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Transient Enhancement ‘Spike-on-Tail’ Observed on NBI Energetic Ion Spectra Using the E||B NPA on NSTX

S. S. Medley, N. N. Gorelenkov, R. E. Bell, E. D. Fredrickson, S. P. Gerhardt, B. P. LeBlanc, M. Podestà, A. L. Roquemore and the NSTX Team

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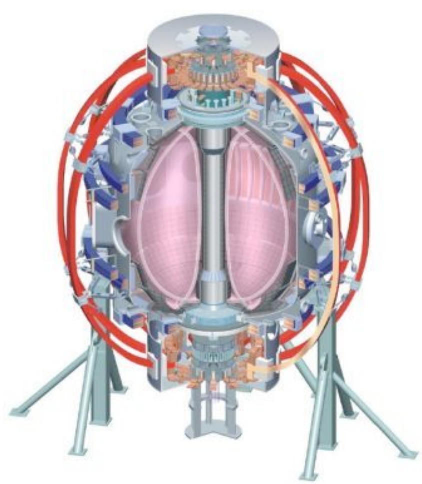

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Abstract

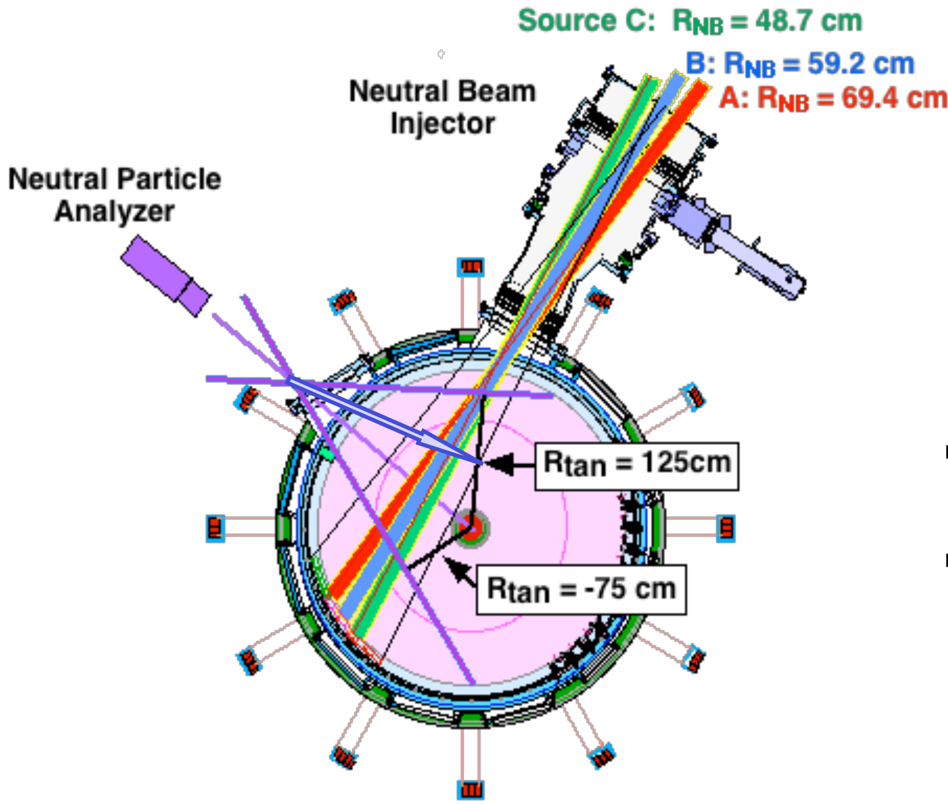
Transient Enhancement ('Spike-on-Tail') Observed on NBI Energetic Ion Spectra Using the EIIB NPA on NSTX, S. S. Medley, N. N. Gorelenkov, R. E. Bell, E. D. Fredrickson, S. P. Gerhardt, B. P. LeBlanc, M. Podestà, A. L. Roquemore, and the NSTX Team (PPPL) – An ~ 4x increase in the EIIB Neutral Particle Analyzer (NPA) charge exchange neutral flux localized at the Neutral Beam Injection (NBI) full energy is observed in the National Spherical Torus Experiment (NSTX). Termed the High-Energy Feature (HEF), it appears only at the NBI full energy, exhibits a growth time of ~ 20 - 80 ms, seldom develops a slowing down distribution and arises only in discharges where kink-type modes (f < 10 kHz) are absent, TAE activity (f ~ 10-150 kHz) is weak and CAE/GAE activity (f ~ 400-1200 kHz) is robust. The HEF is observed 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 is suppressed by vessel conditioning using lithium deposition at ≥ 100 mg/shot. Coincident increases of ~ 10-30 % in neutron yield and total stored energy during the HEF are driven by plasma profile changes and not the HEF itself. Tentatively, the HEF appears to be caused by a form of CAE/GAE wave-particle resonant interaction. *Work supported by US-DOE contract DE-AC02-09CH11466.*

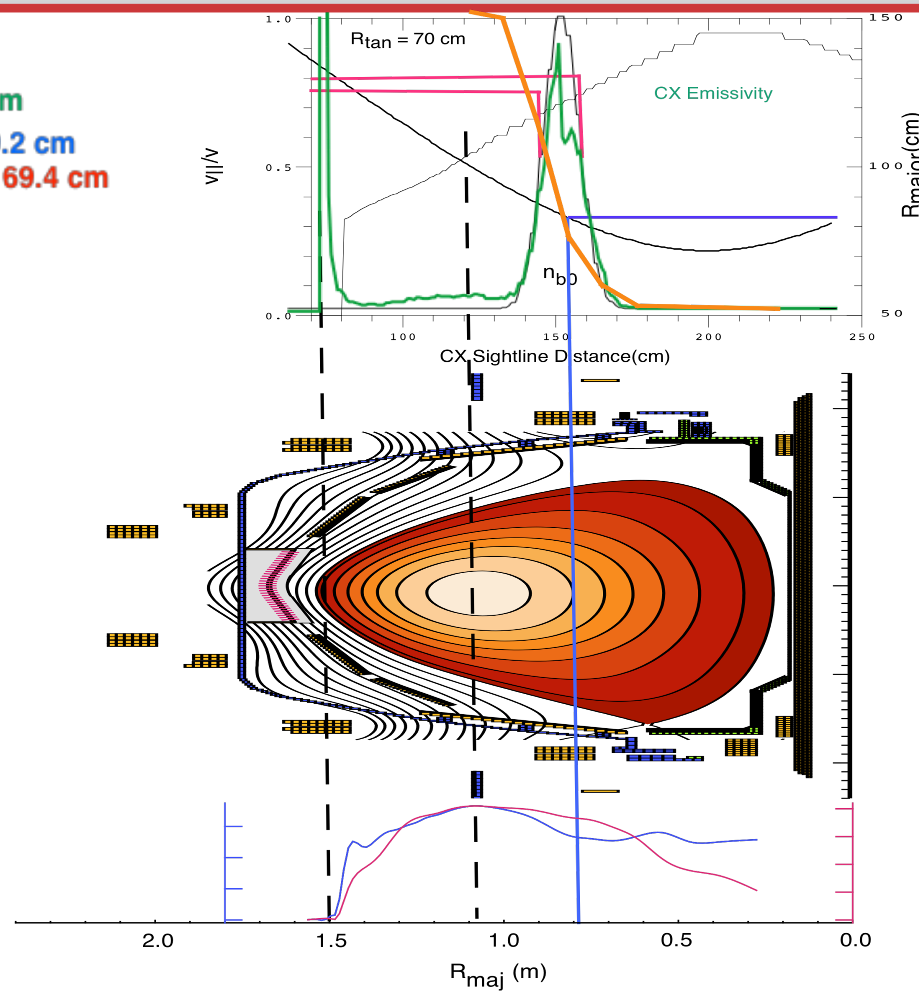
High-Energy Feature (HEF)

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

The HEF is a transient mid-discharge phenomenon with durations ~ 100 - 600 ms.

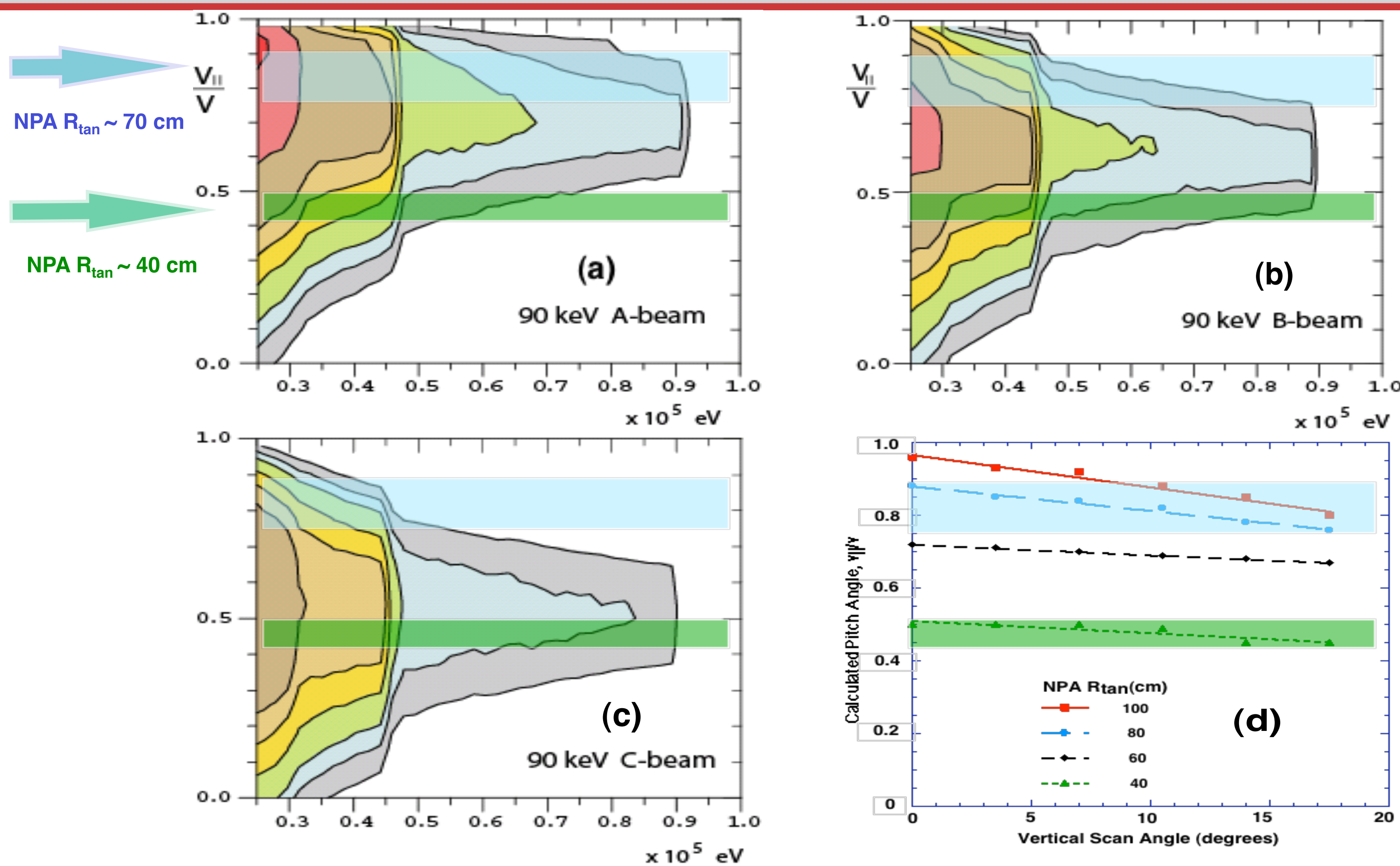
The E||B Neutral Particle Analyzer (NPA) on NSTX Scans Horizontally on a Shot-to-Shot Basis





• 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 $v_{||}/v \sim 0.05$.

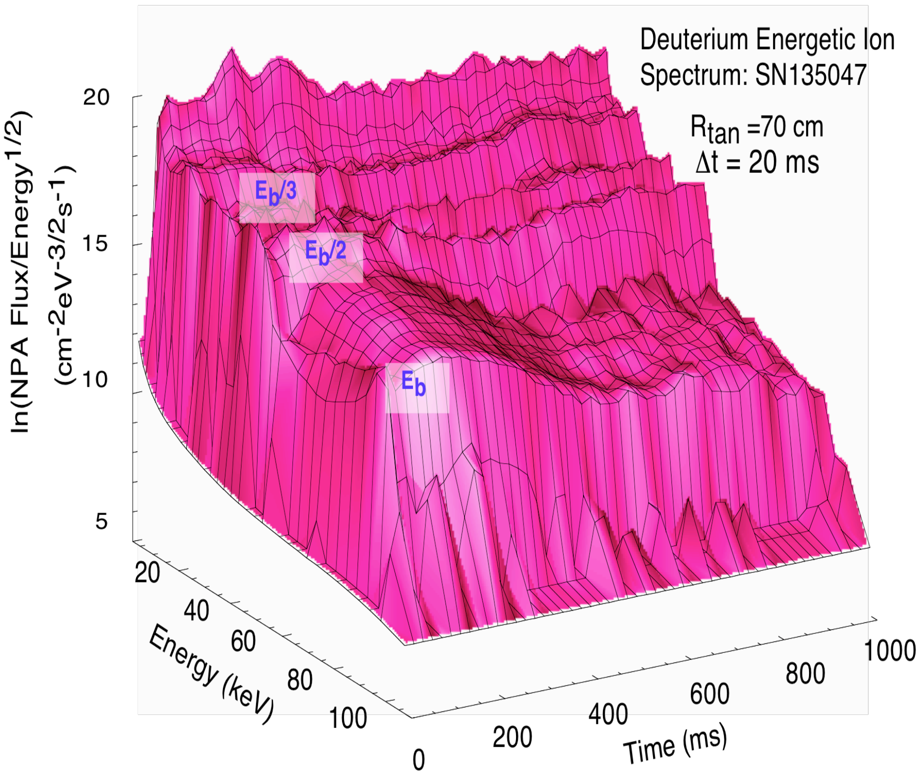
The Pitch Angle, $v_{||}/v$, Viewed by the NPA Depends on Both the Horizontal and Vertical Sightline Setting

