High-Resolution Imaging Neutral Particle Analyzer Measurements Of The Local Fast Ion Distribution Function And Instability Induced Transport In DIII-D

by
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with **M.A. Van Zeeland**[1], **W.W. Heidbrink**[2], **G. Mckee**[3], **M. Austin**[4], **L. Stagner**[5], **D. Lin**[2], **C.S. Collins**[1], **D. Su**[1], **K. Gage**[2], **Y. Zheng**[3]

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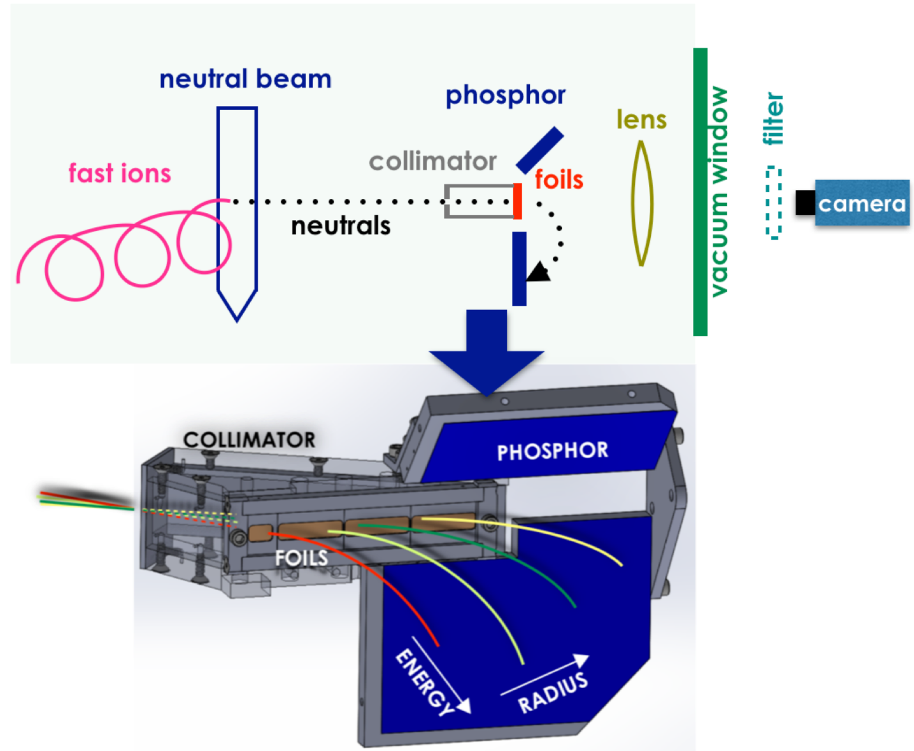
[3]University of Wisconsin-Madison, USA

[4]The University of Texas at Austin, USA

[5]Oak Ridge Associated University USA



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Sep 3-6, 2019

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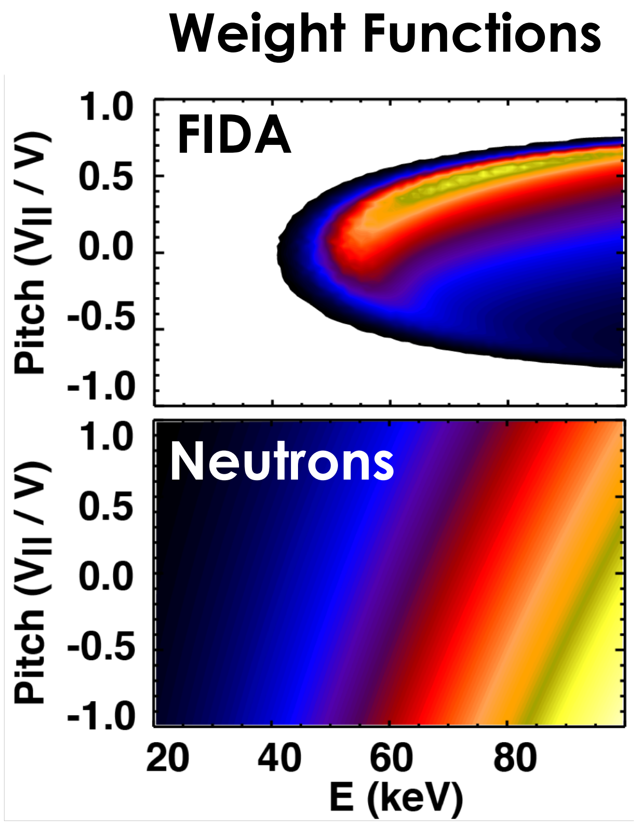
GENERAL ATOMICS

Most EP Diagnostics Integrate Over Large Regions of Phase Space



W.W. Heidbrink, RSI, 2010

Convolution W*F

$$S = \int\int\int\int (W * F) dE\ dp\ dR\ dz.$$

- **Examples show phase space weight functions for:**
  - Doppler shifted fast ion **Dα** light (FIDA)
  - Neutron measurement
- **Weight functions like these are great for global view of EP confinement**
- **Wave-Particle interaction is localized in phase space**

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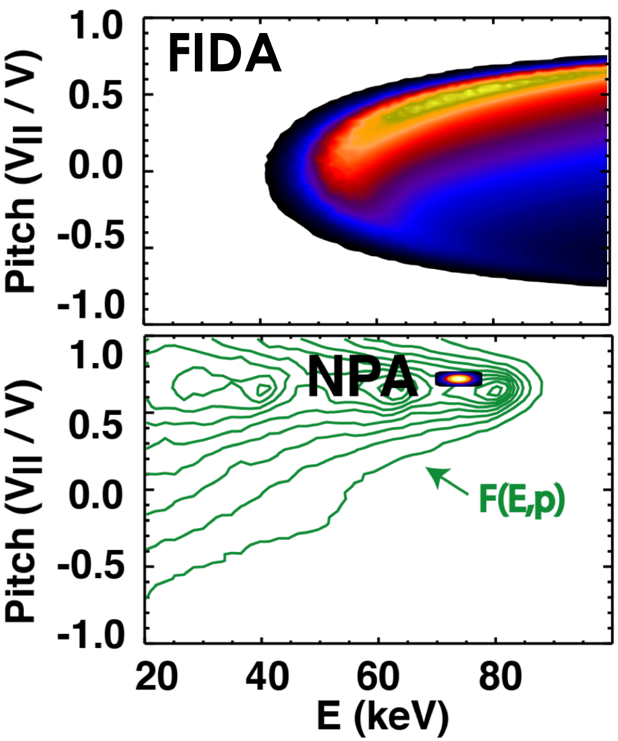

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- **Neutral Particle Analyzers have excellent phase space resolution**
  - Can probe details of phase space interaction
  - Traditionally, hardware size & view limit # channels (< ~10-100)

**X.D. Du et al Nucl. Fusion 2018*
**M.A. Van Zeeland et al JINST 2019*

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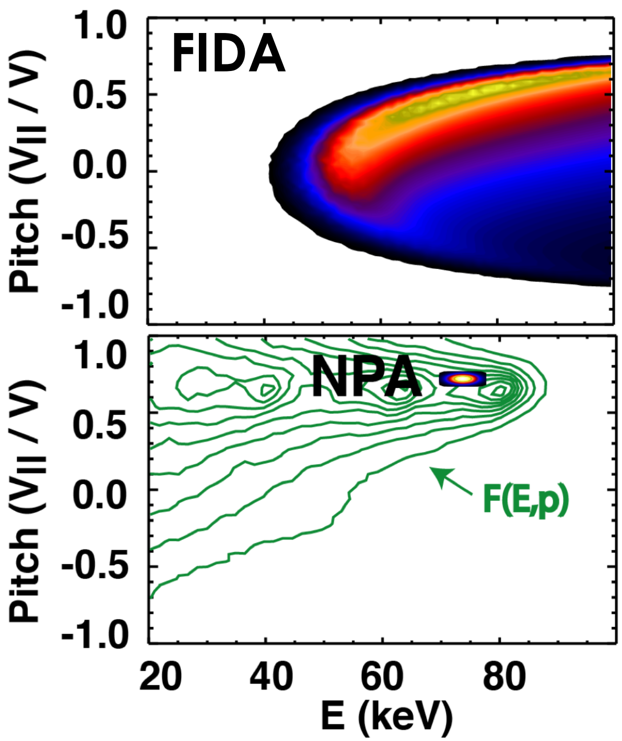

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Talk discusses new Imaging Neutral Particle Analyzer

- ***Provides 10^4+ phase space points simultaneously***
- ***Can resolve details of fast ion transport across velocity space induced by AEs and other MHD***

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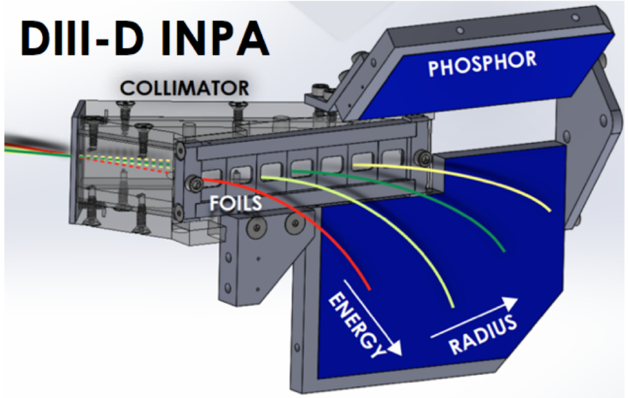
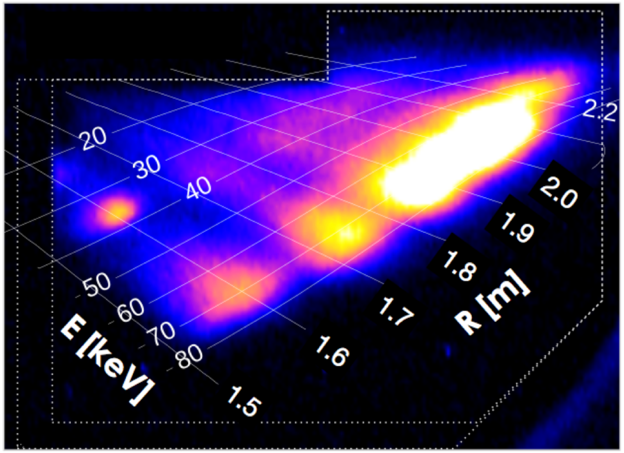
OUTLINE

- **Introduction to INPA system**
  - Principles of the measurement
  - Verification in experiment
- **Resolving the local fast ion distribution with high accuracy**
  - Velocity-space tomography and its application to sawtooth instabilities
- **Measurement of phase-space transport by different AE modes**
  - Multiple TAE&RSAE dominant plasma
  - RSAE dominant plasma
  - BAAE dominant plasma





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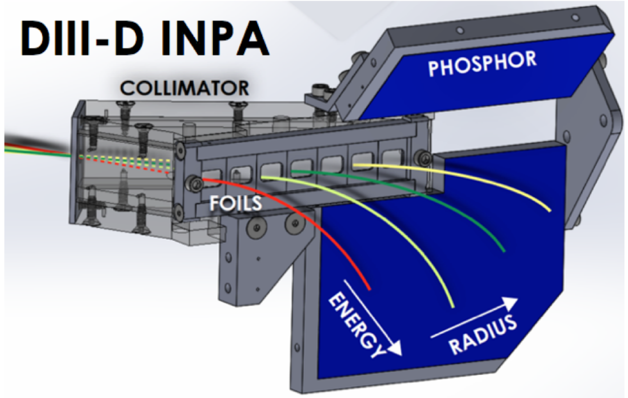
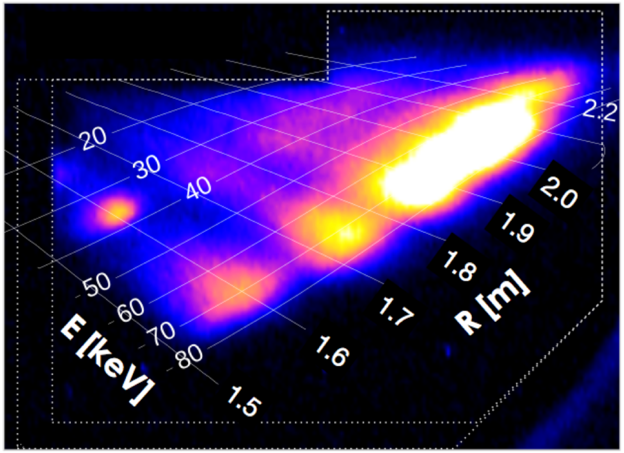
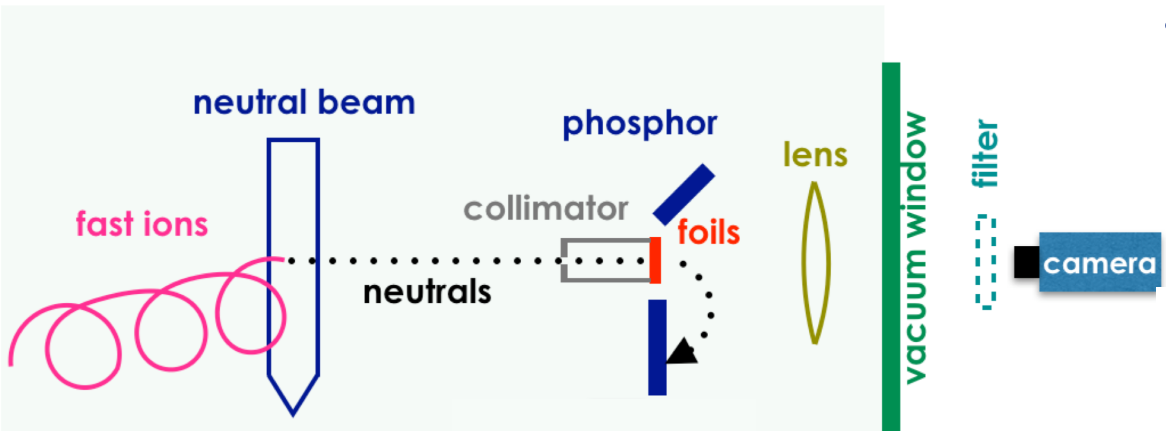




INPA Provides An Energy And Radially Resolved Image Of Confined Fast Ions



- **Escaping neutrals**
  - Stripped by a foil
  - Strike a phosphor.
  - Imaged with a Camera or PMT

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

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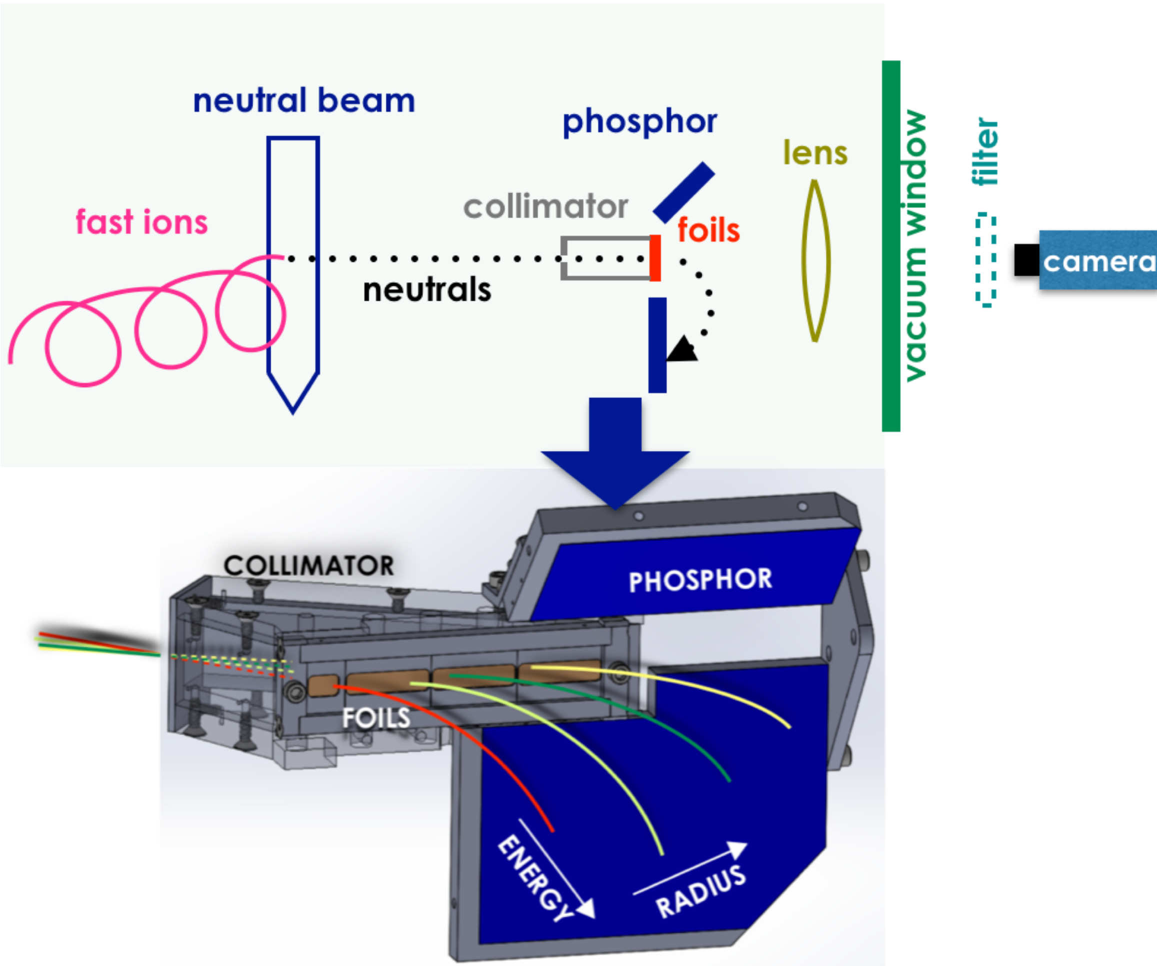

- **Escaping neutrals**
  - Stripped by a foil
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  - Imaged with a Camera or PMT
- **INPA provides an energy and radially resolved image**
  - Gyroradius -> energy
  - Line-of-sight -> Radius
  - Local fast ion distribution function at a given range of pitch
- **INPA leverages best parts of past NPA and FILD**
  - Light emission vs current
  - Low noise
  - Excellent phase space resol.

