NSTX

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Observation of 'Anomalous' E||B Neutral Particle Analyzer Energetic Ion Spectra in the National Spherical Torus Experiment

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S. S. Medley, R. E. Bell, D. S. Darrow, E. D. Fredrickson, N. N. Gorelenkov, B. P. Leblanc, M. Podestà (UC Irvine), A. L. Roquemore

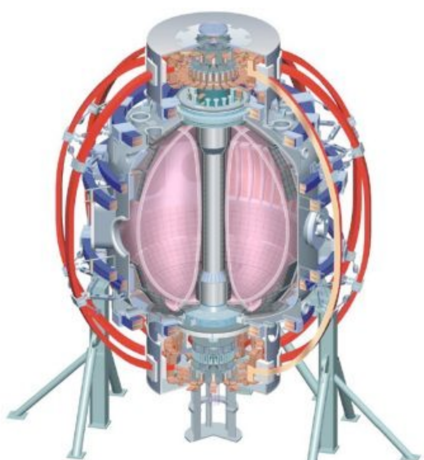
....

and the NSTX Research Team

Princeton Plasma Physics Laboratory

NSTX Physics Meeting

June 22, 2009



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Preamble

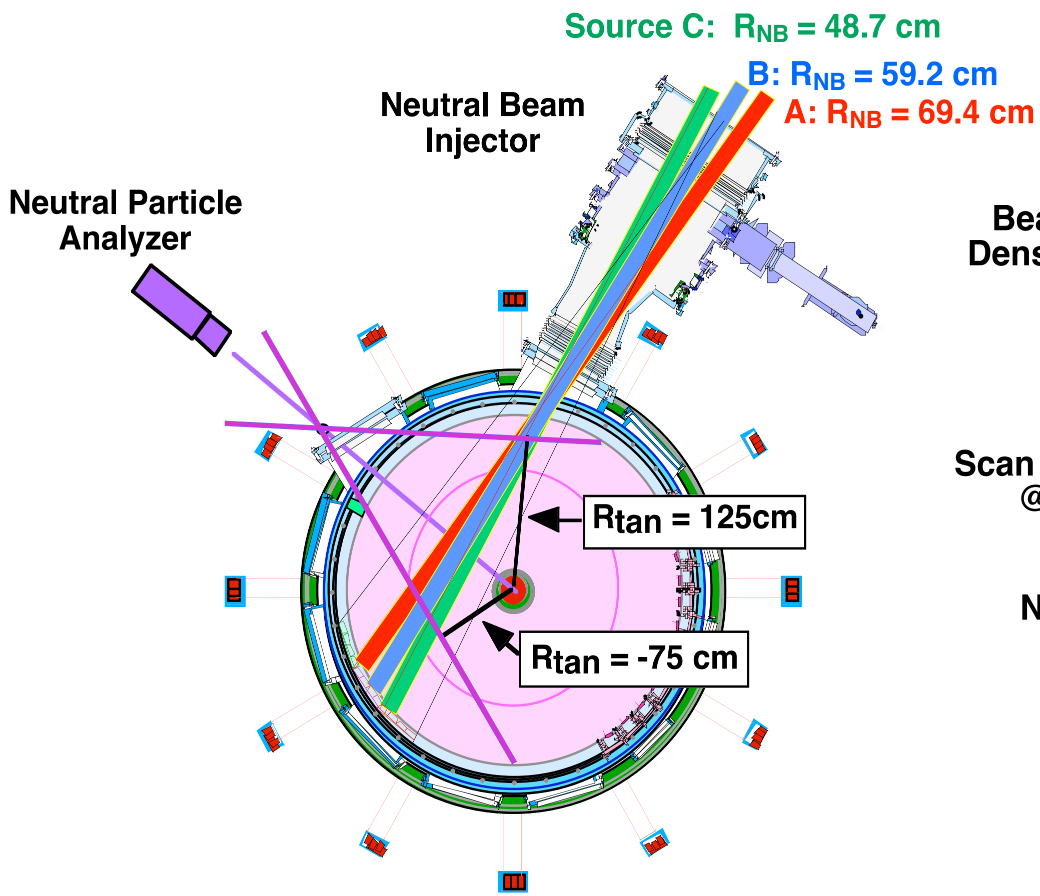
High-Energy Feature (HEF)

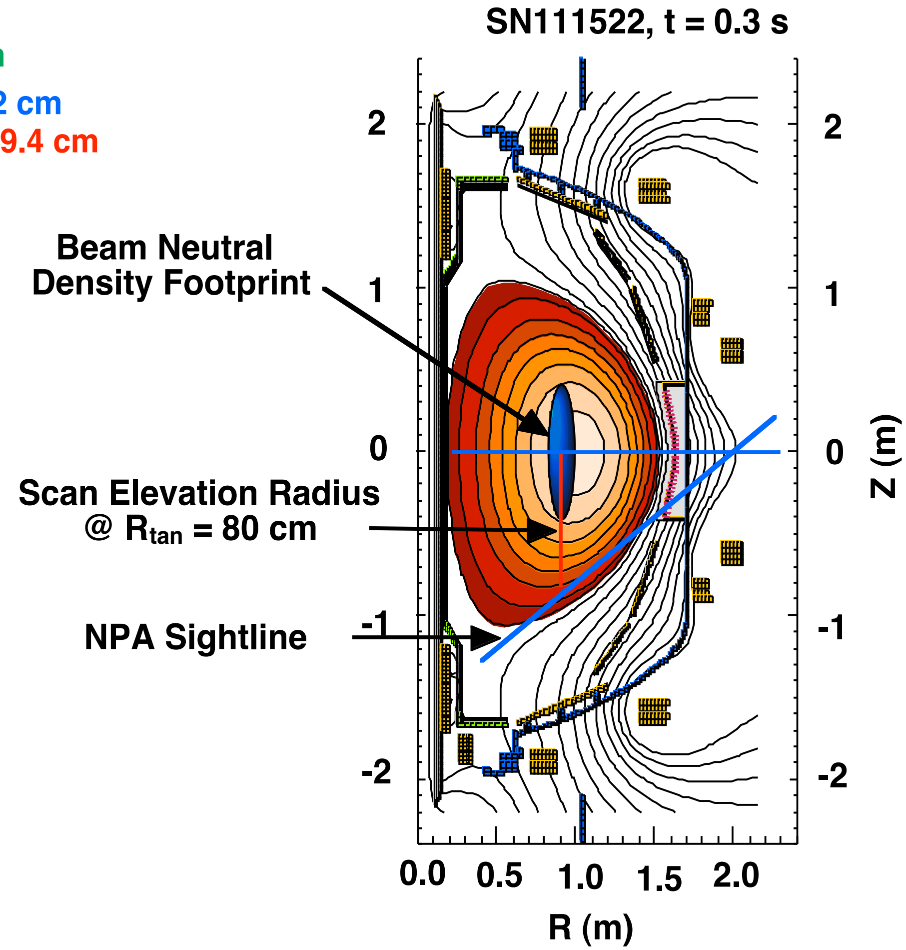
A strong increase (~ 3x) in the EllB NPA charge exchange flux that is narrowly localized around the NB full energy: E_b ~ 90.

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

- **EllB NPA diagnostic characteristics**
- **Experimental observations**
  - NPA charge exchange energetic ion spectra
  - NPA instrumental effect?
  - HEF time evolution
  - MHD activity and high-k ne fluctuations
  - Changes in neutron rate, ΔS_n(%) and total stored energy, ΔW(%)
  - Profile changes [ΔTe(r), Δne(r), ΔTi(r), $\Delta v\phi$(r), ΔZeff(r)]
- **Summary of HEF characteristics**
- **Physical explanation of HEF?**

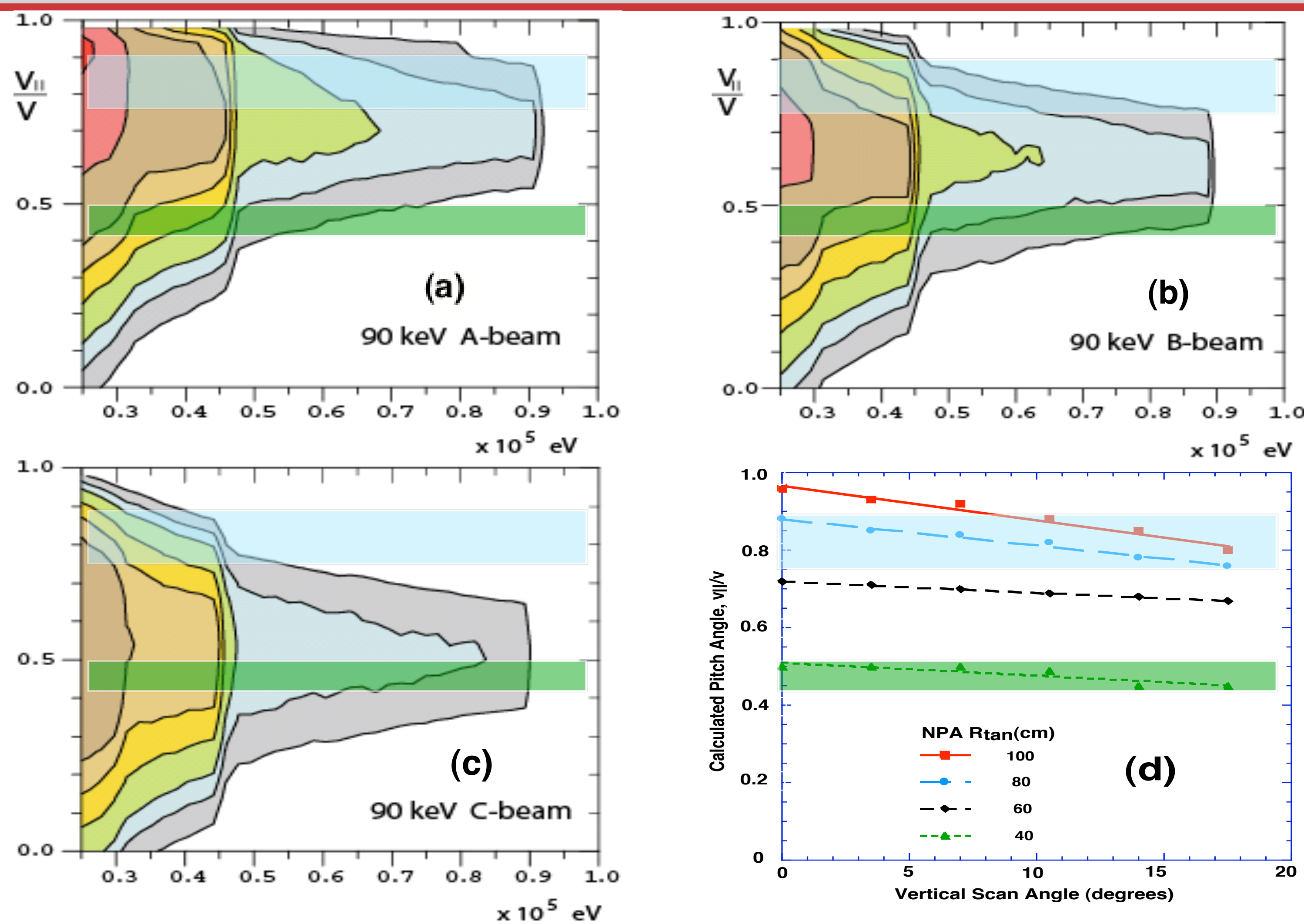
The Neutral Particle Analyzer (NPA) on NSTX Scans Horizontally and/or Vertically on a Shot-to-Shot Basis





- Intersection of NPA sightline with beam neutrals (primary and halo) localizes the charge exchange flux measurement in space and field pitch, vll/v.
- The line-integrated NPA measurements have a spatial resolution ~ 3 cm in elevation and ~ 20 cm in radius with a pitch resolution $v_{||}/v$ ~ 0.05.

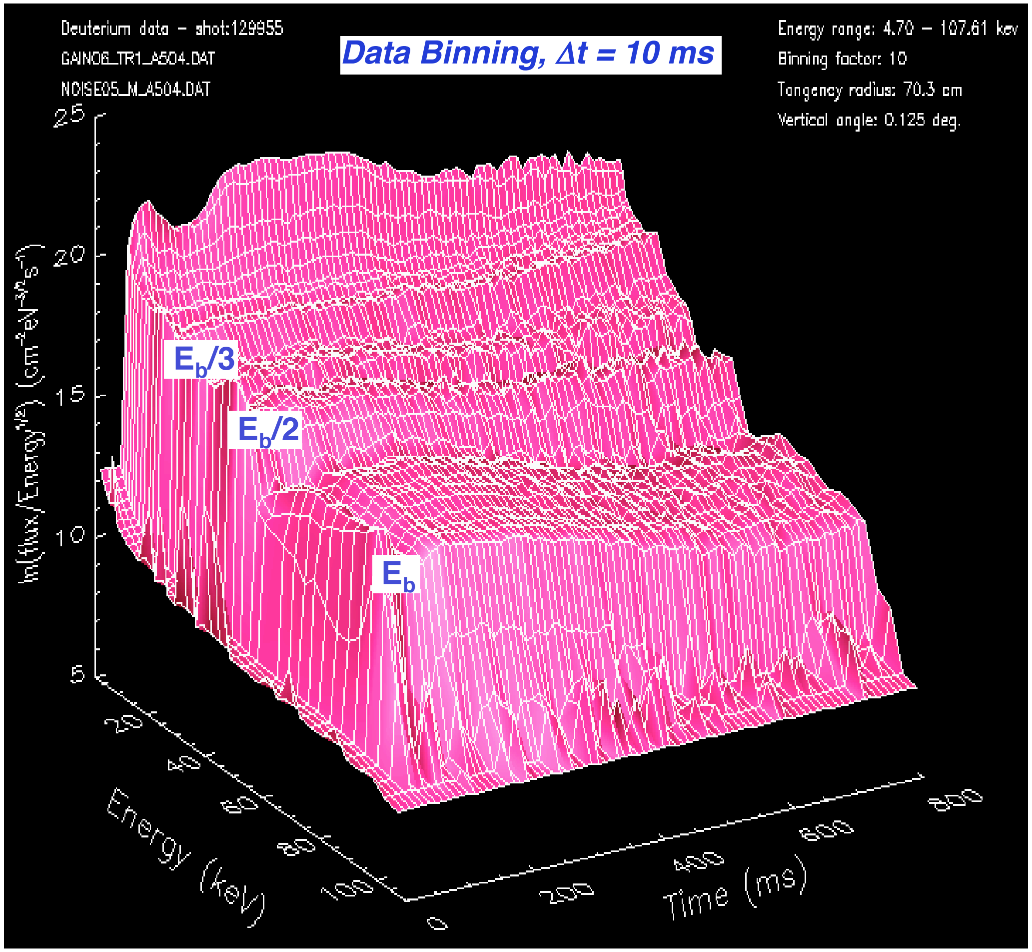
The Field Pitch, $v_{||}/v$, Viewed by the NPA Depends on Both the Horizontal and Vertical Sightline Setting

