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Neutral Particle Analyzer Vertically Scanning Measurements of MHD-induced Energetic Ion Redistribution or Loss in NSTX

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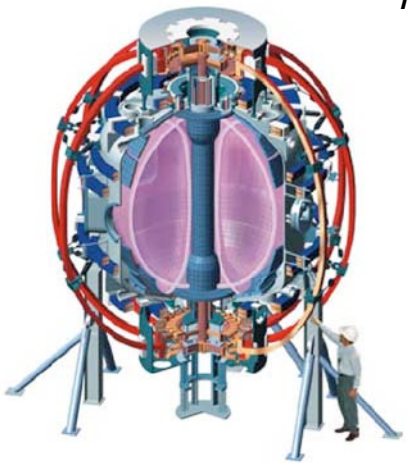
[4]University of California at Irvine, Irvine, CA 92687
[5]Johns Hopkins University, Baltimore, Maryland 21218



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Abstract

Neutral Particle Analyzer Vertically Scanning Measurements of MHD-induced Energetic Ion Redistribution or Loss in NSTX*

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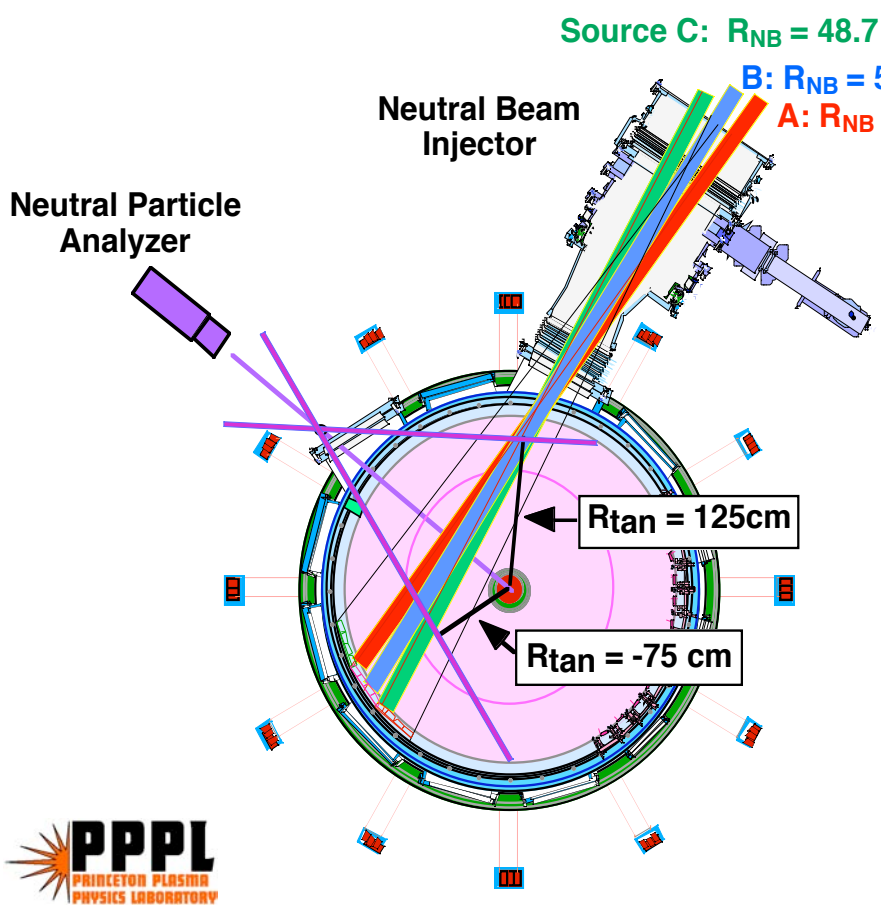
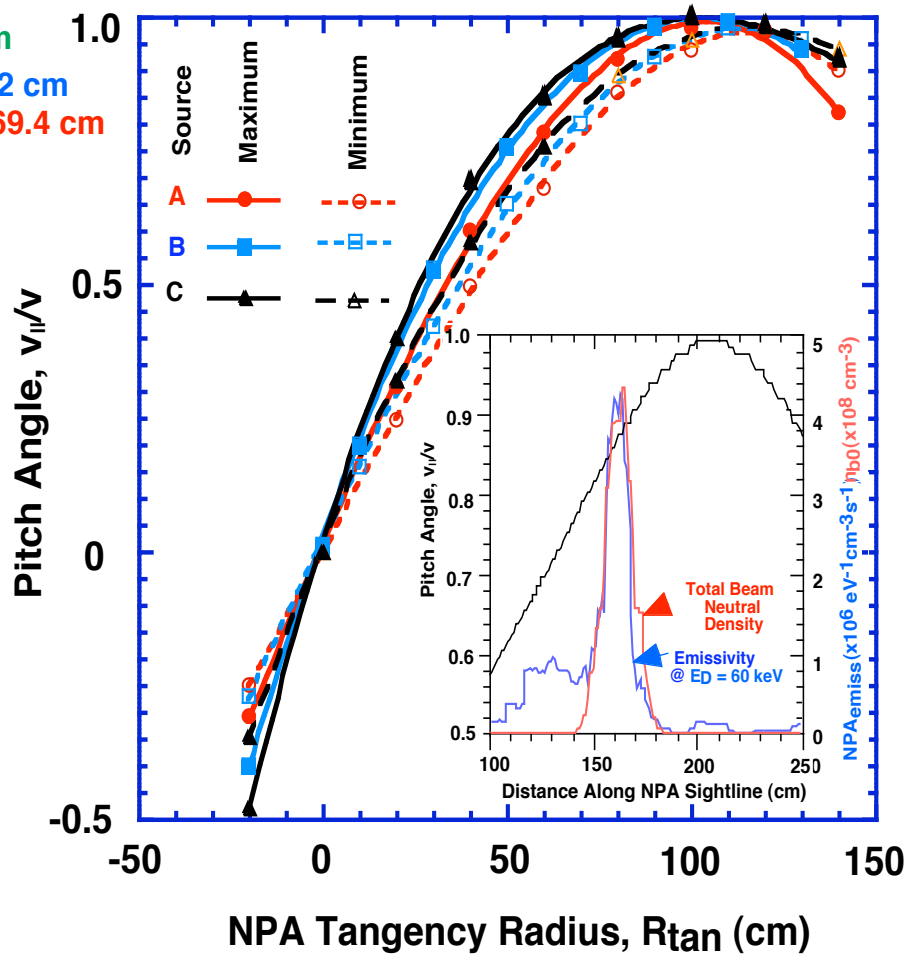
Observations of magneto-hydro-dynamic (MHD) induced redistribution or loss of energetic ions measured using the vertically scanning capability of the Neutral Particle Analyzer diagnostic on the National Spherical Torus Experiment (NSTX) are presented along with TRANSP analysis. Although redistribution or loss of energetic ions due to low-frequency (f ~ 10 kHz) kink-type MHD was reported previously [1,2], here the primary goal is to study redistribution or loss due to continuous Alfvénic (f ~ 20 – 150 kHz) modes, a topic that heretofore has not been investigated in detail for NSTX plasmas. Initial indications are that the former drive energetic ion loss whereas the continuous Alfvénic modes only cause redistribution and the energetic ions remain confined.

[1] S. S. Medley, *et al.*, Nucl. Fusion **44**, (2004) 1158
[2] J. E. Menard, *et al.*, Phys. Rev. Lett. **97**, (2006) 095022
*Research supported by U.S. DOE contract DE-AC02-76-CH03073

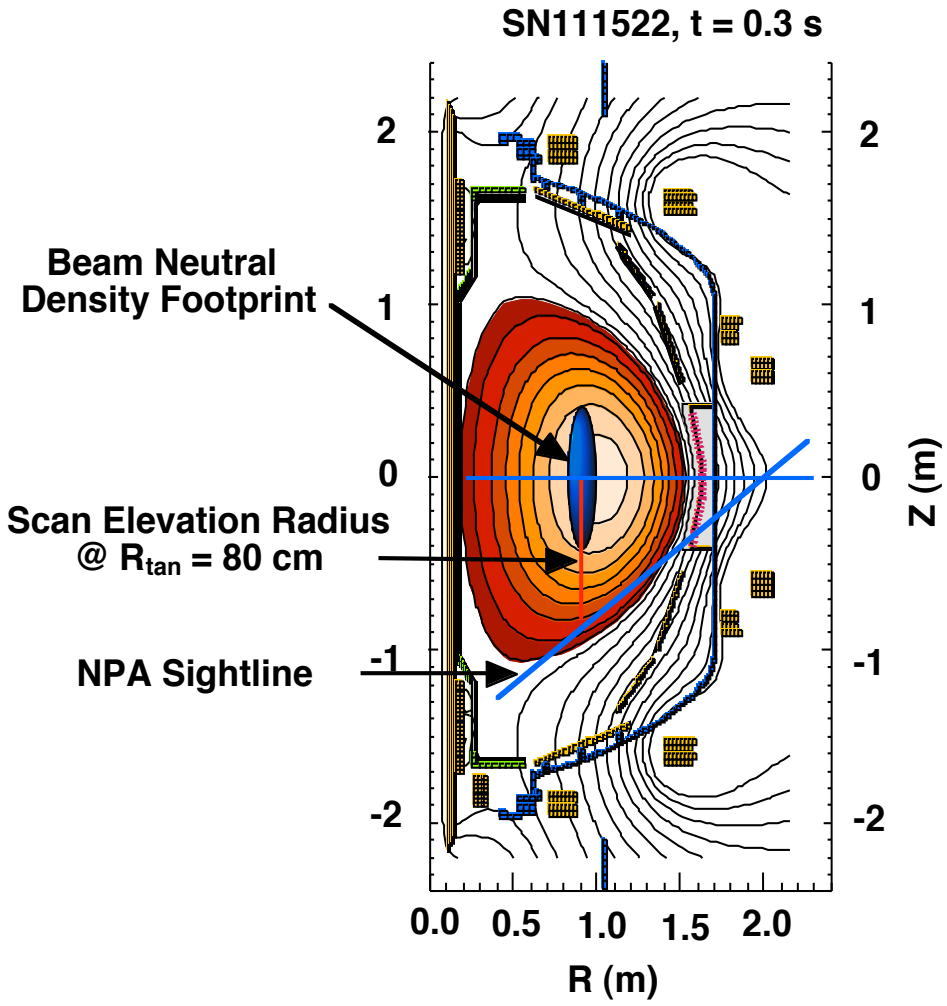
The Neutral Particle Analyzer (NPA) on NSTX Scans Horizontally Over a Wide Range of Tangency Angles on a Shot-to-Shot Basis

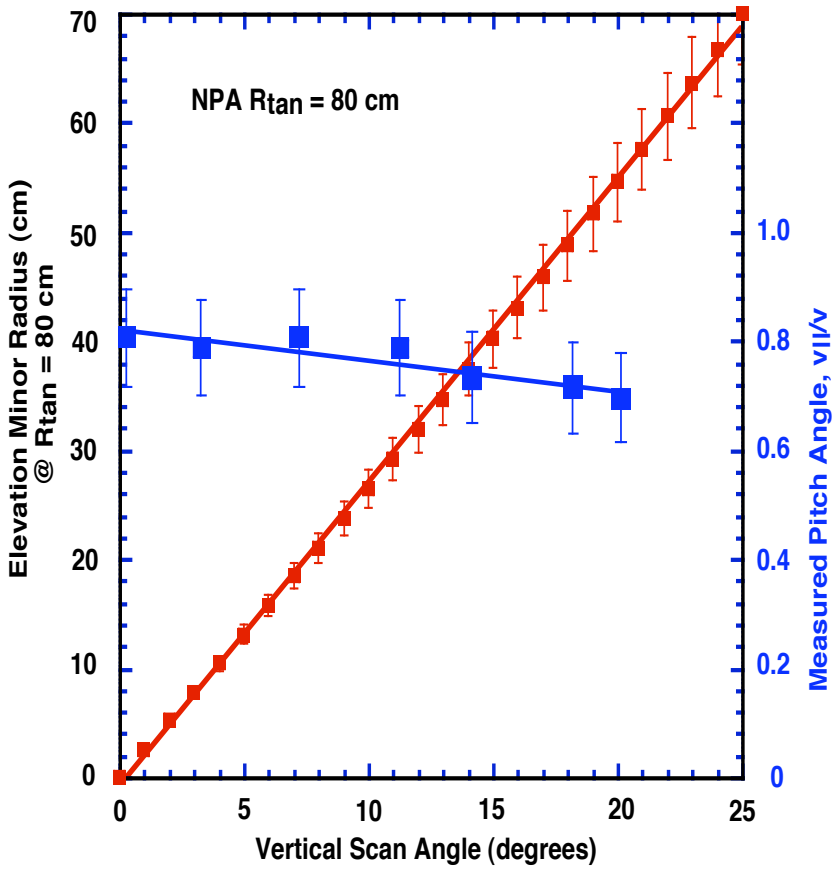




- Line-integrated NPA measurements are 'localized' in pitch and space by beam injected neutrals.