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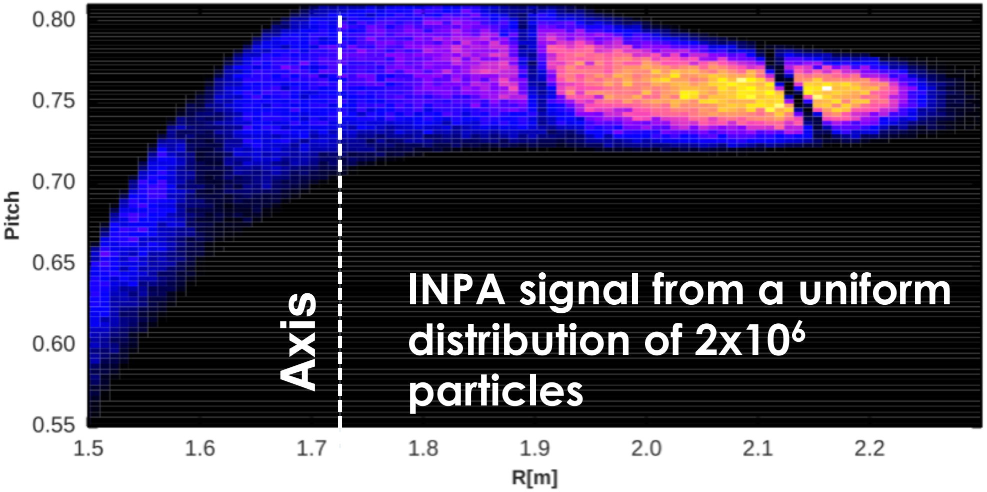
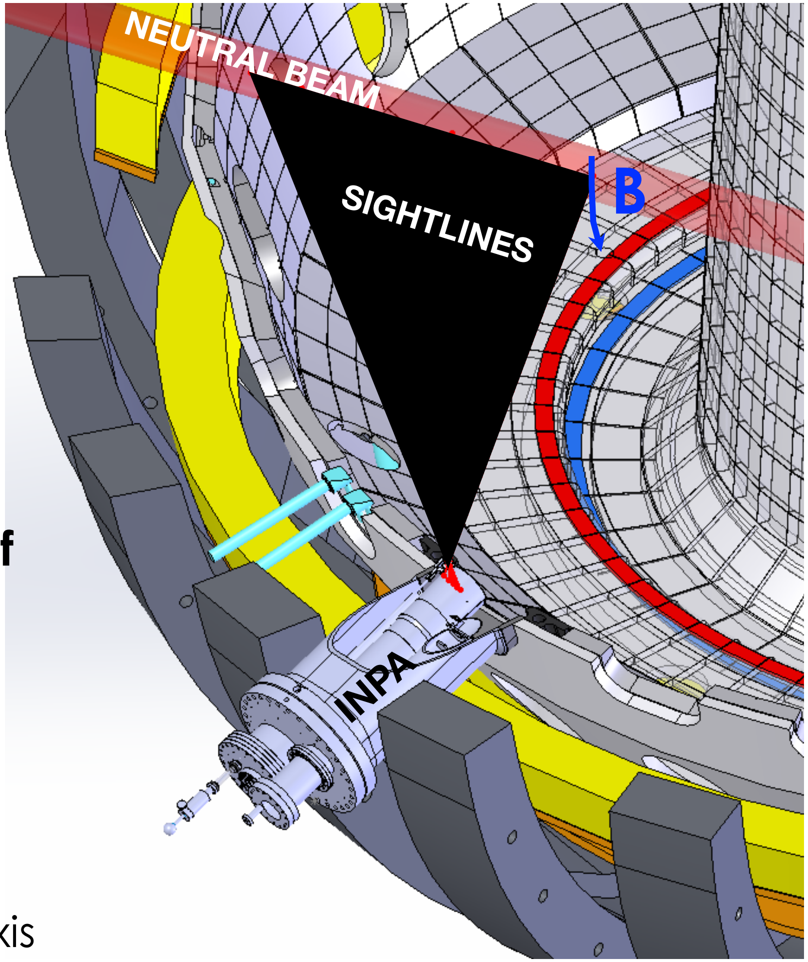
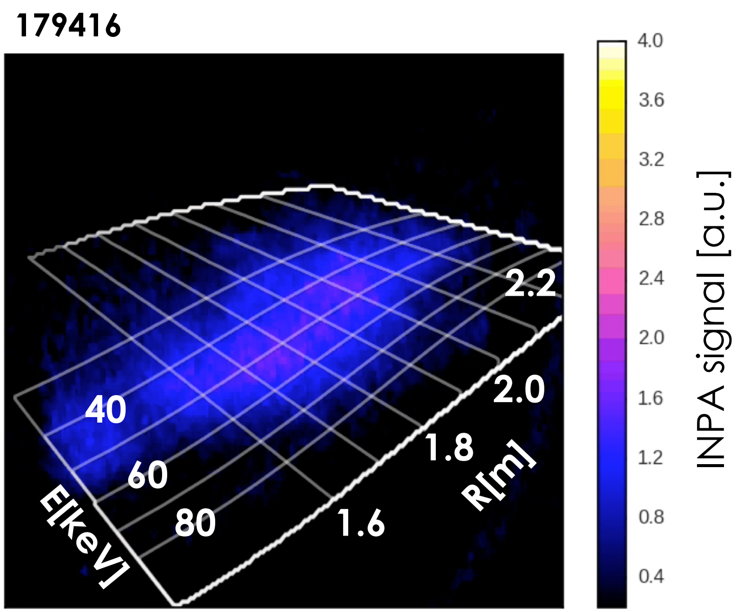
INPA Measures Passing Particles From The Plasma Edge To The Core

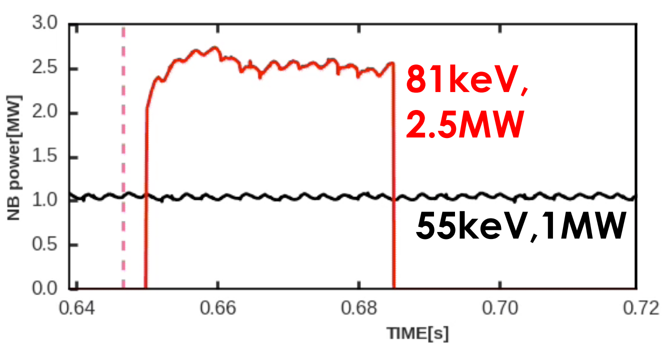


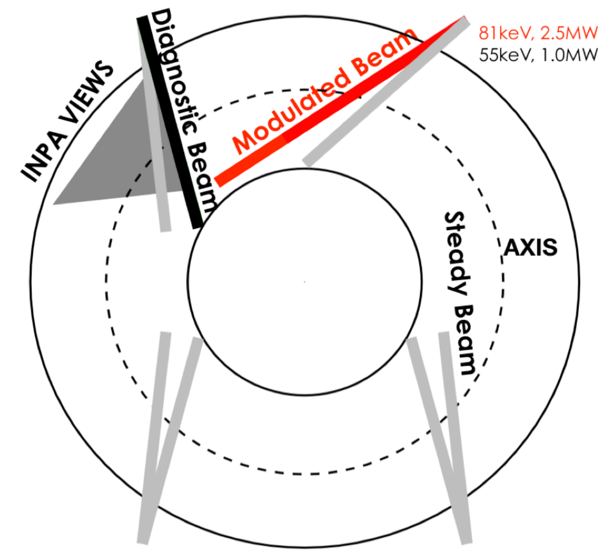


- **Active beam provides dominant source of neutrals for fast ion charge exchange**
  - Defines localization and pitch
- **Probed Pitch $V_{||}/V \sim 0.75$**
  - Passing particles
- **View spans device midplane**
  - From LCFS to high-field-side of magnetic axis

Time Evolution of Signal During Single Beam Blip Shows Many Key Features of Phase Space Dynamics







- **Directly populated by nearly-tangential beams**
  - Not directly populated by nearly-perpendicular beams
- **Signal increases as the beam turns on**
  - A clear slowing-down process is observed
- **As the beam turns off, the highest energy decays**
  - As expected, difference of slowing time in plasma core and edge is seen

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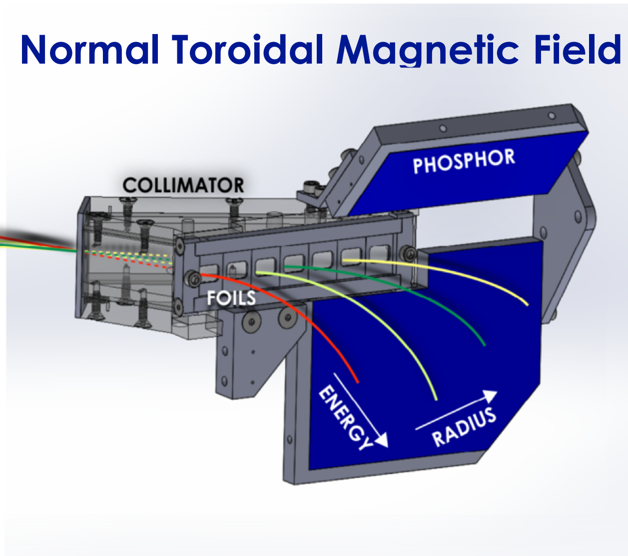
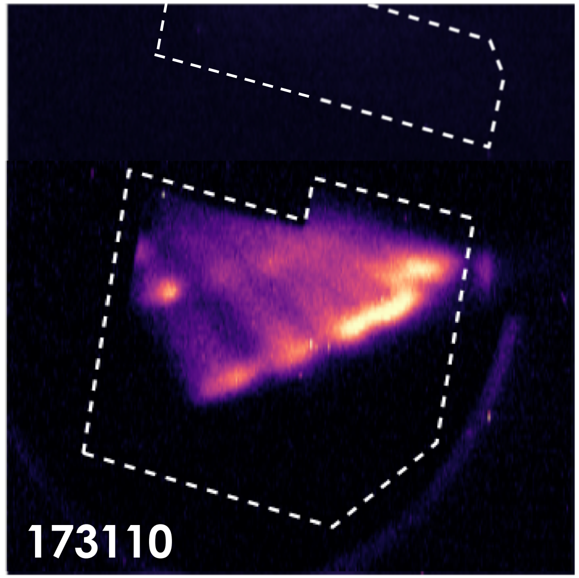
Flip of the Toroidal Magnetic Field Direction Shows The INPA Has Excellent Signal to Noise





- **Two scintillators allow operation in both toroidal field directions as well as provide measure of background level (blind detector)**
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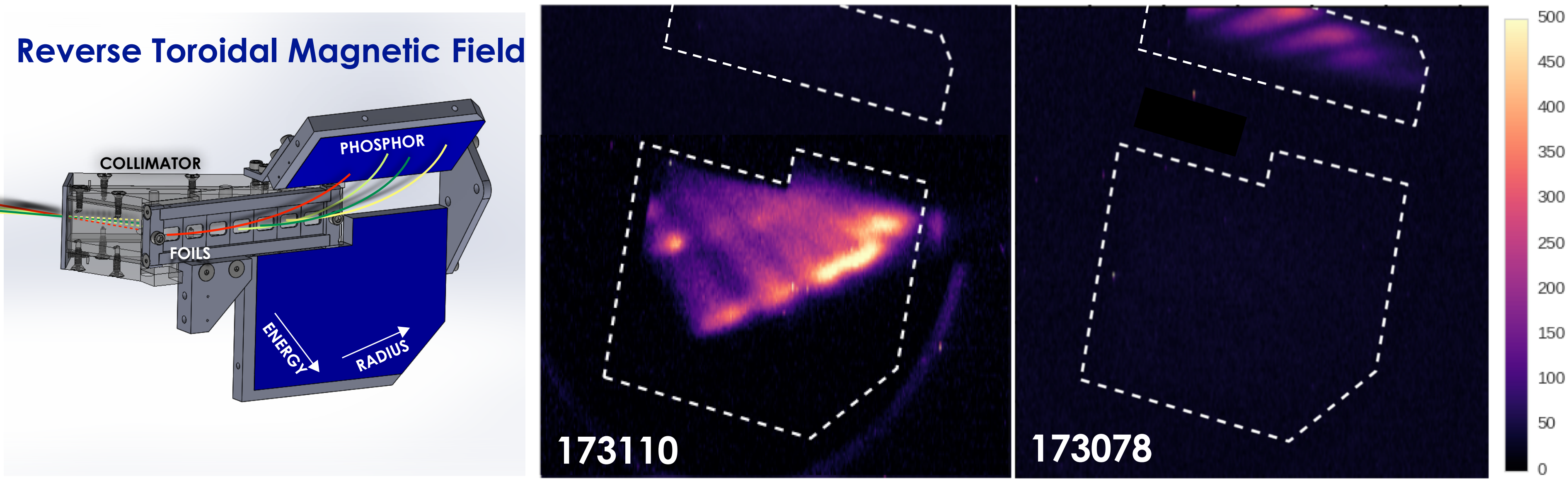