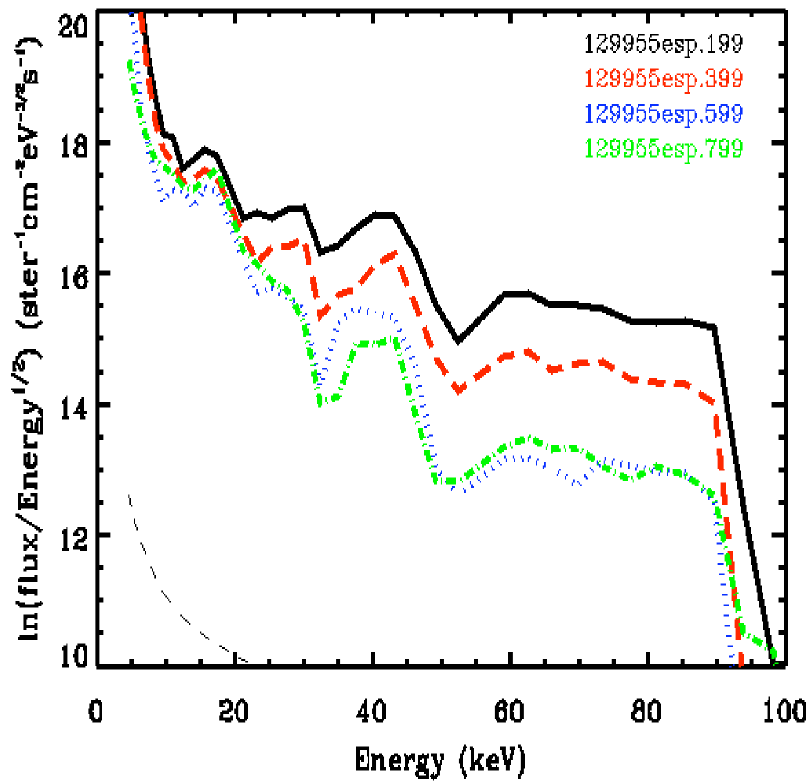


- **For 'standard' values of the NPA R_{tan} ~ 70 - 80 cm, $v_{||}/v$ ~ 0.80 ± 0.05 (blue bar).**

NPA Energetic Ion Spectra: H-mode with Robust MHD Activity

H-mode with I_p = 0.9 MA, B_T = 5.0 kG, P_{NB} = 4 MW, $n_eL \sim 4\times10^{13}$ cm^{-2}

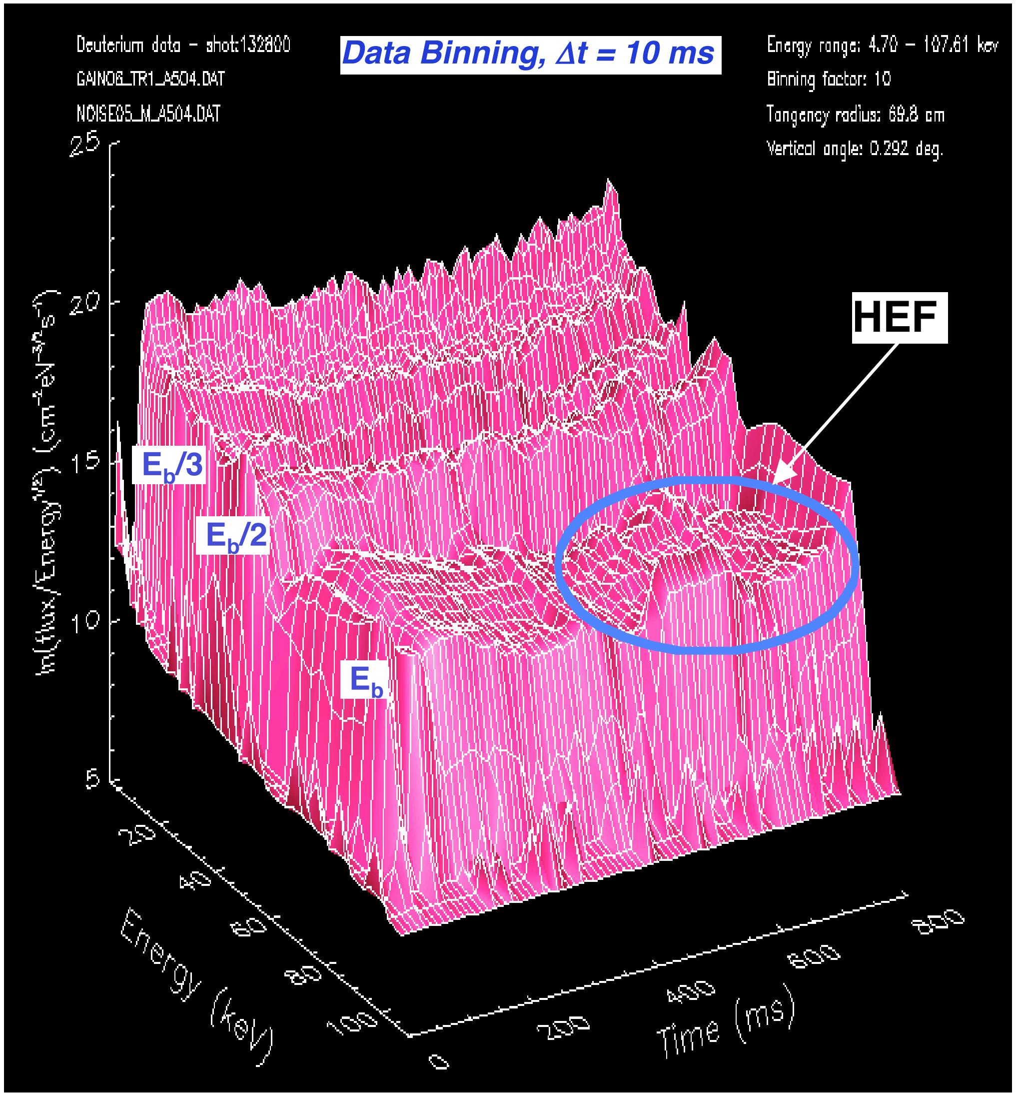


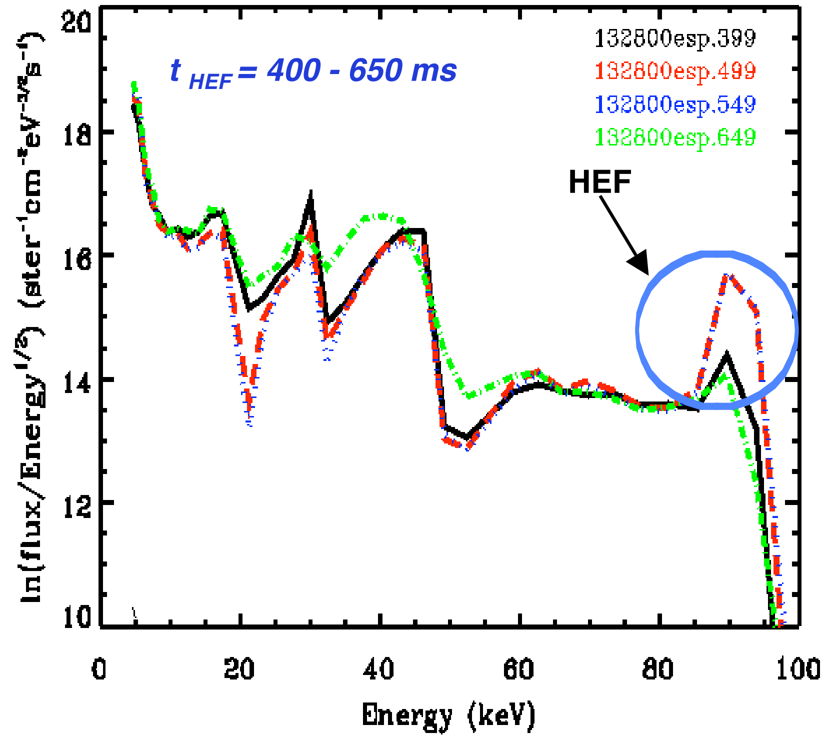


• **Depletion of the NPA spectrum in the range $E_b/2 \le E \le E_b$ by ~ 3 e-foldings is due to the combined effects of n_e ramp-up and MHD-induced energetic ion redistribution.**

Illustration of the High-Energy Feature (HEF) at t ~ 0.5-0.6 s

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

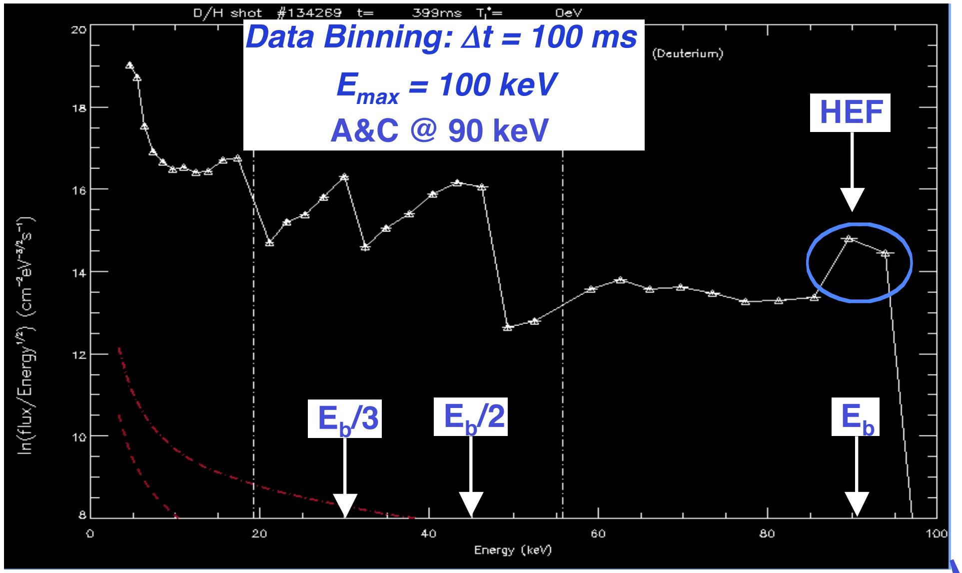


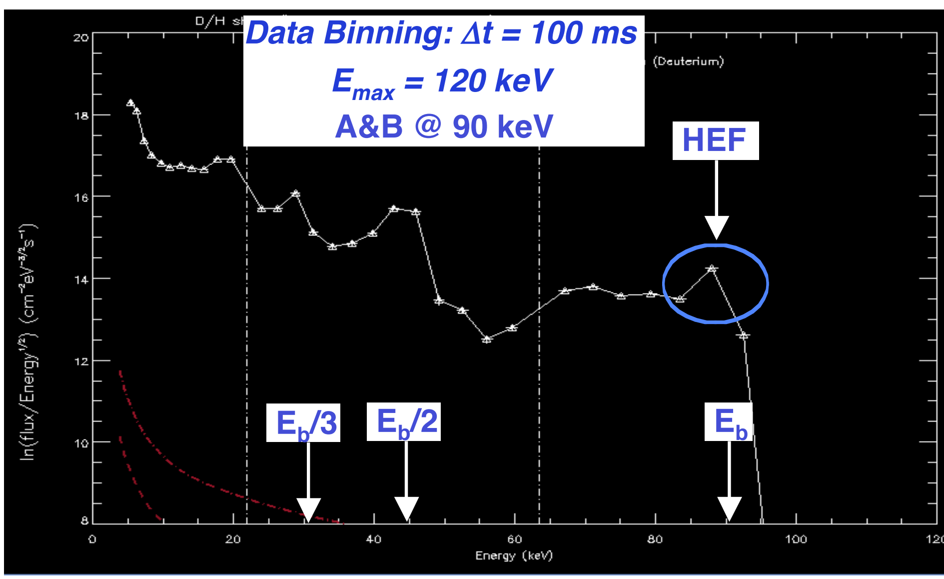


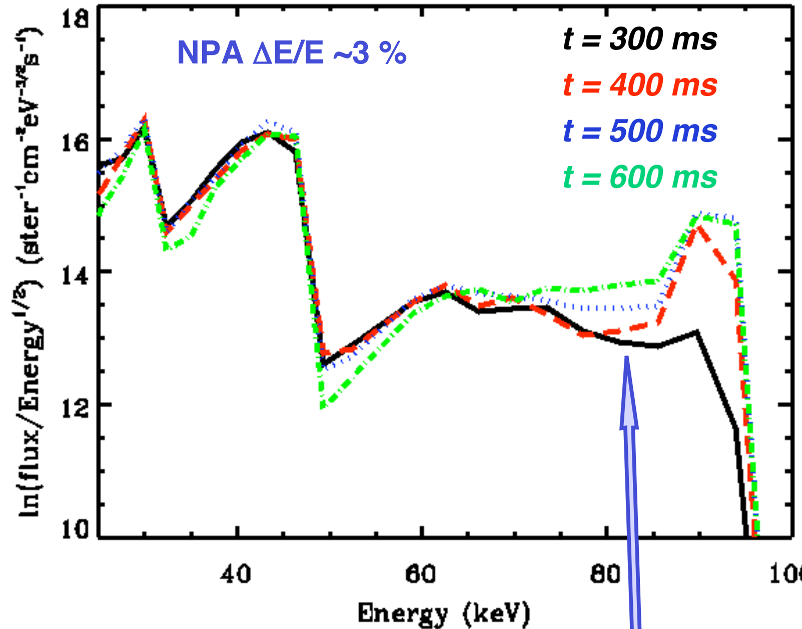
- **NPA charge exchange spectrum exhibits enhanced signal only near E ~ E_b (e.g. never at $E_b/2$ or $E_b/3$).**
- **'Transient' HEF periods can last for 100's of milliseconds in some shots.**

The High-Energy Feature is not a NPA Instrumental Artifact

H-mode with I_p = 1.2 MA, B_T = 5.0 kG, P_{NB} = 4 MW, $n_eL \sim 6\times10^{13}$ cm^{-2}







- Spectrum exhibits slowing down of fast ions from the HEF energy region.

- SN134269: HEF appears on Anode # 35 @ 90 keV and Anode 36 @ 93 keV.

- SN134270: HEF appears on Anode # 32 @ 90 keV.

