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Effect of Sawtooth Crashes on Fast-ion Distribution in NSTX-U

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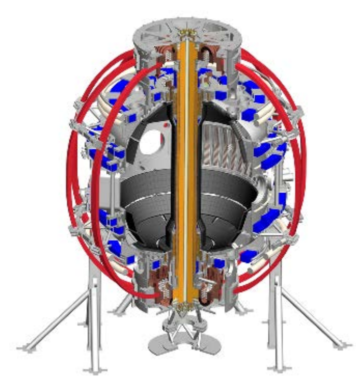
PPPL



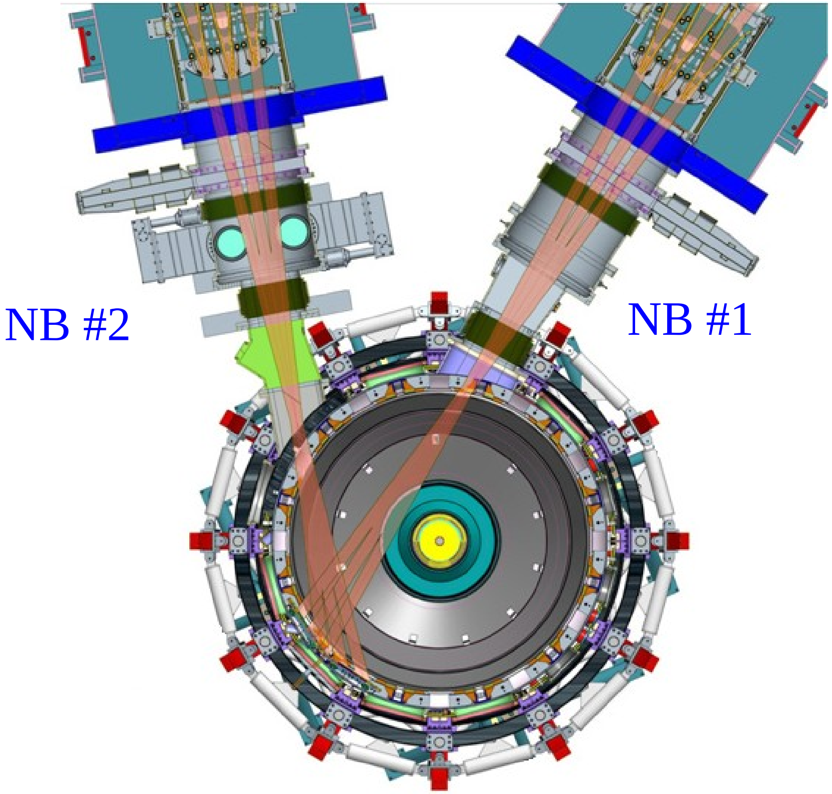
Motivation: Is Sawtooth Behavior in Spherical Tokamak Similar to that in Conventional Tokamak?

- **Sawtooth in conventional tokamaks can cause significant fast ion transport and lead to degradation of fusion production and losses of fast ion to the wall**
- Measurements on TEXTOR, DIII-D, ASDEX-Upgrade suggest that passing particles are more susceptible to sawtooth-induced transport than trapped particles.
- Measurements show fast ion redistribution during sawtooth depends on energy, pitch
- Kadomtsev sawtooth model within TRANSP code qualitatively agrees with measurements.
- Theory predicts two regimes of fast ion transport:

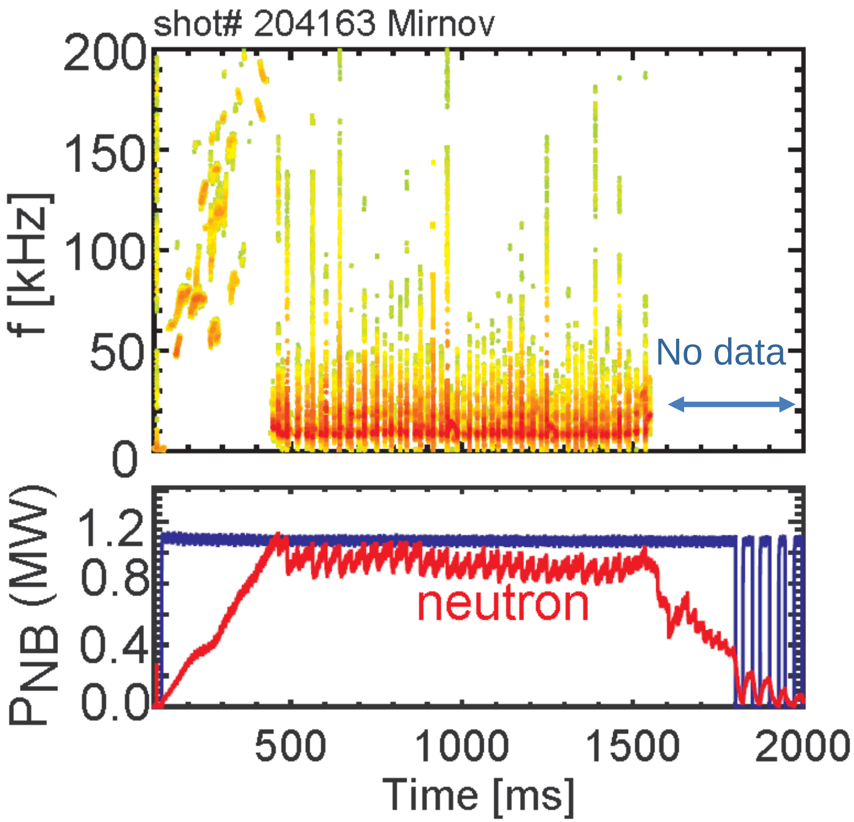
(1) transport by flux attachment → flattening fast ion density profile inside sawtooth mixing radius; (2) transport by resonance → flattening the density profile at resonance

- **Sawtooth study on Spherical Tokamak (ST) can complement that in large-aspect-ratio and high field tokamaks.**
- Large fast ion orbit width in ST, representative of alpha particles in fusion devices
- Extend the sawtooth database for code validation and model development

Long Sawtoothing Discharges are Achieved on NSTX-U with the New 2nd NBI & Central Solenoid



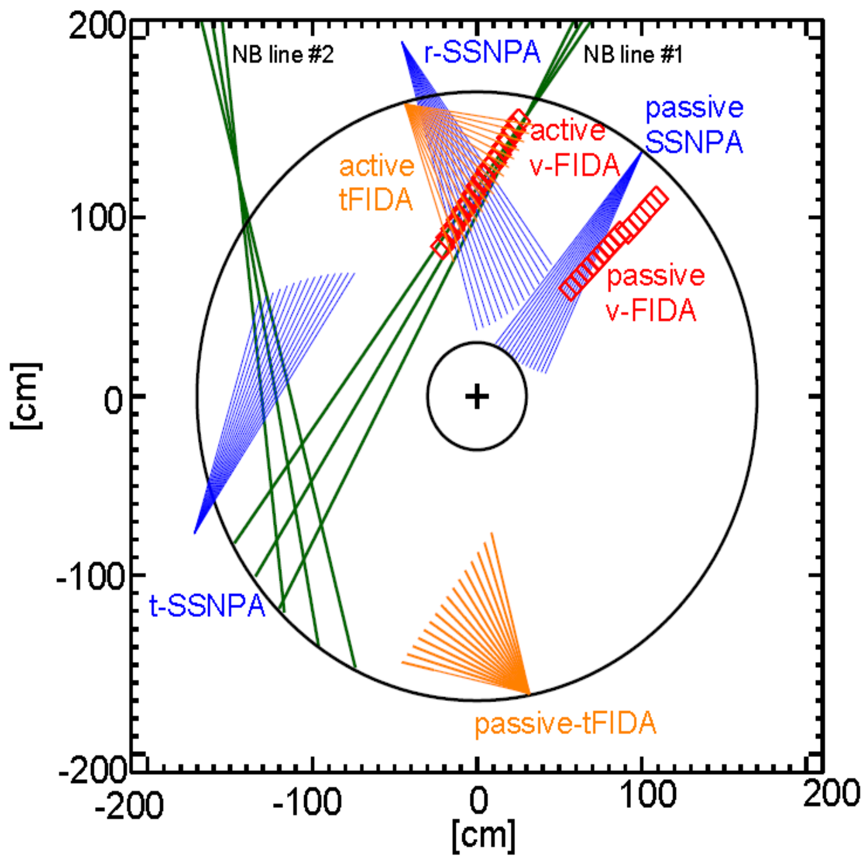
[Menard, NF 2012] [Gerhardt, NF 2012]