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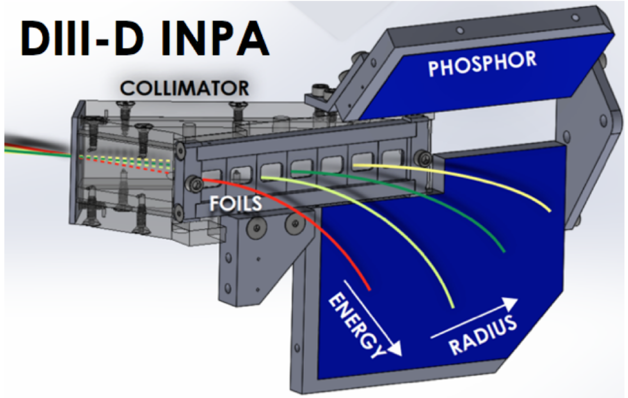
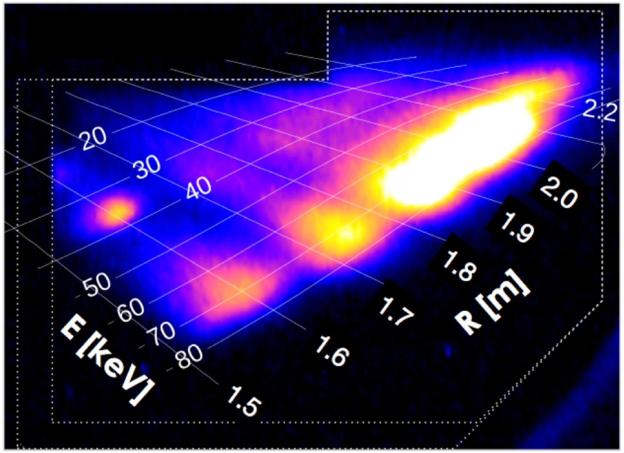
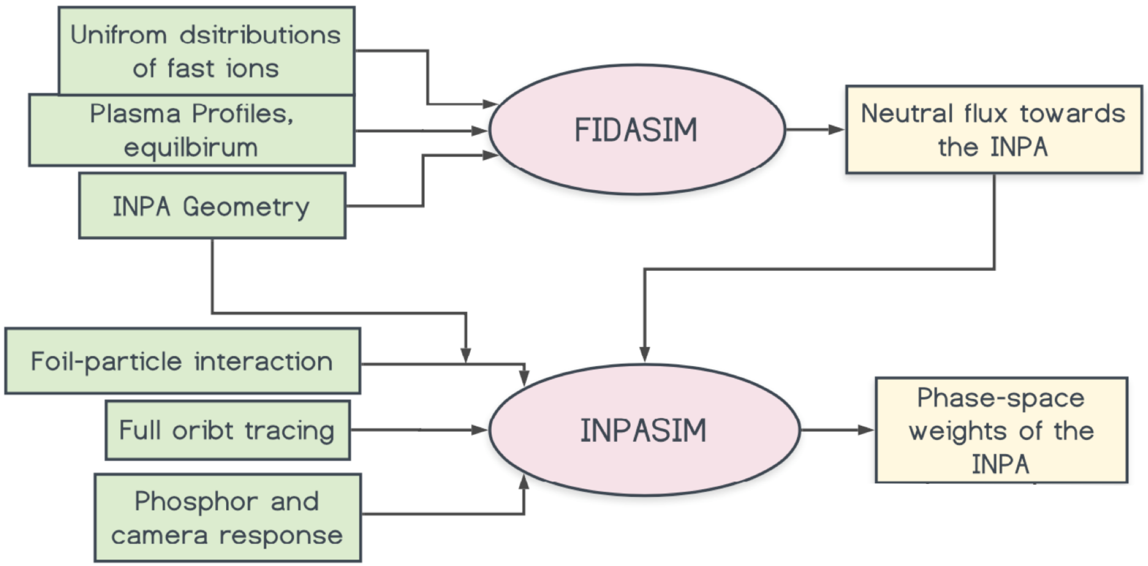




INPA Data Are Interpreted Using TRANSP[1], FIDASIM[2] and INPASIM[3]



- **The INPA phase-space weights are calculated by FIDASIM and INPASIM**

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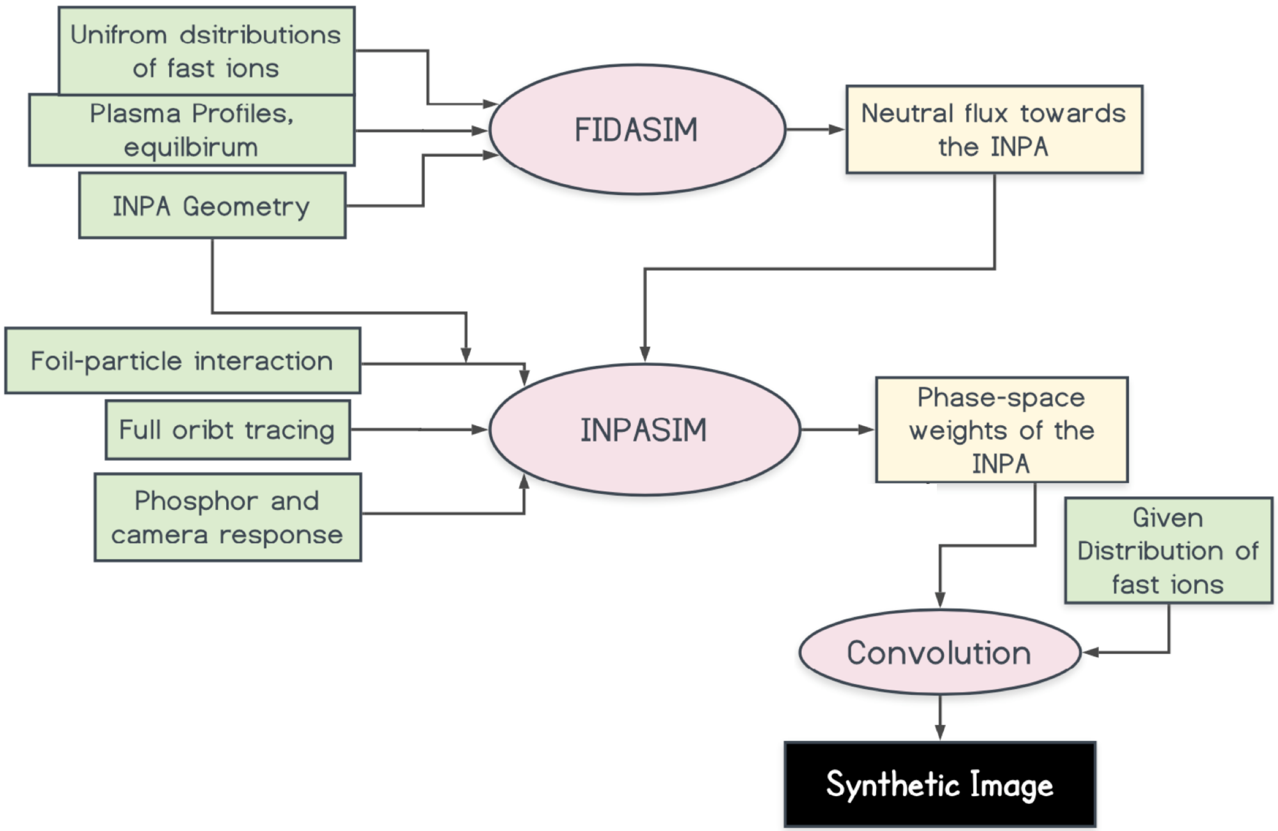

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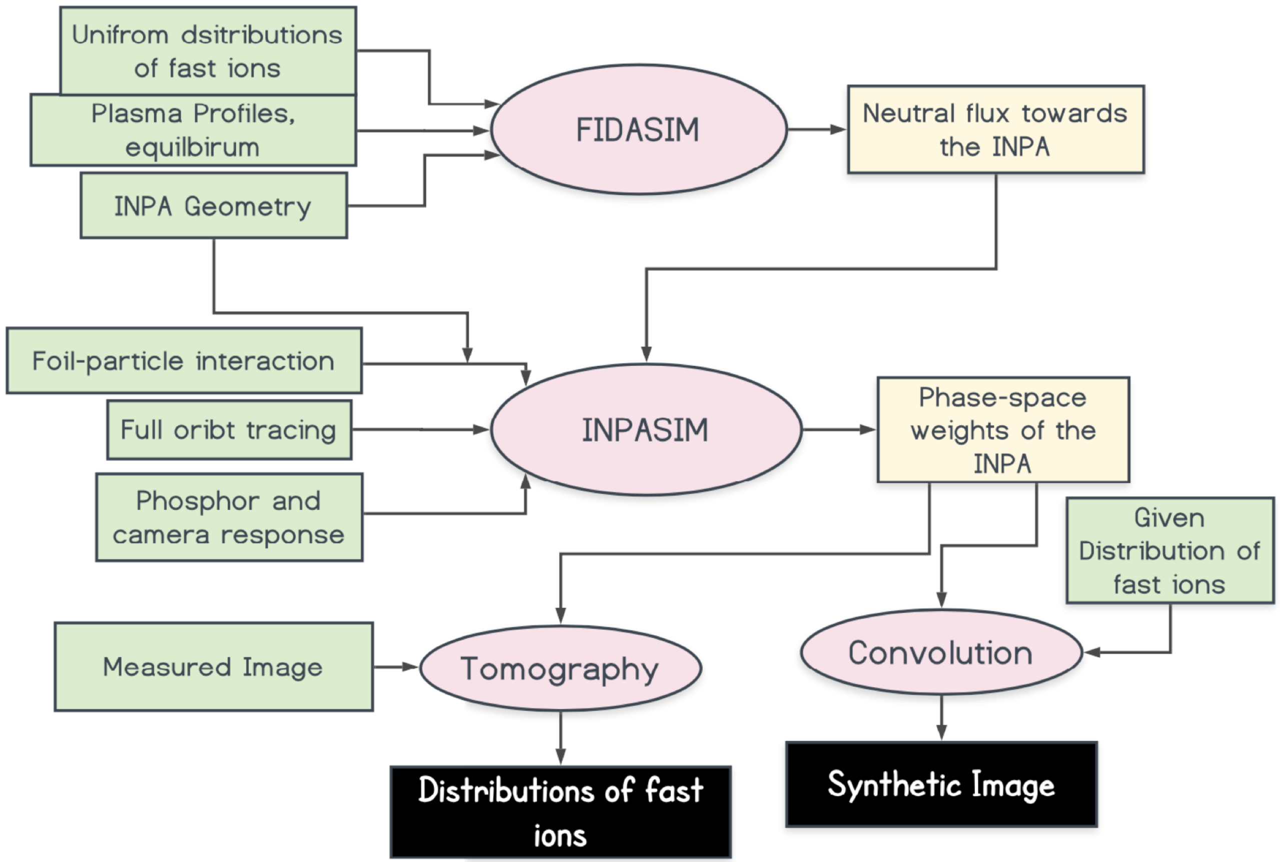

- The INPA phase-space weights are calculated by FIDASIM and INPASIM
- Convolution Integral of any fast ion distribution function gives a synthetic INPA image
- Deconvolution computation using the measured image gives an estimate of the local fast ion distribution from expt.

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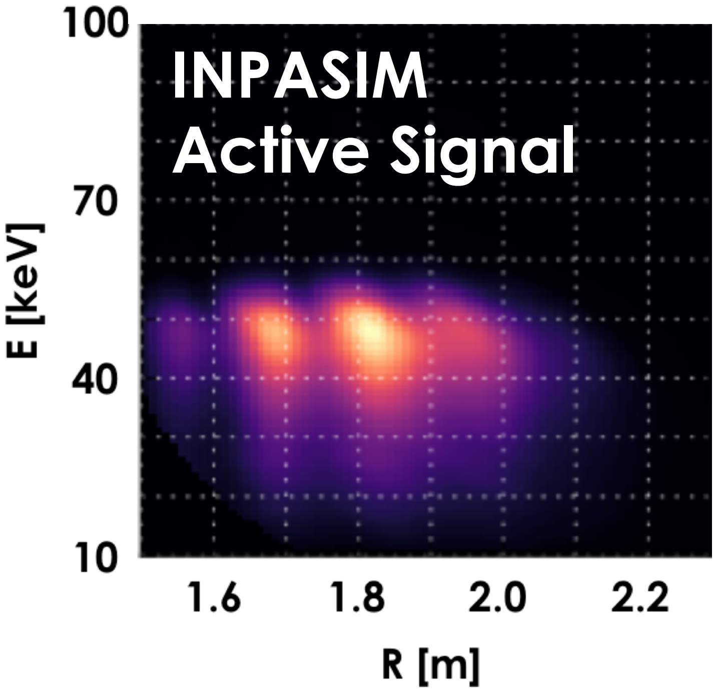

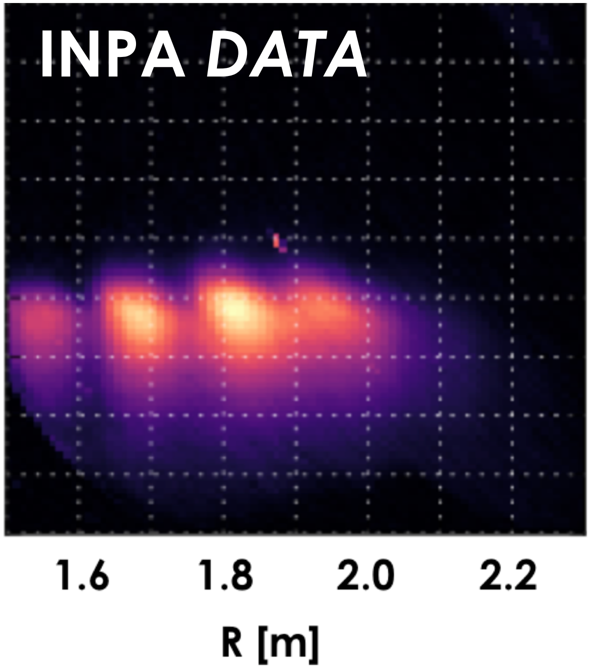

- **The measured image agrees reasonably with the active signal, especially on the low field side**
  - Agrees well from 1.65 m to 2.0 m
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Details were reported in P1-8 by D. Lin et al

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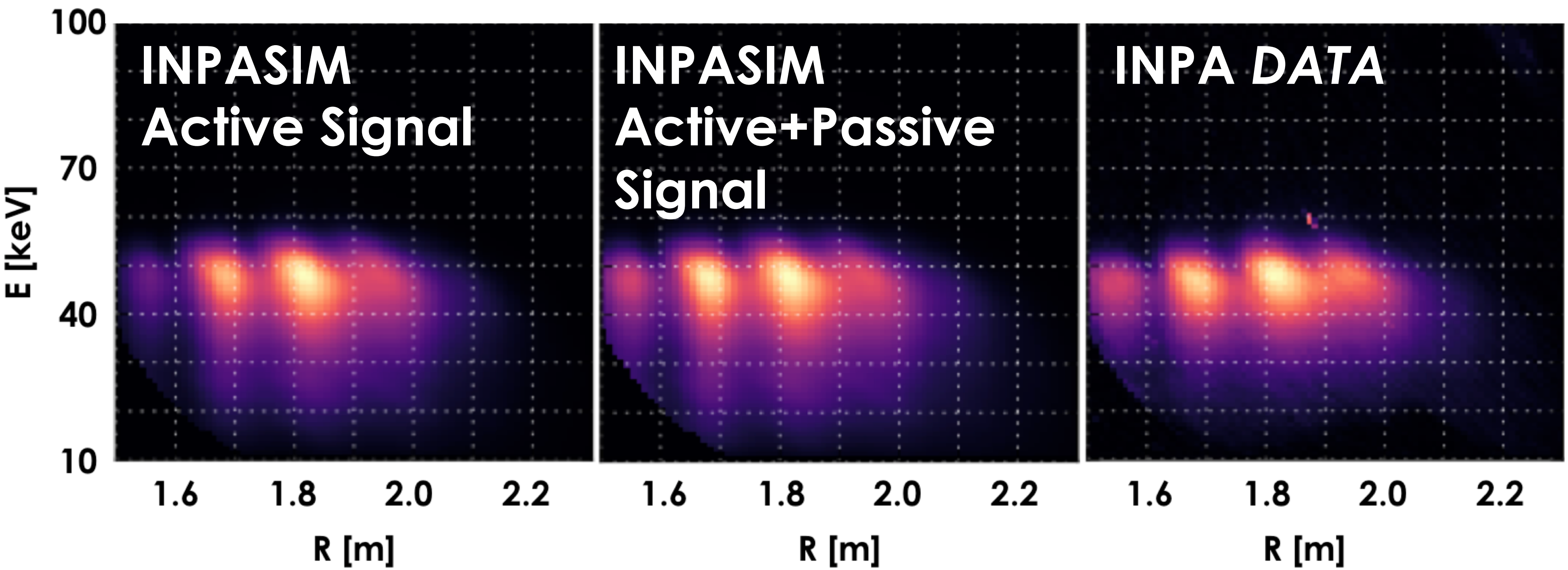