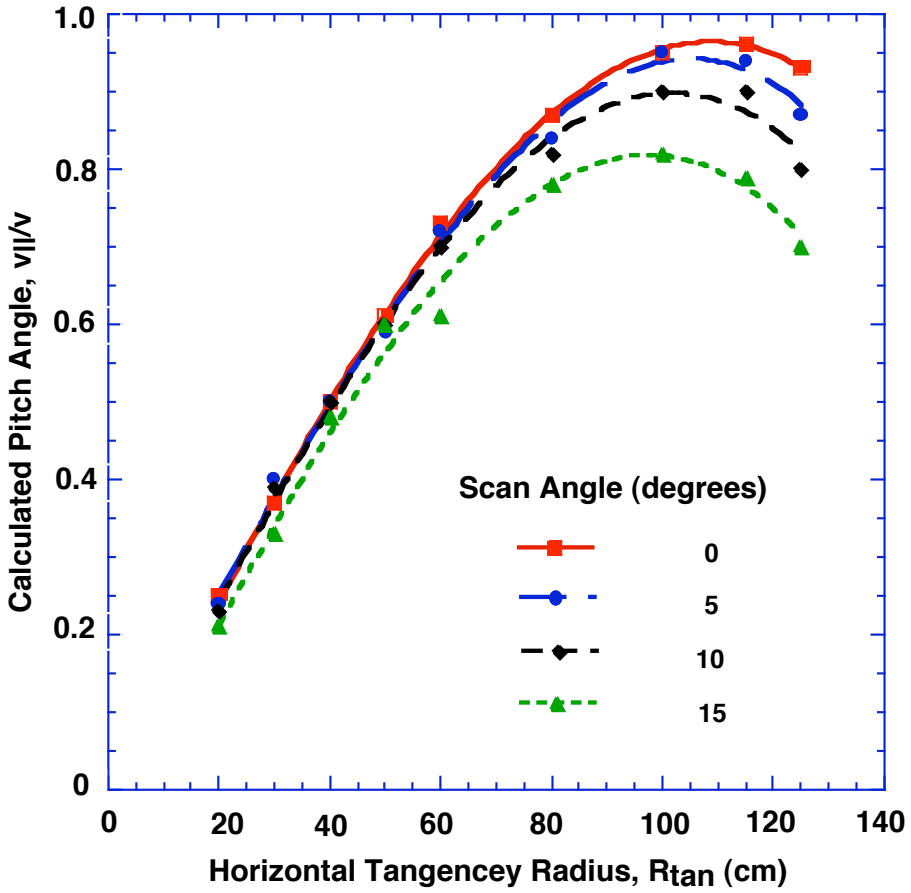
The Neutral Particle Analyzer (NPA) on NSTX Scans Vertically Over a Wide Range of Angles on a Shot-to-Shot Basis

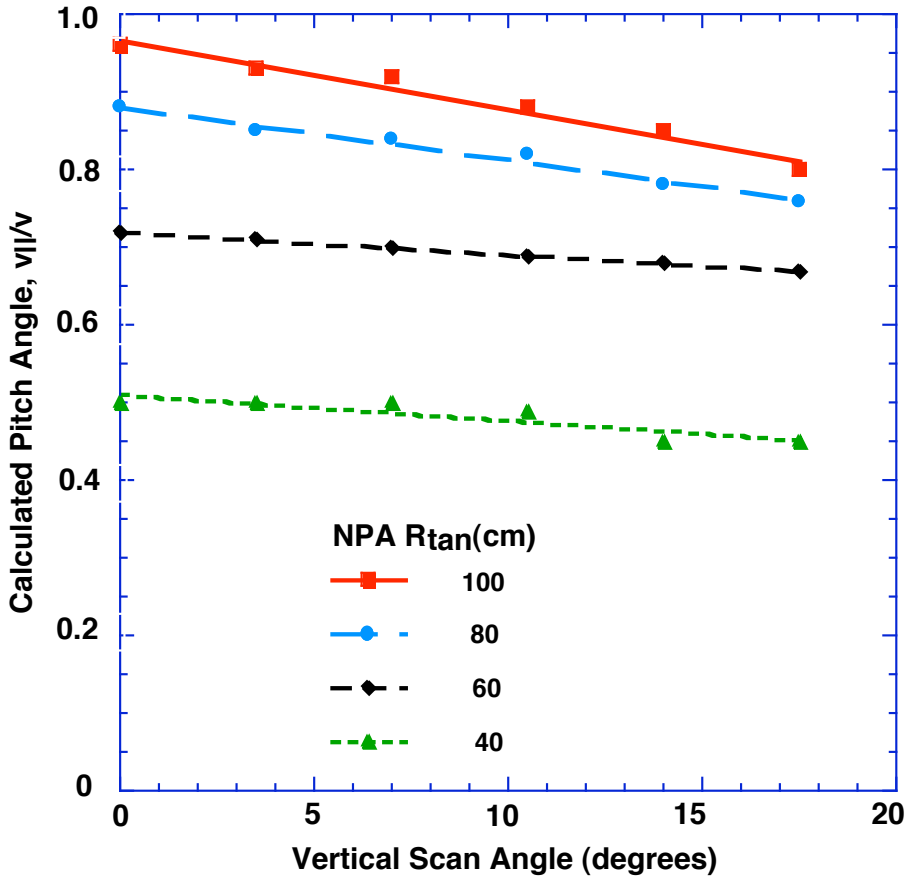




- During vertical scanning, the field pitch varies modestly around a mean value determined by the chosen horizontal tangency radius.

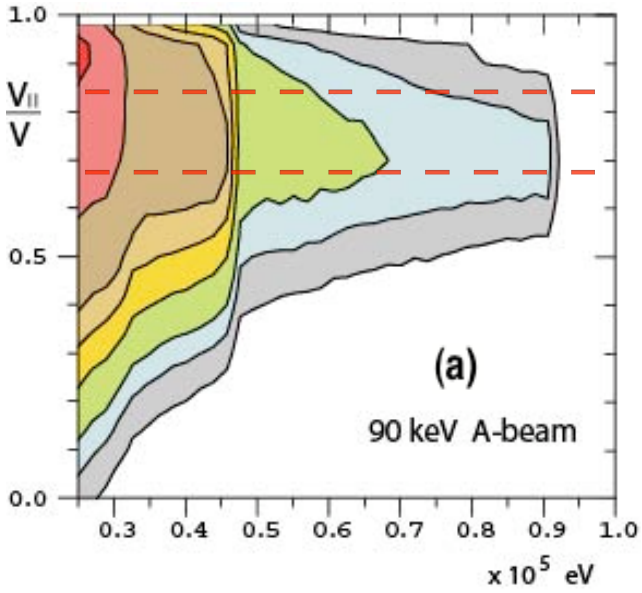
Pitch Angle Variation during NPA Horizontal and Vertical Scanning (Localized by NBI Primary Neutrals)

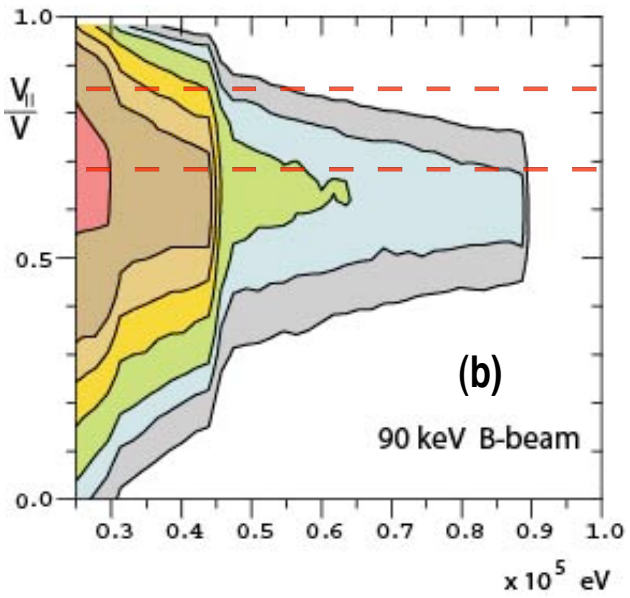


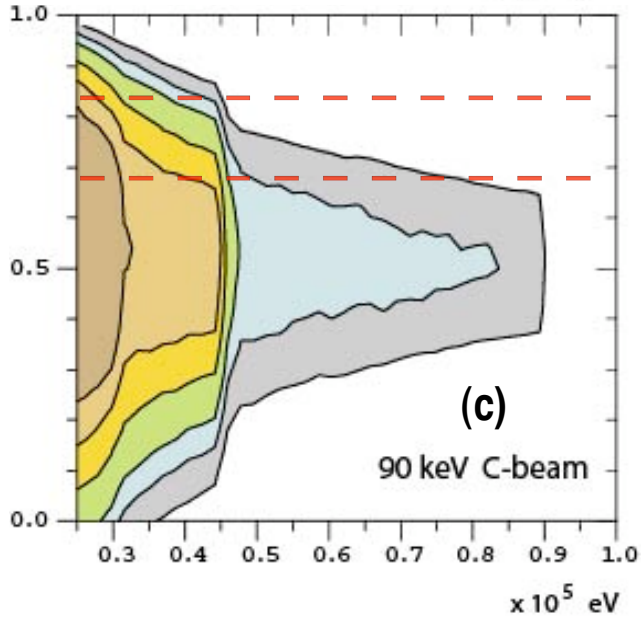


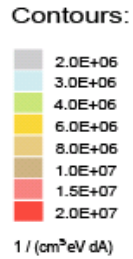
- Data is from TRANSP simulation of NPA scanning

TRANSP-calculated Pitch Angle versus Energy Contour Plots for NSTX NBI Fast Ion Distributions*