- Reproducible sawtoothing L-mode discharges are obtained on NSTX-U
  - Neutron rate can drop as large as ~15% at sawtooth crash
  - Flattening of T_e in the core indicated by Thomson scattering and Soft x-ray diagnostics
  - No MSE measurement is available for these discharges

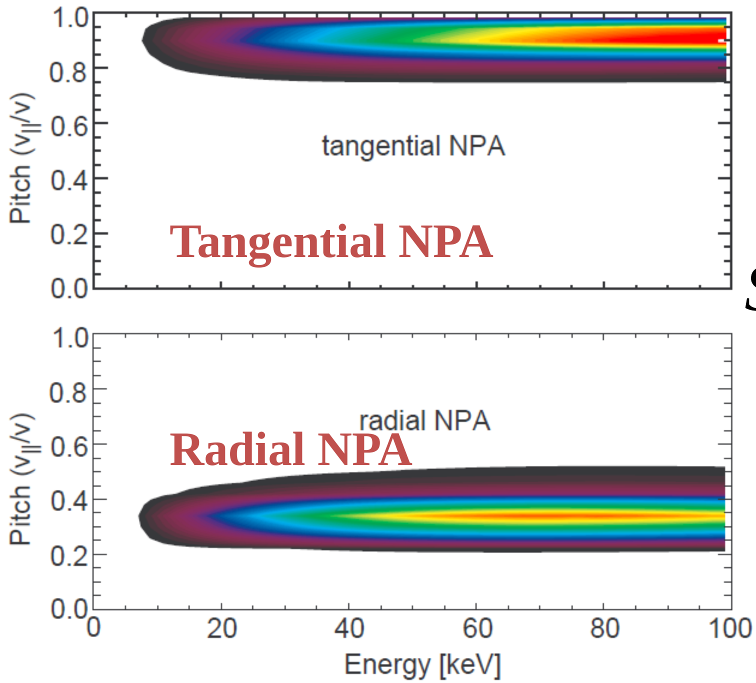
A Comprehensive Set of Fast Ion Diagnostics can Measure Sawtooth-Induced Fast Ion Transport

- **Neutron detectors**
  - dominated by beam-plasma reactions, volume integrated
- **Fast-Ion D-alpha (FIDA) spectrometers**
  - sensitive to a small region in velocity space, spatial profile
- **Solid State Neutral Particle Analyzer (SSNPA) arrays**
  - very localized in pitch angle range, spatial profile, fast time resolution
- **Scintillator-based Fast Loss Ion Probe**
  - lost fast ions, narrow in pitch angle

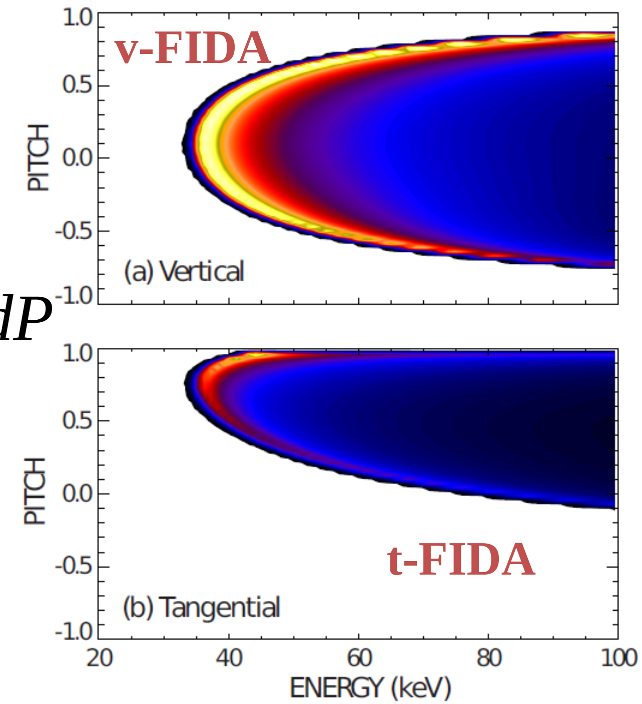


FIDA and SSNPA Diagnostics Can Separate the Response of Passing and Trapped Particles

Weight Function



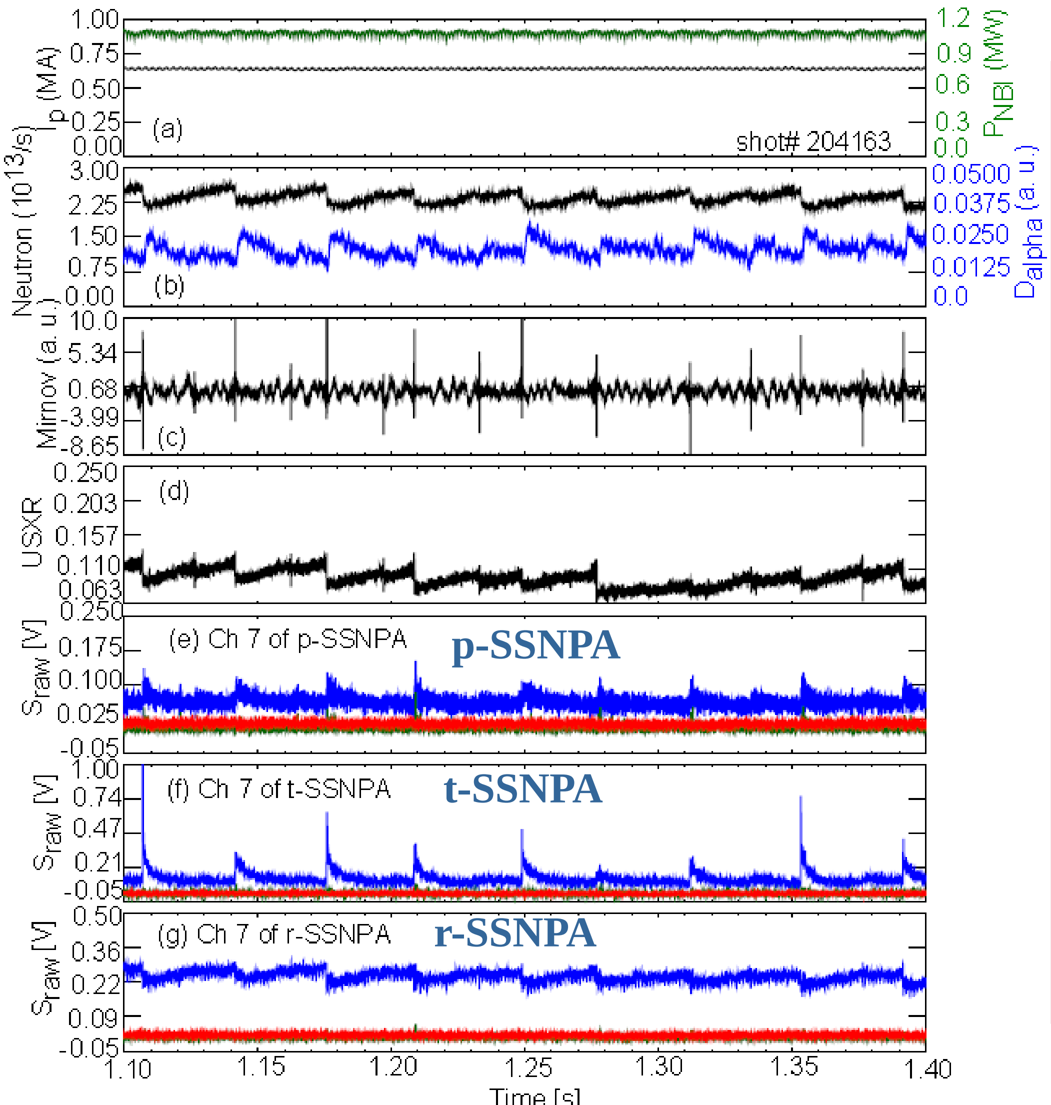
$$S = \iint W F_f \, dE dP$$



- ➢ Localization in velocity space depends on geometric layout
  - ▪ Tangential views (t-SSNPA, t-FIDA): mainly sensitive to passing fast ions
  - ▪ Radial or vertical views (r-SSNPA, v-FIDA): mainly trapped fast ions
- ➢ Reference views monitor passive signals from the plasma edge

Experimental Observations

SSNPA Observation: Passing Particles are Expelled from Core to Edge, Small Depletion for Trapped Particles (1/2)