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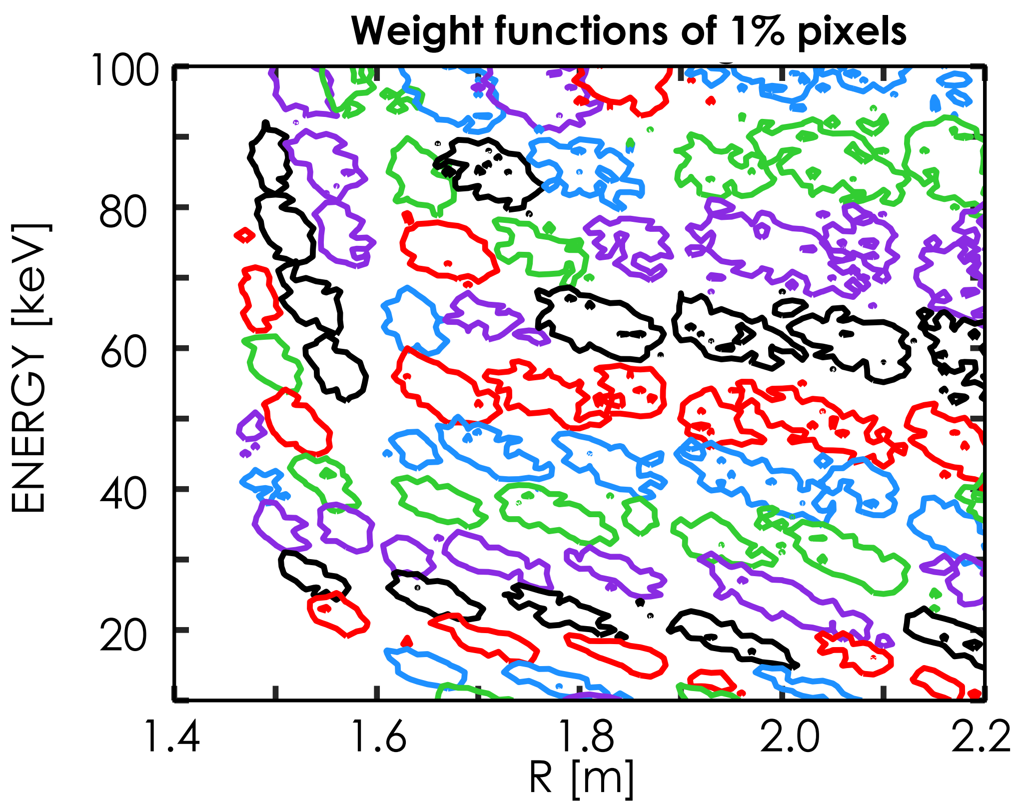
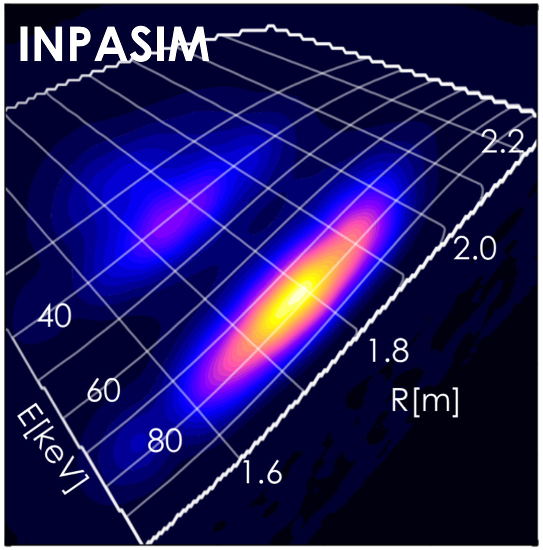
- **The measured image agrees reasonably with the active signal, especially on the low field side**
  - Agrees well from 1.65 m to 2.0 m
  - Deviates on the high field (R<1.6m)
- **The match to the measured image is improved by including the passive component contributed from edge neutrals**

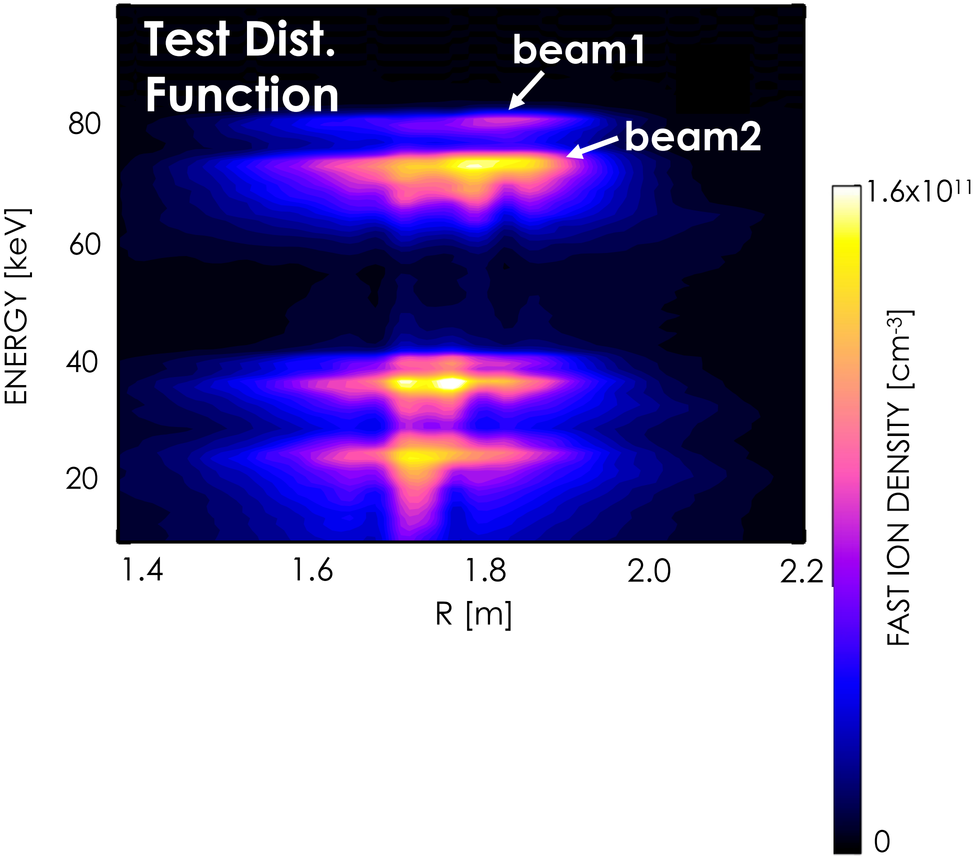
The Localized Weight Function and Large Number of Channels Make INPA Data 'Tomography-Friendly'



- **Each pixels measures a localized region of phase space**
  - Each circle represent a range of particles which contributes 1/e of the total signal at each pixel
  - Typical of NPA weight functions
- **The 4x10^4 measurement points at interrogated pitch allows high-resolution of the local distribution function with tomography**

Tomographic Inversion Can Extract Fine-Scale Structure Of The Local Fast Ion Distribution Function





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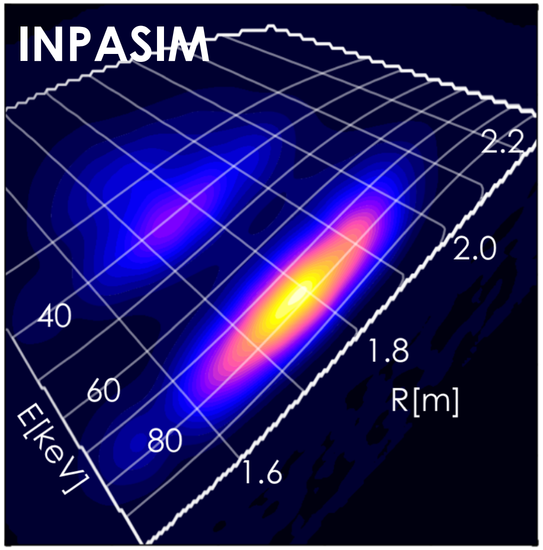

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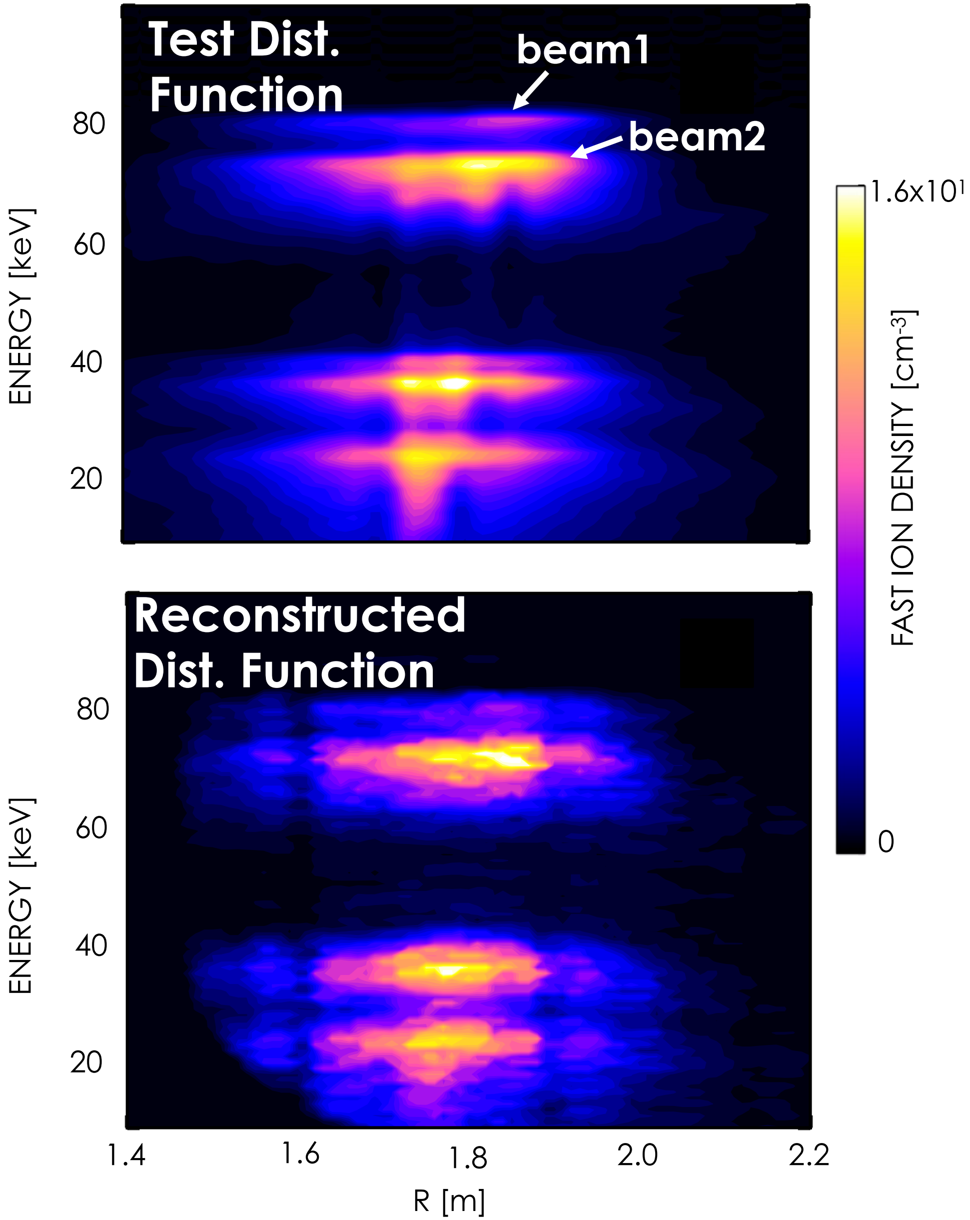

