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Investigation of Fast-ion Redistribution or Loss due to MHD Modes and Alfvén Instabilities in NSTX

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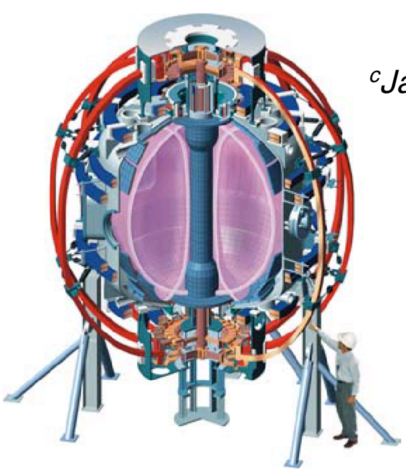

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Neutron and Energetic Neutral Particle Measurements: Matching to TRANSP Simulations using AFID

- In TRANSP, anomalous fast ion diffusion (AFID) is used to emulate MHD-induced energetic ion redistribution and/or loss.

- AFID is specified in time, space and fast-ion energy to optimize the match between calculated and measured neutron yield, NPA signal evolution, and NPA energetic ion distribution simultaneously.

- Modification of the NB driven current profile resulting from application of AFID leads to improved agreement[1,2] between the total calculated toroidal current profile and MSE measurements.

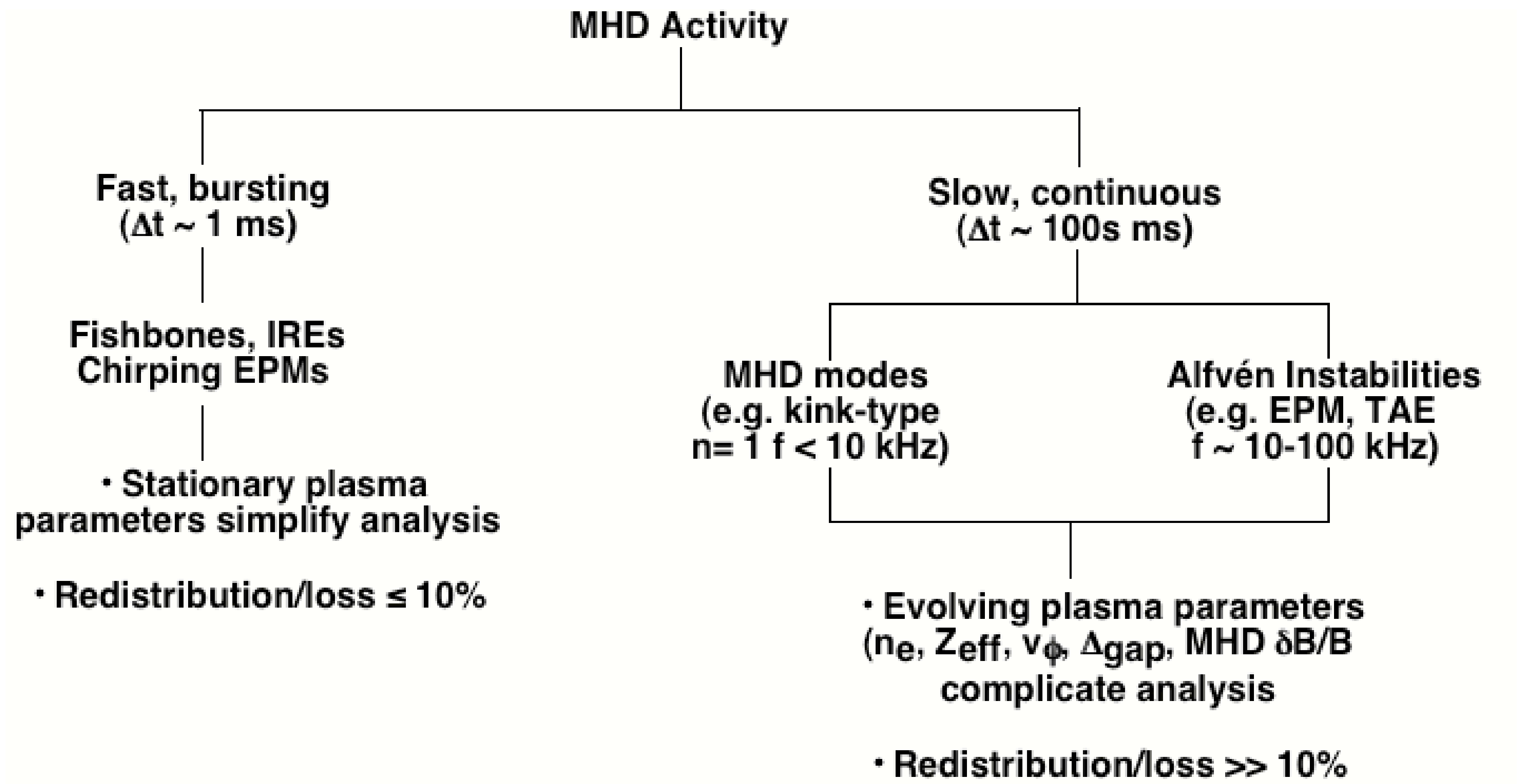
- However, the handling of neutrals in TRANSP (particularly edge and beam halo) can also affect Sn and Snpa matching. Variation of the calculated Sn with cold edge neutral density is illustrated.

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

[2] S. S. Medley, *et al.*, "Investigation of Collective Fast Ion Instability-induced Redistribution of Loss in the National Sperical Torus Experiment," 21st IAEA FEC, Chengdu, China, 16-21 October 2006, EX/P6-13.

Work supported by U.S. DOE Contract DE-AC02-76CH03073 and Grant DE-FG02-99ER54523 (JHU).

Categories of MHD-induced Redistribution/Loss of Energetic Ions



- **Magnitude of the MHD-induced redistribution/loss has been based almost entirely on volume-integrated neutron yield measurements.**

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)

Various Mechanisms Produce Energetic Ion Loss Observed by NPA and Neutron Diagnostics

NSTX

√ **Plasma Effects**

- Outer gap width (i.e. plasma volume)
- Evolution of $n_e(r)$ and Zeff(r) profiles
- Evolution of edge neutral density (gas puffing, wall recycling)

√ **MHD Effects**

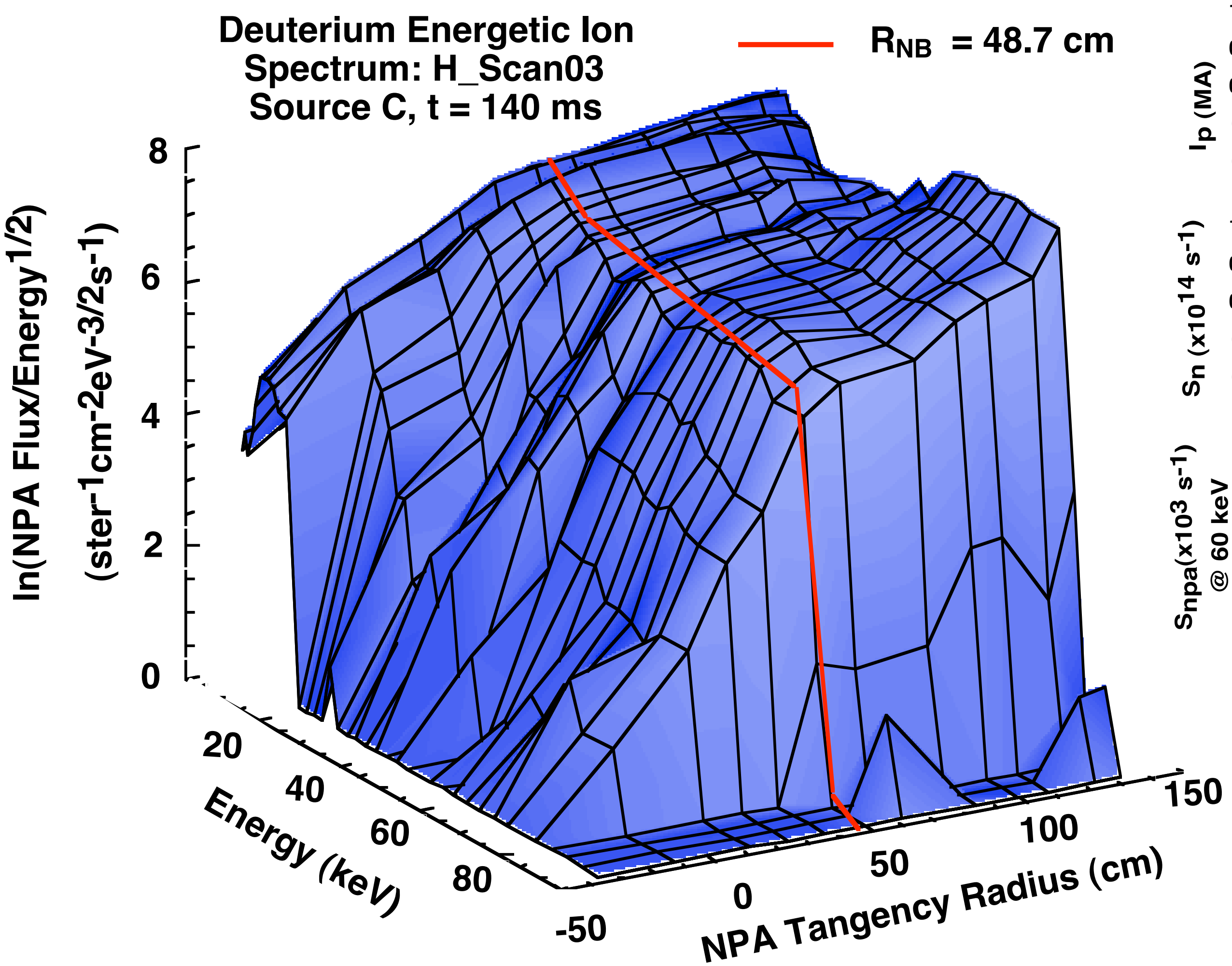
- Strong n=1 or n=2 mode activity and reconnection events [1]
- Fishbones and Alfvén Instabilities [2]
- MHD-induced ion loss is observed during H-mode operation due to high, broad density profile effects [3].

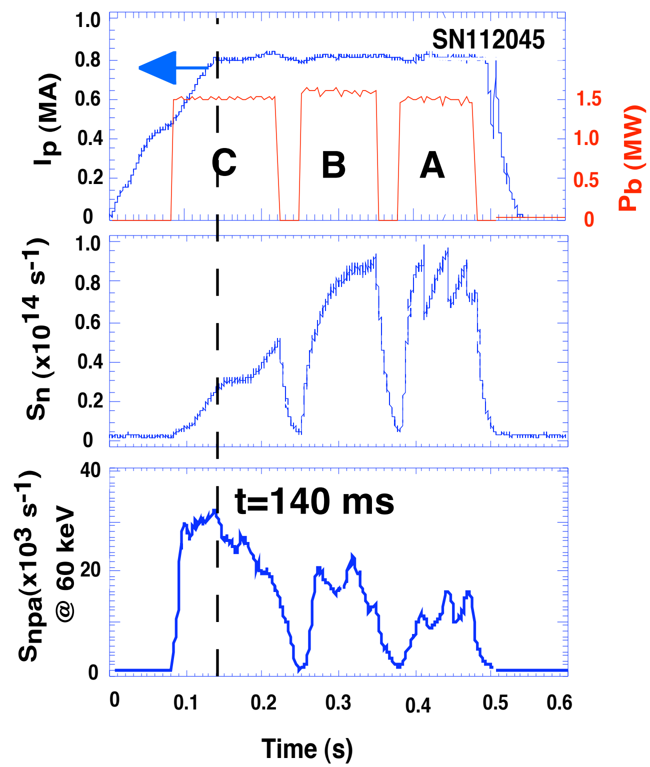
[1] "Neutral Particle Analyzer Measurements of Ion Behavior in NSTX," S. S. Medley, *et al.* PPPL-3668 (February, 2002)