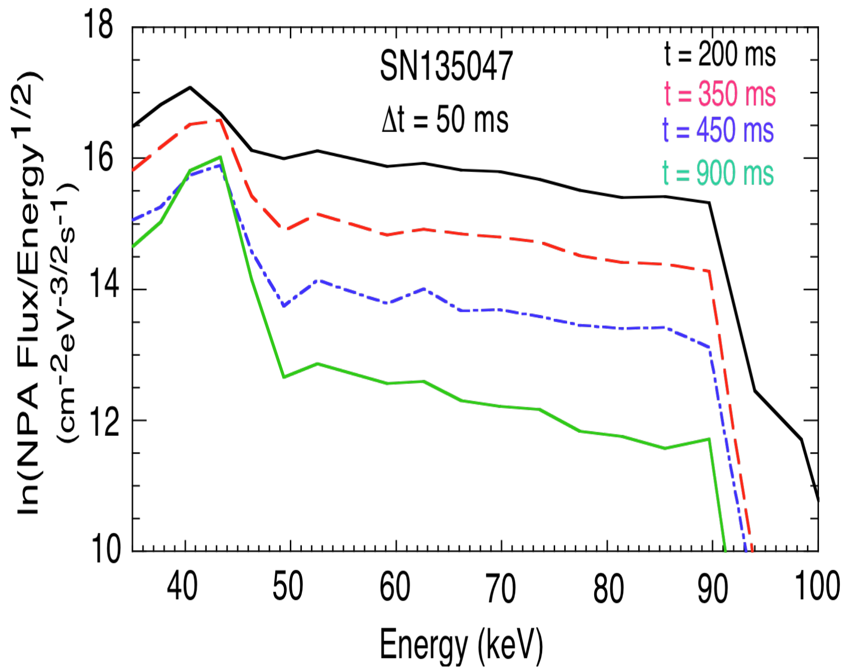


- For 'typical' R_{tan} ~ 70 - 80 cm, the NPA views passing ions with $v_{||}/v$ ~ 0.85 ± 0.05.

Reference NPA Energetic Ion Spectra: no High-Energy Feature

H-mode with I_p = 0.9 MA, B_T = 4.5 kG, P_{NB} = 4 MW, $n_eL \sim 6\times10^{13}$ cm^{-2}

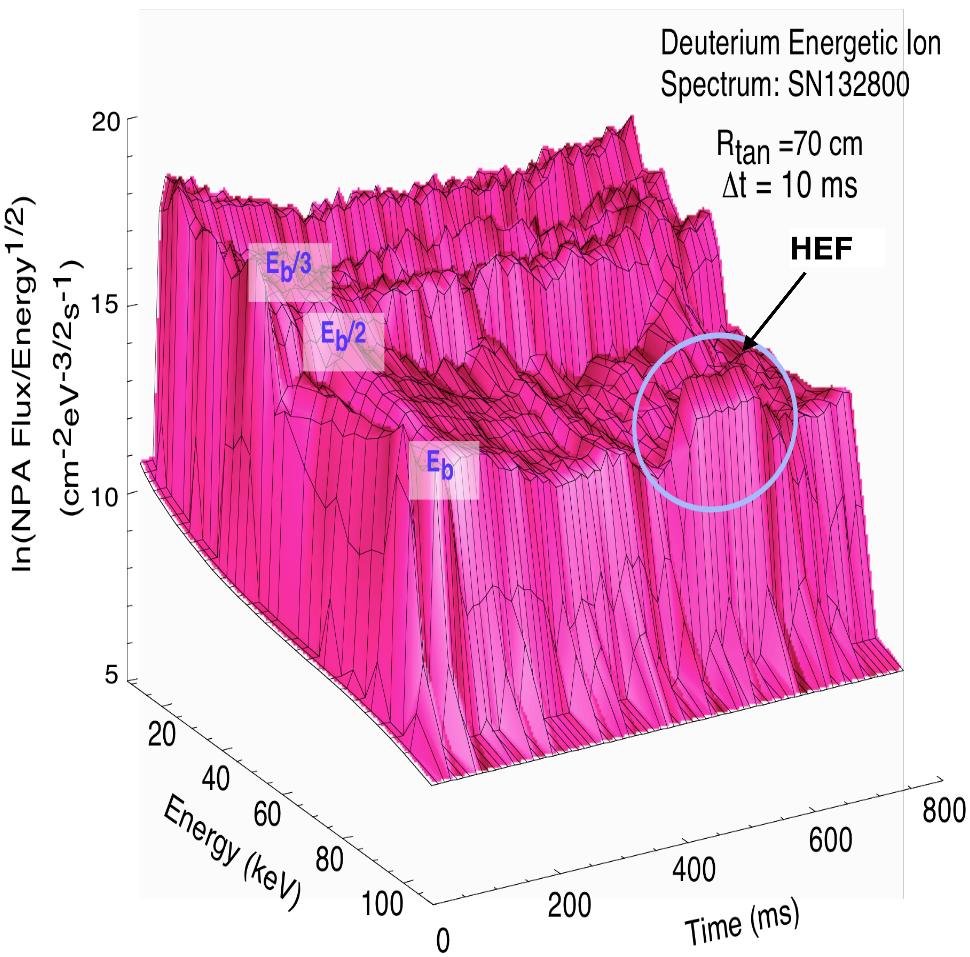


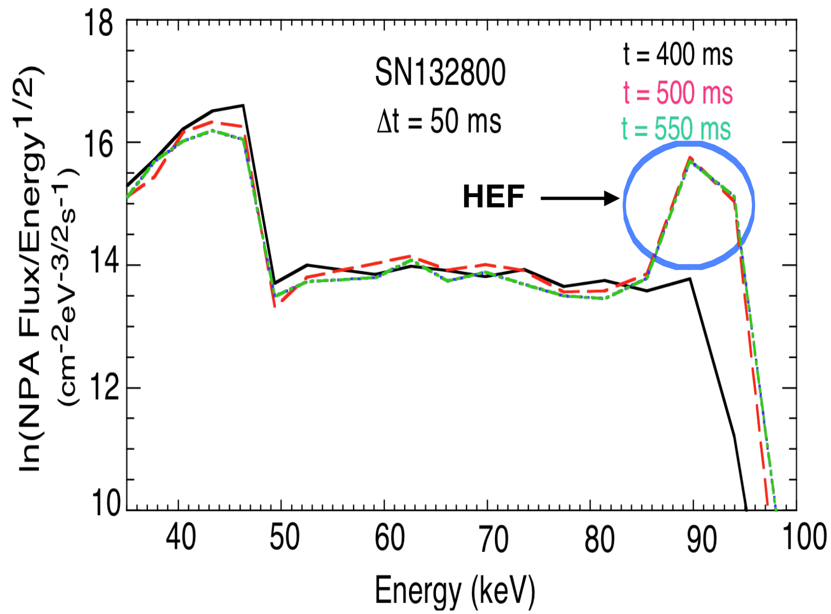


- Depletion of the NPA spectrum in the range $E_b/2 < E \leq E_b$ by ~ 3 e-foldings is due to the combined effects of n_e ramp-up and MHD-induced energetic ion redistribution/loss.

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

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

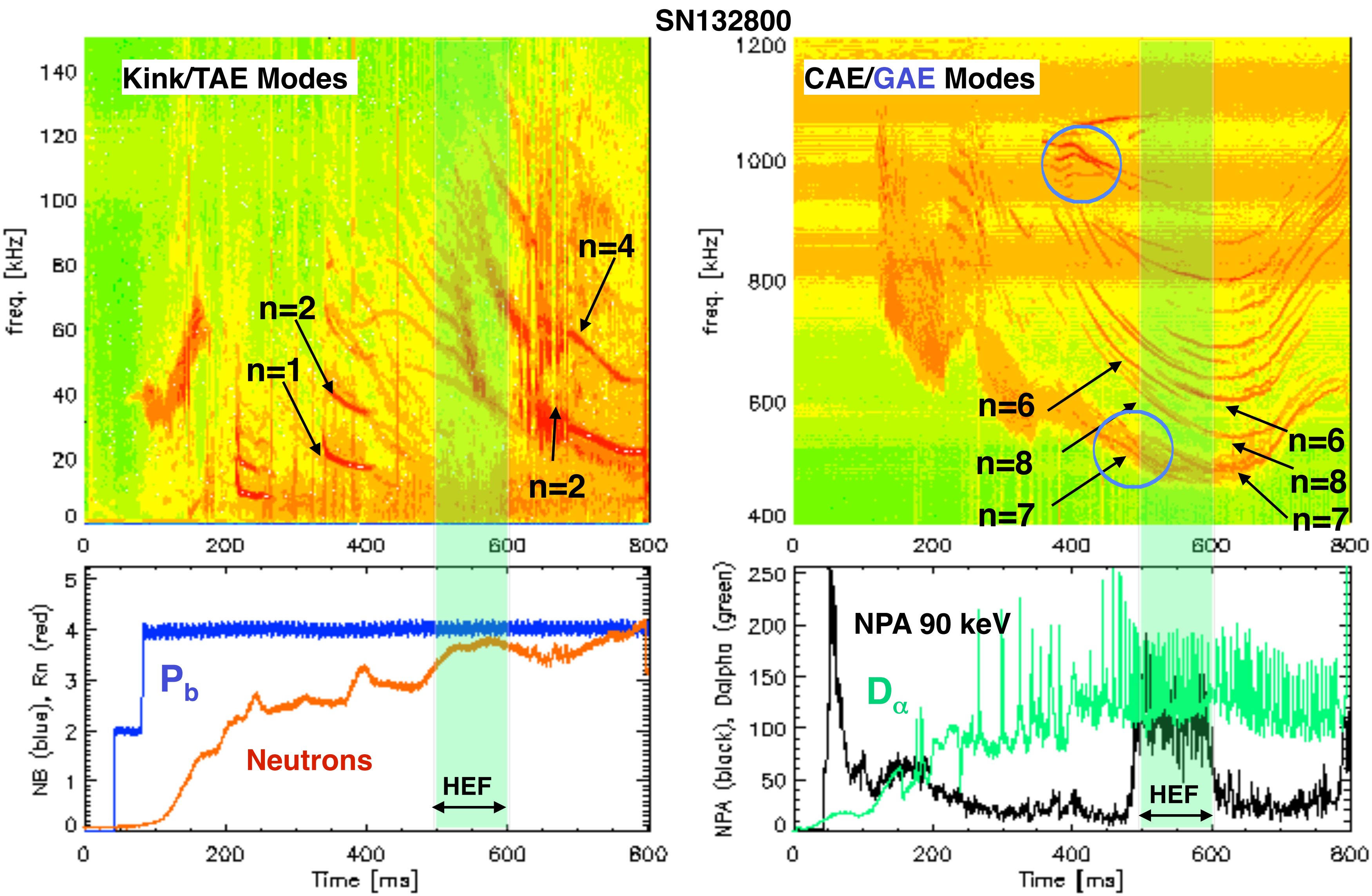




- **The NPA charge exchange spectrum exhibits enhanced signal only near E ~ E_b (e.g. never at $E_b/2$ or $E_b/3$).**
- **Lack of evolution of a slowing-down distribution below the HEF is a common (and not understood) feature.**

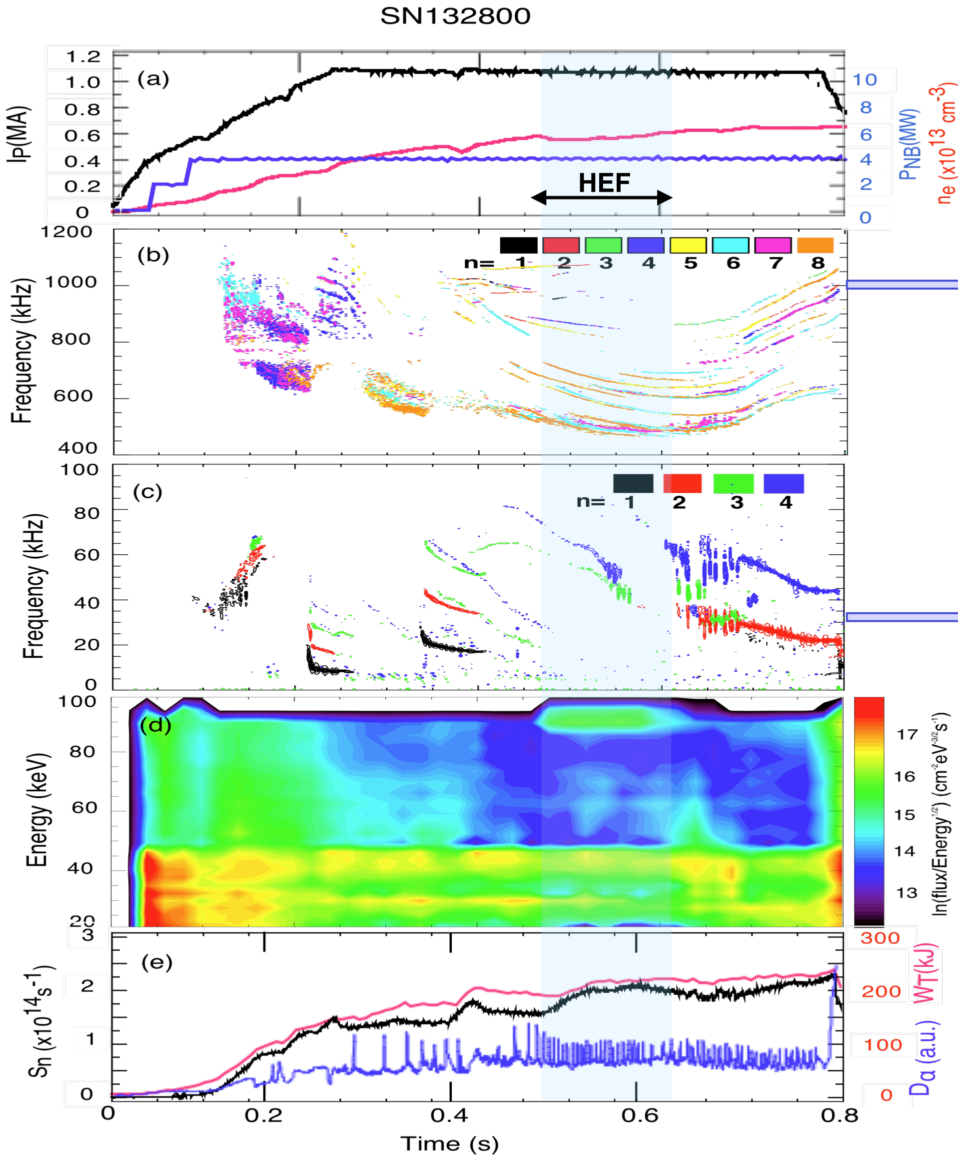
HEF Existence Requires No Kink and Weak TAE MHD Activity

