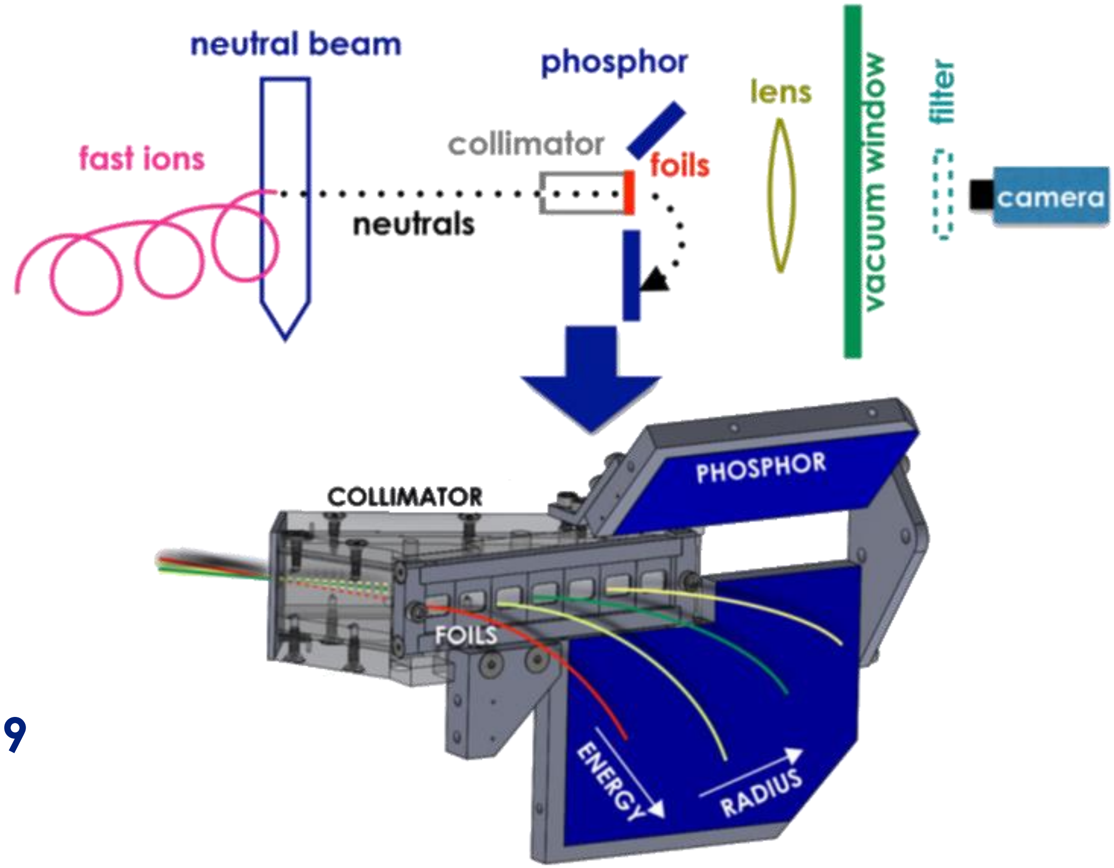
Validation of the Imaging Neutral Particle Analyzer via Pitch Angle Scattering of Injected Beam Ions

by

Daniel J. Lin[1]

X.D. Du[1,2], W.W. Heidbrink[1],
M.A. Van Zeeland[2]

[1]University of California, Irvine
[2]General Atomics



IAEA EP Technical Meeting 2019

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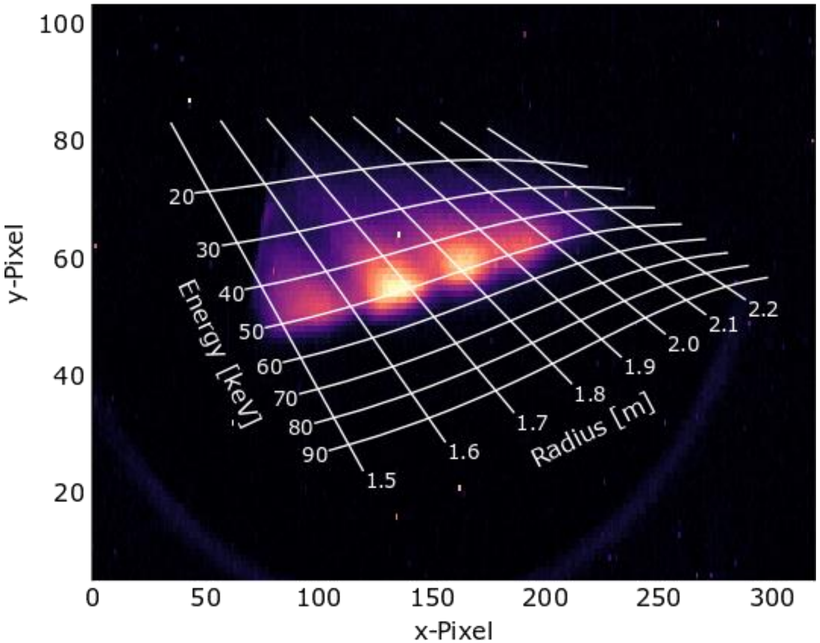
UCI

INPA is a powerful high resolution fast ion diagnostic

- INPA diagnostic
  - Covers broad range of phase space
  - Compact, good signal to noise
  - Fine energy and radial resolution as well as pitch acceptance
- Amazing applications from Xiaodi Du's talk on Friday (I-15)

INPA Scintillator Image



Verify diagnostic with signals during classical fast ion behavior

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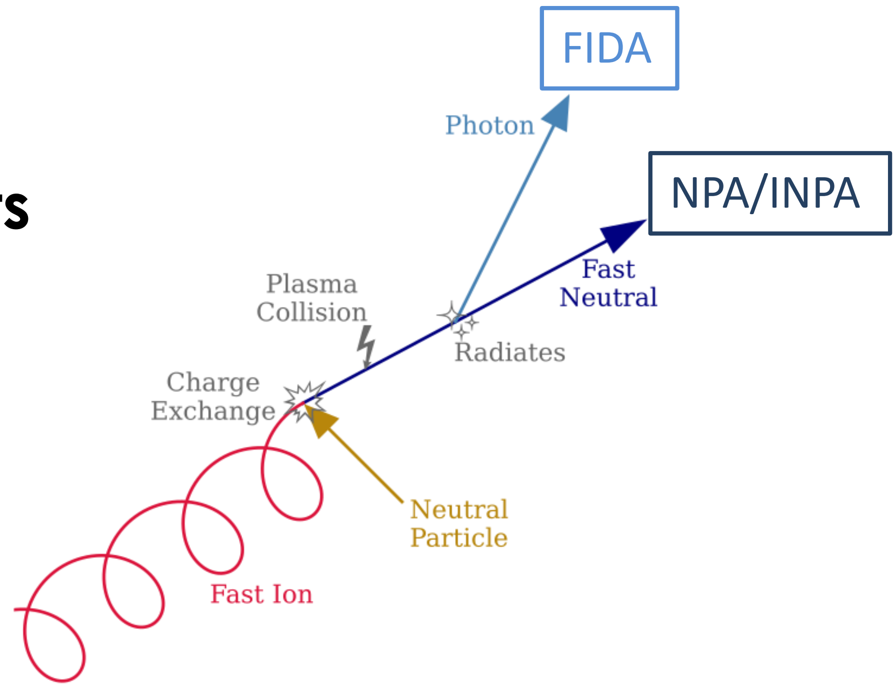
Outline

1. What is an Imaging Neutral Particle Analyzer (INPA)
2. Testing INPA signals with pitch angle scattering
   - Experimental setup
   - Simulation procedure
3. Results
   - Comparing experiment w/simulation
   - Inferring edge neutral density
   - Diagnostic sensitivity on Zeff and density
   - Observations of strong passive signal
4. Summary