[2] "Wave Driven Fast Ion Loss in the National Spherical Torus Experiment," E.D. Fredrickson , *et al.* Phys. Plasmas 10, 2852 (2003)

[3] "MHD-induced Energetic Ion Loss during H-mode Discharges in the National Spherical Torus Experiment," S. S. Medley, *et al.* Nucl. Fusion 44, 1158 (2004)

In L-mode, Slowing Down and Pitch Angle Scattering of NB Ions in NSTX Plasmas is Consistent with Classical Behavior

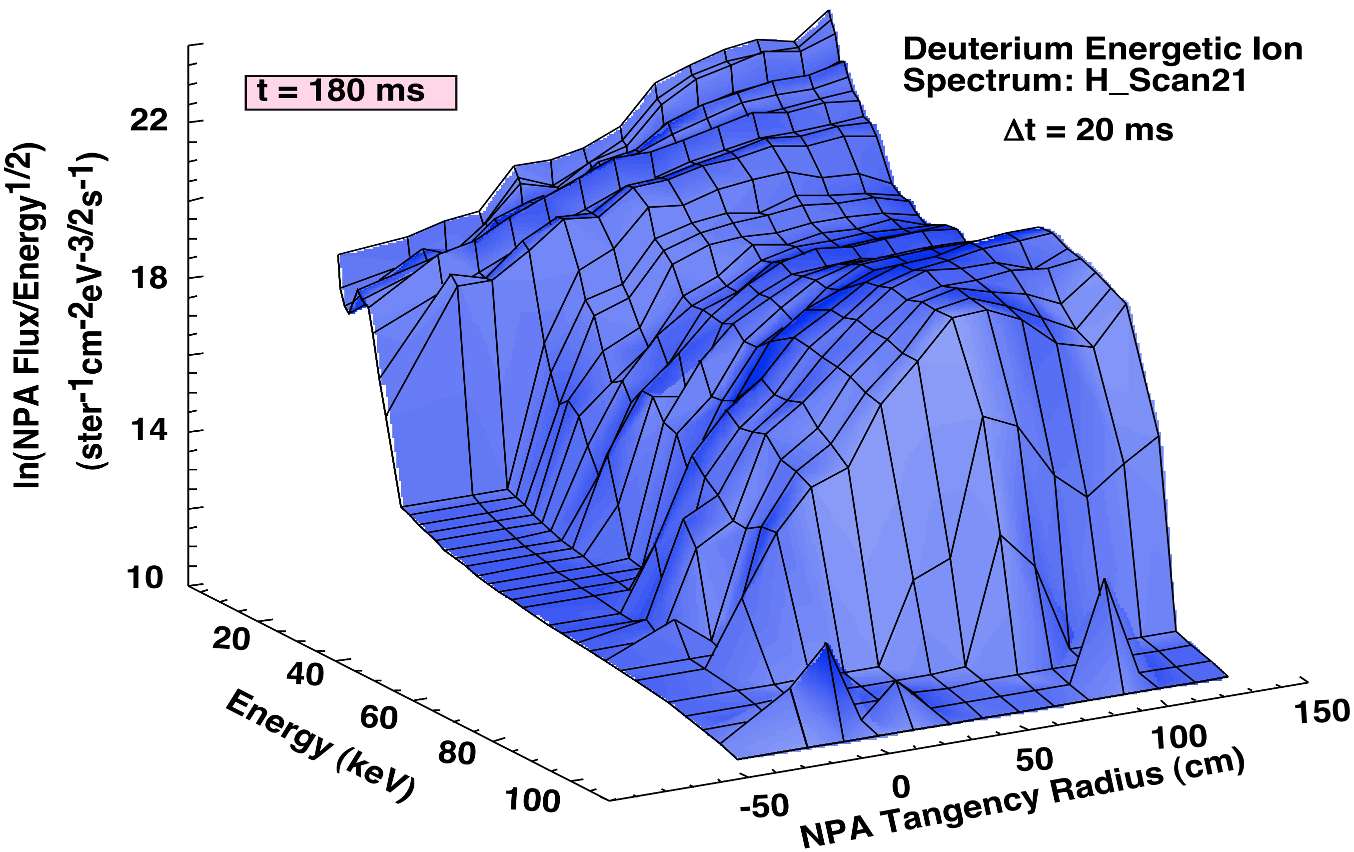




Spectrum at 60 ms after start of NBI

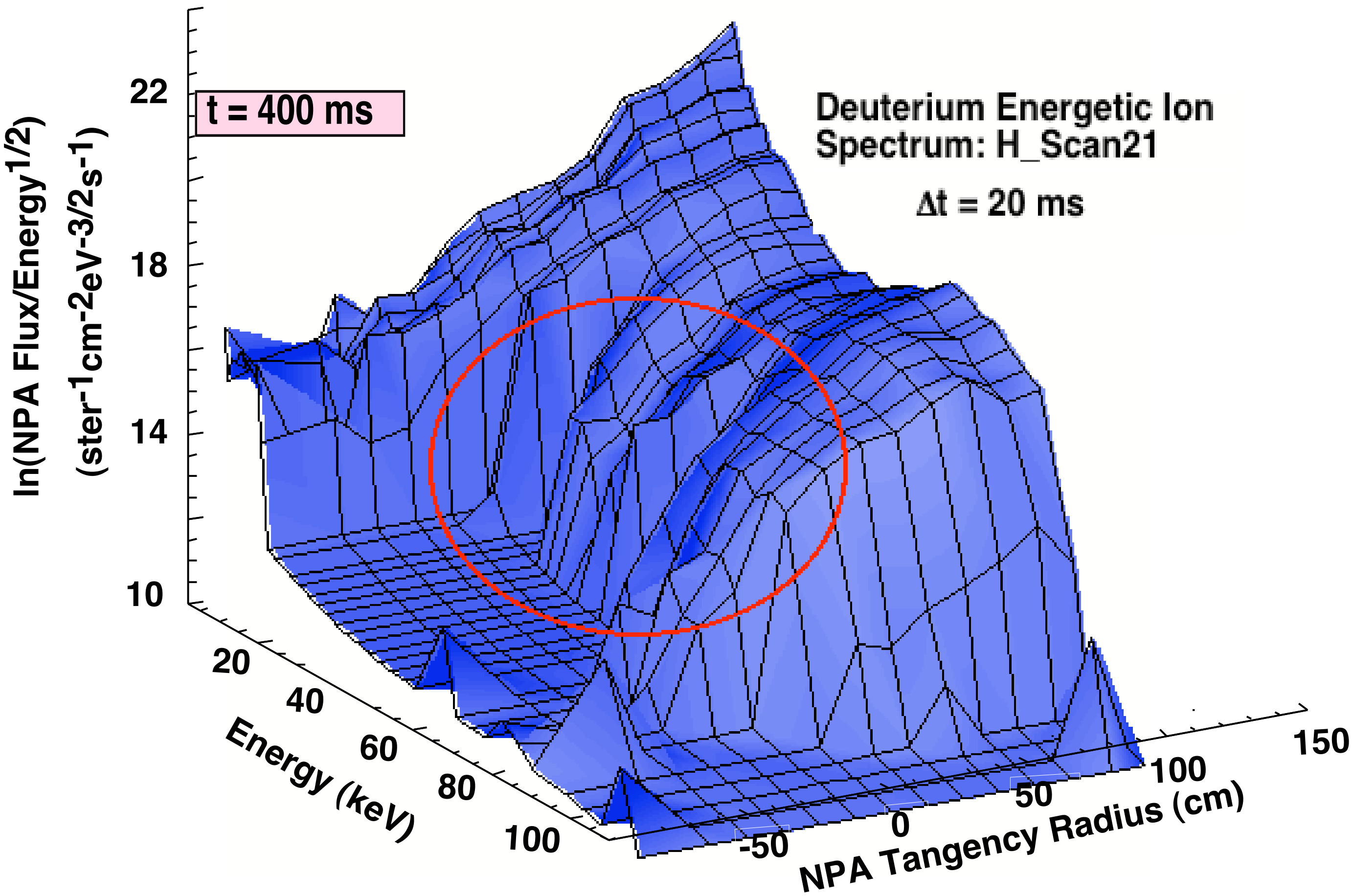
- E_{perp} distribution for $E \leq E_{crit}$ (~15 keV) fills in over ~ 60 ms (classical time: ~ 50 ms)

NPA Horizontal Scan at 180 ms
Preceeding H-mode Onset: No Spectrum Depletion



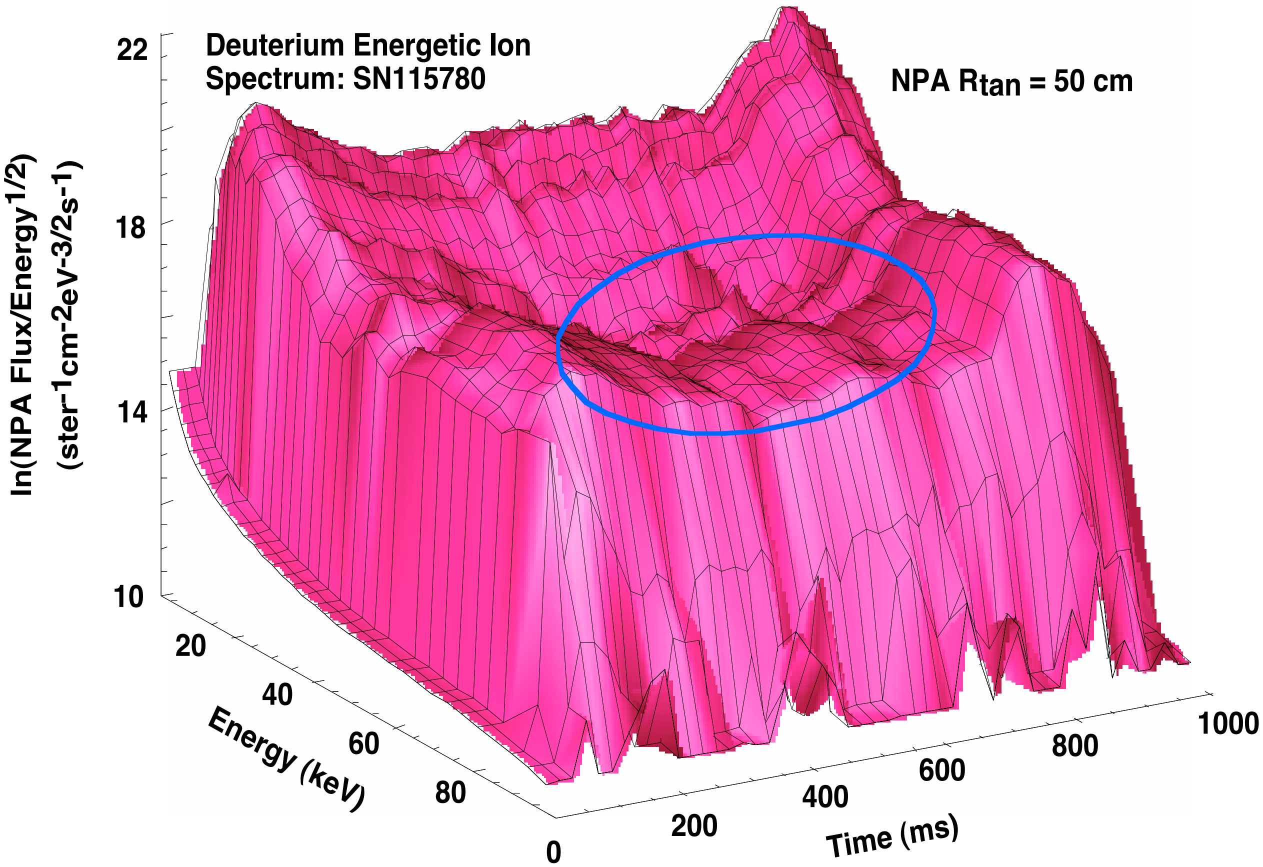
- The spectra at small tangency radii drop off naturally because this region corresponds to trapped orbits not populated by tangential NB injection in NSTX.