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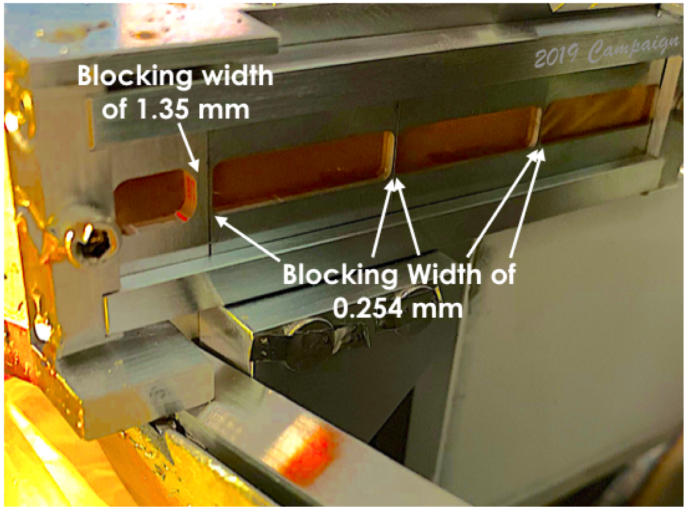
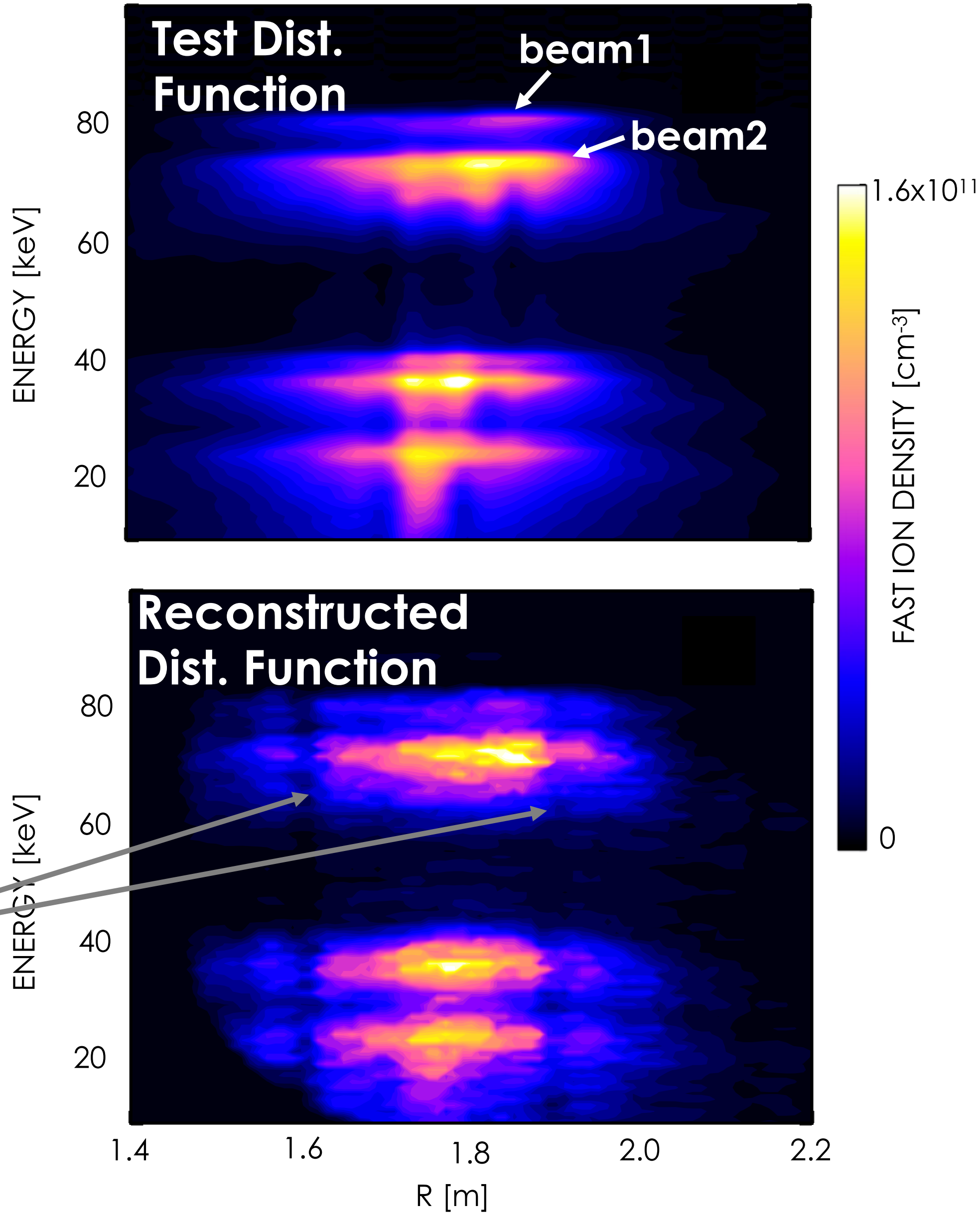
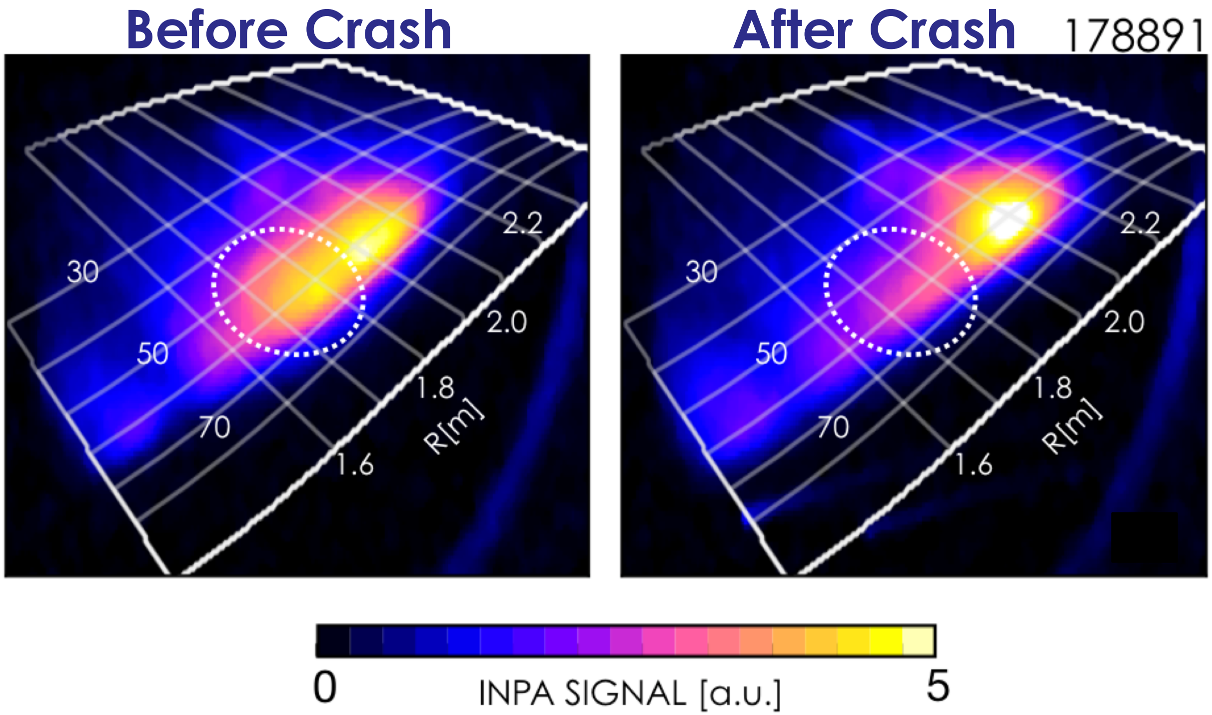
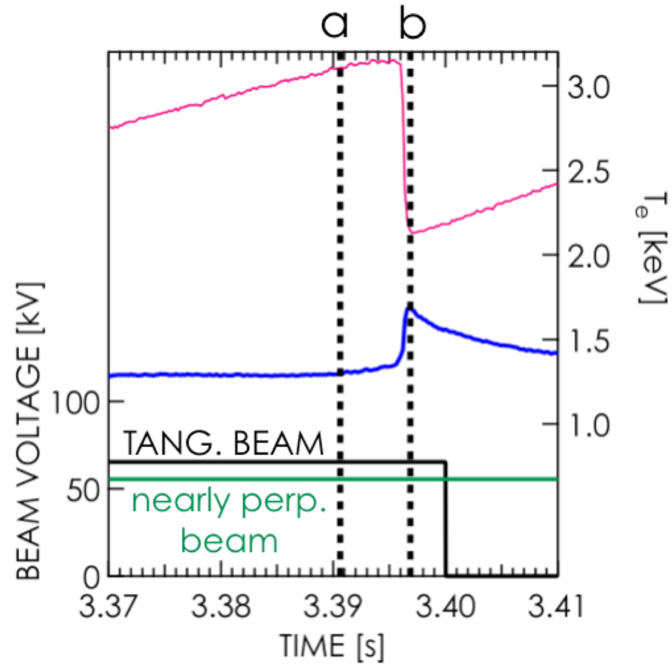




- **Raw INPA images do not resolve two neutral beams with voltages of ~81keV and ~78keV (Energy res. ~7.5keV)**
- **Inversion recovers the local distribution**
- **Foil support structure complicates inversion**
  - Minimization of the blocking width is important

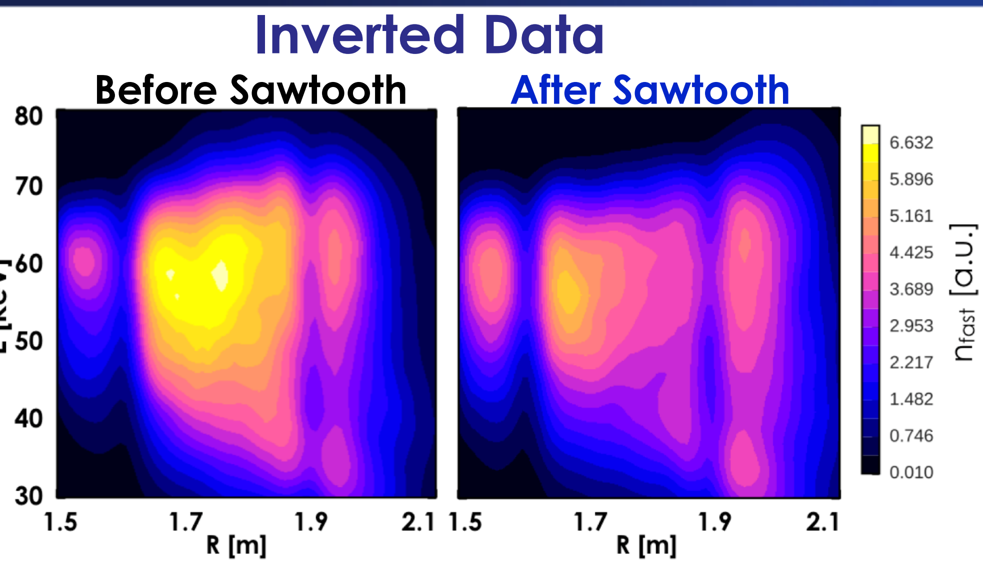
The INPA Shows a Large Impact Of Sawteeth On The Confined Fast Ion Population

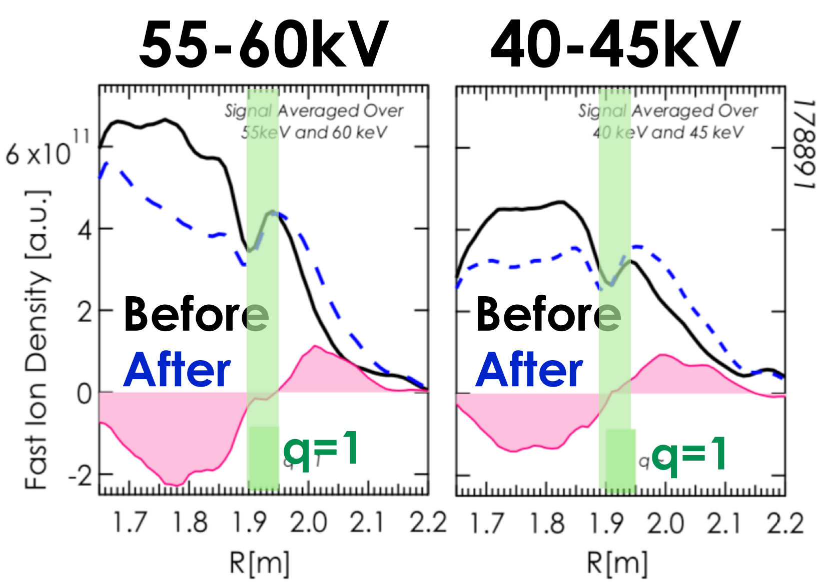




- **The evolution of the INPA signal across a single sawtooth crash shows:**
  - A large central depletion of fast ions
  - Redistribution to larger radius

Inversion Suggests ~30% Of Fast Ion Density In The Interrogated Region Of Phase Space Is Transported From The Core





- **Fast ion profile is peaked in the plasma core before sawtooth**
- **From 55keV to 60kV, a ST causes ~30% reduction in fast ion densities inside q=1 flux surface and increased fast ion density outside the q=1 flux surface**
  - Increase of the density is moderate due to the volume effect
- **Similar level of transport at lower energies is also observed**

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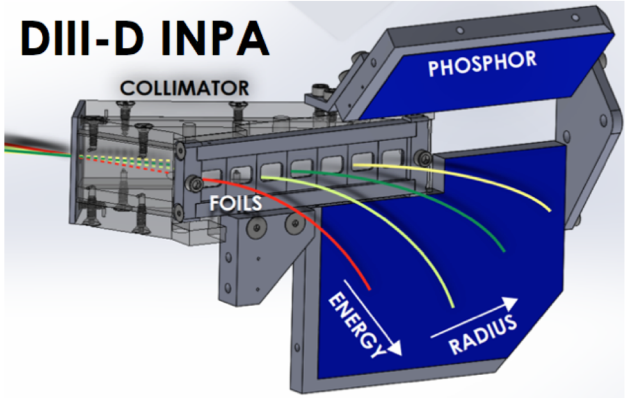
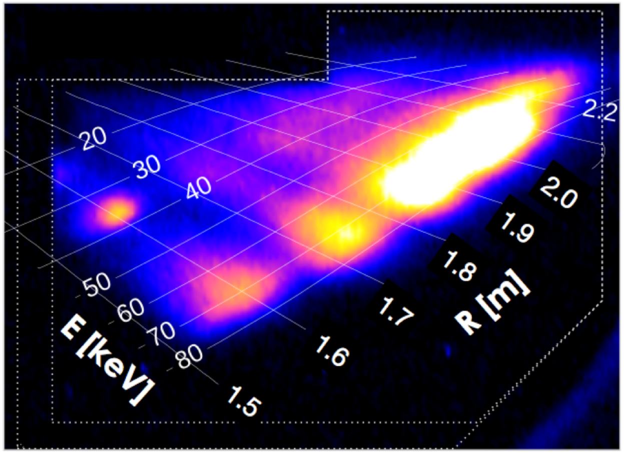
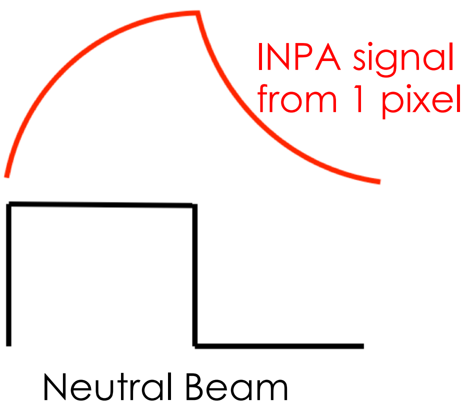




Phase Space Resolved EP Transport is Obtained Using The INPA Combined With A New Beam Modulation Technique

AT CERTAIN LOCAL PHASE SPACE (1 pixel of the INPA)



- **Modulate a neutral beam that populates the INPA interrogated phase space**

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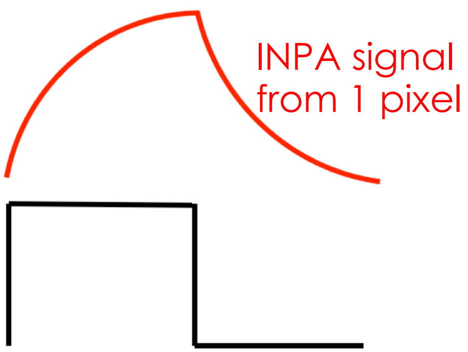
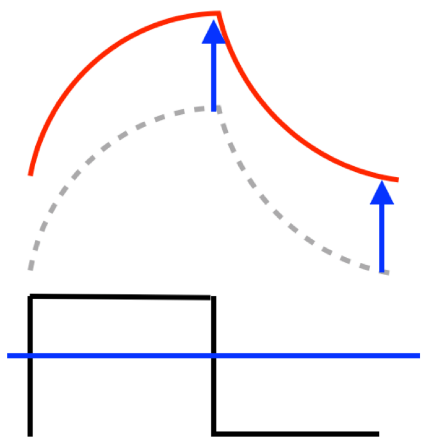


Classically



- **Modulate a neutral beam that populates the INPA interrogated phase space**
- **In next discharge, add a steady beam that populates same phase space.**
- **If plasma is away from an AE stability boundary,**
  - Modulated INPA signal will shift upward, based on the power of the steady beam

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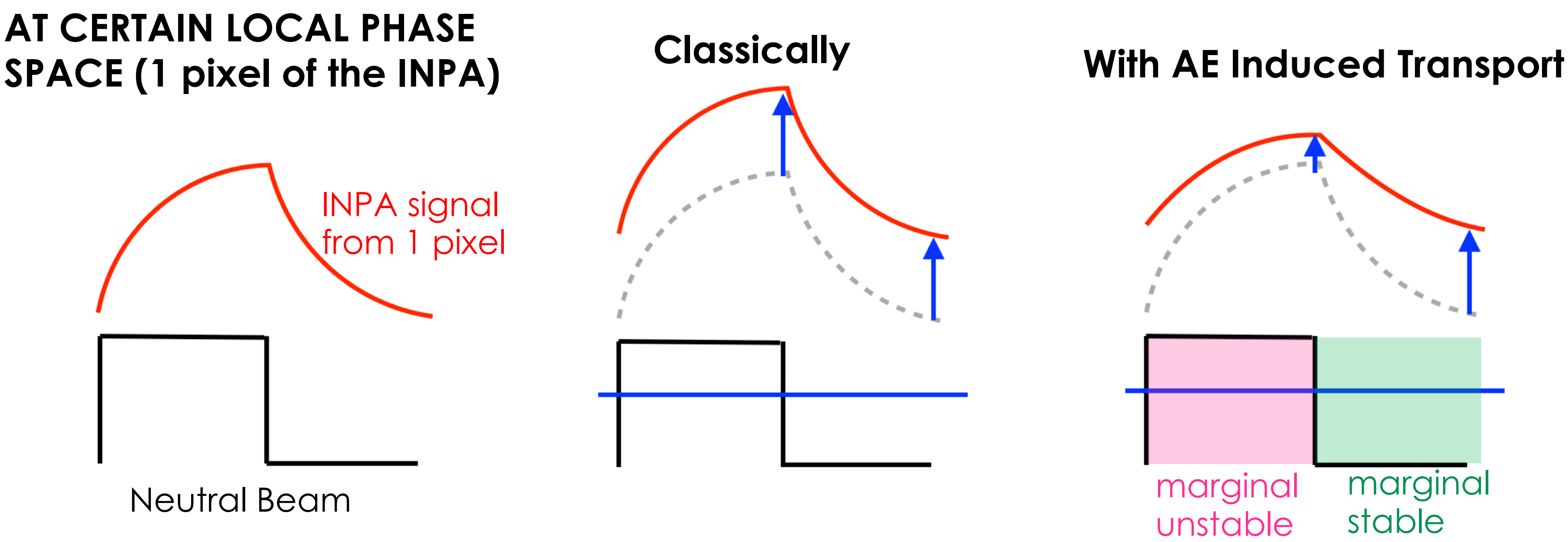

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- **If plasma is away from an AE stability boundary,**
  - Modulated INPA signal will shift upward, based on the power of the steady beam
- **If the plasma is close to AE marginal stability boundary,**
  - AEs are destabilized during the on-period; stabilized during the off-period
  - Reduced increase reflects transport of fast ions from probed region phase space
- **Moderate power of the steady beam is prefered**

