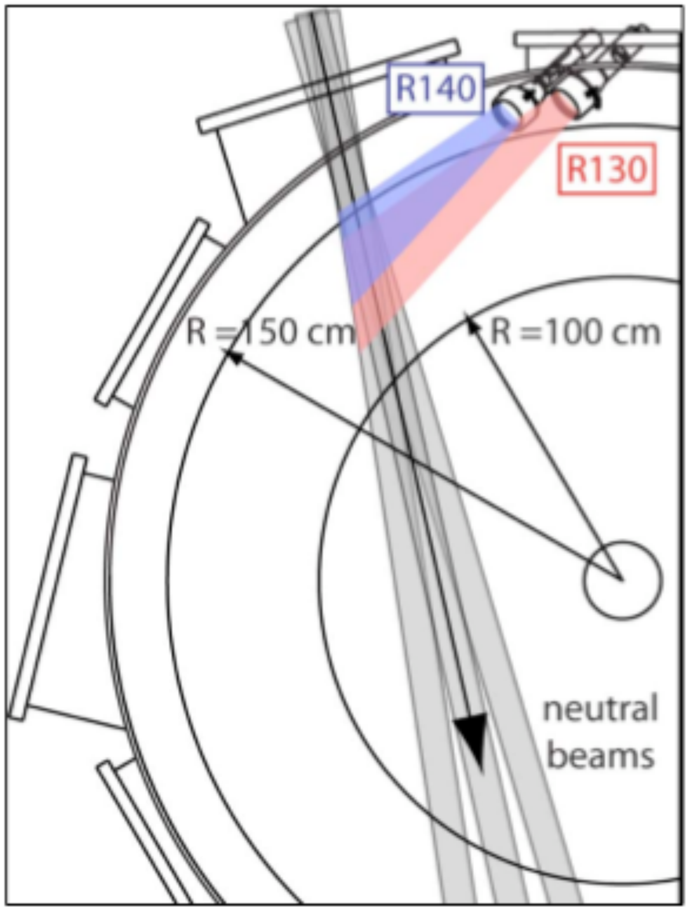
- Panel (a) shows GAE/CAE modes with f ~ 1000 kHz starting at t ~ 0.34 s with the overlaid red curve illustrating the time evolution the scattered power integrated over modes in the range f ~ 1000 ± 100 kHz.

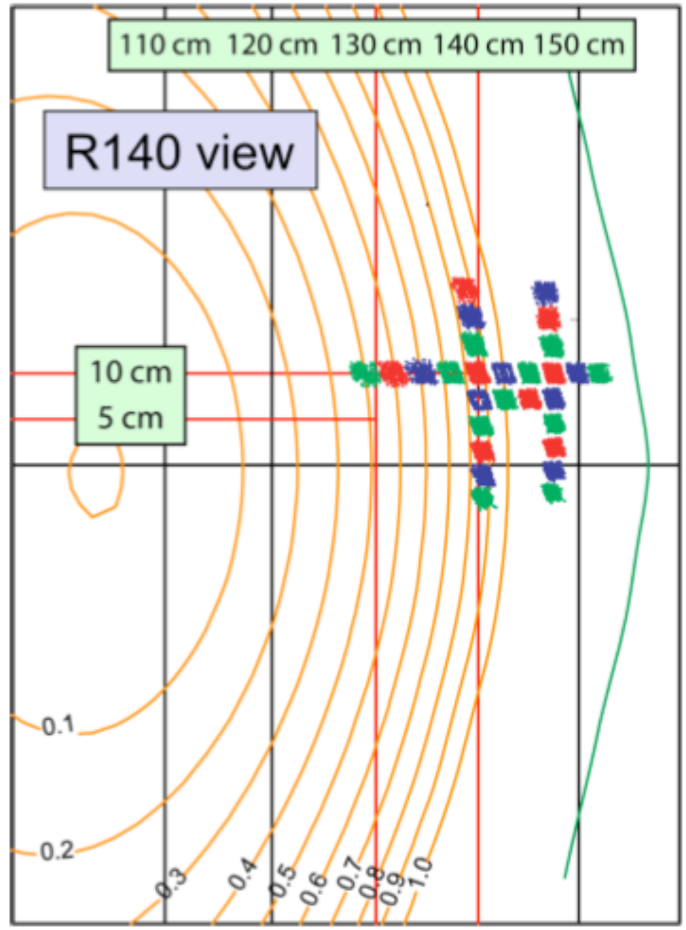
- Panel (b) shows the power spectra in interferometric mode at times demarked by vertical colored lines in panel (a). A growth in density fluctuations around t ~ 0.44 s is observed.