NPA Horizontal Scan at 400 ms Following H-mode Onset: Spectrum Depletion



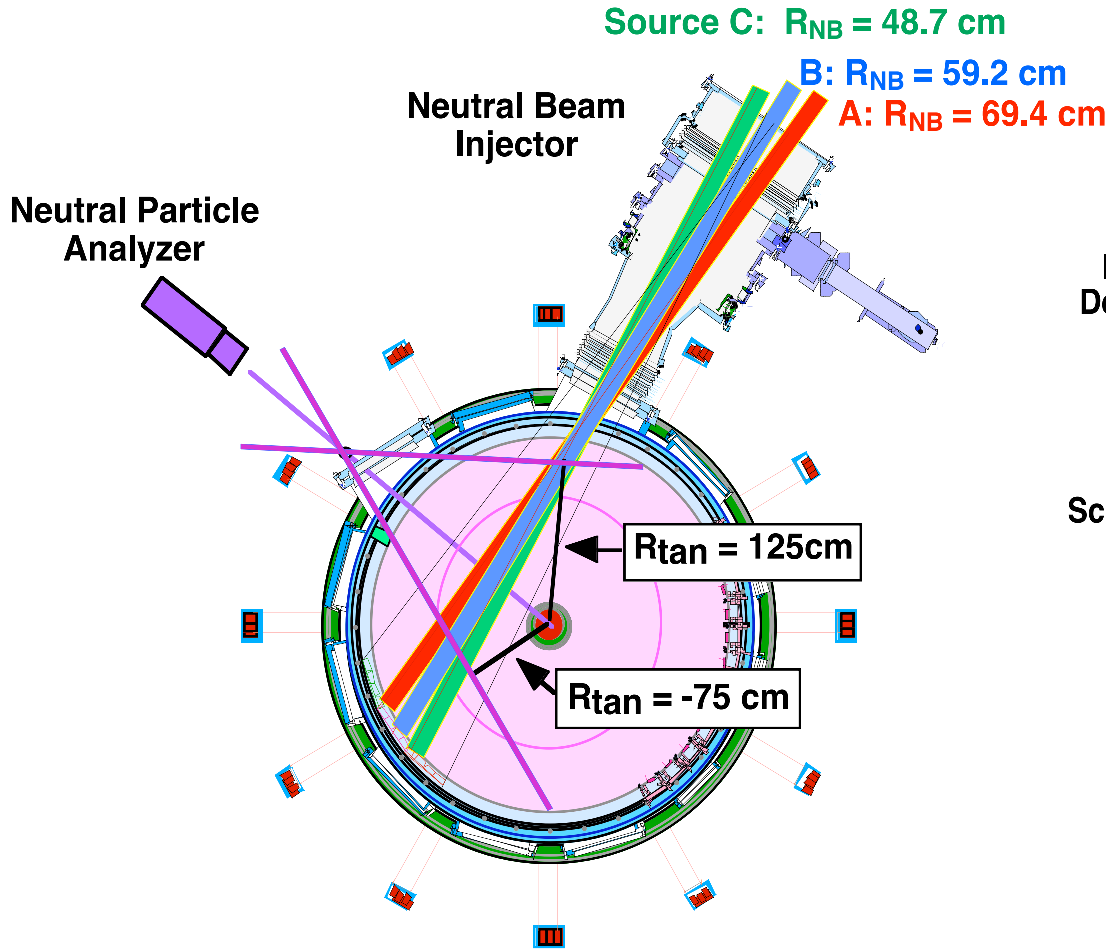
- Following H-mode onset, a clear depletion of the NPA horizontal scan spectrum is observed at E > E_b/3 and R_{tan} < 50 cm (encircled region).

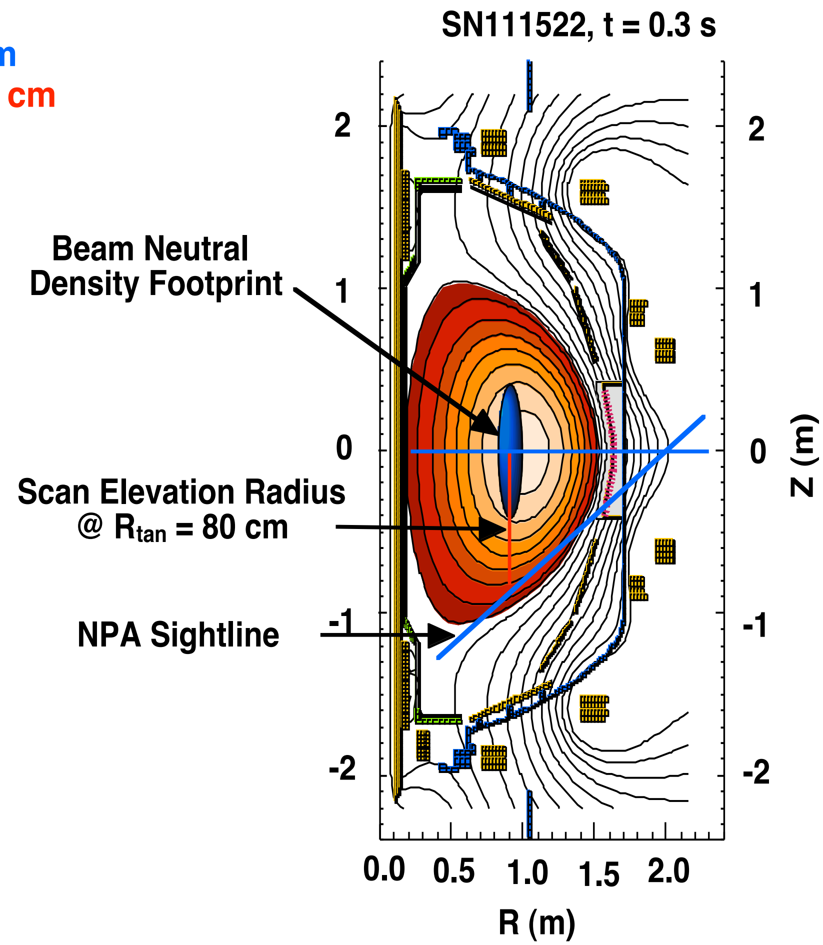
NPA Energetic Ion Spectra at Smaller Tangency Radii are Significantly Depleted



- The NPA energetic ion spectrum for R_{tan} = 50 cm shows significant depletion especially at E > $E_b/3$ (encircled region) following H-mode onset.

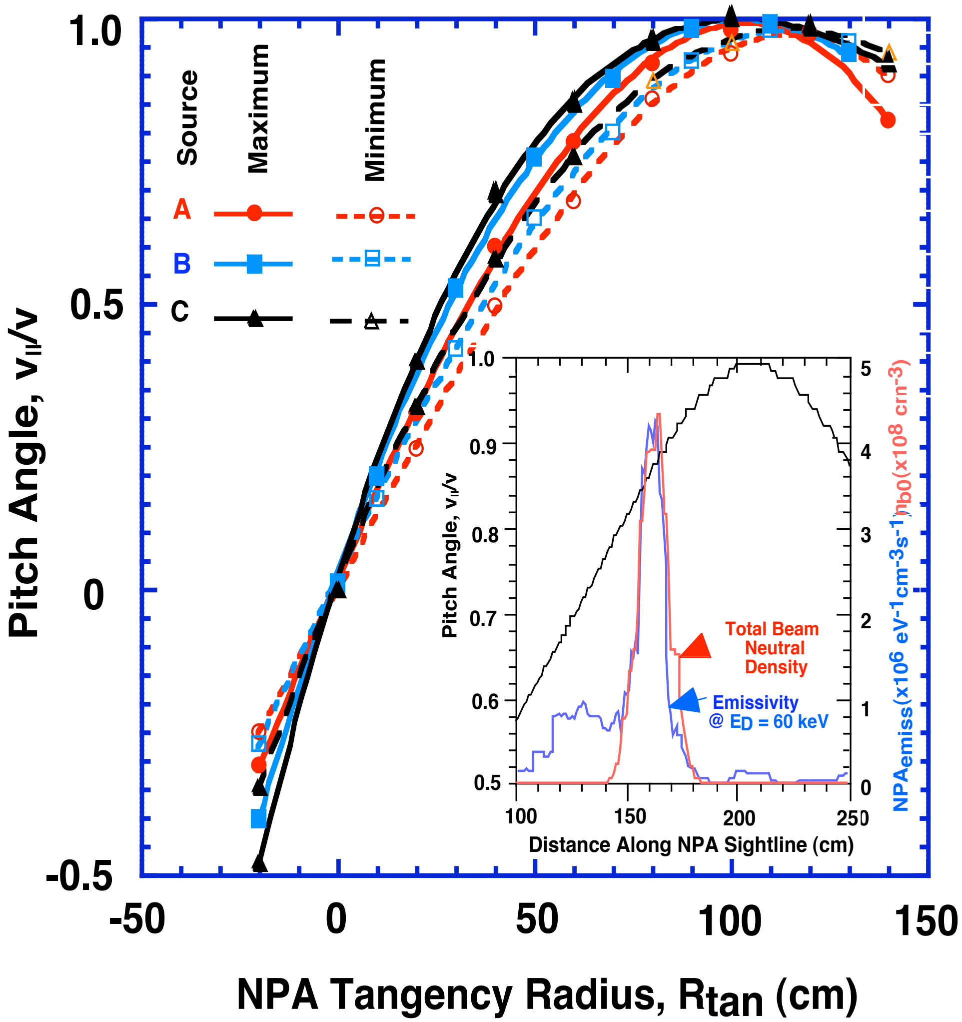
The Neutral Particle Analyzer (NPA) on NSTX Scans Horizontally Over a Wide Range of Tangency Angles on a Shot-to-Shot Basis

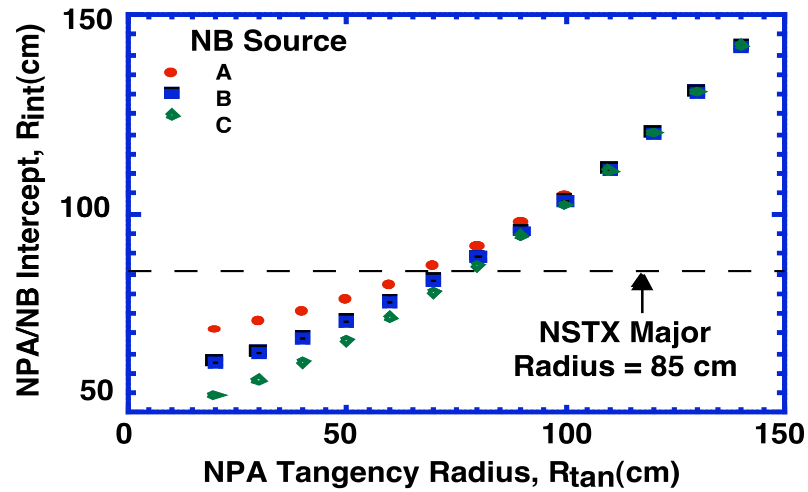


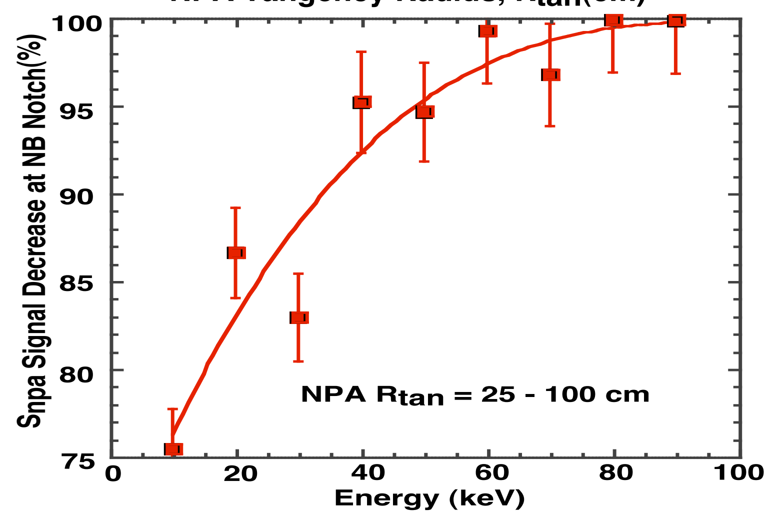


- Covers thermal (0.1 - 20 keV) and energetic Ion (≤ 150 keV) ranges
- Capability exists to simultaneously scan vertically through 26°