Overview of High-E Feature Observations

- tabulation details are discussed in subsequent viewgraphs

← MHD Activity → ← MPTS/CHERS Profiles →

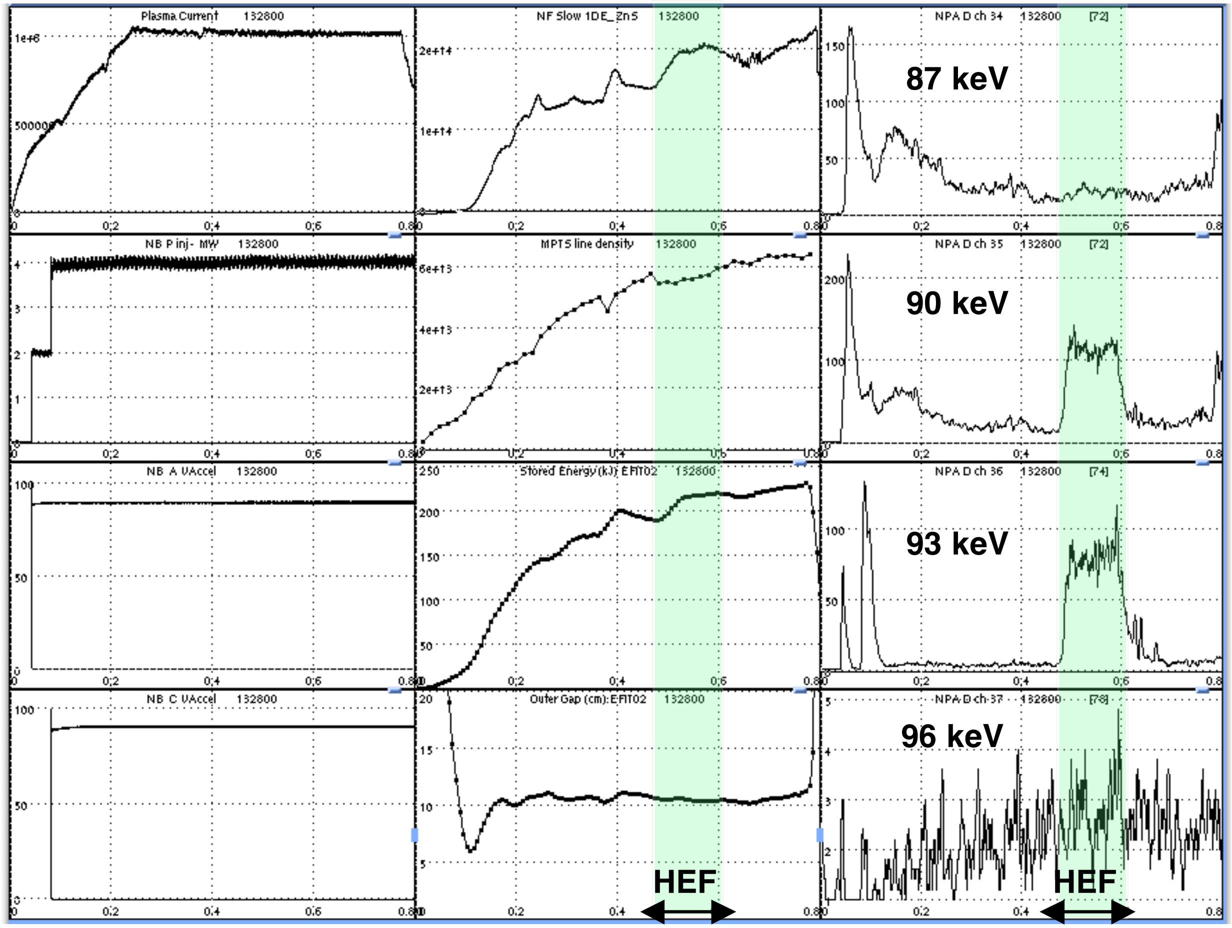
Shot	High-E	Δt(s)	TAE	Kink	CAE	δB_{TAE}	δB_{CAE}	ΔTe(r)	Δne(r)	ΔTi(r)	Δvφ(r)	ΔZeff	ΔSn(%)	ΔW(%)
127216	√	0.50-0.75	x	x	√	20	0.7	x	x	14	41	-12	14	9
127217	√	0.50-0.65	x	x	√	30	0.8	x	x	17	20	0	10	10
*127221	√	0.45-0.80	x	x	√	40	0.9	x	x	14	47	-13	14/30	10/19
127222	√	0.50-0.70	x	x	√	30	1.0	x	x	0	0	0	19	9
127236	√	0.45-0.67	x	x	√	50	0.8	√	x	23	47	0	18	16
127252	√	0.43-0.58	x	√	√	60	1.0	x	√	44	29	-15	27	18
*127253	√	0.35-0.63	x	x	√	15	0.5	x	√	0	0	0	21	33
127254	√	0.24-0.52	x	x	√	15	0.7	x	√	30	75	10	15	20
127256	√	0.43-0.54	x	x	√	20	0.5	x	√	x	x	x	0	5
127723	√	0.48-0.73	x	x	√	60	1.0	x	x	28	0	-14	27	16
*127953	weak	0.55-0.80	√	x	√	70	1.0	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
*127957	√	0.47-0.64	√	x	√	60	1.0	x	√	43	43	14	7/3.5	13/10
128032	√	0.47-0.62	√	x	√	60	3.0	√	√	4	20	0	13	15
128033	√	0.48-0.62	√	x	√	50	3.0	√	√	7	25	11	21	12
128600	√√√	0.35-0.56	x√√	x	√	15	6.0	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
128606	√√√	0.35-0.56	√√√	x	√	70	2.5	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
*128729	√	0.55-0.76	x	x	√	?	?	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
128820	√x	0.38-0.52	x√	x√	√	50	4.0	√	x	49	33	-20	100	33
128852	√	0.50-0.84	x	x	√	50	2.0	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
128857	√	0.45-0.73	x	x	√	60	2.0	x	√	33	73	-55	12	6
128893	√	0.50-0.80	x	x	√	60	4.0	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
***128895**	√√	0.32-0.92	√x	x	√	50	1.0	x	x	12	29	0	18	15
128897	√√	0.32-0.92	√x	√x	√	50	1.5	√	√	33	15	0	20/5	13/4
128931	√	0.50-0.60	x	x	√	20	4.0	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
132340	√	0.44-0.65	x	x	√	60	3.0	x	x	25	24	17	35	34
132800	√	0.48-0.60	x	x	√	50	1.5	x	x	29	19	7	33	16

√ - effect occurs during Δt x - effect does not occur ΔP_b - NB power step obfuscates data #/# = data/TRANSP

HEF Discharge Characteristics: SN132800

H-mode with Ip = 1 MA, B_T = 4.5 kG, NB A&C @ 90 keV, P_{NB} = 4 MW, $n_eL \sim 6\times10^{13}$ cm^{-2}

Shot	High-E	Δt(s)	R_{tan}(cm)
127216	√	0.50-0.75	71
127217	√	0.50-0.65	71
*127221	√	0.45-0.80	71
127222	√	0.50-0.70	71
127236	√	0.45-0.67	71
127252	weak	0.43-0.58	71
*127253	√	0.35-0.63	71
127254	√	0.24-0.52	55
127256	√	0.43-0.54	65
127723	√	0.48-0.73	78
*127953	weak	0.55-0.80	86
*127957	√	0.47-0.64	86
128032	√	0.47-0.62	75
128033	√	0.48-0.62	75
128600	√√√	0.35-0.56	60
128606	√√√	0.35-0.56	62
*128729	√	0.55-0.76	70
128820	√x	0.38-0.52	65
128852	√	0.50-0.84	70
128857	√	0.45-0.73	70
128893	√	0.50-0.80	70
***128895**	√√	0.32-0.92	70
128897	√√	0.32-0.92	70
128931	√	0.50-0.60	70
132340	√	0.44-0.65	70
132800	√	0.48-0.60	70

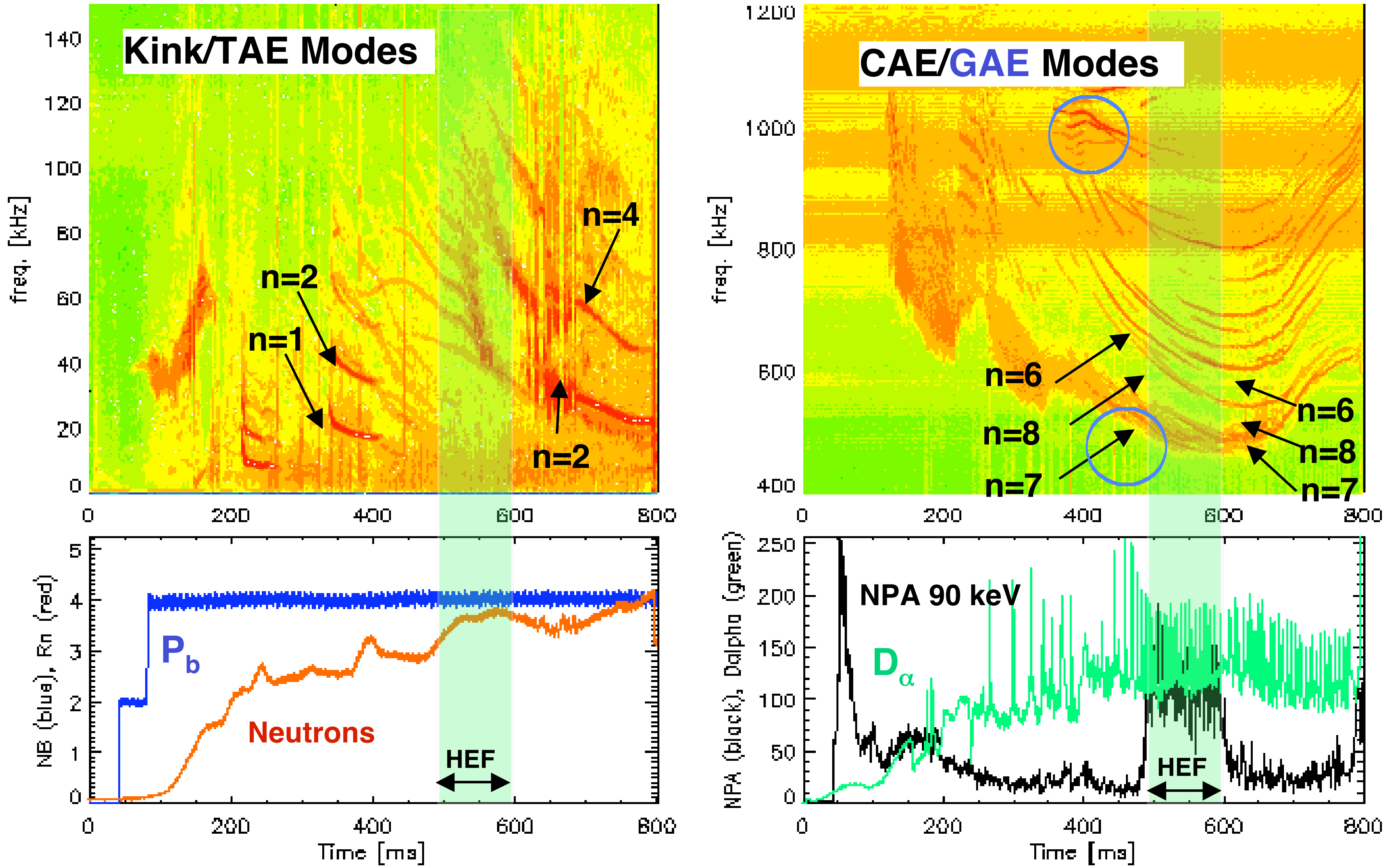


- HEF onset typically occurs during mid-discharge: e.g. t ~ 0.4 - 0.5 s.
- HEF seen for mid-plane NPA sightlines with: R_{tan}~ 55 - 86 cm, $v_{||}/v$ ~ 0.7 - 0.9.

HEF Existence Requires No Kink and Weak TAE MHD Activity

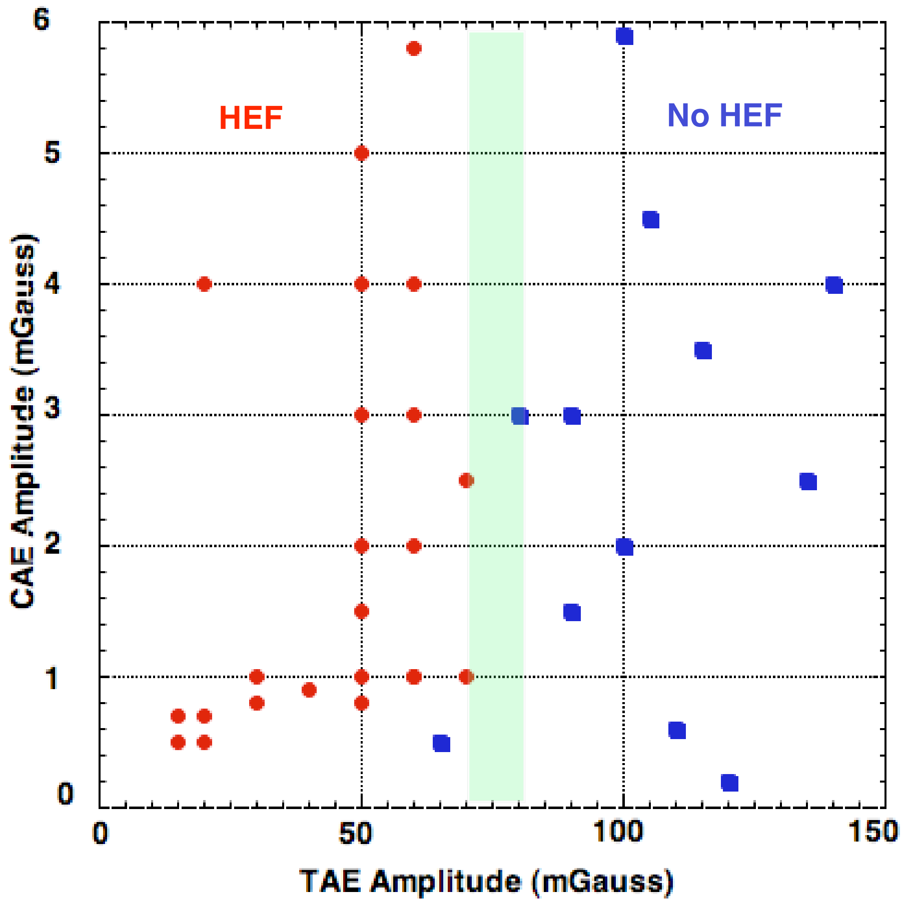
- no MHD 'chirping' is observed on Mirnov signals during HEF interval

