NSTX

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

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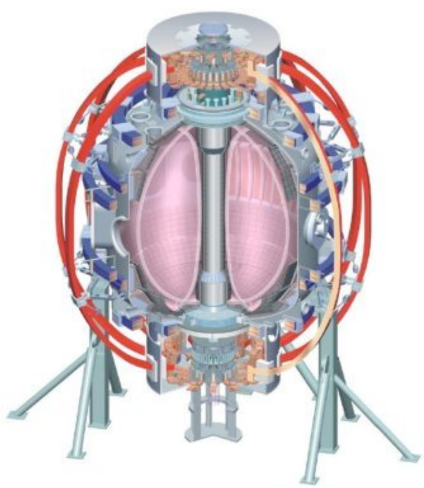
51st Annual APS-DPP Physics Meeting
November 2 - 6, 2009
Atlanta, GA



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Abstract

Observation of ' Anomalous' Energetic Ion Spectra by the EIIB Neutral Particle Analyzer o n NSTX, S. S. Medley, R. E. Bell, D . S. Darrow, E. D. Fredrickson, N. N. Gorelenkov, B. P. LeBlanc, A. L. Roquemore (PPPL), M. Podesta (UC Irvine) – An 'anomalous' increase in EIIB NPA charge exchange neutral flux (~4x) localized at the neutral beam(NB) injection full energy, E_b = 90 keV, is observed in NSTX. This so-called 'High-Energy Feature (HEF)' appears in discharges only when kink-type modes (f < 10 kHz) are absent, TAE activity (f ~ 10-150 kHz) is weak (δB_{rms} < 75 mGauss) and CAE activity (f ~ 400 – 1200 kHz) is robust. The HEF exhibits a growth time of ~ 20-80 ms and develops a slowing down distribution that evolves over 100-400 ms, a time scale long compared with the ~ 50 ms equilib ration time of the NB injected particles. Increases of ~ 10-30% in the measured neutron yield a nd total stored energy are observed to coincide with the HEF alo ng with broadening of the CHERS $T_i(r)$ profile. The HEF is observed only in H-mode (not L-mode) discharges with injected NB power above 4 MW and is suppressed by vessel conditioning using lithium deposition at rates ~ 100 mg/shot sufficient to suppress ELM activity. Though a d efinitive mechanism has yet to be developed, the HEF appears to be driven by a form of CAE resonance.

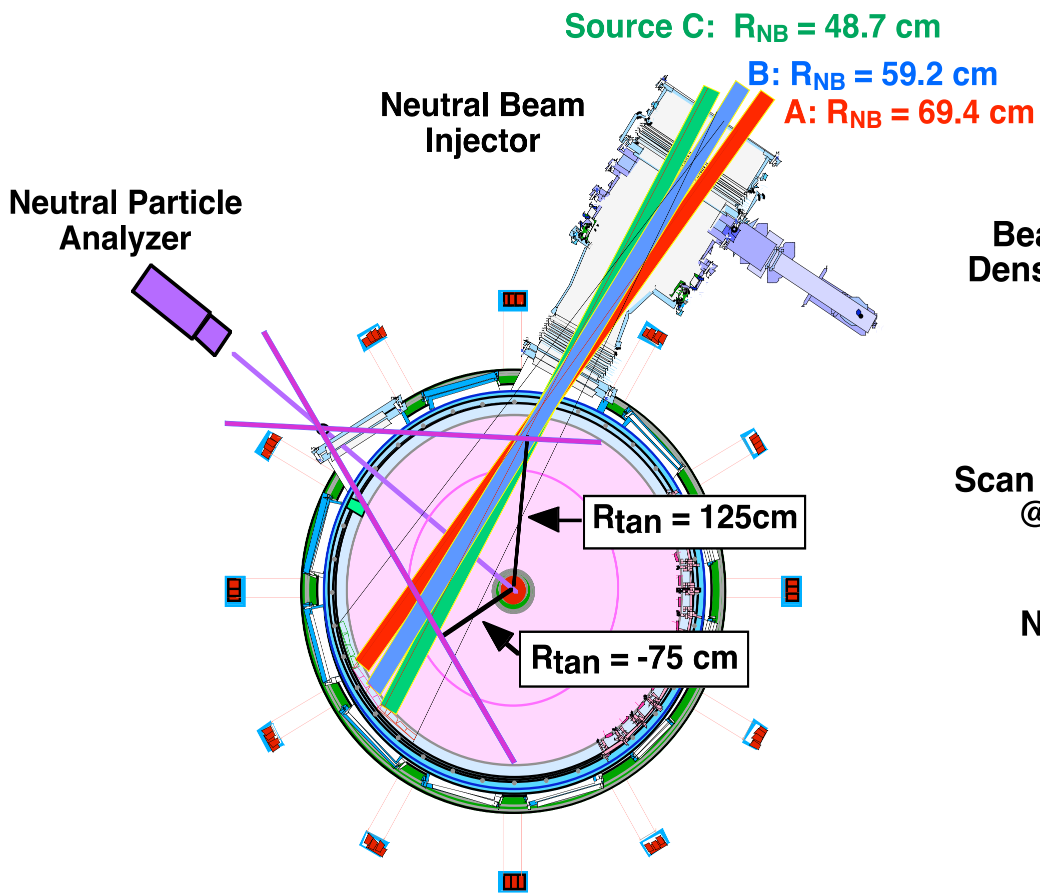
Work supported by US-DOE contract DE-AC02-09CH11466.

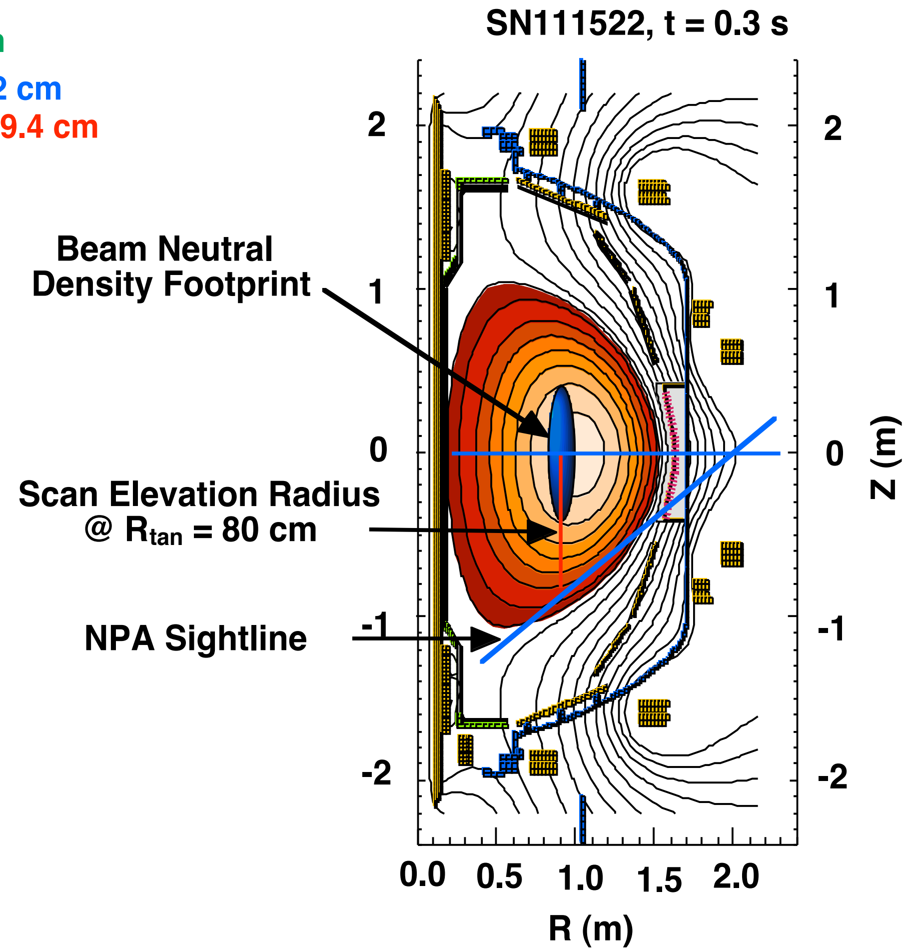
High-Energy Feature (HEF)

A strong increase (~ 3x) in the EIIB 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.

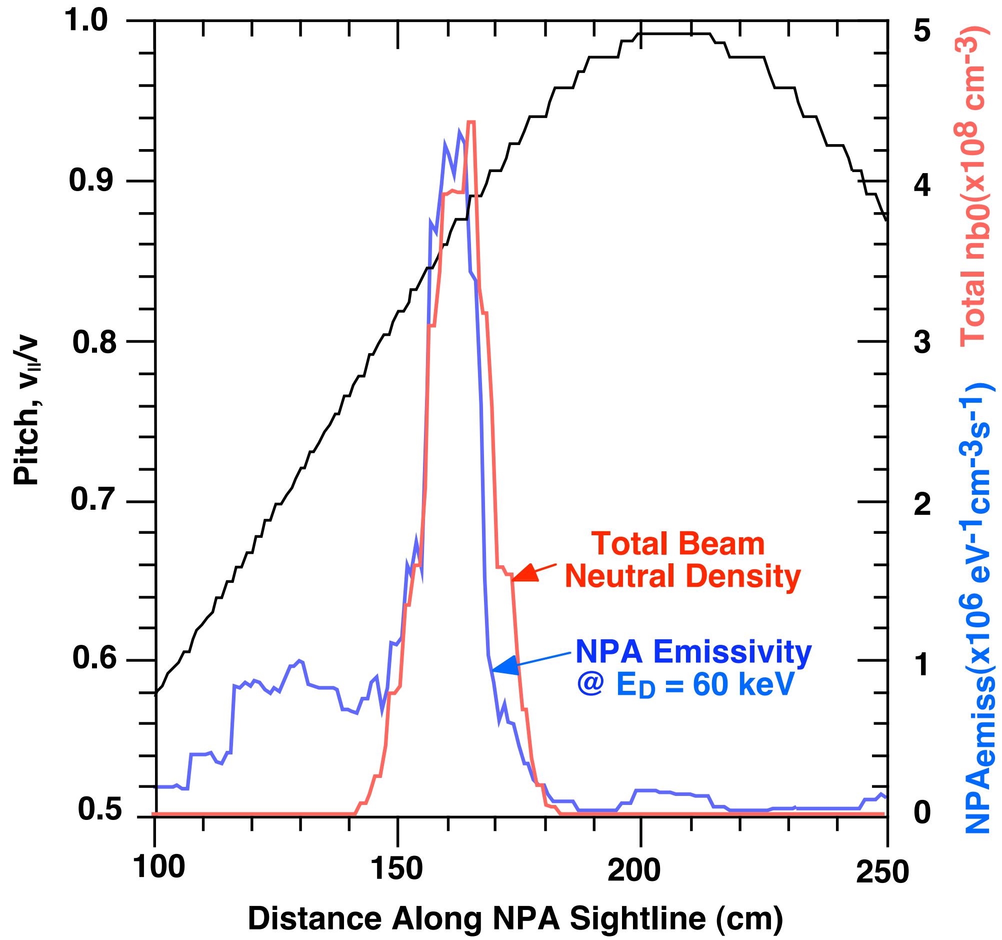
The Neutral Particle Analyzer (NPA) on NSTX Scans Horizontally and/or Vertically on a Shot-to-Shot Basis