Line-integrated NPA Measurements are 'Localized' in Pitch and Space by Beam Injected Neutrals

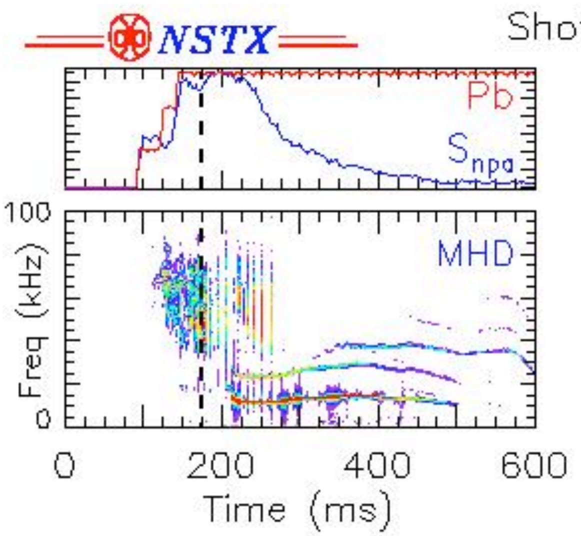


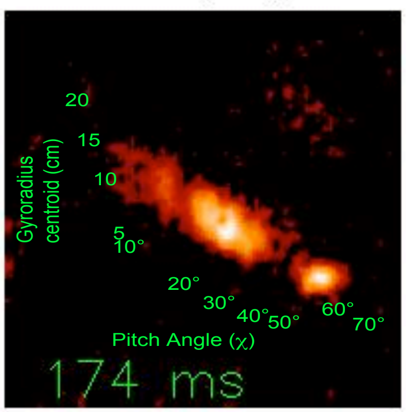


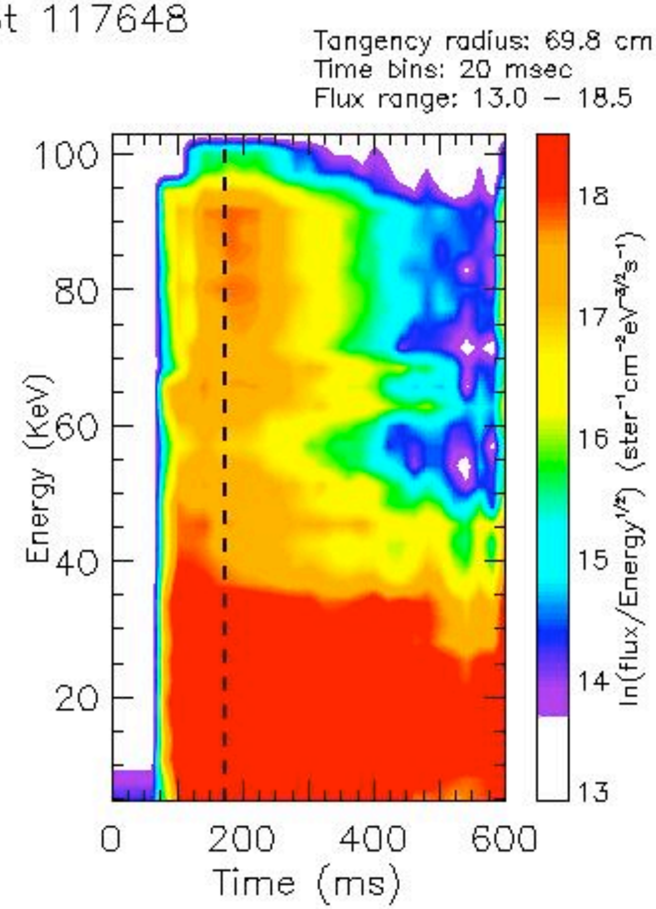


- Dominance of charge exchange emissivity by beam neutrals results in both field pitch and spatial localization of NPA measurements.

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

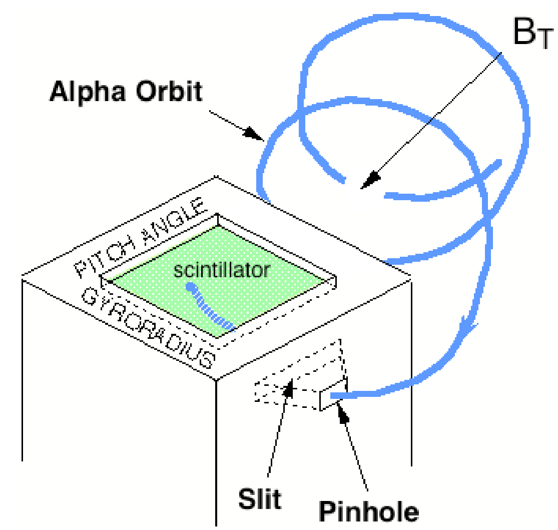






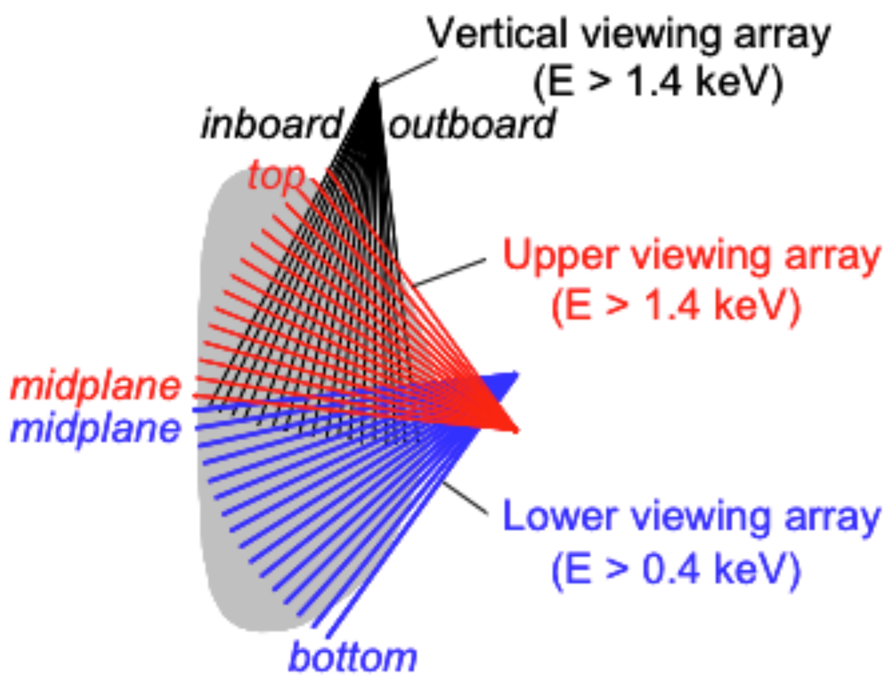
- The scintillator Fast Loss Ion Probe (sFLIP) is a magnetic spectrometer.

- B_T and aperture geometry disperse pitch angles and energies on scintillator.



- In AVI mode, the dashed-line cursor tracks waveforms and MHD activity (top left) and NPA fast-ion distribution (right) to correlate with sFLIP images showing ion loss.

USXR Measurements are used to Localize MHD Mode Activity



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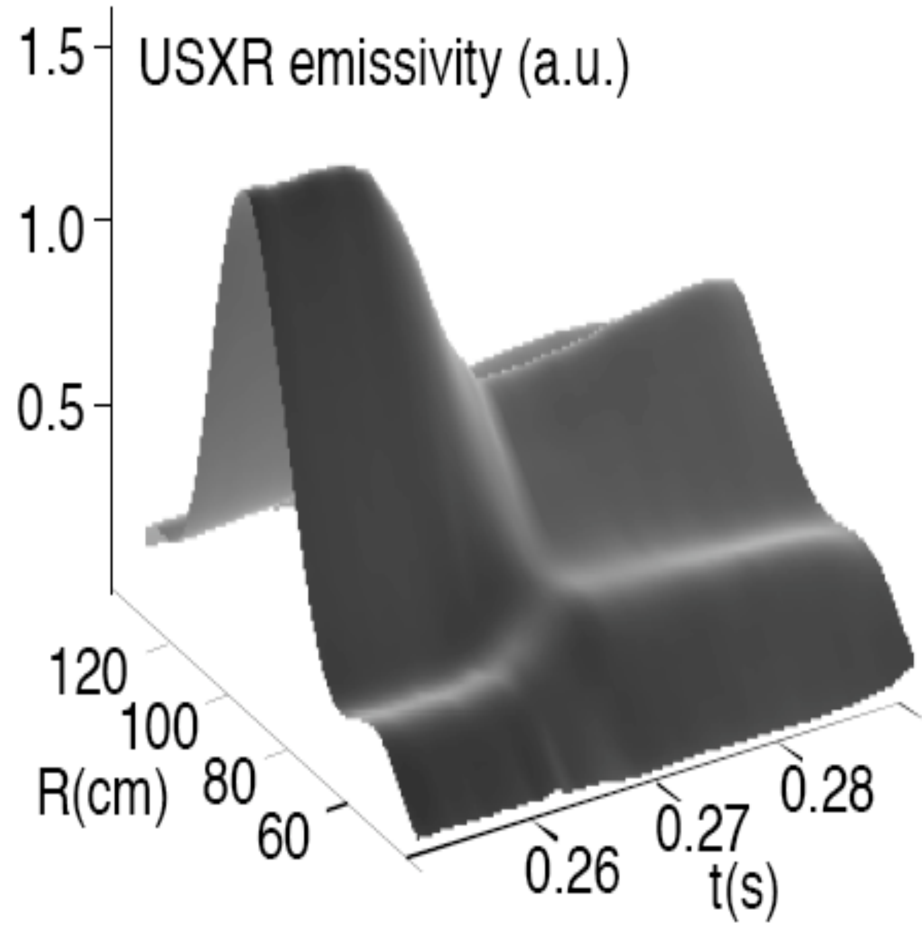
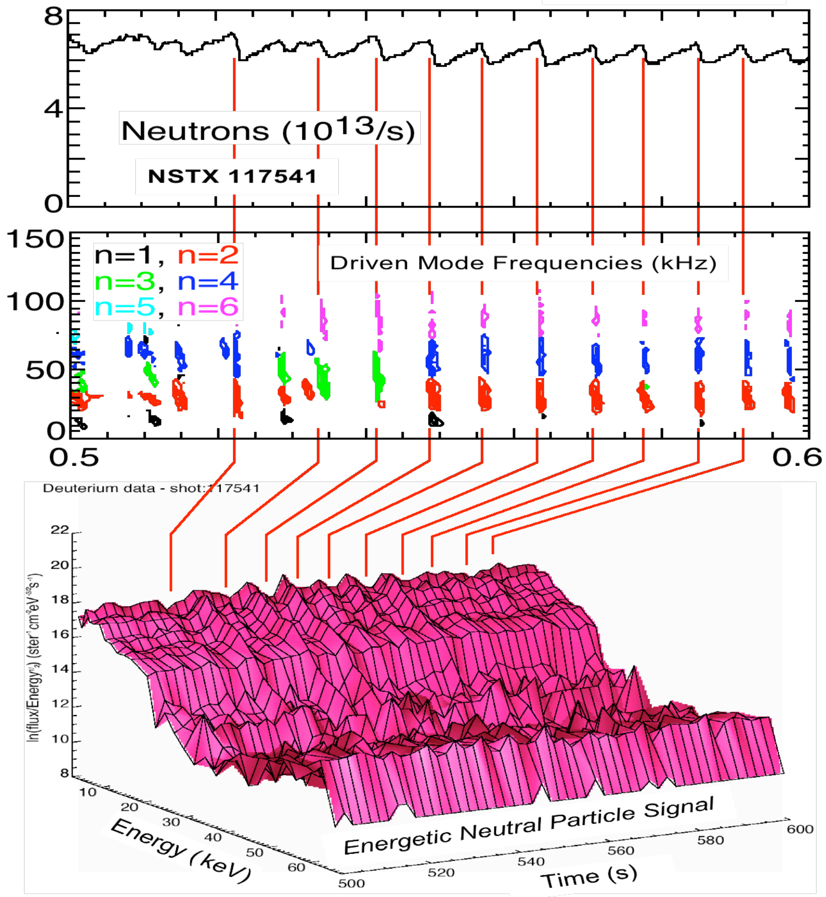
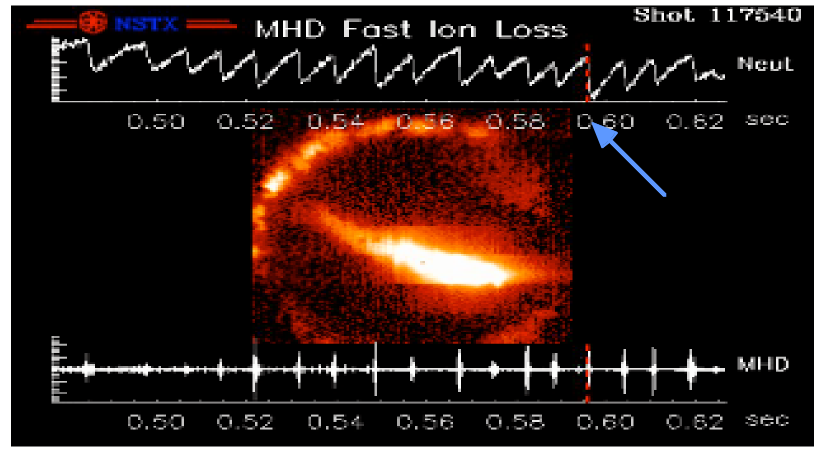
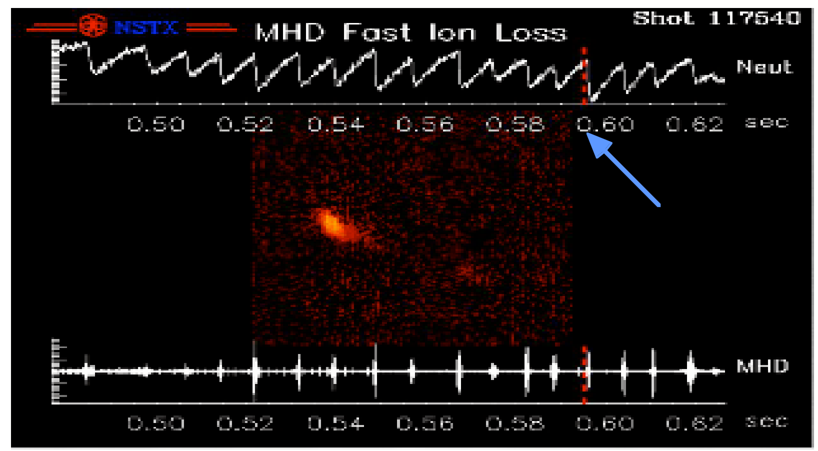