- The fluctuation amplitude of the perturbed electron density is estimated to be of order $\langle \delta n_e \rangle / \langle n_e \rangle \sim 2 \times 10^{-4}$, where the brackets indicate line-averaged values.

Beam Emission Spectroscopy (BES): I

Ion gyroscale fluctuation measurements ($k_\perp\rho_i < 1$) are spatially localized to the NB footprint

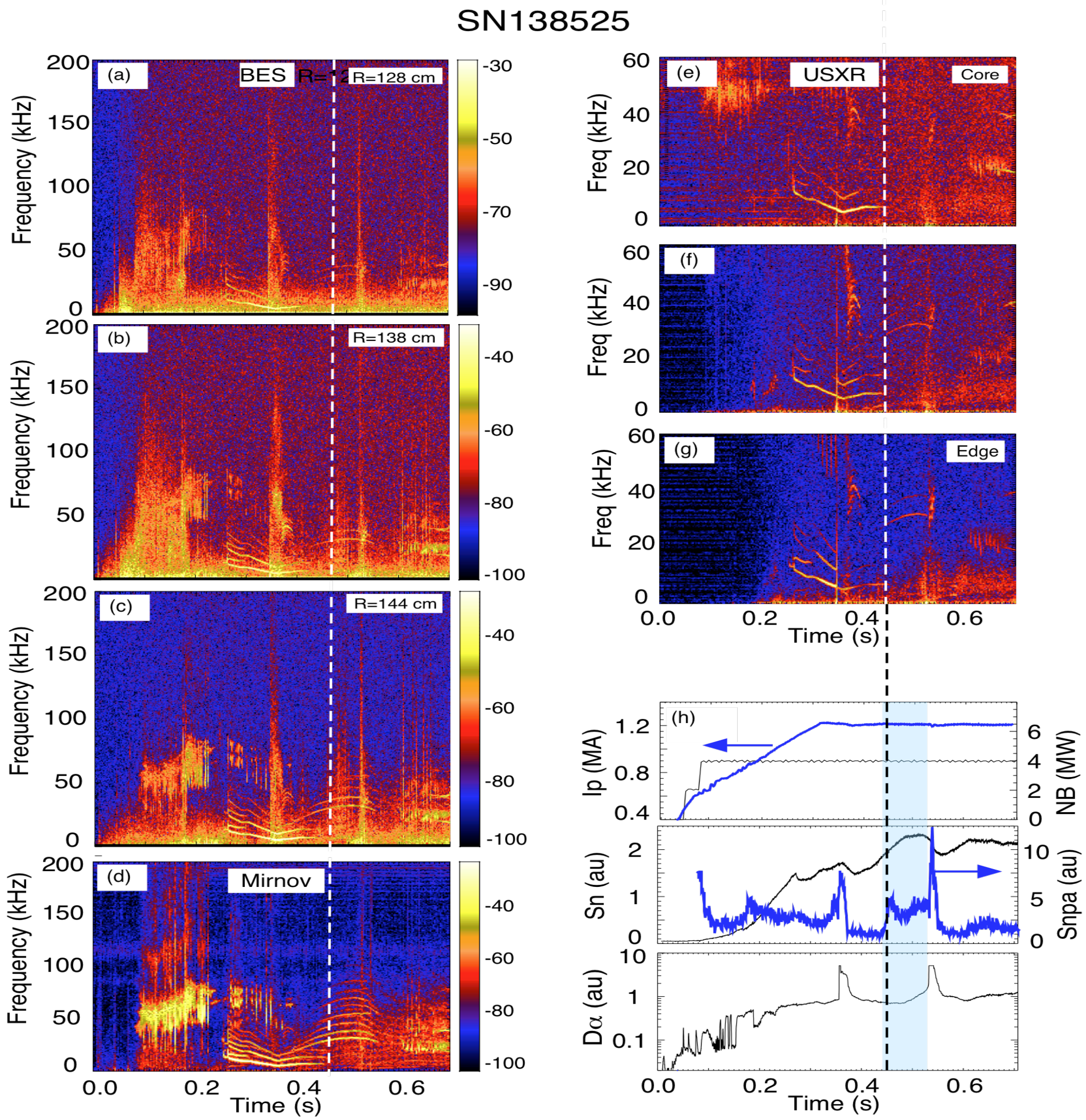




- **BES channel layout provides radial and poloidal correlation lengths and k-spectra.**

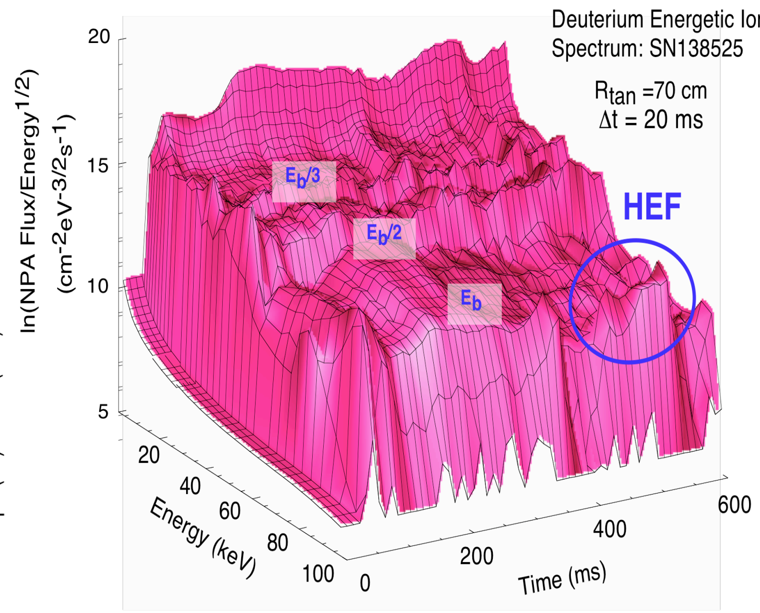
Beam Emission Spectroscopy (BES): II

TAE activity (f ~ 30-100 kHz) is localized toward the plasma outboard region



- **Panel layout**

(a-c) - BES spectrograms
(d) - Mirnov spectrograms
(e-g) - Ultra Soft X-Ray
(h) - SN138525 waveforms



- **Robust HEF @ t = 0.44-0.54 s**

HYM – Parallel Hybrid/MHD Code*

PPPL code used to investigate kinetic effects on MHD modes in toroidal geometry

- GAE and CAE modes are predicted to be driven unstable by super Alfvénic NBI ions with $V_b \sim 3V_A$ (90 keV) through the Doppler shifted cyclotron resonance.

- GAE and CAE modes can induce redistribution of beam ions.