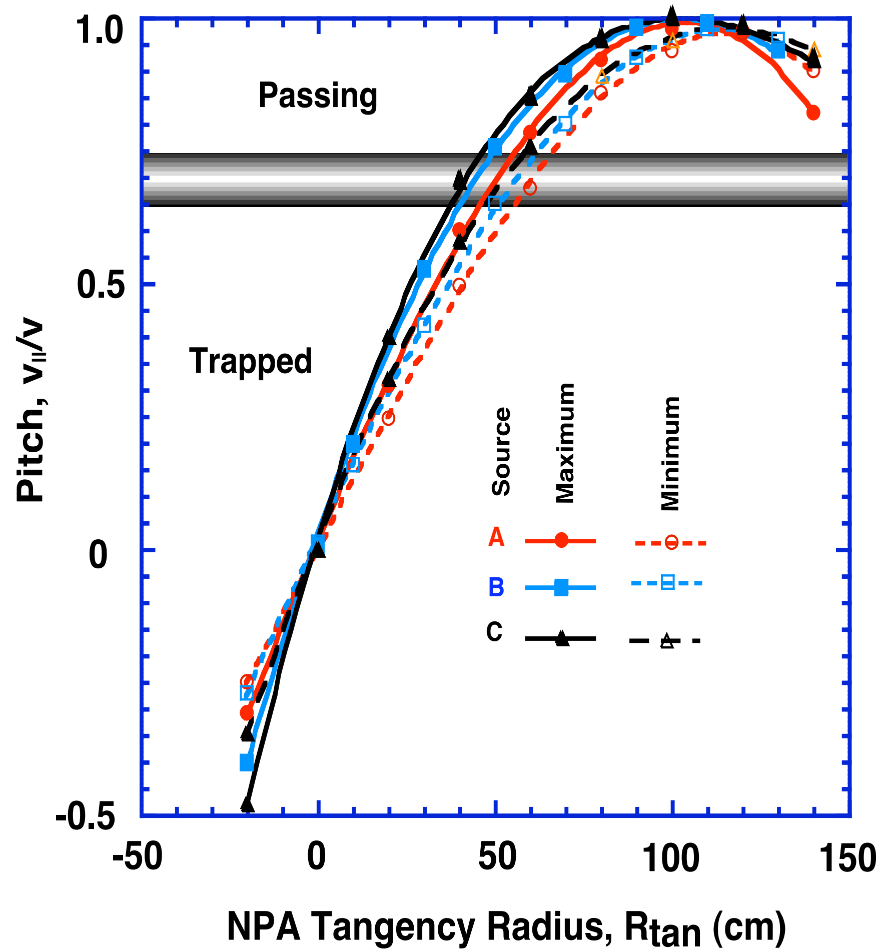




- Intersection of NPA sightline with beam neutrals spatially localizes the charge exchange flux measurement with a spatial resolution of $\Delta R \sim 20$ cm and $\Delta Z \sim 3$ cm.

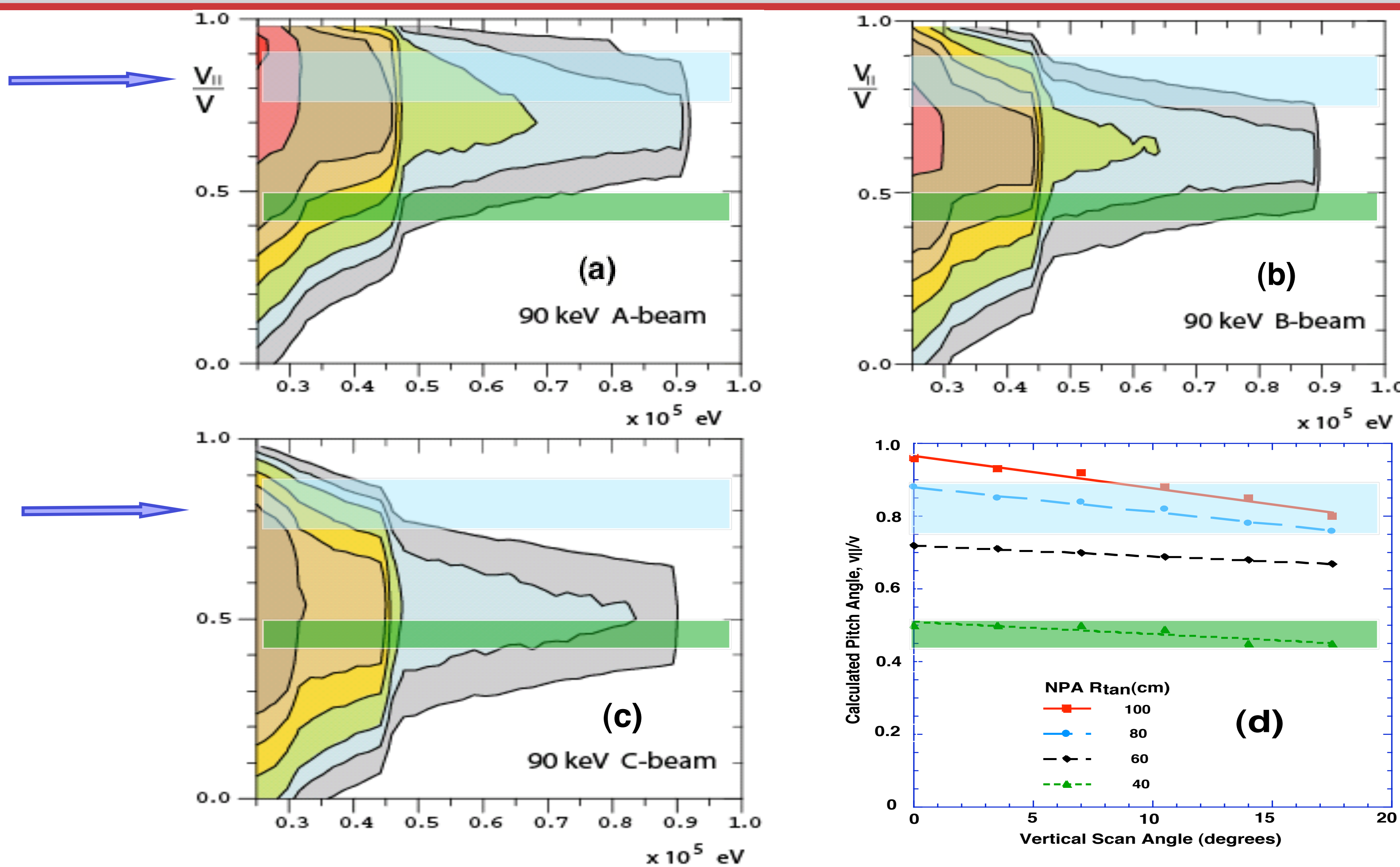
The Pitch Angle Viewed by the NPA is Localized by the Sightline/NB Intersection Region





• The pitch angle viewed by the NPA depends on the sightline R_{tan} and has a resolution of $v_{||}/v \sim 0.1$.

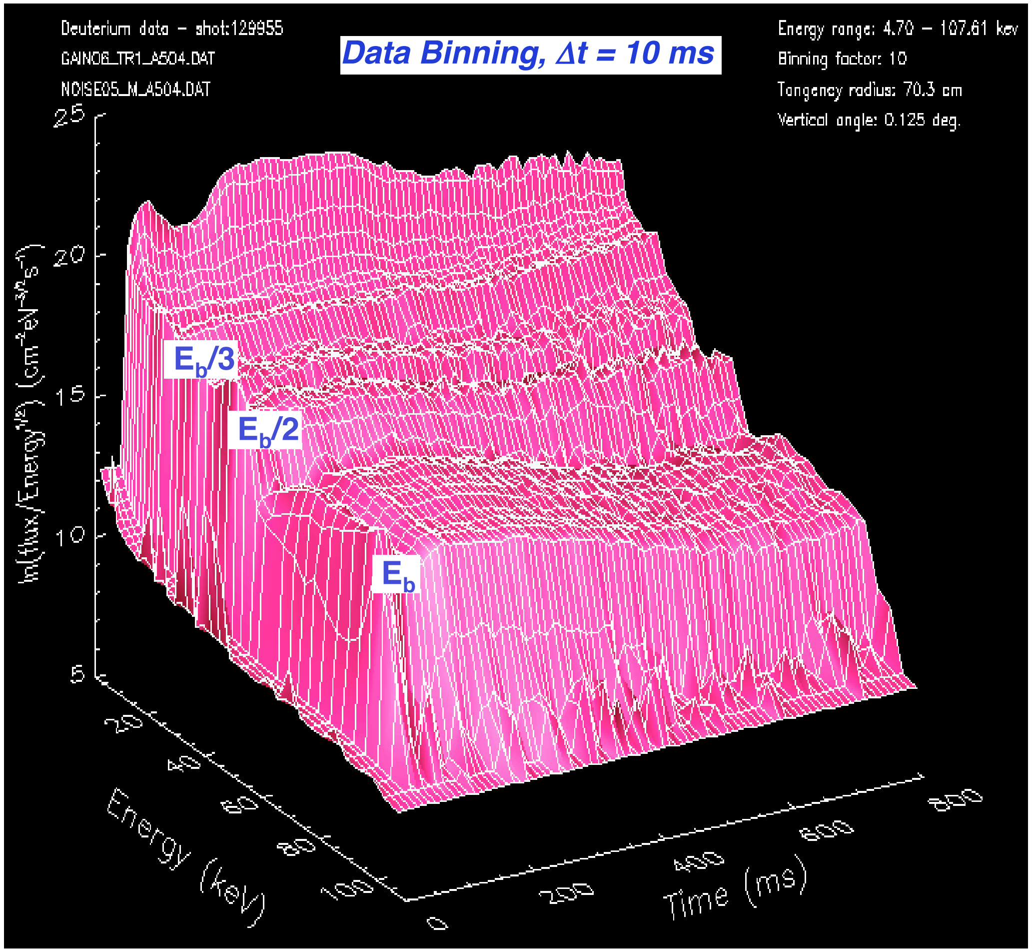
The Pitch Angle, $v_{||}/v$, Viewed by the NPA Depends on Both the Horizontal and Vertical Sightline Setting

