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Spatially Resolved Measurements of Neutral Beam Energetic Ion Distribution in NSTX

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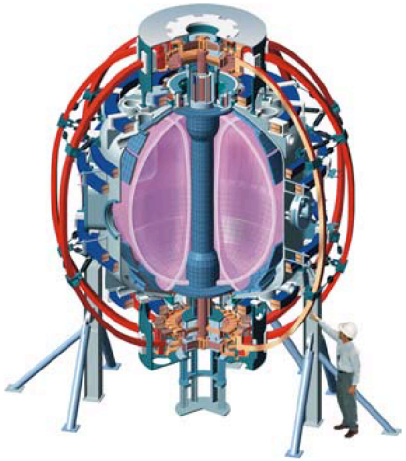

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Abstract

Spatially Resolved Measurements of NB Energetic Ion Distributions in NSTX*

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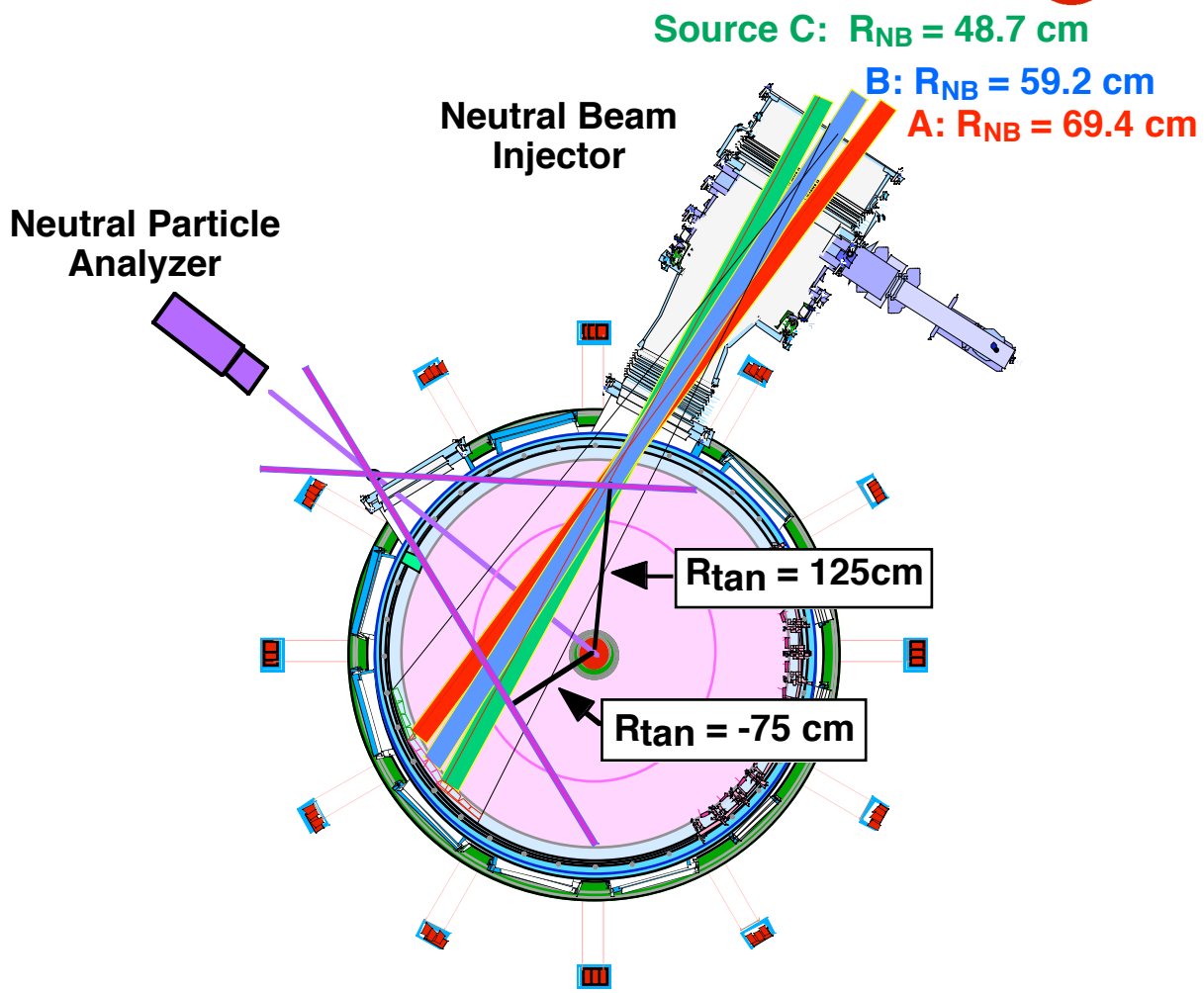
Princeton U.

The mass and energy resolving superimposed EIIB Neutral Particle Analyzer (NPA) on NSTX can be scanned over NPA sightline tangency radii from R_{tan} = +125 cm to R_{tan} = -75 cm on a shot-to-shot basis. This capability was used to measure the spatially resolved energy distribution of Neutral Beam (NB) ions in both L-mode and H-mode discharges. In L-mode discharges, the NPA spectra exhibit classical slowing down and pitch angle scattering behavior in agreement with TRANSP code simulations. Also, the measured and TRANSP-calculated neutron emission rates are in good agreement. The same is true for H-mode discharges in which low n = 1-3, low frequency f < 50 kHz MHD tearing mode activity is absent. However, when MHD activity of this type is present in H-mode discharges, the NPA spectra exhibit a significant depletion of energetic ions that depends on time, energy and spatial location. Concurrently, the TRANSP-calculated neutron emission rate generally exceeds measurements by ~ 10-20%. TRANSP analysis of these observations using a model for anomalous energetic ion diffusion as a function of energy, space and time will be presented.

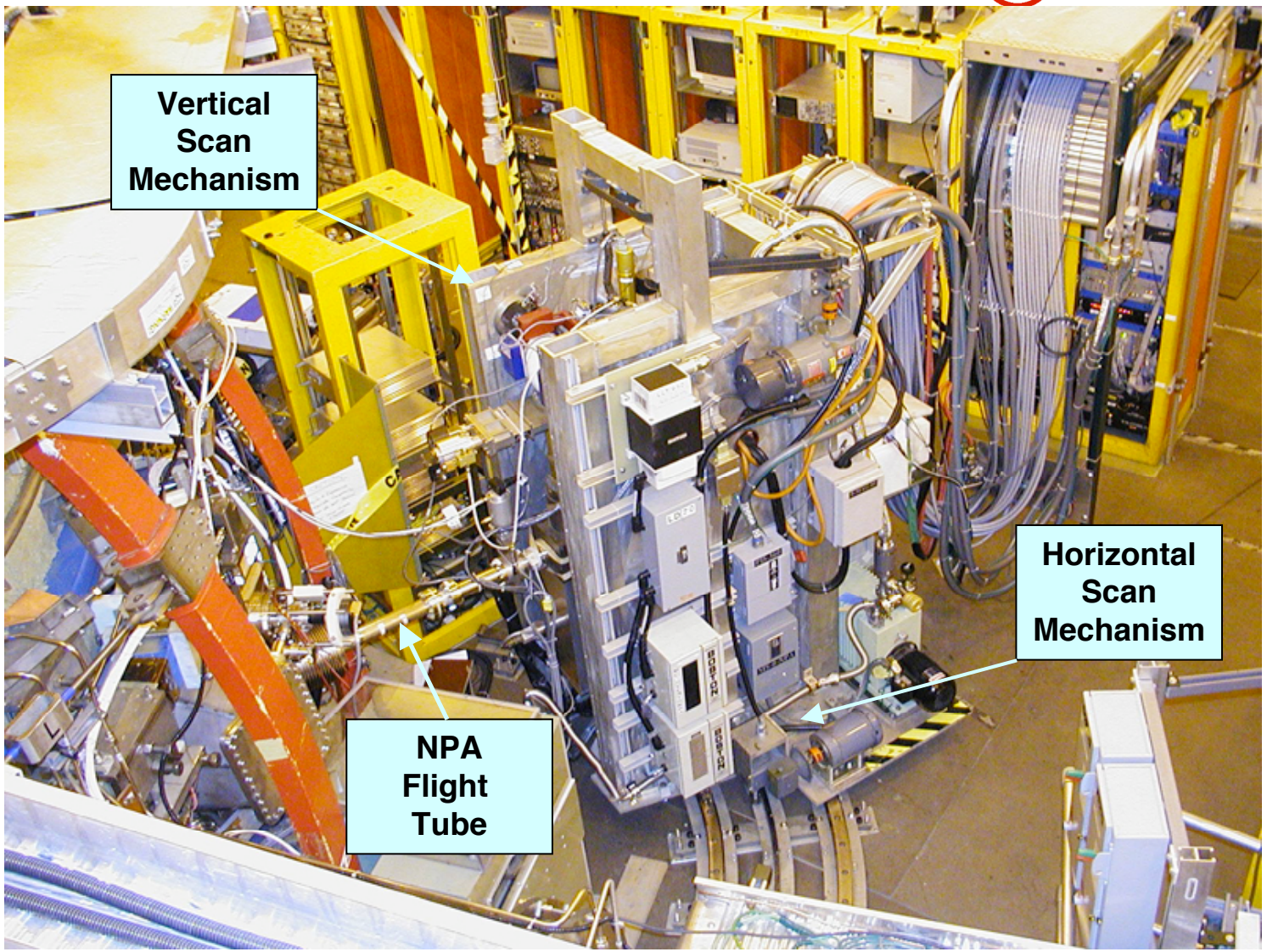
*Supported by U. S. DOE Contract DE-AC02-76CH03073