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

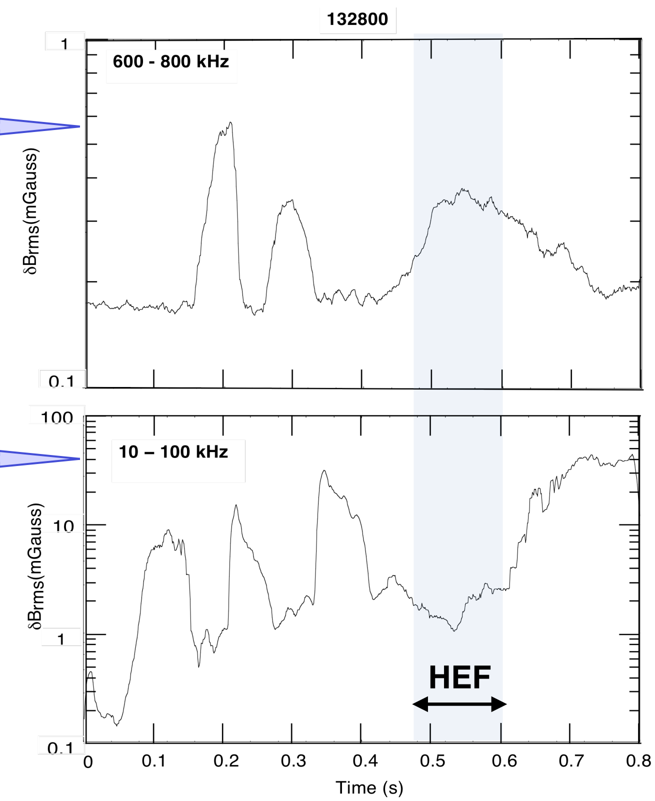


Discharge Data and Mirnov δB_{rms} Evolution for the 'Brief' HEF

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 the 'Brief' HEF: SN132800

Only significant T_e profile evolution is observed during the HEF phase

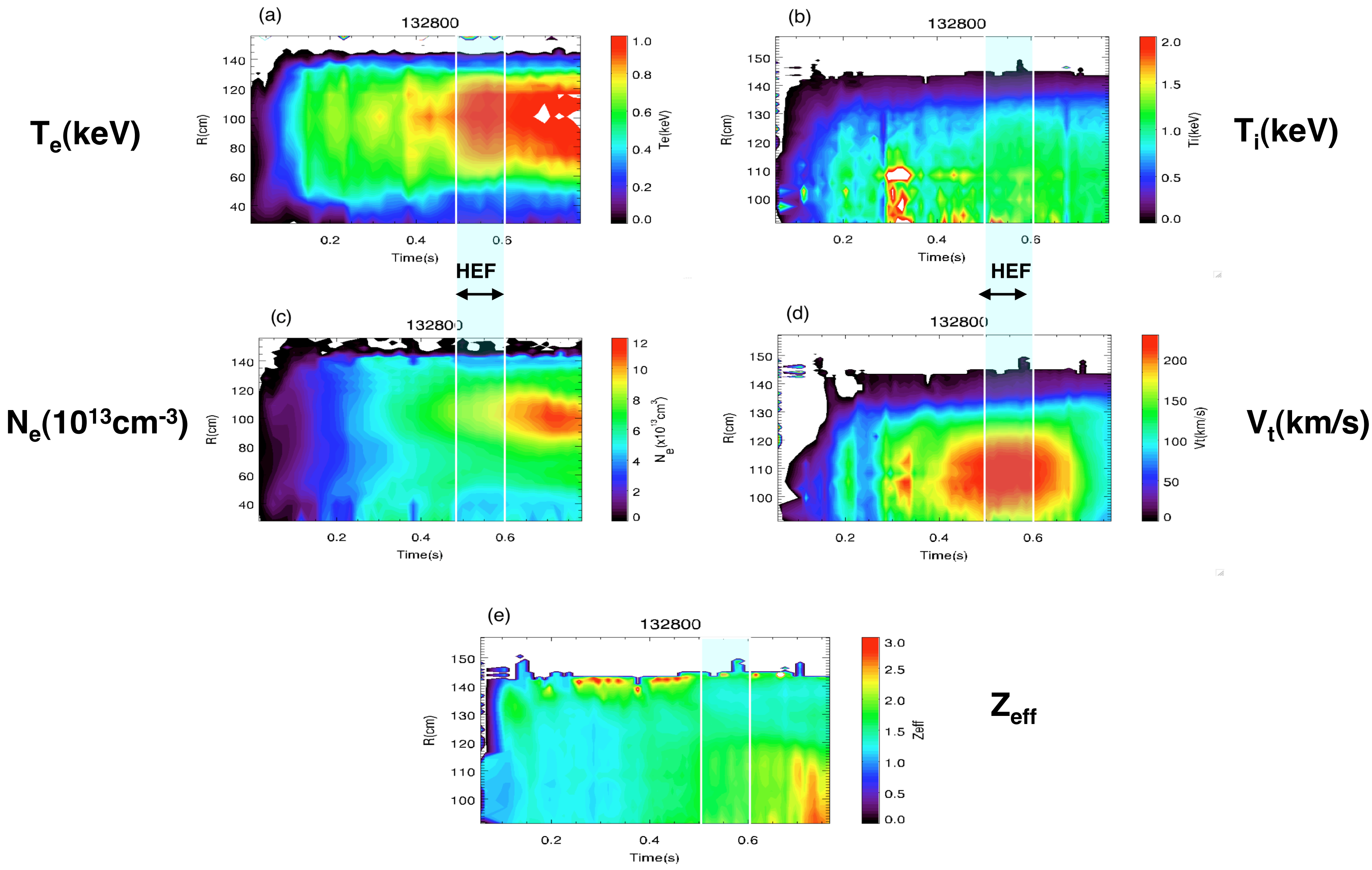
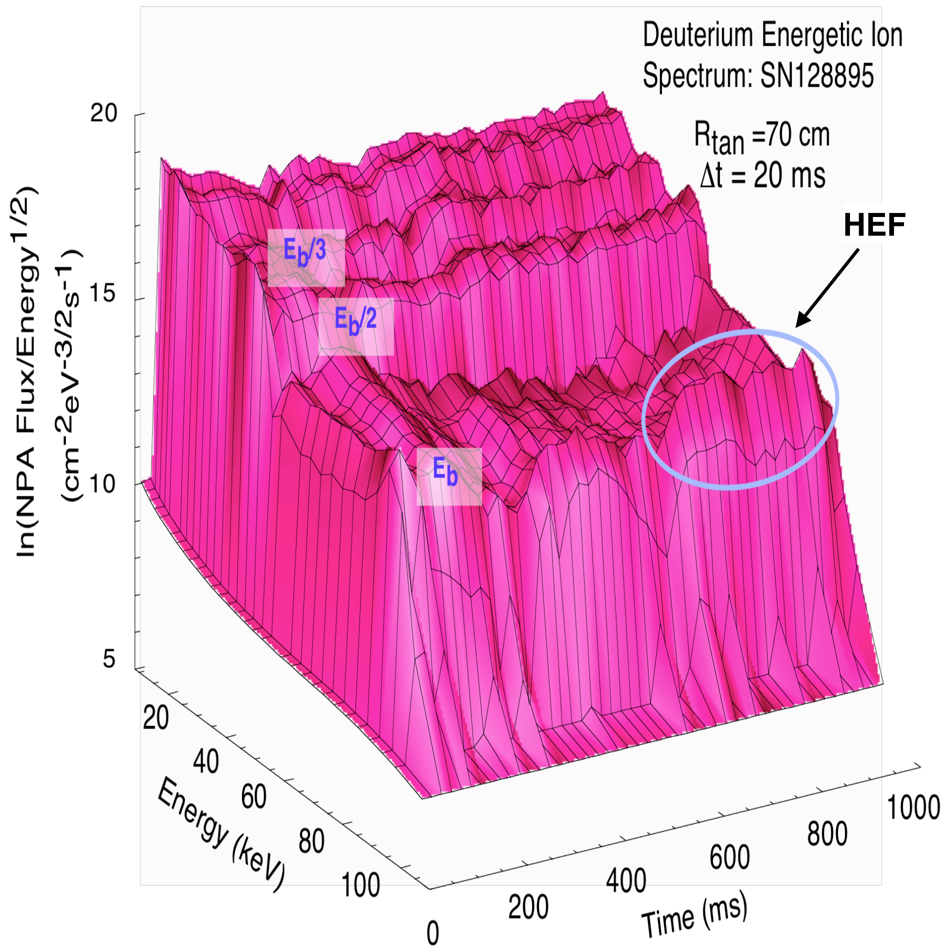
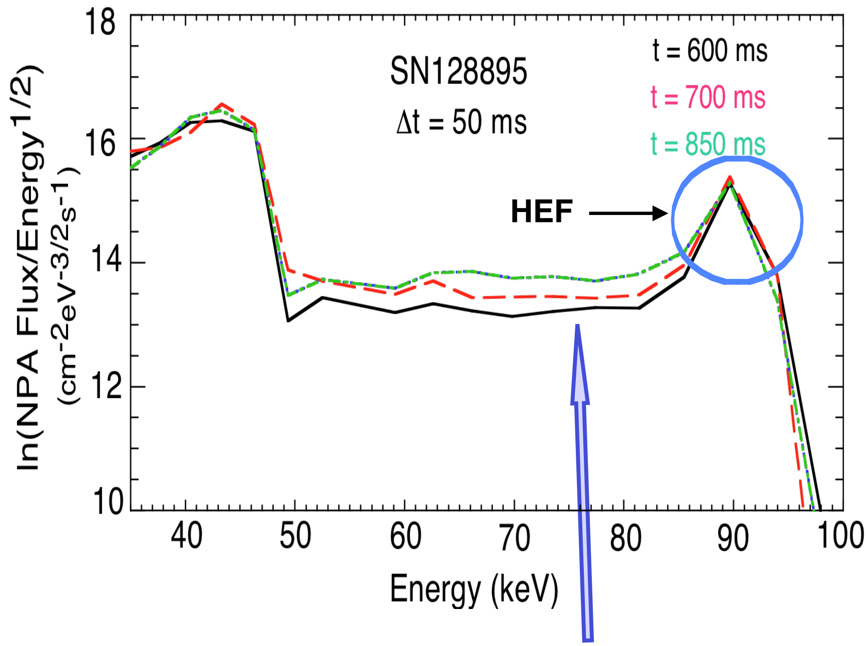


Illustration of a ‘Extended’ HEF: Duration ~ 300 ms

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

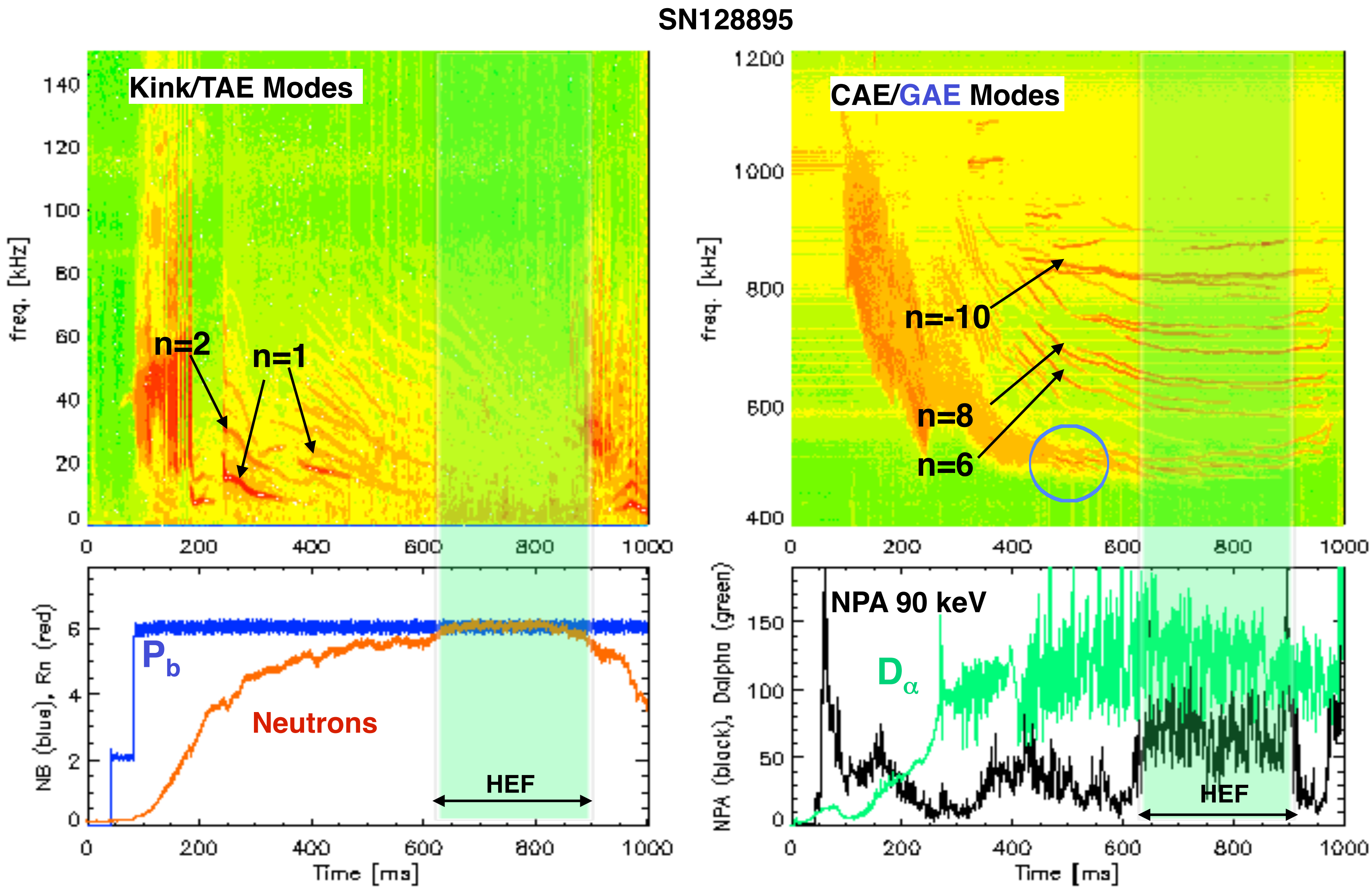




- **Spectrum exhibits modest slowing down of fast ions below the HEF energy.**
- **The slowing down distribution evolves over a period of ~ 300 ms.**
- **The evolution is ~ 10x longer than the usual NB slowing down time, τ_s ~ 30 ms.**