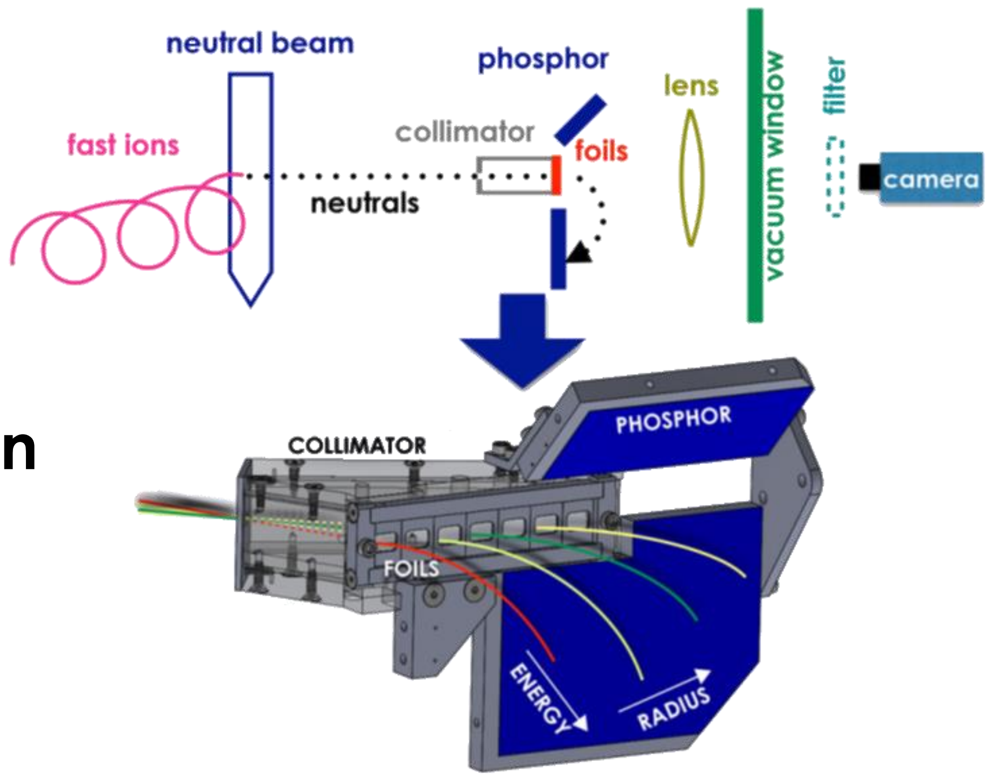
Fast ion charge exchange utilized for measurements

- **Fast ions charge exchange with injected neutrals**
  - **NPA/INPA measures neutralized particle and its energy**
- **Resulting fast neutral can be born into an excited state**
  - **FIDA measures Doppler shifted photon from the visible Dα (656.1 nm) emission**



INPA provides energy resolved radial profiles of confined fast ions

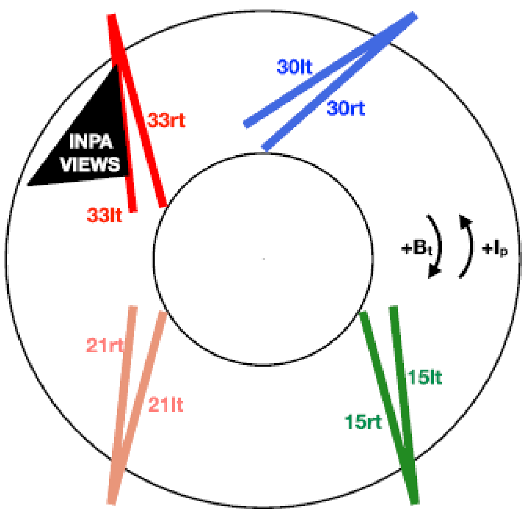
- Fast neutrals are ionized at stripping foils
- Strikes the phosphor before completing first gyro period
  - Gyroradius depends on particle energy
- Camera records light emitted from the phosphor

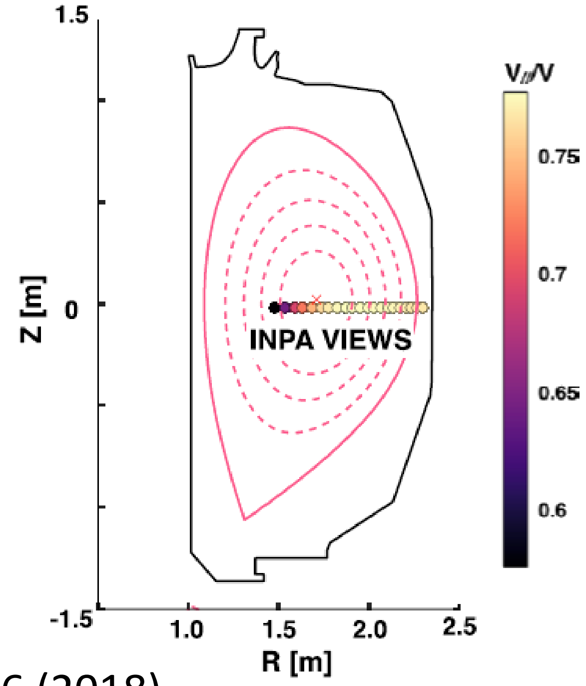


X. D. Du, Nucl. Fusion 58, 082006 (2018)

INPA measures neutralized fast ions along its line of sight

- Chords intersect at radius ~1.5 m to ~2.3 m at 2 cm below the midplane
- INPA designed to measure pitches $\zeta = v_{||}/v \sim 0.77$
- Active measurements taken from both nearly-parallel (33lt) and nearly-perpendicular (33rt) neutral beams

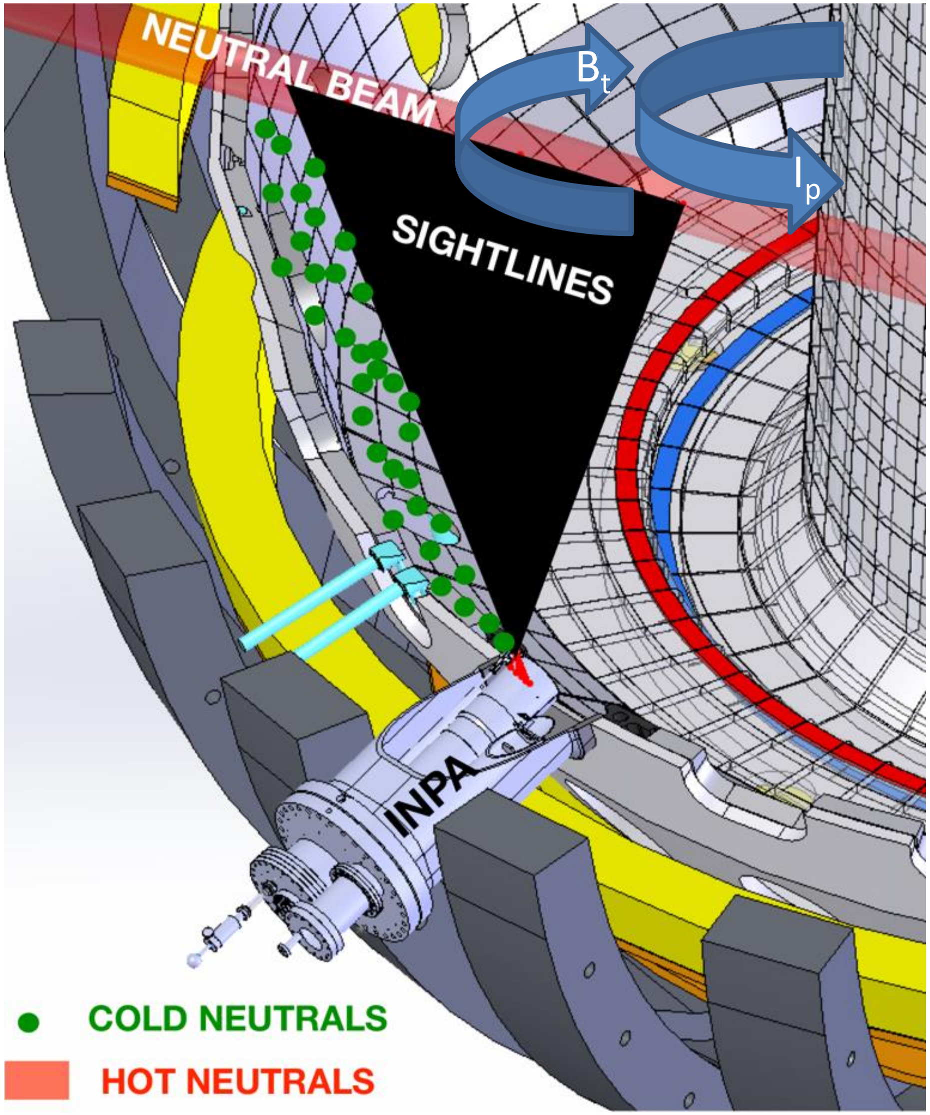




X. D. Du, Nucl. Fusion 58, 082006 (2018)

INPA is installed inside the vacuum vessel for a broad radial view

- System is in vacuum vessel close to plasma to achieve desired view
- Passive emission can also come from edge regions but are heavily weighted towards closest region



Scattering affects the fast ion distribution function

- **Drag:**

$$\frac{1}{\tau_{se}}\frac{\partial}{\partial v}[(v^3 + vc^3)f]$$

- **Energy diffusion:**

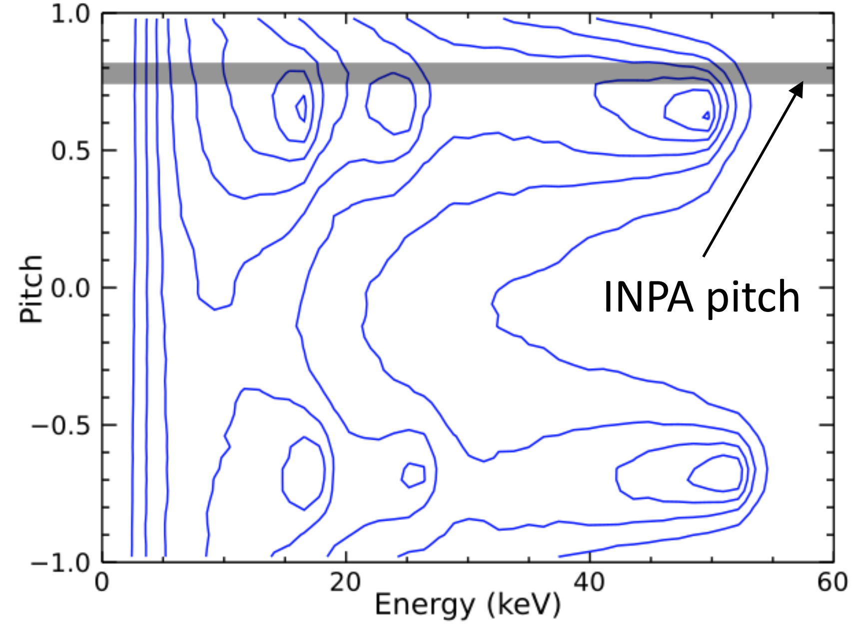
$$\frac{1}{2\tau_{se}}\frac{\partial}{\partial v}[\frac{{v_e}^2 m_e}{m_f} + \frac{v_c {v_i}^2 m_i}{v^3 m_f}]\frac{\partial f}{\partial v}$$