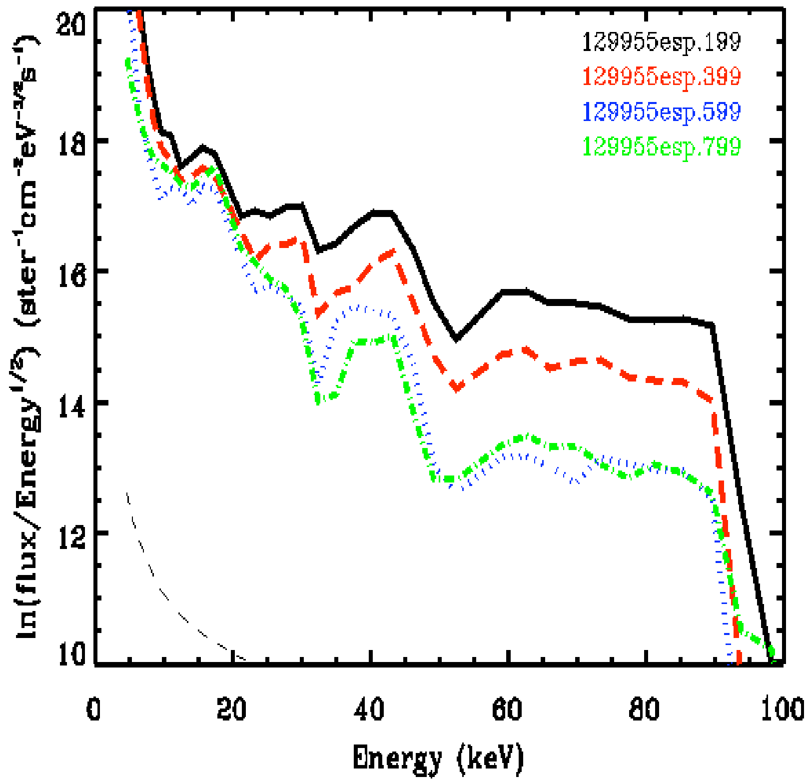


- For **'typical' Rtan ~ 70 - 80 cm,** **the NPA views passing ions with $v_{||}/v$ ~ 0.80 ± 0.1.**

‘Normal’ 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, $n_eL \sim 4 \times 10^{13}$ cm^{-2}

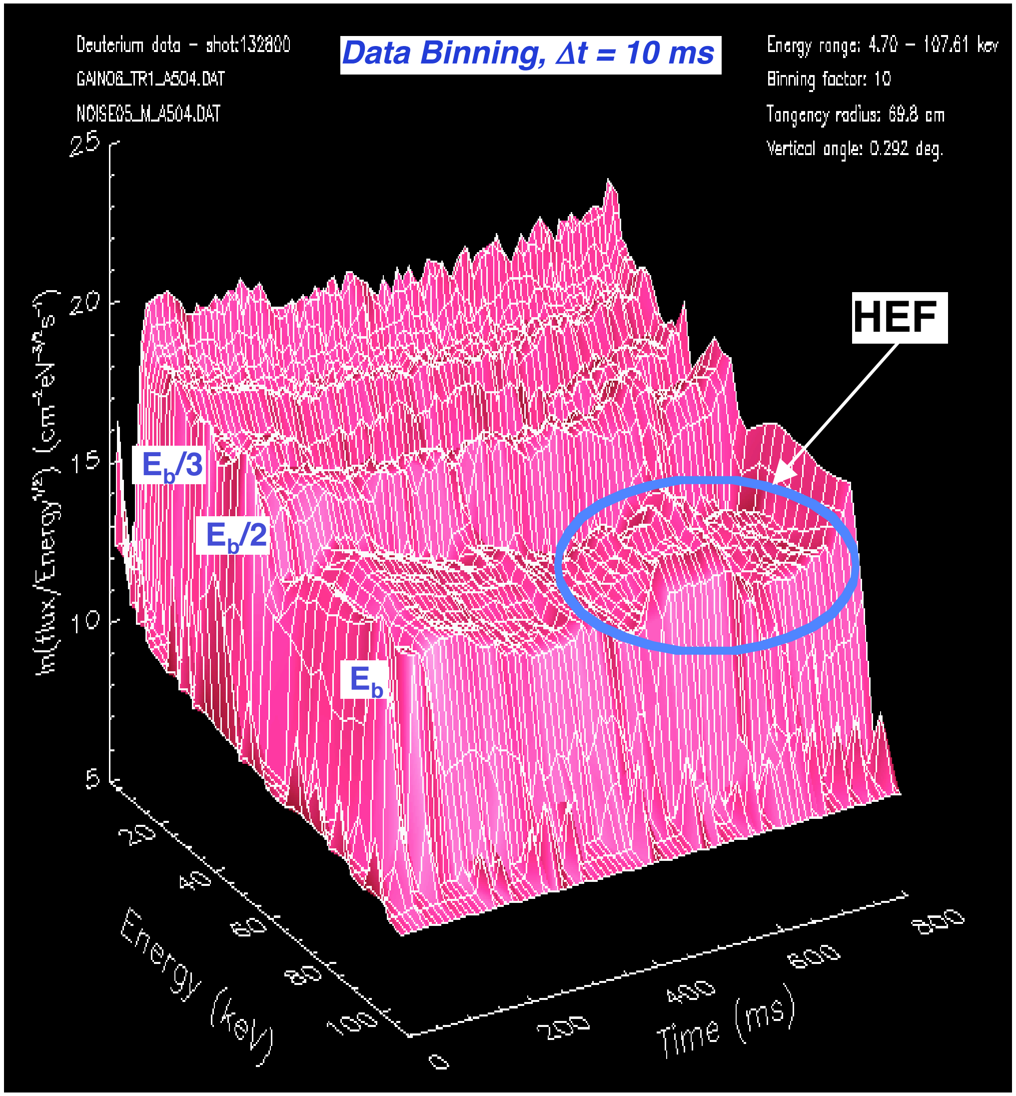


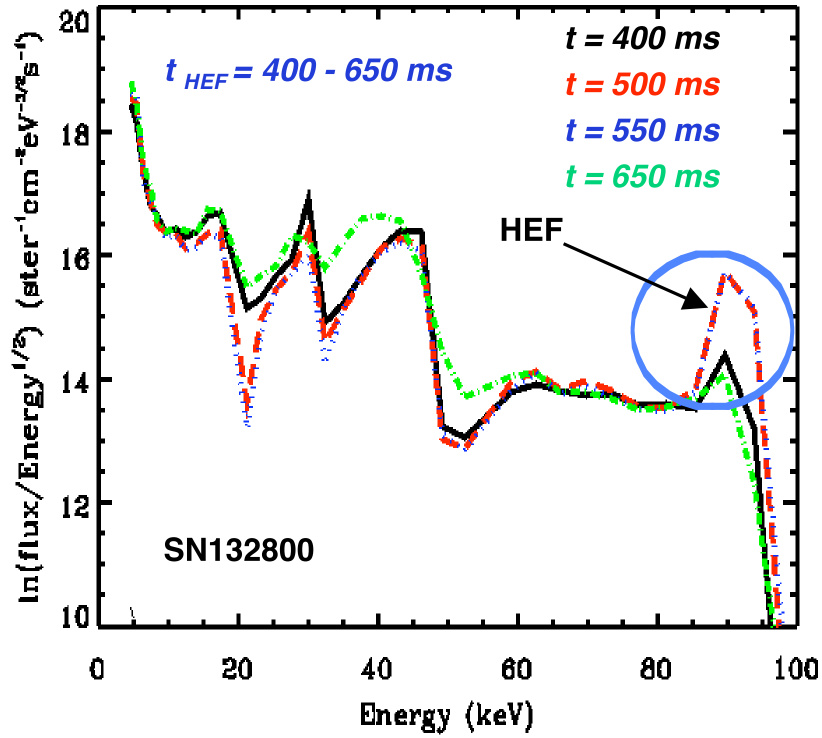


- **Depletion of the NPA spectrum in the range $E_b/2 \leq E \leq E_b$ by ~ 3 e-foldings is due to the combined effects of n_e ramp-up and MHD-induced energetic ion redistribution.**

Illustration of a ‘Brief’ 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, $n_eL \sim 6 \times 10^{13}$ cm^{-2}

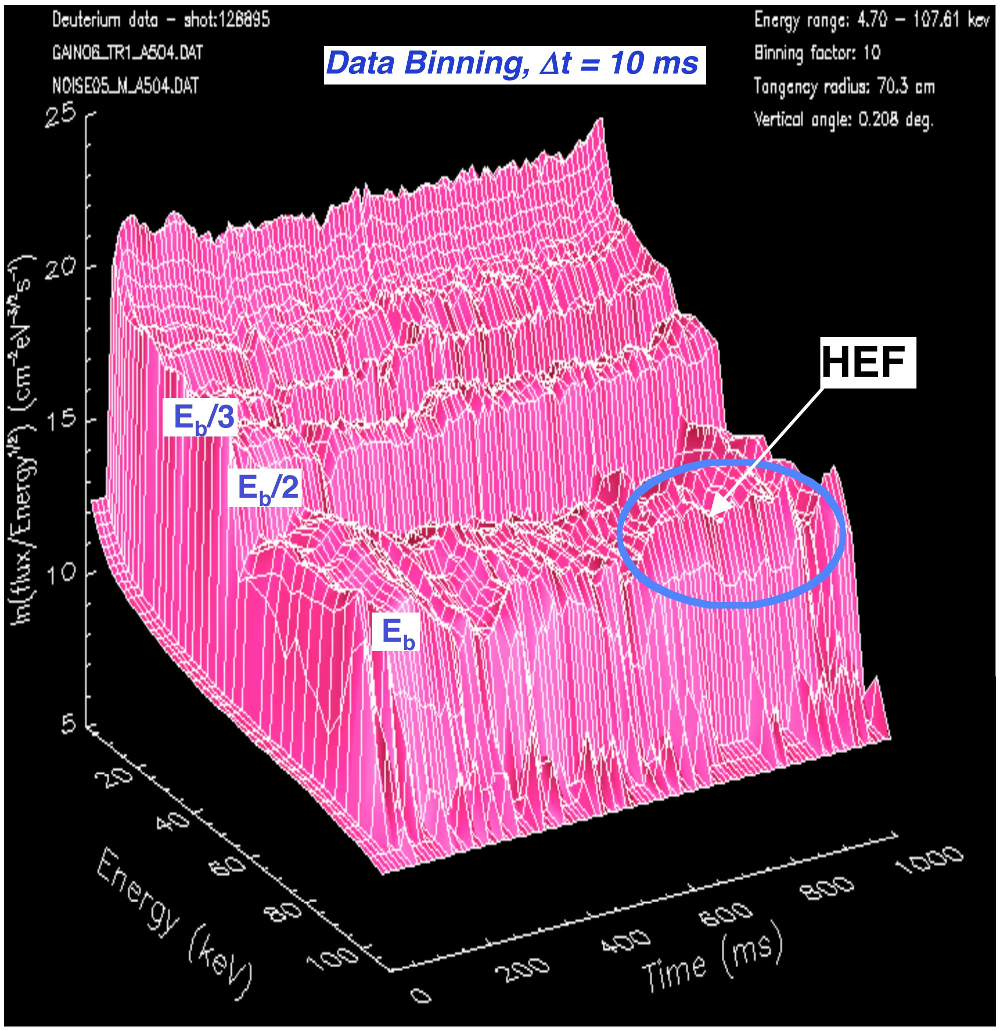


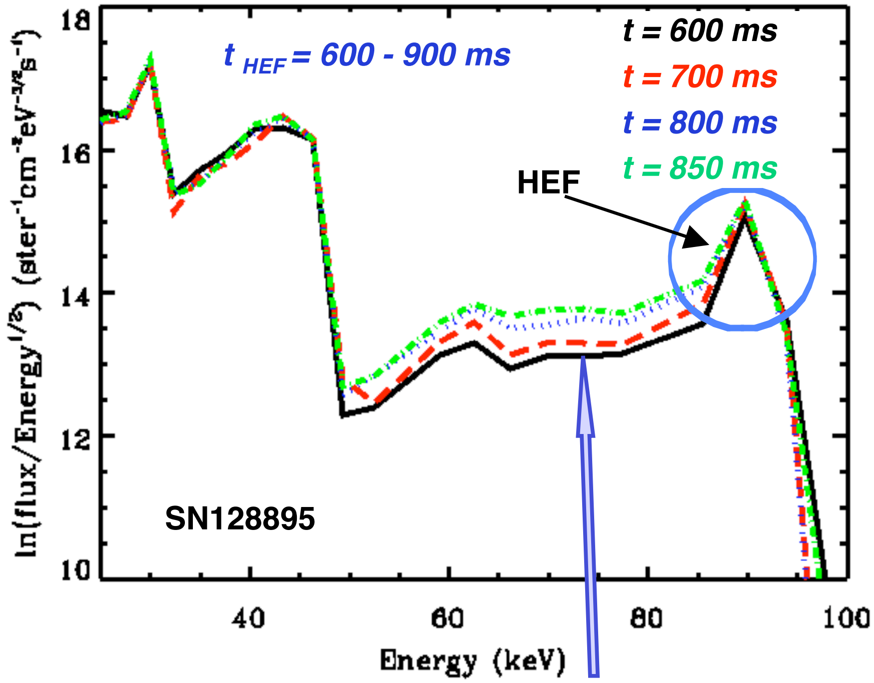


- NPA charge exchange spectrum exhibits enhanced signal only near E ~ E_b (e.g. never at $E_b/2$ or $E_b/3$).
- ‘Transient’ HEF periods can last for 100’s of milliseconds in some shots.