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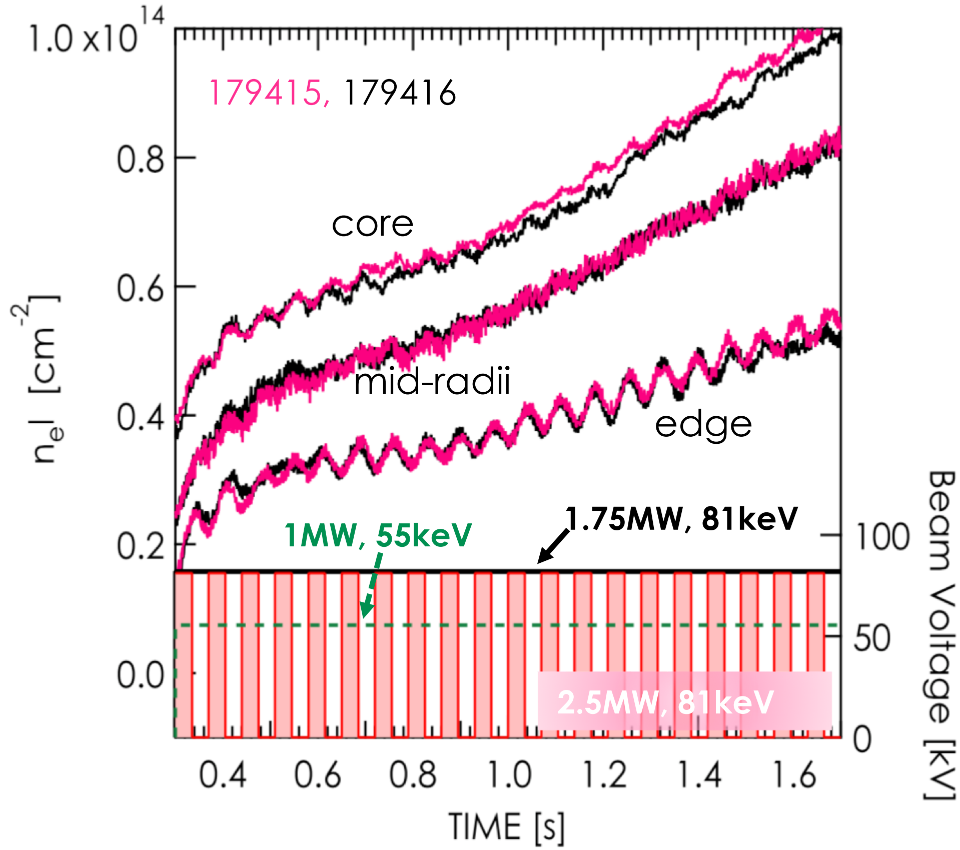
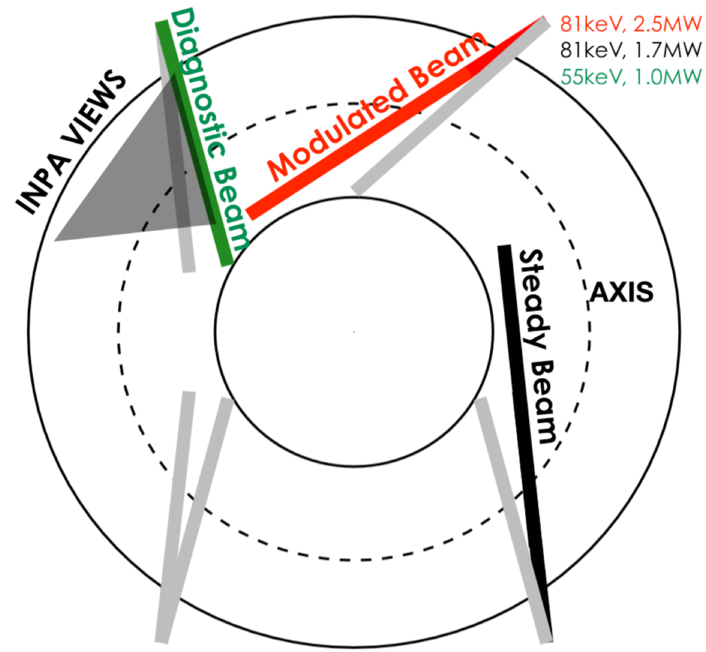
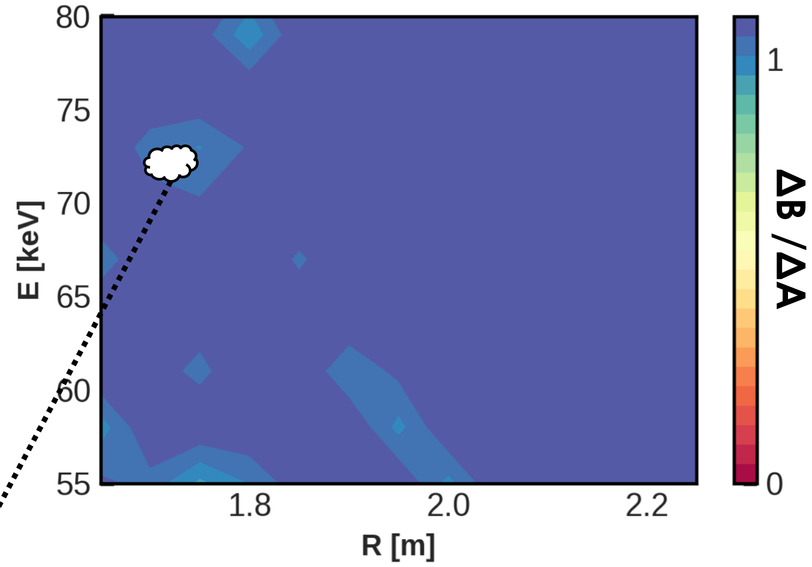
A Well-Matched Density Profile In Low-Power And High-Power Discharges Is Important For This Beam Modulation Experiment



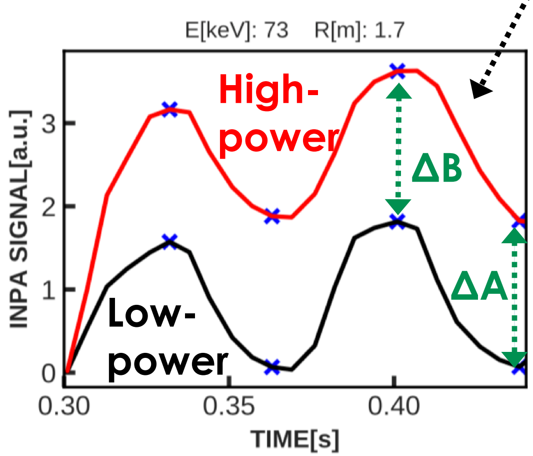


- **Low power, 1MW 55kV Diagnostic beam held steady**
  - It does not populate the interrogated phase space of the INPA
- **Modulated beam and *Steady beam* populate the same phase space**
  - Modulated beam: 2.5MW, 81keV
  - Steady beam: 1.7MW, 81keV
- **Density profile well matched from 0.3s to 1.7s**

TRANSP+INPASIM Predictions Show A `1:1' Increase In Signals Is Expected For Classical Conditions With Well-matched Density

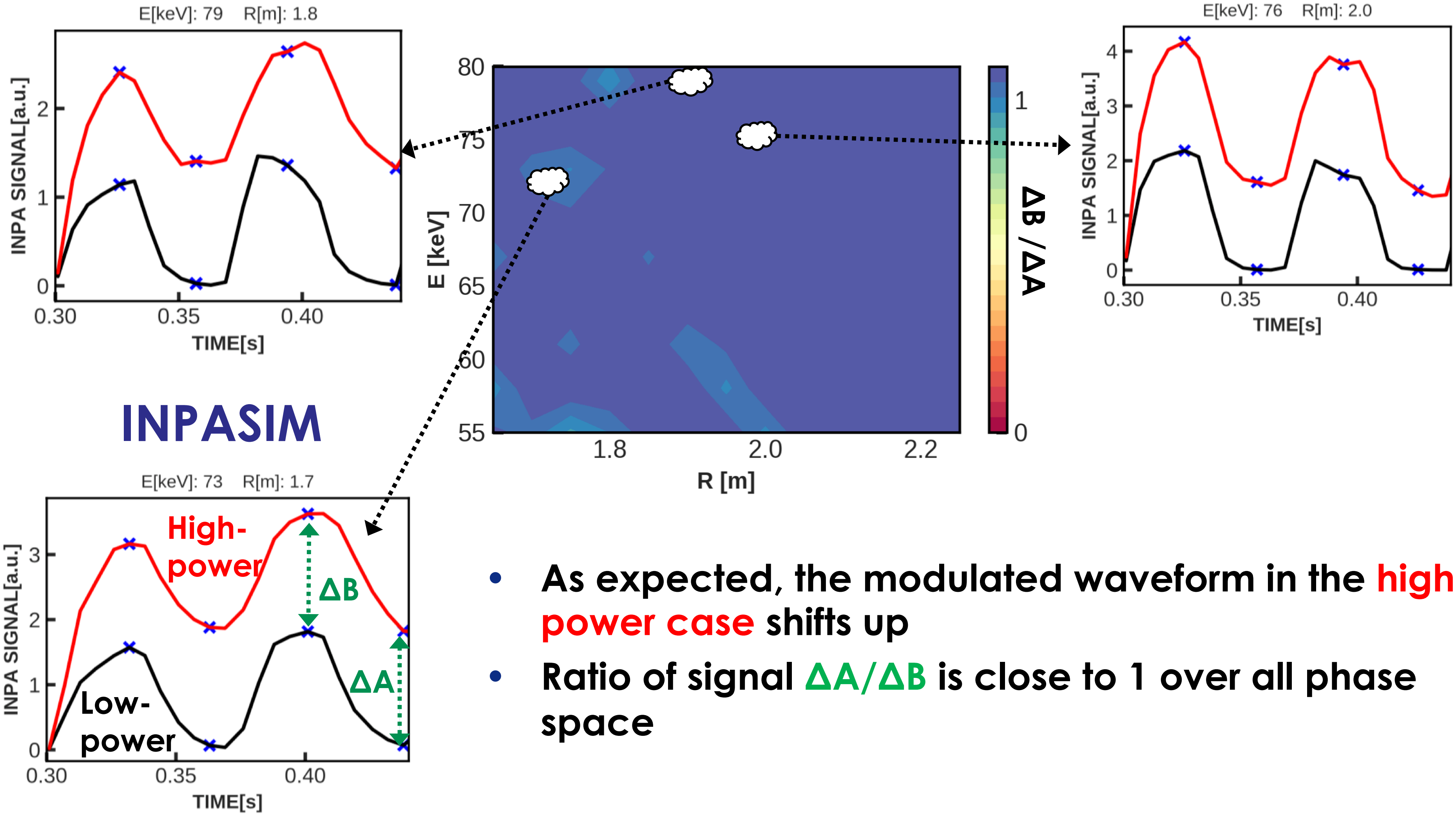


INPASIM



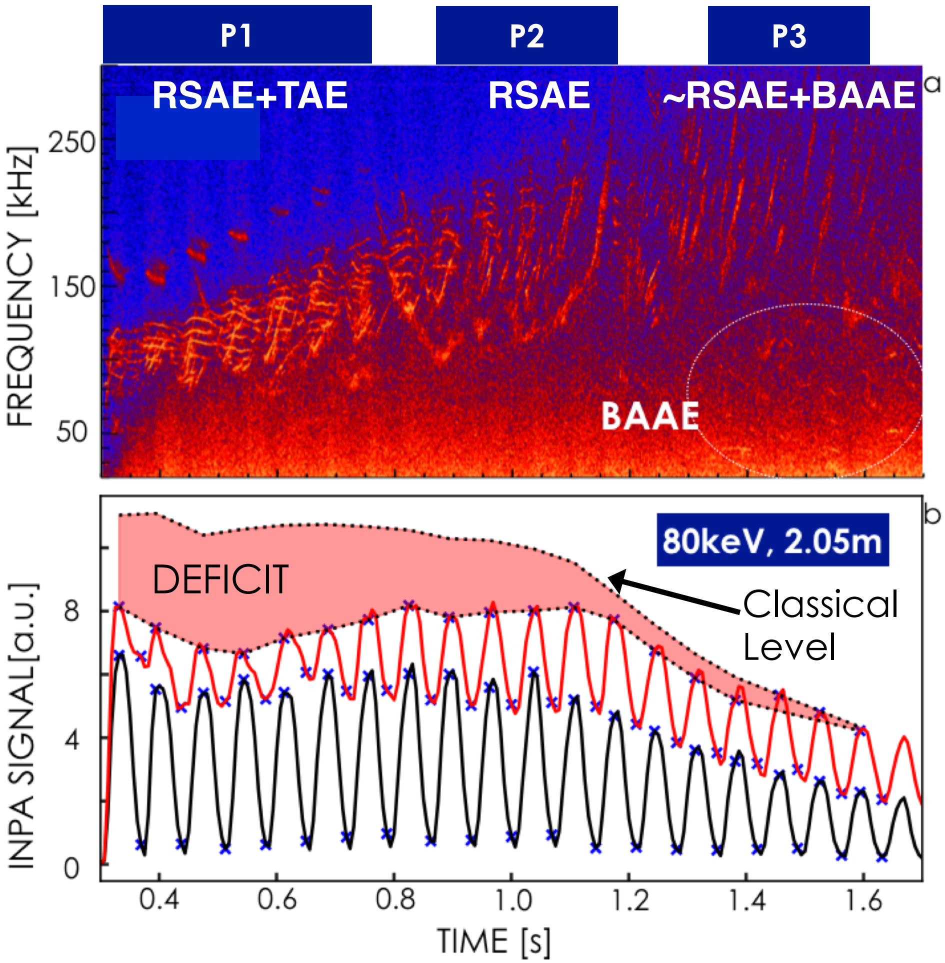
- As expected, the modulated waveform in the high power case shifts up
- Ratio of signal ΔA/ΔB is close to 1 over all phase space

TRANSP+INPASIM Predictions Show A `1:1' Increase In Signals Is Expected For Classical Conditions With Well-matched Density



- As expected, the modulated waveform in the high power case shifts up
- Ratio of signal ΔA/ΔB is close to 1 over all phase space

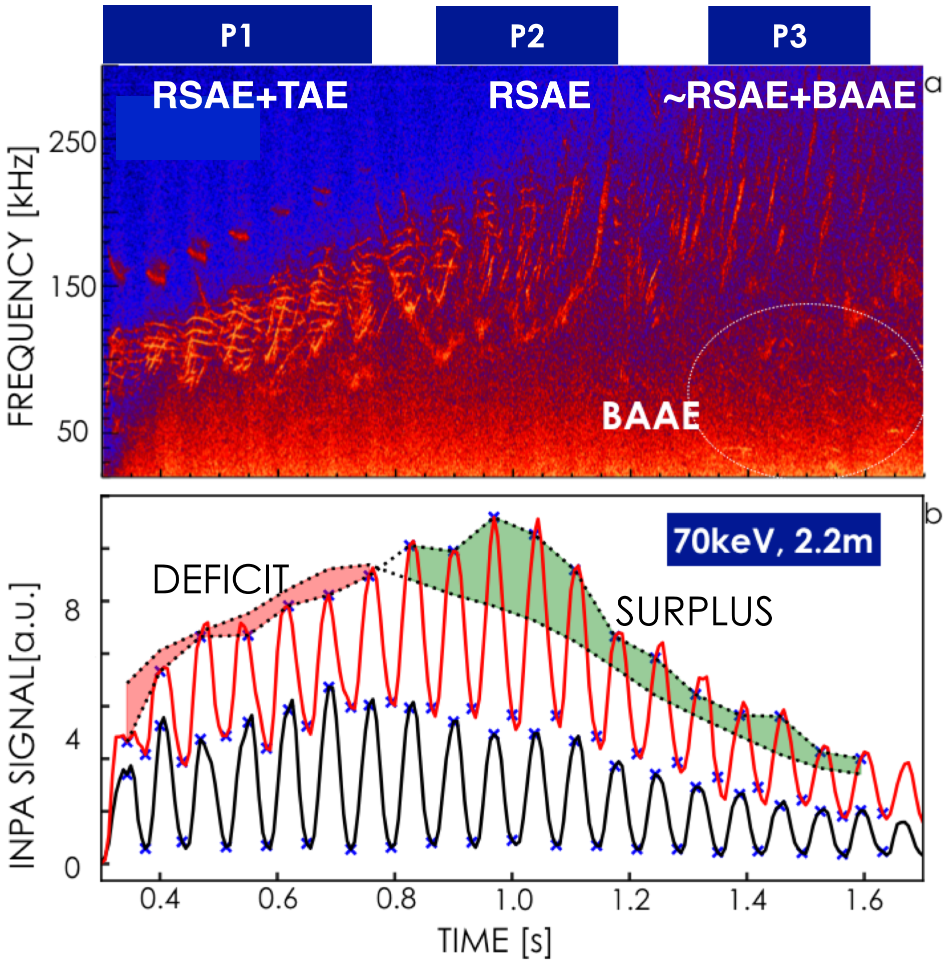
Phase Space Behavior Can Largely Deviate From Classical Predictions When AEs Are Destabilized