SN132800



HEF Exists for TAE Activity Below a δB_{rms} "Threshold"

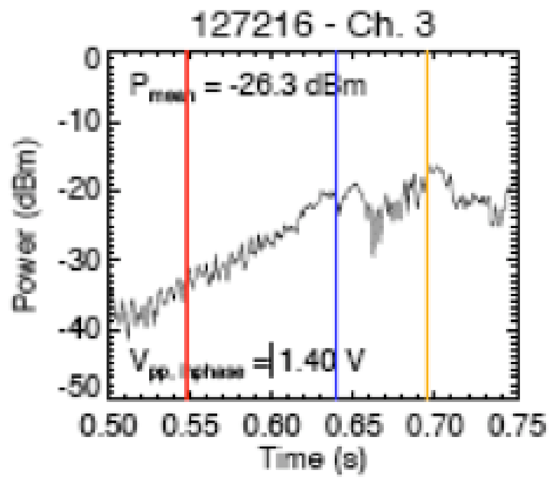
Shot	High-E	TAE	CAE	δB_{TAE}	δB_{CAE}
127216	√	x	√	20	0.7
127217	√	x	√	30	0.8
*127221	√	x	√	40	0.9
127222	√	x	√	30	1.0
127236	√	x	√	50-150	0.8
127252	weak	x	√	60	1.0
*127253	√	x	√	15	0.5
127254	√	x	√	15	0.7
127256	√	x	√	20	0.5
127723	√	x	√	60	1.0
*127953	weak	√	√	70	1.0
*127957	√	√	√	60	1.0
128032	√	√	√	60	3.0
128033	√	√	√	50	3.0
128600	√√√	x√√	√	15	6.0
128606	√√√	√√√	√	70	2.5
*128729	√	x	√	?	?
128820	√x	x√	√	50-200	4.0
128852	√	x	√	50	2.0
128857	√	x	√	60	2.0
128893	√	x	√	60	4.0
***128895**	√√	√x	√	50	1.0
128897	√√	√x	√	50	1.5
128931	√	x	√	20	4.0
132340	√	x	√	60	3.0
132800	√	x	√	50	1.5

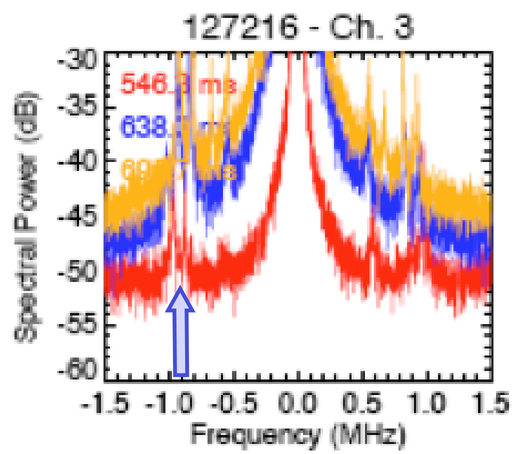


- HEFs occur at *low* TAE activity (δB_{rms} < 75 mGauss) but over a wide range of CAE MHD.

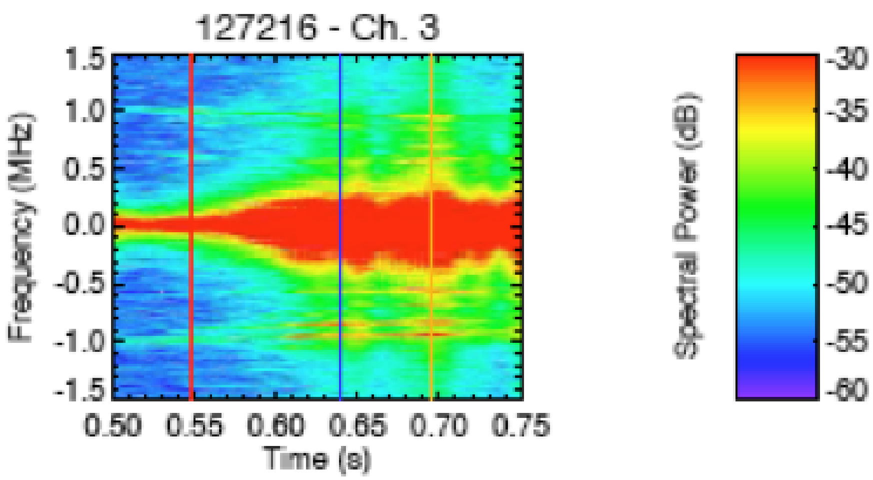
High-k Scattering Shows Density Fluctuation Activity during the HEF

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





Samples per FFT = 8192
FFT window (ms) = 1.26
Freq res. (kHz) = 0.79
Smoothing points = 20
Norm radius (cm) = 0.0
Dig amp (dB) = 12
Blackman-Harris window



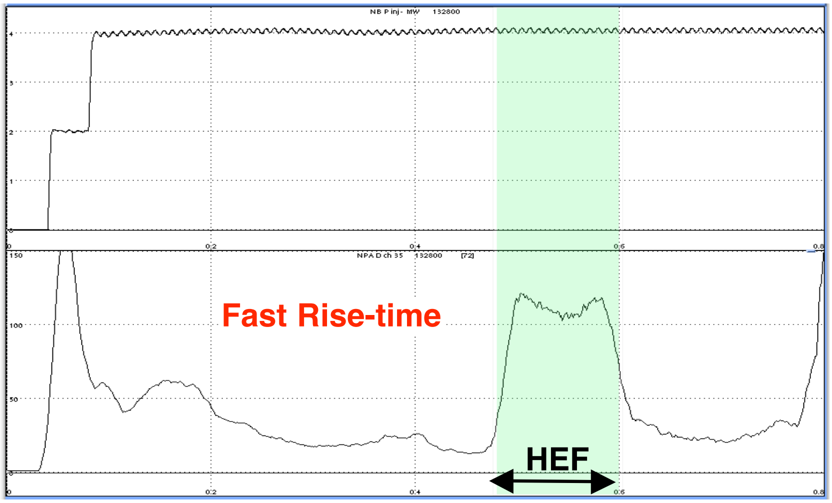
- **High-k fluctuations are in the CAE/GAE frequency range ~ 0.5 - 1.0 MHz consistent with Mirnov data.**
- **High-k data localizes fluctuations to R_{maj} ~ 120 - 135 cm.**

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

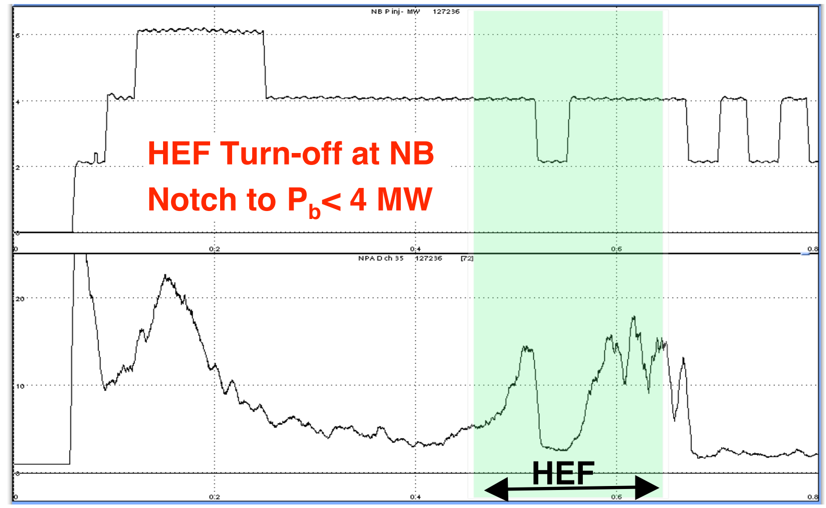
Courtesy of Jeehyun Kim (POSTECH) and K. C. Lee (UC Davis)