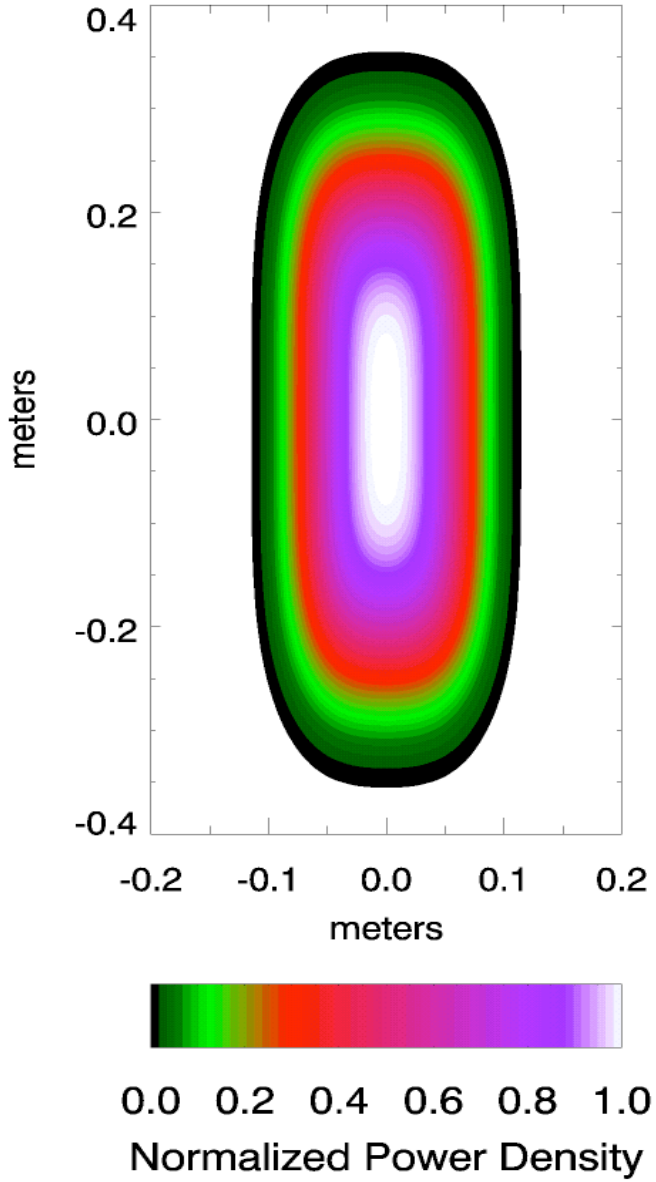


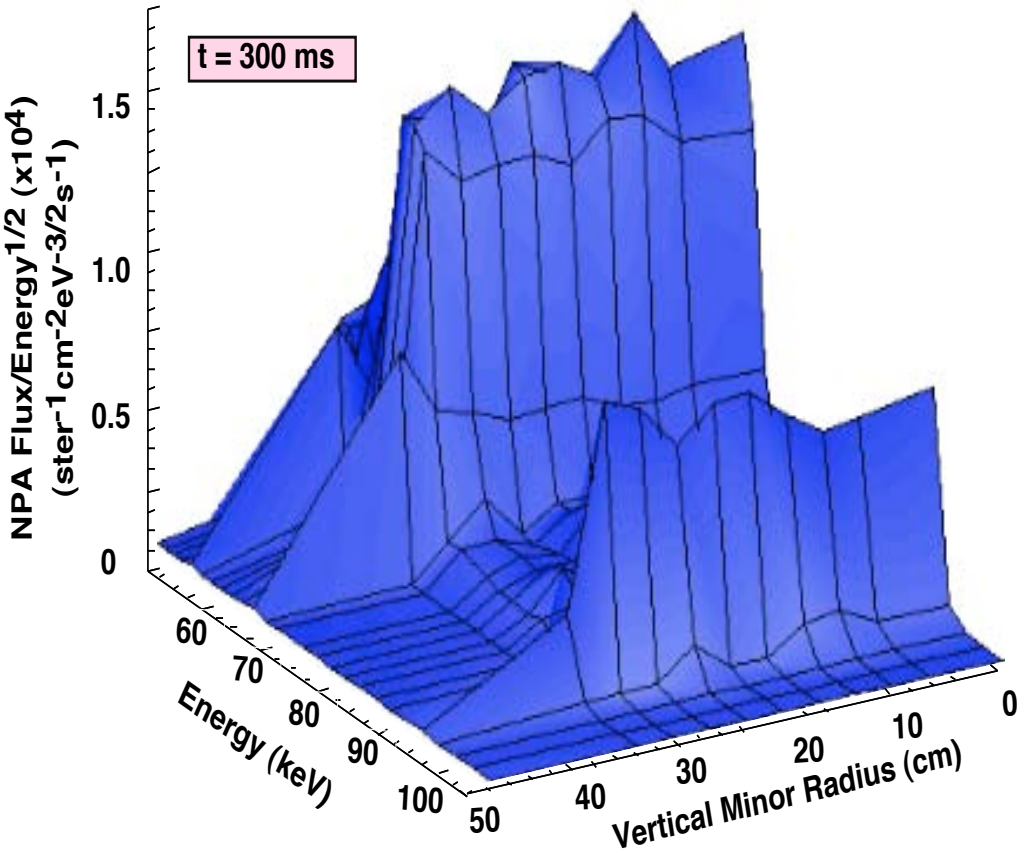


- Contours vary from $2x10^6$ (gray) to $2x10^7$ (red) and are volume-averaged (but the shape is largely invariant of integration volume).
- Dashed lines show pitch angle range sampled during vertical scan at R_{tan} ~ 80 cm.

* Courtesy E. Ruskov, UC Irvine

NPA Vertical Scanning Measurement of the Beam Neutral Footprint is Consistent with NB Calibration Data





- **Neutral Beam Particle Fractions**

NPA Data: $E_b/3: E_b/2:E_b = 0.42:0.42:0.16$

NB Calibration: $E_b/3: E_b/2:E_b = 0.44:0.39:0.17$

Overview of Diagnostics for Evaluation of MHD-induced Energetic Ion Redistribution/Loss

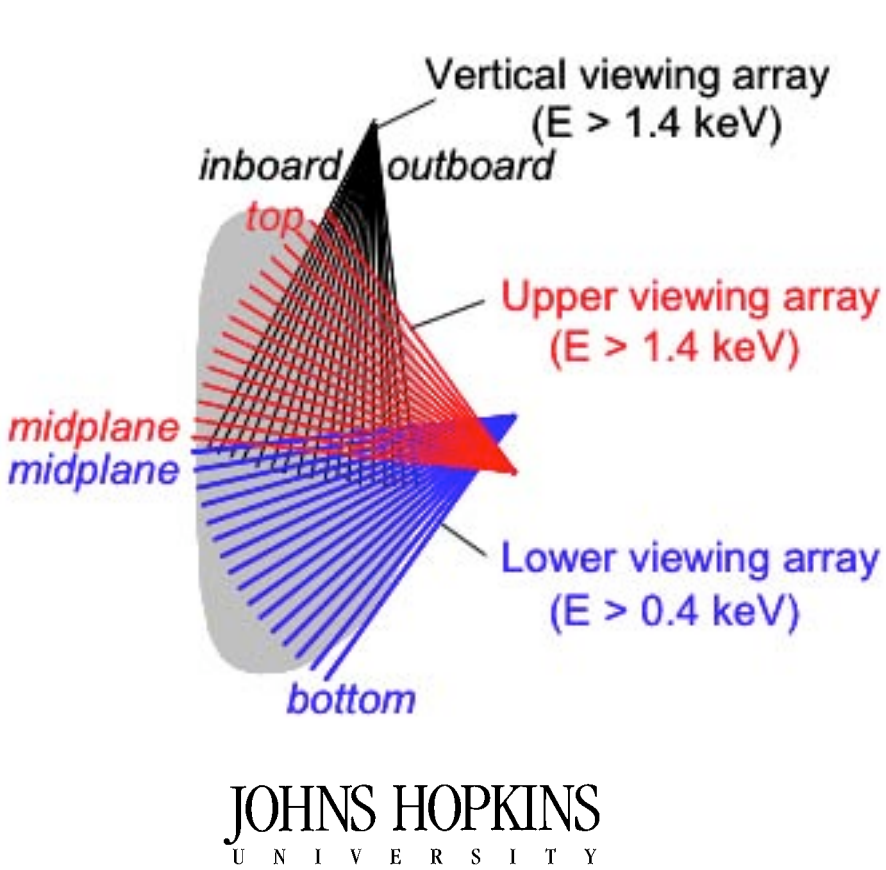
- Mirnov, USXR, FireTip…characterize MHD activity (mode, amplitude, localization)
- $S_n(t)$…volume-averaged neutron rate
- $S_{npa}(E, t, R_{tan})$…line-integrated charge exchange neutral efflux

> - Both the volume-averaged $S_n(t)$ and line-averaged $S_{npa}(E, t, R_{ta})$ show MHD-induced fast ion depletion, but cannot distinguish between redistribution and loss effects .

- sFLIP Imaging…identifies energetic ion loss to the outer wall
- MSE + LRDFIT…identifies redistribution because outward displacement of the core-peaked energetic beam ions modifies the beam-driven current profile and hence the core q-profile [1]

[1] J. E. Menard, *et al.*, "Observation of Instability-induced Current Redistribution in a Spherical Torus Experiment," Phys. Rev. Lett. 97, 095002 (2006)

USXR Measurements are used to Localize MHD Mode Activity



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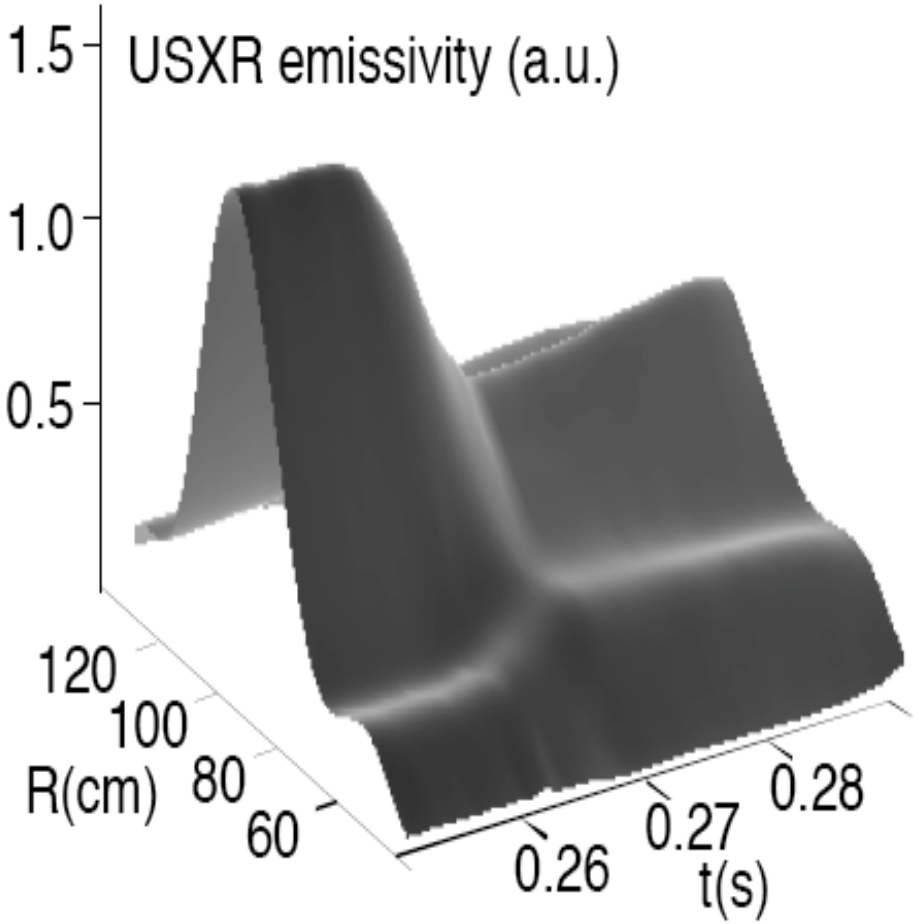
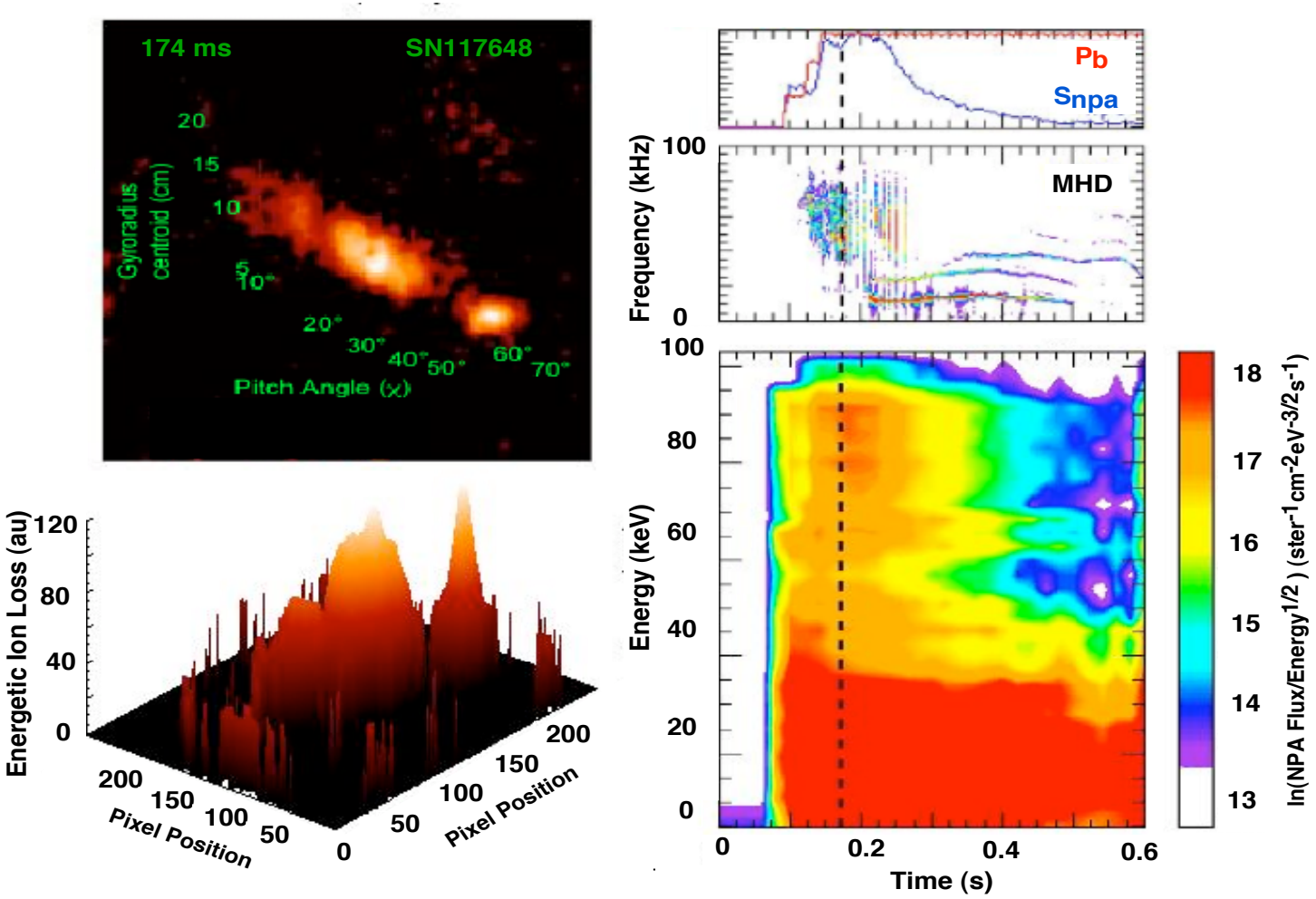