- **Inversion of ultra-soft x-ray (USXR) line-integrated emission data from multiple arrays (left) enables spatial localization of MHD activity (right).**

Example of Fast-ion Loss due to Bursting EPM Activity *aka* Bounce Resonance Fishbones

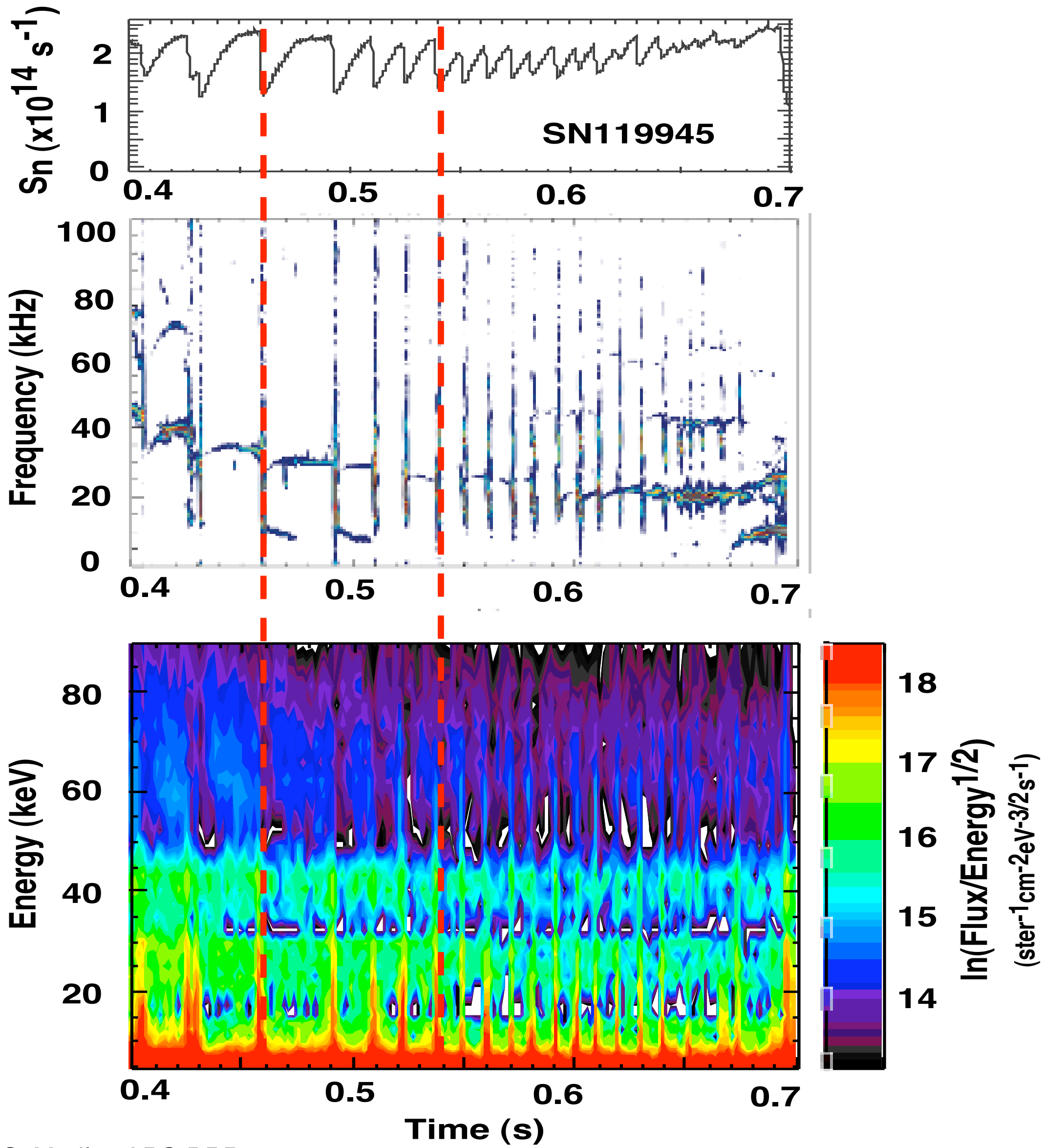






- **Bursting EPM activity (center panel) causes cyclic decrements in the neutron rate of order 5-10% (top panel) and correlated spikes in the NPA fast ion spectrum (bottom panel) that occur primarily at lower energies. The flash in the sFLIP image (top right panel) indicates that fast ions are expelled rather than redistributed.**

Example of Fast-ion Loss due to Sawtooth Activity



- Sawtooth activity (center panel) can causes drops in the neutron rate of up to 50% (top panel) and correlated spikes in the NPA fast ion spectrum (bottom panel).

- NPA spikes occur at all energies, albeit with a larger variation in the charge exchange neutral flux at lower energies.

- sFLIP data indicate that fast ions are not redistributed but are expelled.

NPA Fast-ion Loss During a Sawtooth Correlates with the Neutron Drop

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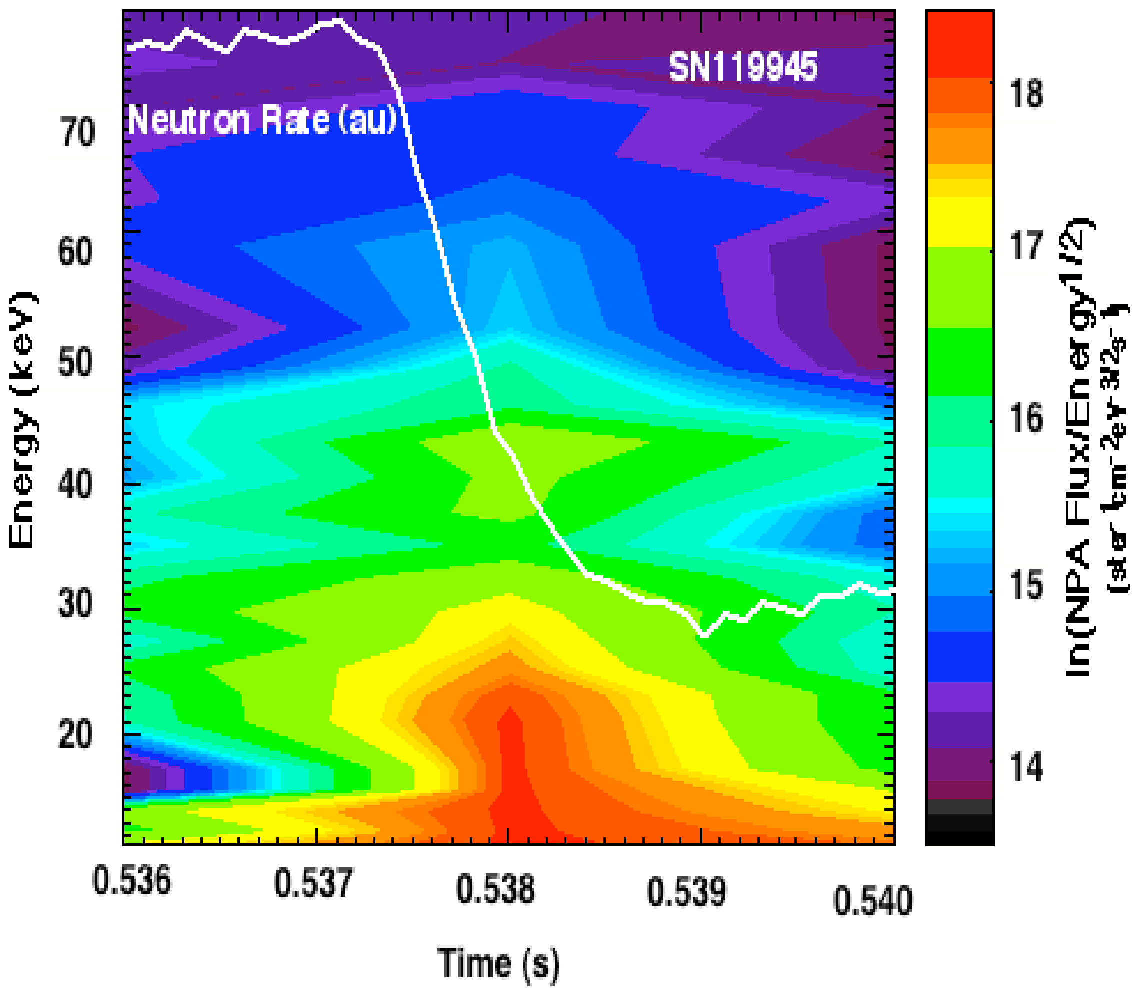