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

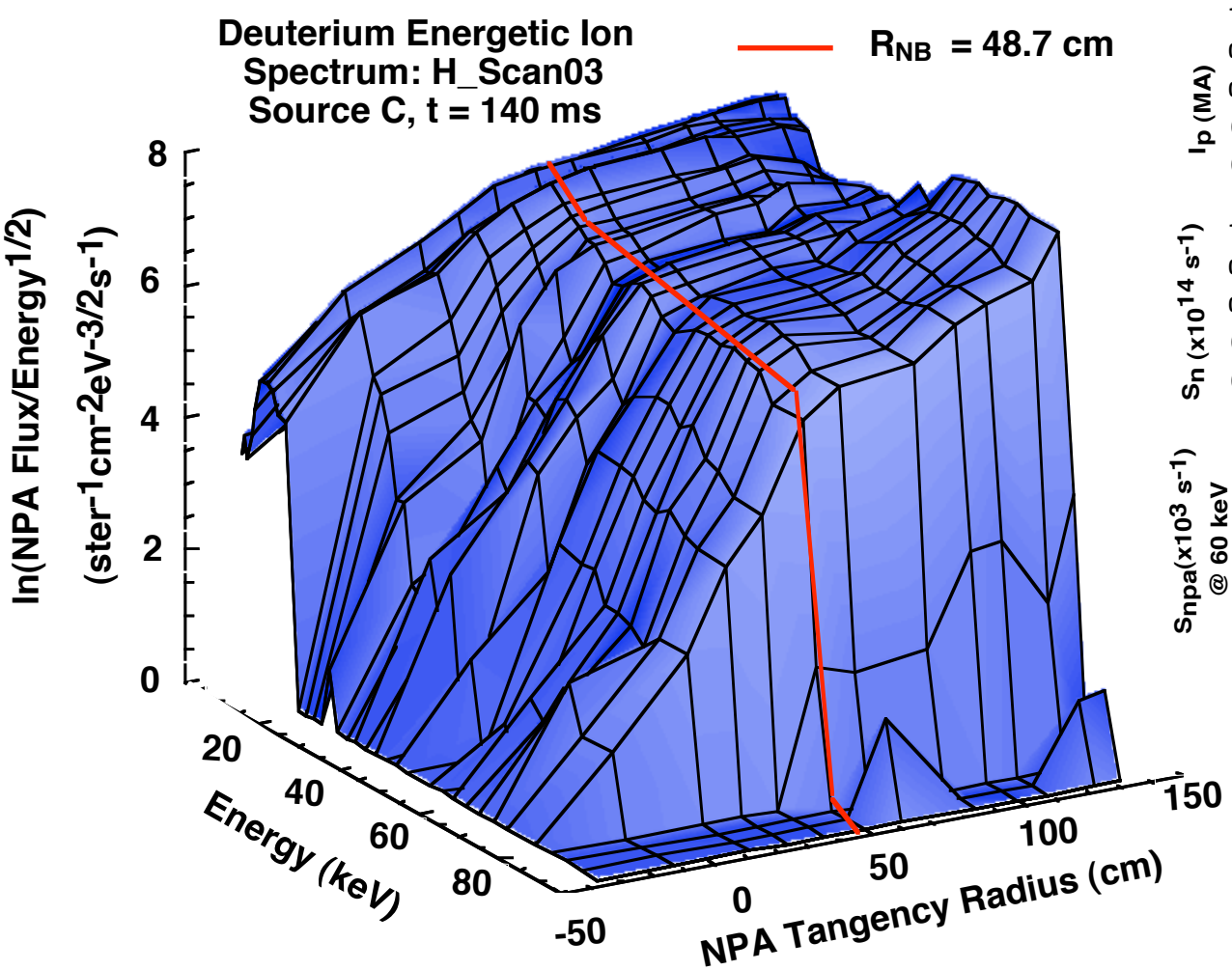


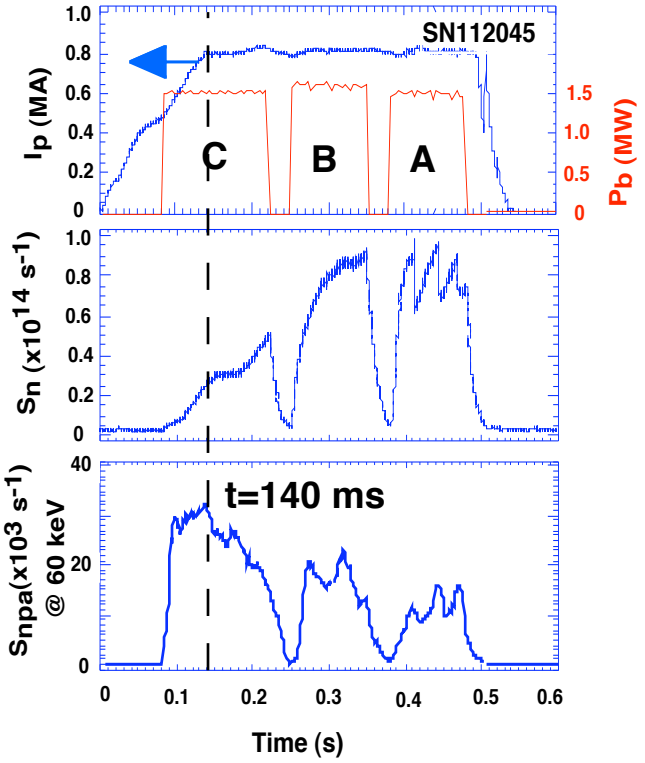
- Covers Thermal (0.1 - 20 keV) and Energetic Ion (≤ 150 keV) Ranges

Overhead View of the Neutral Particle Analyzer (NPA) Diagnostic on NSTX



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

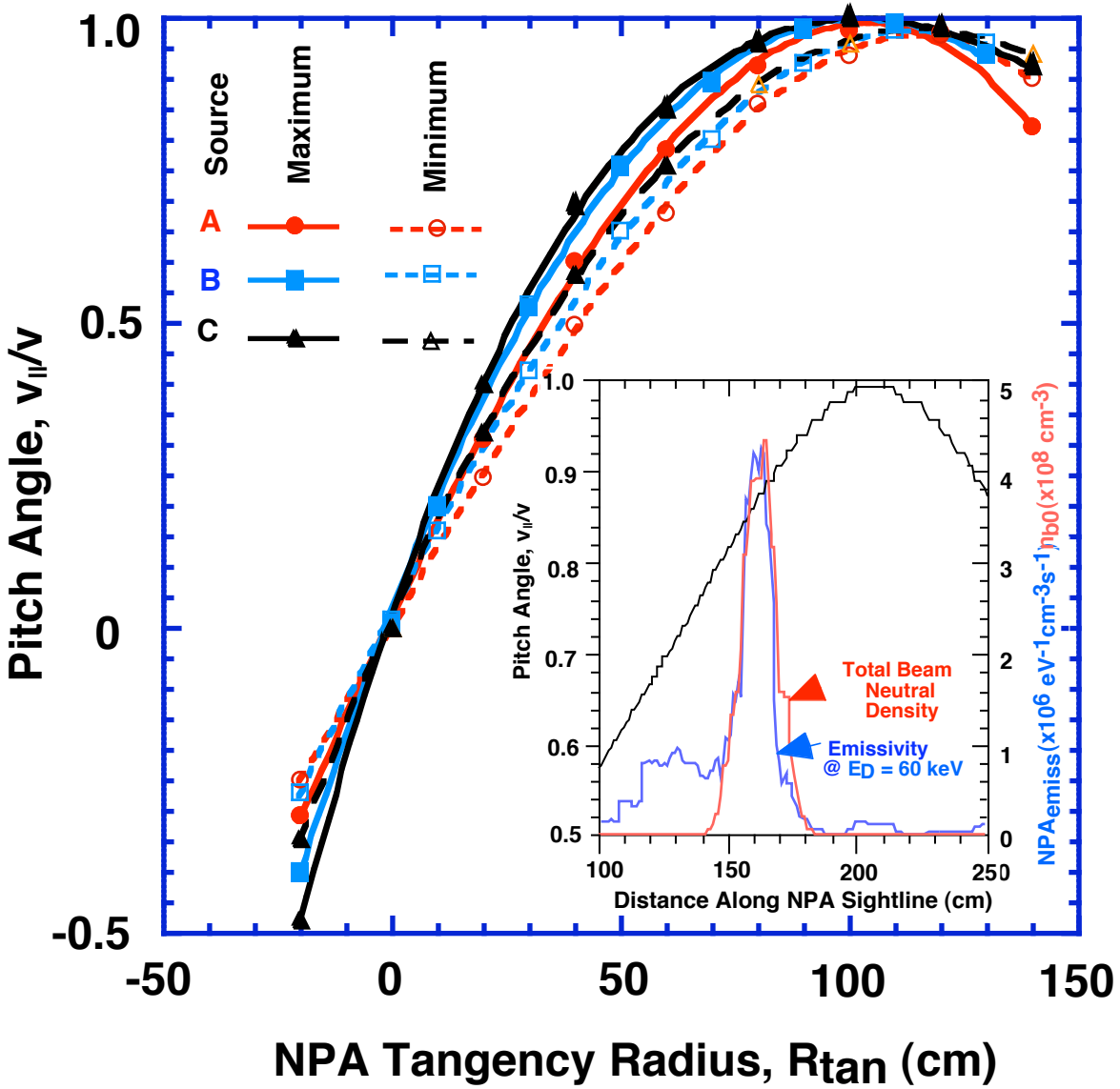




Spectrum at 60 ms after start of NBI

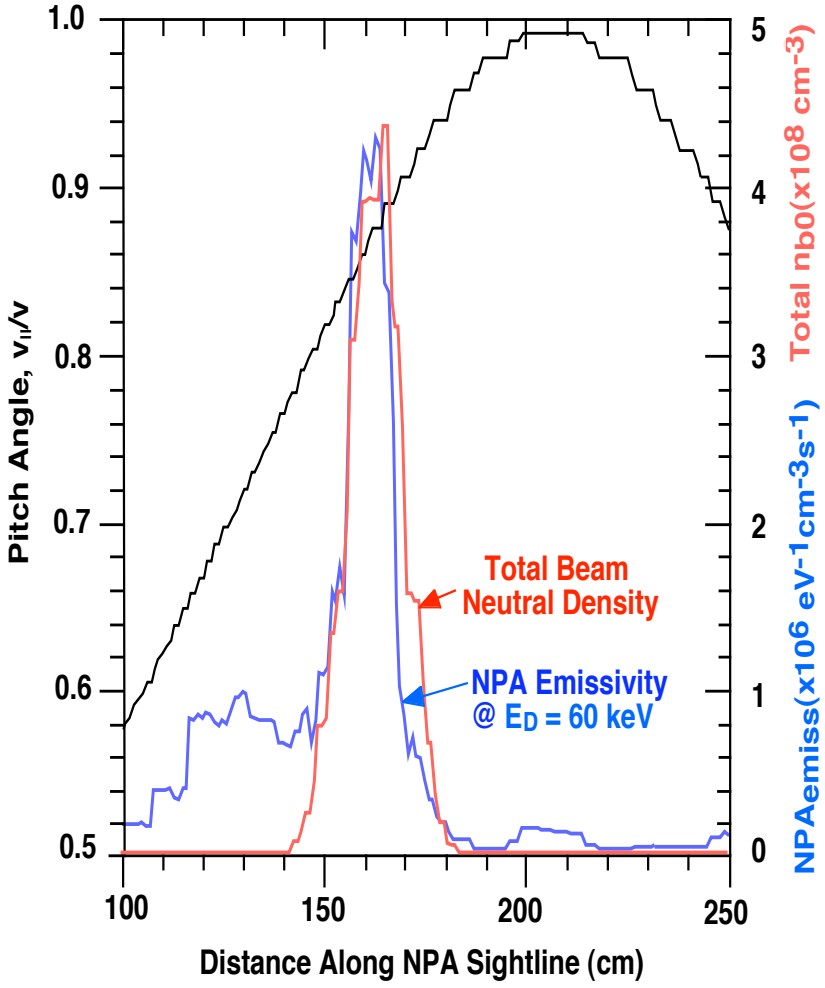
- E_{perp} distribution for $E \leq E_{crit}$ (~15 keV) fills in over ~ 60 ms (classical time: ~ 50 ms)