Illustration of a 'Long' High-Energy Feature (HEF) at t ~ 0.6-0.9 s

H-mode with I_p = 1.2 MA, B_T = 4.5 kG, AB&C @ 90 keV, P_{NB} = 6 MW, $n_eL \sim 6.6\times10^{13}$ cm^{-2}



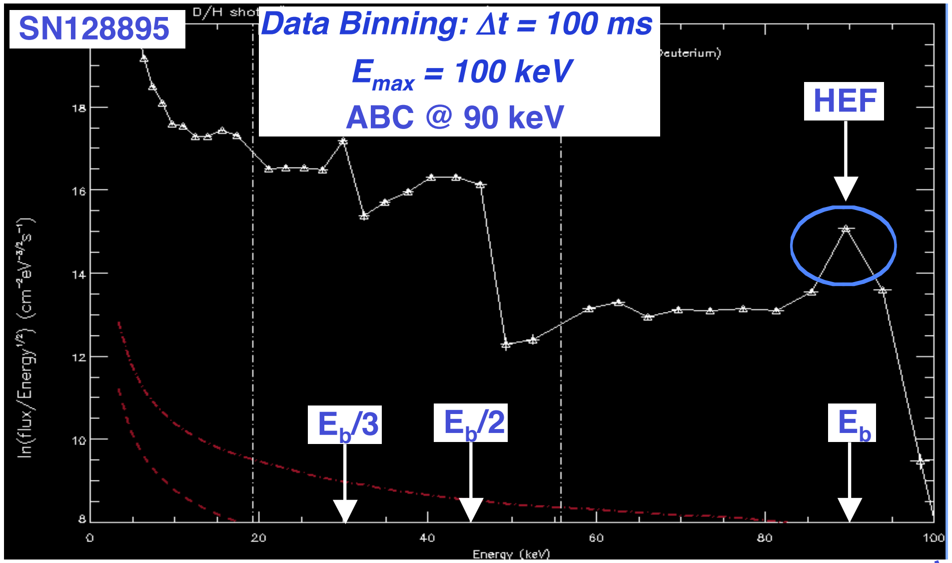


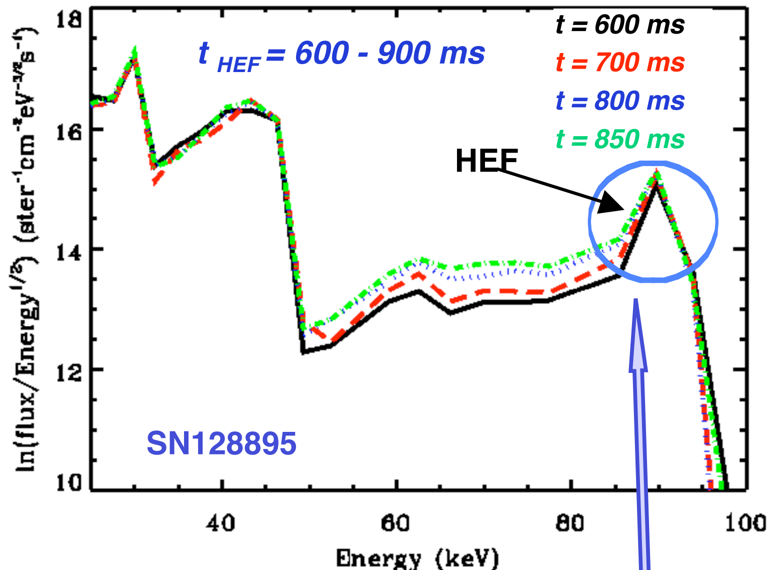
- Spectrum exhibits **strong slowing down** of fast ions from the HEF energy region.
- The slowing down distribution continues to grow over a period of 300 ms.

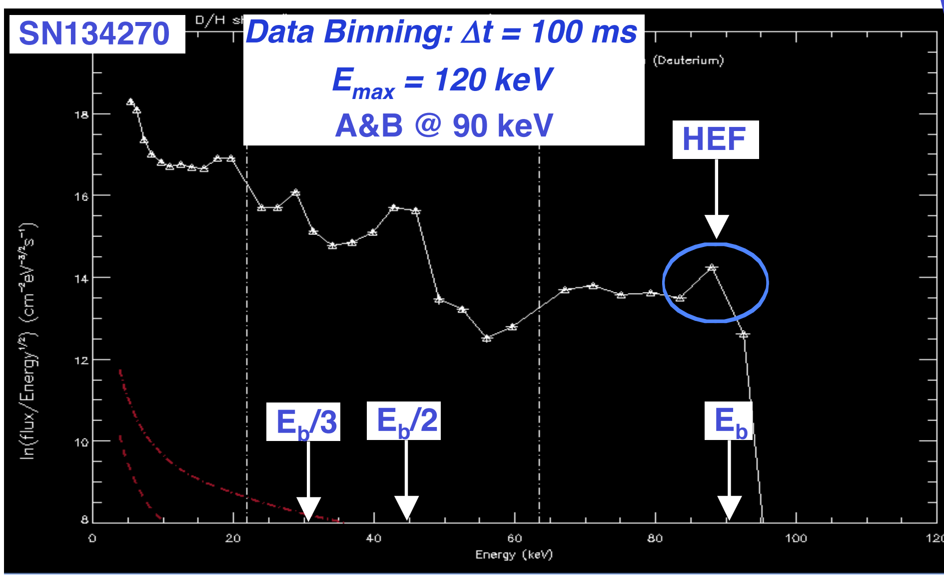
- SN128895: HEF appears only on **Anode # 35 @ 90 keV.**

The High-Energy Feature is not a NPA Instrumental Artifact

H-mode with I_p = 1.2 MA, B_T = 4.5 kG, P_{NB} = 6 MW, n_eL ~7×10^{13} cm^{-2}







- Spectrum exhibits slowing down of fast ions from the HEF energy region.
- Slowing down continues to evolve over the duration of the HEF: ~ 300 ms.

- HEF appears on Anode # 35 @ 90 keV.

- HEF appears on Anode # 32 @ 90 keV.

Overview of High-E Feature Observations

- tabulation details are discussed in subsequent viewgraphs

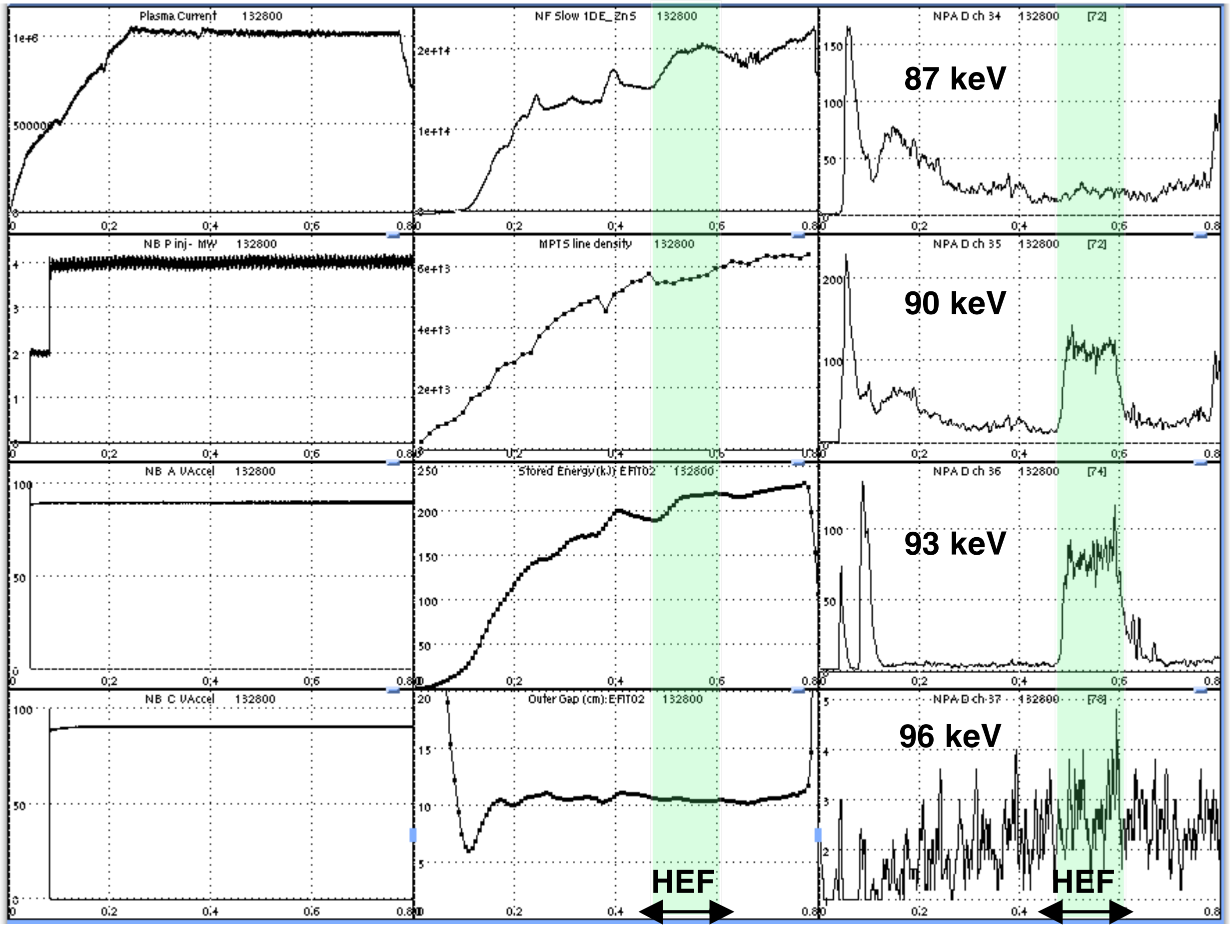
			← MHD Activity →					← MPTS/CHERS Profiles →						
Shot	High-E	Δt(s)	TAE	Kink	CAE	δB_{TAE}	δB_{CAE}	$\Delta T_e(r)$	$\Delta n_e(r)$	$\Delta T_i(r)$	$\Delta v_\phi(r)$	ΔZ_{eff}	$\Delta S_n(\%)$	ΔW(%)
127216	√	0.50-0.75	x	x	√	20	0.7	x	x	14	41	-12	14	9
127217	√	0.50-0.65	x	x	√	30	0.8	x	x	17	20	0	10	10
*127221	√	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}