- **Pitch angle scattering:**

$$\frac{1}{2\tau_{se}}\frac{m_i}{m_f}\frac{Z_{eff}}{[Z]}\frac{{v_c}^3}{v^3}\frac{\partial}{\partial\zeta}[(1-\zeta^2)\frac{\partial f}{\partial\zeta}]$$

D. L. Jassby, Nucl. Fusion 17, 309 (1977)

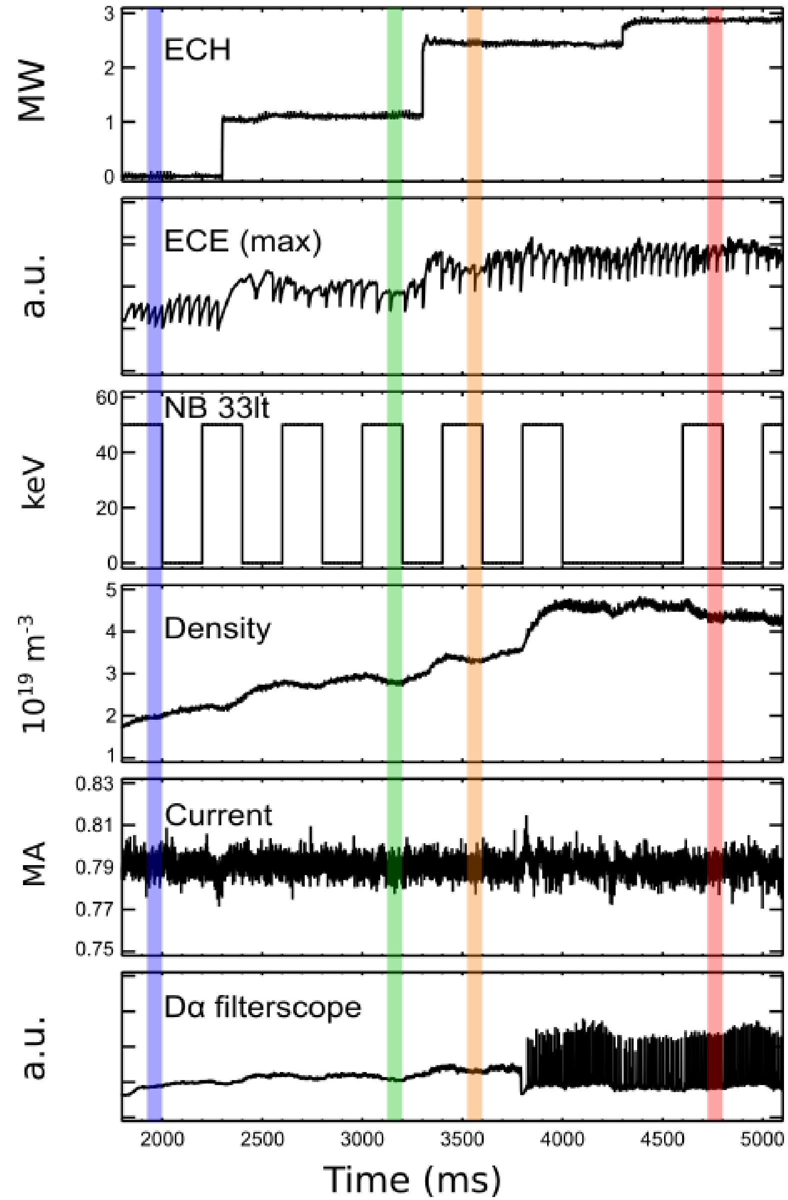
Fast ion Distribution (steady state)



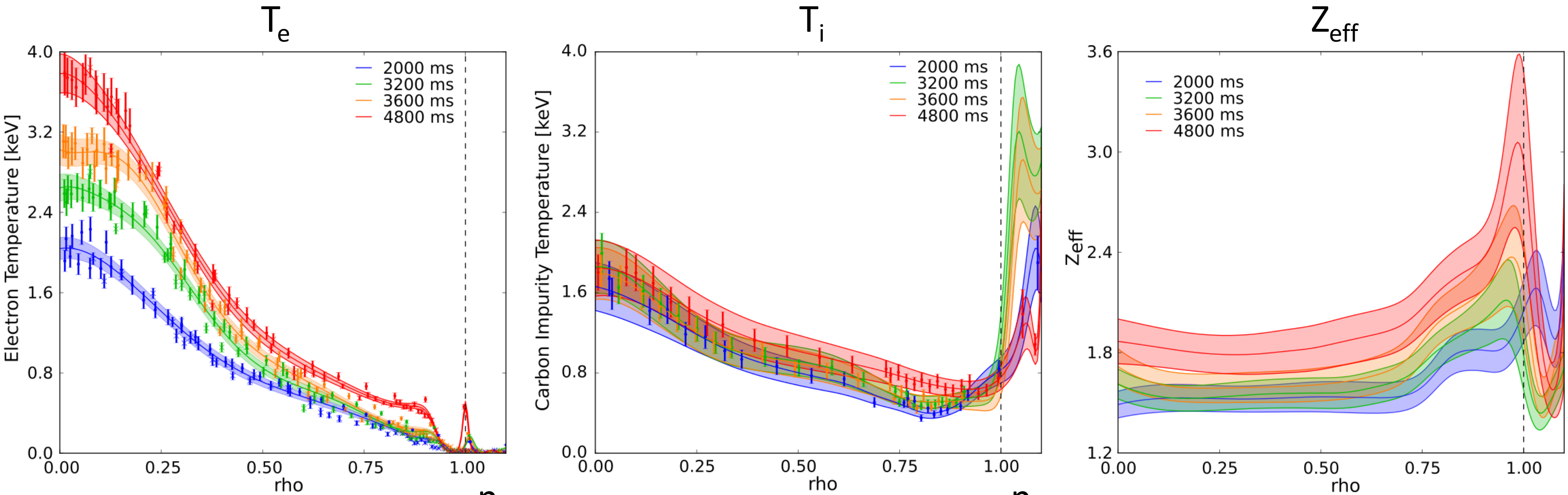
Vary pitch angle scattering by changing relative speed between fast ions and background electrons

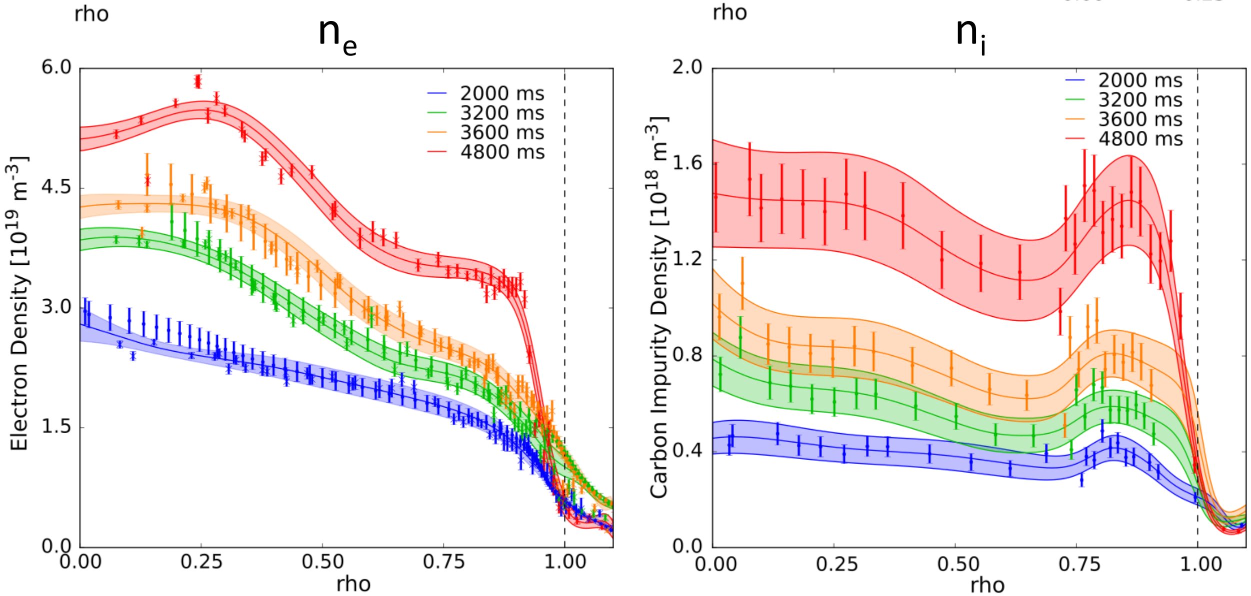
Times with different ECH powers were selected