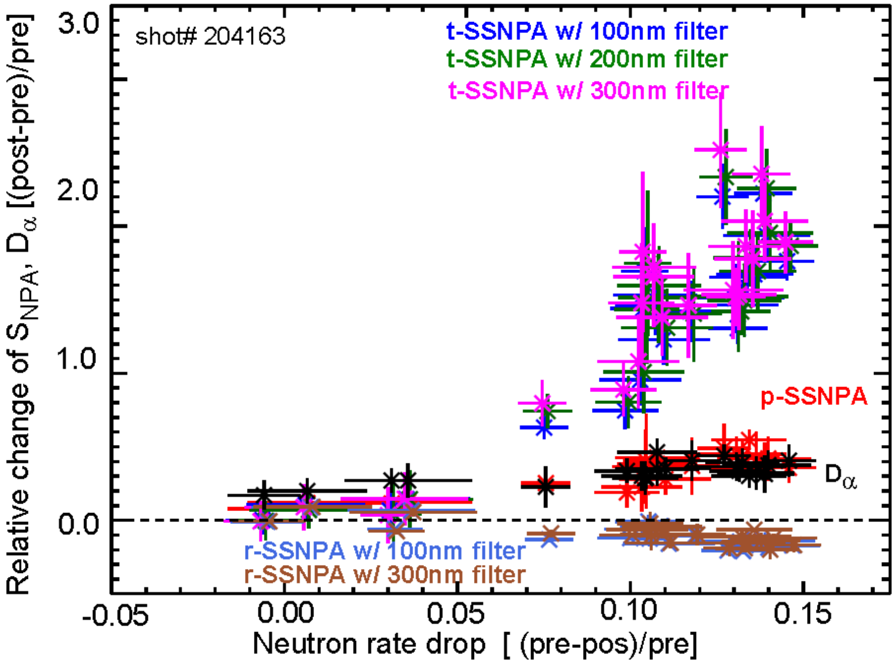


[Liu, RSI 2016]

- ➢ NB source 1B injects steady, active source for r-SSNPA arrays
- ➢ Low density L-mode, no Alfven eigenmode or fishbone detected
- ➢ SSNPA observations
  - ▪ p-SSNPA observes small signal increase
  - ▪ t-SSNPA observes big spikes
  - ▪ r-SSNPA observes small depletion

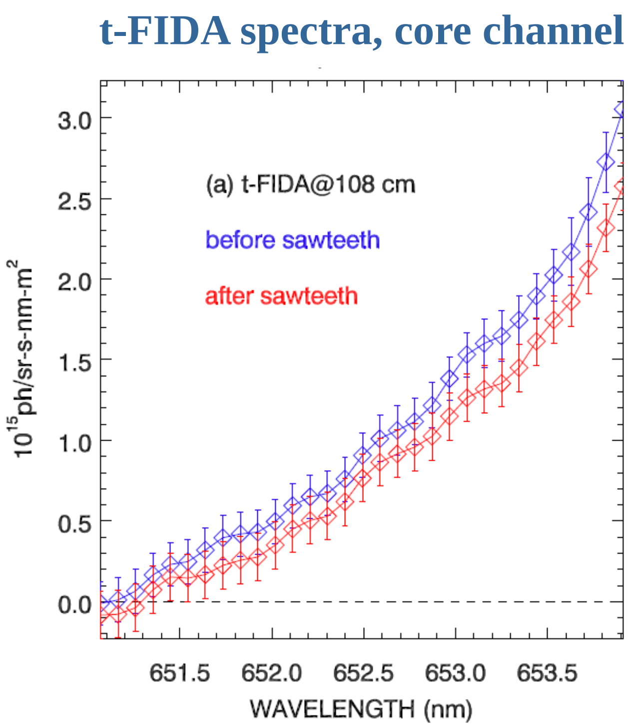
→Passing particles are strongly expelled from core to edge; much weaker transport for trapped particles (database analysis see next slide)

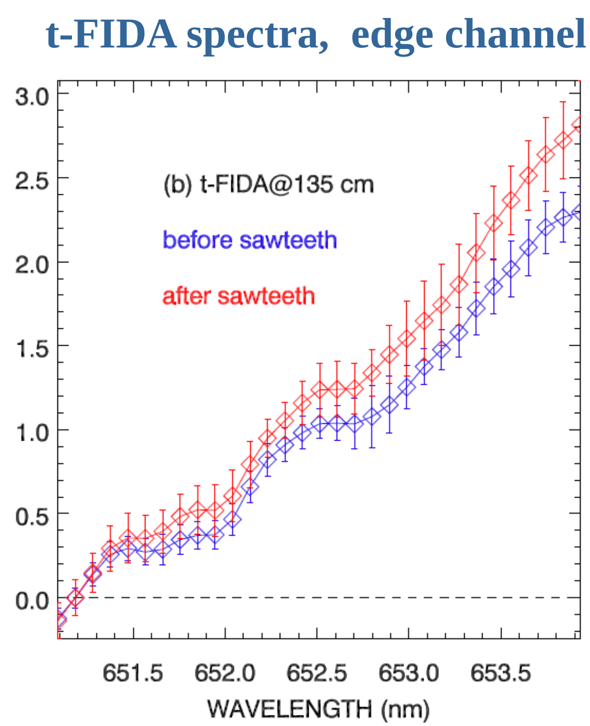
SSNPA Observation: Passing Particles are Expelled from Core to Edge, Small Depletion for Trapped Particles (2/2)

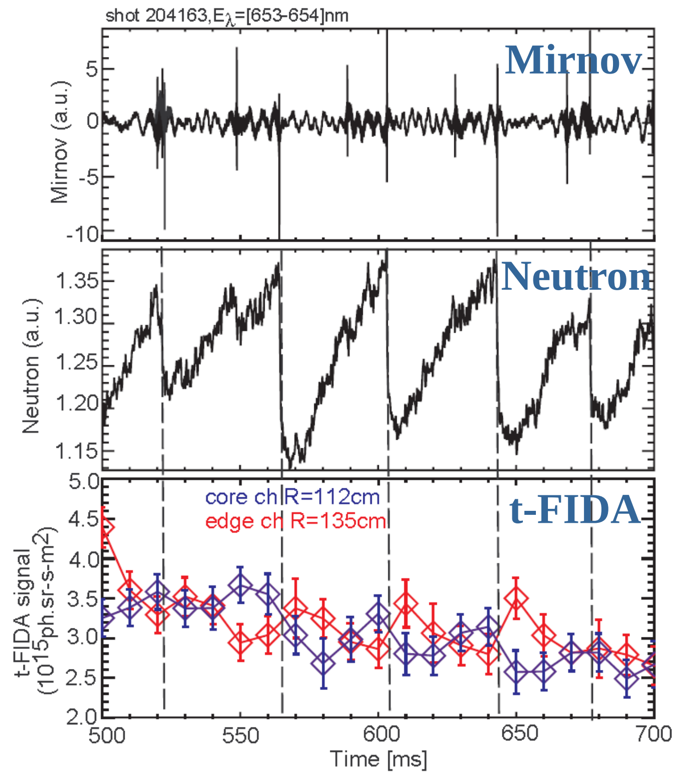


- ➢ Strong correlation between SSNPA signal change and neutron rate drop at sawtooth crash
  - Large increase in passive t-SSNPA →passing particles are expelled to edge
  - Similar change in p-SSNPA and D_α
    →the change of p- SSNPA signal is due to edge neutral density change
  - Small drop of r-SSNPA
    → some depletion of trapped particles
- ➢ SSNPA arrays with different energy threshold observe similar behavior →sawteeth affect a wide energy range
- ➢ All channels in the same port observe similar behavior, unable to infer dependence on space

t-FIDA Observation: Decrease in the Core, Increase in the Edge (1/2)