HEF Rise-time and Duration Show Considerable Variation

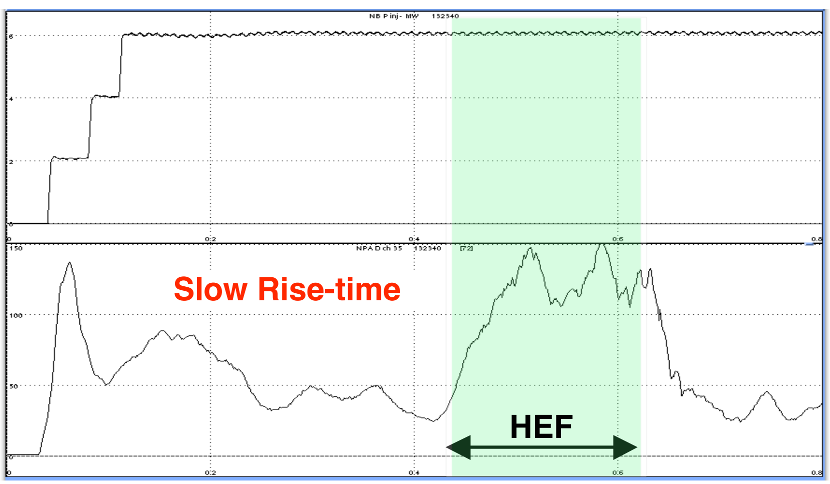
- NPA data at 90 keV



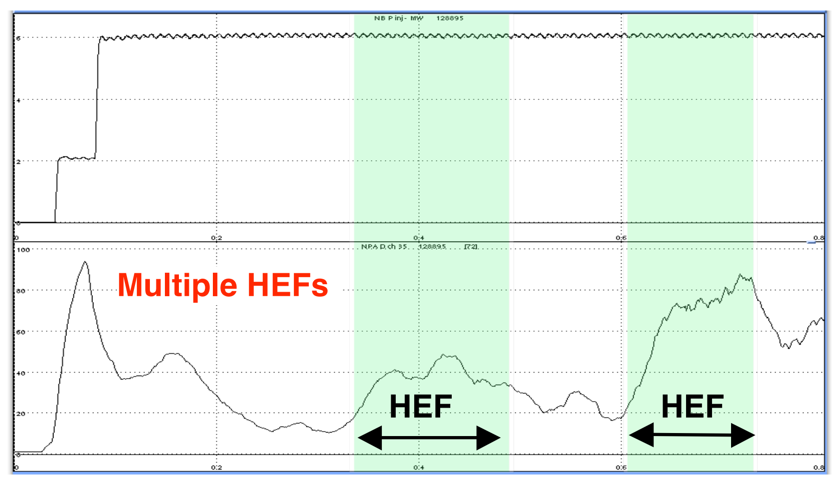
• SN132800, P_b= 4 MW, t_{rise}= 20 ms



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

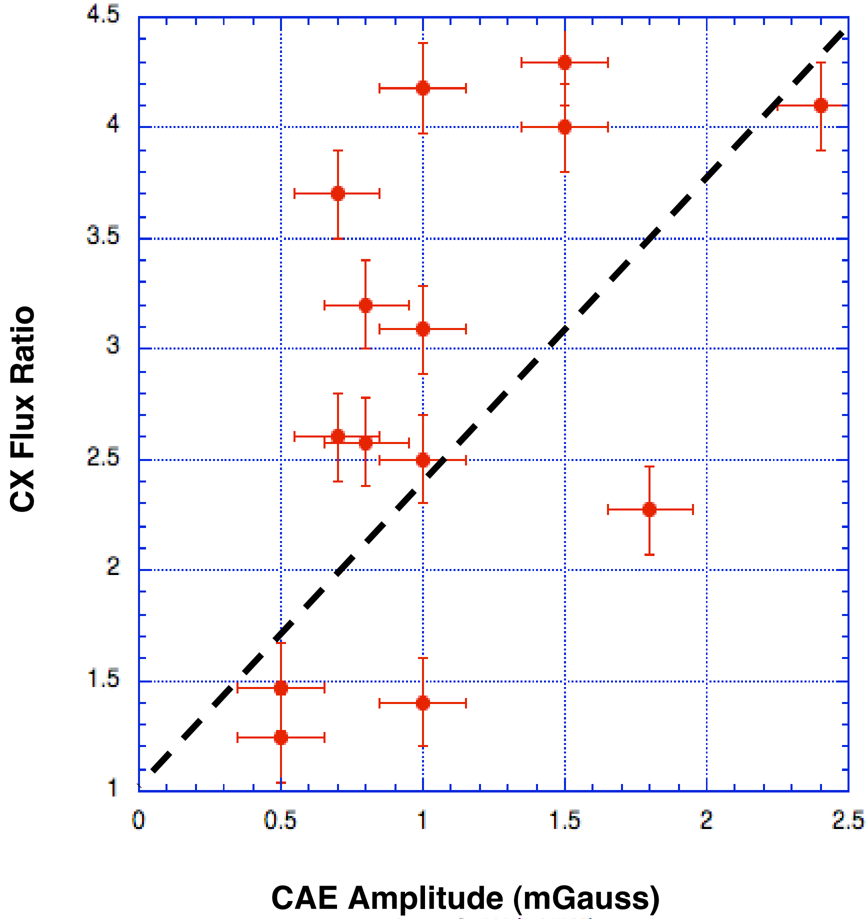


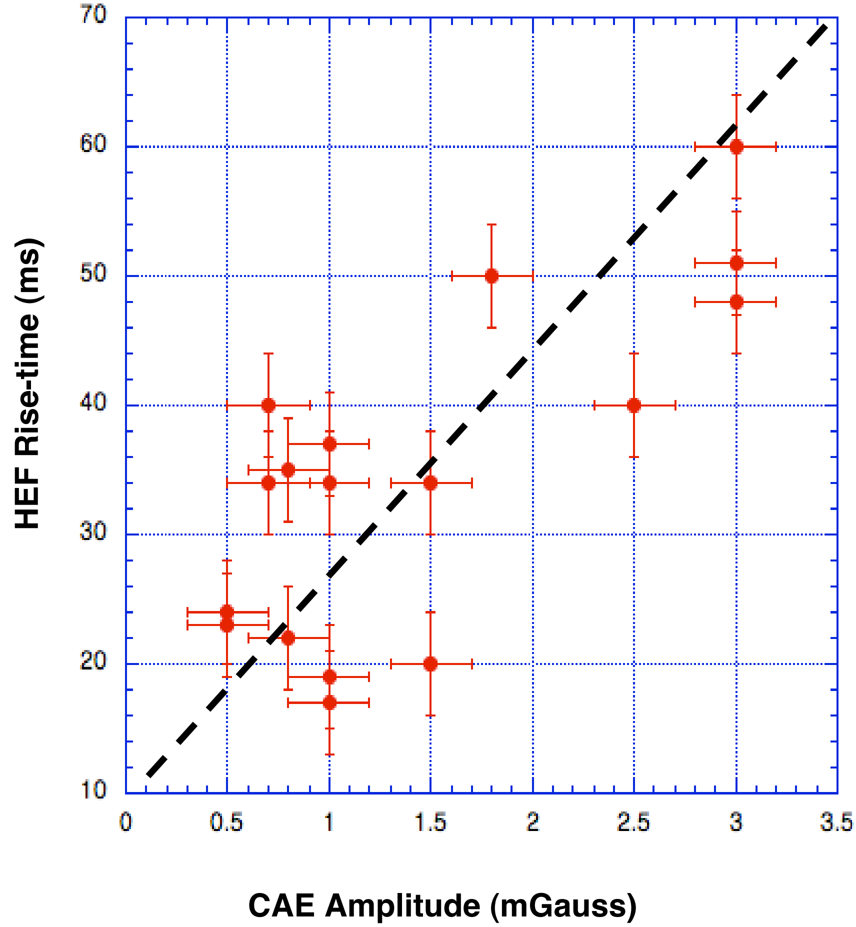
• SN132340, P_b= 6 MW, t_{rise}= 80 ms



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

HEF Rise-time and Flux Increase Vary with CAE Strength

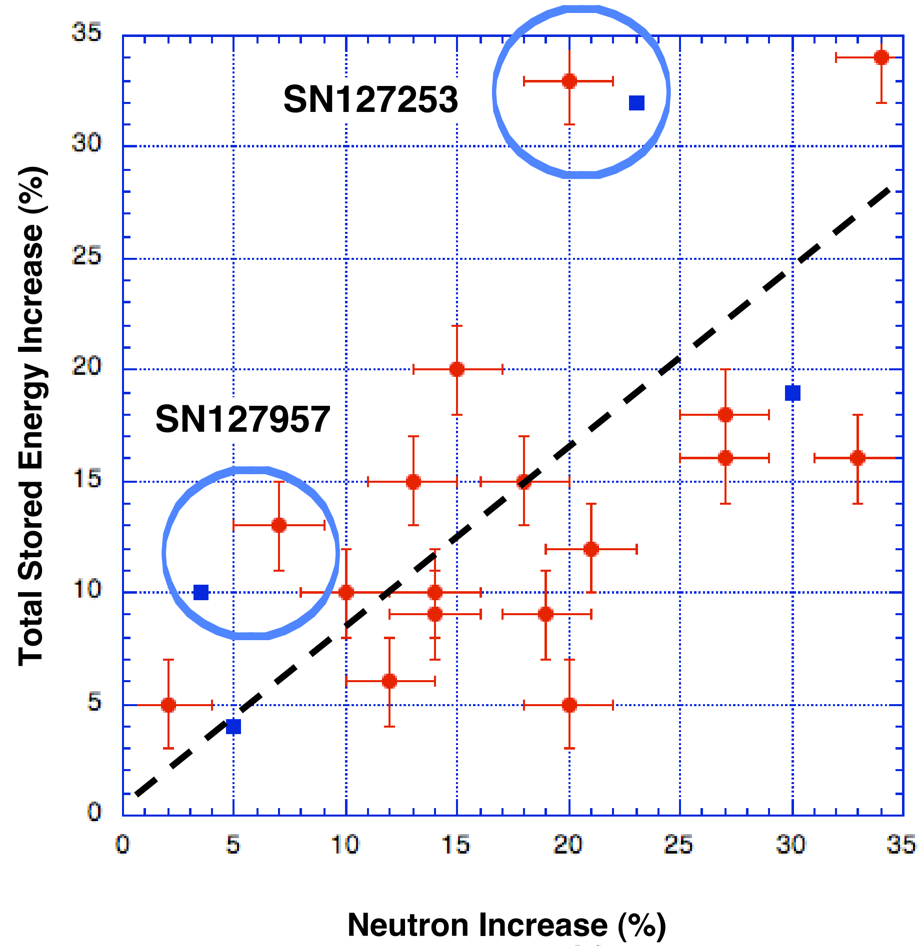




- HEF rise-time shows correlation with CAE δB_{rms} amplitude, but flux increase less so.

Neutron Yield and Stored Energy Variation during HEF Interval

Shot	High-E	Δt(s)	Δ Sn(%)	ΔW(%)
127216	√	0.50-0.75	14	9
127217	√	0.50-0.65	10	10
*127221	√	0.45-0.80	14/30	10/19
127222	√	0.50-0.70	19	9
127236	√	0.45-0.67	Δ Pb	Δ Pb
127252	weak	0.43-0.58	27	18
*127253	√	0.35-0.63	20/23	33/32
127254	√	0.24-0.52	15	20
127256	√	0.43-0.54	0	5
127723	√	0.48-0.73	27	16
*127953	weak	0.55-0.80	Δ Pb	Δ Pb
*127957	√	0.47-0.64	7/3.5	13/10
128032	√	0.47-0.62	13	15
128033	√	0.48-0.62	21	12
128600	√√√	0.35-0.56	Δ Pb	Δ Pb
128606	√√√	0.35-0.56	Δ Pb	Δ Pb
*128729	√	0.55-0.76	Δ Pb	Δ Pb
128820	√x	0.38-0.52	Δ Pb	Δ Pb
128852	√	0.50-0.84	Δ Pb	Δ Pb
128857	√	0.45-0.73	12	6
128893	√	0.50-0.80	Δ Pb	Δ Pb
*128895	√√	0.32-0.92	18	15
128897	√√	0.32-0.92	20/5	13/4
128931	√	0.50-0.60	Δ Pb	Δ Pb
132340	√	0.44-0.65	35	34
132800	√	0.48-0.60	33	16



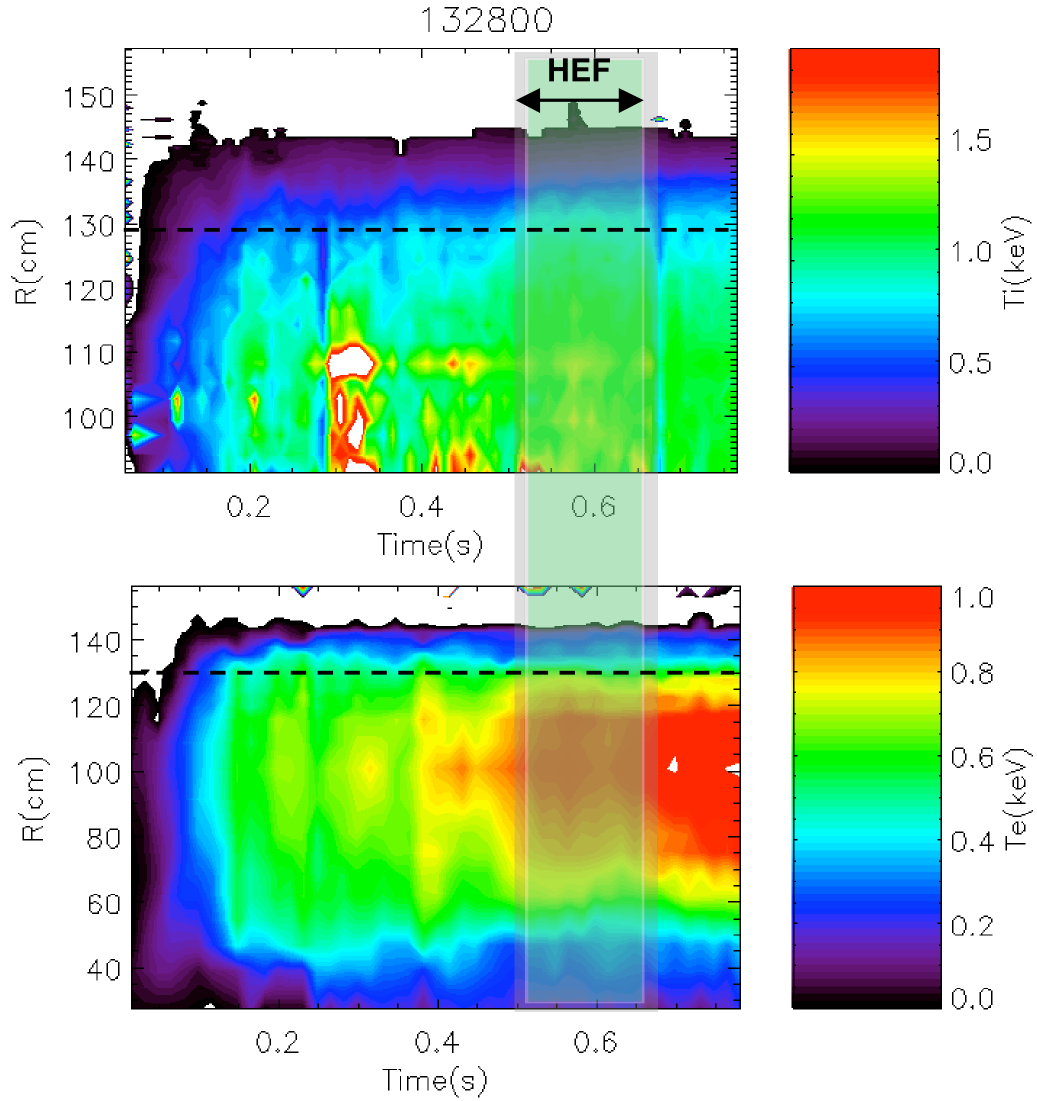
- The experimental neutron rate and total stored energy increase during the HEF.
- Similar increases are observed in TRANSP analyses (blue squares).

Does HEF Drive Changes in Temperature or Density Profiles?

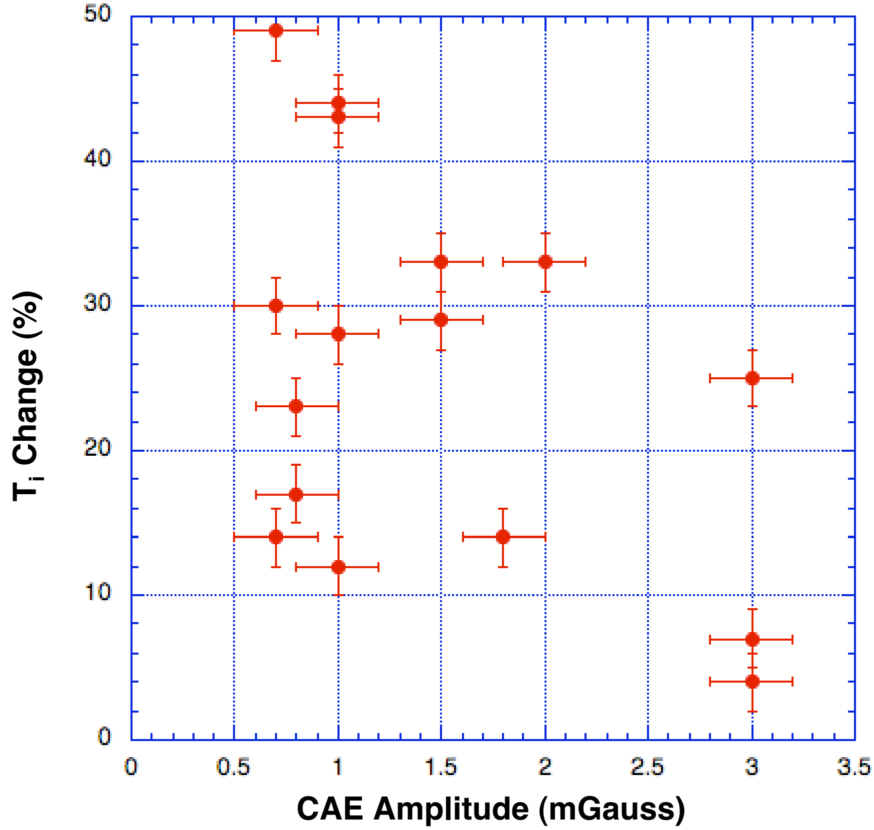
Example shows edge broadening of $T_i(r)$ at R_{maj} ~ 130 cm, but none for $T_e(r)$

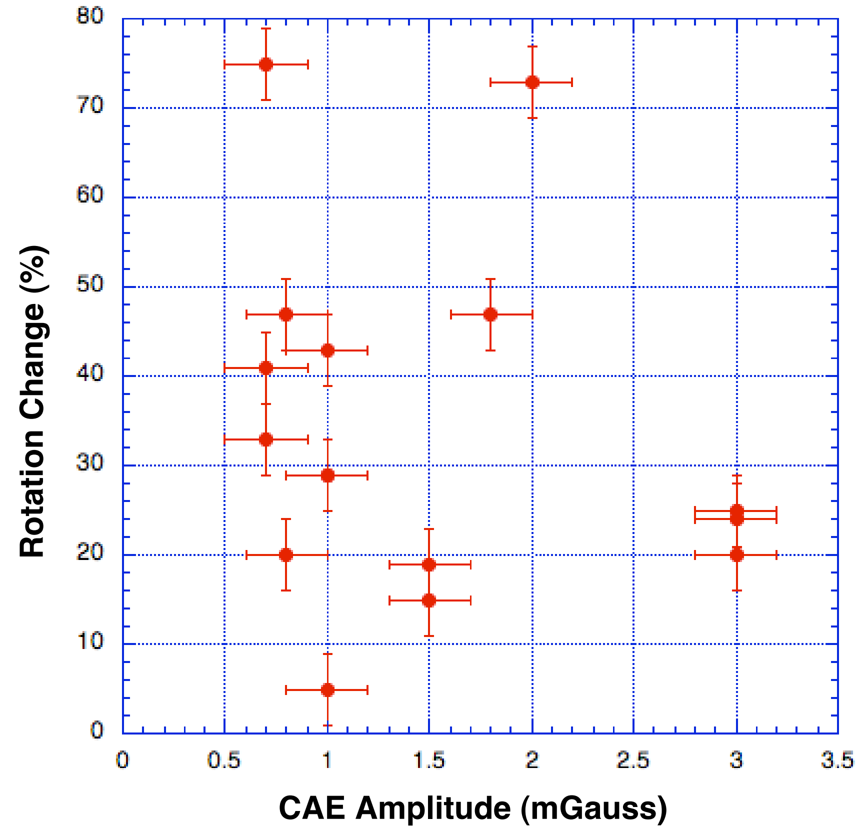
% Change @ R~130 cm

Shot	High-E	ΔTe(r)	Δne(r)	ΔTi(r)	Δvφ(r)	ΔZeff
127216	√	x	x	14	41	-12
127217	√	x	x	17	20	0
*127221	√	x	x	14	47	-13
127222	√	x	x	0	0	0
127236	√	√	x	23	47	0
127252	√	x	√	44	29	-15
*127253	√	x	√	0	0	0
127254	√	x	√	30	75	10
127256	√	x	√	x	x	x
127723	√	x	x	28	0	-14
*127953	weak	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
*127957	√	x	√	43	43	14
128032	√	√	√	4	20	0
128033	√	√	√	7	25	11
128600	√√√	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
128606	√√√	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
*128729	√	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
128820	√x	√	x	49	33	-20
128852	√	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
128857	√	x	√	33	73	-55
128893	√	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
***128895**	√√	x	x	12	29	0
128897	√√	√	√	33	15	0
128931	√	Δ Pb	Δ Pb	Δ Pb	Δ Pb	Δ Pb
132340	√	x	x	25	24	17
132800	√	x	x	29	19	7



Does HEF Drive Changes in T_i or v_Φ Profiles?