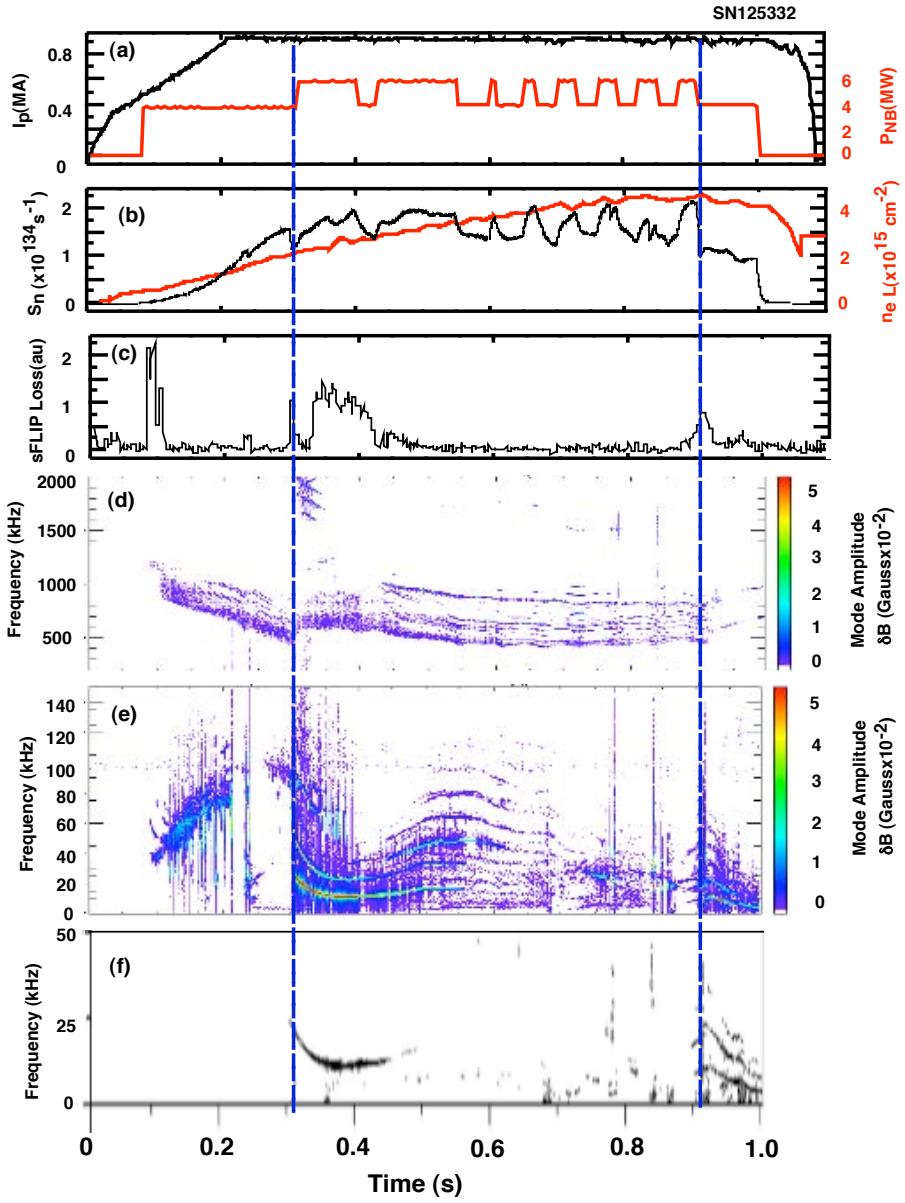
- **Inversion of ultra-soft x-ray (USXR) line-integrated emission data from multiple arrays (left) enables spatial localization of MHD activity (right).**

Correlation of NPA Flux and Mirnov Data with sFLIP Images Identifies Redistribution vs Loss



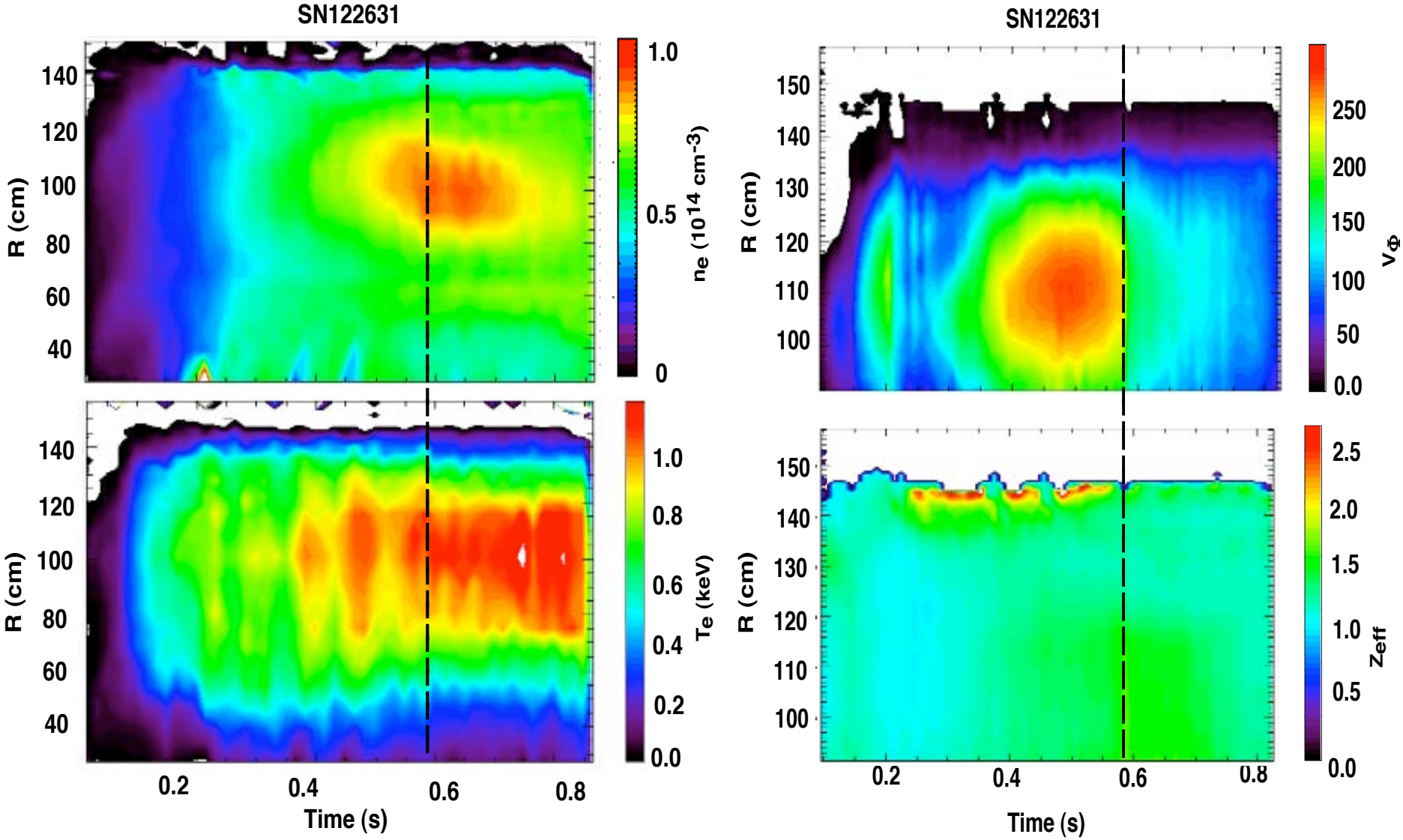
- The scintillator Fast Loss Ion Probe (sFLIP) is a magnetic spectrometer.
- B_T and aperture geometry disperse pitch angles and energies onto a scintillator.

FIReTIP $\delta n_e/n_e$ Fluctuations and sFLIP Ion Loss Correlate with Low-f Kink-type MHD Activity

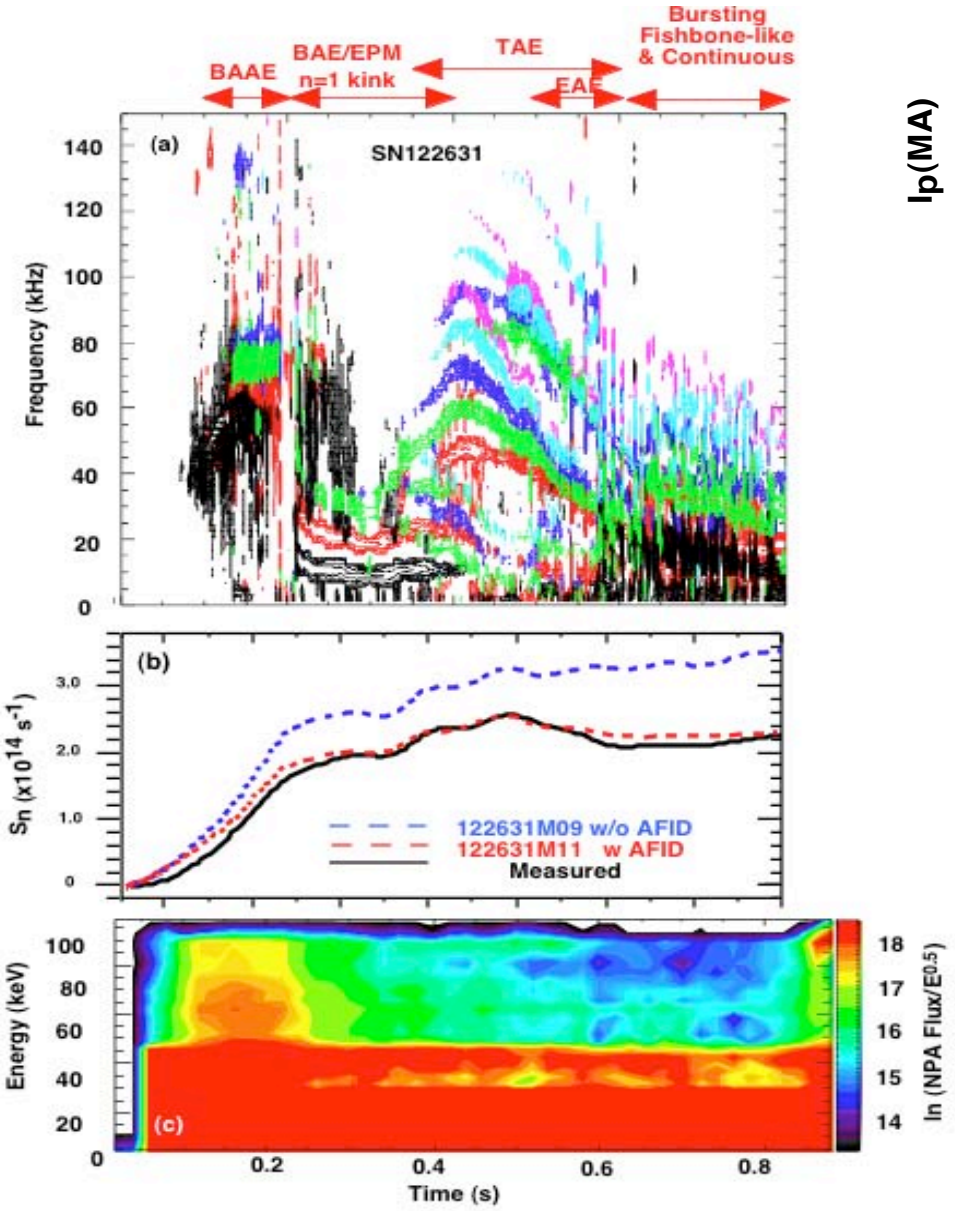


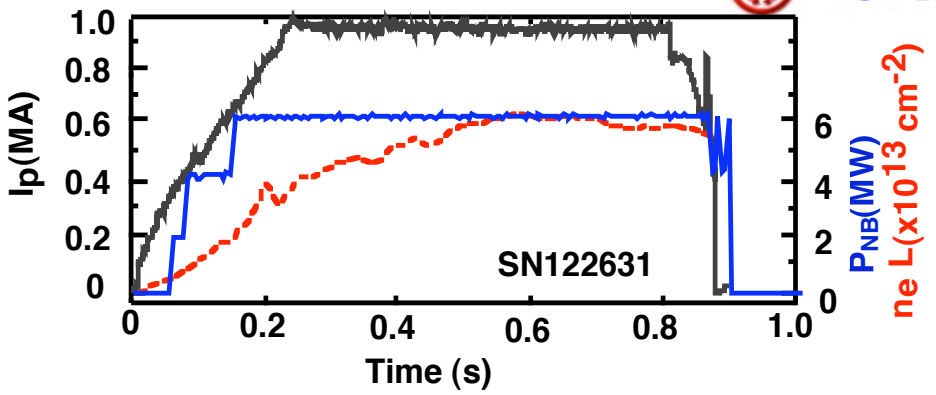
- Discharge parameters are similar to 122631 in the NPA vertical scan except source C is modulated.
- Onset of sFLIP energetic ion loss (panel c) and FIReTIP $\delta n_e/n_e$ fluctuations (panel f) at t ~ 0.3 s and t ~ 0.9 s (vertical lines) correlate with onset of low-f < 20 kHz MHD activity (panel e).
- sFLIP/FIReTIP signatures are absent during TAE/CAE/GAE only activity from t ~ 0.43 - 0.9 s.
- Conclude that TAE/CAE/GAE can drive energetic ion redistribution (from TRANSP analysis of neutron deficit and NPA depletion) but not loss.