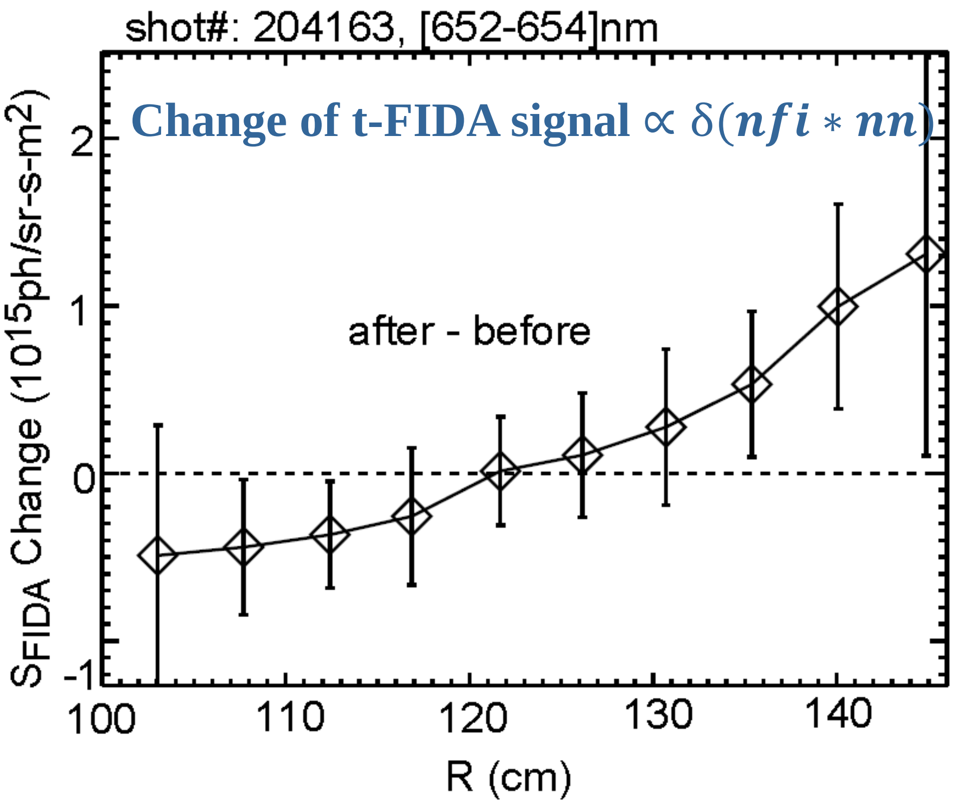


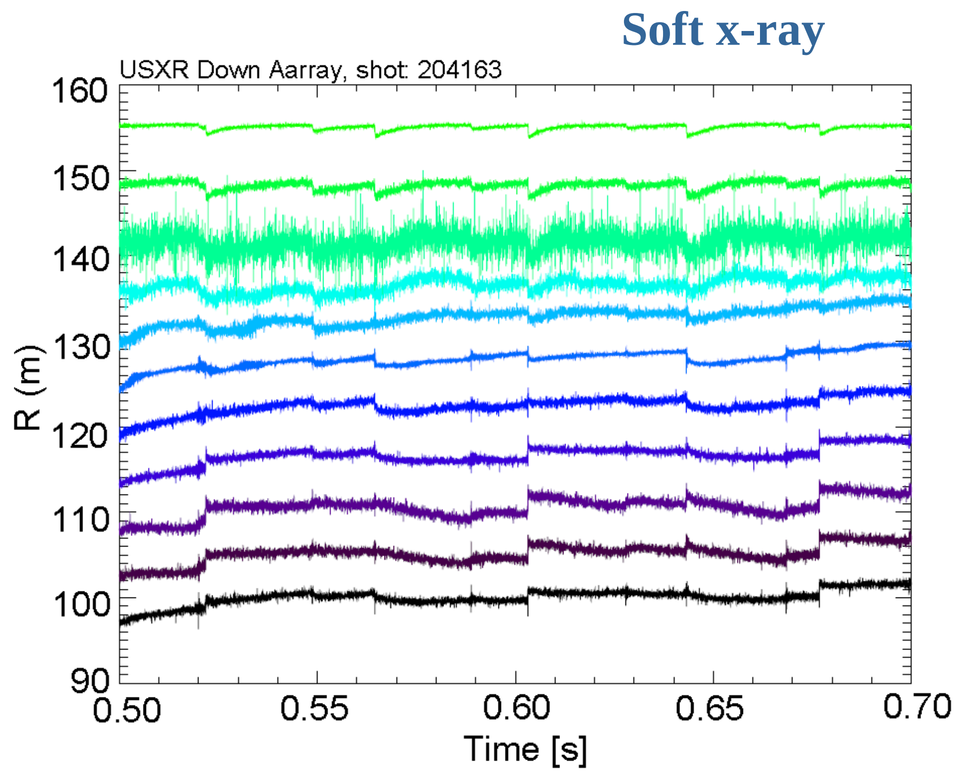




- ➢ t-FIDA observes signal drop in the core and increase at the edge
- → Passing fast ions are redistributed from core to edge
- ➢ V-FIDA signal is relatively weak, almost no change before and after sawtooth
  → trapped particles are weakly affected

t-FIDA Observation: Decrease in the Core, Increase in the Edge (2/2)

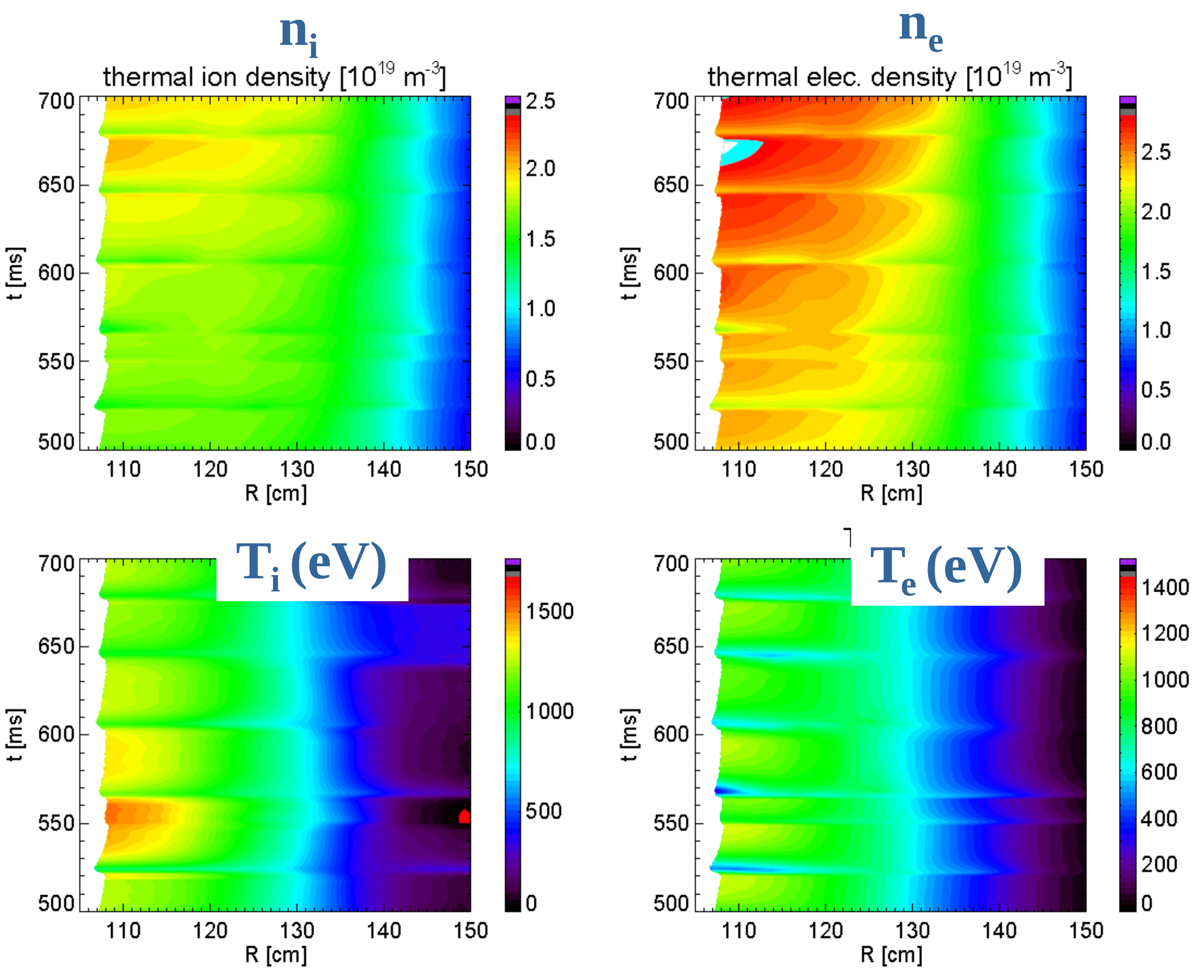




- t-FIDA signal: ~25% decrease in the core, ~35% increase in the edge
- The crossover point is close to sawtooth inversion radius (~125cm)
- As estimated from Soft x-ray data, sawtooth crash time is typically ~40µs, sawtooth period is ~25ms