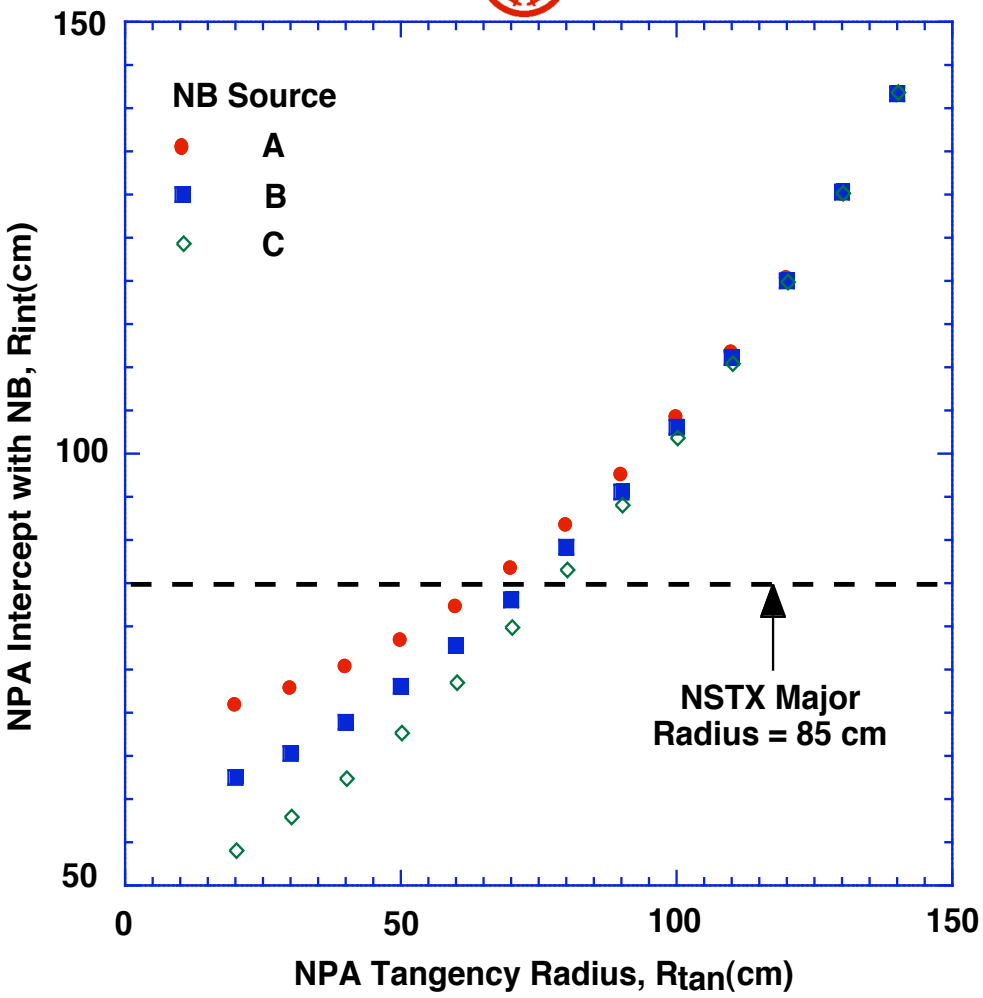
NPA Measurements are Constrained in Pitch Angle by Beam Injected Neutrals



- The beam injected neutrals spatially localize the NPA signal (insert).
- Up to 2/3 of the line-integrated flux can originate in the NB region.
- This spatial localization also constrains the range of pitch angles viewed by the NPA (main panel).
- The spatial localization weakens with increasing NB penetration distance (due to attenuation of the beam neutrals) and increasing n_e.

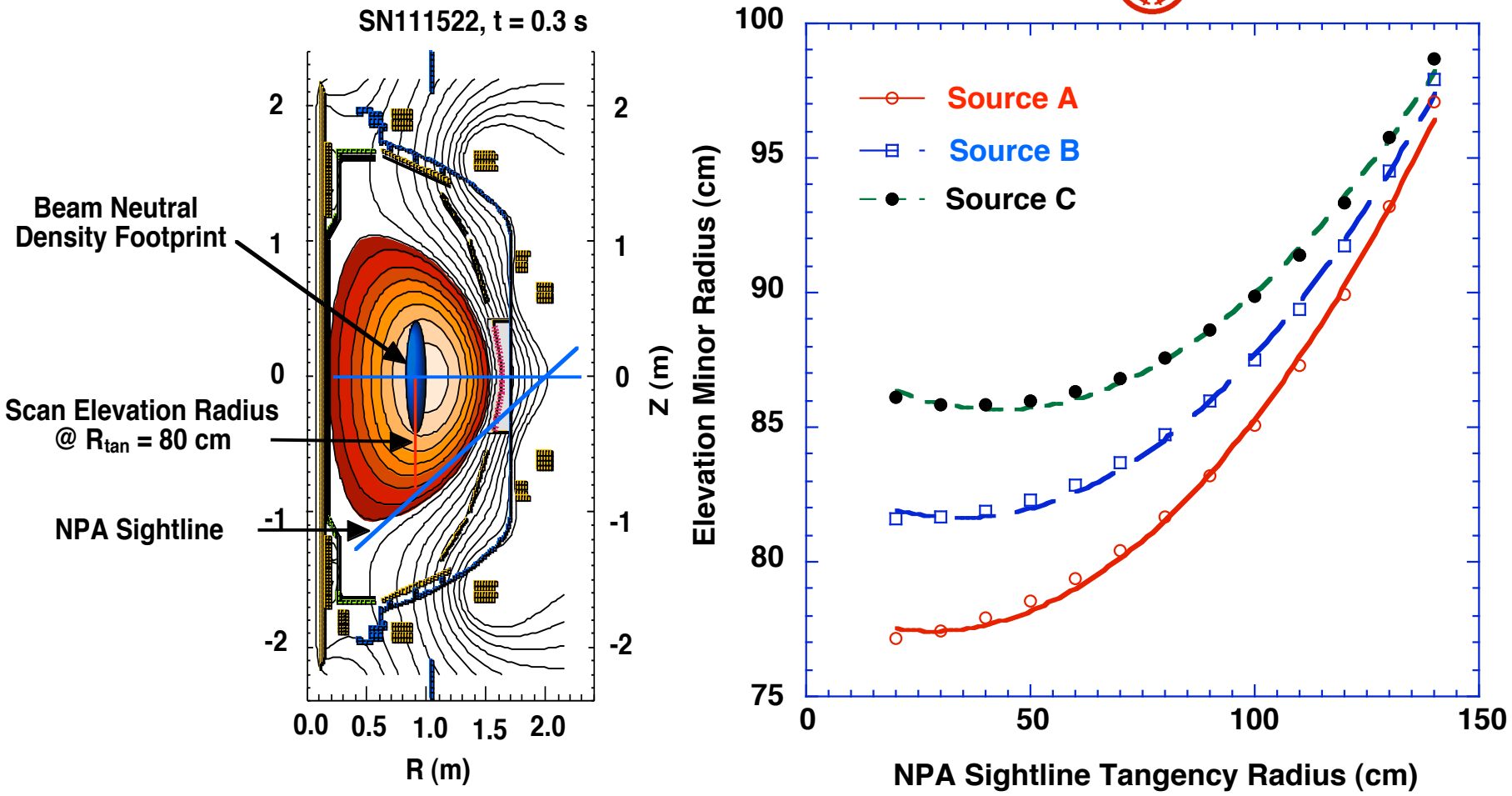
NPA Measurements are Spatially Localized by Beam Injected Neutrals





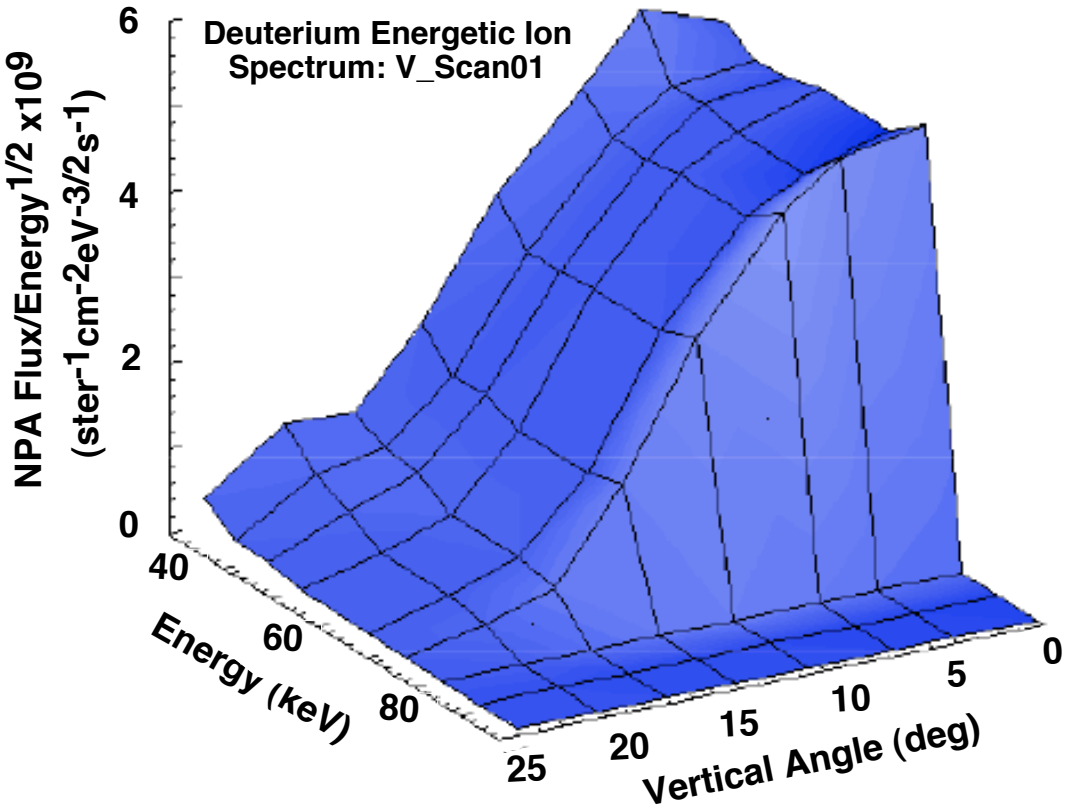
- **Dominance of charge exchange emissivity by beam neutrals results in both field pitch and spatial localization of NPA measurements.**

The NSTX NPA Scans 26° Vertically Downward



The elevation minor radius at the intersection of the NPA sightline with a given neutral beam line depends on the NPA mid-plane tangency radius.