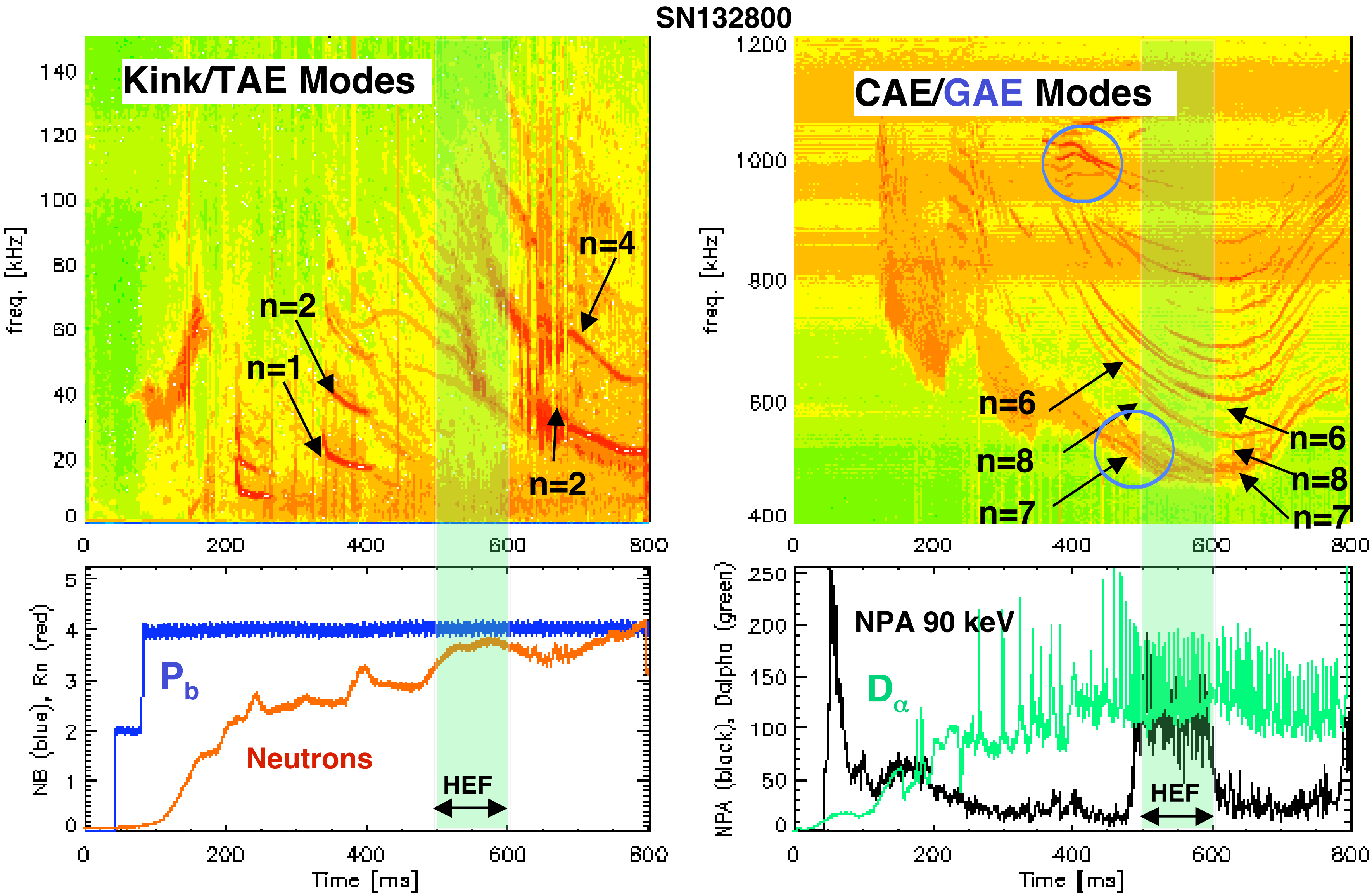
Shot	High-E	Δt(s)	R_{tan}(cm)
127216	√	0.50-0.75	71
127217	√	0.50-0.65	71
*127221	√	0.45-0.80	71
127222	√	0.50-0.70	71
127236	√	0.45-0.67	71
127252	weak	0.43-0.58	71
*127253	√	0.35-0.63	71
127254	√	0.24-0.52	55
127256	√	0.43-0.54	65
127723	√	0.48-0.73	78
*127953	weak	0.55-0.80	86
*127957	√	0.47-0.64	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.**

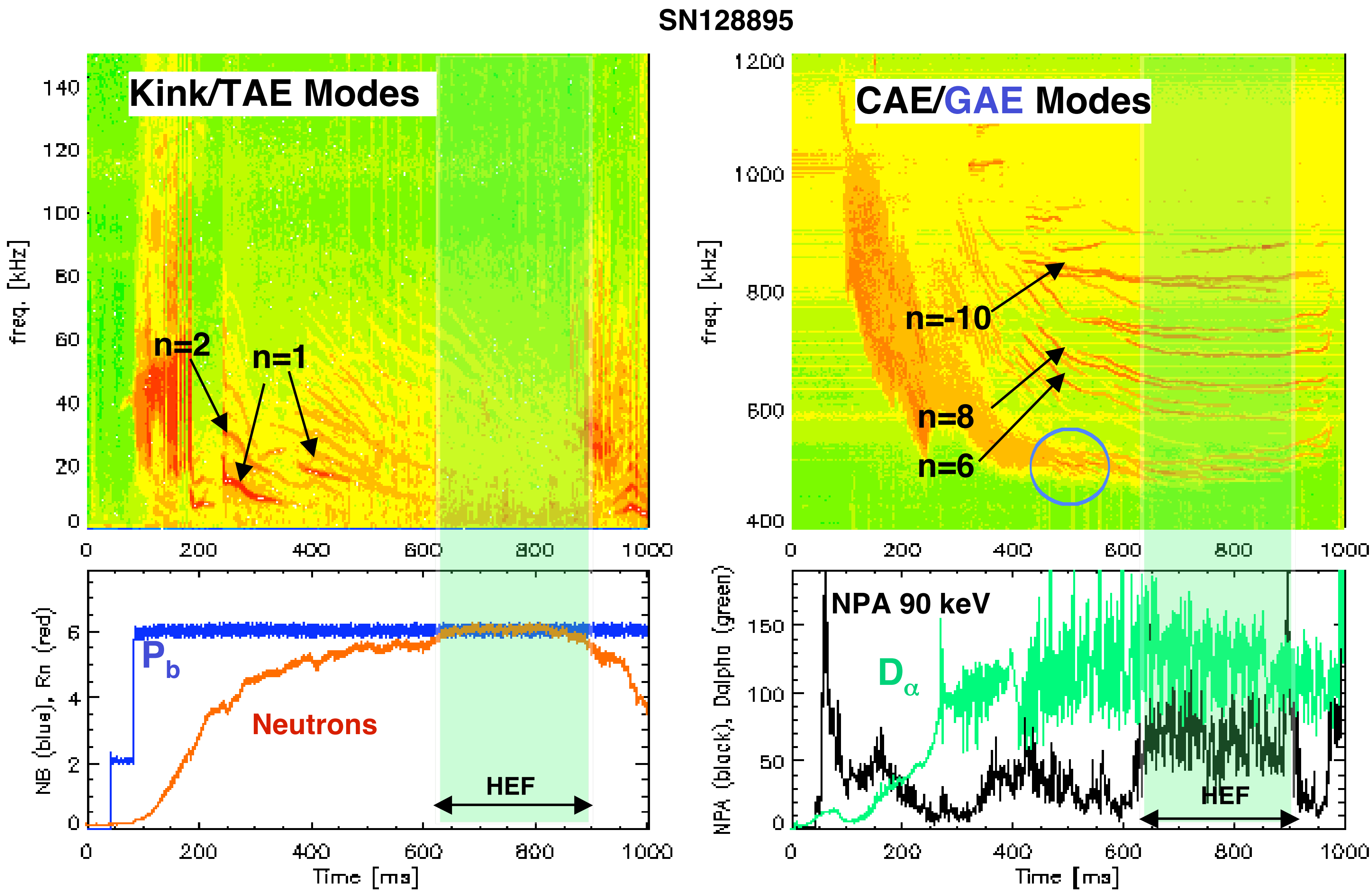
HEF Existence Requires No Kink and Weak TAE MHD Activity

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



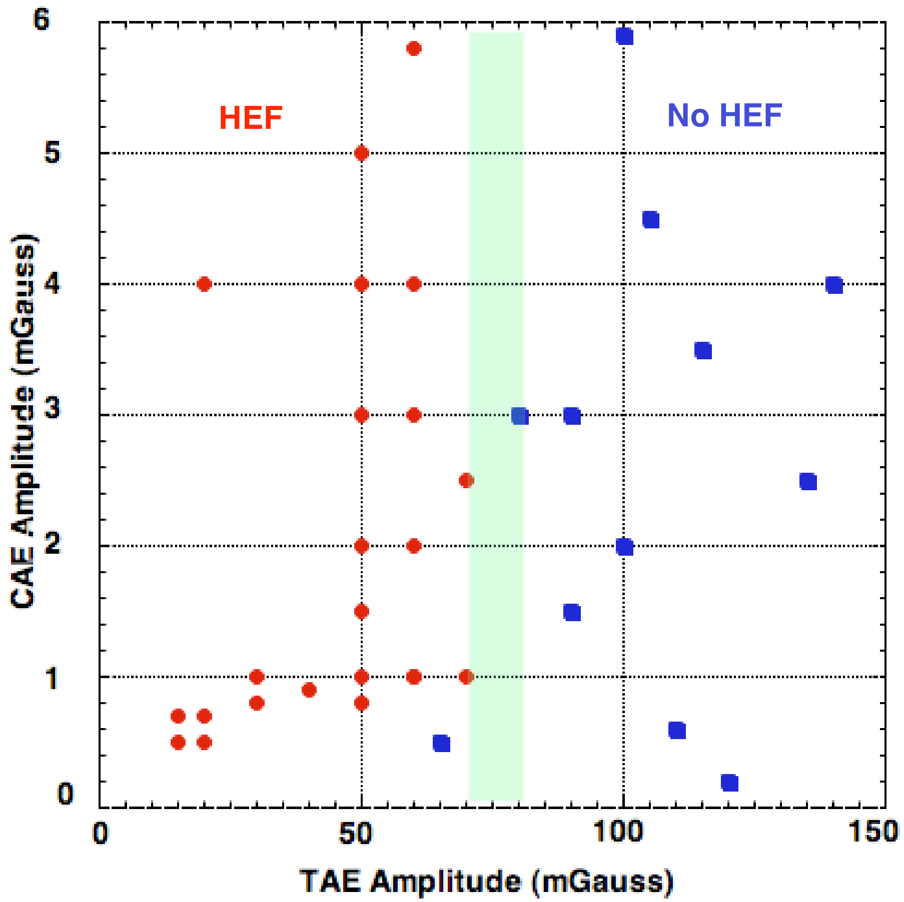
HEF Existence Requires Feeble Kink/TAE MHD Activity: SN128895