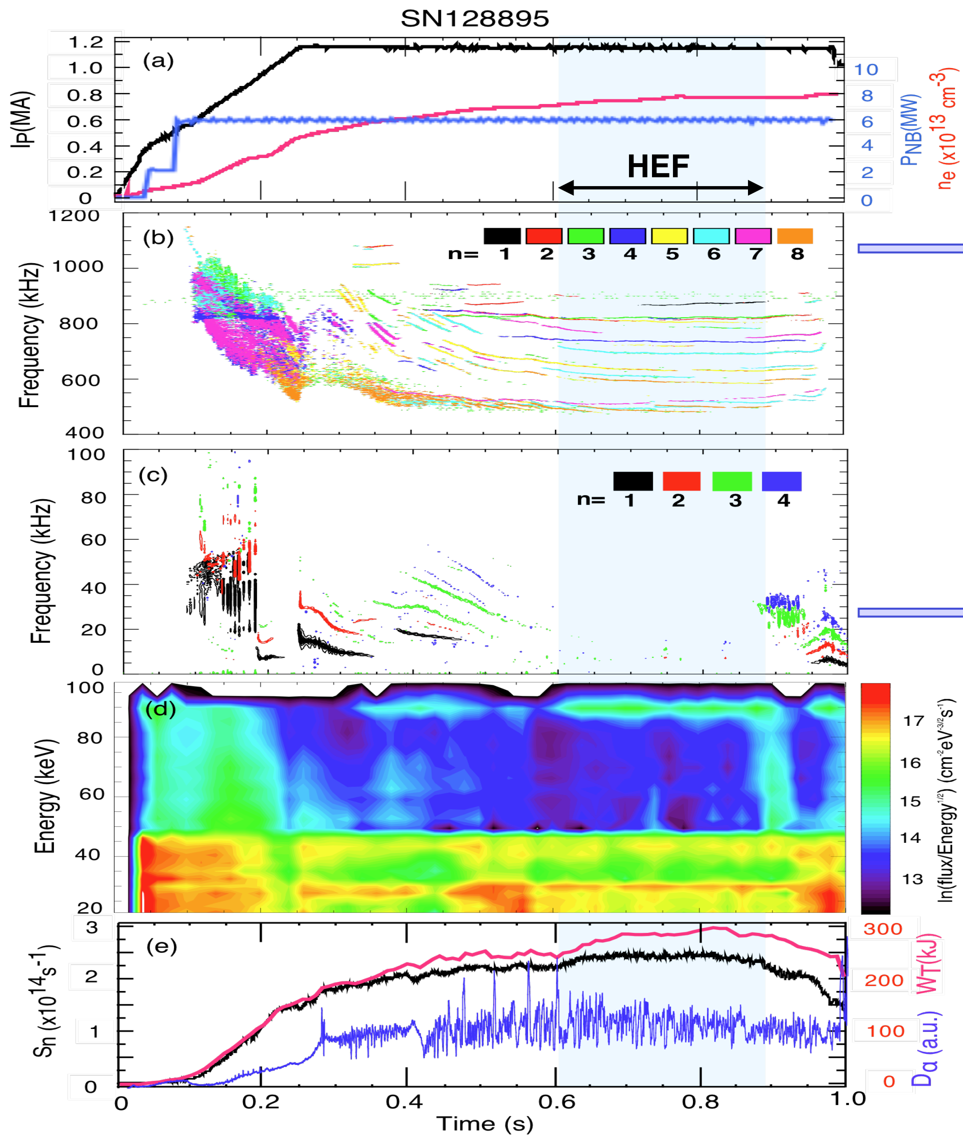
HEF Occurs during Quiescent Kink/TAE MHD Activity: SN128895

No modulation of the CAE/GAE activity is observed during the HEF

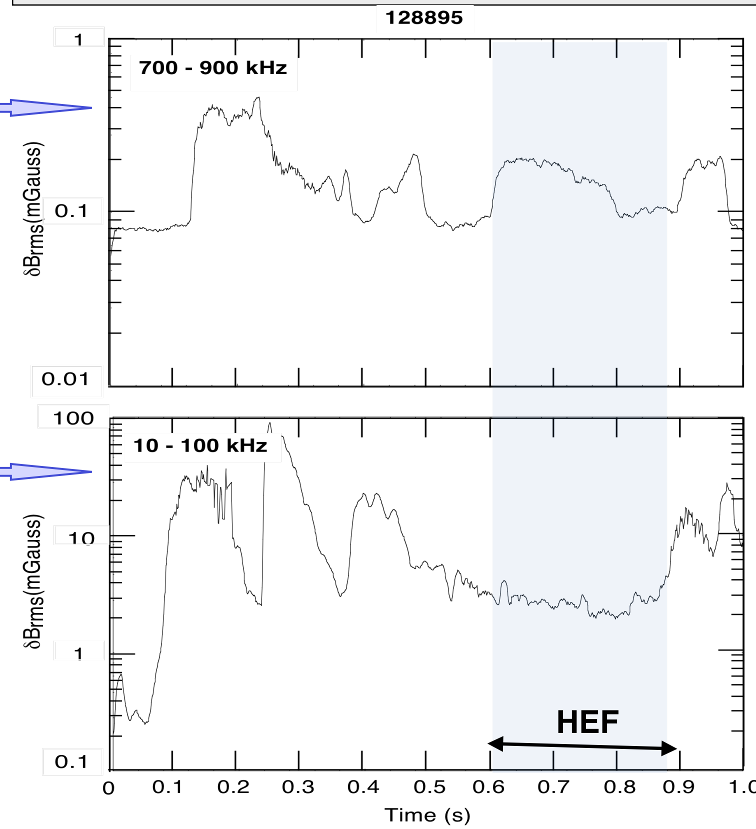


Discharge Data Mirnov δB_{rms} Evolution for the 'Extended' HEF

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



- **HEFs are observed for NPA R_{tan} viewing $v_{||}/v \sim 0.7\text{-}0.9$ (passing ions).**



- **Modest increases in S_n and W_T usually accompany the HEF phase.**

Plasma Profiles for the 'Extended' HEF: SN128895

T_e, N_e, and V_t profiles evolve significantly during the HEF phase

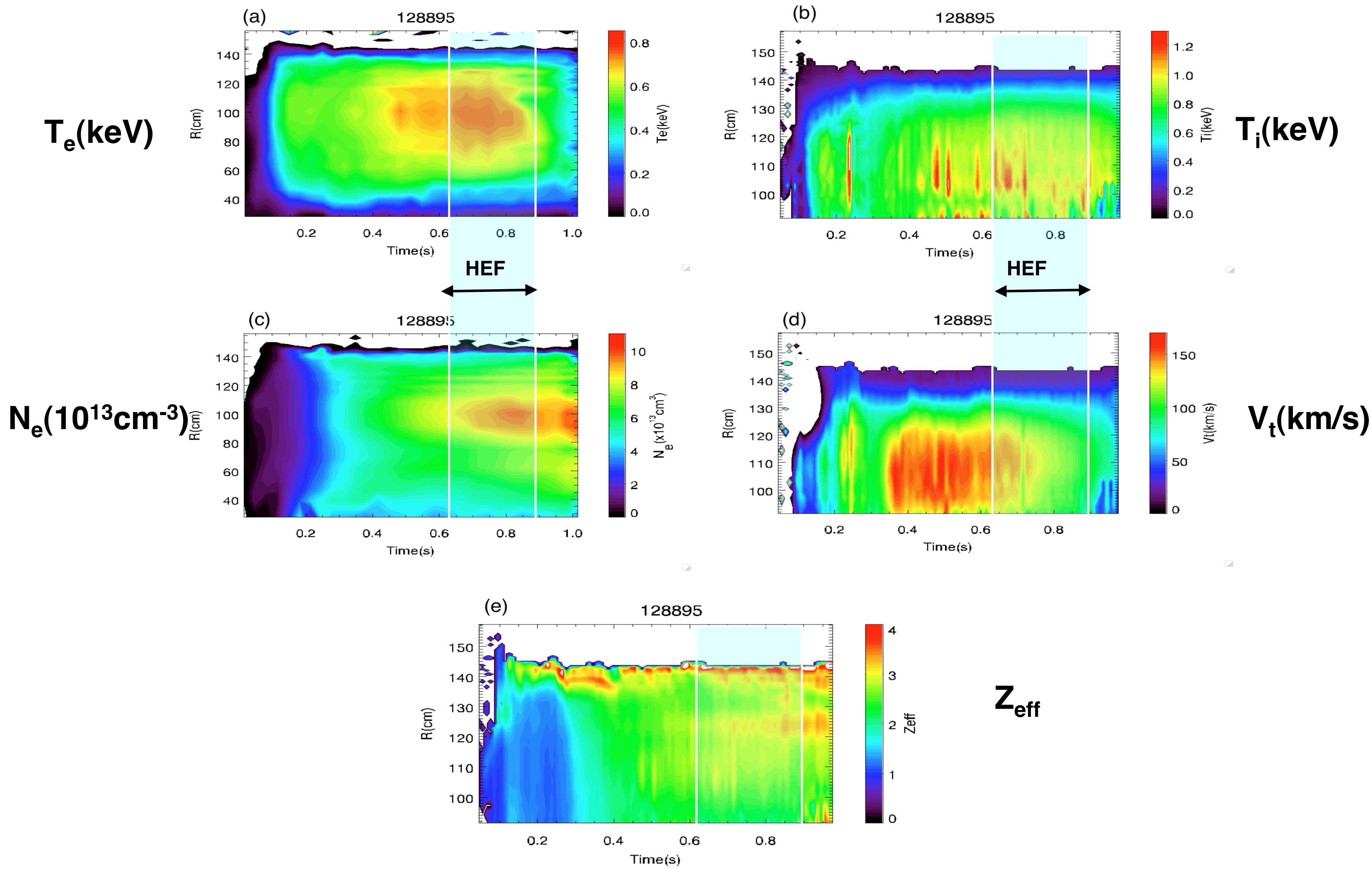
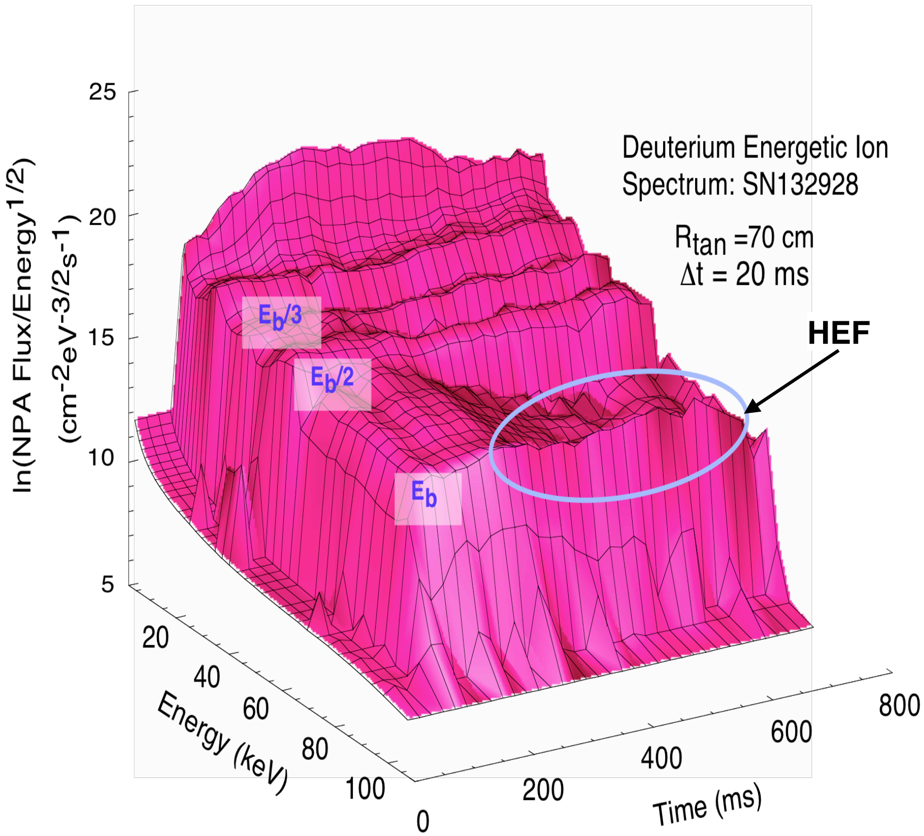
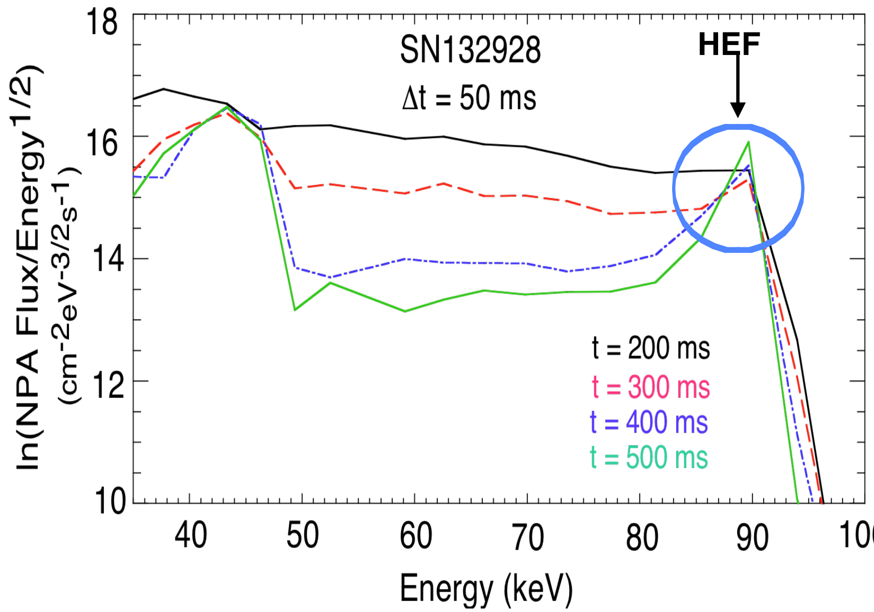