•Driving Mechanism for GAE Modes (n=9)

$$w = \frac{\delta f}{f}, \quad f = f_0 + \delta f$$

$$\frac{d}{dt}\delta f = -\frac{d}{dt} f_0 = -\underbrace{\frac{d\varepsilon}{dt}\frac{\partial f_0}{\partial \varepsilon}}_{\text{stabilizing}} - \underbrace{\frac{dp_\phi}{dt}\frac{\partial f_0}{\partial p_\phi}}_{\text{stabilizing}} - \underbrace{\frac{d\lambda}{dt}\frac{\partial f_0}{\partial \lambda}}_{\text{destabilizing – responsible for instability}}$$

•Pitch angle distribution has strong effect on the GAE growth rate:

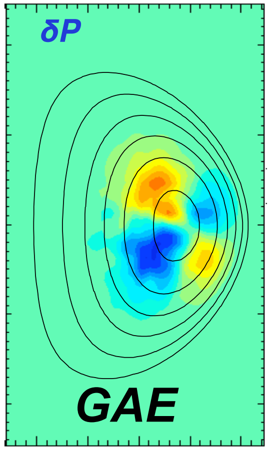
$$f_0 \sim \exp[-(\lambda-\lambda_0)^2/\Delta\lambda^2], \; \lambda = \mu B_0/\varepsilon$$

*E. Belova et al, Phys. Plasmas 7, 4996 (2000)

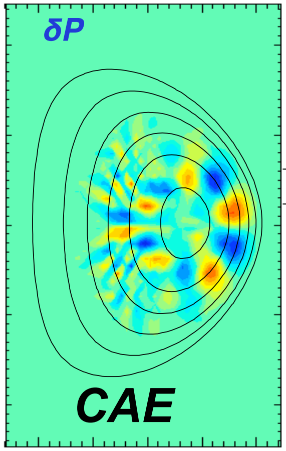
3D simulations of energetic ion-driven instabilities in NSTX

Linearized delta-f simulations

- For $q_0 \sim 1$, simulations show instability of low-n Global Alfvén Eigenmodes (GAE) with large $k_{||}$.
- For $q_0 \sim 2$, simulations show unstable GAE for $n \sim 6 - 9$.
- GAE modes are more unstable than CAE (agrees with analytical calculations) with $\gamma/\omega \sim n_b/n_0$.
- GAE modes are core localized, whereas CAE modes are edge localized.
- GAE mode propagates counter to beam direction.
- Both GAE and CAE modes have large compressional magnetic component near the plasma edge.
- Most unstable mode toroidal number shifts to larger n for larger q_0.



n=4 (m=-2)

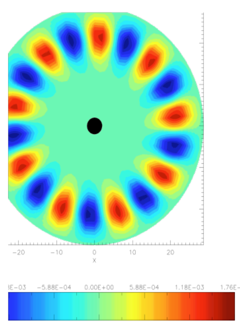


n=8

GAE Mode Structure: Magnetic Field (n=9)

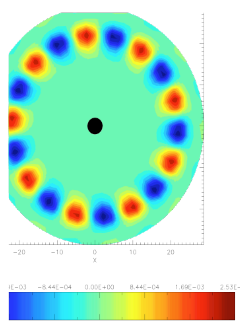
- $\delta B_{||}$ is small near magnetic axis, but it is peaked at low-field side mostly due to large δB_Z.
- $\delta B_{||}$ is large at the edge due to wide radial profile of δB_ϕ .
- At peak amplitude $\delta B_{||} < 1/3\ \delta B_\perp$; at the edge the compressional component dominates $\delta B_{||} > \delta B_\perp$.
- $\delta B_{||} > \delta B_\perp \sim 10^{-4} B_0$ (at the edge), $<\delta n>/<n_0> \sim 10^{-4}$.
- Taking into account mode localization and time-averaging, for peak amplitude: $\delta n \sim 3 \cdot 10^{-3} n_0$.