- **Different ECH power affects electron scattering ($\alpha\, T_e^{-3/2}$)**
- **Density steadily increased and transitions to H-mode around 3800 ms**
- **Sawtooth instability with q=1 surface around 1.9 m (rho ~ 0.21)**
  - **Time averaged distribution function to mitigate impact**



Density and electron temperatures varied





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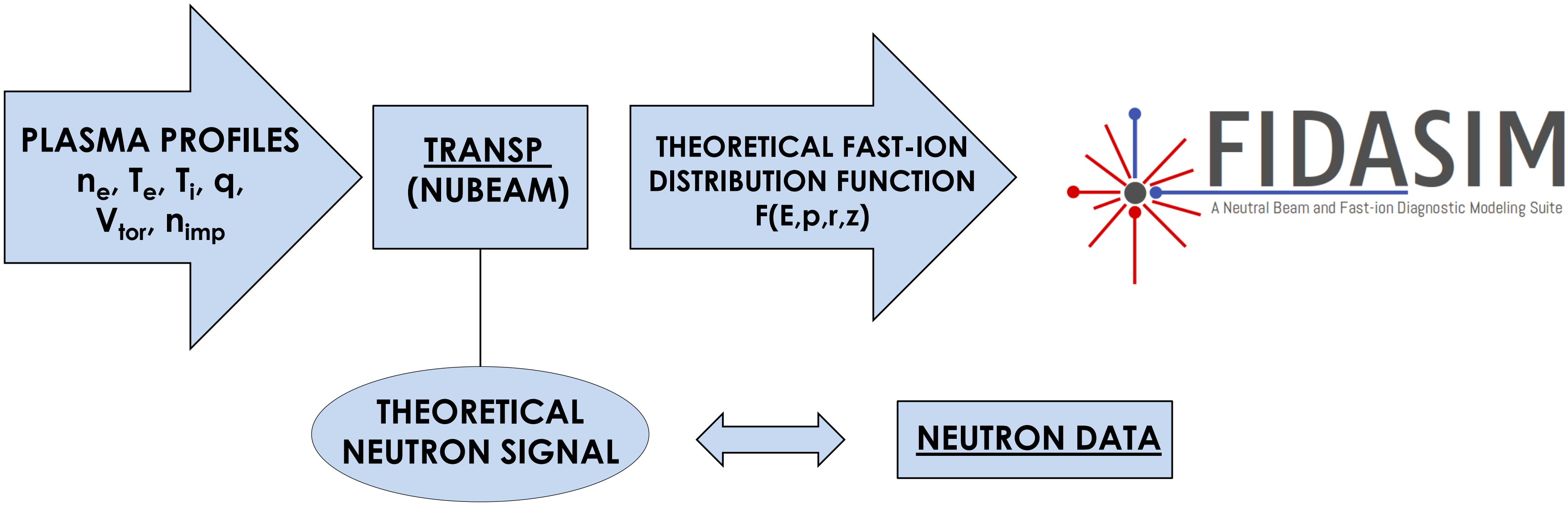
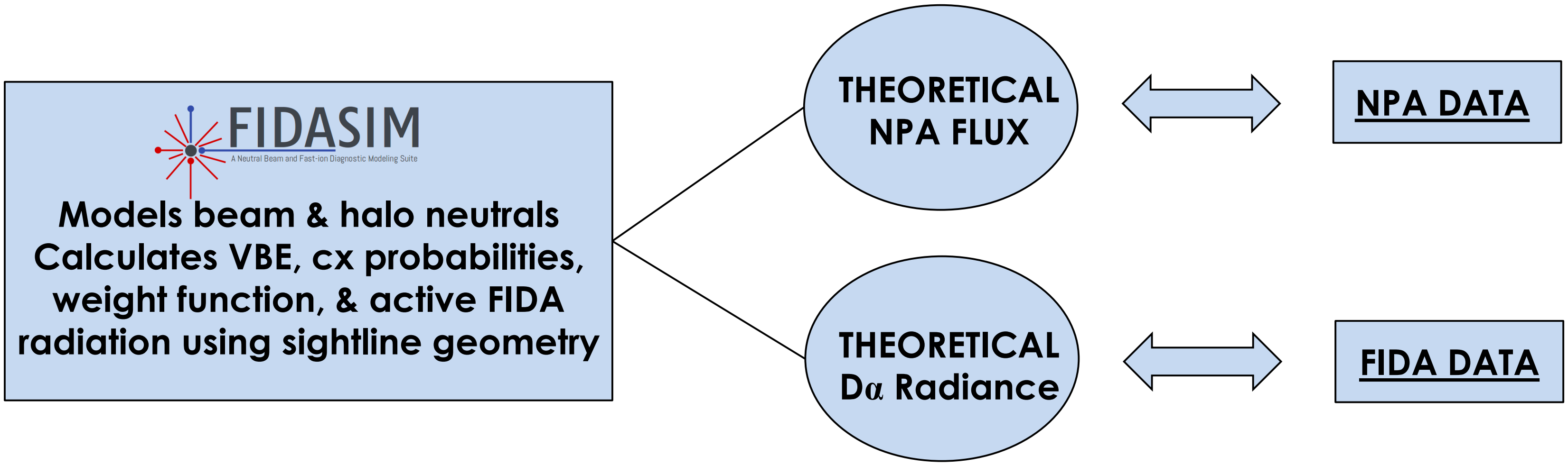
Fast ion distribution function obtained through TRANSP/NUBEAM



- **NUBEAM models the heating sources and its deposition into the plasma**
- **Distribution function is time evolved through plasma collisions and reactions**

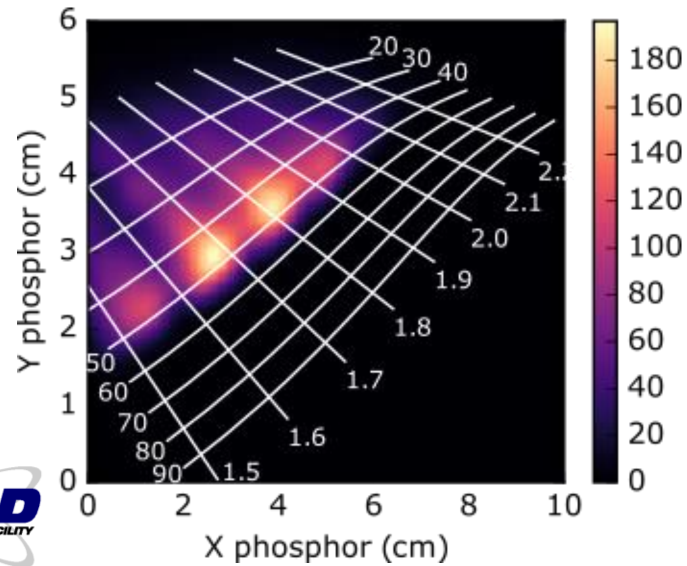
FIDASIM simulates fast ion charge exchange

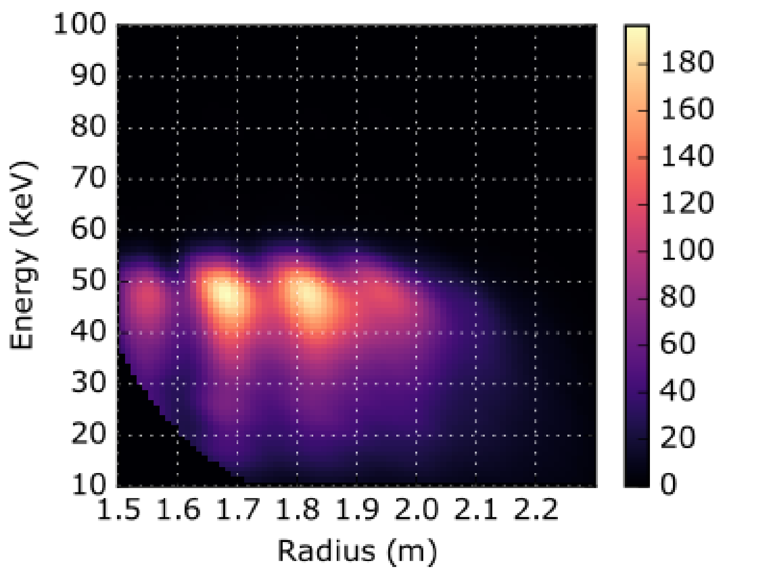


- **Models spectroscopic features like beam, halo neutrals, visible bremsstrahlung, and FIDA emissions**
- **Calculates particles that pass through the diagnostic aperture and reach the detector**
- **More information about FIDASIM capabilities are presented by Alvin Garcia (P1-13)**