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



HEF Exist for TAE Activity Below a δB "Threshold"

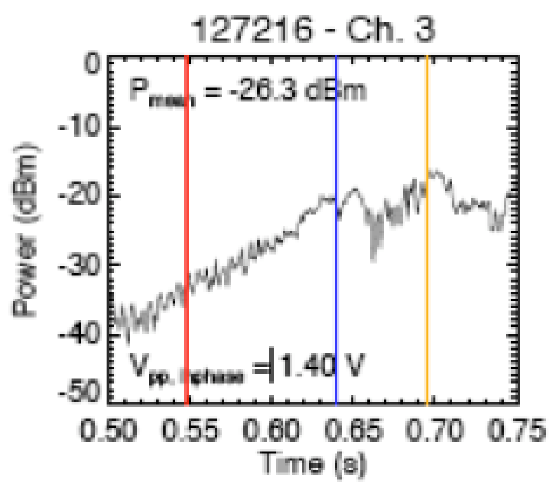
Shot	High-E	TAE	CAE	δB_{TAE}	δB_{CAE}
127216	√	x	√	20	0.7
127217	√	x	√	30	0.8
*127221	√	x	√	40	0.9
127222	√	x	√	30	1.0
127236	√	x	√	50-150	0.8
127252	weak	x	√	60	1.0
*127253	√	x	√	15	0.5
127254	√	x	√	15	0.7
127256	√	x	√	20	0.5
127723	√	x	√	60	1.0
*127953	weak	√	√	70	1.0
*127957	√	√	√	60	1.0
128032	√	√	√	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

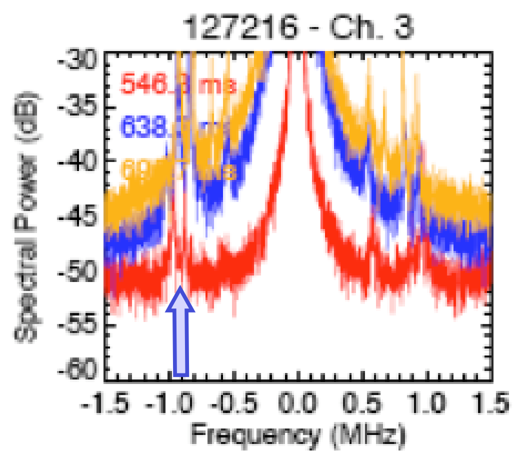


- HEFs occur at *low* TAE activity (δB_{rms} < 75 mGauss) but over a wide range of CAE MHD.

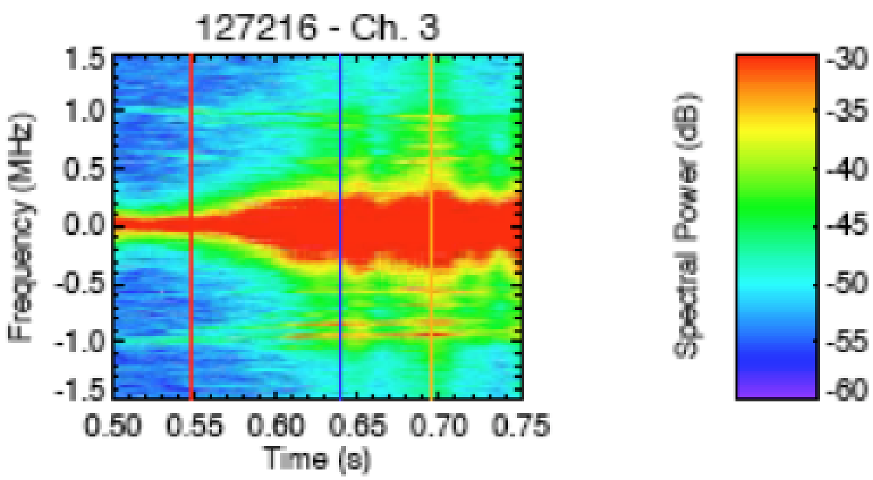
High-k Scattering Shows Density Fluctuation Activity during the HEF

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



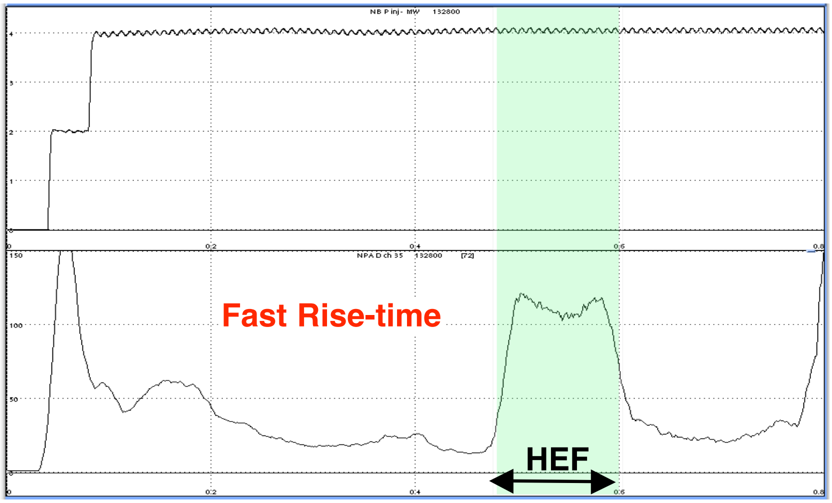
Courtesy of Jeehyun Kim (POSTECH) and K. C. Lee (UC Davis)

- **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.**

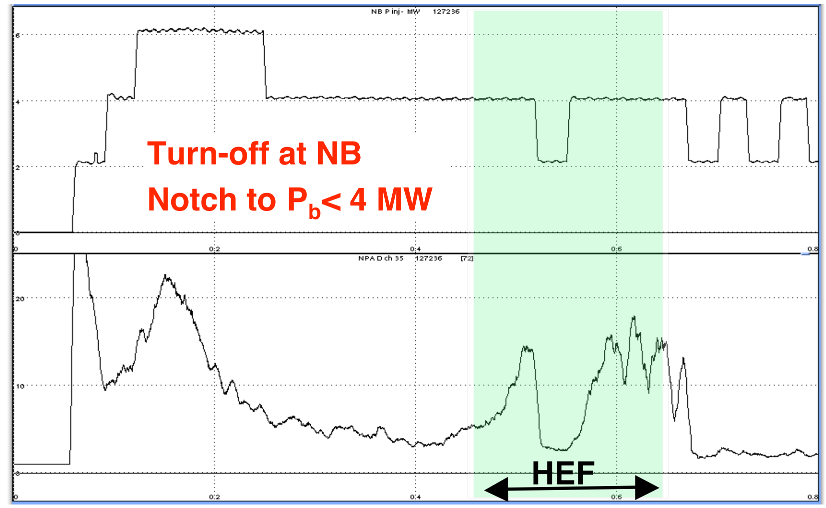
$$\frac{\tilde{n}}{n} = -\frac{\tilde{B}_{\parallel}}{B}$$