NPA Vertical Scan Reveals the Beam Neutral Footprint



NPA measurement of the NB elevation profile versus beam energy and vertical scan angle obtained at R_{tan} = 80 cm reveals a spatial distribution of the Source A below the mid-plane that is consistent with NB design parameters.

Various Mechanisms Produce Energetic Ion Depletion Observed by the NPA Diagnostic

- √ **MHD Effects**
  - **Strong n=1 or n=2 mode activity and reconnection events [1]**
  - **Fishbones [2]**

- √ **Plasma Opacity Effects**
  - **Outer gap width (i.e. plasma radius)**
  - **High density, broad $n_e(r)$ profiles**

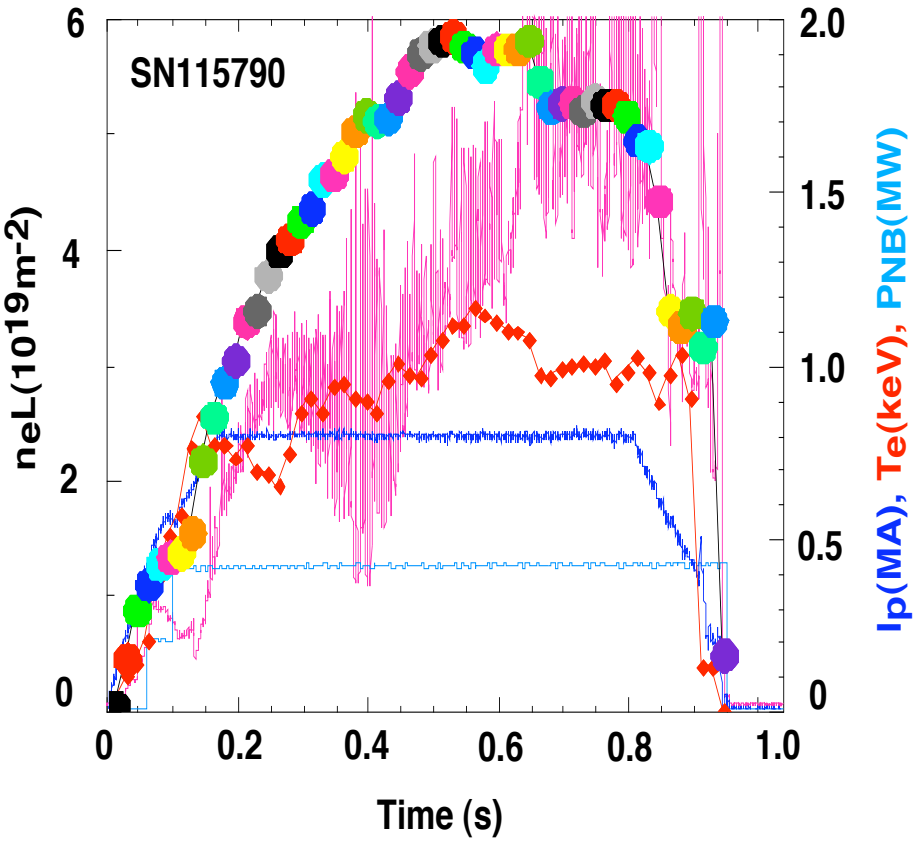
- √ **H-Mode Effects**
  - **MHD-induced ion loss is observed during H-mode operation due to high, broad density profile effects [3].**

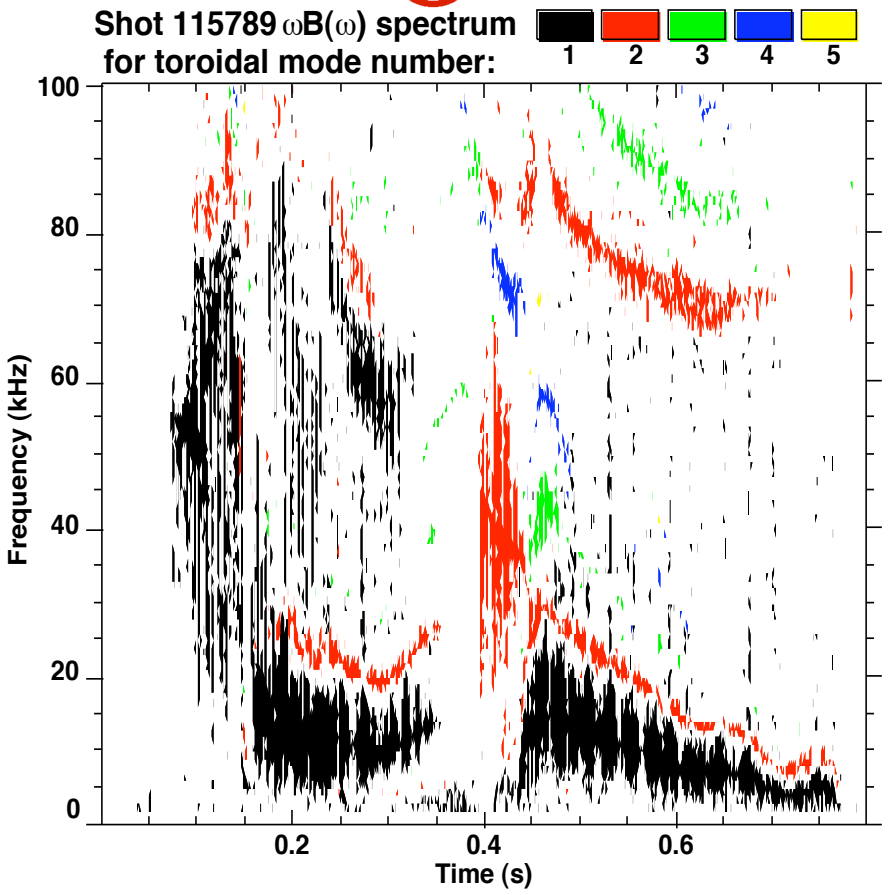
[1] "Neutral Particle Analyzer Measurements of Ion Behavior in NSTX," S. S. Medley, *et al.* PPPL-3668 (February, 2002

[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)

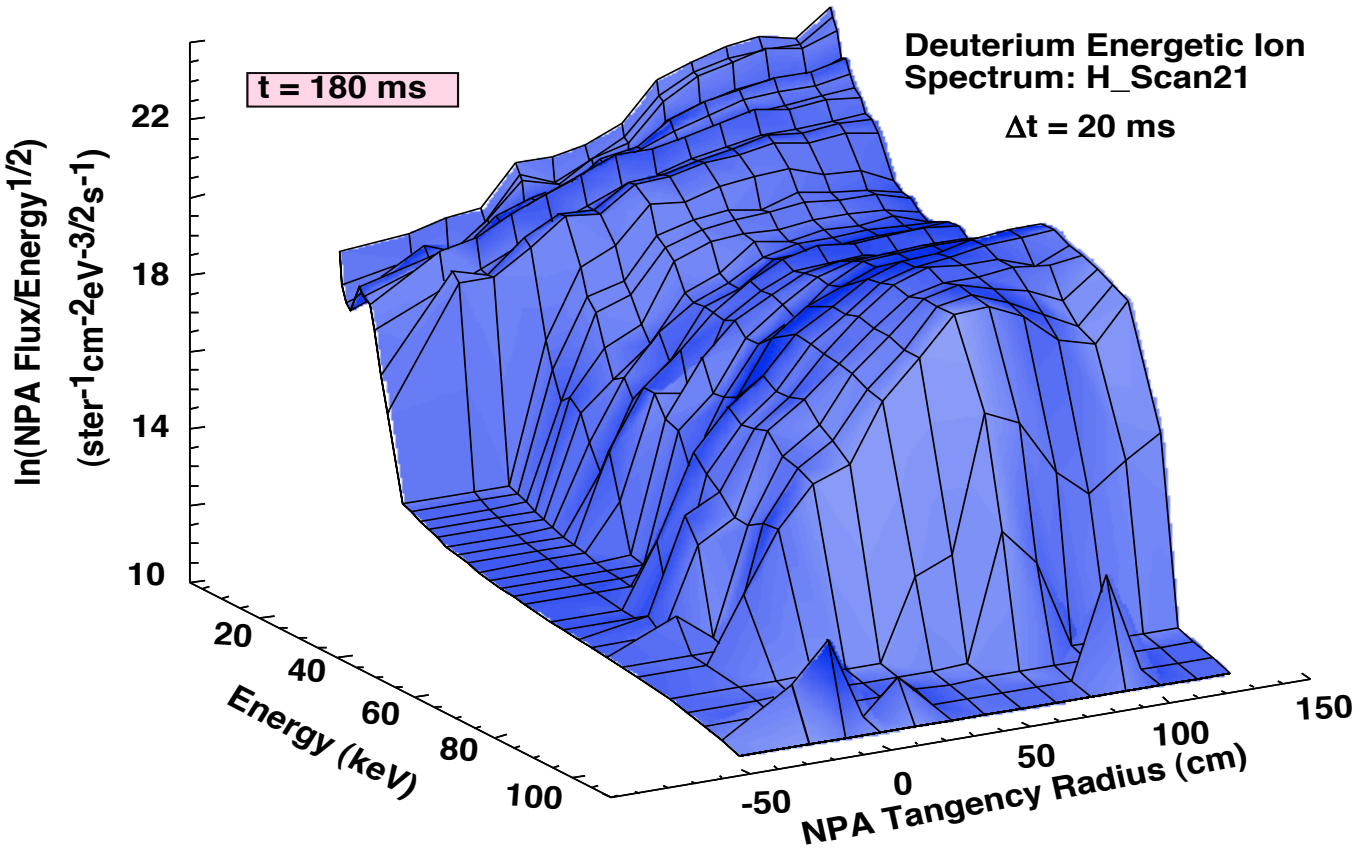
NPA Energetic Ion Spectra Exhibit a Temporally and Spatially Dependent Depletion in H-mode Discharges