At 80kV and R=2.05m

- **P1: During the RSAE & TAE dominant phase**
  - Large transport at inj. energy
  - 80% signal from the steady beam missing
  - Transport threshold is ~2.9MW for this local phase space
- **P2: RSAE dominant phase with weakened TAE**
  - Reduced transport at injection energy
  - 50% signal from the steady beam missing
  - Transport threshold is ~3.4MW for this local phase space
- **P3: BAAE dominant phase with weakened RSAE**
  - Reaches classical

The Inferred Fast Ion Transport Can Vary Significantly Depending On The Interrogated Region of Velocity Space



At 70kV and R=2.2m

- **P1: During the RSAE & TAE dominant phase**
  - Small deficit at 70kV and R=2.2m
- **P2: RSAE dominant phase with weakened TAE**
  - Signal exceeds the classical expectations
- **P3: BAAE dominant phase with weakened RSAE**
  - Nearly classical

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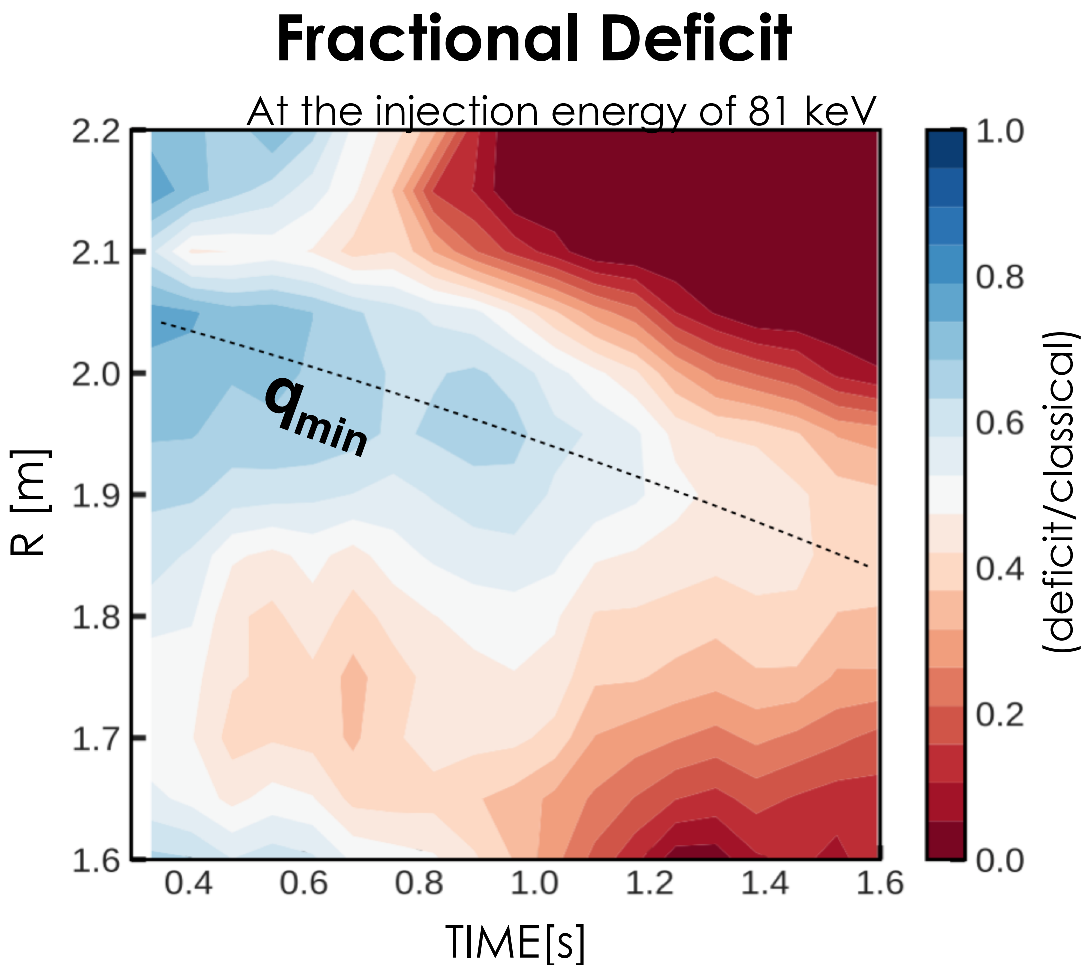
Temporal and Spatial Evolution Of The Fast Ion Transport At The Injection Energy Is Resolved By The INPA



- **Particles are transported out of the phase space immediately before slowing down**
- **This means there is no significant scenario benefit of adding one more beam**
  - Reduced heating efficiency and torque
- **The region with largest transport follows the the q-min location**
  - Potential issue for advanced tokamak operation scenario

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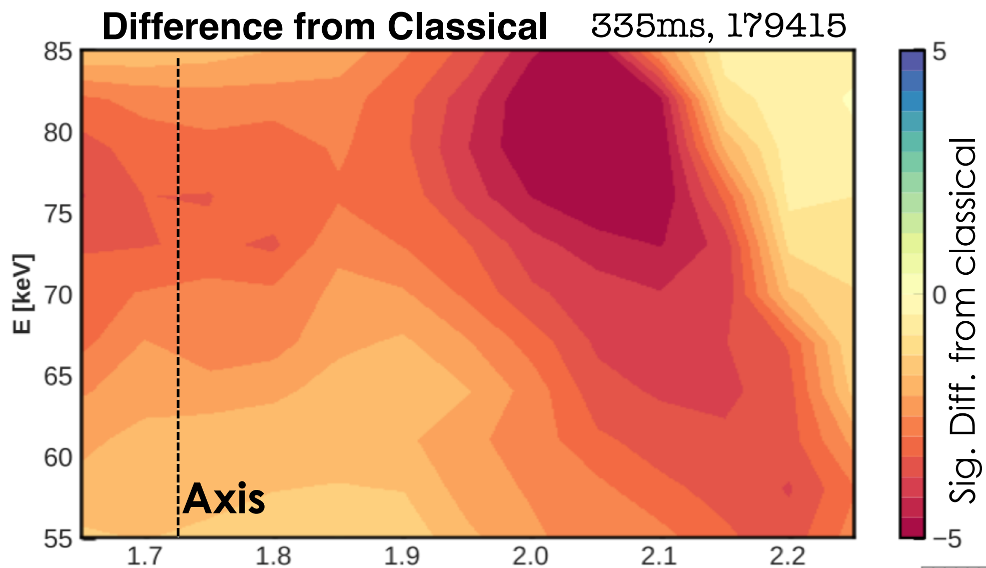
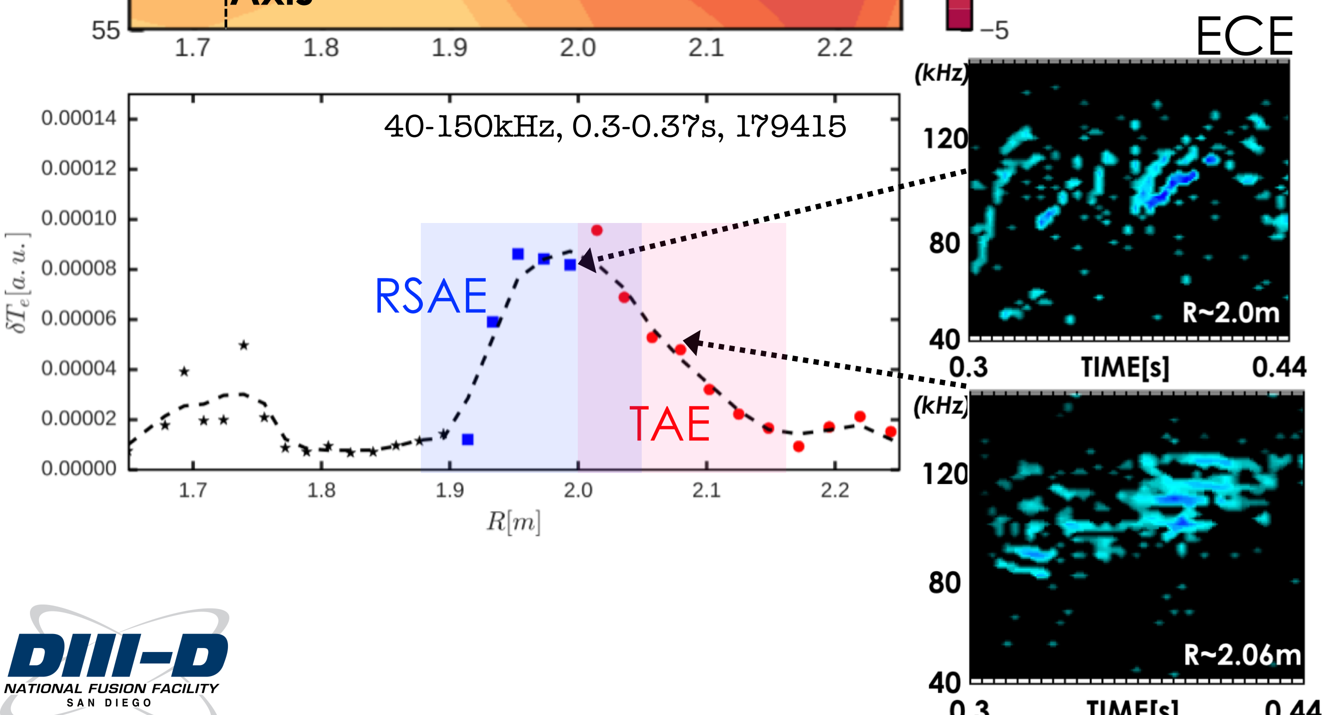
A Phase Space Map Of The Fast Ion Transport Due To Different Modes Can Be Obtained



- **The plasma is dominated by a combination of RSAE and TAE**
  - RSAE, R~1.9 - 2.0m
  - TAE, R~2.05 - 2.1m
  - TAE and RSAE overlap at 2.03m



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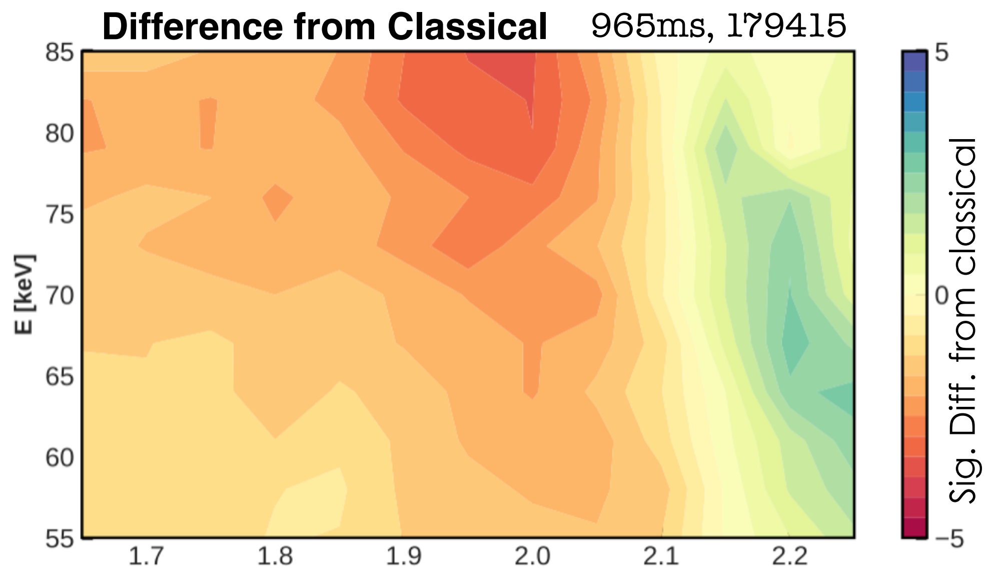
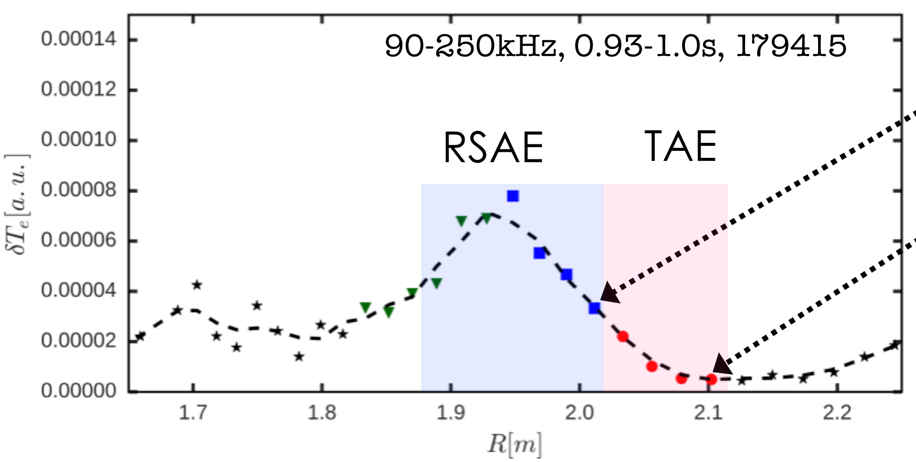
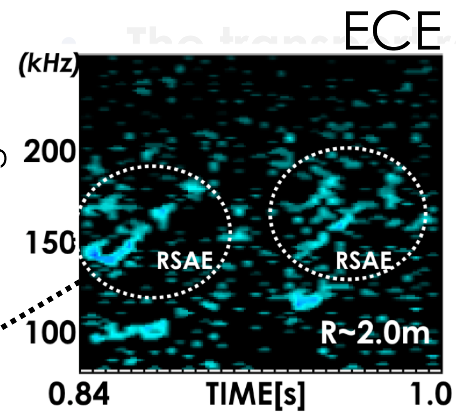
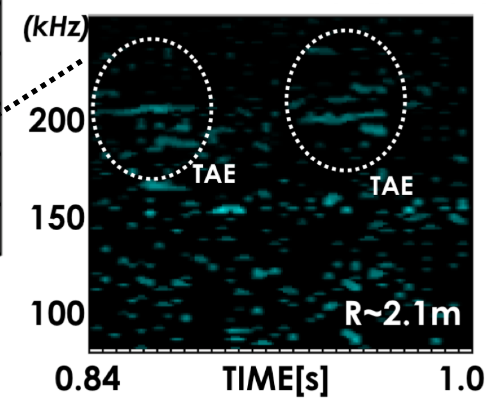
Evolution Of The Phase Space Transport Map Is Consistent With The Change In AE Activity