MPTS and CHERS Data
(Dashed Line Shows Toroidal Rotation Collapse)



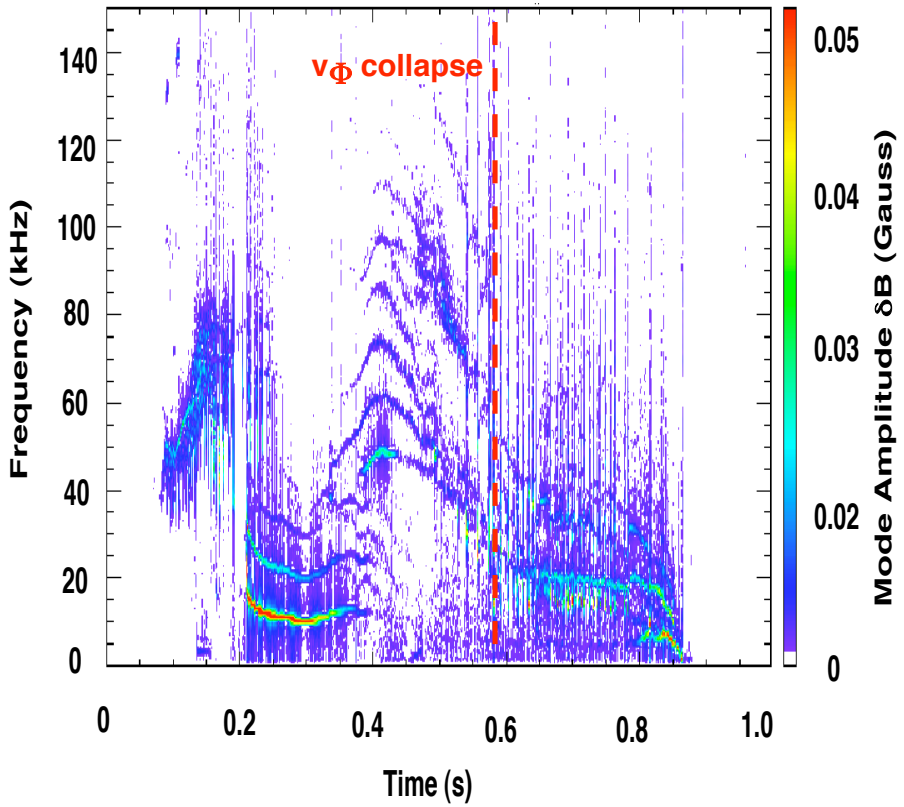
Vertical Scan Discharge Characteristics: 122631

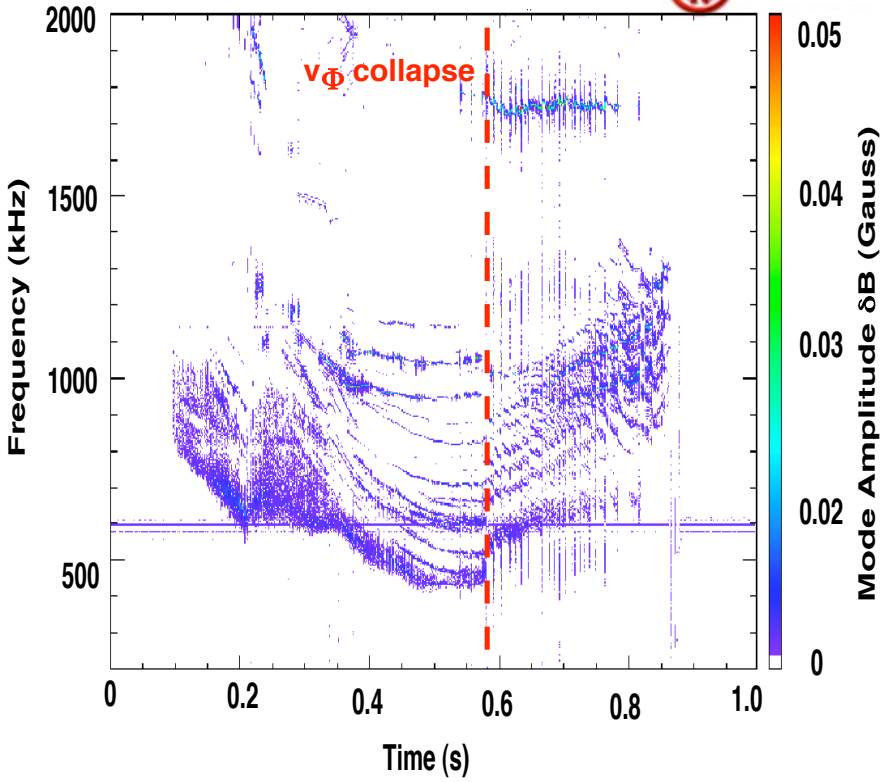


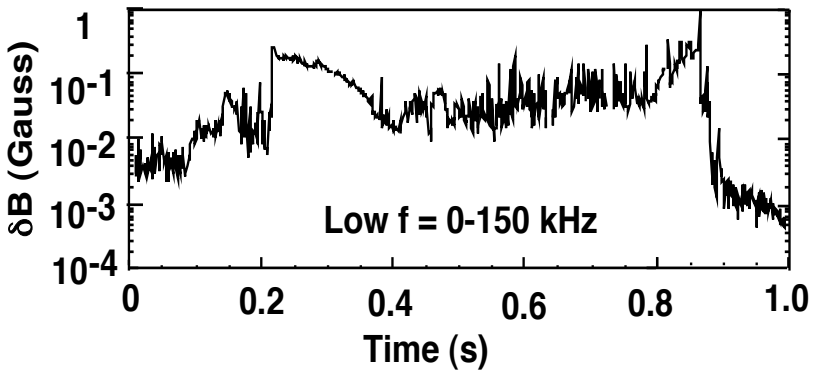


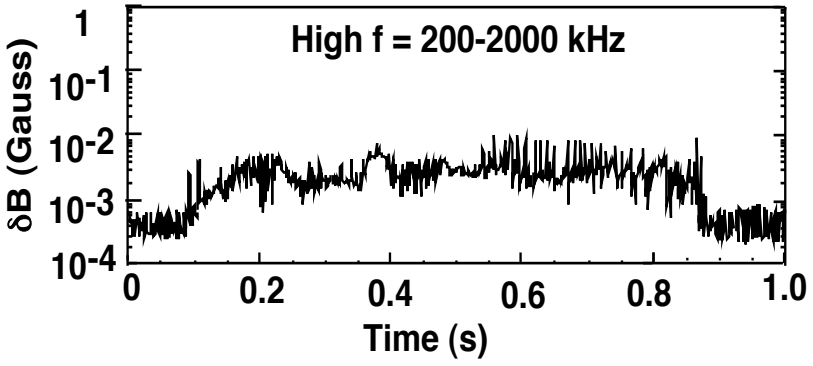
- H-mode with Ip = 1 MA, B_T = 4.5 kG A, B, C @ 90 keV and P_{NB} = 6 MW. Shot range: 122626 - 122645.
- Calculated neutrons ~ 2x measured.
- Stable outer gap ~ 10 cm early in discharge and $n_e(r)$ 'flattop' at t > 0.5 s (i.e. no 'faux' depletion effects).
- Strong energetic ion depletion primarily above E/2.

MHD Activity during the NPA Vertical Scan is Robust and Reproducible









Initially Monotonic NPA Vertical Scan Profile is Flattened by MHD-Induced Fast Ion Redistribution

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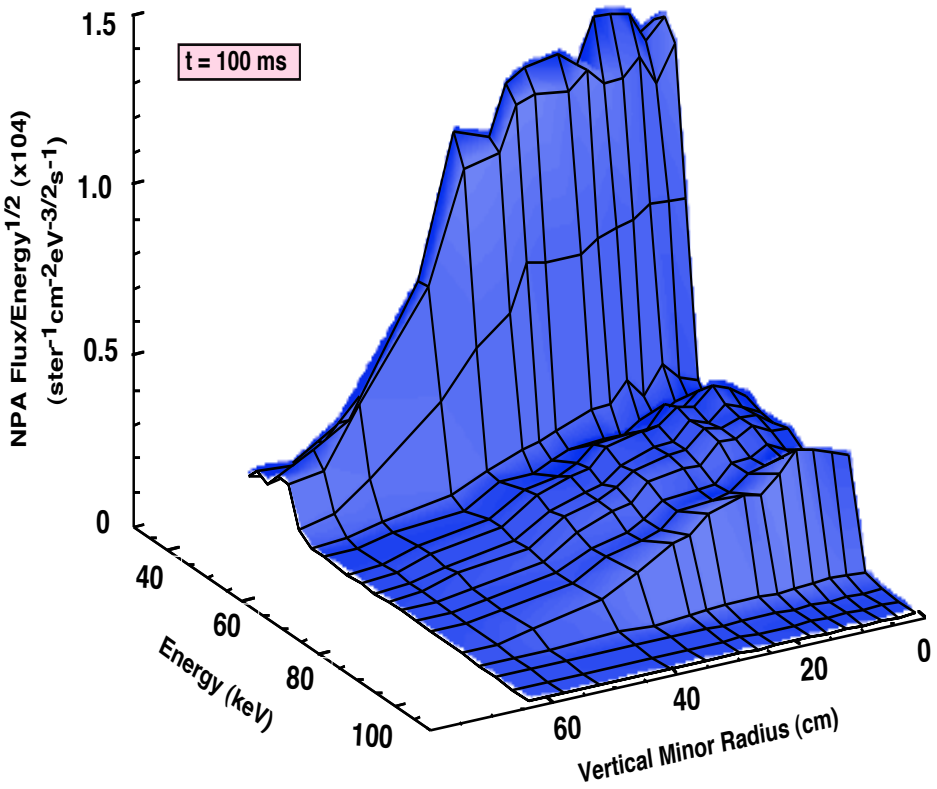
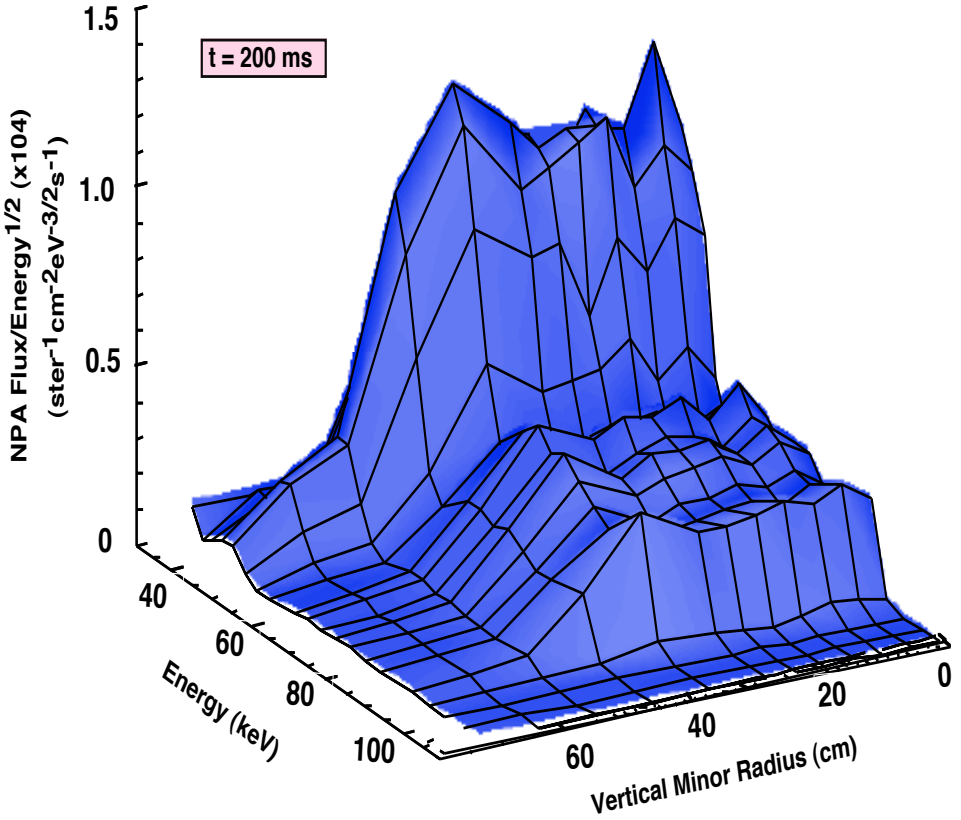
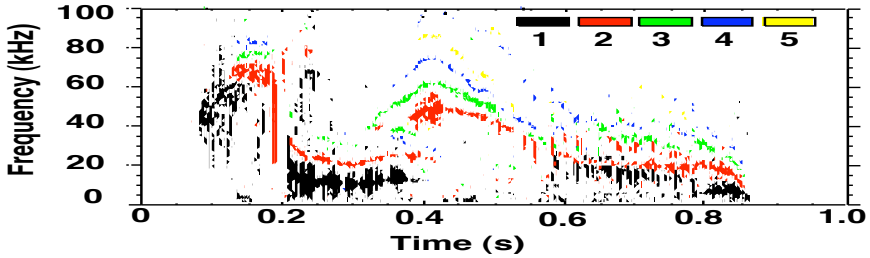
L-mode "Quiescent"