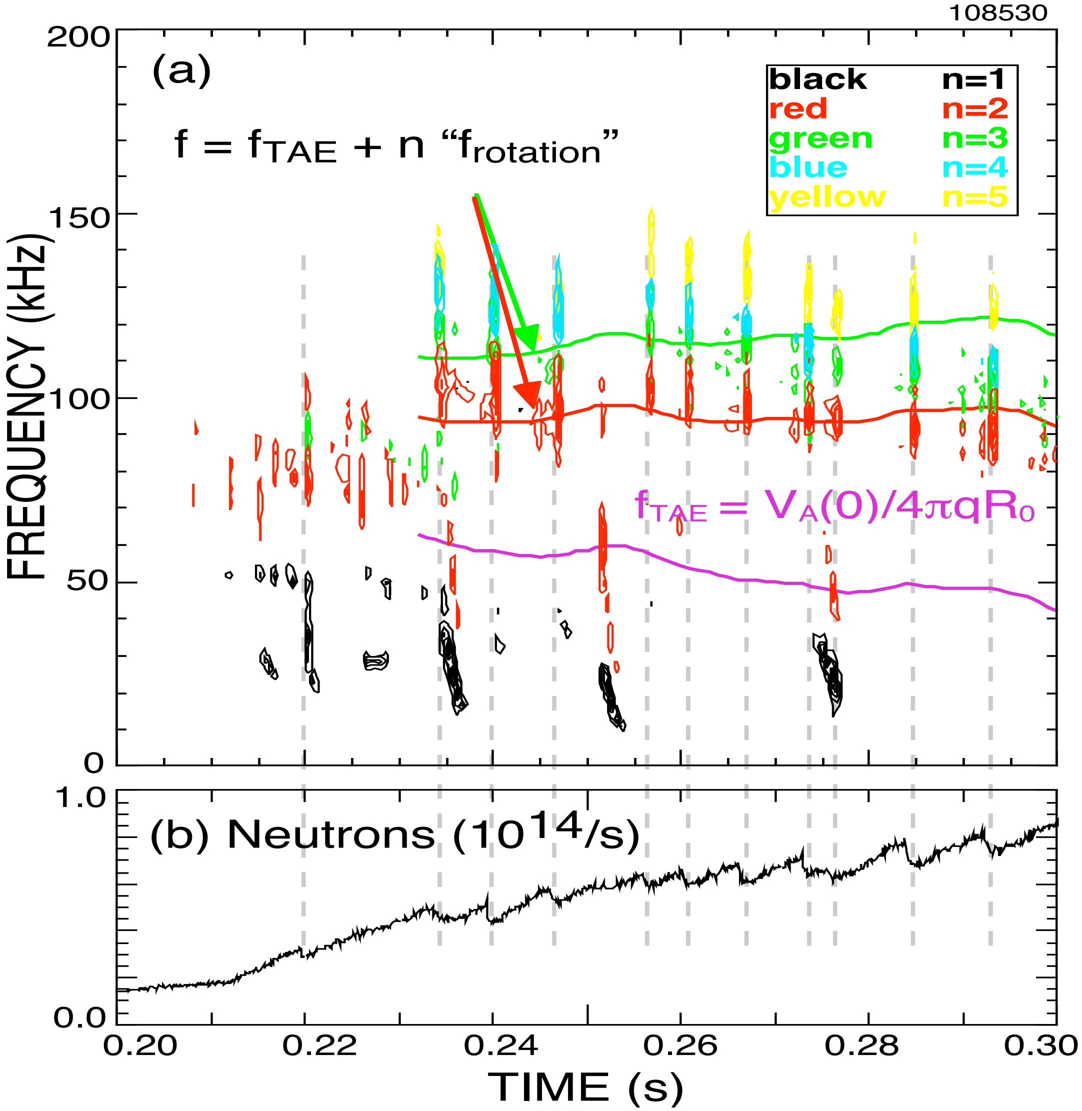
- Neutron rate and contour plot of the NPA energetic ion distribution are shown for a single sawtooth crash.

- NPA spikes occur at all energies, albeit with a larger variation in the CX neutral flux at lower energies.

- During the sawtooth, NPA efflux increases about 1/2 e-folding at $E \geq E_b/2$ and ~ 1 e-folding at $E \sim E_b/3$ where E_b= 90 keV is the NB full energy.

- sFLIP data indicate that fast ions are expelled rather than redistributed.

Example of Fast-ion Loss due to Bursting TAE Activity



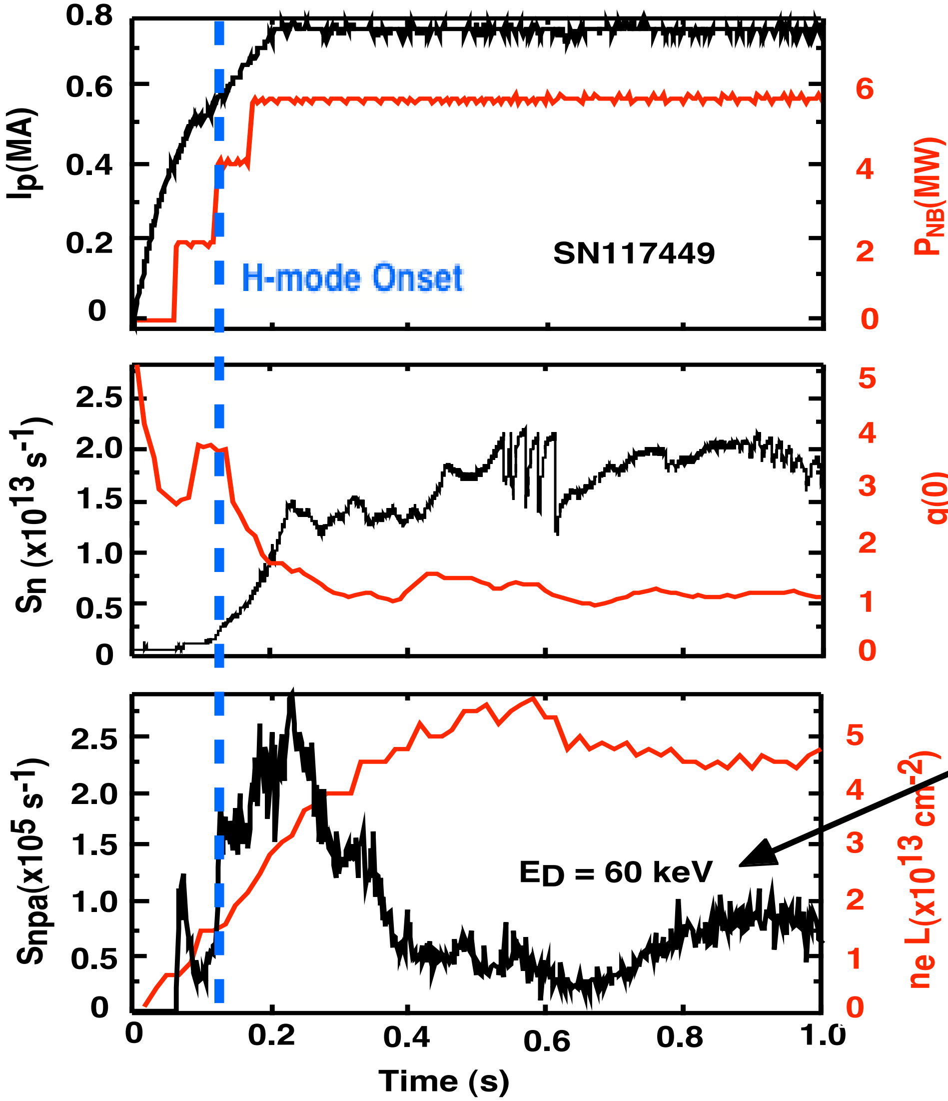
- The Mirnov spectrogram (upper panel) shows TAE bursts in the range f ~ 80 - 130 kHz with color-coded toroidal mode numbers n = 2-5 . The n=1 mode is a fishbone.

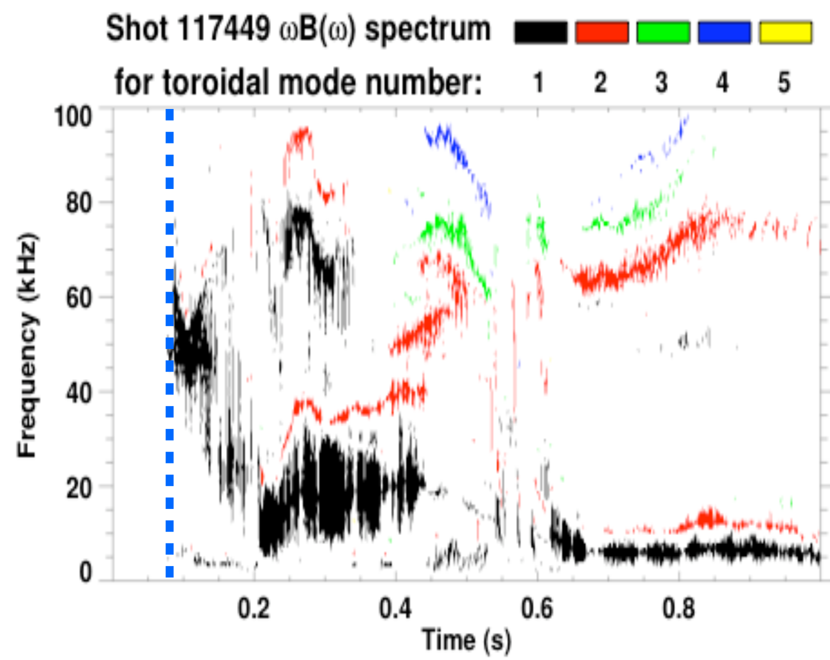
- Evolution of estimated core TAE frequency (magenta) when Dopper shifted using CHERS core plasma rotation match data for the dominant toroidal mode numbers n=2 (red) and n=3 (green) .

- sFLIP data indicate that the neutron drops correspond to fast ions being expelled rather than redistributed.