- Plots show broadening of $T_i(r)$ and v_Φ profiles measured at R_{maj} ~ 130 cm.
- Changes in $T_e(r)$ and $n_e(r)$ are difficult to quantify: e.g. $n_e(r)$ usually rising.

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.

- Onset of the HEF is not 'abrupt' but exhibits a growth time of ~ 20 - 50 ms.

- **MHD Activity**

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

-The magnitude of the HEF flux is modulated by strong bursting MHD EPM activity, just like the slowing down ion distribution.

- 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).

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).

- **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.

-- No ssNPA detection of HEFs…but energy resolution, ΔE ~ 10 keV, is modest.

Physical Explanation of the High-Energy Feature?

• The NPA is typically operated in the mid-plane with R_{tan} ~ 60 - 80 cm.
- this corresponds to sampling v_{II}/v ~ 0.8 ± 0.1 (passing energetic ions).

• At these settings, the NPA views Source A in the region of E_b.
- but not Sources B&C that peak at v_{II}/v << 0.80 ± 0.05 (more trapped energetic ions).

• A mechanism that does not absorb energy but transfers v_{perp} energy to v_{II} would explain the observations.
- source B&C ions at the full beam energy would thus be 'pumped' into the v_{II}/v range viewed by the NPA

• This would require a narrow CAE 'resonance' near the beam full energy.
- though the absence of bursting or frequency changes in the CAE modes on the Mirnov spectrograms is an issue.

• This 'pumping' of energetic ions toward passing orbits might also cause the observed increase in measured neutron yield and stored energy.
- postulate that TRANSP 'sees' these increases because the 'pumping' from more trapped to more passing orbits drives changes in measured profiles as shown earlier

Physical Explanation of the High-Energy Feature?

• **Alternative mechanism suggested by Herb Berk**

- During robust TAE activity, a large fraction of the energetic ions in the outer region of the NSTX plasma are toroidally trapped and the high energy component would be more easily lost than passing particles. Thus there would be a deficiency of the high energy component during the MHD active phase.

- In the TAE 'quiescent' phase, the high energy component could build up, but first at high energy of injection. Particle 'pinch' effects could 'un-trap' ions onto passing orbits observed by the NPA.

- Thus, there may be an additional source of passing energetic particles that is observed by the NPA. At later times, a slowing down distribution from the source of particles that were born during the quiescent phase could develop, as observed.

Future Work

Dedicated XP for Exploration of the High-Energy Feature(HEF): Total ~ 34 Shots

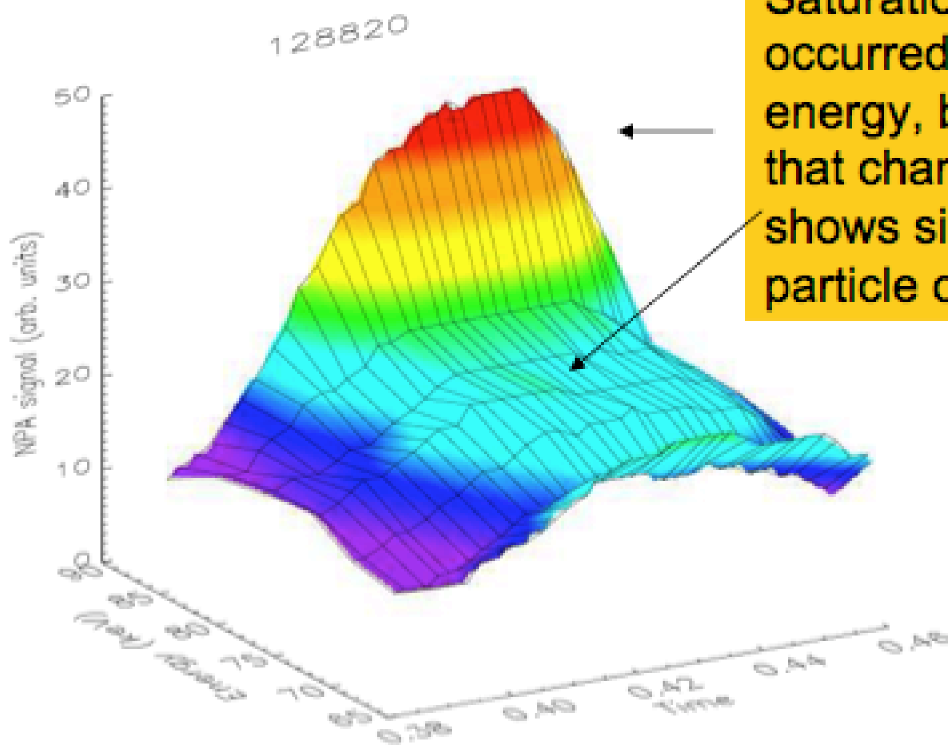
- **Does the HEF track E_b?**
  - E_b scan with ABC @ 100, 90, 80, 70 keV
    (Fiducial + 3 shots…Lithium free)
- **Does the HEF depend on NB sources?**
  - Select E_b from above scan: run with AB, AC BC (need $P_b > 4$ MW)
    (3 shots)
- **Does the HEF occur with NB sources @ mixed E_b?**
  - For example, A @ 100 keV, B@ 90 keV, C@80 keV
    (3 shots for permutations)
- **Does Lithium suppress HEFs?…use a robust scenario from above**
  - LITER deposition @ 50, 100, 150, 200 mg/shot (4 shots)
- **Horizontal and vertical NPA scans with all NBs at a selected E_b**
  - Hscan requires ~ 12 shots and Vscan ~ 8 shots
    (20 shots)

Backup

PWRoss Conundrum

A better question might be: Where did the fast ions come from?

Even when the modulation lasted significantly longer than the slowing-down time, fast particle spectrum deviates significantly from expectations



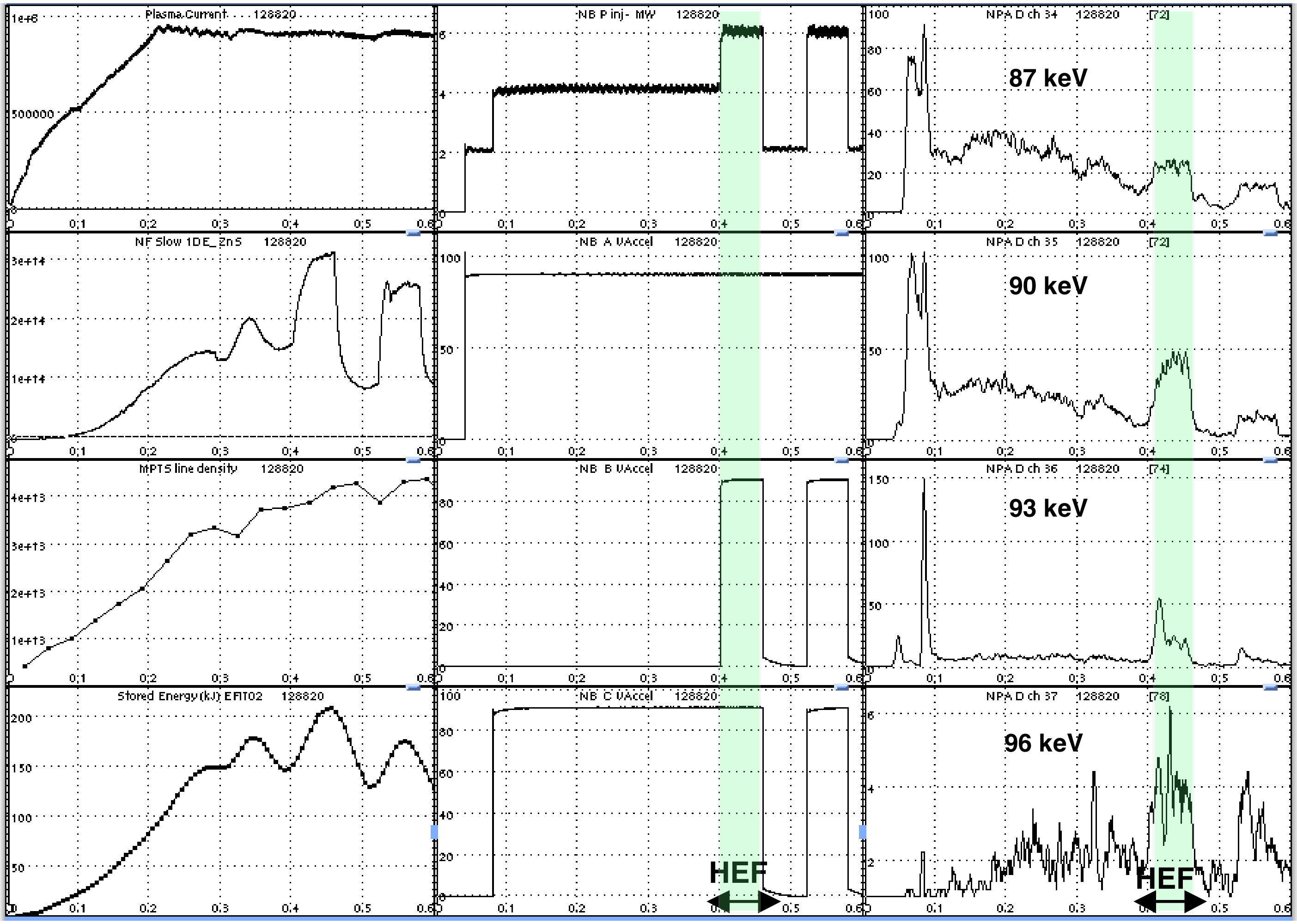
Saturation has occurred at full energy, but ONLY that channel shows significant particle density.

Where did the fast ions go?

"Investigation of Power Balance and Excess Ion Heating in the National Spherical Torus Experiment,"
Presented by P W. Ross at General Atomics, Friday, February 13, 2009

HEF with NB Modulated at Δt = 60 ms: SN128820

H-mode with I_p = 0.9 MA, B_T = 4.5 kG, NBs @ 90 keV, P_{NB} = 4-6 MW, $n_eL \sim 4\times10^{13}$ cm^{-2}