HEF Rise-time and Duration Show Considerable Variation

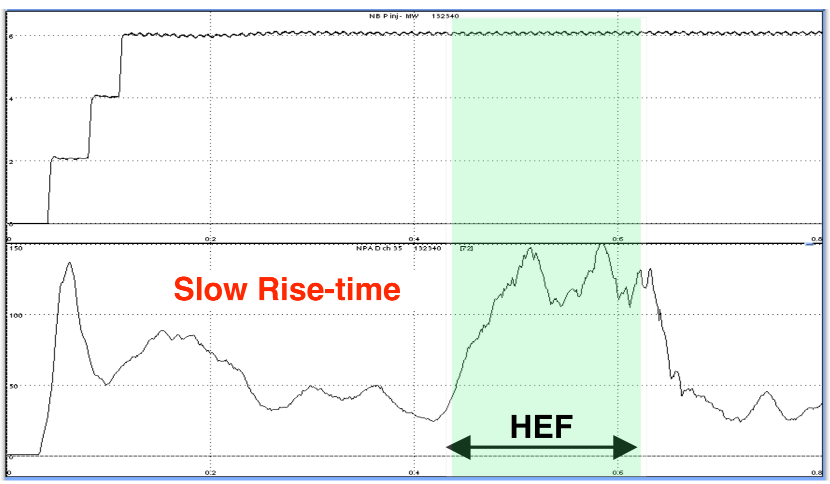
- NPA data at 90 keV



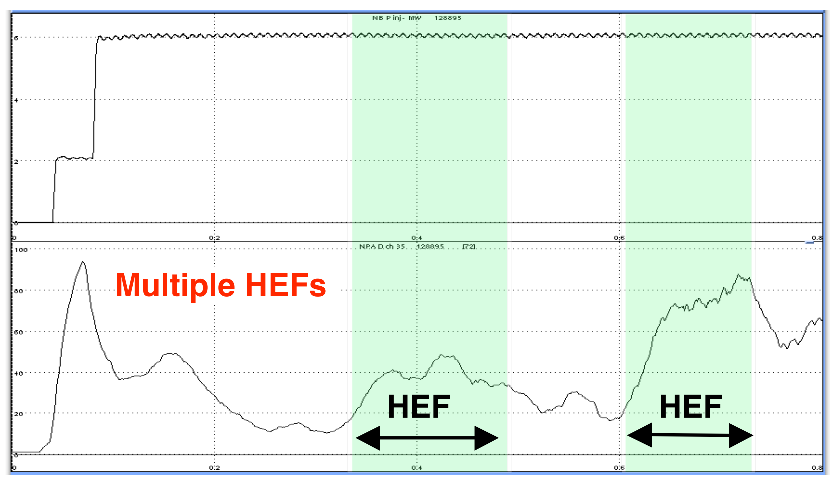
- SN132800, P_b= 4 MW, t_{rise}= 20 ms



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

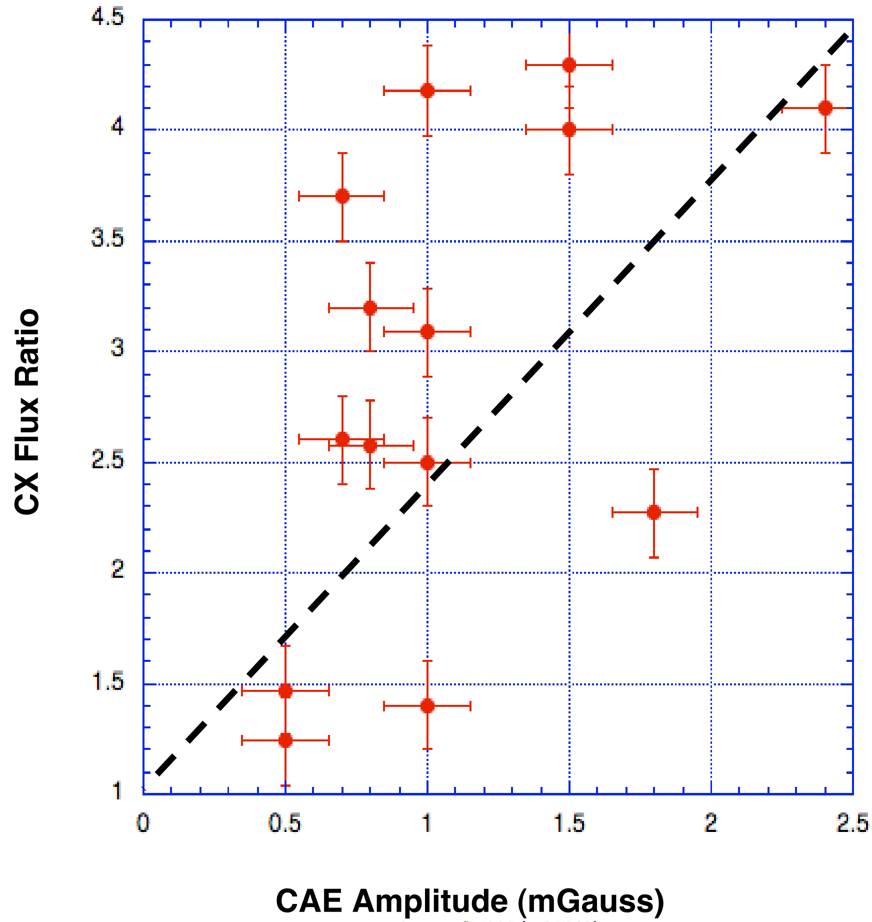


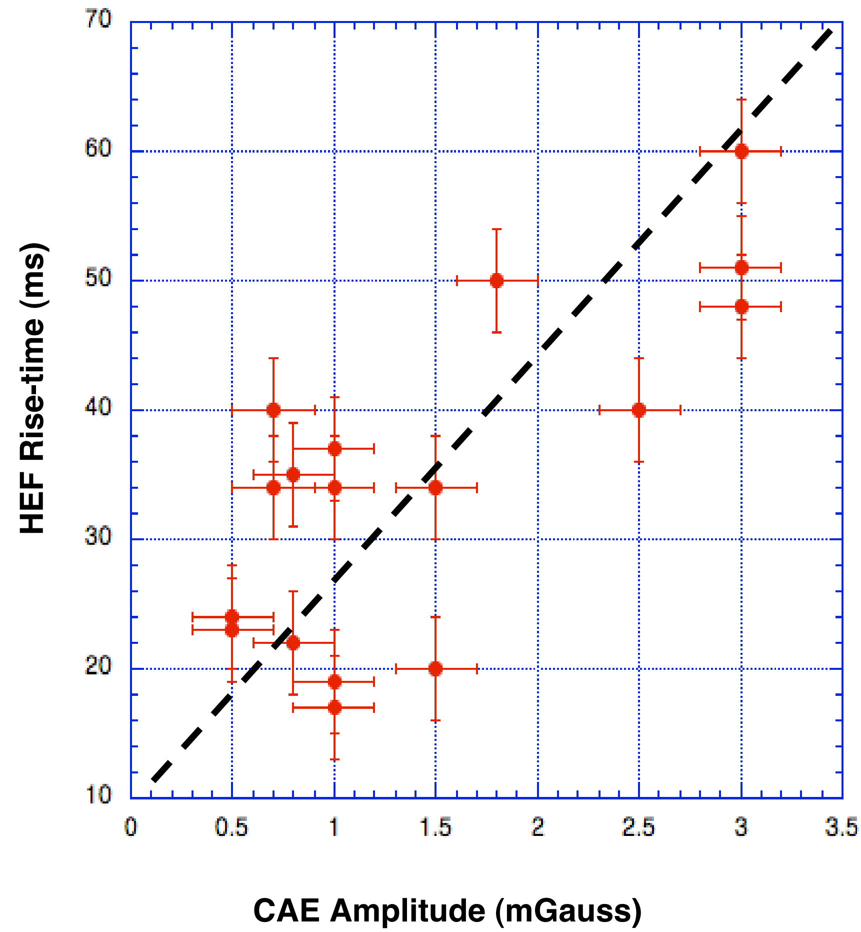
- SN132340, P_b= 6 MW, t_{rise}= 80 ms



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

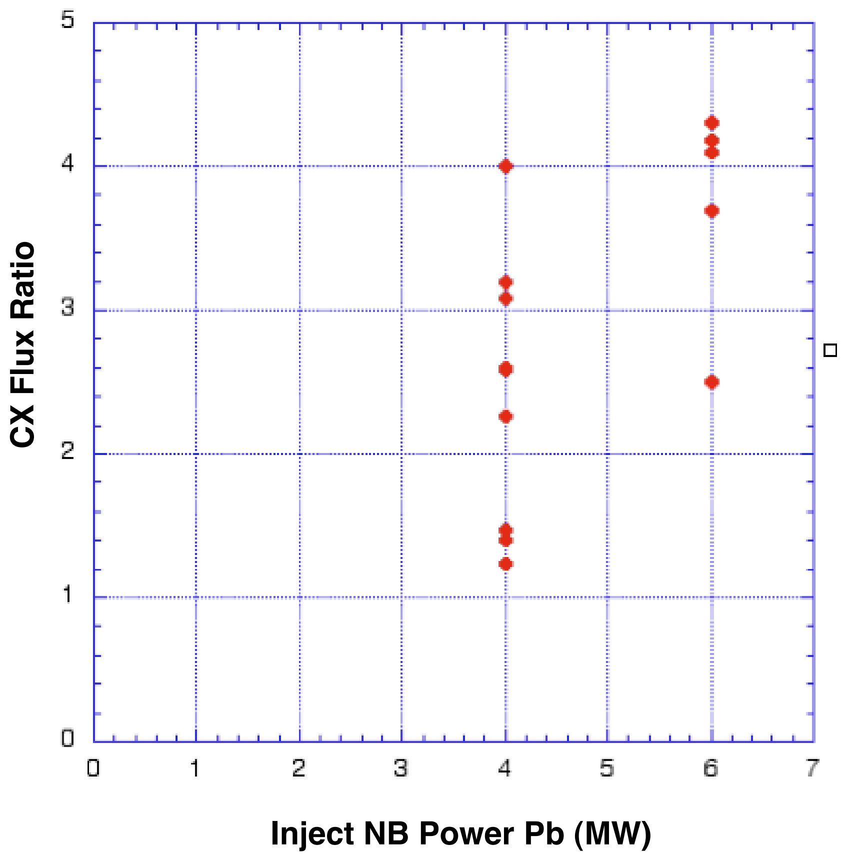
HEF Rise-time and Flux Increase Vary with CAE Strength

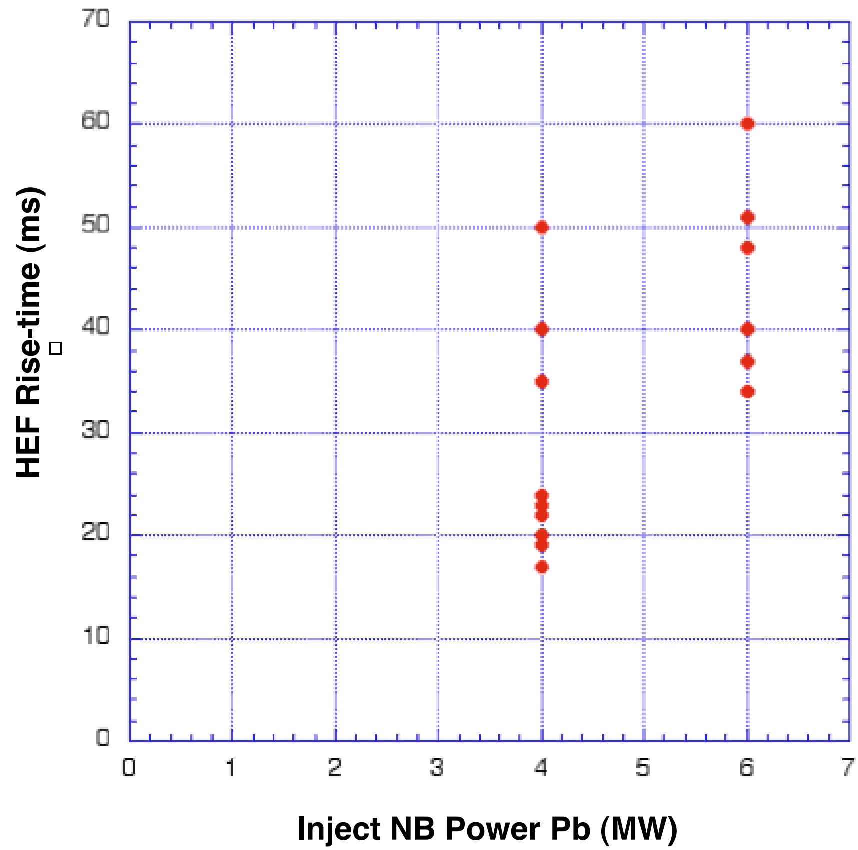




- **HEF rise-time shows correlation with CAE δB_{rms} amplitude, but flux increase less so.**

HEF Rise-time and Flux Increase Variation with NB Power

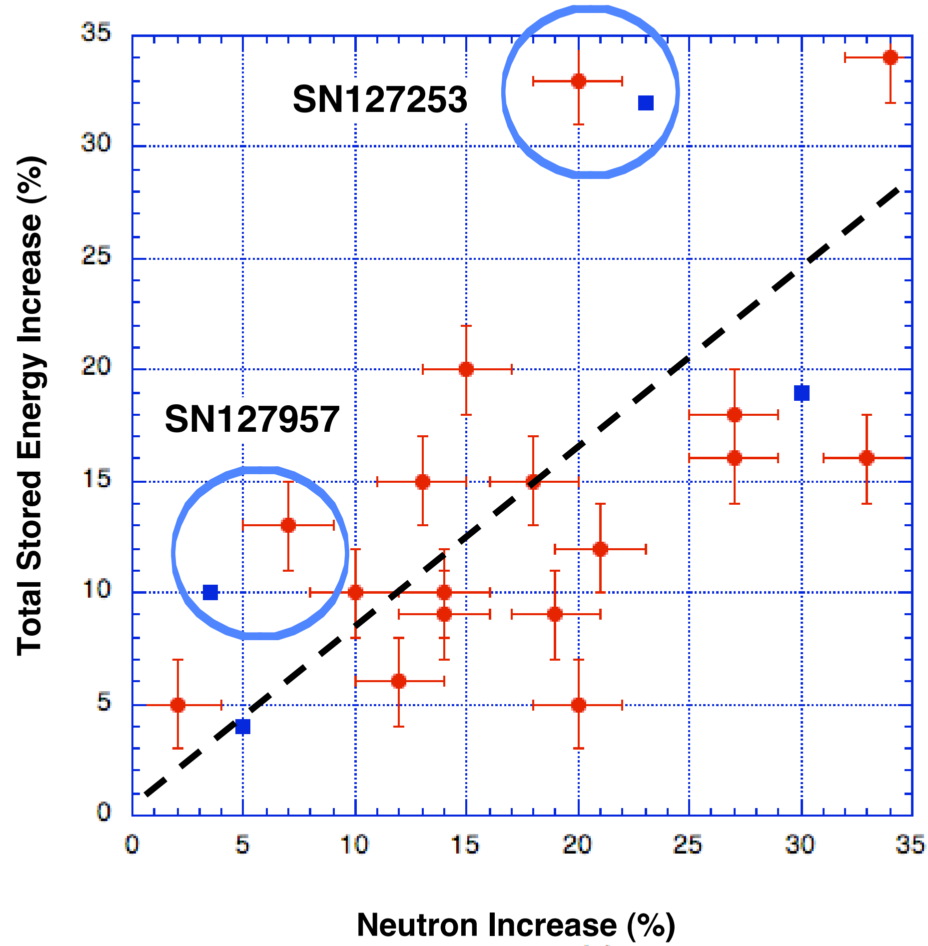




- **The scatter plot suggests a trend towards longer, stronger HEFs with increased P_b.**