The synthetic image of the INPA is calculated using INPASIM code

- Calculates the neutral interaction with stripping foil
- Traces ionized neutral orbit onto the phosphor
- Grids were created by using test particles with a given starting location and energy
- Both simulation and data are projected onto the radius and energy grid





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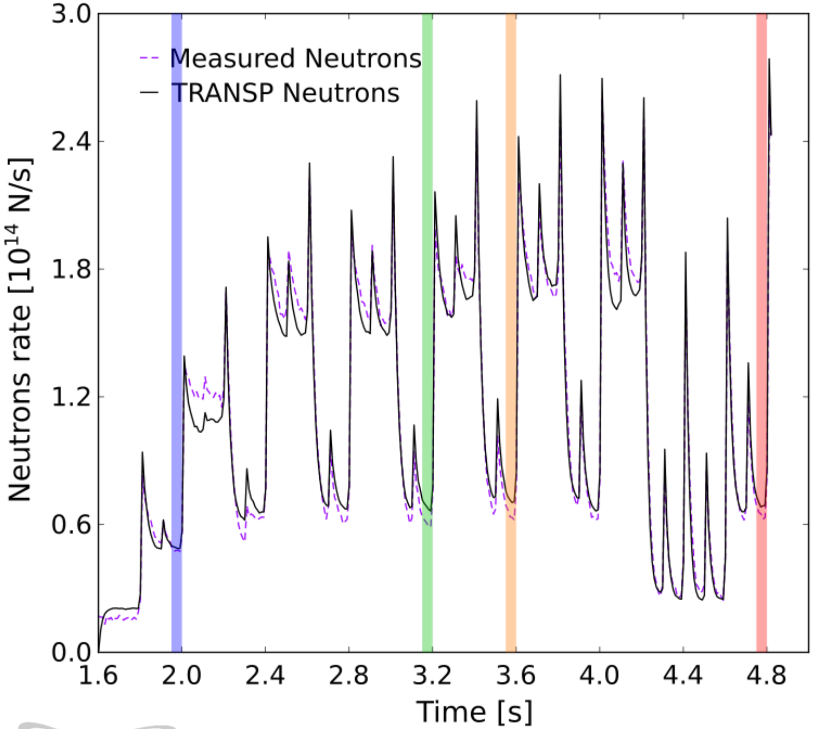
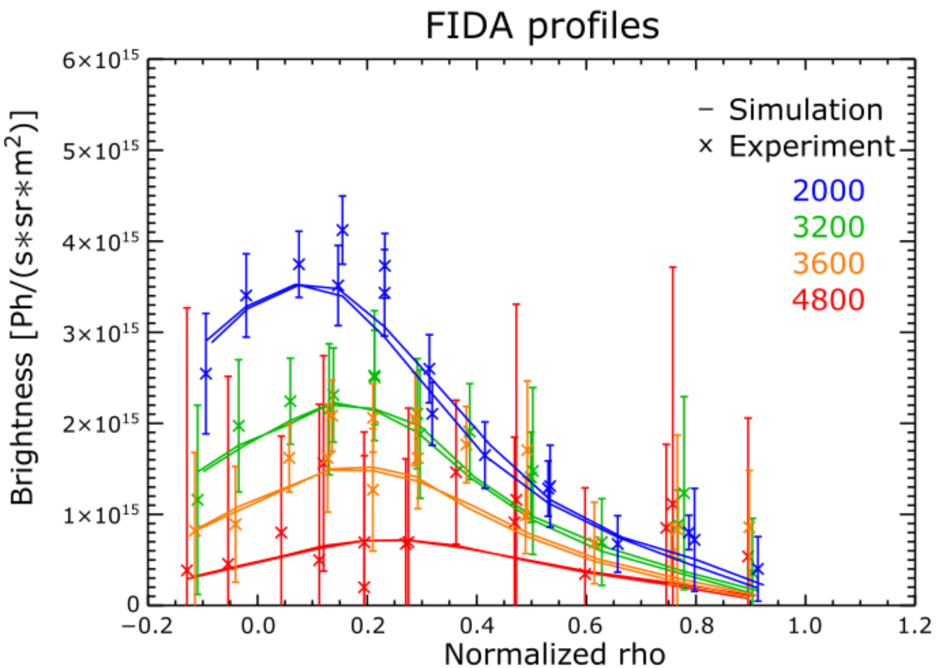
Simulated neutron and FIDA signals are consistent with experiment

- **Simulated neutron rate from TRANSP agrees with the measurement**





- **EP profiles from FIDA are consistent with simulation by FIDASIM after passive correction**

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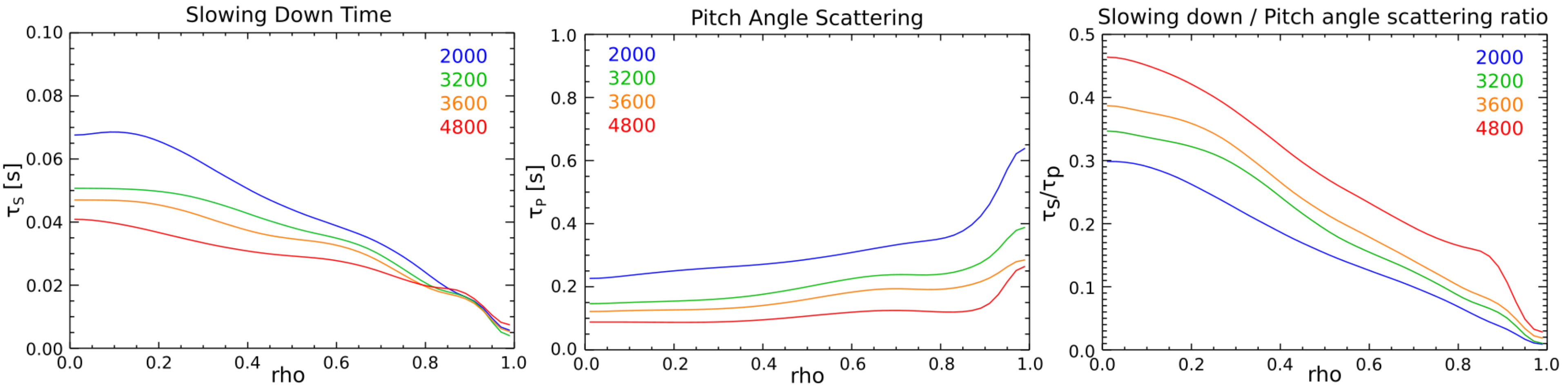
Slowing down and pitch angle scattering time varies with ECH power



- **Scattering rates of electrons decrease with increasing temperature**
- **Fast ions that scatter off of thermal ions change their pitch angle**
- **Difference in slowing down to pitch angle scattering ratio indicates different distribution shape**