R



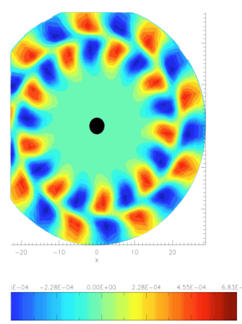
δB_R

R

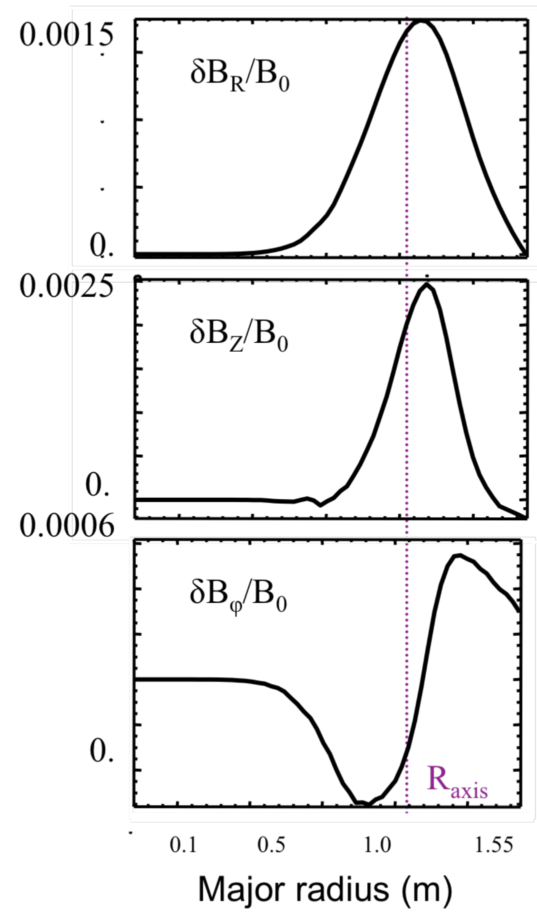


δB_Z

R



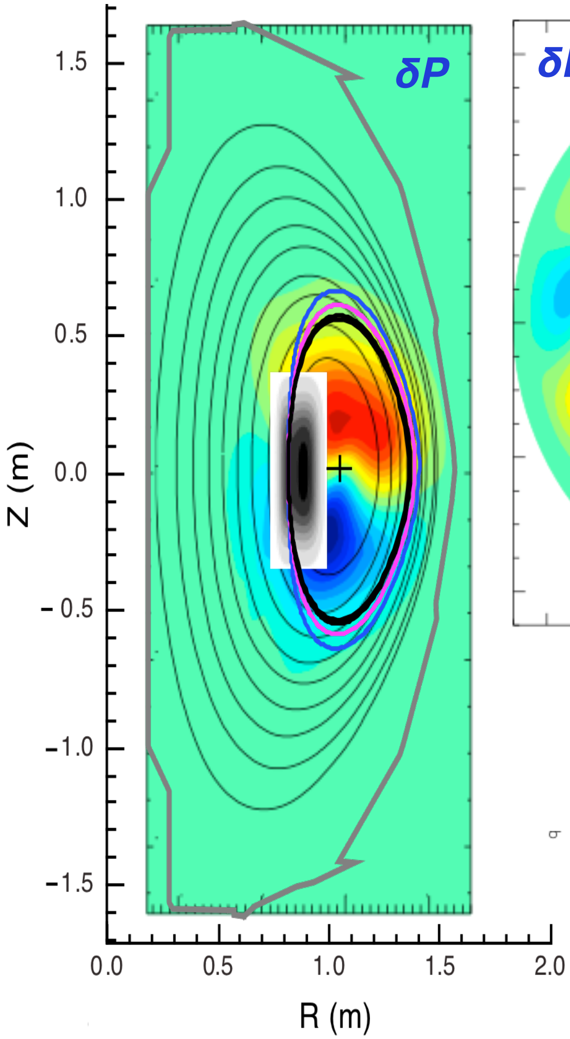
δB_φ



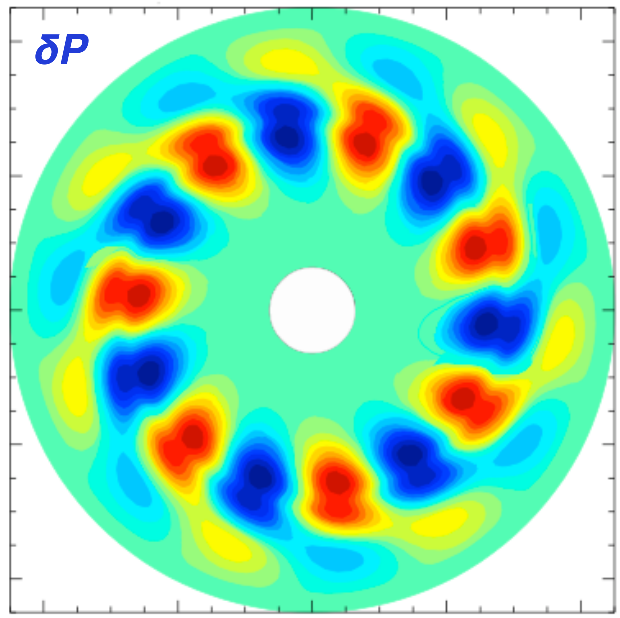
Radial profiles of perturbed magnetic field at the midplane.

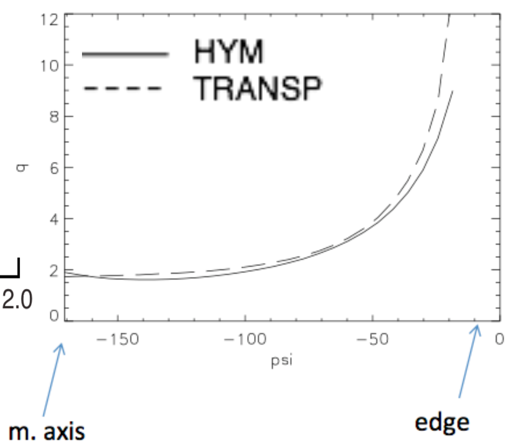
HYM Simulation of GAE Mode Structure for the HEF: SN132800

H-mode with I_p = 1.0 MA, B_T = 4.5 kG, E_B = 90 keV, P_{NB} = 4 MW, n_eL ~ 6×10^{13} cm^{-2}



n = 7 (m = -1)