Comparison with Sawtooth Modeling

Conditional Average Reconstruction is Applied for TRANSP's Input Profiles

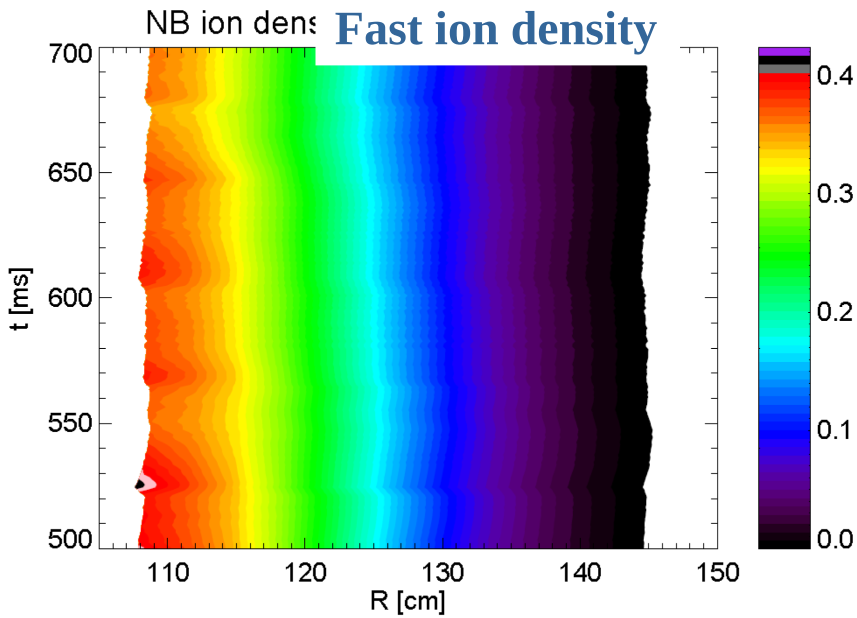


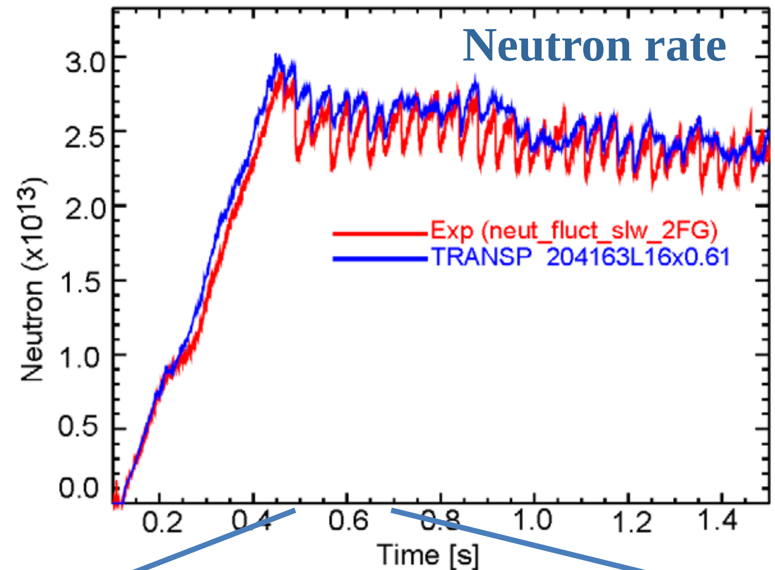
Conditional average plasma profile

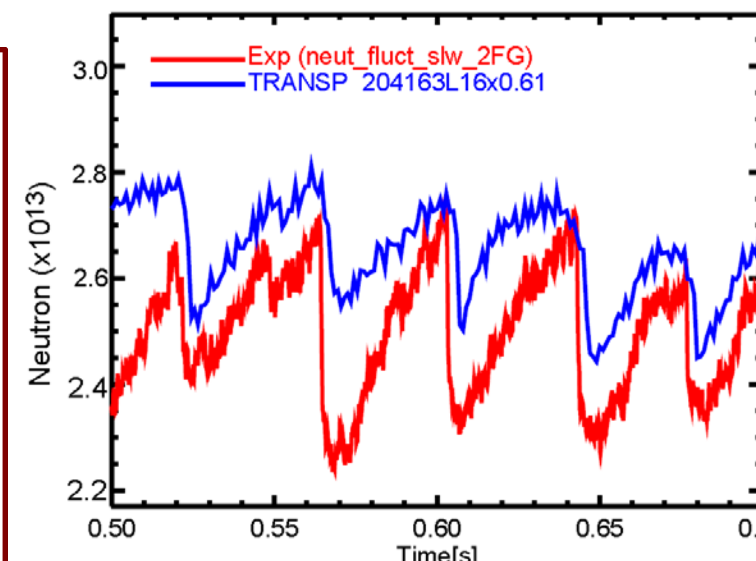
- Raw experimental data have insufficient time resolution for accurate time dependent modeling
  - n_e, T_e from MPTS Thomson scattering diagnostic (60Hz sampling rate)
  - T_i, v_{tor} from CHERS (100Hz sampling rate)

- TRANSP runs use thermal profiles from conditional averaging reconstruction
  - Combine CHERS & real-time velocity data for T_i, v_{tor}, n_D
  - Re-sample results from MPTS measurments
  - All profiles resampled on 1 ms time-scale

TRANSP Simulations Indicate ~50% of Total Neutron Drop is Due to Thermal Profile Evolution