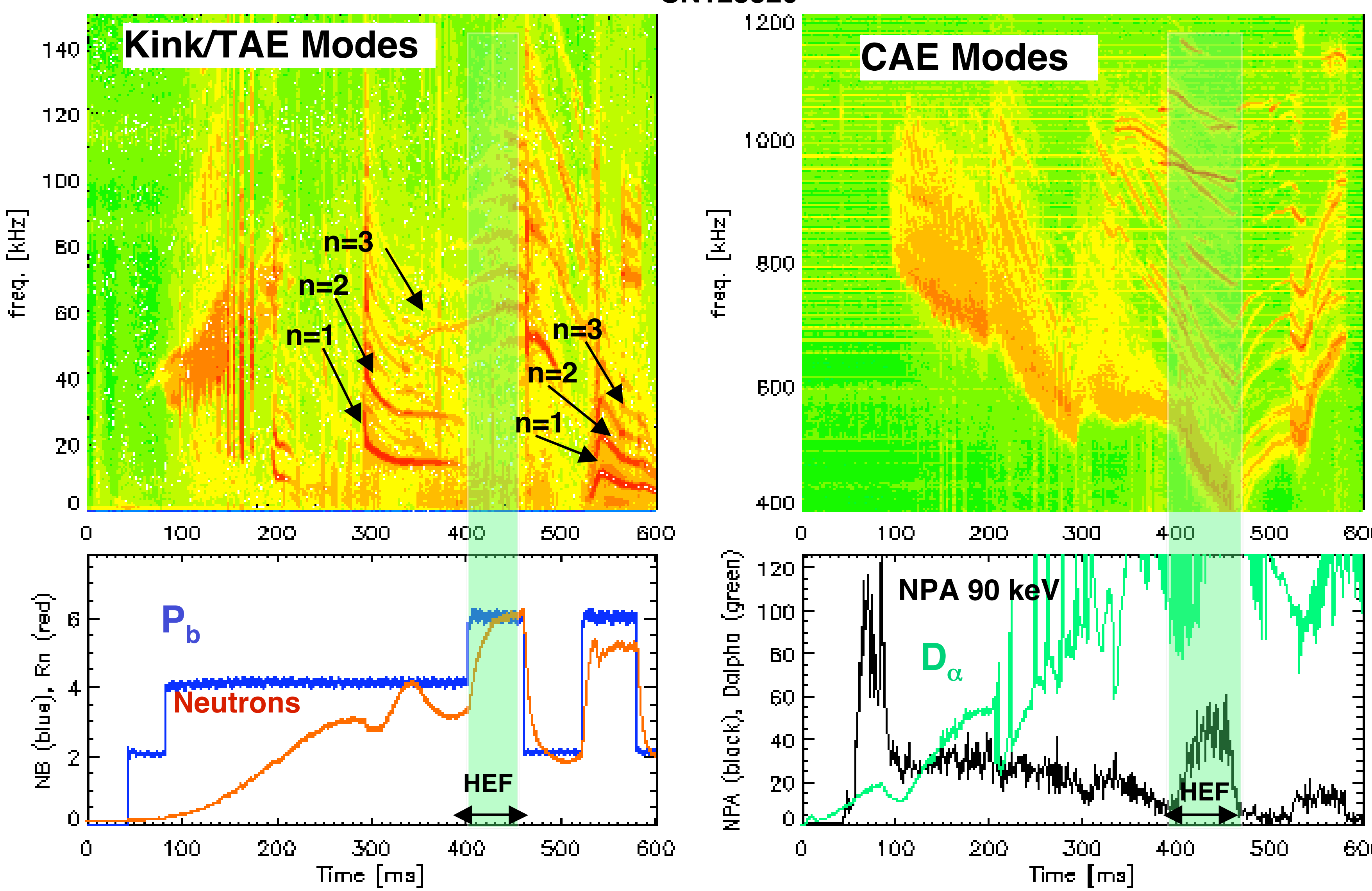


- **The 1ST NB blip created a strong HEF but not the 2ND blip due to MHD.**

HEF with NB Modulated at Δt = 60 ms

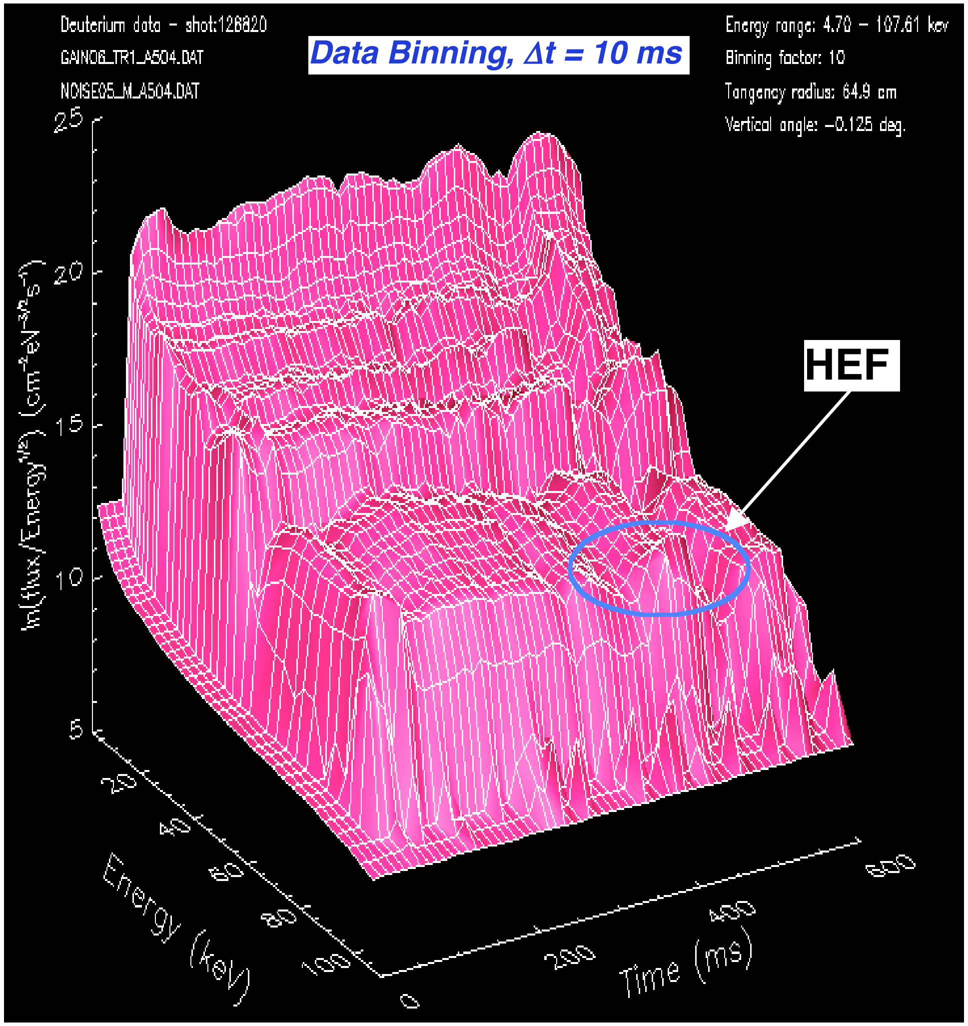
H-mode with I_p = 0.9 MA, B_T = 4.5 kG, NBs @ 90 keV, P_{NB} = 4-6 MW, $n_eL \sim 4\times10^{13}$ cm^{-2}

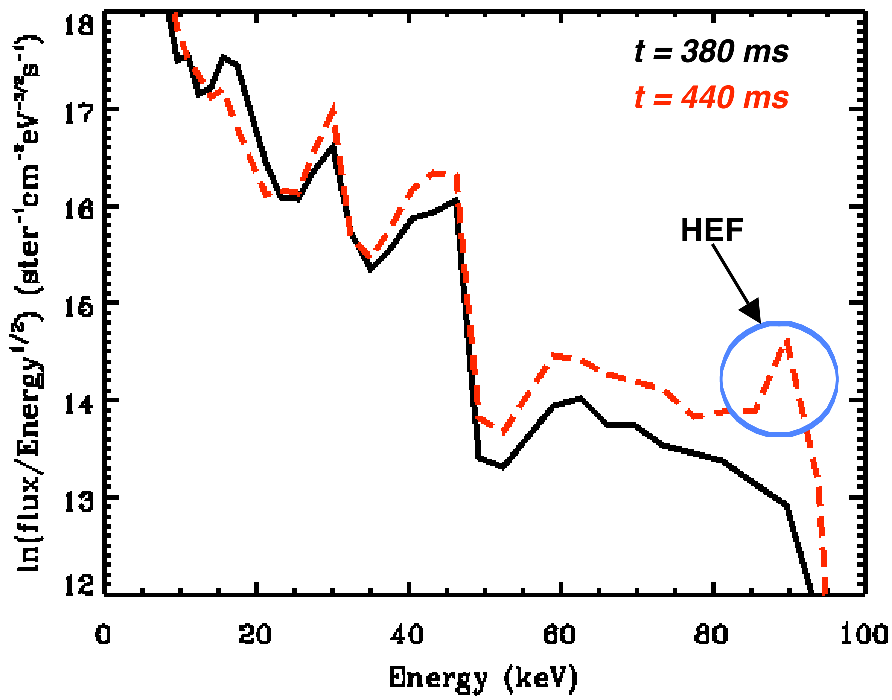
SN128820



HEF with NB Modulated at Δt = 60 ms: SN128820

H-mode with I_p = 0.9 MA, B_T = 4.5 kG, NBs @ 90 keV, P_{NB} = 4-6 MW, $n_eL \sim 4\times10^{13}$ cm^{-2}



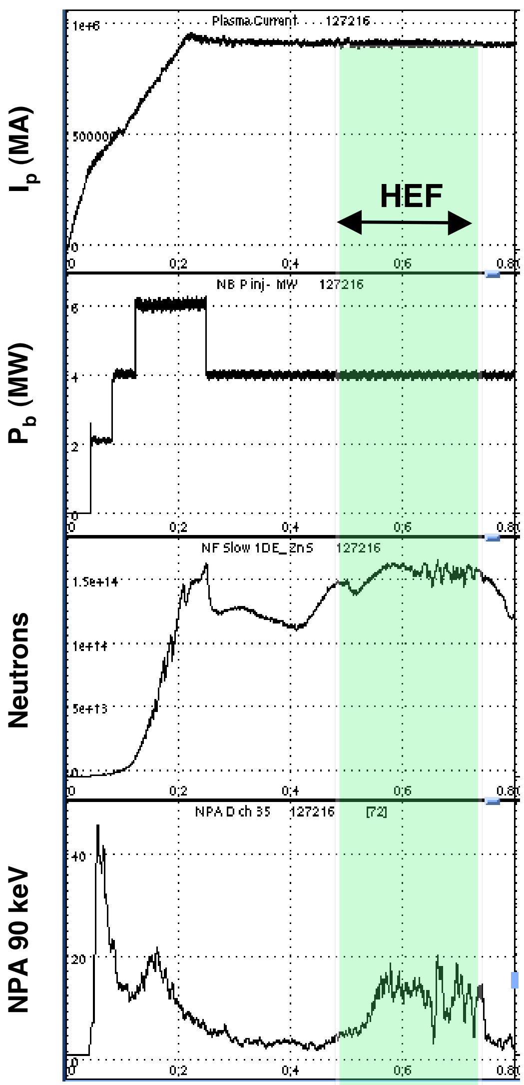


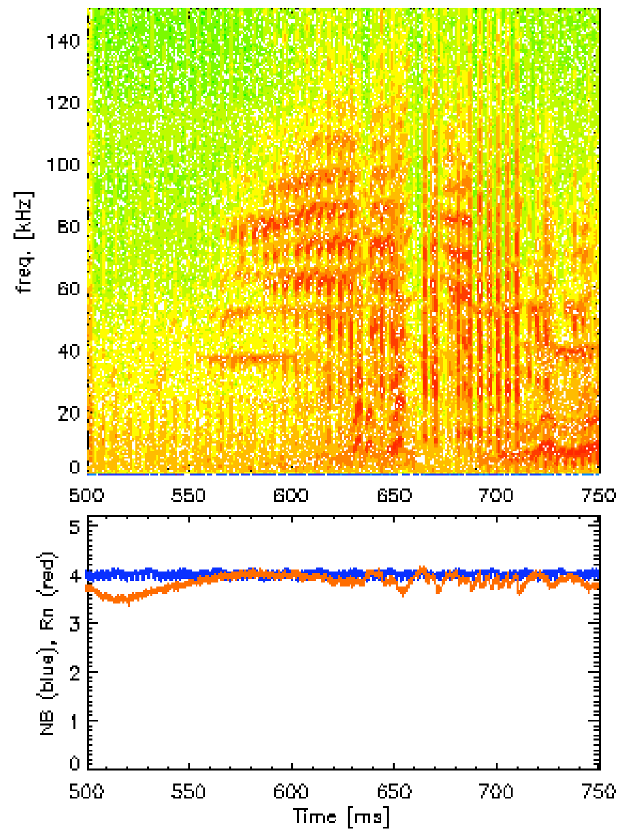
- Above shows NPA spectra before (black) and during (red) the 1ST NB blip.
- During blip CX flux increases at all E due to additional NB primary neutrals.
- *Extra* CX flux appears at the HEF.

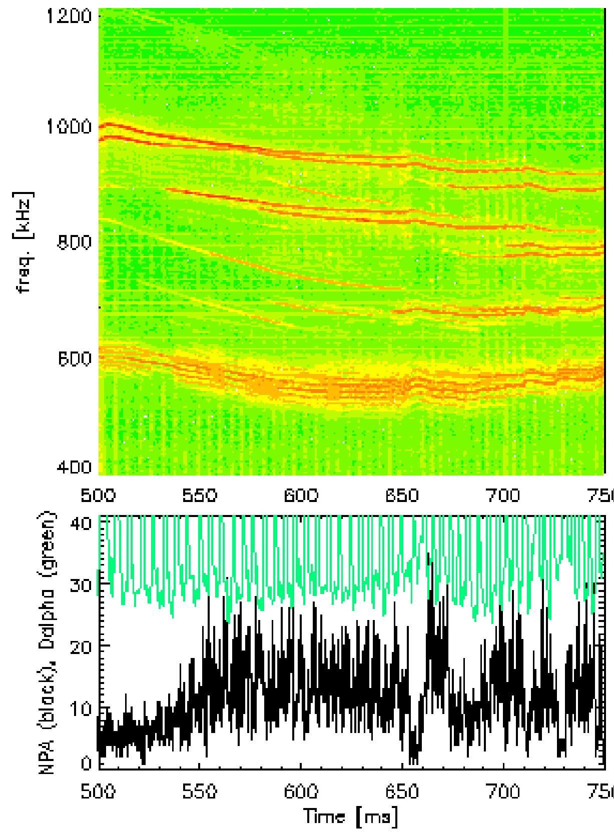
More Backup

High-E Feature (HEF) Data for SN127216

H-mode with I_p = 0.9 MA, B_T = 5.0 kG, A&B @ 90 keV, P_{NB} = 4 MW, $n_eL \sim 5\times10^{13}$ cm^{-2}



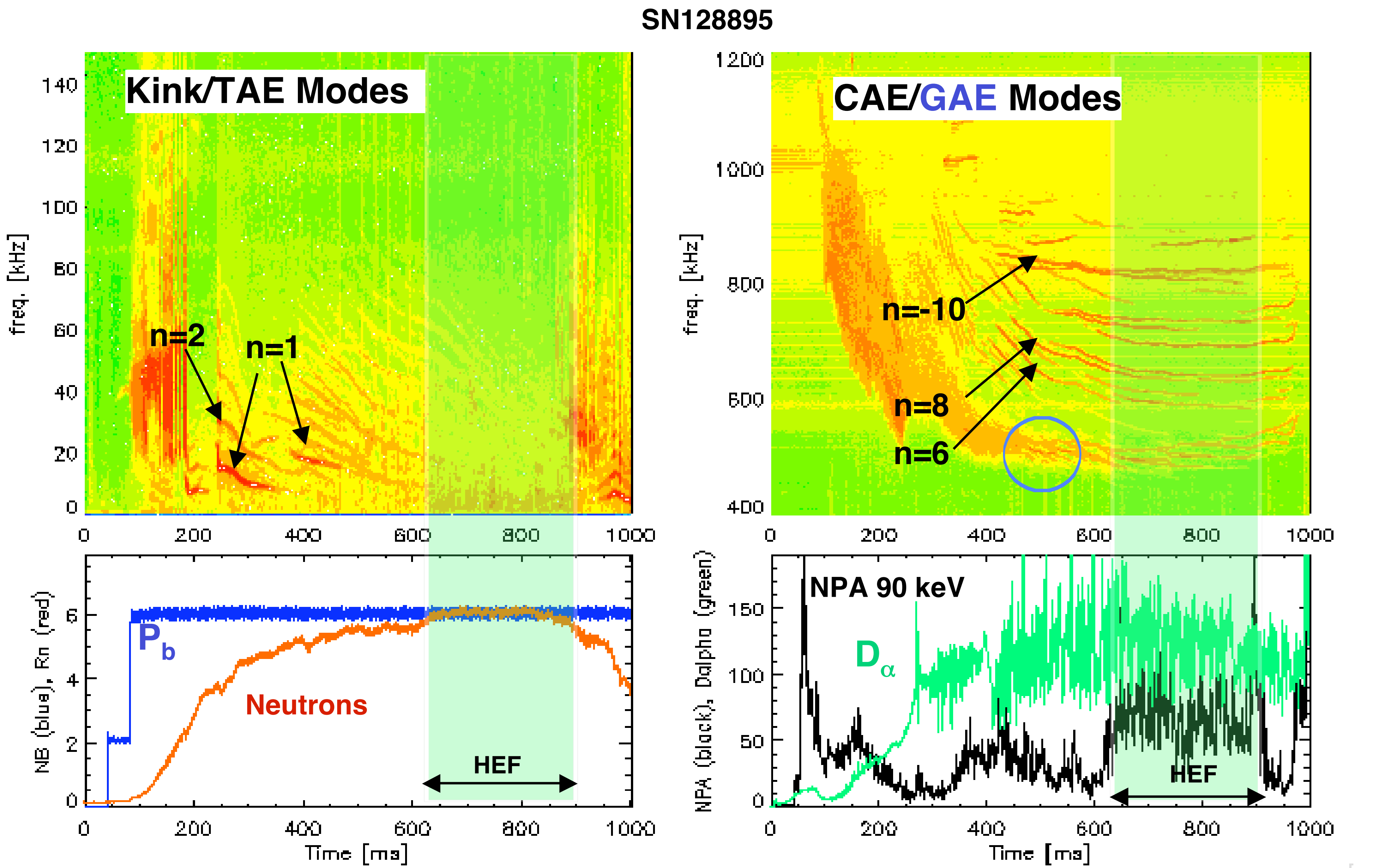




- The Mirnov spectrogram shows TAE bursting activity during the HEF at t ~ 0.65 - 0.75 s.
- TAE bursting activity is also seen on NPA and neutrons.