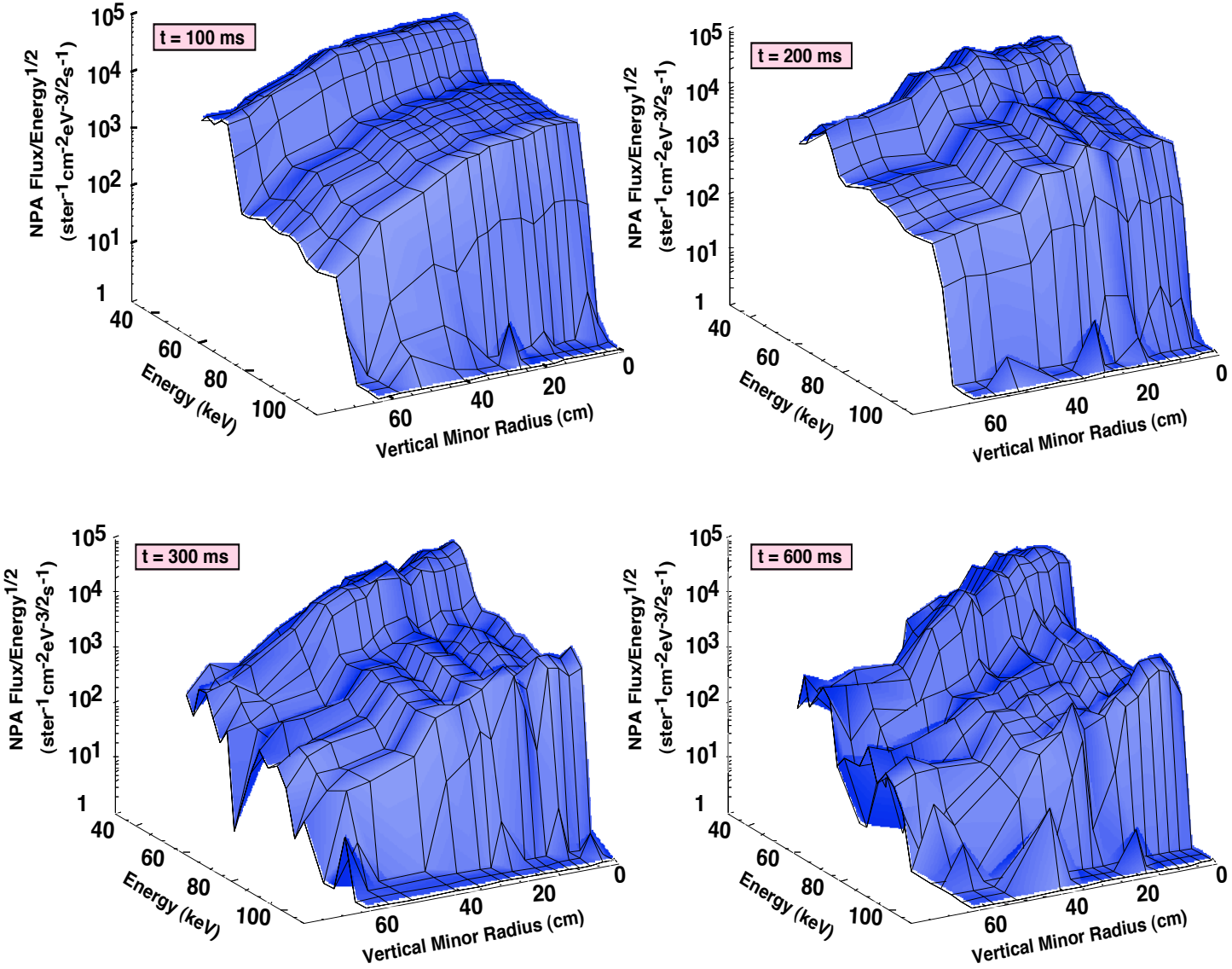


H-mode "MHD Active"

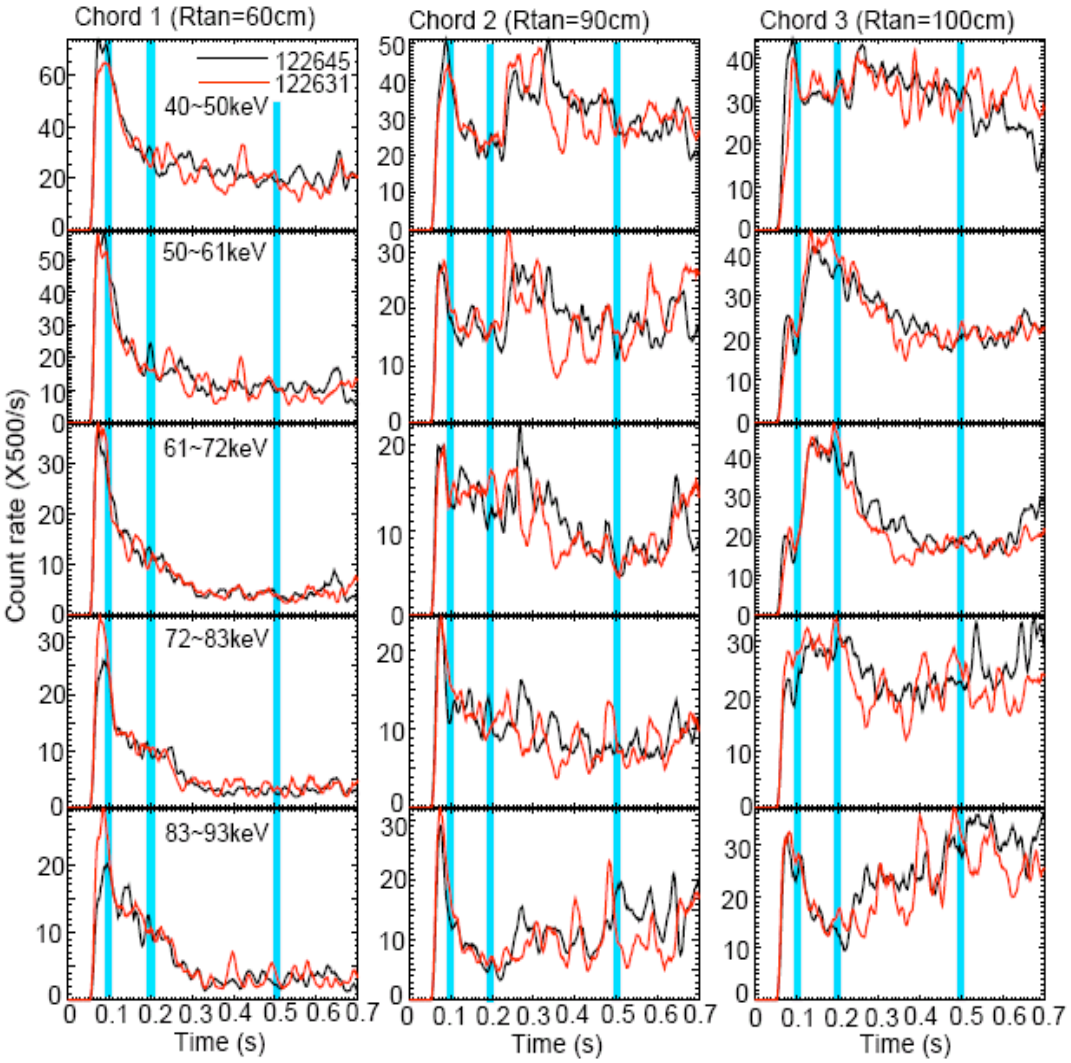


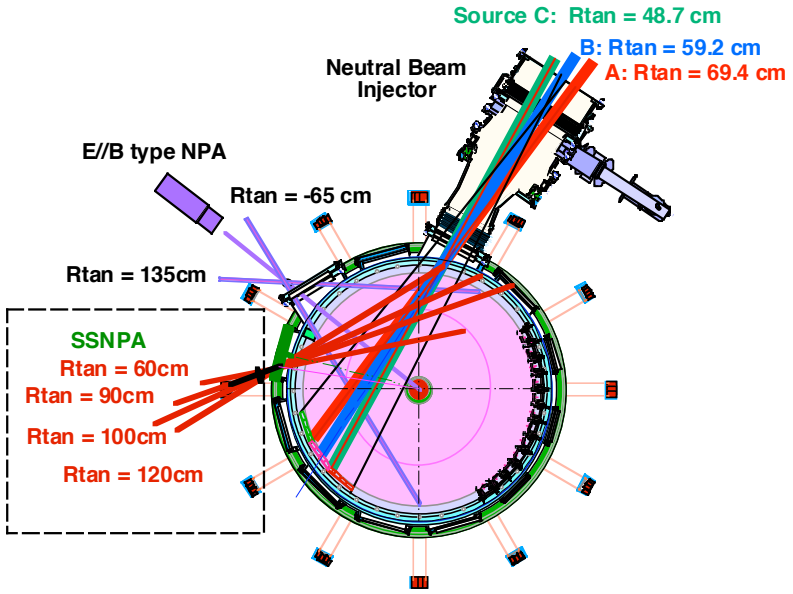


Later in the Discharge the NPA Vertical Scan Profile is Further Depleted by MHD-induced Fast Ion Redistribution



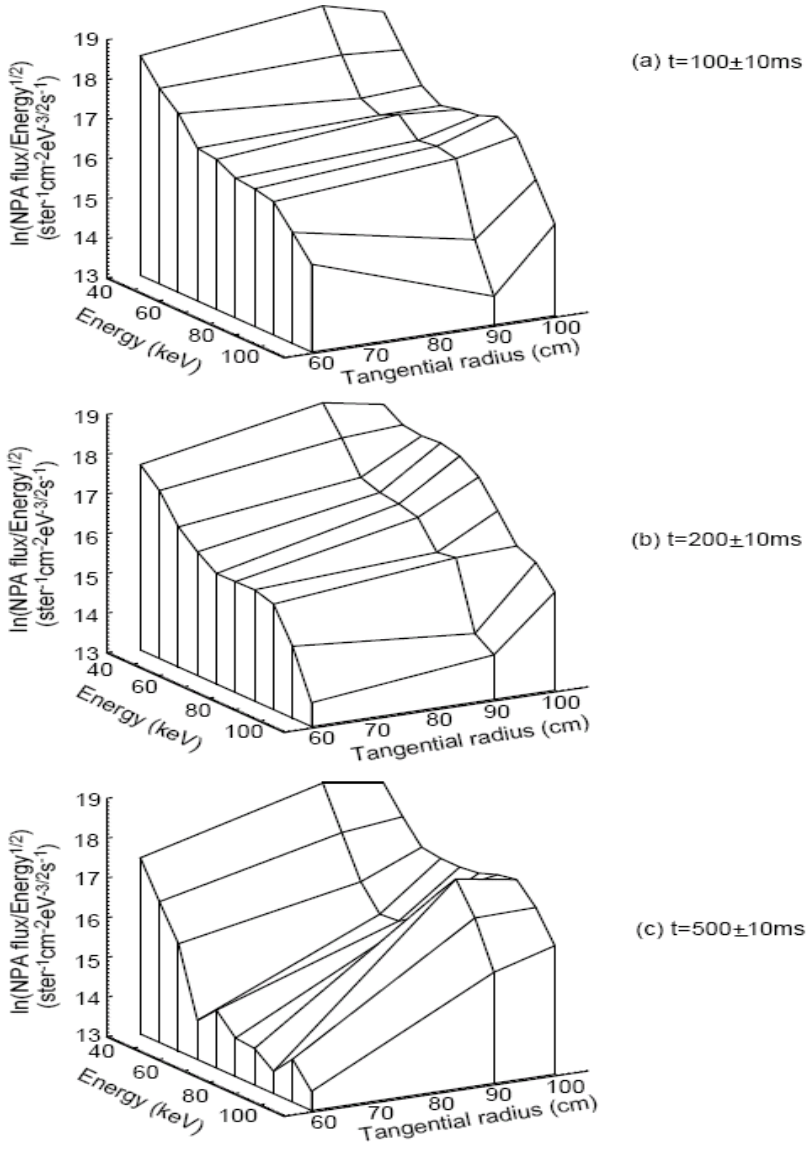
The solid state Neutral Particle Analyzer (ssNPA) is a Fixed Horizontal Array with Four Sightlines





- The outermost ssNPA sightline, R_{tan} = 120 cm, is not well-localized to the beam neutral footprint because of a significant contribution from wall neutrals so has been omitted from this analysis.

ssNPA Measurements Support MHD-induced Energetic Ion Redistribution/Loss



- Shown are ssNPA spectra for Chord 1 (R_{tan} = 60 cm), Chord 2 (R_{tan} = 90 cm) and Chord 3 (R_{tan} = 100 cm) at three selected time slices t = 100, 200 and 500 ms with 20 ms time-averaging.

- Chords 1 & 2 are spatially localized by intersection of the ssNPA sightline with the NB footprint at R_{maj} = 66 and 92 cm on the inboard side of the Shafranov-shifted magnetic axis .

- Chord 3 is localized at R_{maj} = 118 cm outboard of the Shafranov-shifted magnetic axis at R_{maj} ~ 110 cm.