Illustration of a 'Persistent' HEF: Duration ~ 600 ms

This HEF appears to evolve as a *depletion* of CX flux below E_b = 90 keV

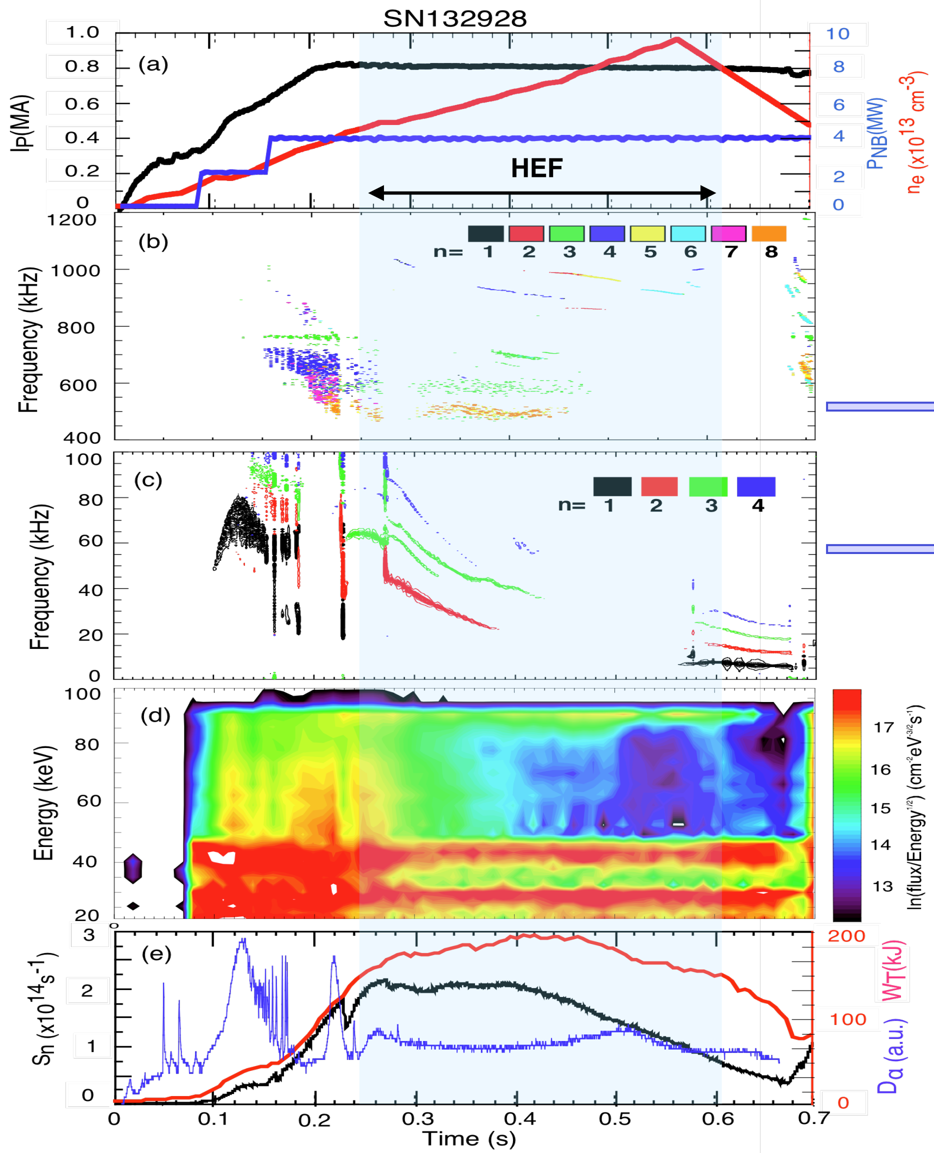




- **Persistent HEF occurrence is relatively rare compared with transient HEFs.**
- **Persistent HEFs have been observed at both E_b = 90 keV and E_b = 65 keV.**

Discharge Data and Mirnov Spectrograms for the 'Persistent' HEF

Unlike transient HEFs, the CAE/GAE activity for the persistent HEF is minimal.



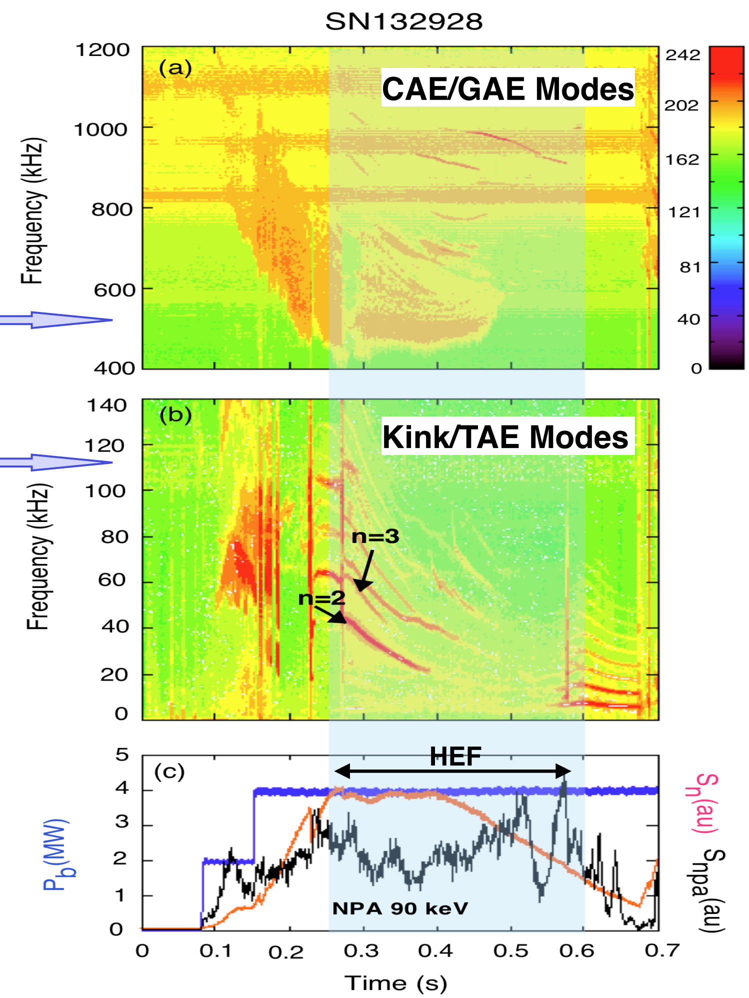
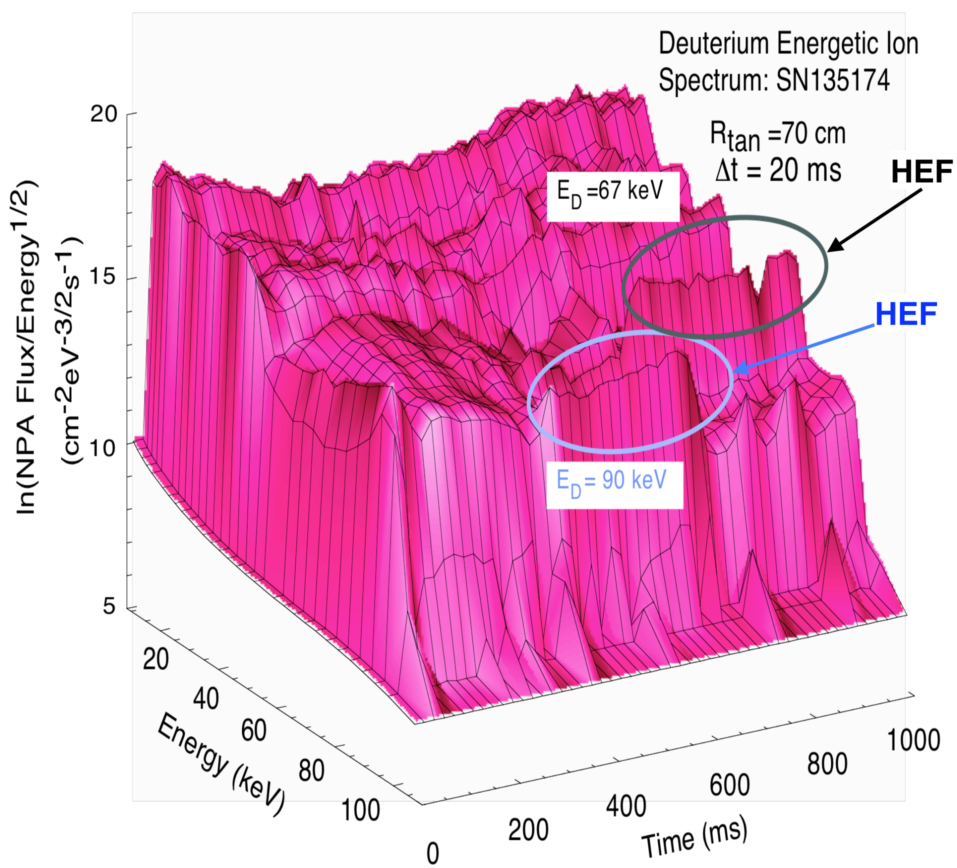
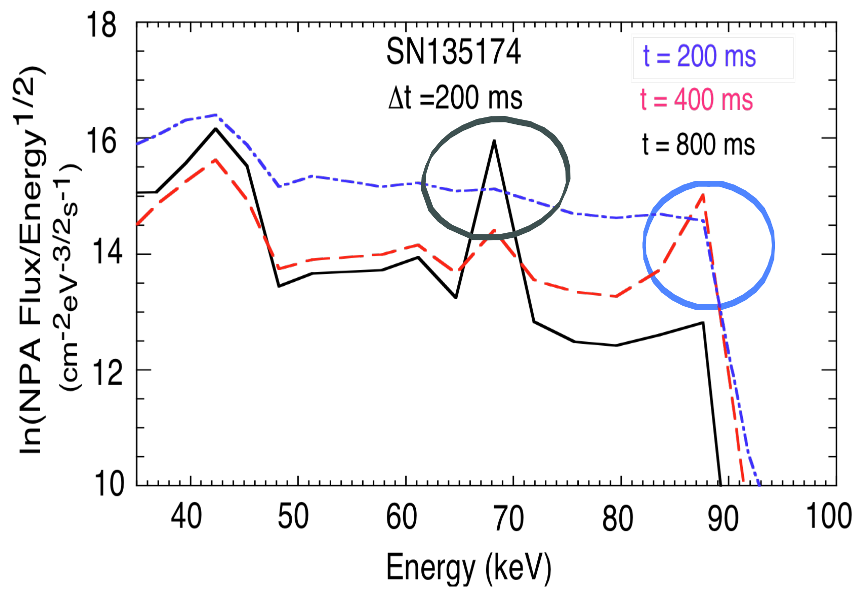