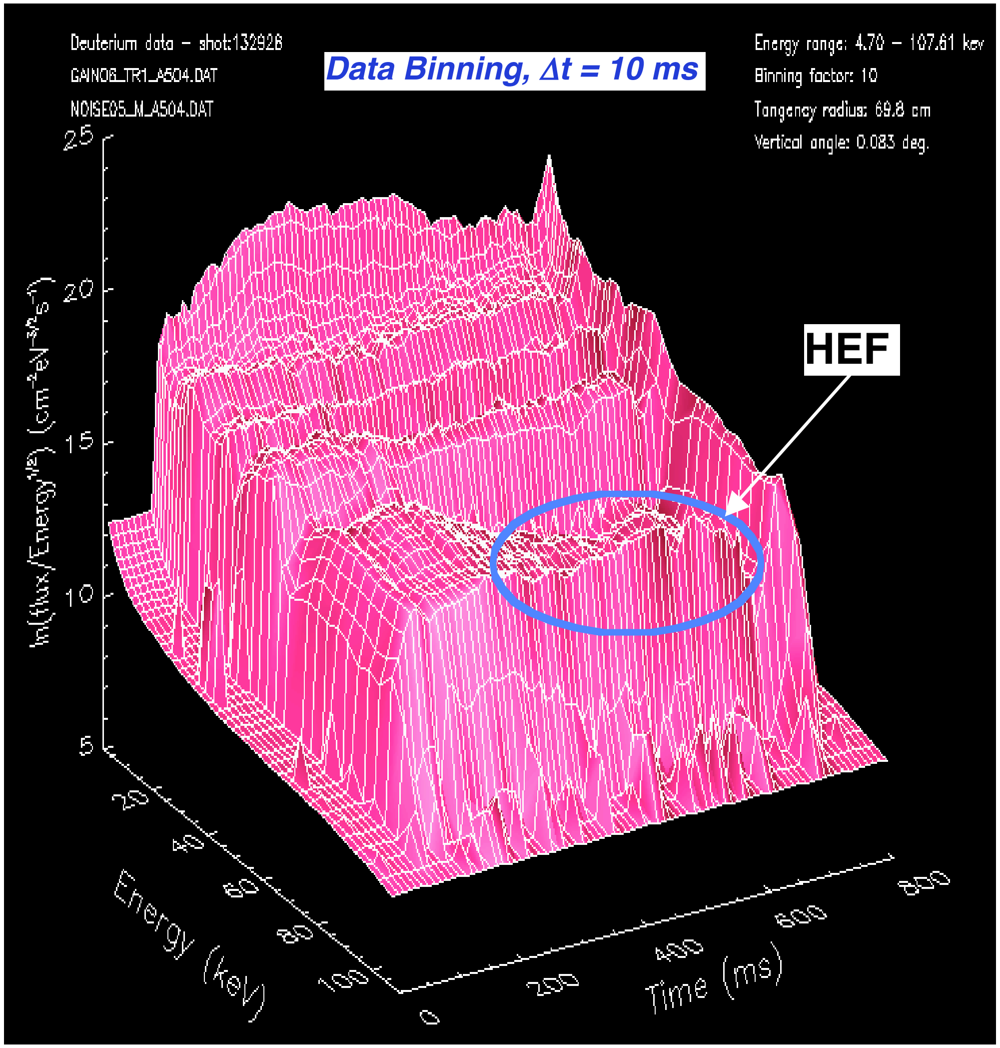
HEF Existence Requires Feeble Kink/TAE MHD Activity: SN128895

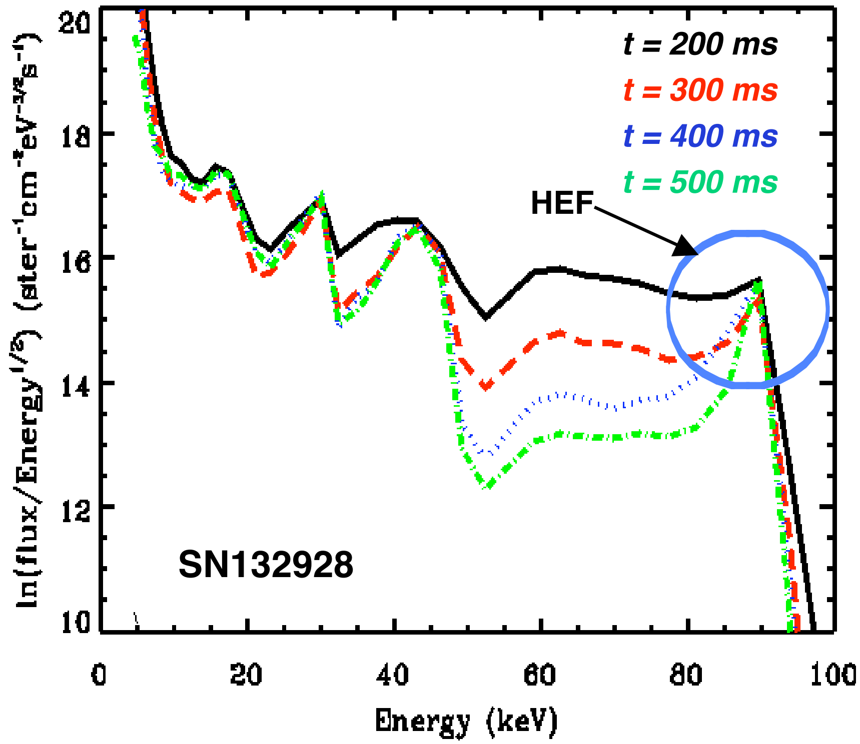
- no MHD ‘chirping’ is observed on Mirnov signals during HEF interval



Unusual Occurrence of Persistent High-E Feature (HEF)

H-mode with I_p = 0.8 MA, B_T = 4.5 kG, A& B @ 90 keV, P_{NB} = 4 MW, $n_eL \sim 8 \times 10^{13}$ cm^{-2}

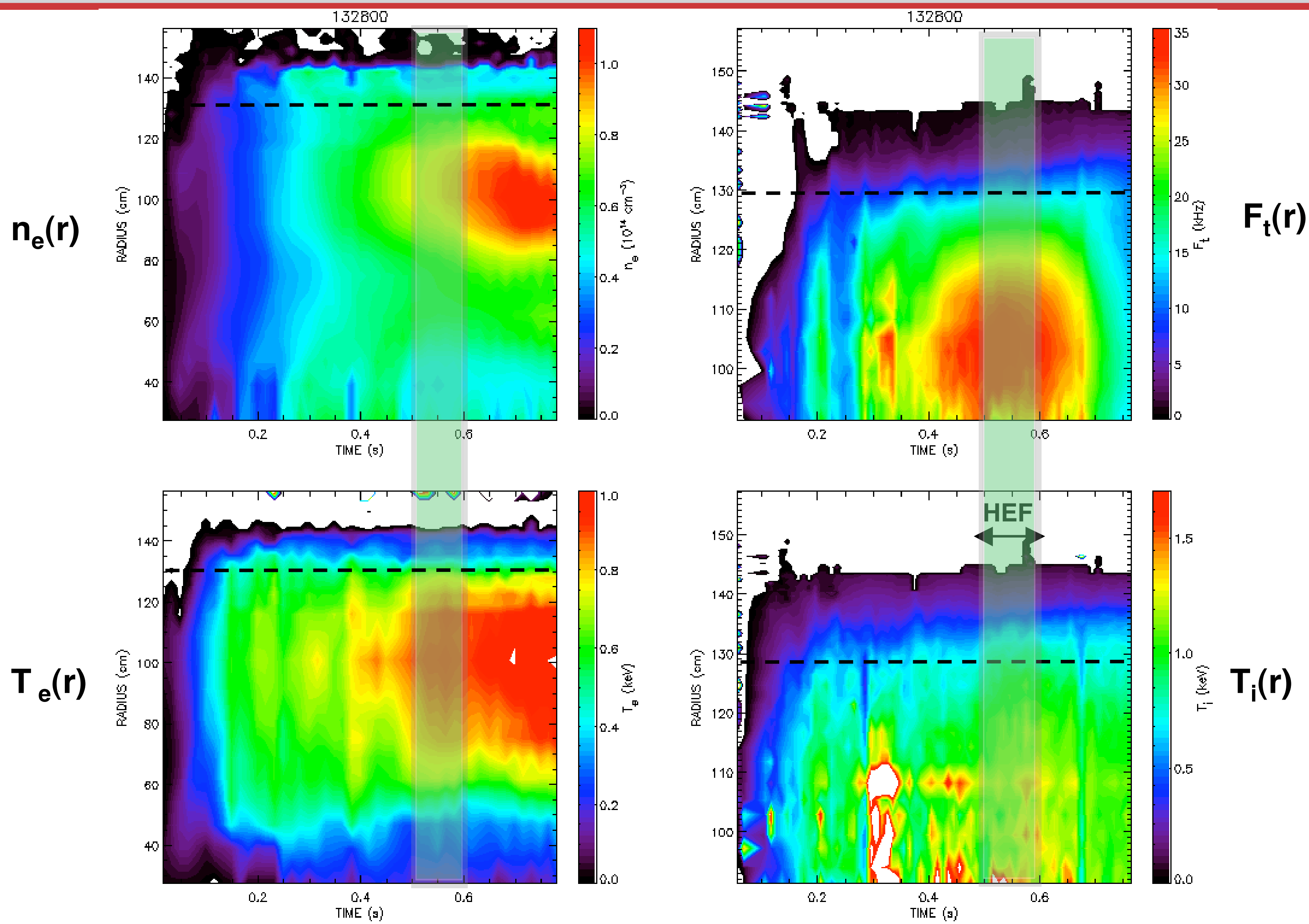




- The NPA charge exchange neutral spectrum exhibits strong depletion from t ~ 200 - 600 ms in the energy range $E/2 \leq E < E_b$, but not *at* E_b.

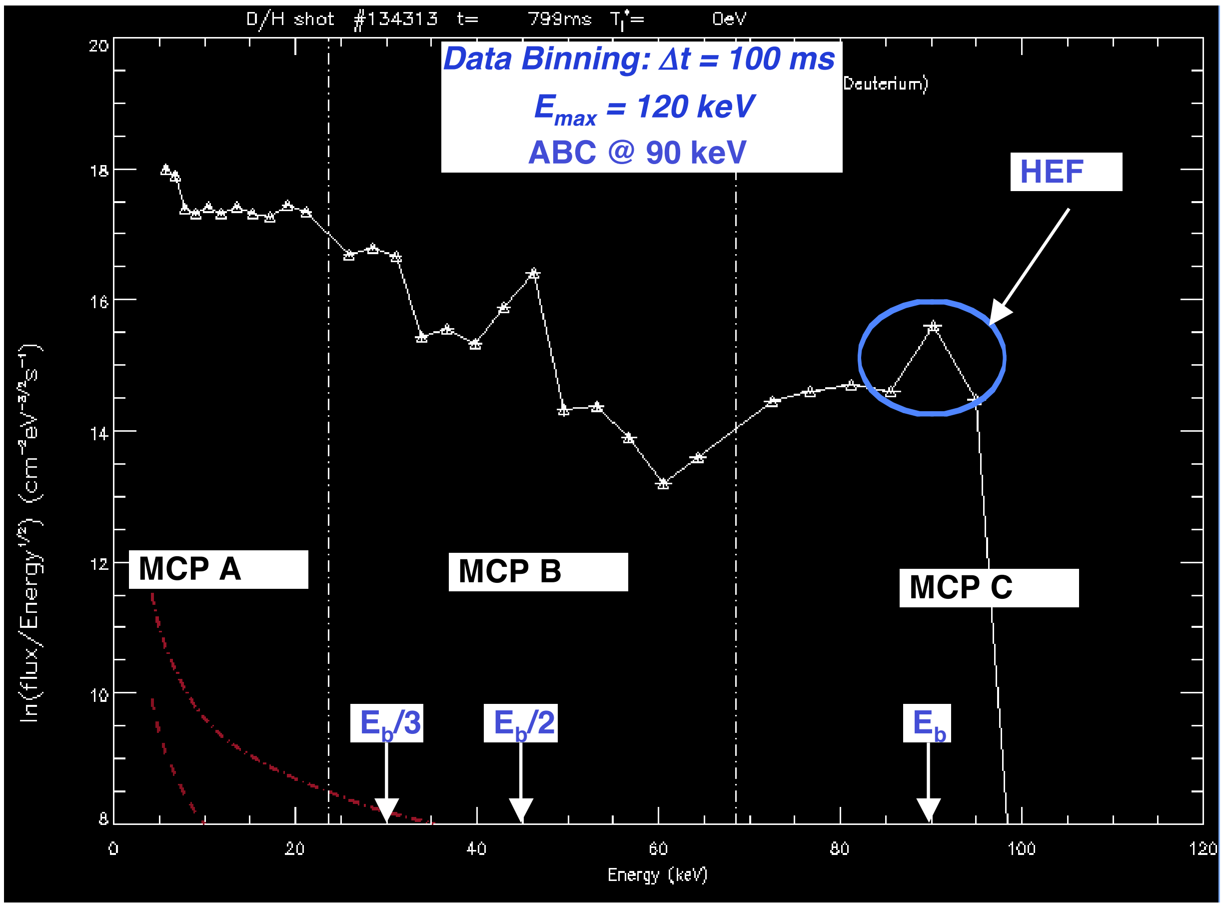
Does HEF Drive Changes in Temperature or Density Profiles?

- broadening of $T_i(r)$ at R_{maj} ~ 130 cm (---), but not for other profiles



The High-Energy Feature is not a NPA Instrumental Artifact

H-mode with I_p = 0.9 MA, B_T = 4.5 kG, P_{NB} = 6 MW, n_eL ~ $6x10^{13}$ cm^{-2}



- **SN134313: HEF appears on Anode # 31 @ 90 keV.**

Rough Correlation Between NPA Rise-time and Flux Increase For HEF Events