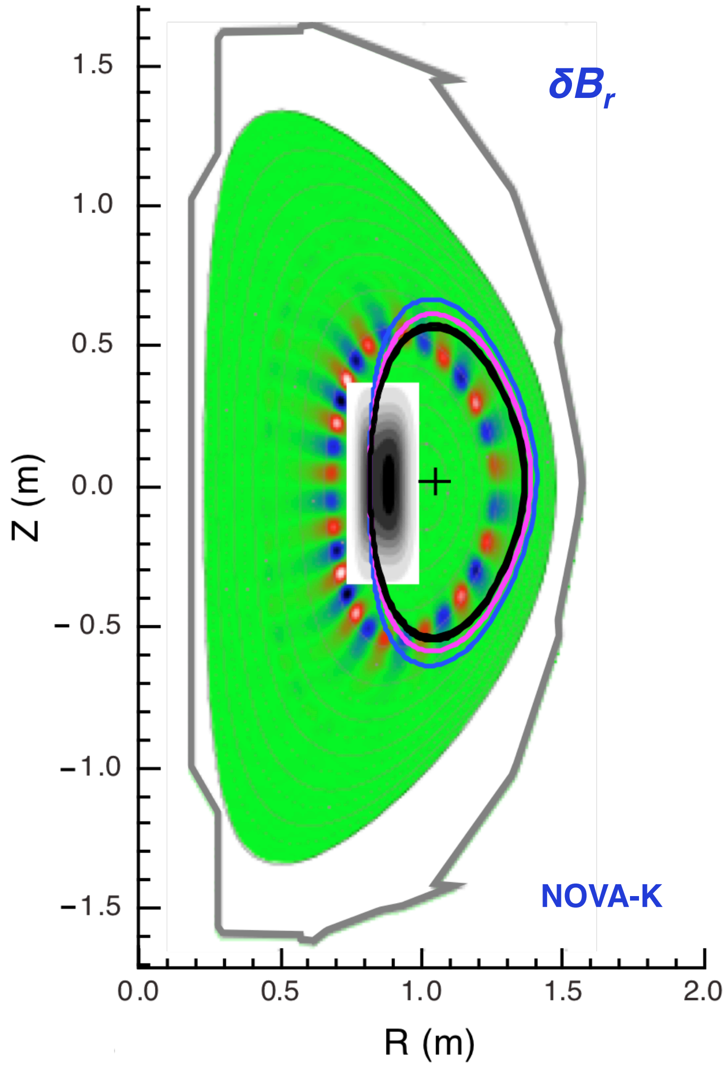




- **Simulations show unstable GAE for n ~ 6 – 9, consistent with Mirnov coil data.**
- **The n = 7, m = -1 GAE mode exhibits the largest growth rate with γ/ω ~ 10%.**
- **The n = 6, m = -2 GAE mode is also unstable but with smaller growth rate.**
- **Lower-m modes have stronger particle resonant interaction due to their wider radial structure.**
- **Next, SPIRAL will be used to compute $\delta f_i(E,v_{||}/v,r)$ driven by eigenmode structures.**