Illustration of 'Dual-Energy' HEFs at E_b = 90 keV & E_b = 65 keV

Dual-Energy HEFs can occur sequentially or overlapping in time



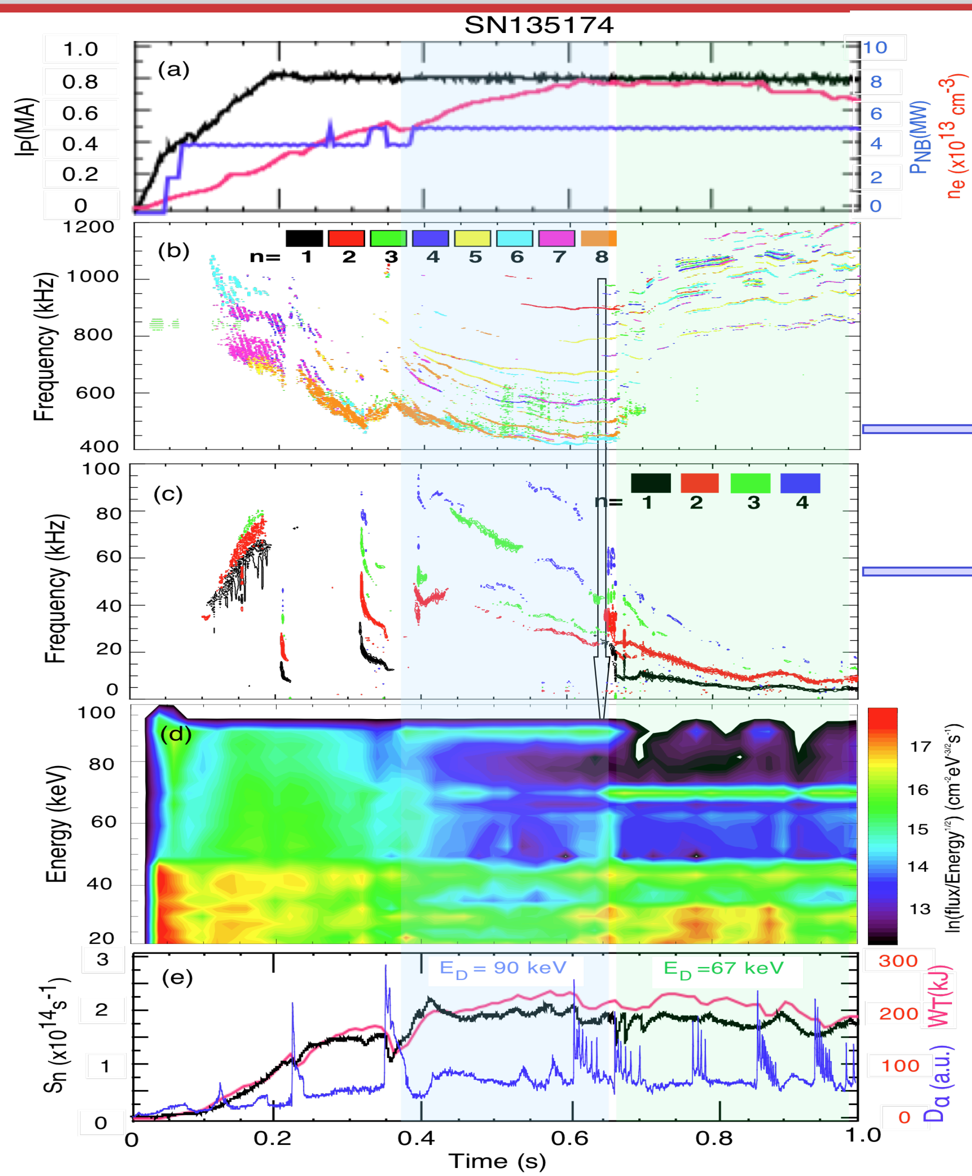


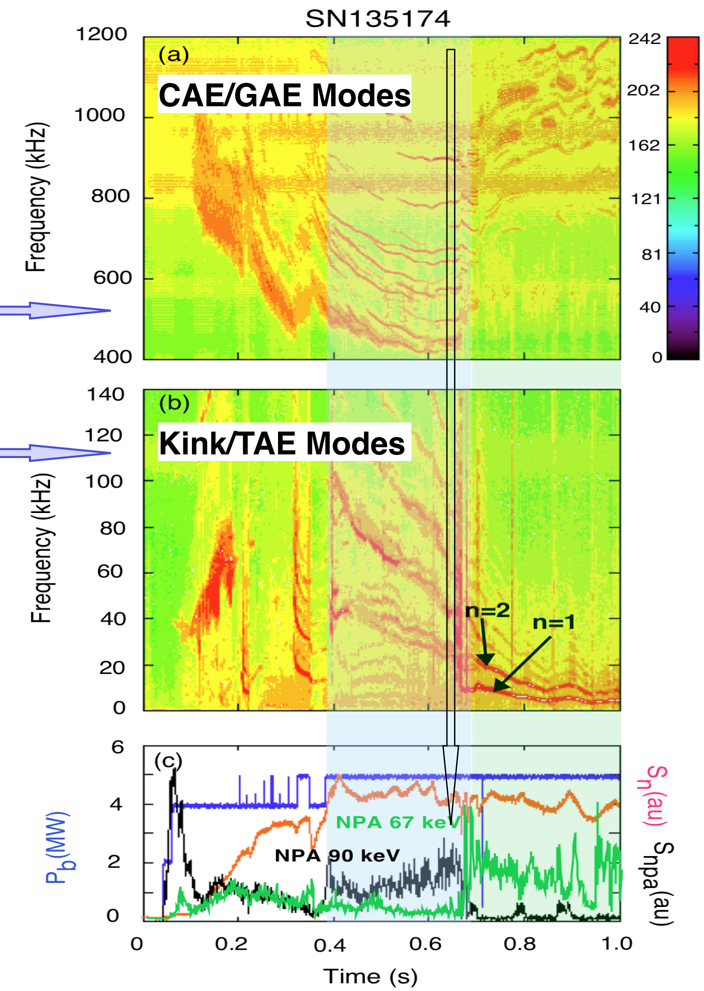
- The HEF at E_b = 90 keV appears to evolve as a ***depletion*** of CX flux in the region $E_b/2 < E < E_b$.

- 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 the ‘Dual-Energy’ HEF

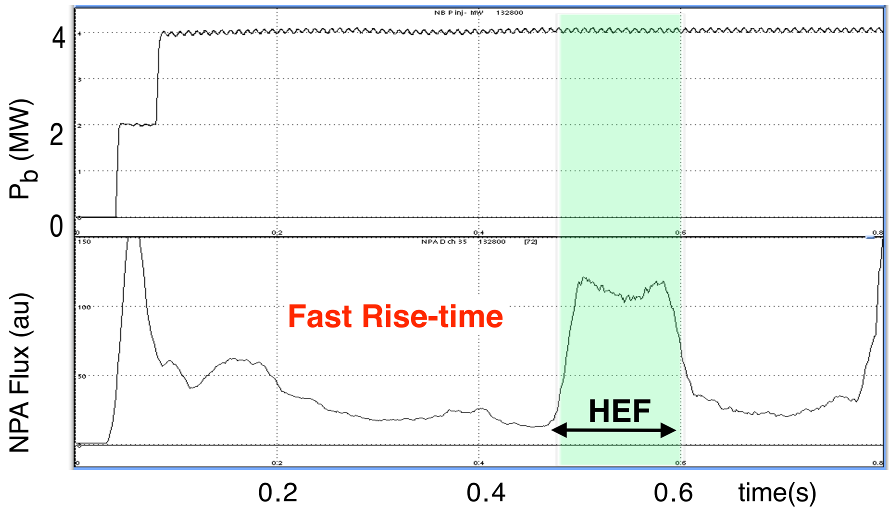
The E_b = 90 to 65 keV HEF transition coincides with abrupt MHD change (down arrow)