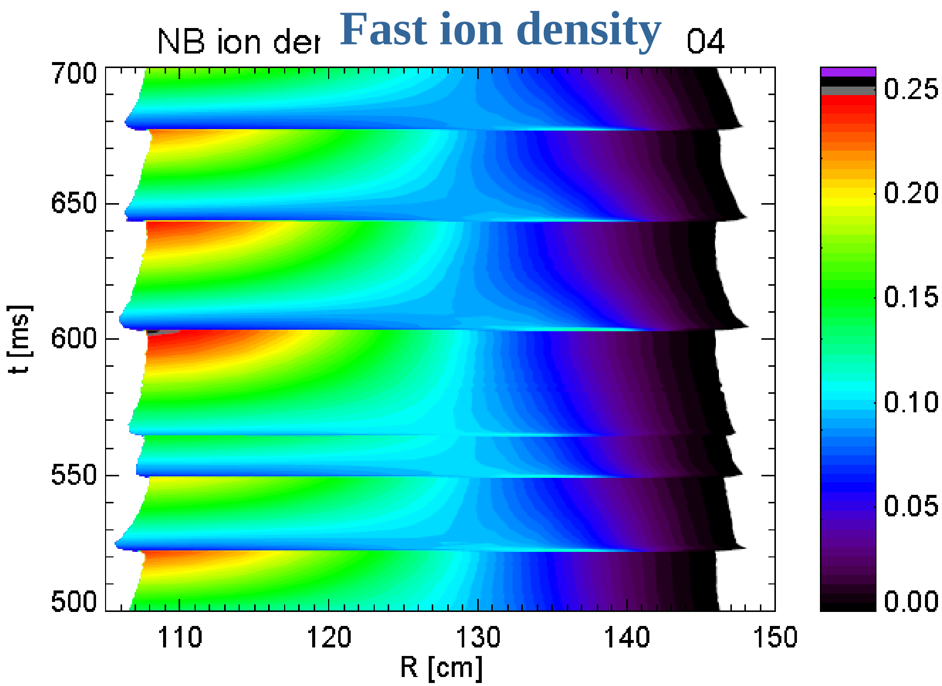


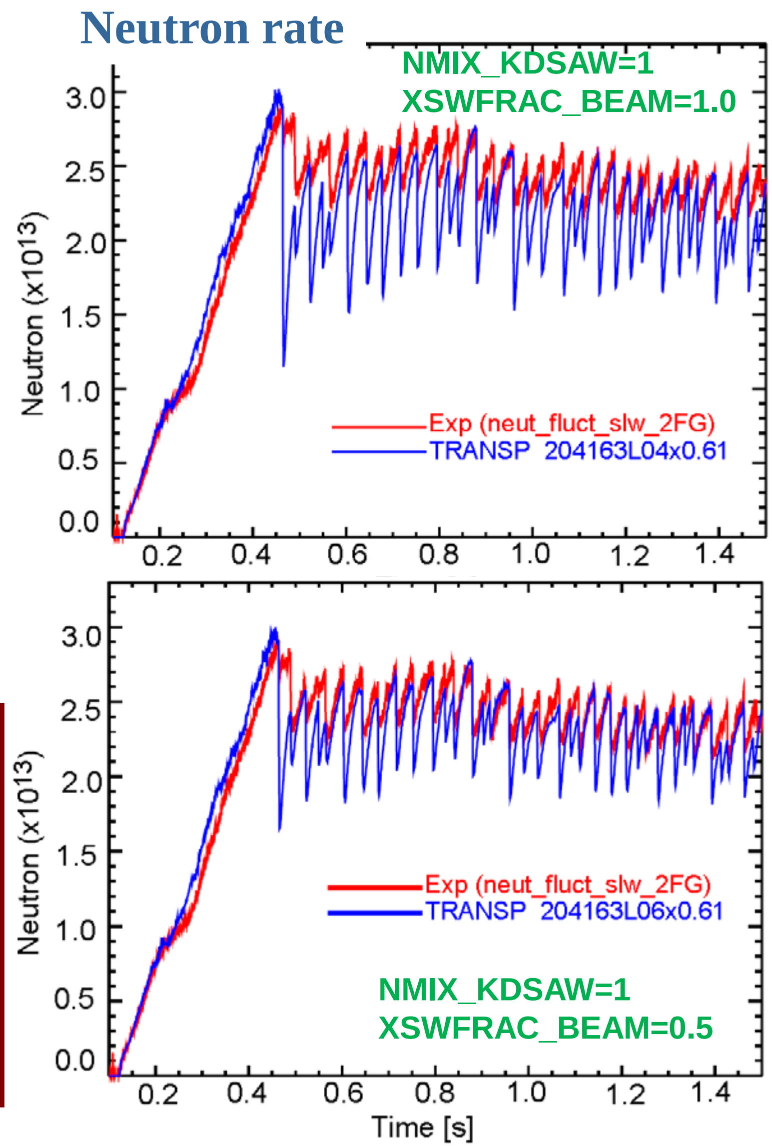




- In TRANSP simulation
  - Sawtooth model **ON** for q-profile evolution
  - Sawtooth model **OFF** for fast ions
- Little modulation in fast ion density profile
- Neutron drops caused by thermal plasma profile evolution can be ~50% of the measured neutron rate drop.

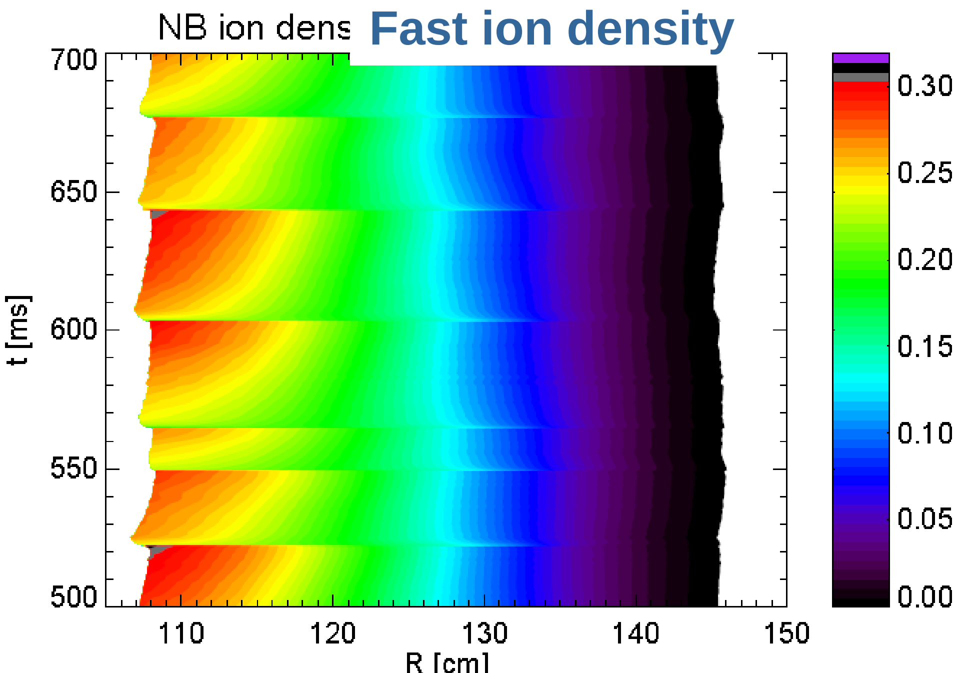
Standard Kadomtsev Model Overestimates Neutron Rate Drop at Sawtooth

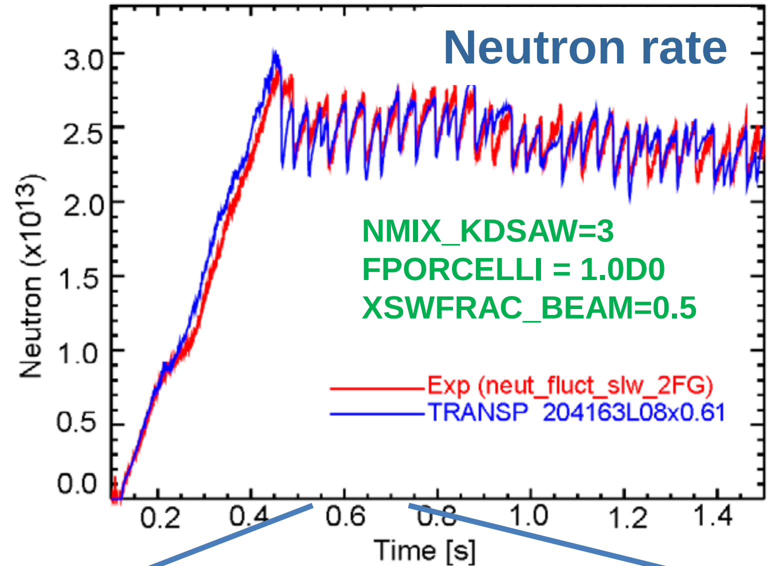


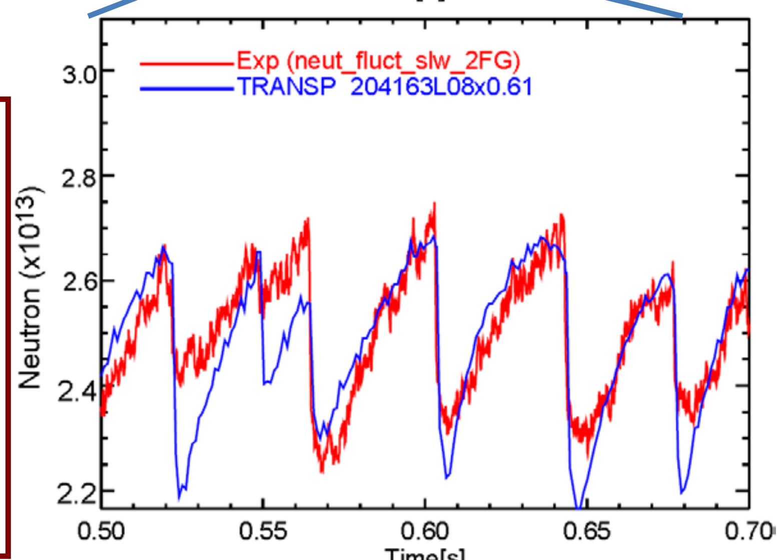


- ➢ TRANSP with standard Kadomtsev model
- ▪ XSWFRAC_BEAM: fraction of beam fast ions participating in mixing
- ➢ Standard Kadomtsev sawtooth model overestimated neutron rate drops at sawteeth