Data for NSTX H-mode Discharge SN117449

I_p=0.75 MA, B_T=4.5 kG, A&B@90 keV, C@80 keV

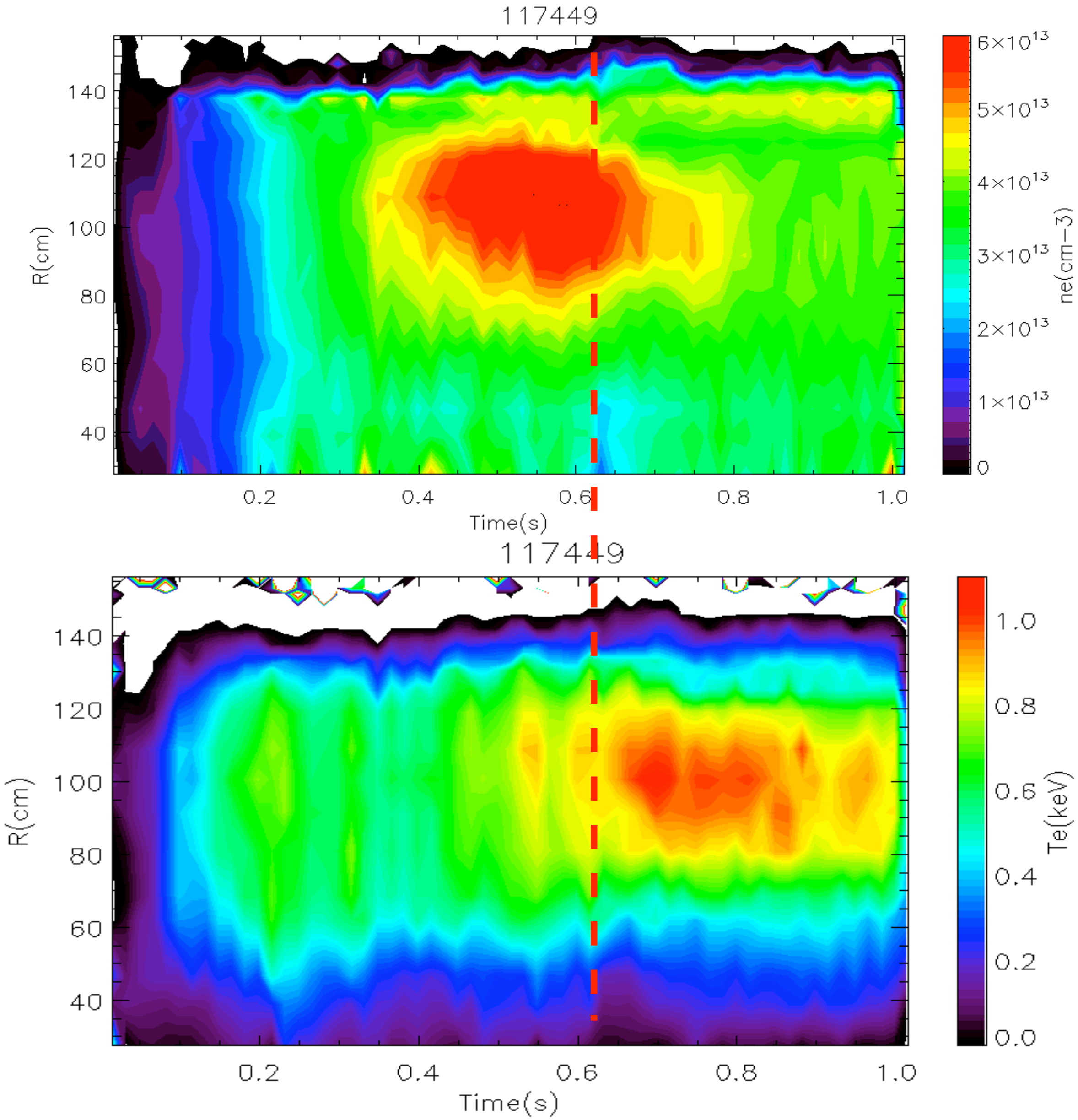




- S_{npa} depletion during n_e rise (t = 0.2-0.6 s) is due to combined effects of CX emissivity and MHD instabilities.

- The time of interest for TRANSP analysis is t = 0.6-1.0 s during n=1, f ~ 5-10 kHz kink-type MHD activity.

MPTS Electron Density and Temperature Data for NSTX H-mode Discharge SN117449

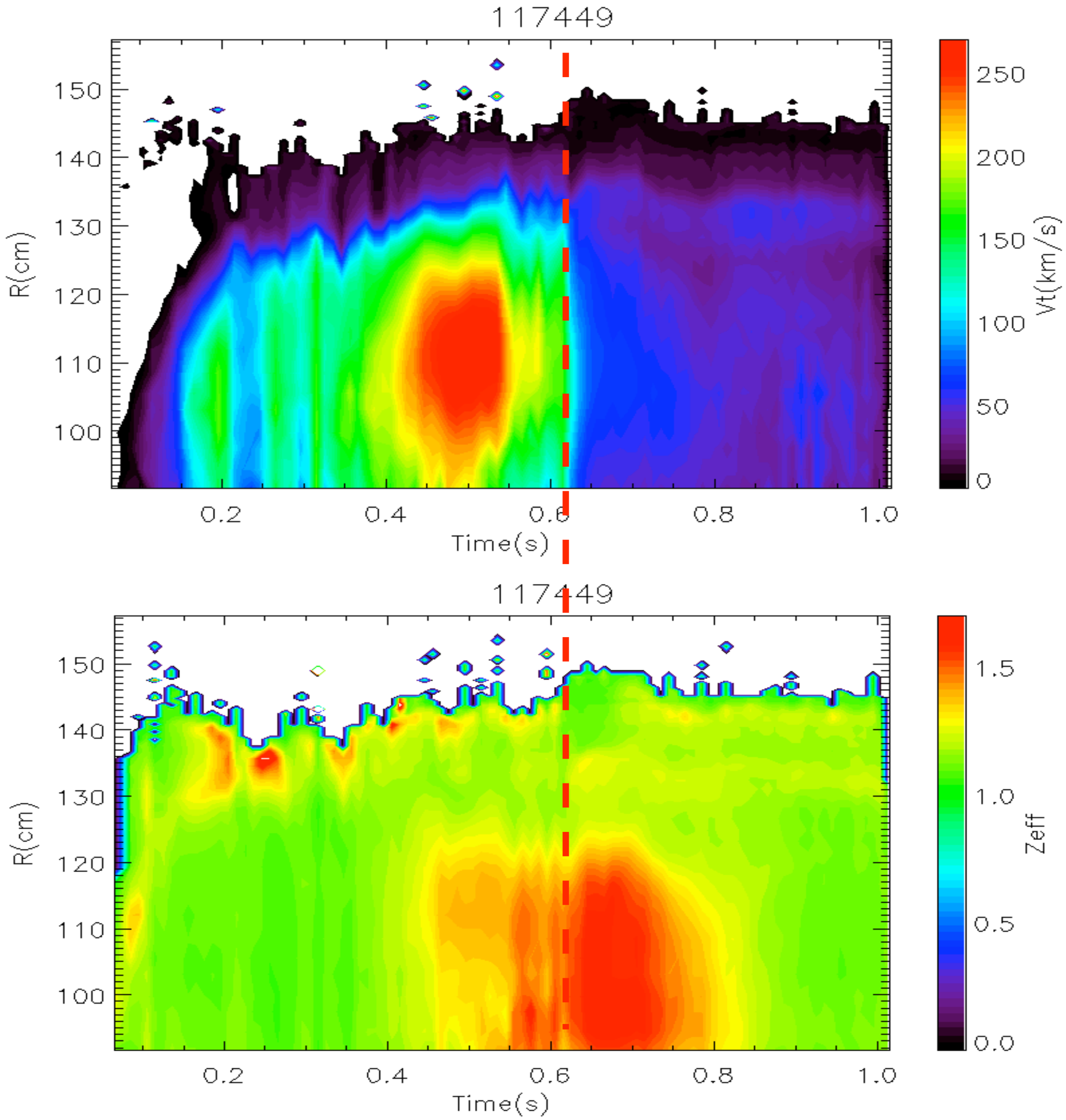


- In the previous viewgraph, the Mirnov spectrogram shows continuous TAE activity starting at t~0.2 s and transitioning to bursting EPMs that cause a neutron crash and trigger n=1 kink-type MHD at t~0.62 s.

- MPTS contour plots (left) show that n_e drops and T_e rises concurrent with onset of the n=1 kink-type MHD (dashed line).

- These offsetting effects extend the fast-ion slowing down time, $\tau_e \alpha\, T_e^{3/2}/n_e$, which contributes to the post-crash recovery of S_n.

CHERS Toroidal Rotation and Zeff Data for NSTX H-mode Discharge SN117449

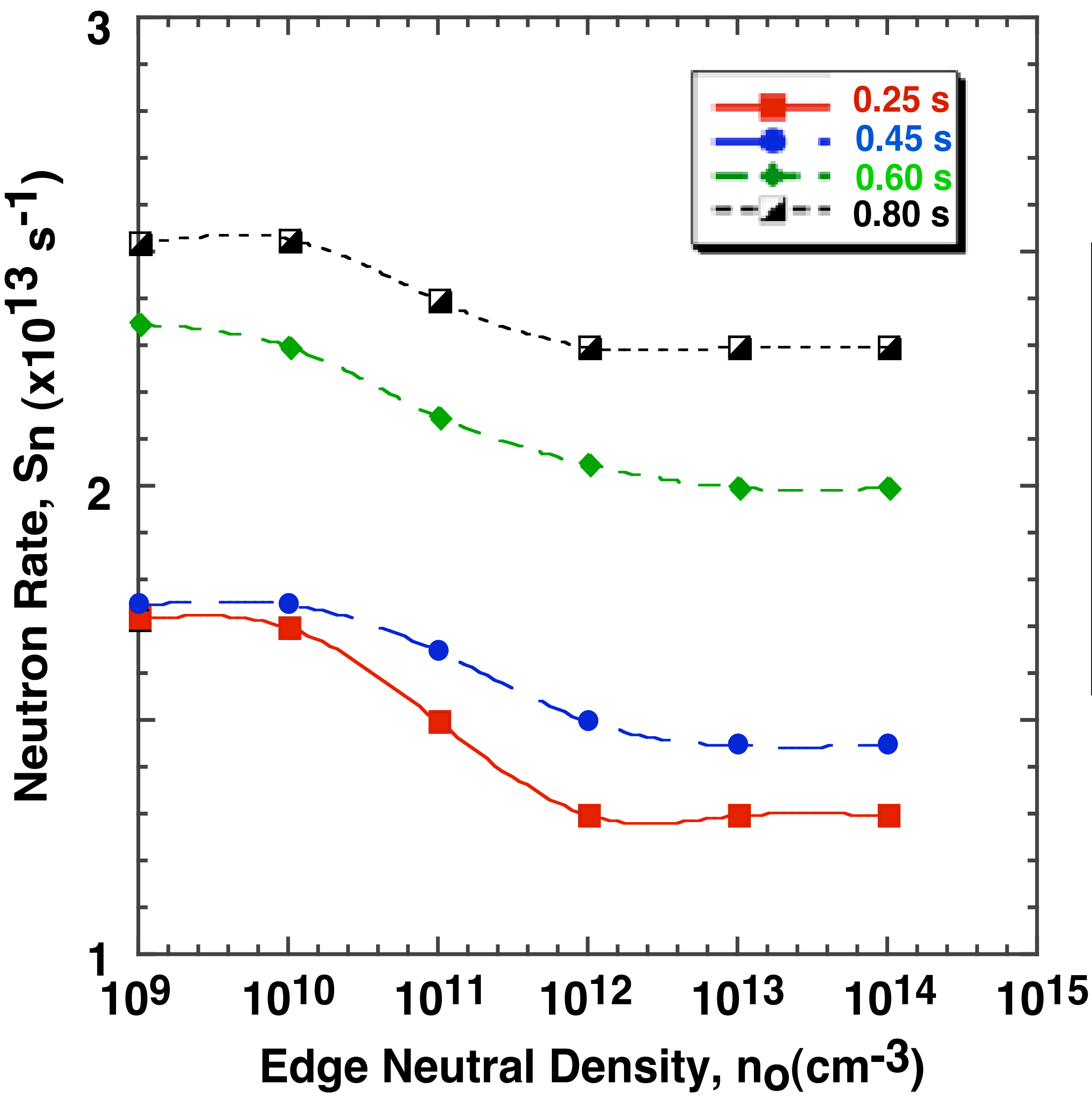


- As stated previously, the Mirnov spectrogram shows continuous TAE activity starting at t~0.2 s and transitioning to bursting EPMs that cause a neutron crash and trigger n=1 kink-type MHD at t~0.62 s.

- CHERS contour plots (left) show that toroidal rotation drops and Z_{eff} rises starting with EPM activity and accelerates concurrent with onset of the n=1 kink-type MHD (dashed line).

- The post-crash increase in Z_{eff} contributes to the S_n drop.