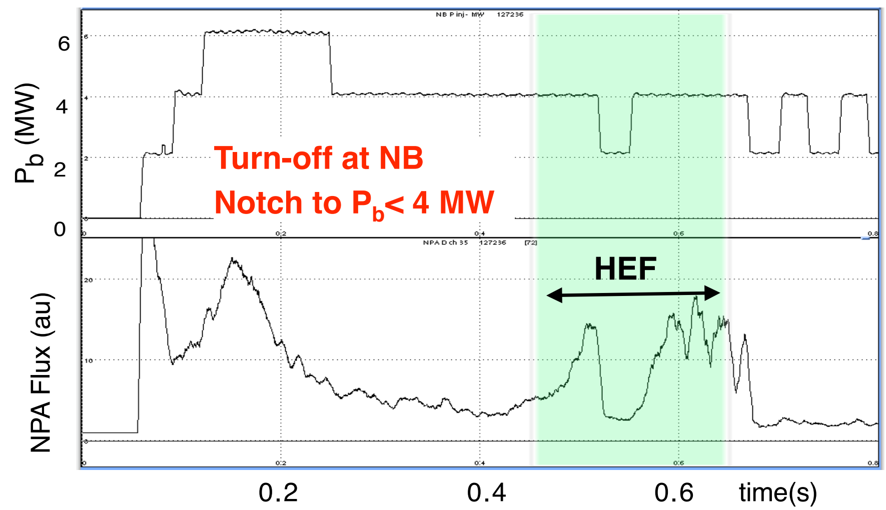


HEF Rise-time and Duration Show Considerable Variation

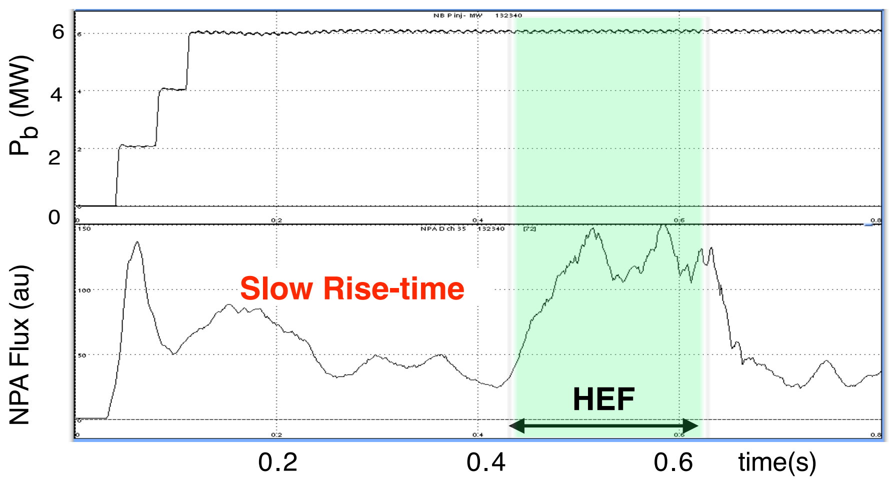
NPA data at E_D = 90 keV



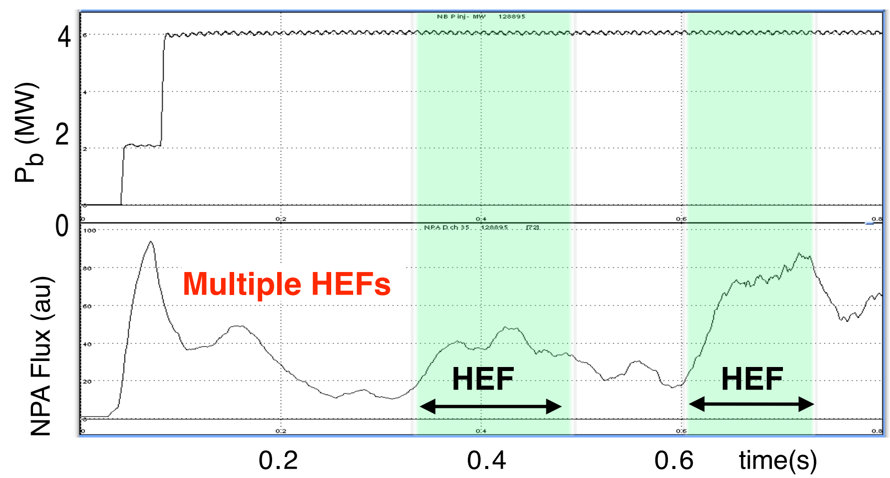
• SN132800, P_b= 4 MW, t_{rise}= 20 ms



• SN 127236, P_b= 4 ⟶ 2 MW, t_{rise}~ 55 ms



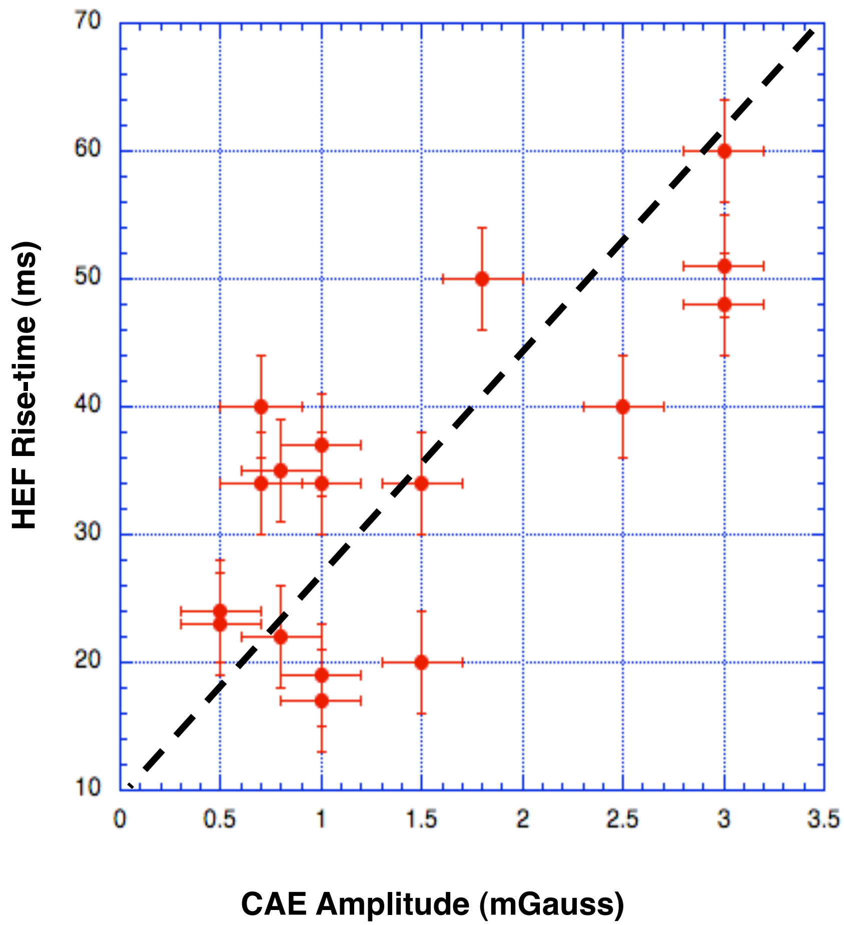
• SN132340, P_b= 6 MW, t_{rise}= 80 ms

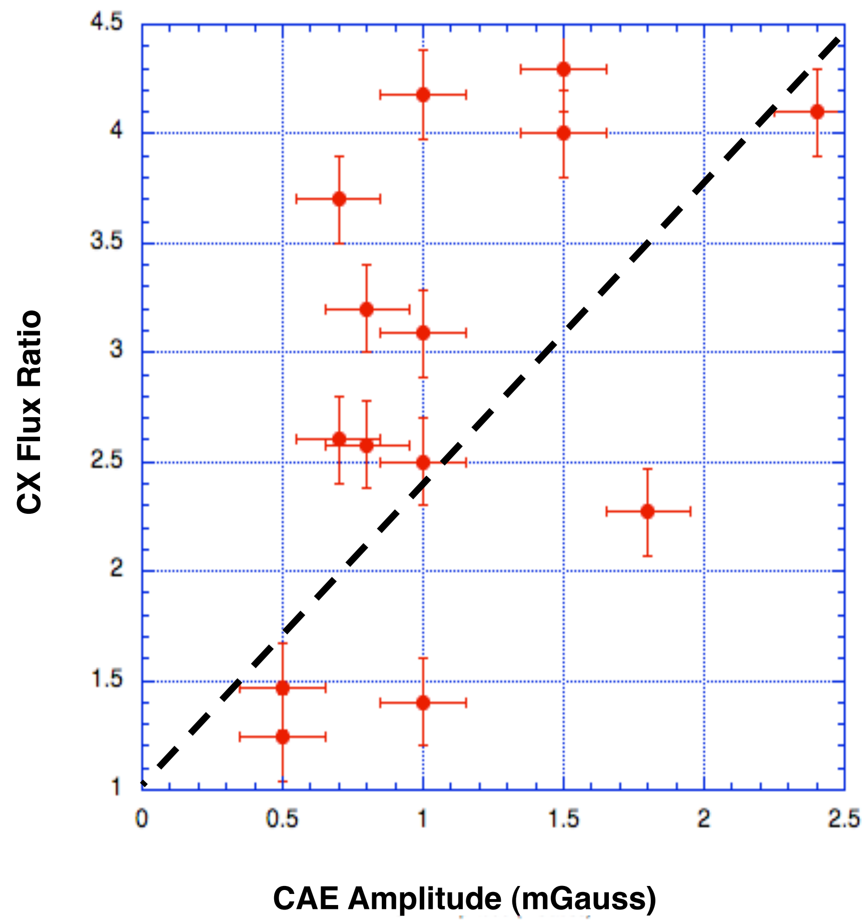


• SN128895, P_b= 6 MW, t_{rise}~ 50 ms

HEF Rise-time and Flux Ratio Vary with CAE Strength

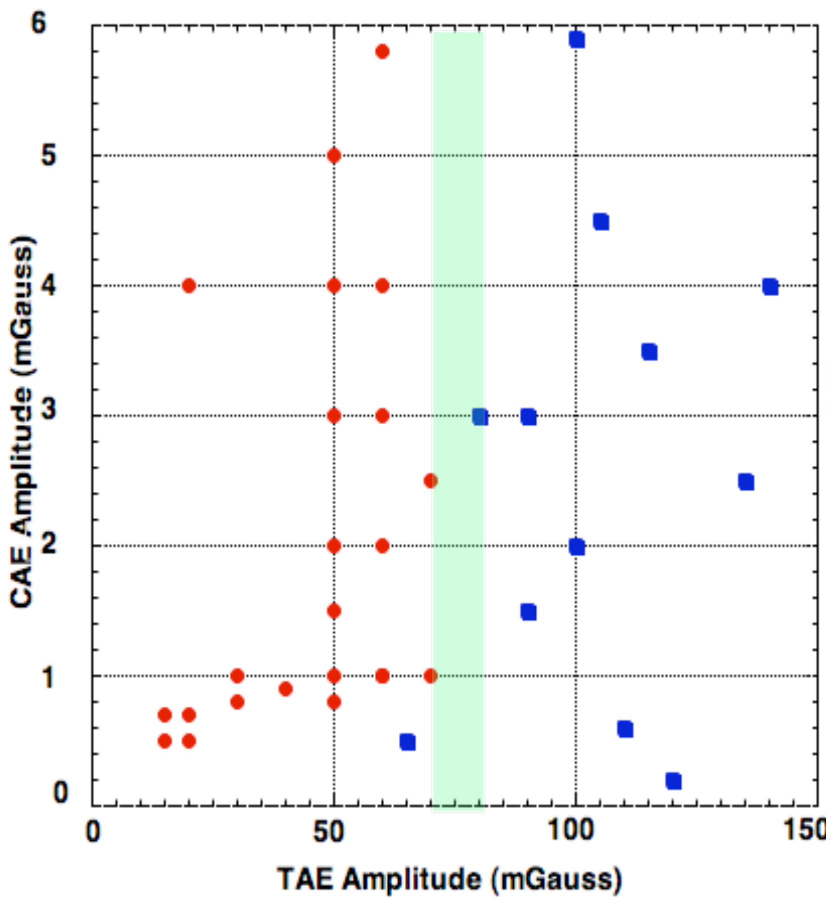
Attempt to link HEF characteristics with the dominant residual CAE activity

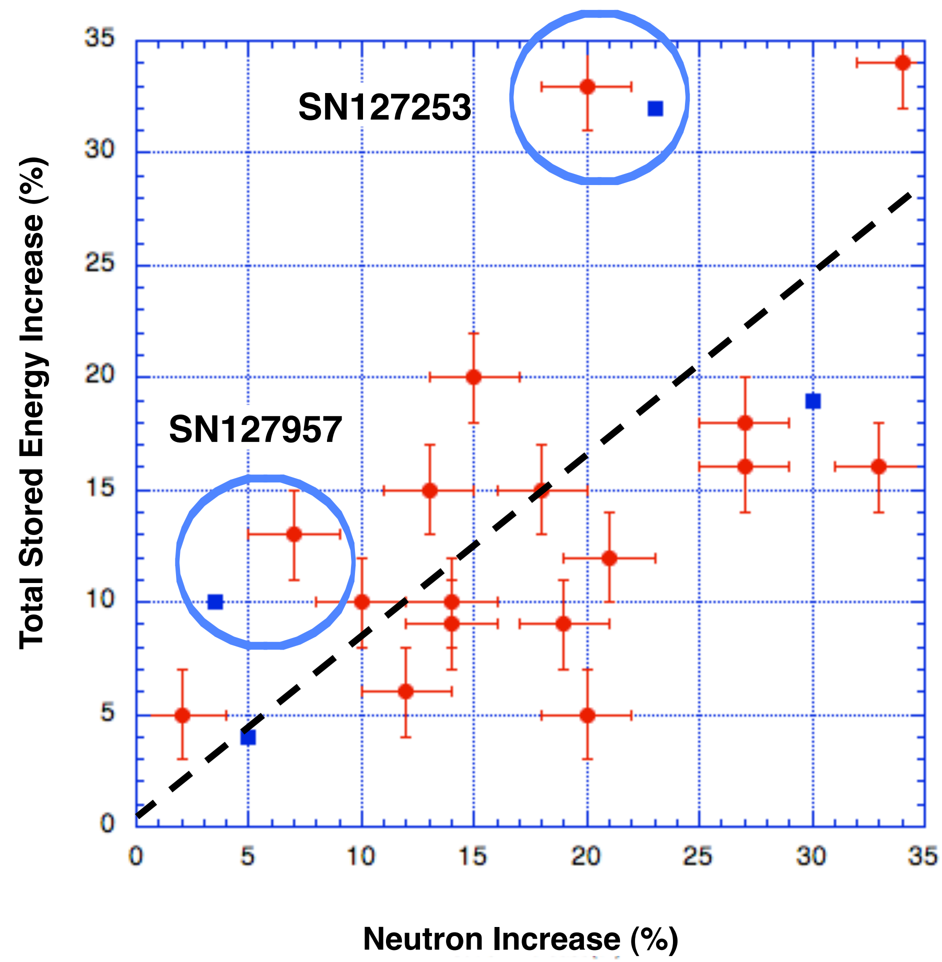




- HEF rise-time shows correlation with CAE δB_{rms} amplitude, but flux increase less so.

HEFs occur at *low* TAE activity (δB_{rms} < 75 mGauss) but over a wide range of CAE amplitude.

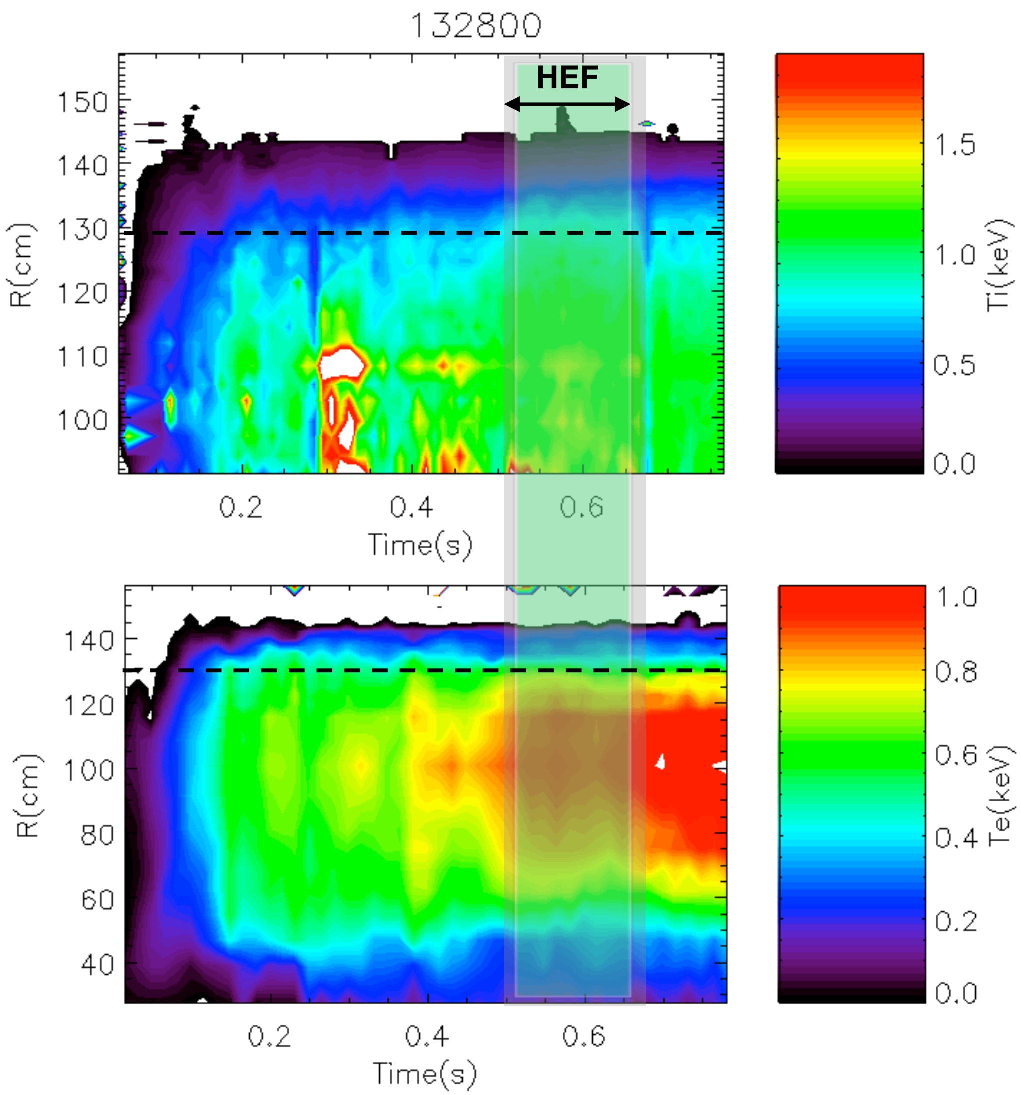


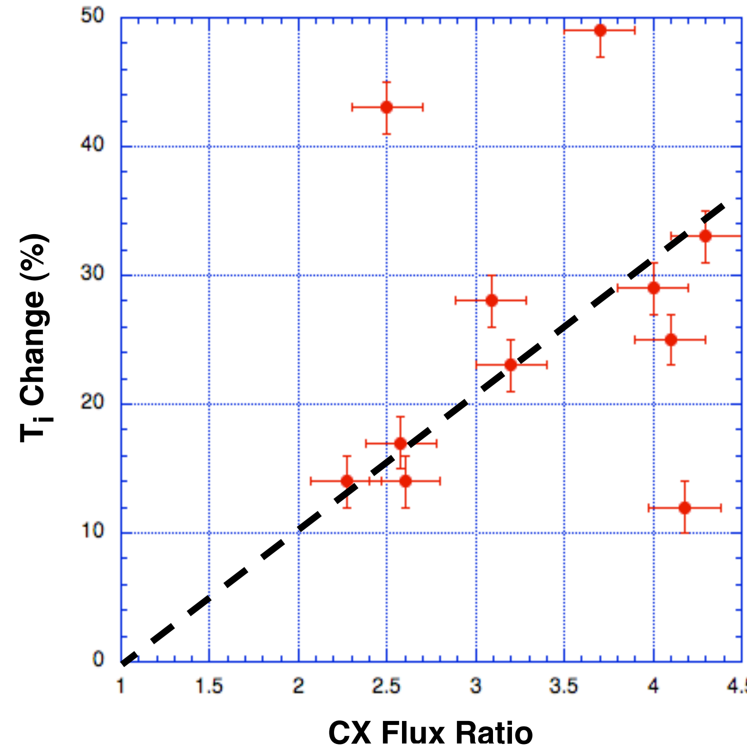


• The experimental neutron rate and total stored energy increase during the HEF (right plot). Similar increases are observed in some TRANSP analyses (blue circles).

Does HEF Drive Changes in Temperature or Density Profiles?

Example shows edge broadening of $T_i(r)$ at R_{maj} ~ 130 cm, but none for $T_e(r)$





- **During the HEF, a change in CHERS T_i at R_{maj} ~ 130 cm shows some correlation with the increased CX flux.**

Summary of 'Factoids' Related to Observation of HEFs: 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 a growth time of ~ 20 - 80 ms.

• **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.