Tuning the Parameters of Porcelli Model can Reasonably Match the Neutron Rate



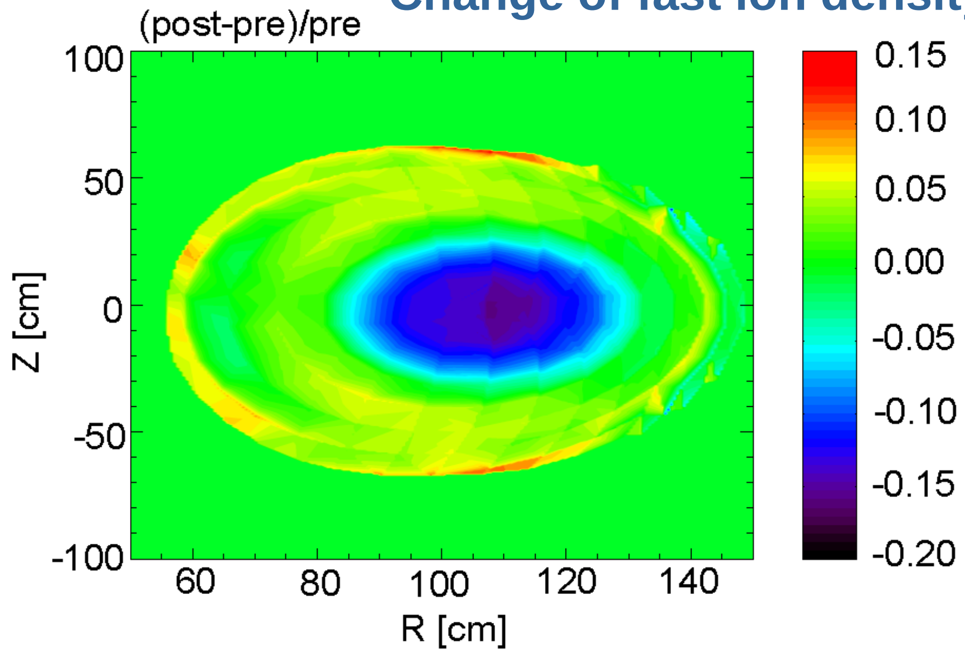


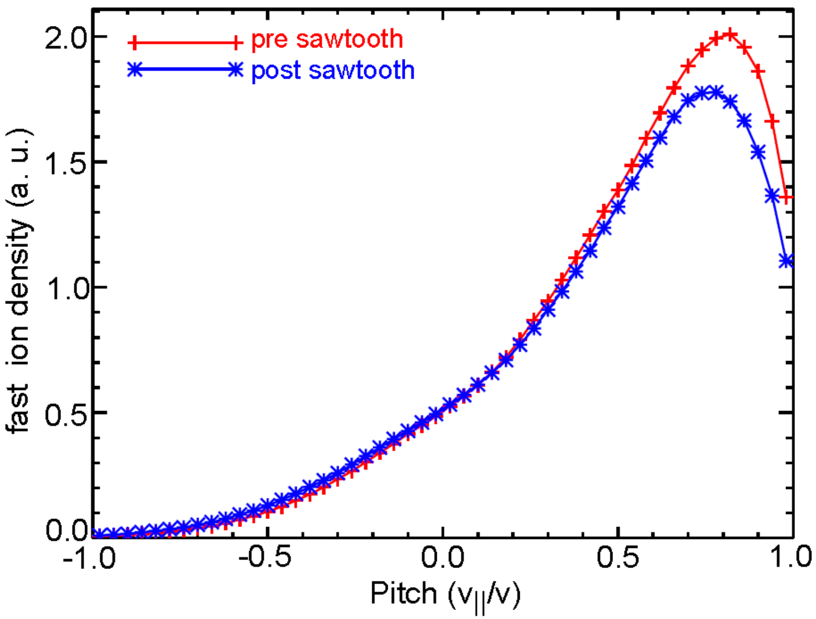


- Porcelli Model
  - Incomplete reconnection model
- Neutron rate from TRANSP simulation with Porcelli model can agree with measurements, but not sensitive to fraction of reconnection (FPORCELLI in namelist).

Simulations with Porcelli Model Suggest that Fast Ions are Redistributed from Core to Edge

Change of fast ion density

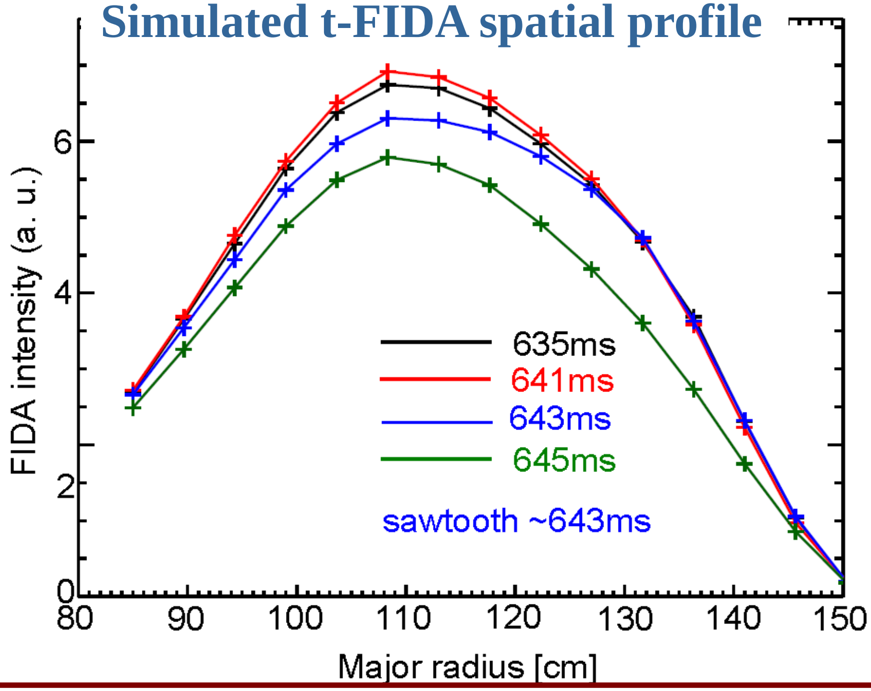




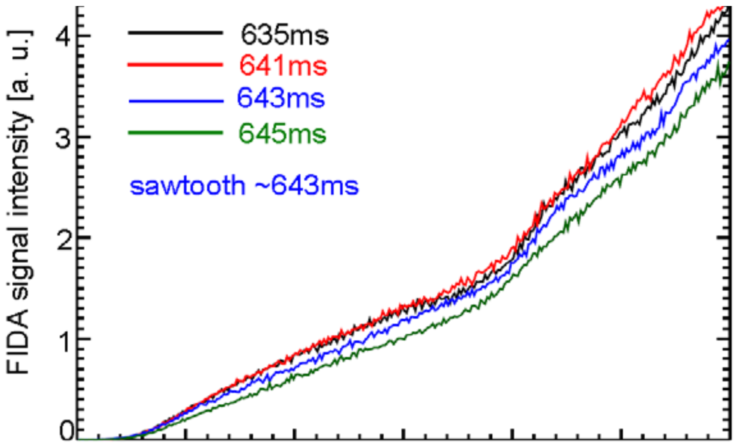
- TRANSP simulations with Porcelli model show ~20% decrease of fast ion density in the core.
- Porcelli model shows passing particles are strongly affected compared with trapped particles although all fast ions are treated thermally and redistributed according to the rearrangement of flux surfaces. This is mainly because most fast ions in the core are passing particles.

TRANSP+FIDAsim Simulations With Porcelli Model Partially Agree with FIDA Measurements

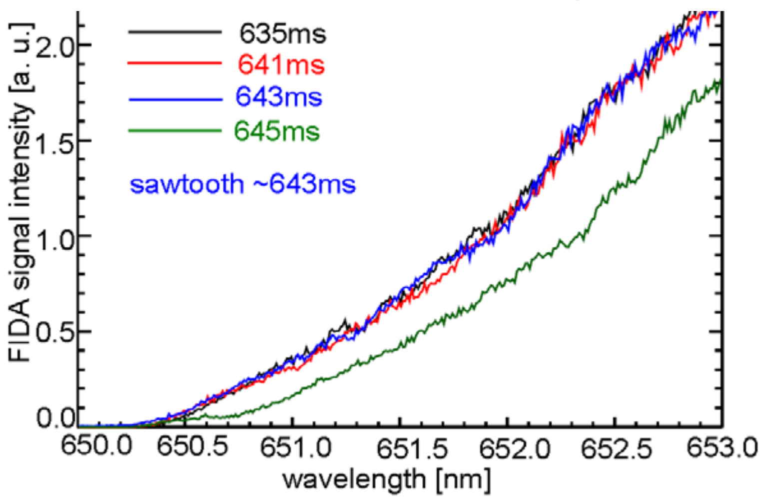
Simulated t-FIDA spatial profile



Simulated t-FIDA spectra, core channel



Simulated t-FIDA spectra, edge channel



- TRANSP+FIDASIM simulations suggest
  - 10% decrease of FIDA signal in core channels
  - Little increase or no change at outer channels at sawtooth crash; Decrease after sawtooth crash.
  - Partially agree with FIDA measurements. The FIDA data shows a signal drop in the core, but an increase at the edge, see slide 9 and 10

Observed Differences in Passing and Trapped Particles Qualitatively Agrees with Theory

- Kolesnichenko and Yakovenko [NF 1996] describes fast ion transport during sawtooth with three time scales
  - Crash time τ_{cr}
  - Particle longitudinal motion: τ_{ψ} (period about the perturbed flux surface)

    → attachment to evolving flux surfaces → **strong** redistribution
  - Toroidal drift motion: τ_{pr}

    → decorrelation between particle and mode → **weak** redistribution
  - Conditions for strong transport: **Passing: $\tau_{\psi} << \tau_{pr}$, Trapped: $\tau_{cr} << \tau_{pr}$**