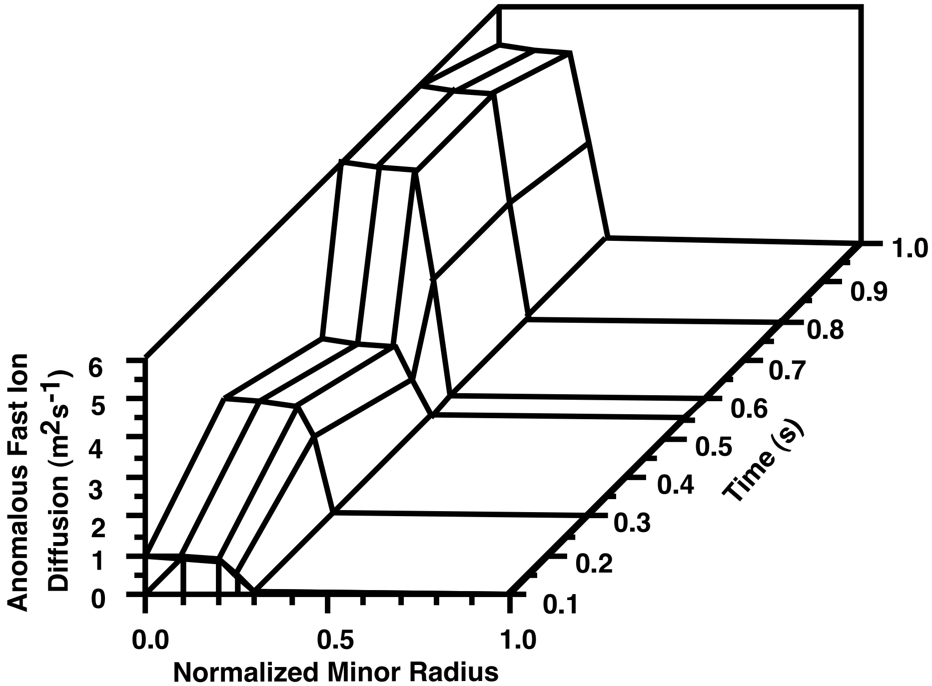
Edge Neutral Density Affects TRANSPP-calculated Neutron Rates

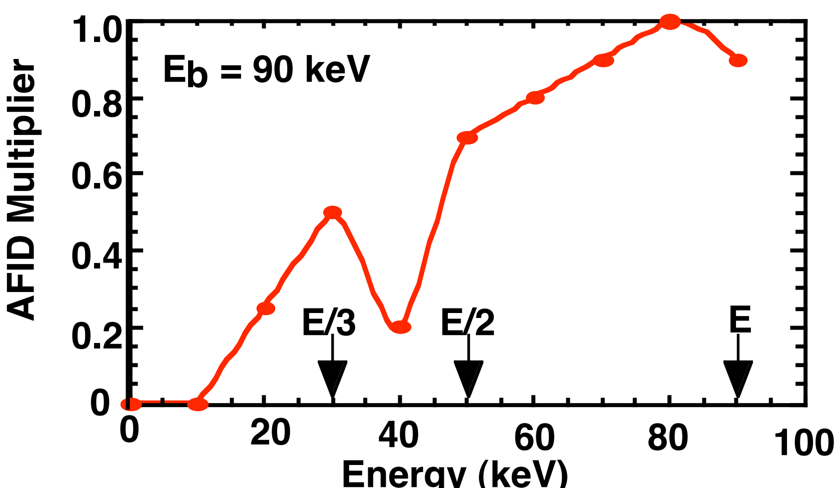


- Edge neutral density affects the TRANSP-calculated neutron rate, S_n, only over a limited range: $10^{10} < n_0(cm\text{-}3) < 10^{12}$.

- Effect on S_n decreases with time due to penetration screening by rising n_e.

TRANSP Uses Anomalous Fast Ion Diffusion (AFID) to Emulate MHD-induced Redistribution/Loss





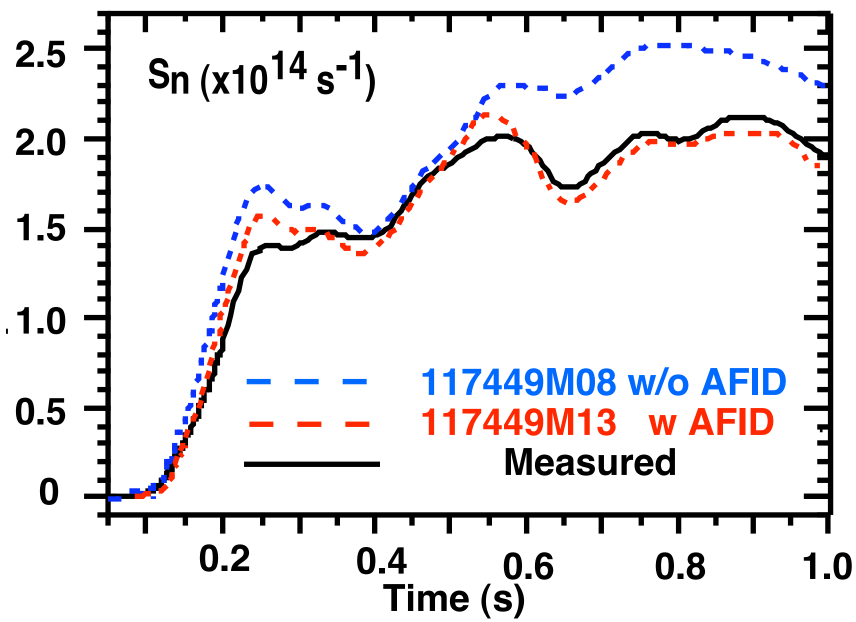
- In TRANSP, anomalous fast ion diffusion can be specified in time, space and fast-ion energy.

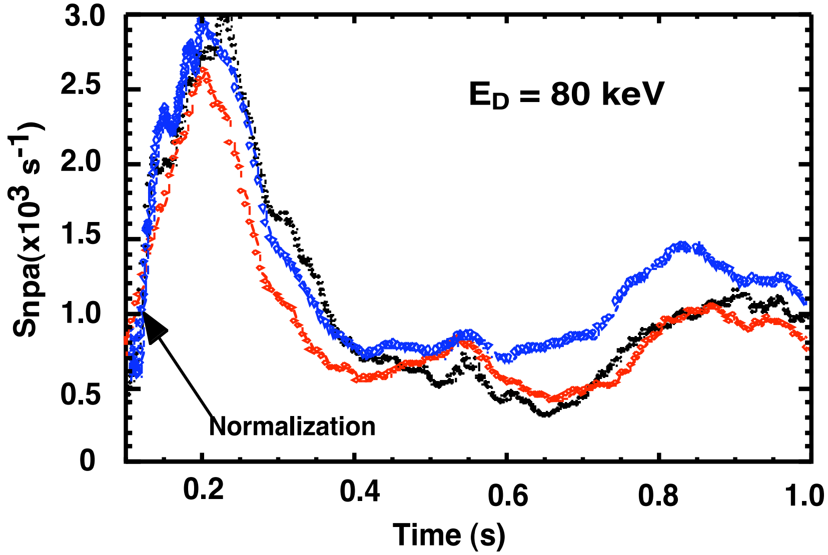
- Core-weighted anomalous fast ion diffusion is appropriate for MHD-induced redistribution. In H-mode discharges, outwardly displaced NB ions remain confined in a region of comparable n_e, T_e so neutron yield is minimally affected.

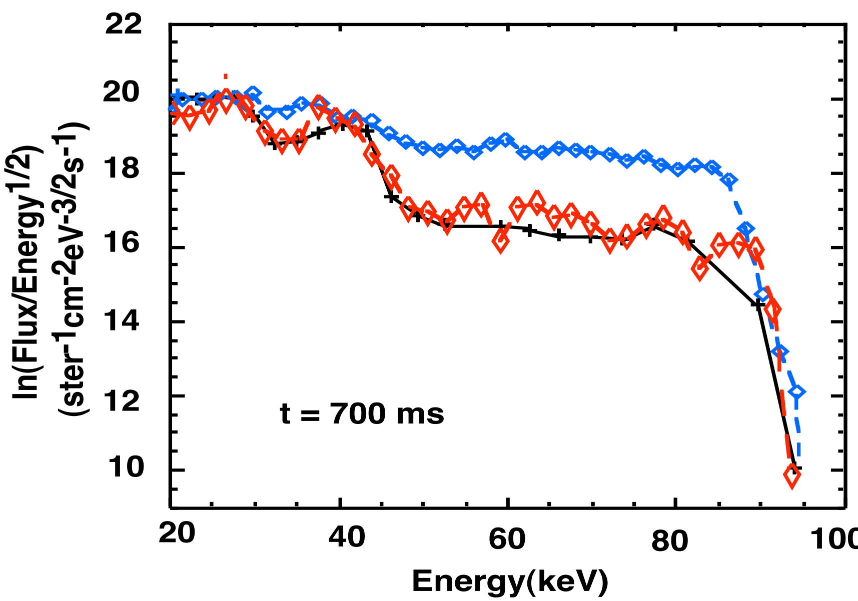
- Outboard-weighted AFID favors ion loss and significantly reduces the neutron yield.

- Energy dependence is chosen to emulate the measured NPA spectrum distribution.

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



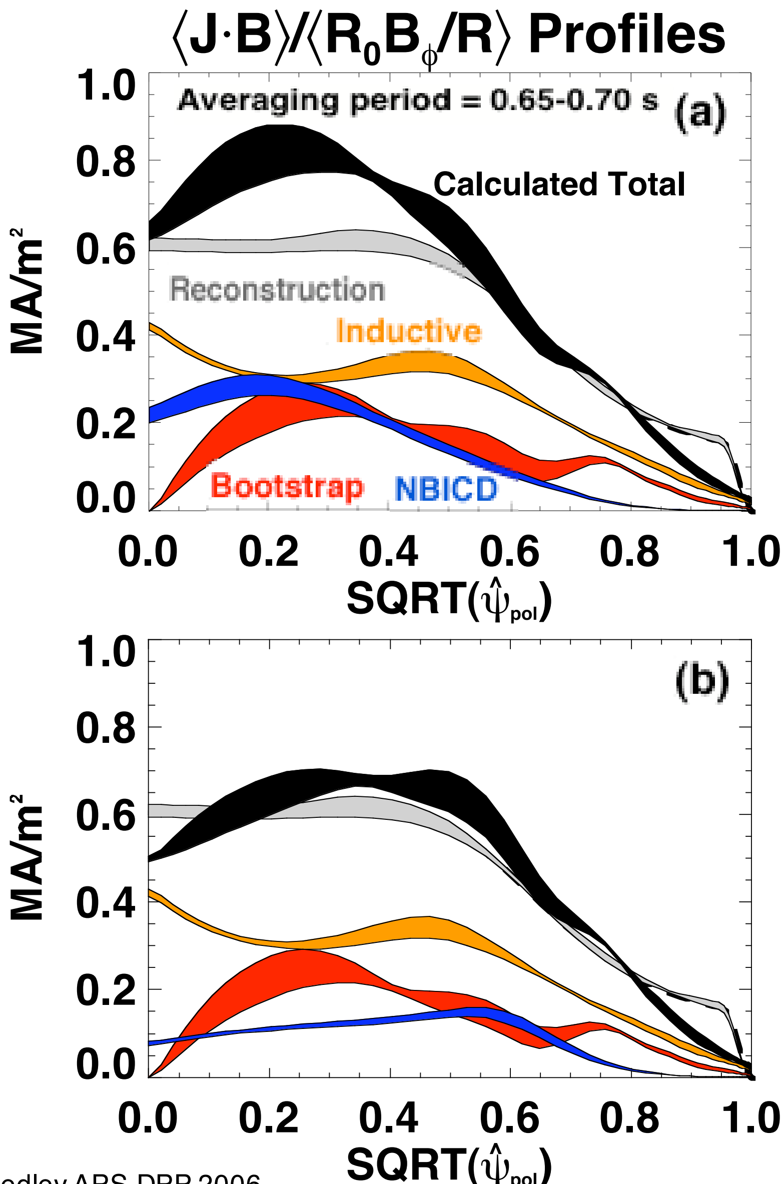




- In this TRANSP analysis, the AFID model was optimized for a time of interest (TOI) period t = 0.6-1.0 s during n=1, f = 5-10 kHz kink-type MHD.

- In the TOI, good matching of neutron rate and the NPA efflux evolution and energy spectra are obtained.

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.

Summary

- NSTX is well equipped with a suite of diagnostics to characterize MHD activity (mode, amplitude, localization) including Mirnov coils , USXR, FireTip and reflectometry.

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

- MSE-constrained current profile reconstruction and sFLIP are being utilized to distinguish between energetic ion redistribution and loss effects.

- MHD activity can reduce the neutron rate, modify the measured NPA fast ion efflux and induce NBICD profile redistribution.

- TRANSP analysis using anomalous fast ion diffusion models these effects and, in particular, can yield agreement between the calculated total current profile and that from MSE-constrained reconstruction.