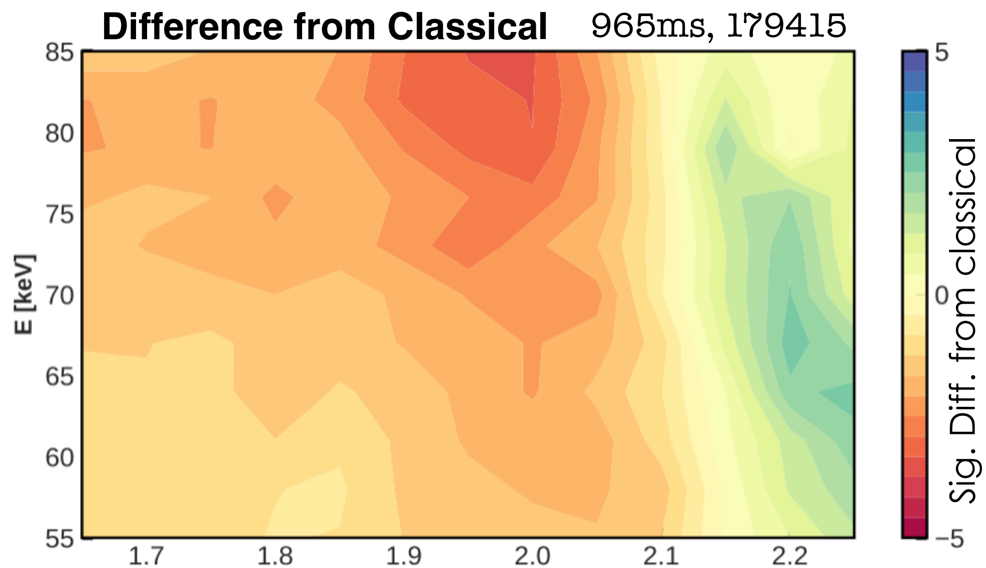
- **The plasma is dominated by the RSAE**
  - TAE amplitude is reduced

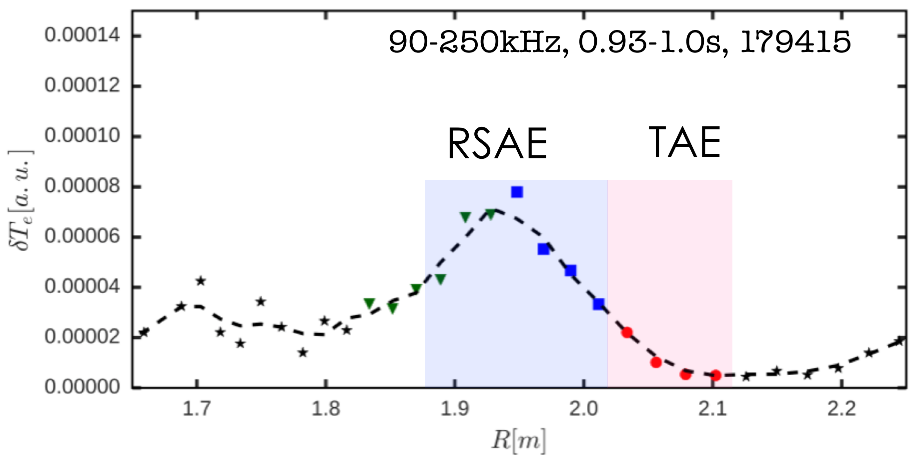






Evolution Of The Phase Space Transport Map Is Consistent With The Change In AE Activity





- **The plasma is dominated by the RSAE**
  - TAE amplitude is reduced
- **The transport region moves inward with q_{min}**
  - Significant transport aligns with the RSAE locations
- **A portion of phase space outside R~2.1m now exceeds classical levels**
  - Clear redistribution in phase space is observed
- **The transport in the plasma core R~1.7m is reduced**

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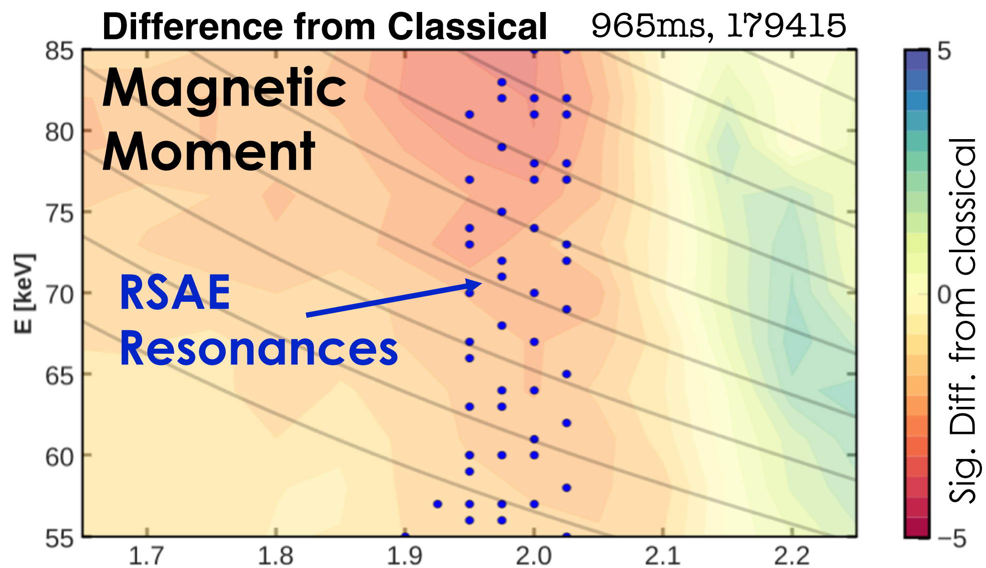
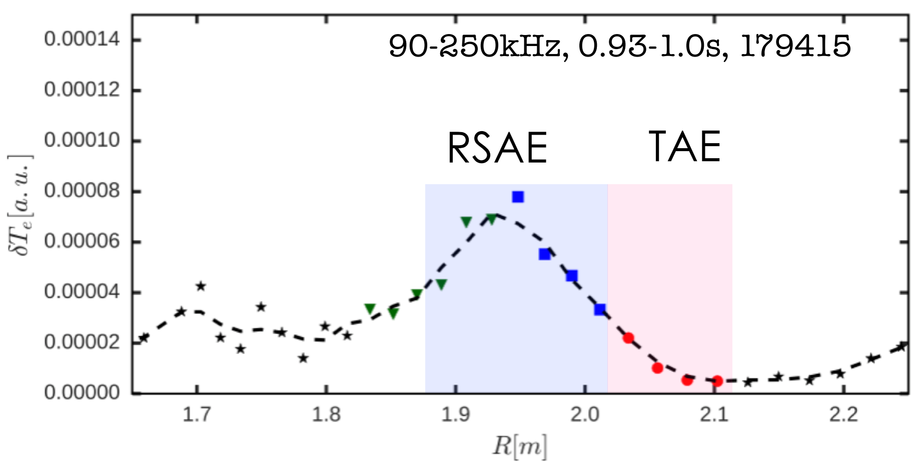
Evolution Of The Phase Space Transport Map Is Consistent With The Change In AE Activity





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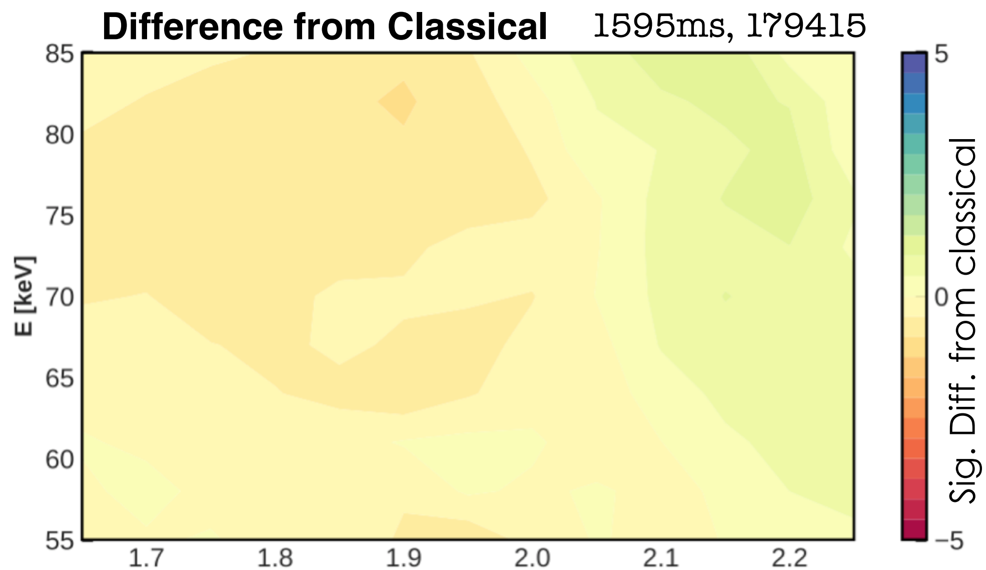
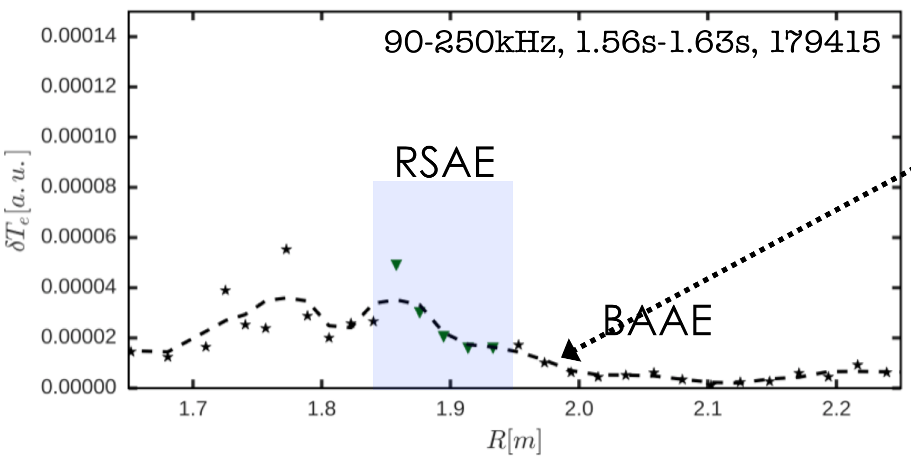
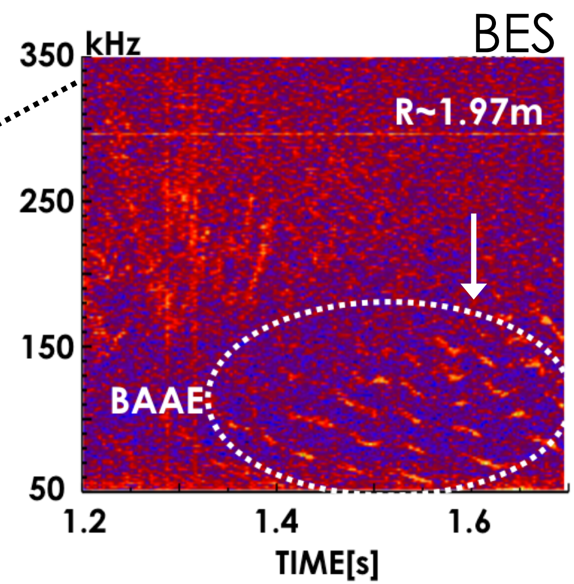
BAAE Does Not Transport Passing Fast Ions In The Interrogated Region Of Phase Space



- **At later times, the plasma is dominated by BAAEs and weak RSAE**
- **Very modest fast ion transport is observed during the BAAE dominant phase and at BAAE location**





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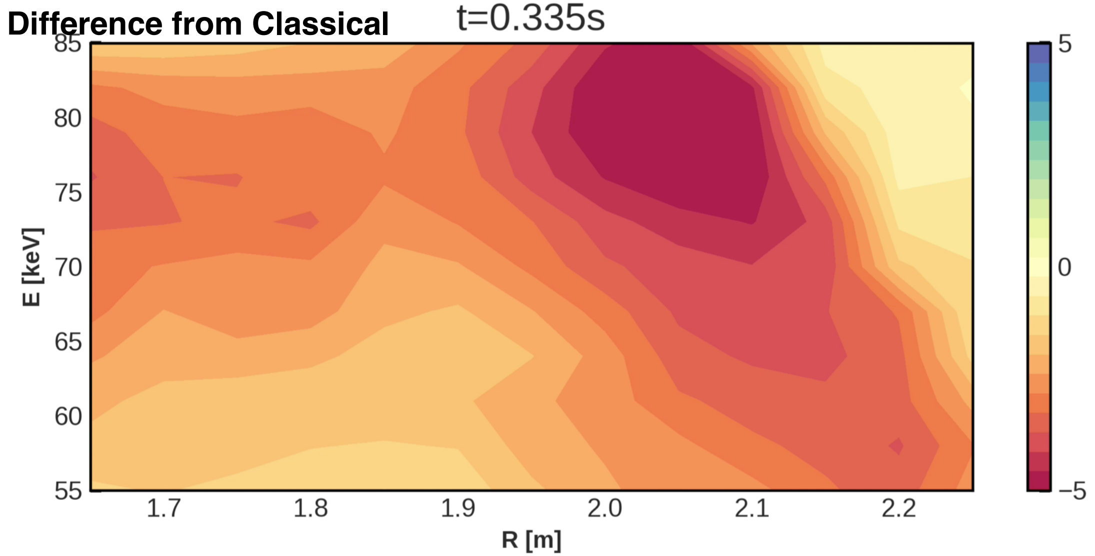
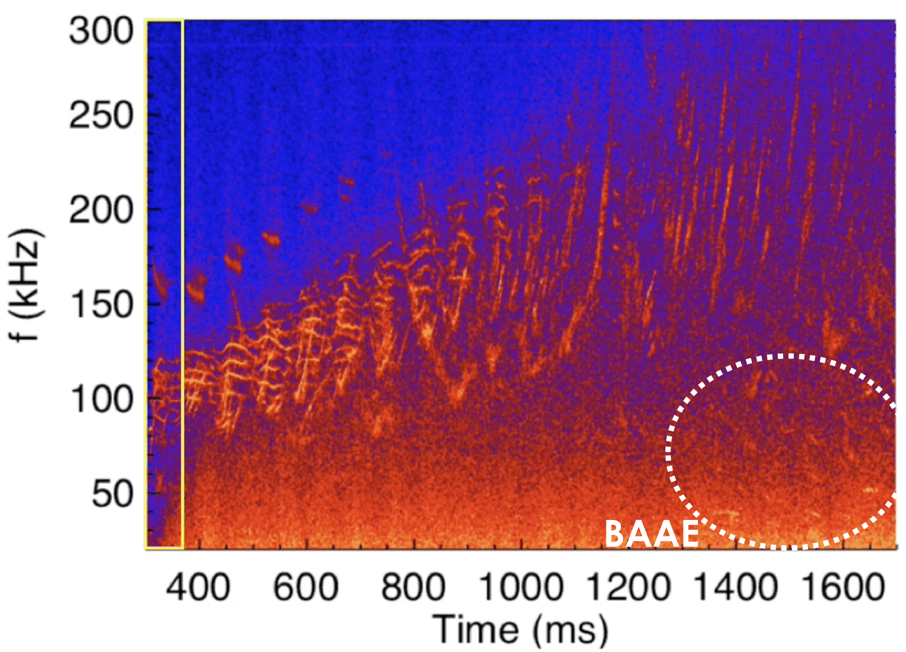
A Smooth Transition Across Each Stage Is Measured By The INPA





- **Phase 1 (TAE, RSAE dominant phase):**
  - AE modes overlap around q_{min}
  - Very stiff transport at plasma injection energy
- **Phase 2 (RSAE dominant phase):**
  - Significant redistribution is observed in phase space at ~70keV. This is observed when TAE becomes weak
- **Phase 3 (BAAE dominant)**
  - Classical in measured phase space

Summary

- **An new Imaging Neutral Particle Analyzer (INPA) has been developed on DIII-D[1,2]**
  - INPA probes a broad region of phase space with excellent energy and radial resolution
- **Through tomographic inversion of INPA data, the local fast ion distribution and impact of instabilities at the interrogated phase space can be accurately derived**

AE-induced transport is systematically studied in a DIII-D current ramp:

- **RSAE & TAE dominant phase**
  - Large fast ion transport is observed across plasma - even for low power ~3MW
  - Transport is particularly stiff at the injection energy of 80keV and q_{min} location
- **RSAE dominant phase**
  - Significant redistribution of fast ions is found from core to edge where fast ion densities can exceed classical expectations
- **BAAE does not induce measurable transport in the interrogated phase space**

Future Work

- 2nd INPA to measure trapped particles underway
- Adding large bandwidth capability to see fluctuations

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1. X.D. Du, Nucl. Fusion, 58, 082006 (2018)
2. M.A. Van Zeeland, JINST, (2019)