TRANSP Anomalous Fast Ion Diffusion (AFID) Can Simultaneously Match $S_n(t)$, $S_{npa}(t)$ and $f_{npa}(E)$

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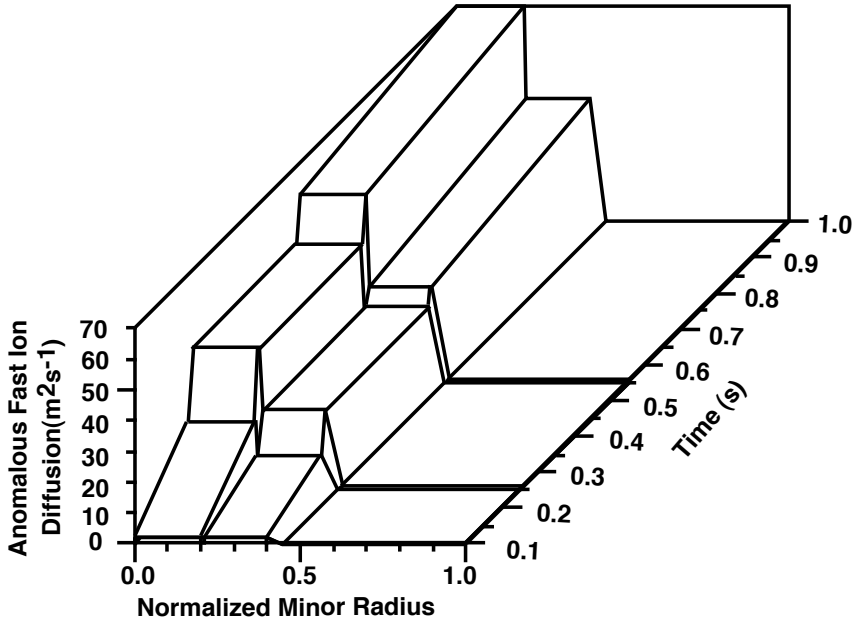
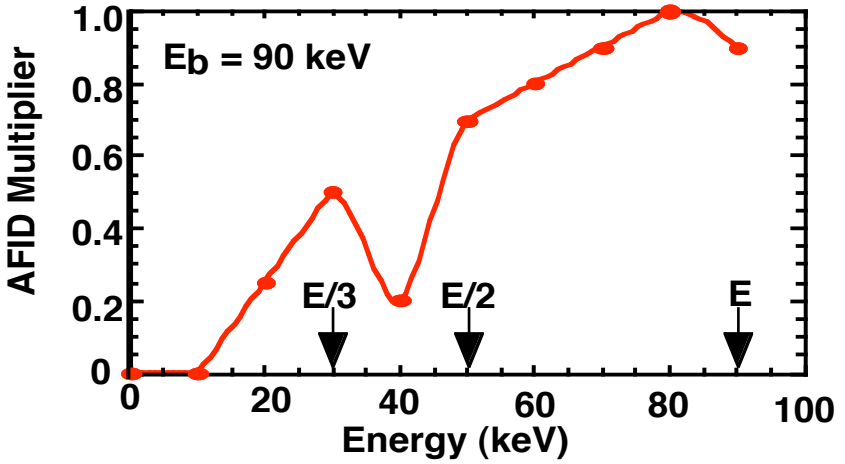
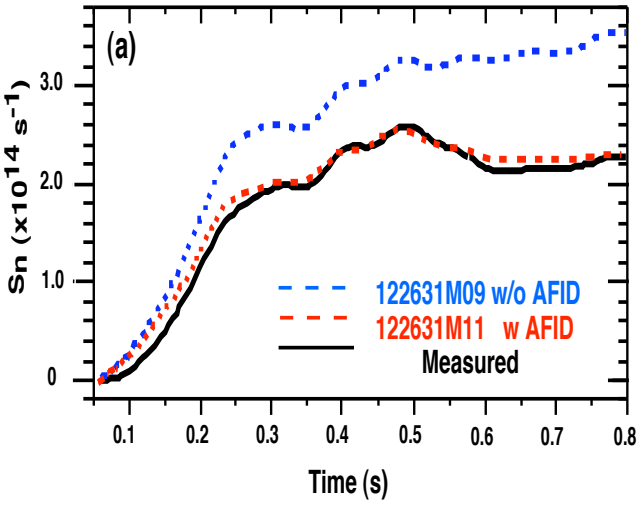
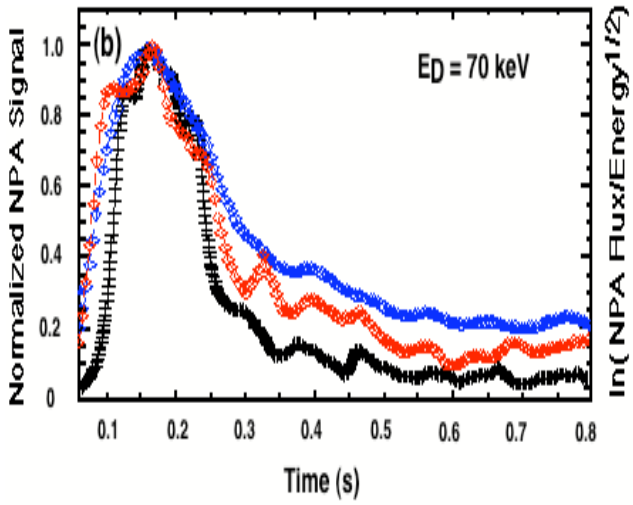
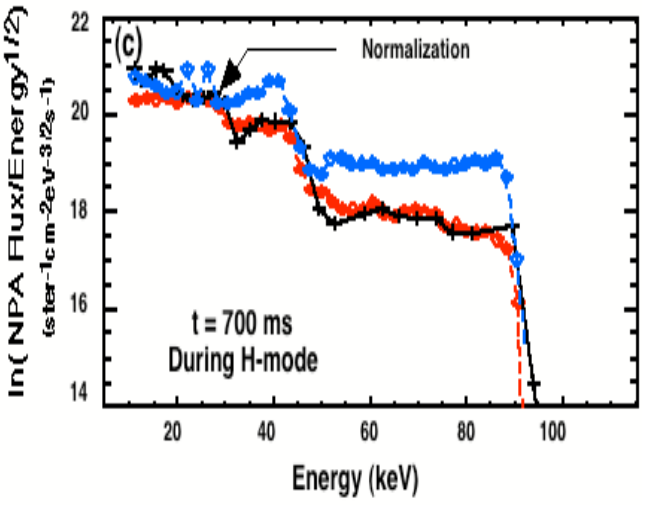


- In TRANSP, AFID can be specified in space, time and fast-ion energy.

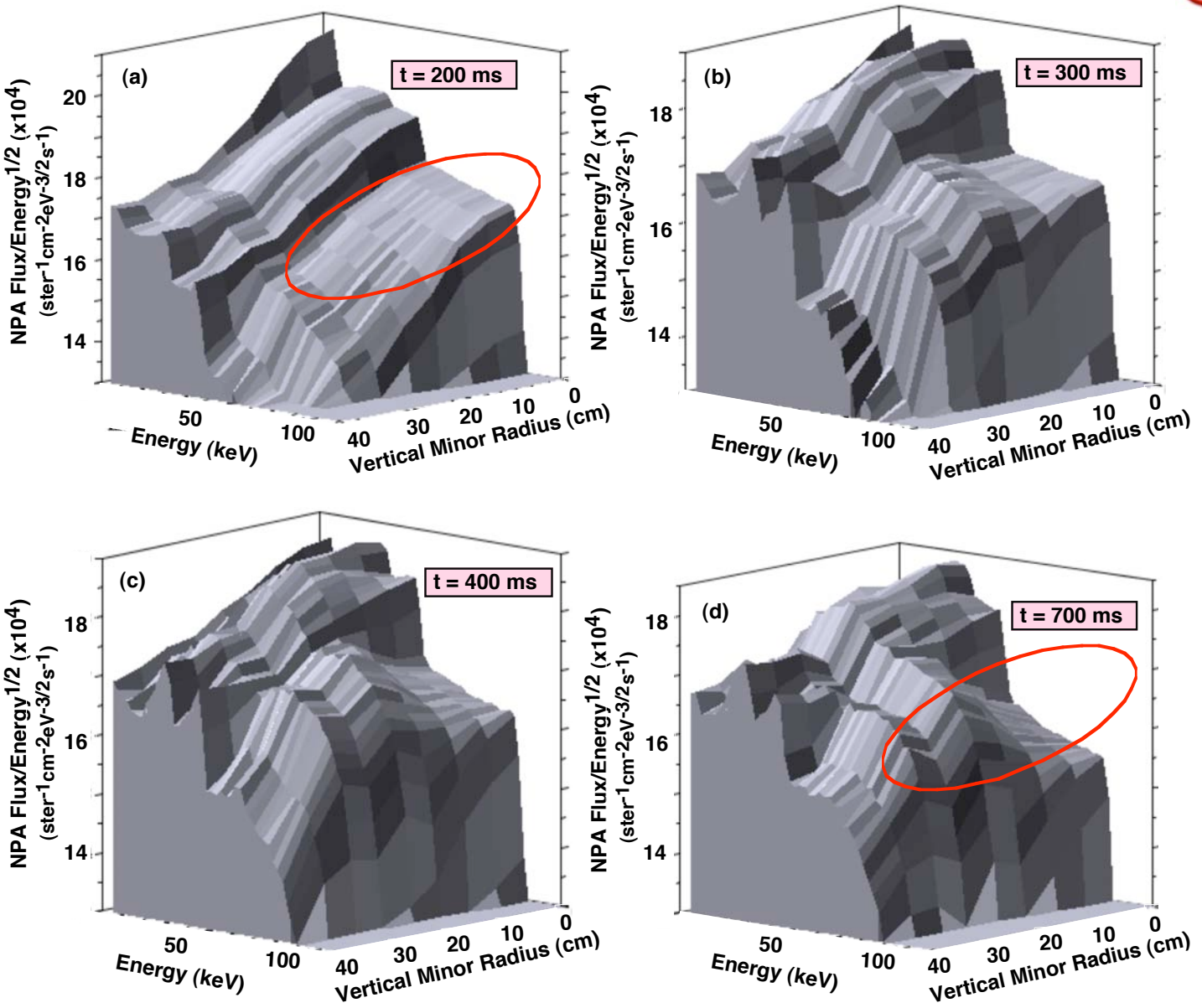




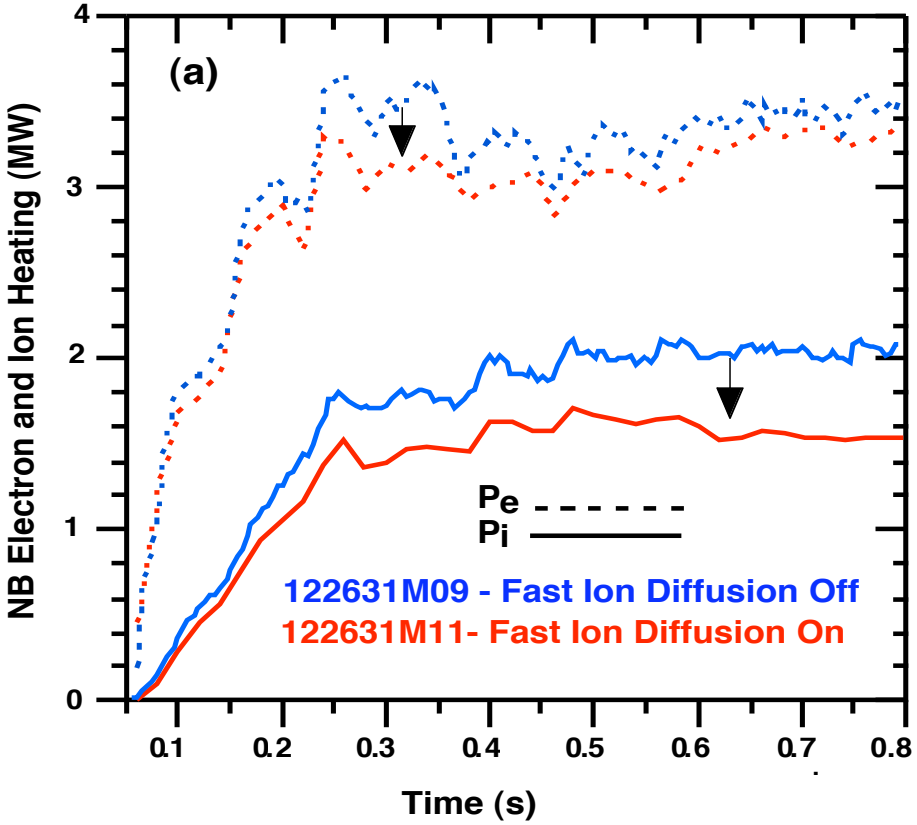


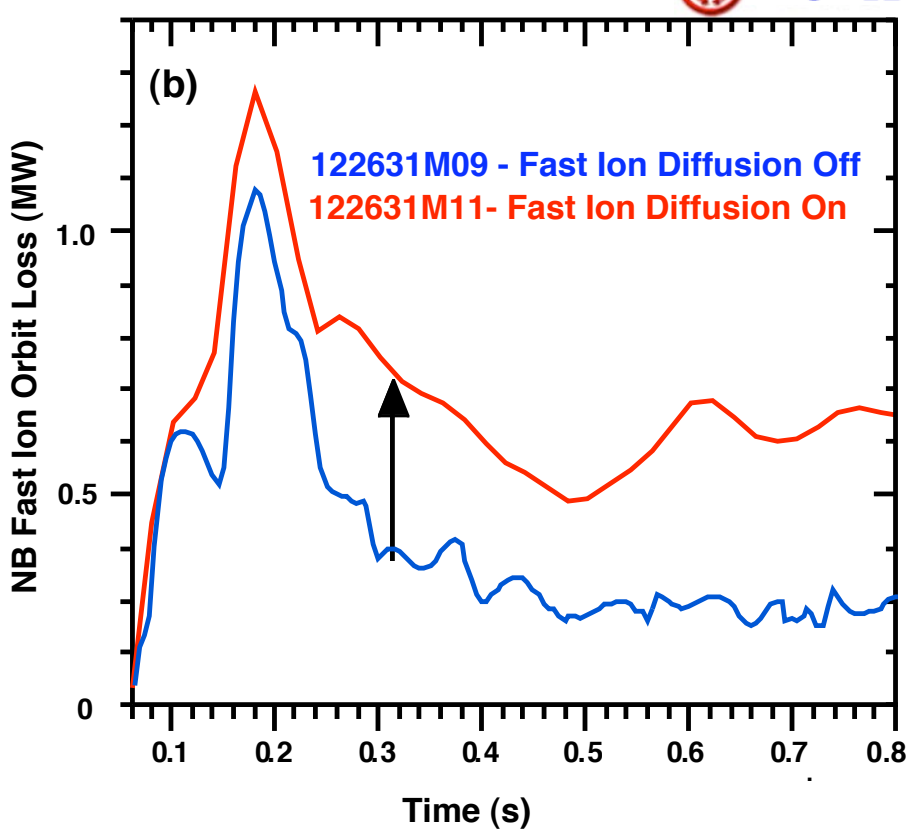


TRANSP Simulation of a NPA Vertical Scan with AFID Shows Outward Redistribution of Core Fast Ions