SPIRAL Code Simulation

SPIRAL imports $f_i(E,v_{||}/v,r)$ from TRANSP and evolves it under *AE wave-particle interactions



Analysis Process

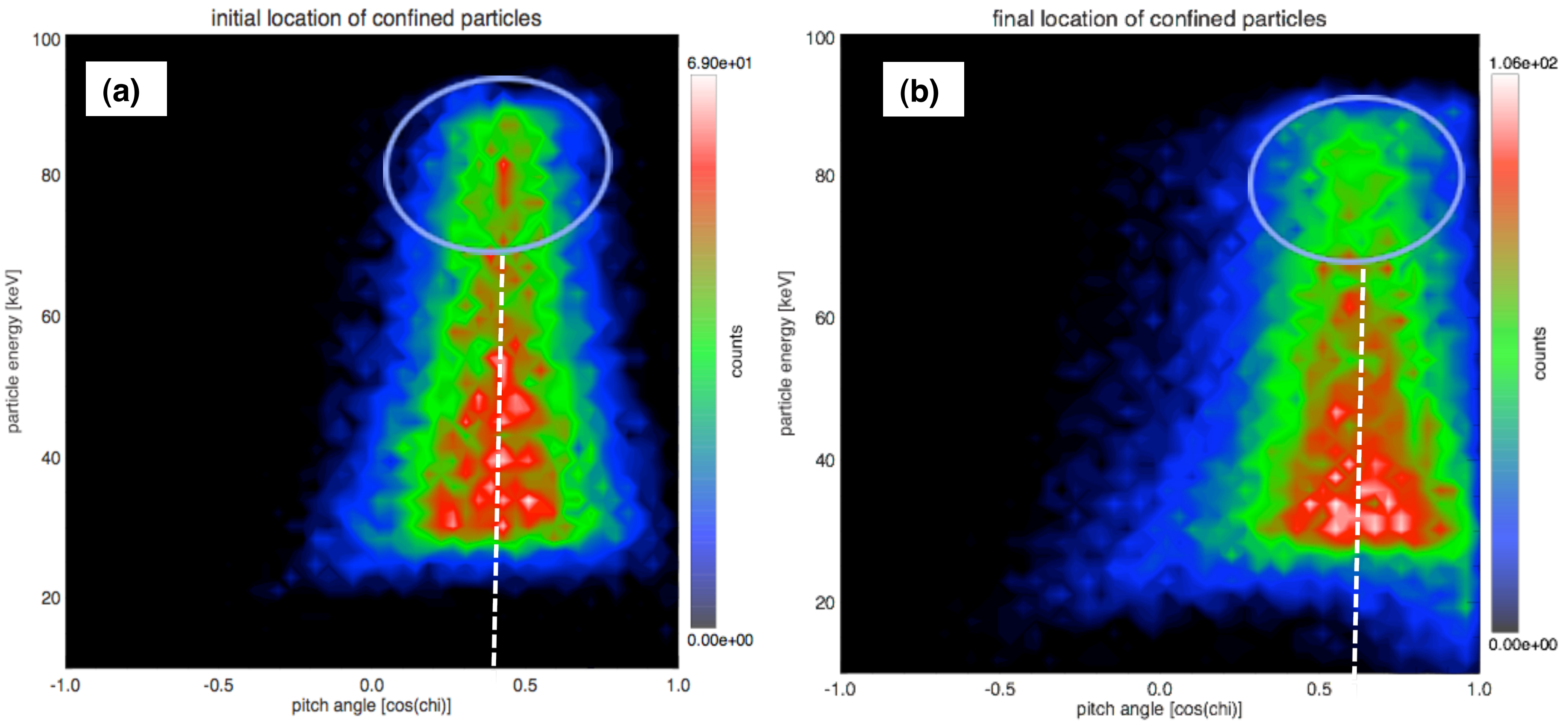
- Construct equilibrium for HEF case
  – e.g. using EFIT, LRDFIT, HYM codes.
- Construct candidate Alfvén eigenmodes
  – e.g. using NOVA-K, HYM codes.
- Compute $\delta f_i(E,v_{||}/v,r)$ due to wave-particle interactions using SPIRAL.