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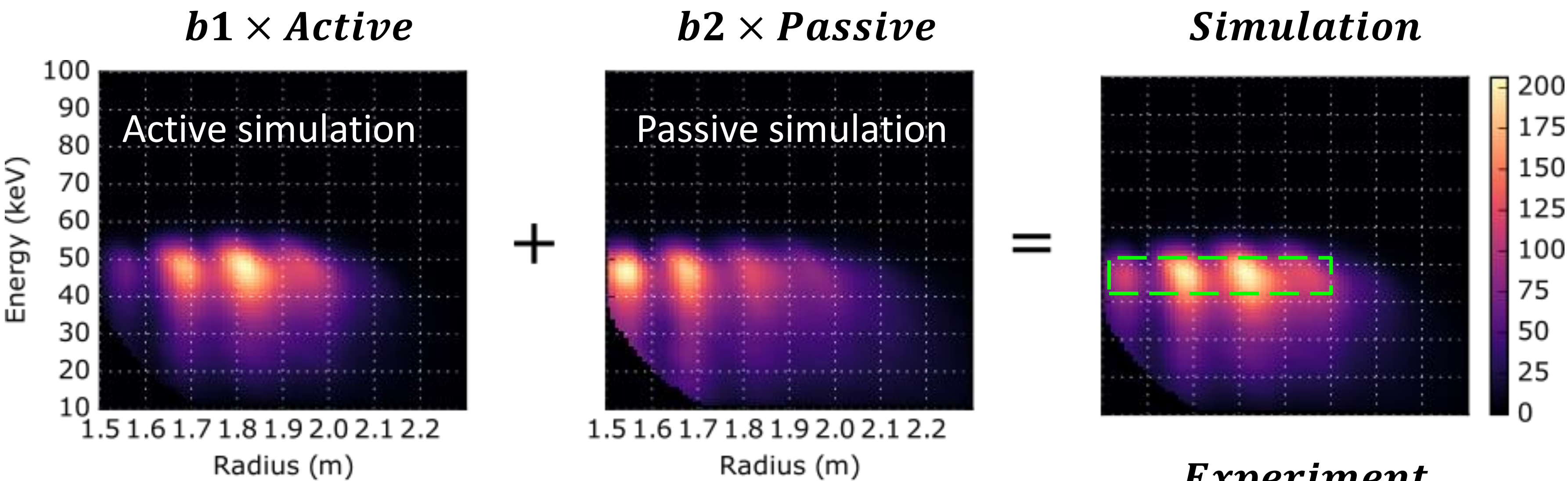
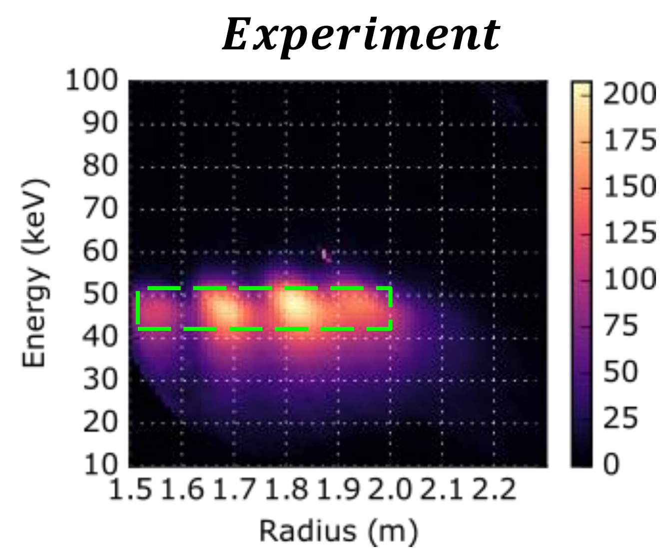
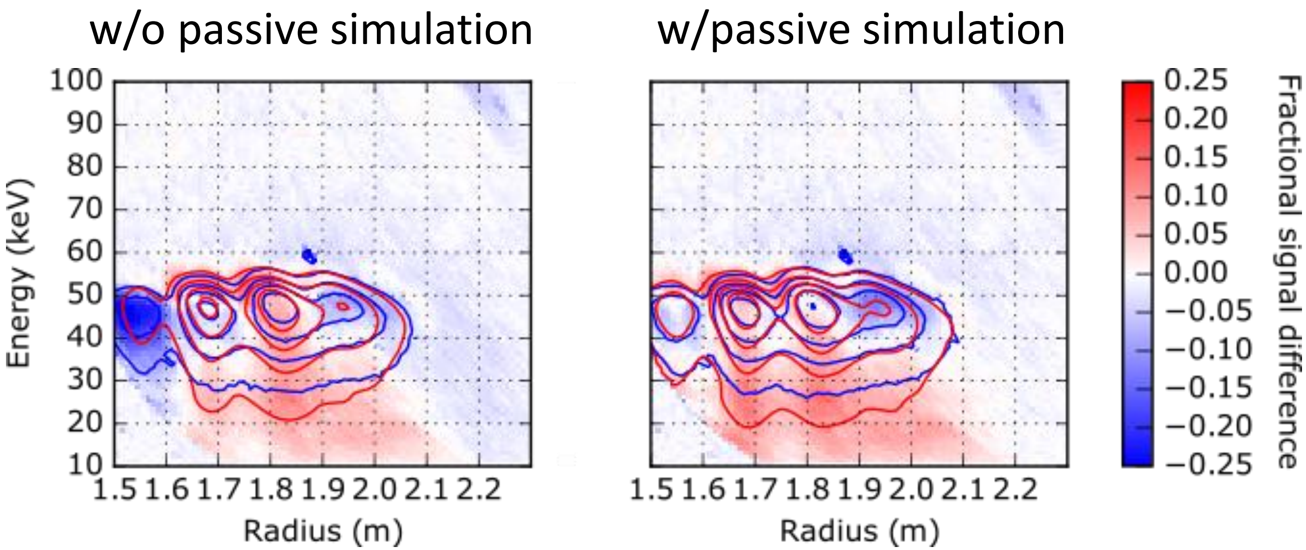
Simulated signals are scaled to match uncalibrated experimental values



- **Difference in boxed regions are minimized to obtain coefficients ($b1$, $b2$) for each contribution**
- **$b1$ is fixed as it corresponds to the calibration**



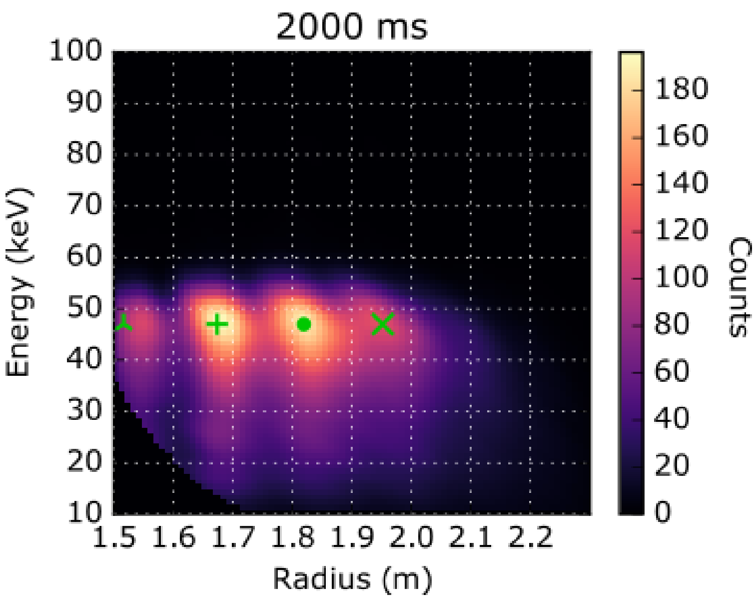
Passive simulation resolves some of the differences in signal

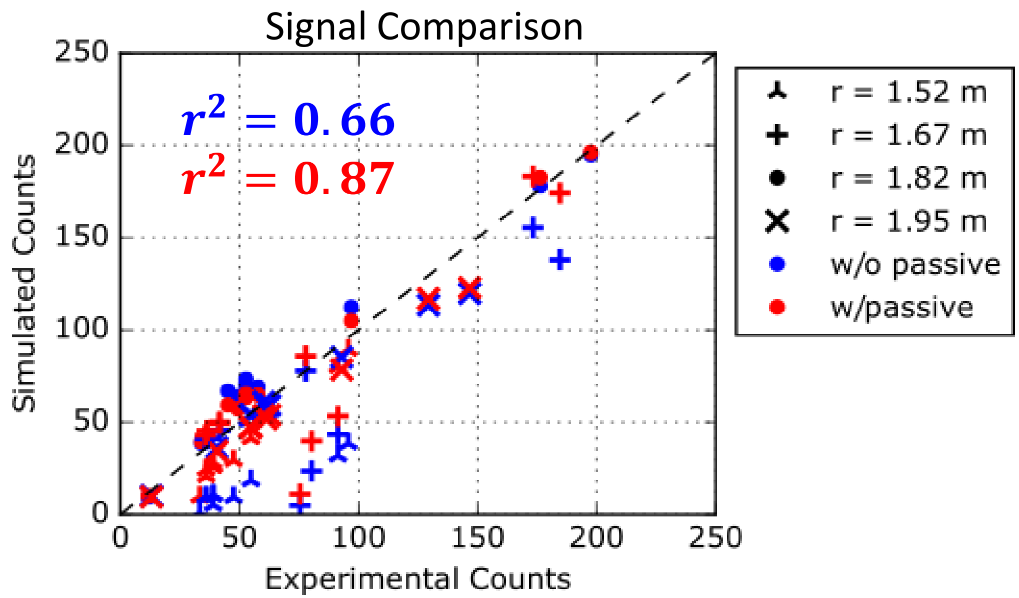


Simulation
Experiment

- **Addition of passive signal increases the overall agreement with the experiment**
- **Inaccurate model of light emission at lower energy leads to overestimation in simulation**
- **Incorrect neutral density profile shape can possibly account for the other differences**

Simulation with passive signals increase agreement with experiment





- **Simulated counts from 4 different radii at 47 keV are compared to experimental counts at the same location for multiple similar time frames**
- **Addition of passive simulation increases the r^2 value from $r^2 = 0.66$ to $r^2 = 0.87$**