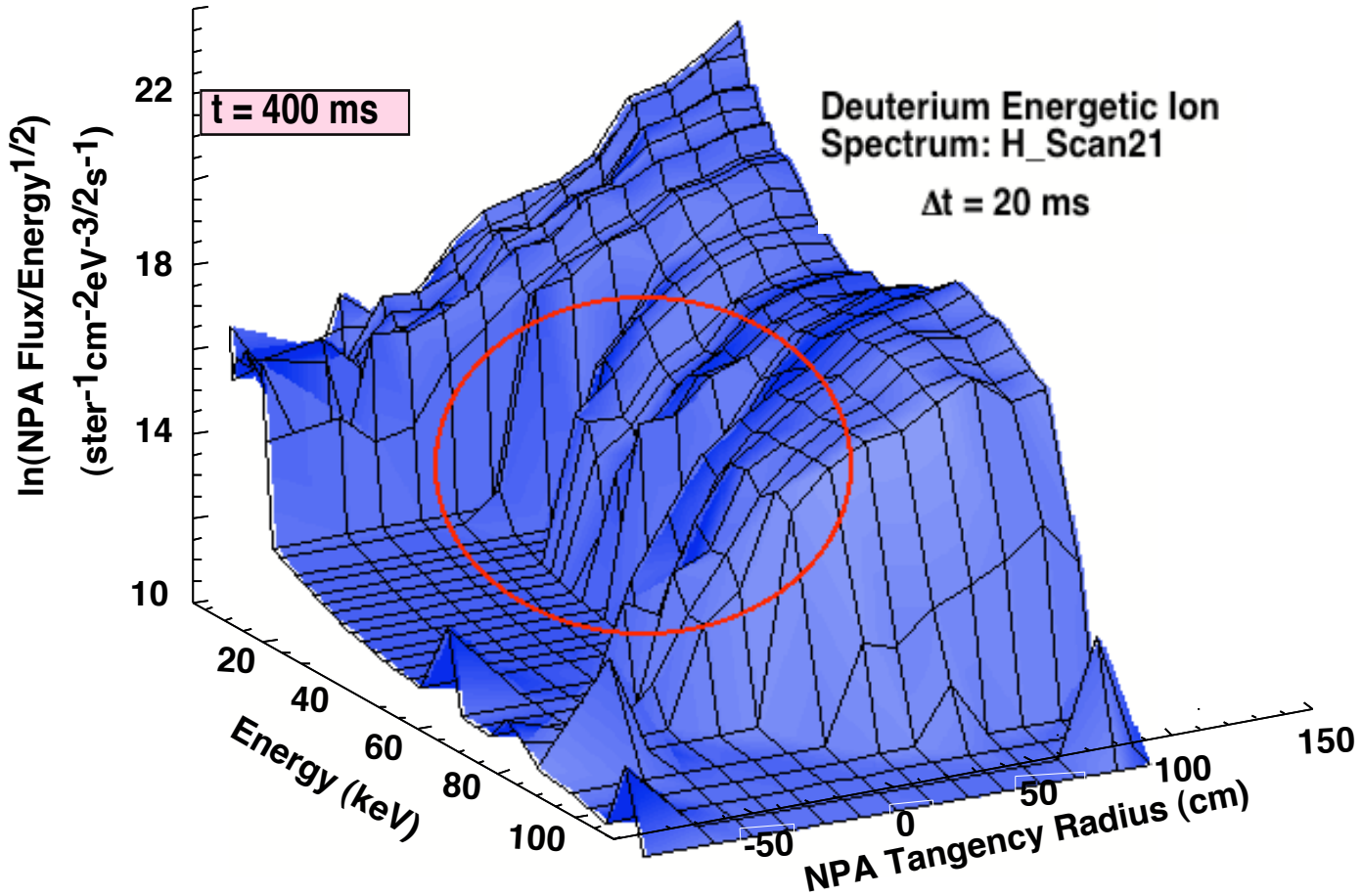
- Shown are selected waveforms (left) and the Mirnov spectrogram (right) associated with the NPA horizontal scan spectra shown below.

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



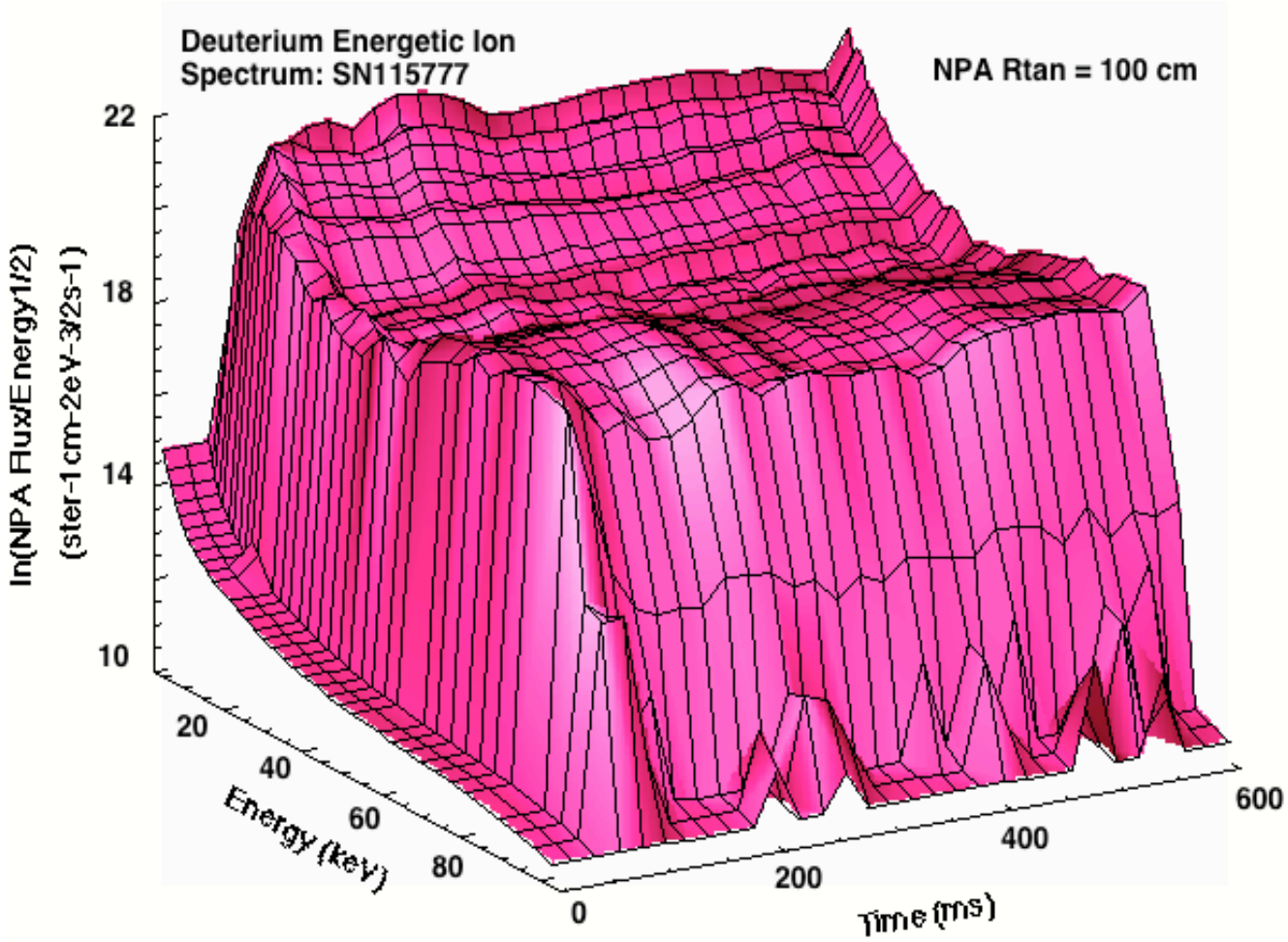
- The spectra at small tangency radii drop off naturally because this region corresponds to trapped orbits not populated by tangential NB injection in NSTX.

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



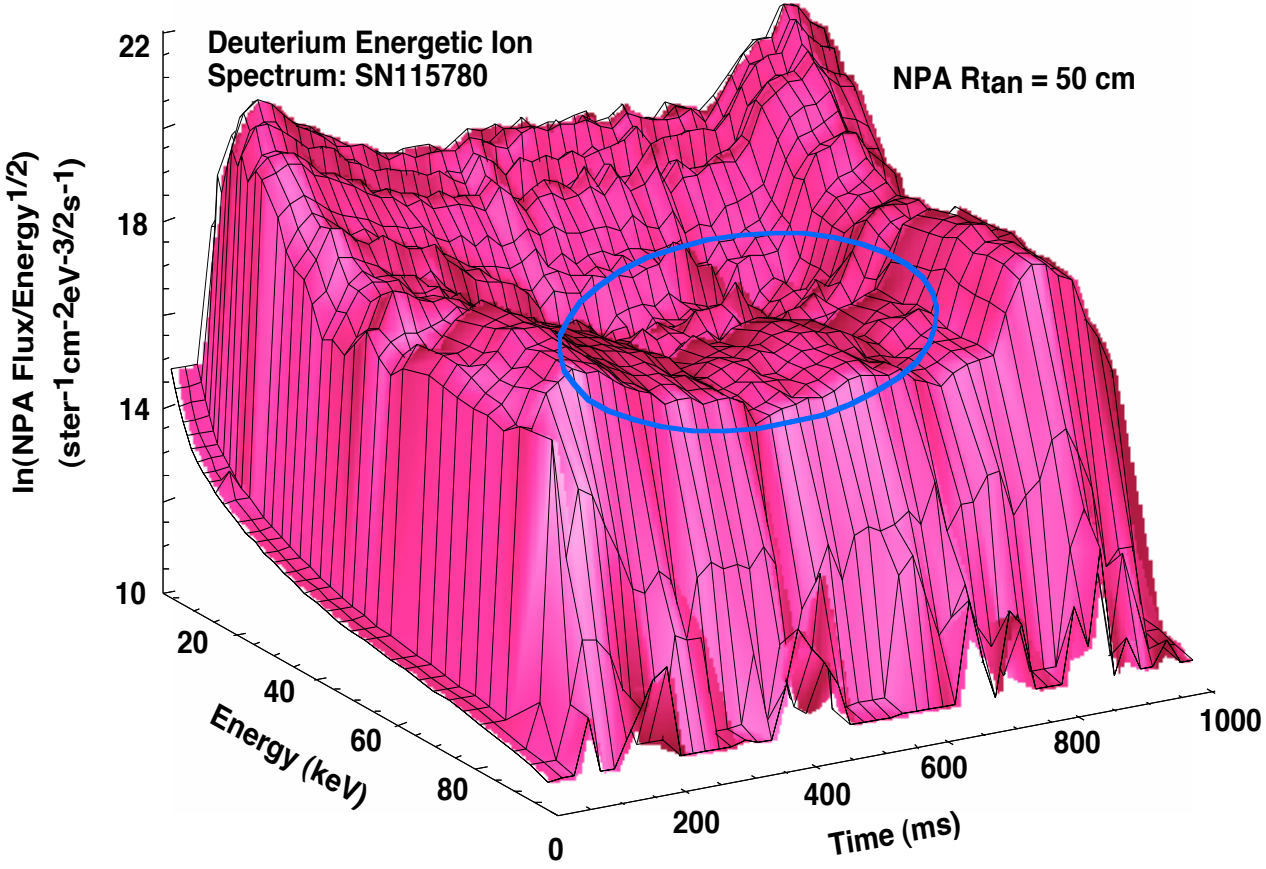
- Following H-mode onset, a clear depletion of the NPA horizontal scan spectrum is observed at $E > E_b/3$ and $R_{tan} < 50$ cm (encircled region).