Plot Legend

- EFIT equilibrium flux surfaces: (black).
- NOVA-K n = 3, m ~ 10 mode structure (red/blue).
- Passing orbits: E_b = 90 keV, $v_{||}/v$ = 0.7 ± 0.2
- Footprint of NB primary neutrals (shaded box).

Illustration of SPIRAL Code Simulation

SPIRAL is a full-orbit following code



- **(a) Initial distribution function imported from TRANSP for SN132800.**

- **(b) Final distribution function calculated by SPIRAL shows full energy redistribution (circle) and $f_i(E,v_{||}/v)$ shift to larger $v_{||}/v$ (dashed line).**

Summary of HEF Phenomenology: I

• **High-Energy Features (HEFs)**

- Observed as enhanced CX flux near the NB full energy E ~ 90 keV (i.e. does not exhibit an 'ion tail' aka HHFW heating). Not observed at the beam fractional energies.

- HEFs can 'turn-on' and 'turn-off' multiple times during a discharge, in 'counter-sync' with f < 140 kHz MHD activity and can persist for ~100 - 600 ms.

- Onset of the HEF is not 'abrupt' but exhibits growth times of ~ 20 - 80 ms.

• **Not a NPA Instrumental Effect**

- Not due to 'quirky' anodes because feature moves to other MCP anodes as the E||B NPA fields are adjusted. Only observed at ~ E_b, never at $E_b/2$ or $E_b/3$.

- HEFs have been observed for mid-plane NPA sightlines in the range R_{tan} ~ 55 - 86 cm corresponding to $v_{||}/v$ ~ 0.7 - 0.9 (but no horizontal or vertical scan data exist).

- In some cases, sFLIP energetic ion loss is observed which implies that the HEF flux, at least in part, is due to orbit excursions into the high edge neutral density region.

Summary of HEF Phenomenology: II

- **Discharge Parameters**

- Not observed during L-mode discharges (only in H-modes).

- Not observed for P_b < 4 MW (even during brief P_b notches to lower power).

- Suppressed during robust LITER operation (e.g. > 50 mg/shot or at a level sufficient to suppress ELMs).

- **MHD Activity**

- Not observed in the presence of n=1 kink modes or robust (δB_{rms} > 75 mGauss) TAE activity. Not correlated with ELM activity.

- The magnitude of the HEF flux is modulated by strong bursting EPM activity, similar to other energies in the NPA fast ion charge-exchange spectra.

- HEFs appear to coincide with the frequency down-sweeping phase of CAE activity and usually terminate at sweep reversal (i.e. ramp down of toroidal rotation, v_Φ).