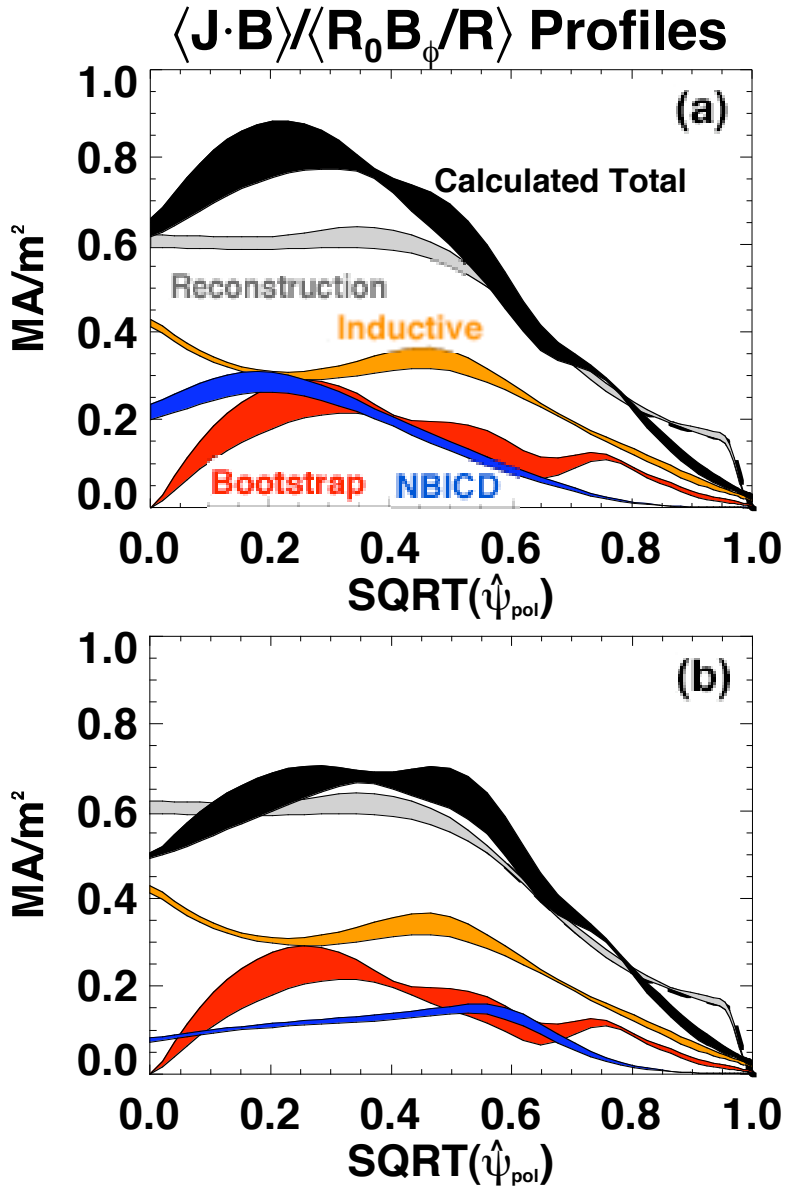
AFID Reduces Electron and Ion Heating and Increases Fast Ion Orbit Loss





- Electron heating is reduced by ~ 10% and ion heating is reduced by ~ 25%.
- Fast ion orbit loss approximately doubles, increasing by ~ 0.25 MW and reaching ~ 10% of the injected beam power.
- TRANSP compensates for loss of heating by reducing all diffusivities.

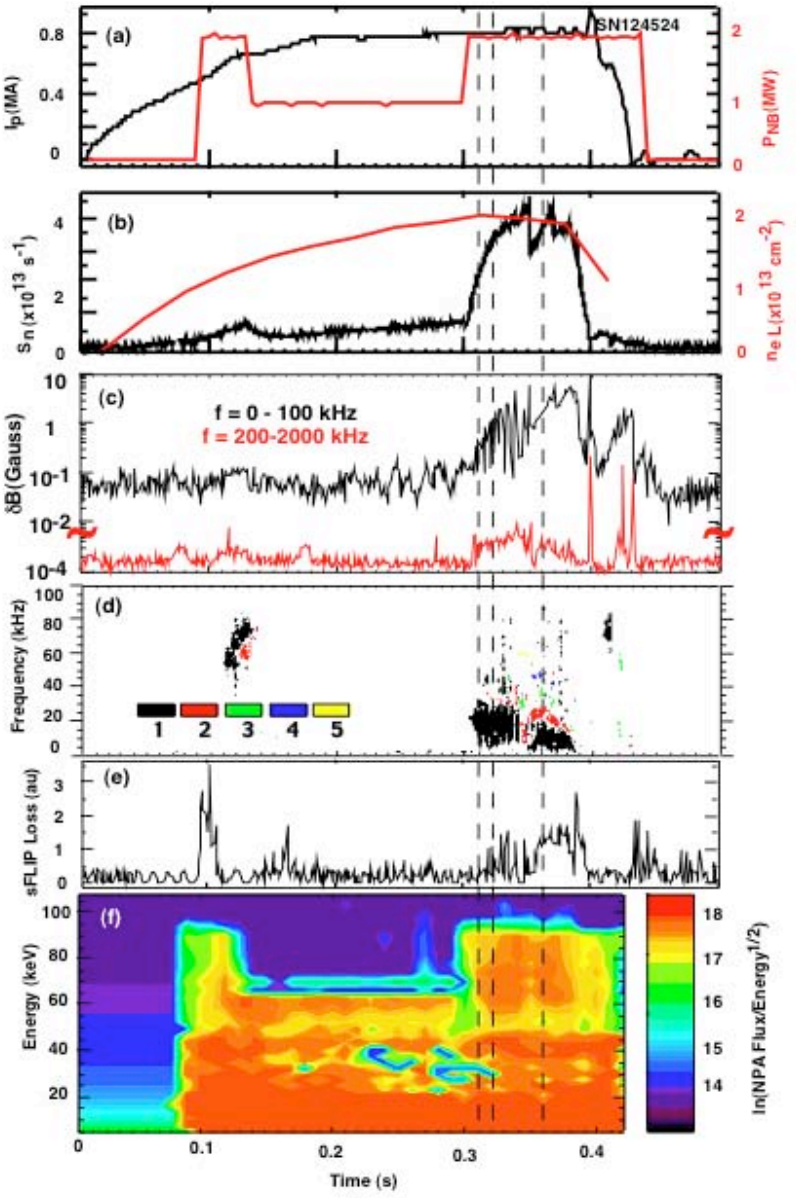
MHD-induced Current Redistribution is Confirmed using MSE-constrained Current Reconstruction

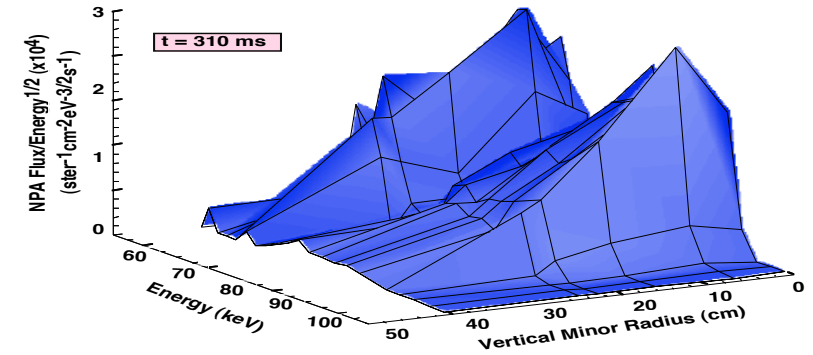


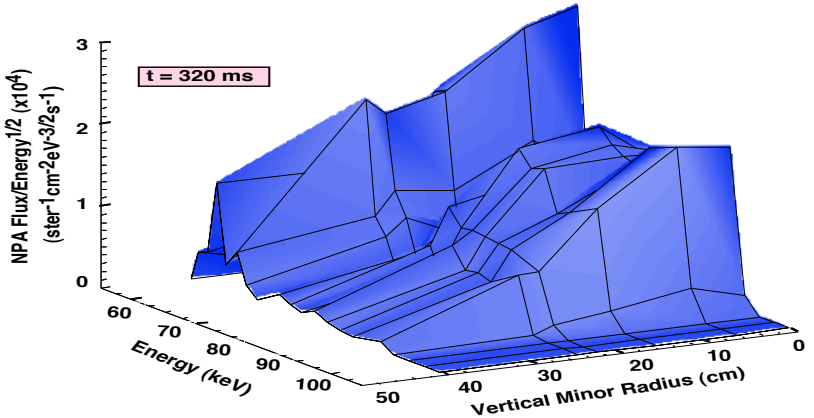
- An equilibrium code is used to calculate the inductive (orange) and bootstrap (red) current profile components.
- The profile of the neutral beam injection current drive (NBICD, blue) is calculated in TRANSP. Summation of the above components yields the calculated total current density (black).
- As shown in panel (a), the calculated total (black) exceeds the MSE-reconstructed value (gray) by 20-30% when NBICD redistribution is neglected.
- In panel (b), including core anomalous fast ion diffusion of ~ 5-6 m^2/s in the TRANSP-calculated NBICD component yields good agreement between the calculated total and MSE-constrained reconstruction current profiles.

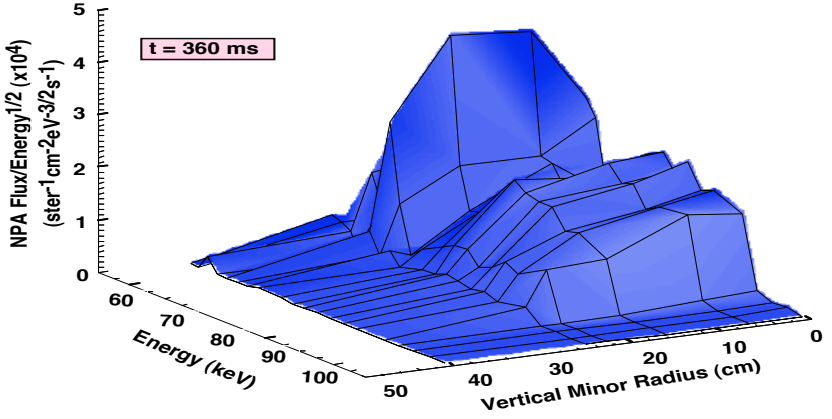
First Observation of MHD-induced Energetic Ion Redistribution in He L-mode Plasmas (Fredrickson, XP-705)

NSTX









Summary

- NPA vertical scanning provides a direct measurement (minimal $v_{||}/v$ variation) of MHD-induced energetic ion redistribution.

- The NPA vertical scan presented herein views passing energetic ions having a narrow range in field pitch: $v_{||}/v \sim 0.78 \pm 0.06$.

- MHD-induced energetic ion redistribution modeling using anomalous fast ion diffusion reduces the TRANSP-calculated neutron yield, NPA fast ion efflux and core-driven NBICD.

- sFLIP was not available during the vertical scan. A surrogate discharge with sFLIP loss and FIReTIP $\delta n_e/n_e$ fluctuation data indicates low-f modes drive energetic ion loss but TAE/CAE/GAE causes only redistribution and energetic ions remain confined.

- First observation of MHD-induced energetic ion redistribution in He L-mode plasmas was made during a vertical scan in XP-705.