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



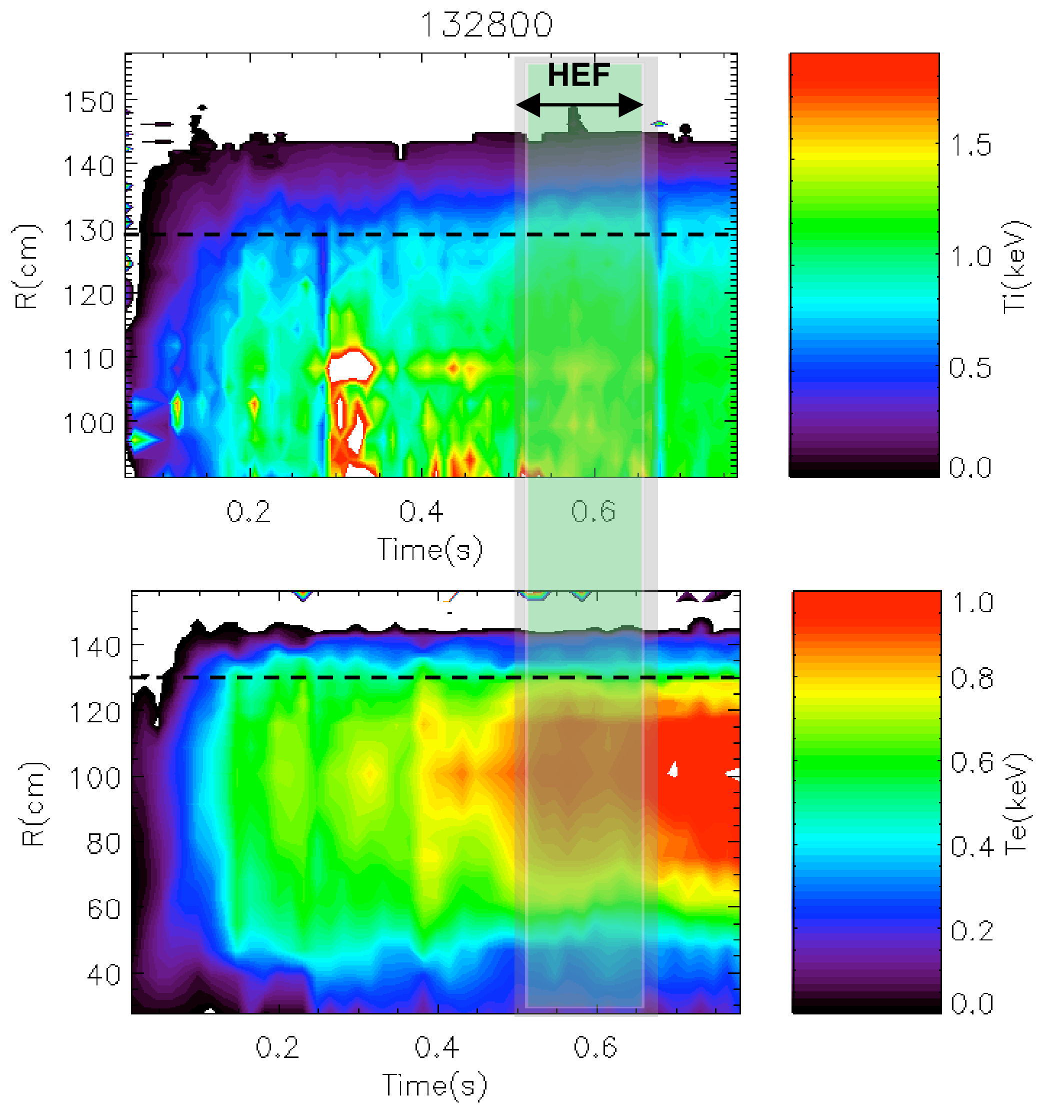
- **The experimental neutron rate and total stored energy increase during the HEF.**
- **Similar increases are observed in *some* TRANSP analyses (blue squares).**

Does HEF Drive Changes in Temperature or Density Profiles?

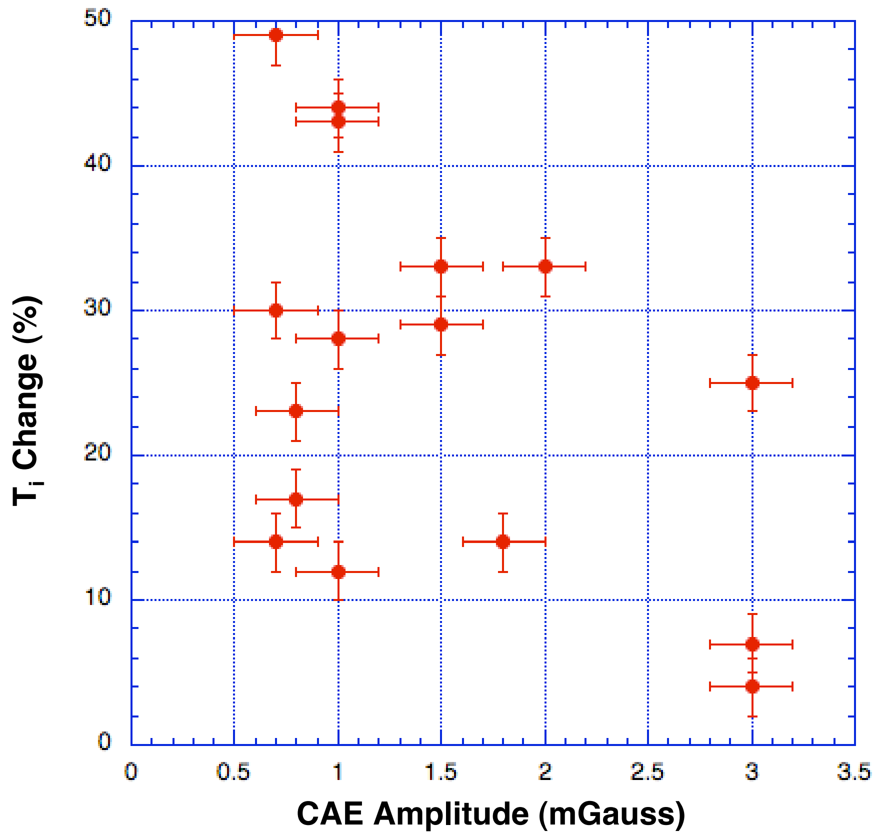
Example shows edge broadening of $T_i(r)$ at R_{maj} ~ 130 cm, but none for $T_e(r)$

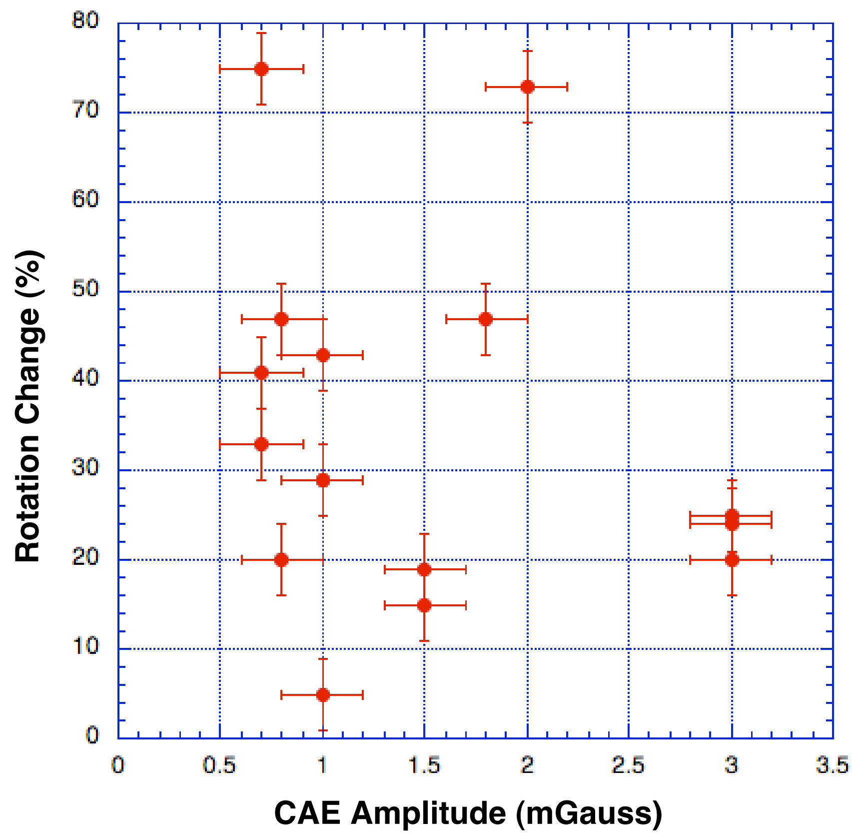
% Change @ R~130 cm

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 'Factiods' 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.

- **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.

Summary of 'Factiods' Related to Observation of HEFs: II

- **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, similar to other energies in 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).

- **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).

Physical Explanation of the High-Energy Feature?

(…with acknowledgments to Herb Berk and Nikolai Gorelenkov)

• **The NPA is typically operated in the mid-plane with R_{tan} ~ 60 - 80 cm. At these settings, the NPA views passing energetic ions ($v_{||}/v$ ~ 0.8 ± 0.1) injected primarily by Source A with contributions being less from Source B and negligible from Source C (due to increasing trapped ion deposition).**

• **During robust TAE/Kink activity preceding the HEF, MHD-induced redistribution and/or loss causes depletion of the high-energy region of the NPA spectrum as reported in earlier work. Thus there would be a deficiency of the high energy component during the MHD active phase.**

• **In the TAE/Kink 'quiescent' phase, the above depletion could relax thus building the observed HEF fast ion distribution first at the NB full energy.**

• **A mechanism that does not absorb energy but transfers v_{perp} energy to $v_{||}$ would augment the observed HEF growth by 'pumping' Source B&C ions (more trapped) into the $v_{||}/v$ range viewed by the NPA (more passing). Could a CAE/GAE 'resonance' near the beam full energy be a driver? Could a particle 'pinch' effect exist that 'pumps' trapped ions onto passing orbits observed by the NPA?**

• **This 'pumping' of energetic ions toward passing orbits might also cause the observed increase in measured neutron yield and stored energy.**

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