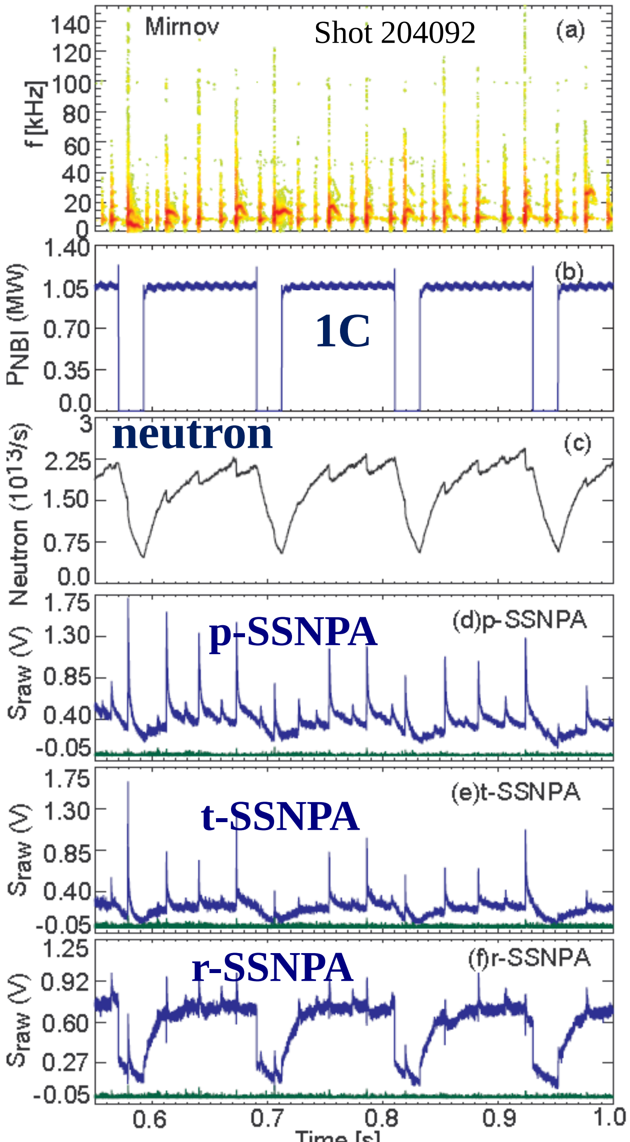
    or in terms of E, pitch, $E < E_{crit}$

- Preliminary NSTX-U calculations indicate
  - Sawtooth crash time ~40 μs, E_{inj}=70keV
  - Passing particles: E_{crit}~60keV
  - Trapped particles: E_{crit}~15keV

  → Passing particles will be strongly redistributed by sawtooth

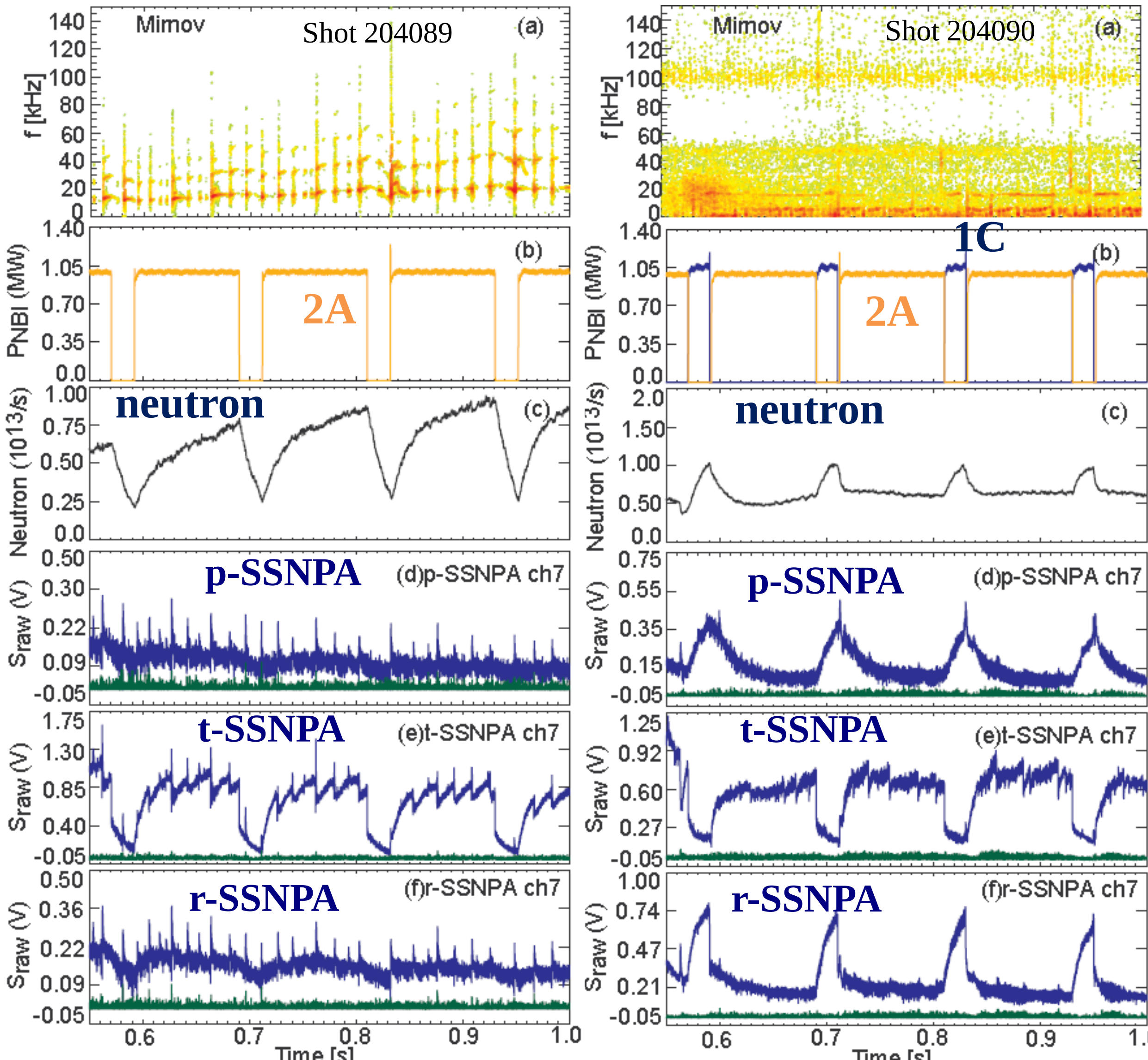
Other Interesting Observations

Sawtooth Behavior Seems Different when Using Different Neutral Beam Sources (1/2)



- Strong sawtooth during 100ms pulses of NB source 1C (most perpendicular) source
- Neutron rate drops at sawtooth crashes
- Spikes on edge D_{α} at sawtooth crashes
- Big spikes on passive radial reference view (p-SSSNPA) and passive tangential view (t-SSNPA) → comparable passing and trapped particles are redistributed/lost to the edge
- Big spikes on passive radial reference view (p-SSSNPA) and small increase in active radial view (r-SSNPA) → some trapped particles are expelled from the core

Sawtooth Behavior Seems Different when Using Different Neutral Beam Sources (2/2)



- When beam 2A (most tangential source) is used, sawtooth is weaker or disappears. No obvious neutron rate drop.
- Active tangential view (t-SSNPA) shows small drops at sawtooth. Passive radial views (p-SSNPA and r-SSNPA) observe little increase.
  →sawtooth and fast ion transport are strongly reduced when beam 2A is used. Could be because q profile change and/or rotation profile change

Summary

- **Experimental observations of sawtooth on NSTX-U**
- Sawtooth causes neutron rate drop as large as ~15%.
- FIDA signal shows a decrease in the core and an increase at edge
- SSNPA observes big spikes on passive tangential view and small changes in radial view; signal changes are strongly correlated with neutron rate drop →passing particles are strongly expelled from core to edge. Trapped particles are much less affected.

  →similar to sawtooth observations in conventional tokamaks

- **Comparison with sawtooth modeling**
- Standard Kadomtsev model overestimates the neutron rate drops at sawtooth.
- Porcelli model qualitatively agrees with neutron and FIDA measurements when slightly tuning the input parameters. However, it fails to predicts t-FIDA signal increase at edge.
- Preliminary analysis suggest the observed response differences of passing and trapped particles qualitatively agrees with Kolesnichenko and Yakovenko's sawtooth theory

Future work: A new model is being developed to include particle's energy, pitch and orbit width, see D. Kim's poster PP11.00049 this session. Simulations will be performed with this new model and will be compared with neutron and FIDA measurements.