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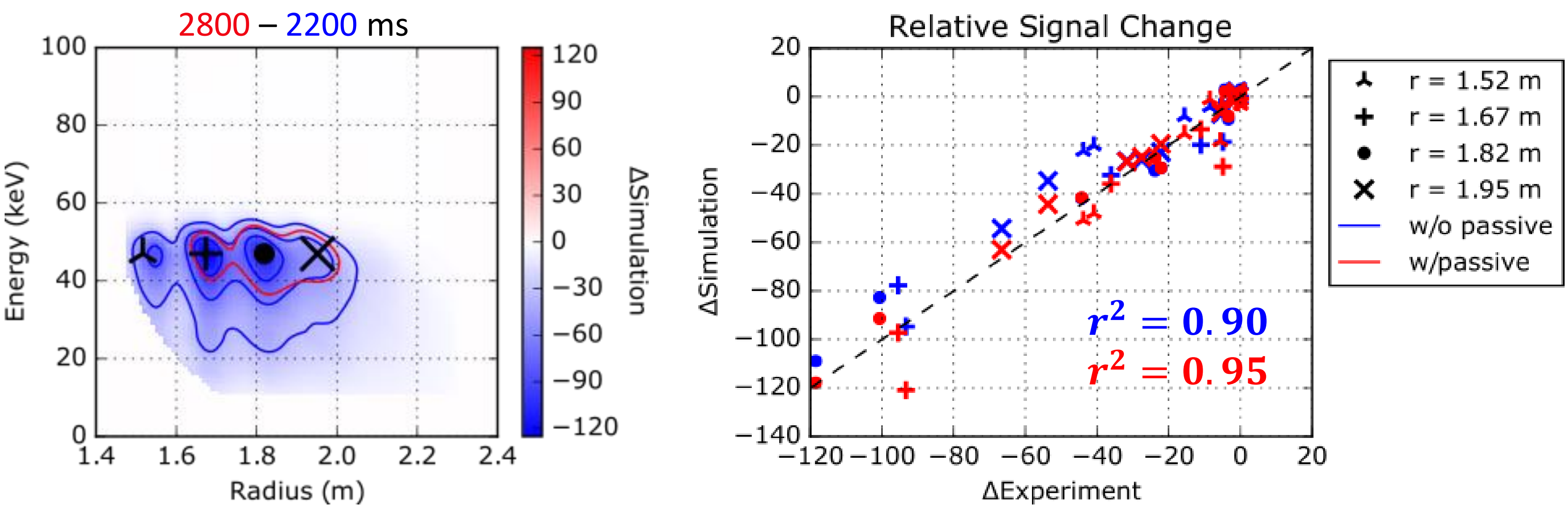
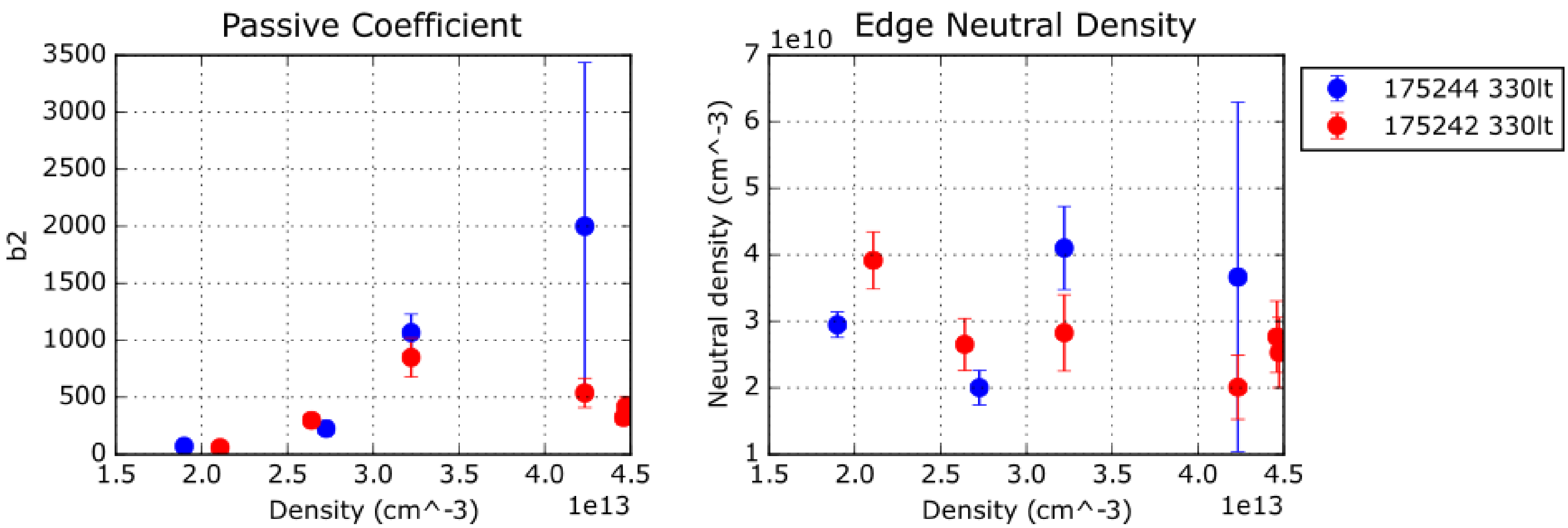
Passive simulation accurately depicts changes in signal



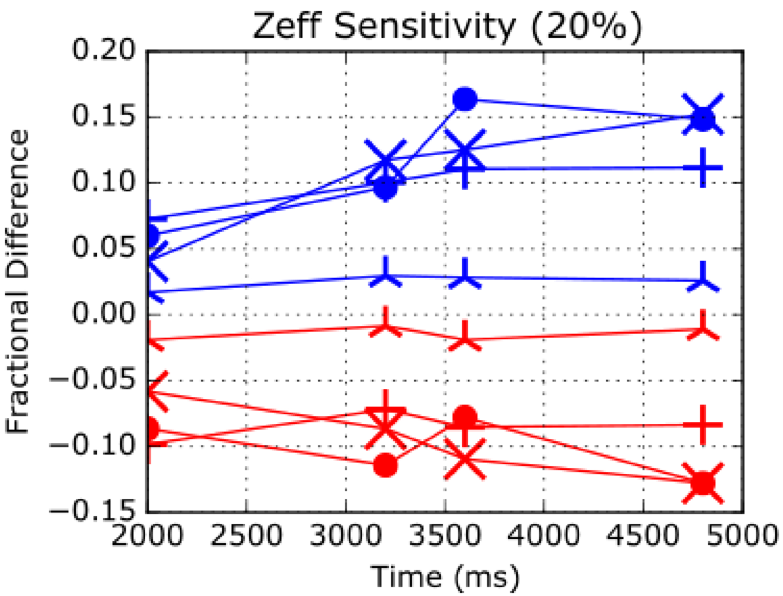
- Temporal changes in simulation are compared to changes in experiment for 4 different radii at 47 keV
- Changes in simulated signal tracks well with changes in experiment
  - Slightly better agreement with addition of passive signals

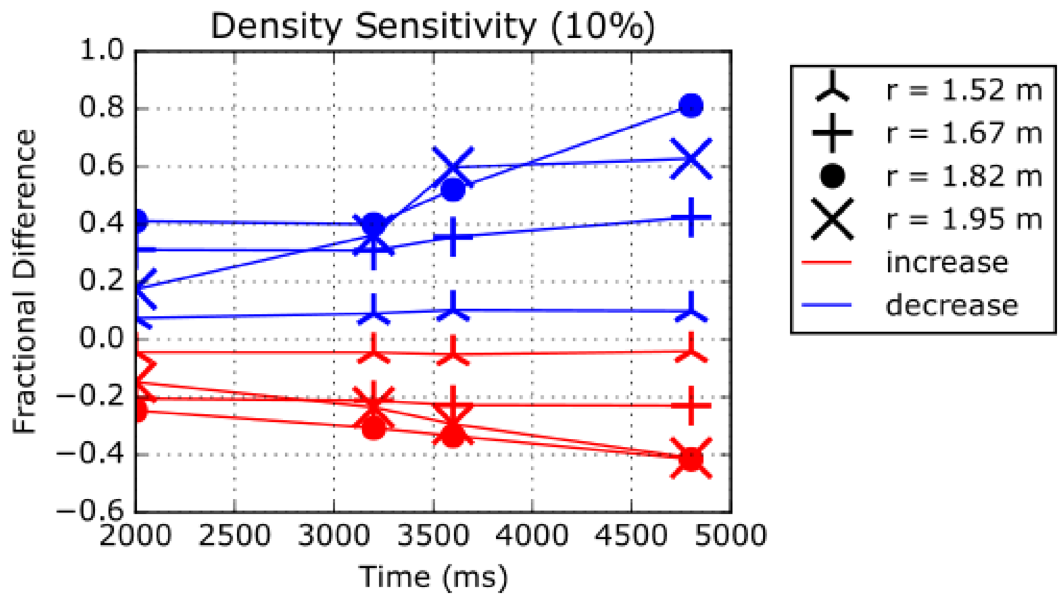
Edge neutral densities inferred through coefficients

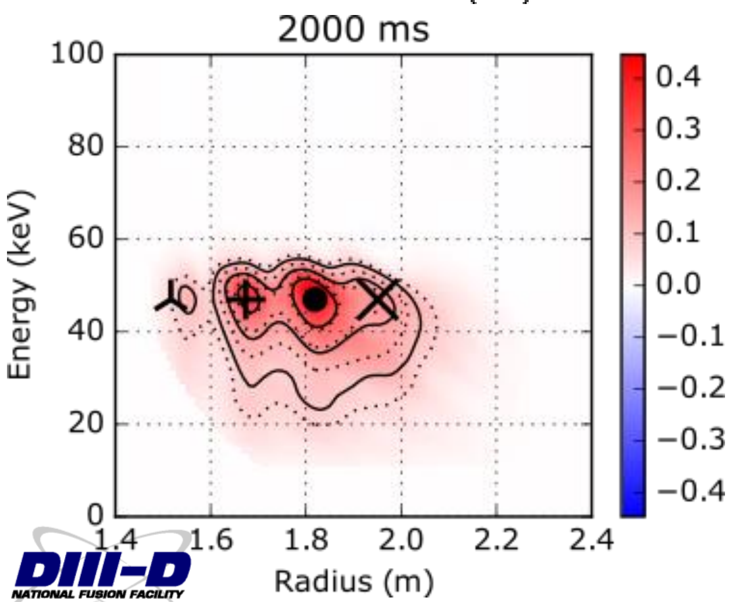


- **Signal decreased with increasing density**
  - **SNR increased**
- **Error bars determined by simulation agreement with experiment**
- **Uncertainties in input profiles contribute to discrepancies**