NPA Energetic Ion Spectra at Larger Tangency Radii are not Significantly Depleted



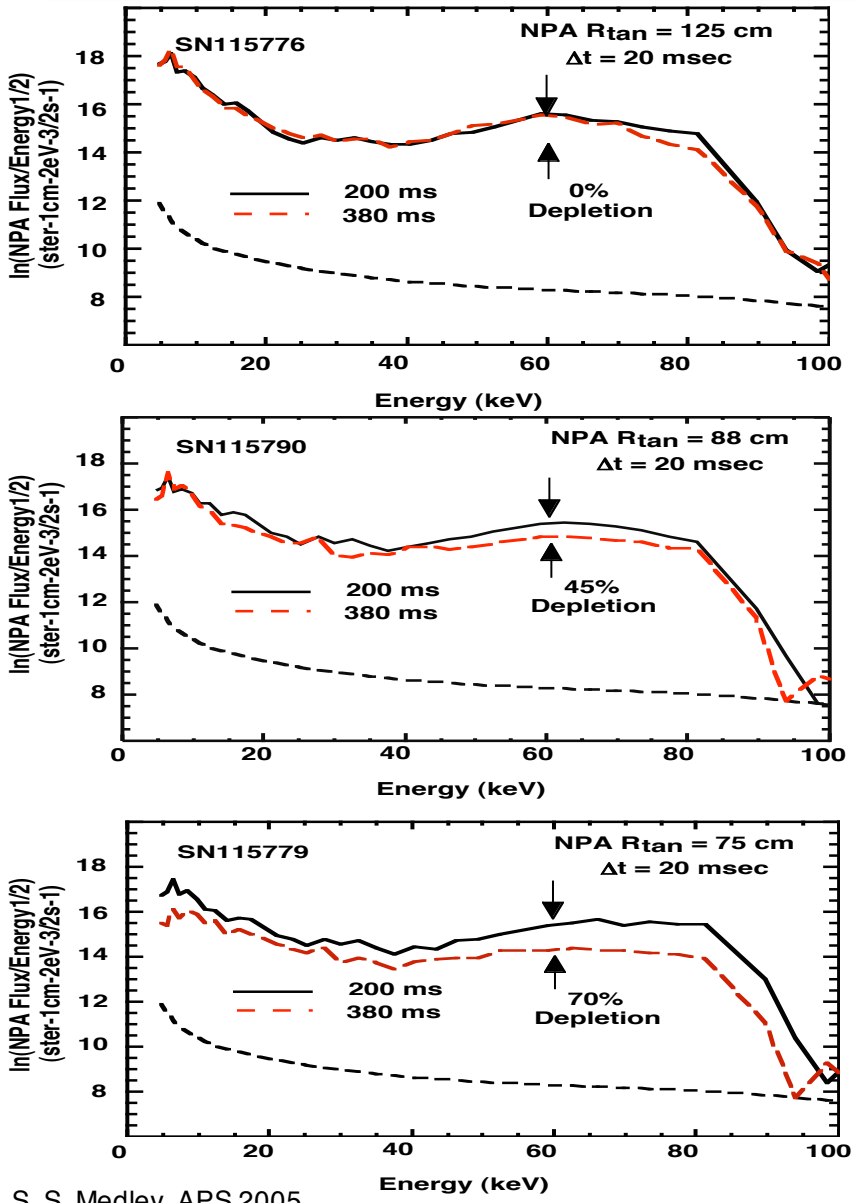
- The NPA energetic ion spectrum for R_{tan} = 100 cm shows only minor depletion at $E > E_b/2$ following H-mode onset.

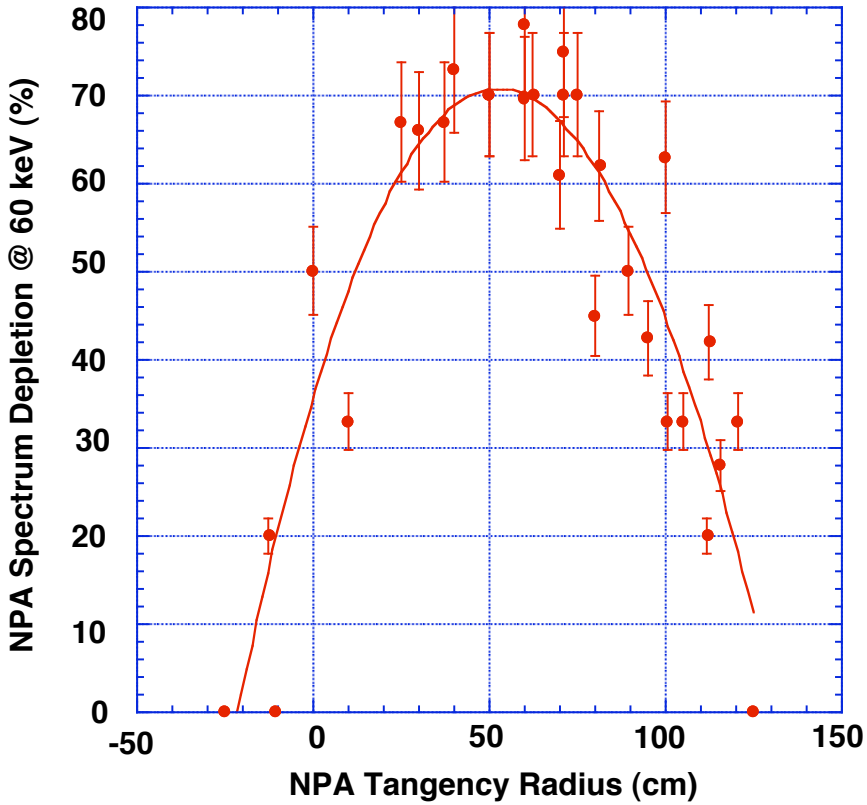
NPA Energetic Ion Spectra at Smaller Tangency Radii are Significantly Depleted



- 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.

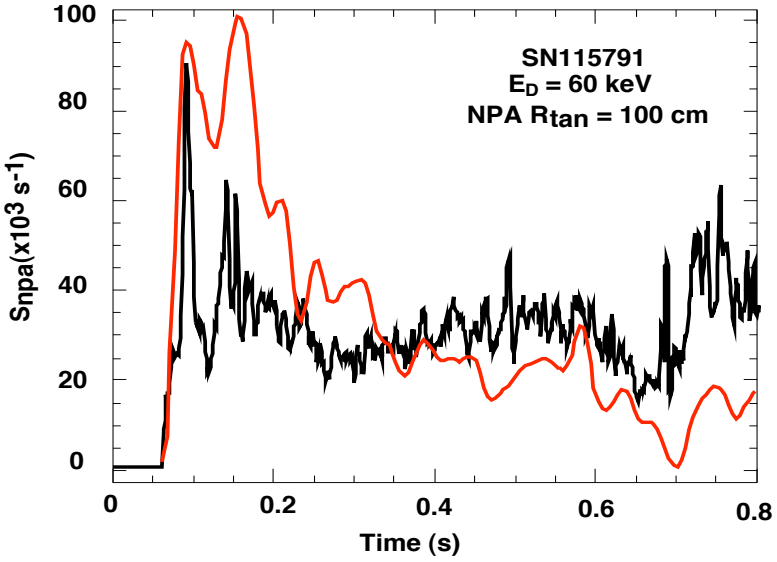
Depletion of the NPA Energetic Ion Spectra Exhibits a Spatial Dependence

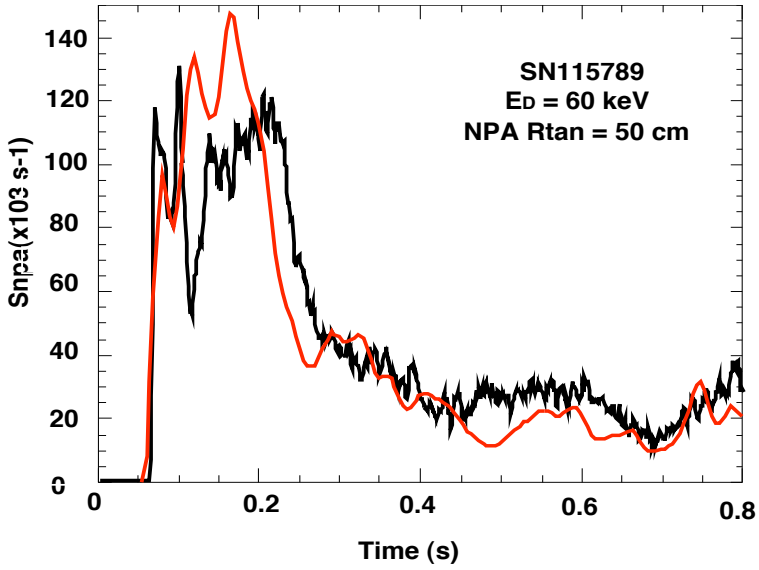


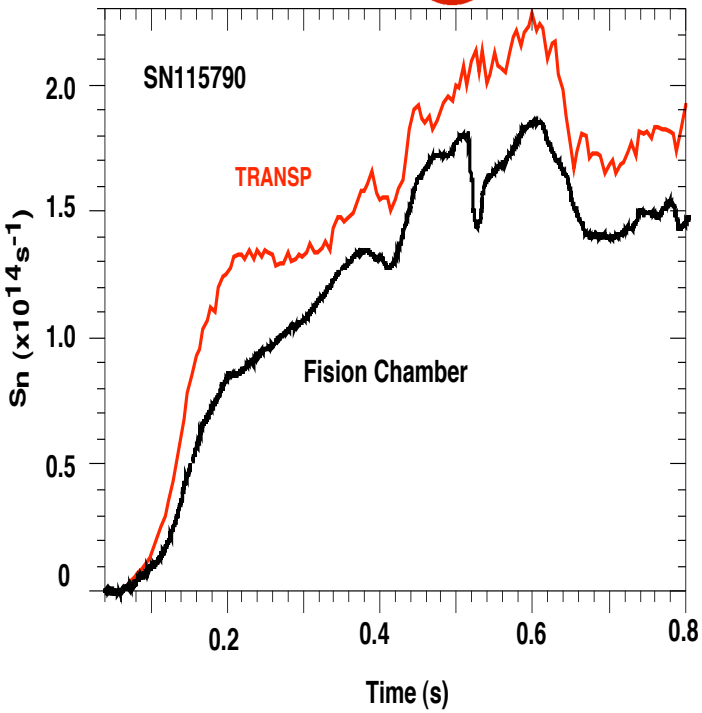


- The left panels show spectra at various R_{tan} preceeding (t = 200 ms) and following (t = 380 ms) H-mode onset.
- The right panel shows the spatial dependence of the depletion at E = 60 keV.