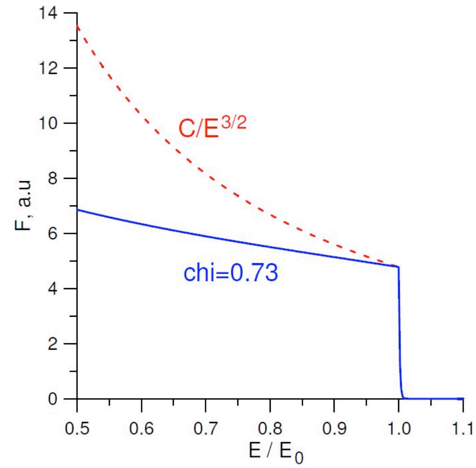
-HEFs appear to coincide with the frequency down-sweeping phase of CAE activity and usually terminate at sweep reversal (i.e. ramp down of toroidal rotation, v_{Φ}).

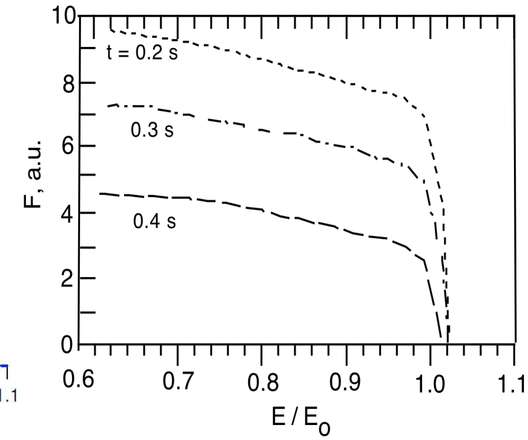
Proposed Physics of the HEF

Courtesy of Ya. Kolesnichenko and Yu. Yakovenko
Institute for Nuclear Research, Kyiv, Ukraine

•HEF is formed due to a combined action of Coulomb collisions and Alfvén modes destabilized by the beam particles.

1. Coulomb pitch-angle scattering makes the distribution function of the beam ions (F_b) almost flat over the energy at the pitch angles close to the pitch angles of the injection, i.e., it makes $F_b(V)$ at $\chi \equiv V_{\|}/V \sim 0.8$ much more flat than $F_b \sim 1/V^3$. Because of this, even weak influence of the destabilized waves on $F_b(V)$ becomes noticeable.



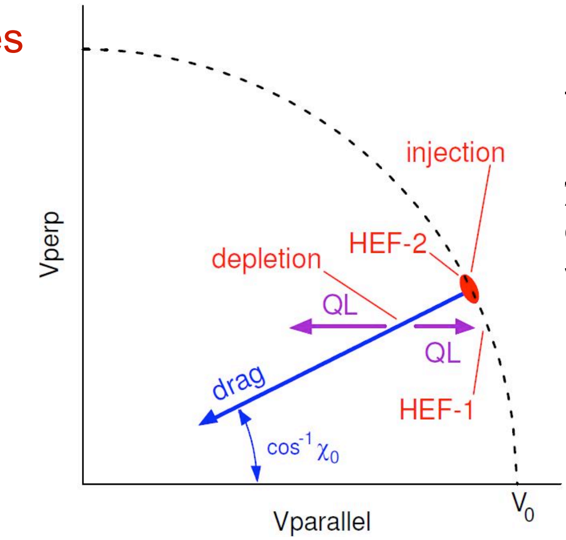


•Left panel: Fokker-Planck calculation (solid line) that demonstrates flattening of $F_b(v)$ by Coulomb pitch-angle scattering .

•Right panel: TRANSP calculation taking into account both the pitch-angle scattering and the radial diffusion.

Proposed Physics of the HEF
(cont'd)

2. The instabilities observed are driven by spatial inhomogeneity of the beam ions. Their frequencies are considerably less than the gyro-frequency. Therefore, the Quasi-Linear (QL) diffusion does not change the particle magnetic moment. Then, as seen from the figure, it can lead to two types HEFs at *E*~90keV. HEF-1 is a bump with $F_b > F_{b0}$ in the region $\chi > \chi_0$ [F_{b0} is F_b *(90 keV)* in the absence of instabilities]. HEF-2 is a bump with $F_b = F_{b0}$ at $\chi \approx \chi_0$.



•Sketch explaining the formation of the bump at $V \sim V_0$ and $\chi \sim \chi_0$ due to QL-diffusion in the velocity space.

•Here $V_0=(2E_0/M)^{1/2}$, E_0 =90 keV.

The HEF occurs when QL-diffusion overcomes the effect of the collisional drag; the flattening of $F_b(V)$ by collisional pitch-angle scattering facilitates this. Our preliminary analysis shows that the wave amplitudes required to produce the HEF are quite reasonable.

Because instabilities are driven by ∇n_b , the resonant particles lose their energy moving outwards during the instabilities. This depletes $F_b(V, \chi)$ in one region and enriches it in another one. Therefore, the mechanism described above dominates in a certain plasma region (around the middle of the mode location). In other regions $F_b(V, \chi)$ is determined by quasi-linear diffusion in both velocity and space.

Summary of 'Factoids' Related to Observation of HEFs: 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).

- **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).

-No sFLIP energetic ion loss signatures are observed which also implies that the HEF flux is not due to orbit excursions into the high edge neutral density region.

Backup

On the Physics of the HEF

Courtesy of Ya. Kolesnichenko and Yu. Yakovenko
Institute for Nuclear Research, Kyiv, Ukraine

Instabilities driven by energetic ions are normally excited through resonant interaction of a group of these ions and the waves. This means that the instabilities are possible when the energetic ions satisfy a certain resonance condition.

The resonance condition for circulating particles can be written as follows:

$$\omega = k_{\parallel eff} v_\parallel + n\omega_D + l\omega_B, \tag{1}$$

where ω is the mode frequency; ω_B is the particle gyrofrequency; ω_D is the frequency of the toroidal precession; $l = 0, \pm1, \pm2, \ldots$;

$$k_{\parallel eff} = k_\parallel \left(1 + \frac{s}{k_\parallel qR}\right); \tag{2}$$

$$\omega = k_\parallel \left(1 + \frac{s}{k_\parallel qR}\right), \tag{3}$$

is the longitudinal wave number; m and n are the polodal and toroidal mode numbers, respectively; s is integer; the perturbation is taken in the form $\propto \exp(-i\omega t + im\theta - in\phi)$.

When $n\omega_D \ll \omega \ll \omega_B$ — a condition which is satisfied for the high-frequency instabilities observed in NSTX (200 kHz – 1 MHz) — the resonance condition takes the form

$$\omega = k_\parallel \left(1 + \frac{s}{k_\parallel qR}\right), \tag{4}$$

where $k_\parallel qR \gg 1$. When the orbit width is small, the resonances with $s = \pm1$ are the strongest for energetic ions. However, finite orbit width makes resonances with $s = 0$ and $s \gtrsim 1$ also important.

Note that Eq. (3) often repesents the resonance condition for the TAE instabilities, in which case $q = (m + 1/2)/n$, $\omega = k_\parallel v_A$, $k_\parallel qR = 1/2$ and $s = \pm1$; therefore, Eq. (3) with $s = \pm1$ yields $v_\parallel = -v_A$ and $v_\parallel = v_A/3$ for $k_\parallel > 0$.

A necessary condition of instability is (for simplicity we assume that $v_\parallel =$ const and that the orbit width is small)

$$\hat{\Pi} F_b \equiv \frac{\partial F_b}{\partial \mathcal{E}} + \frac{1-\chi^2}{\chi \mathcal{E}} \frac{\partial F_b}{\partial \chi} + \frac{m}{r\omega_B \omega} \frac{\partial F_b}{\partial r} > 0, \tag{5}$$

where $F_b = F_B(\mathcal{E}, \chi, r)$, $\mathcal{E}$ is the particle energy, $\chi = v_\parallel/v$, and r is the radial coordinate. For the considered NSTX instabilities the last term exceeds the others, which means that the instability is driven by the spatial inhomogeneity of the beam ions.

The destabilized waves affect the distribution function of the energetic ions, which is described by the quasi-linear theory. The equation of the quasi-linear diffusion has the form

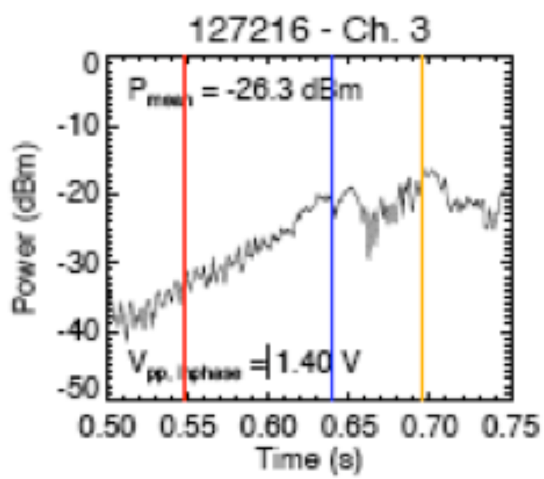
$$\frac{\partial F_b}{\partial t} = \sum_k \hat{\Pi}_k D_k \hat{\Pi}_k F_b + \hat{C}^{\rm coll} F_b + S, \tag{6}$$

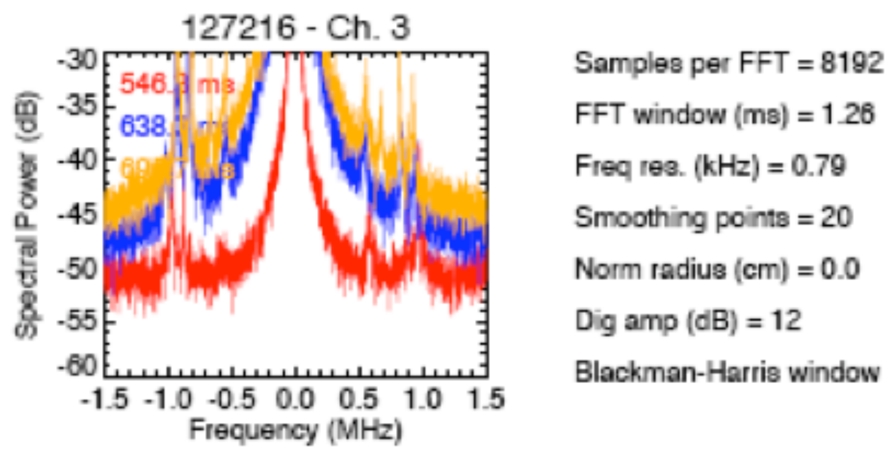
where k refers to all waves participating in the process, S is the particle source (e.g., injection), $\hat{C}^{\rm coll}$ is the operator describing the effects of Coulomb collisions. The operator $\hat{C}^{\rm coll}$ is a sum of a first-order (advective) term describing the drag (slowing down) and second-order (diffusive) terms, which describe scattering in the velocity space and spatial diffusion, D is the quasi-linear diffusion coefficient, D is proportional to square of the wave amplitudes, $D \neq 0$ only for particles satisfying the resonance condition (1).

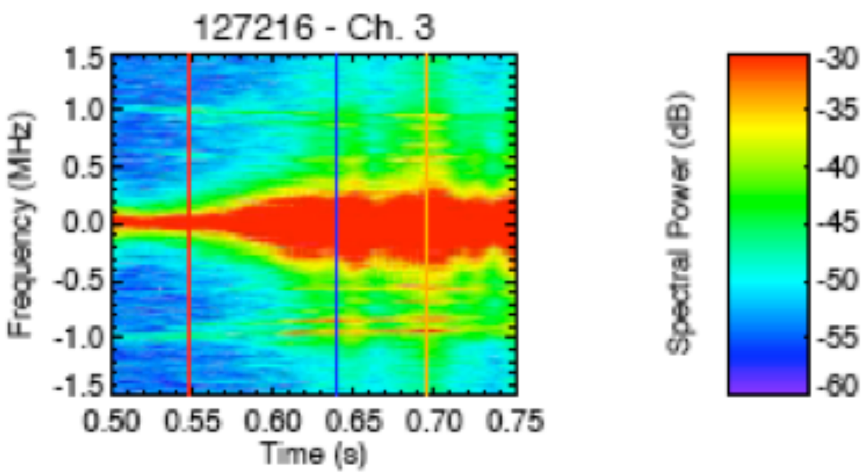
Eq. (6) describes the evolution of F_b in 3D space, e.g, in $\mathcal{E}$, χ, and r. For simplicity, we consider first 2D-problem, neglecting the radial diffusion. A relevant picture is shown in the Figure of the PowerPoint file. The spatial diffusion represents an additional factor. To solve a 3D-problem is difficult, but physics of the influence of the diffusion of the HEF is simple. The diffusion helps to form the HEF in the region where it decreases the number of particles (the inner part of the mode location) and prevents the HEF formation in the region where particles are accumulated (the outer part of the mode location). No considerable influence of the spatial diffusion on the HEF is expected in the intermediate region.

High-k Scattering Shows Density Fluctuation Activity during the HEF

H-mode with Ip = 0.9 MA, B_T = 5.0 kG, NB A&B @ 90 keV, P_{NB} = 4 MW, $n_eL \sim 5 \times 10^{13}$ cm^{-2}







Courtesy of Jeehyun Kim (POSTECH) and K. C. Lee (UC Davis)

- **High-k fluctuations are in the CAE/GAE frequency range ~ 0.5 -1.0 MHz consistent with Mirnov data.**
- **High-k data localizes fluctuations to R_{maj} ~ 120 - 135 cm.**

$$\frac{\tilde{n}}{n} = -\frac{\tilde{B}_{\parallel}}{B}$$

Future Work

Dedicated experiment on NSTX for exploration of the High-Energy Feature (HEF)

- Does the HEF track E_b?
  - E_b scan with ABC @ 100, 90, 80, 70 keV
- Does the HEF depend on NB sources?
  - Select E_b from above scan: run with AB, AC, BC (need $P_b > 4$ MW)
- Does the HEF occur with NB sources @ mixed E_b?
  - For example, A @ 100 keV, B@ 90 keV, C@80 keV
- Does Lithium suppress HEFs?…use a robust scenario from above
  - LITER deposition @ 50, 100, 150, 200 mg/shot
- Horizontal and vertical NPA scans with all NBs at a selected E_b
  - Hscan requires ~ 12 shots and Vscan ~ 8 shots
- Obtain detailed High-k scattering and FIReTIP data