Uncertainties in input profiles can be a source of error







- **Slightly sensitive to Zeff and very sensitive to density**
- **Increasing(/decreasing) Zeff scatters more(/less) fast ions out of INPA pitch range**

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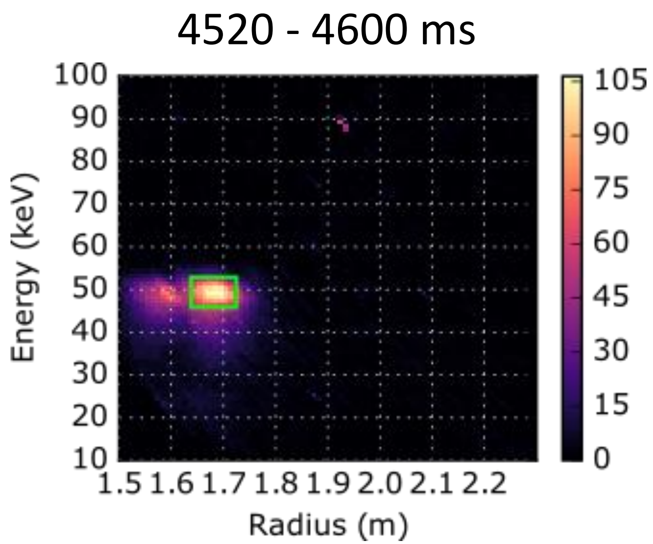
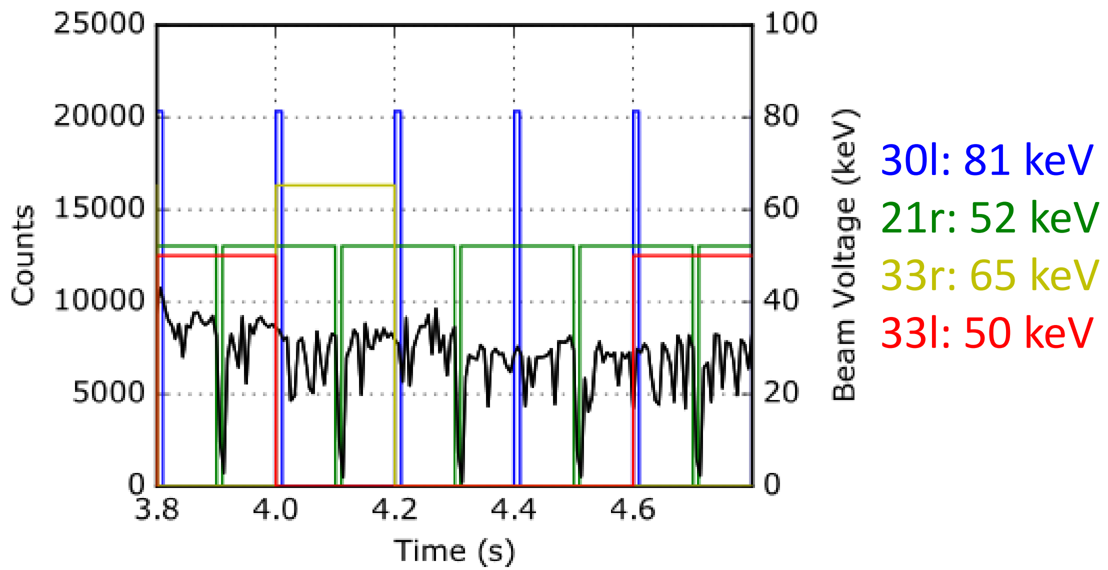
Observed strong passive signal correlates to the 210rt counter beam





- **Signal appears despite the lack of an active beam**
  - **Magnitude of signal remains unchanged**
- **Appearance of the signals match with the timing and energy of the 210rt beam**

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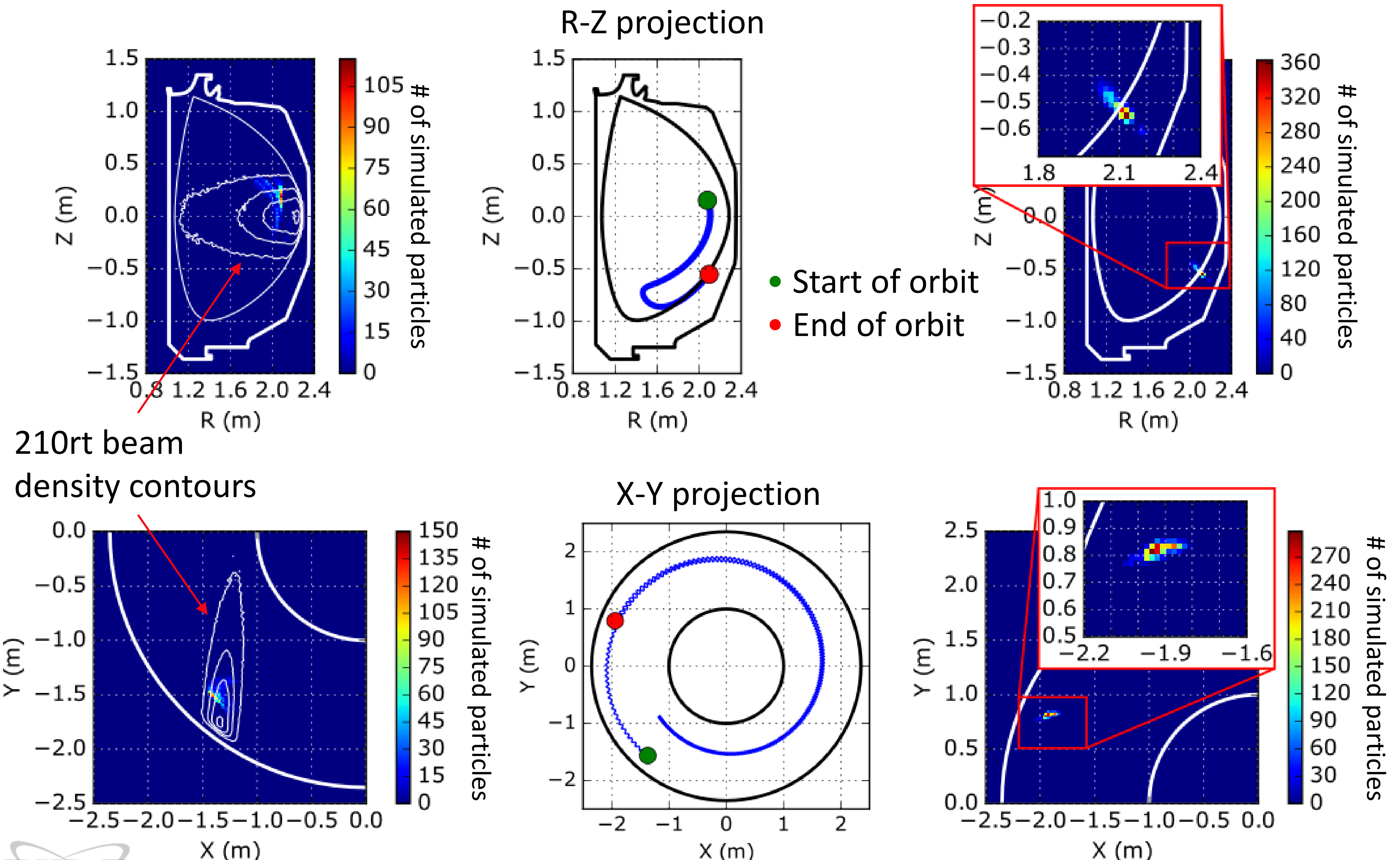
Strong passive signal originates from trapped orbits from 210rt beam that neutralize outside of the plasma

- 2 different regions are checked for comparison
  - Channel with signal (1): R = 1.63-1.73
  - Channel without signal (3): R = 1.91-2.01
- Simulated over 1e7 orbits (49–55 keV)
  - Channel 1: 953 possible orbits
  - Channel 3: 9 possible orbits
  - Does not account for reaction cross section
- Experimental signal (49–55 keV)
  - Channel 1: 3723 counts
  - Channel 3: 542 counts
  - Signals contain active and passive components

Strong passive signal originates from trapped orbits from 210rt beam that neutralize outside of the plasma



Summary

- INPA is a novel diagnostic with high energy and radial resolution
- Simulated images with passive signals significantly improve agreement with experiment
- Changes in simulated signals match very well with changes in experimental signal
- Edge neutral densities can be inferred through simulation
- Prominent passive signals from trapped fast ions with edge neutrals are observed
  - Can potentially be used to diagnose edge fast ion distribution