TRANSP Analysis - I: NPA & Neutron Waveforms

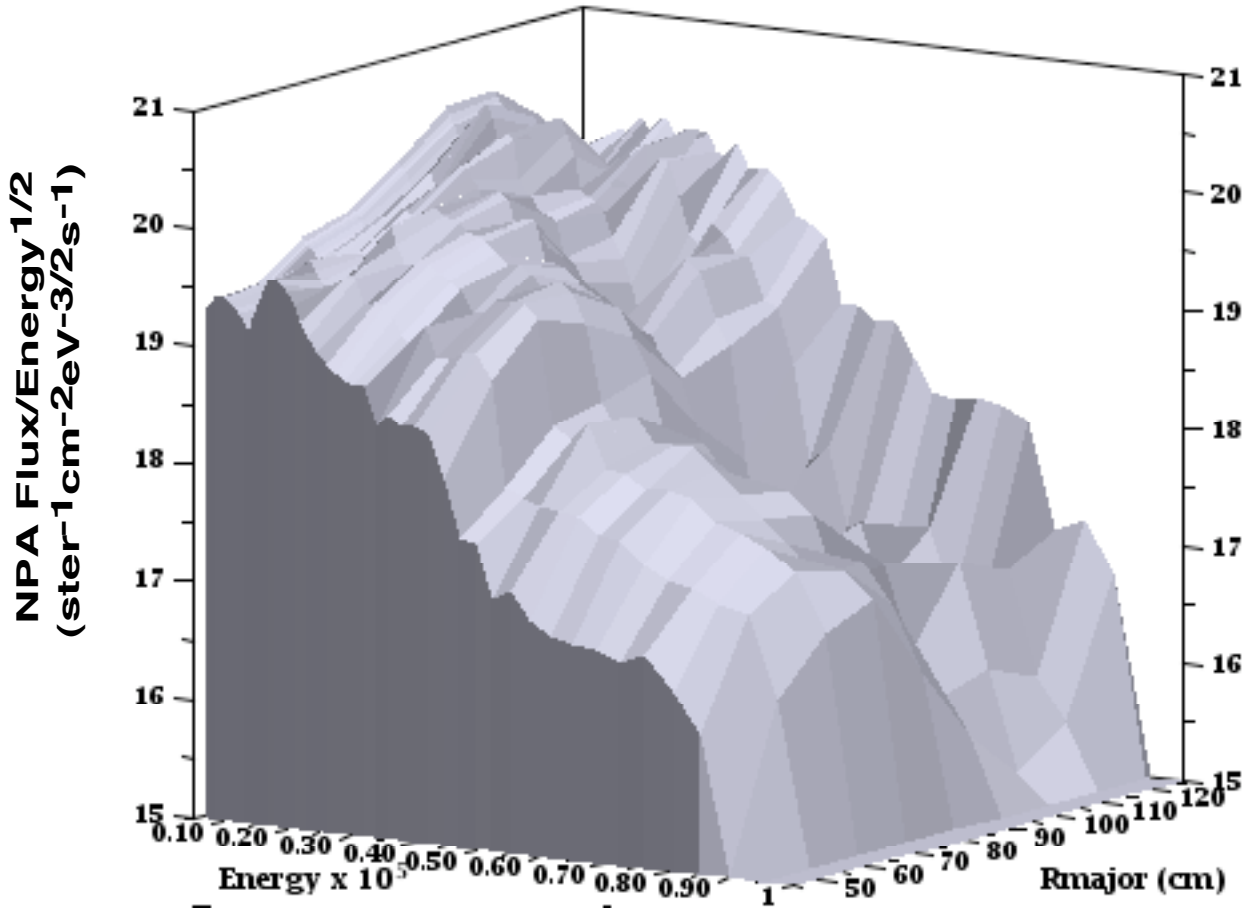






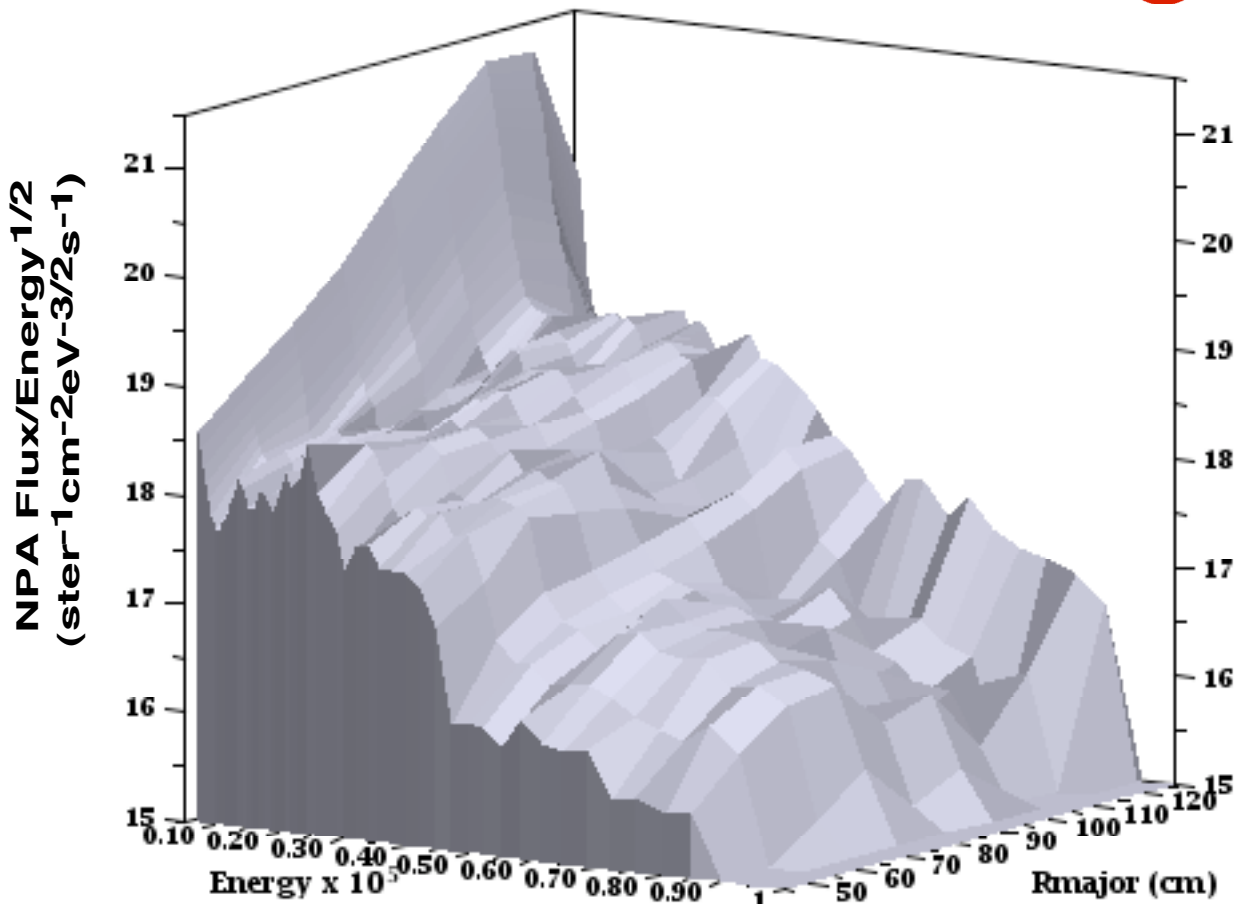
- TRANSP-simulated (red) and measured (black) NPA signals, S_{npa}, are often (but not always) in reasonable agreement (left panels).
- TRANSP-calculated (red) neutron rates, S_n, frequently exceed measurements (black) suggesting NPA spectrum depletion, at least in part, is possibly due to actual ion loss.

TRANSP Analysis - IIIa: Energetic Ion Spatial Distribution at t = 160 ms



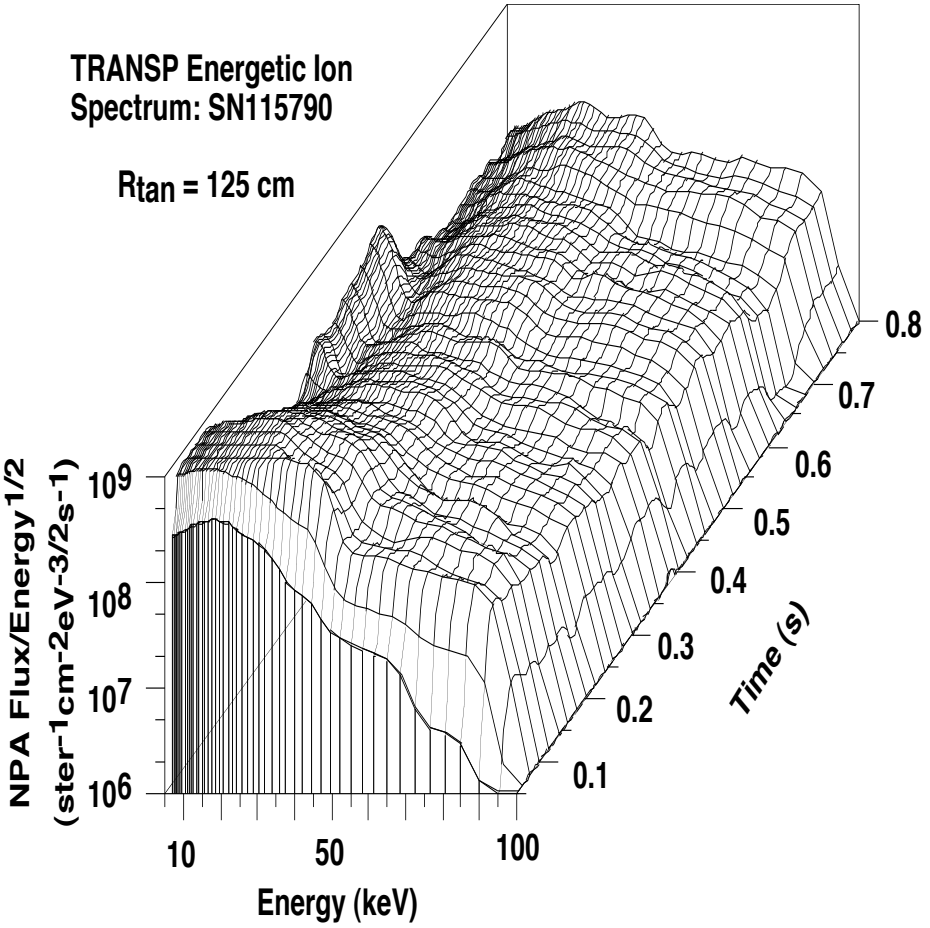
- TRANSP simulation of NPA spectra preceding H-mode onset at t = 160 ms exhibits some similarities to measured spectra. The increase of the spectrum at R_{tan} = 125 cm is likely due to an issue in the TRANSP modeling of edge neutral density.

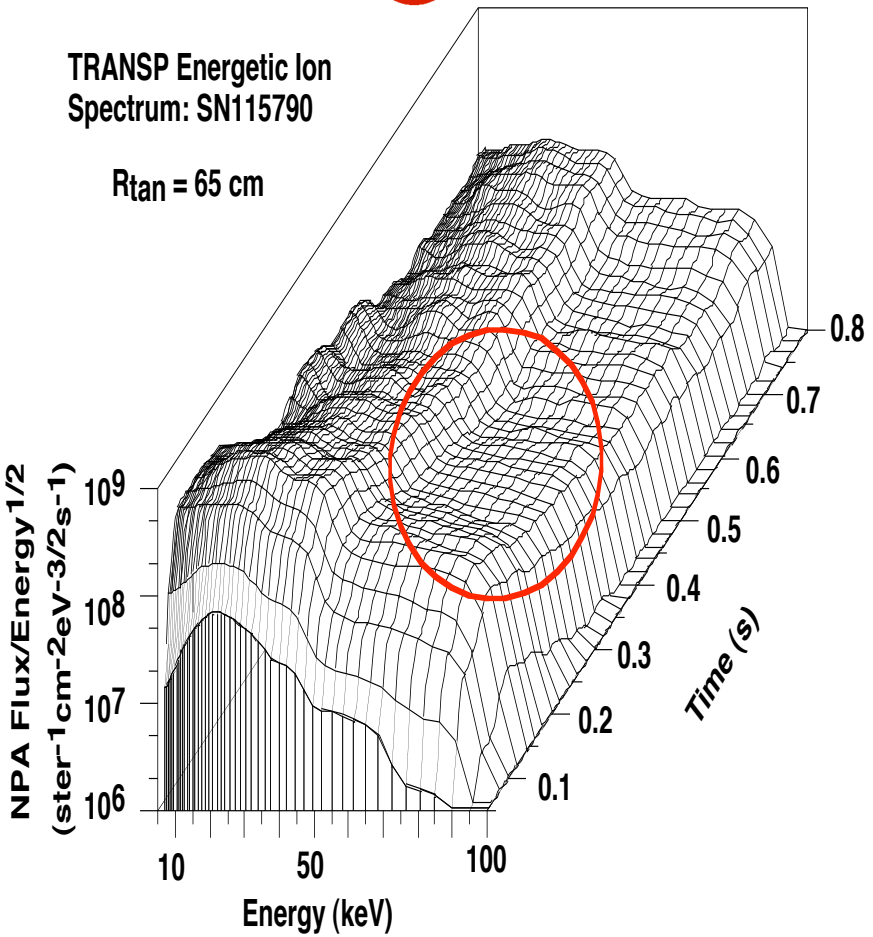
TRANSP Analysis - IIIb: Energetic Ion Spatial Distribution at t = 400 ms



- TRANSP simulation of NPA spectra at t = 400 ms exhibit some similarities to measured spectra although differences appear at low E and at E > $E_b/2$.

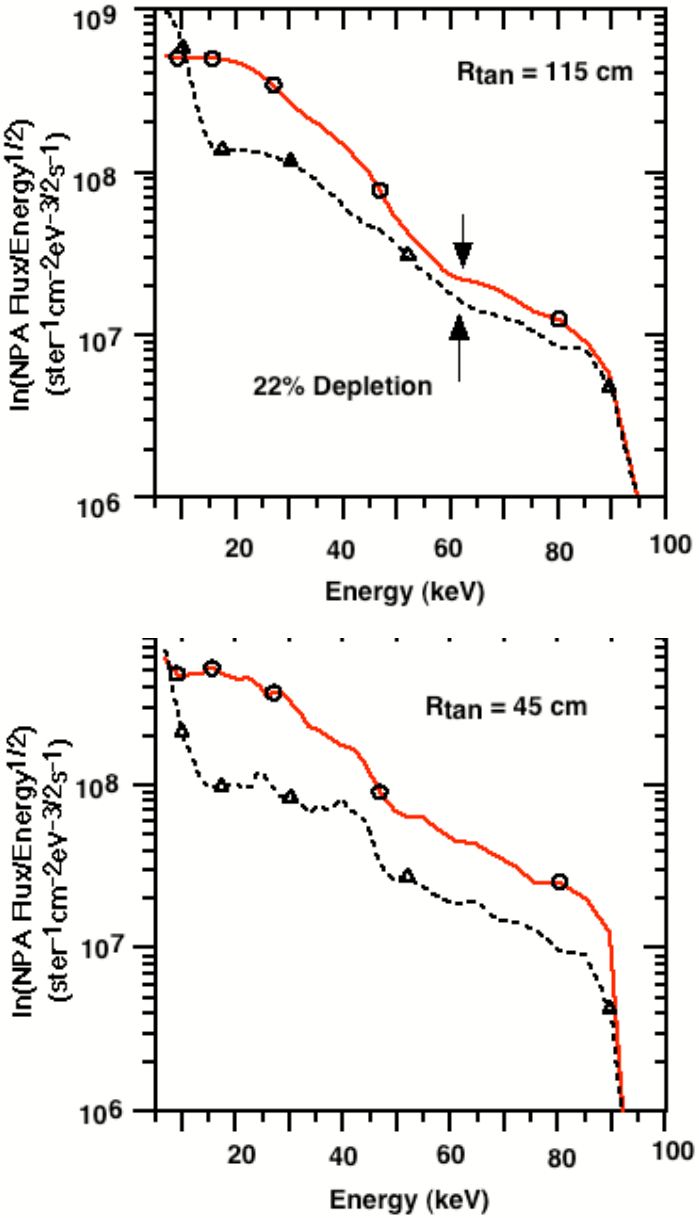
TRANSP Analysis - II: Energetic Ion Spectra

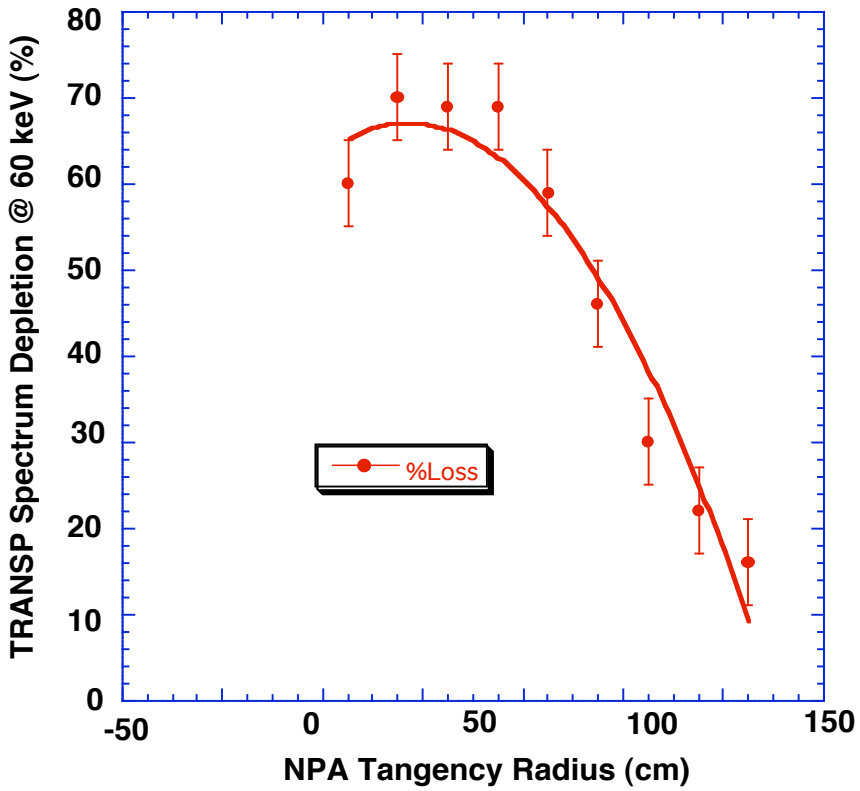




• **TRANSP simulation of NPA spectra exhibit some similarities to measured spectra, including enhanced spectrum depletion at $E > E_b/2$ at smaller R_{tan} (right panel, encircled region). However, depletion at low E is comparable: contrary to measured spectra.**

TRANSP Analysis - IV: Spectrum Depletion





- The TRANSP-calculated spectra show a spatial dependence similar to NPA measurement (right).
- However, the depletion increases with decreasing energy, contrary to measurements (left).

Summary

- For L-mode discharges, measured NPA energetic ion spectra exhibit classical ion behavior.

- For H-mode discharges, measured NPA energetic ion spectra exhibit energetic ion depletion primarily for $E > E_b/3$.

- The measured spectrum depletion exhibits a spatial dependence, peaking around $R_{tan} \sim 50 \pm 10$ cm and vanishing at larger R_{tan}.

- TRANSP modeling exhibits some features similar to the measurements, but the energy dependence of the depletion is different (depletion increases with decreasing E).

- TRANSP modeling indicates that charge exchange emissivity effects can account for part, but not all, of the observed energetic ion depletion behavior.