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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Most EP Diagnostics Integrate Over Large Regions of Phase Space

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

Weight Functions

\[
S = \int \int \int \int (W \ast F) dE \ dp \ dR \ dz.
\]

W.W. Heidbrink, RSI, 2010
Most EP Diagnostics Integrate Over Large Regions of Phase Space

Weight Functions

Convolution $W*F$

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- Weight functions like these are great for global view of EP confinement
- Wave-Particle interaction is localized in phase space
- Neutral Particle Analyzers have excellent phase space resolution
  - Can probe details of phase space interaction
  - Traditionally, hardware size & view limit # channels ($< \sim 10-100$)

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

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

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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.

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** $V_{\parallel}/V \sim 0.75$
  - Passing particles
- **View spans device midplane**
  - From LCFS to high-field-side of magnetic axis

INPA signal from a uniform distribution of $2 \times 10^6$ particles
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
Two scintillators allow operation in both toroidal field directions as well as provide measure of background level (blind detector).

- Signal to noise is estimated $\approx 10^3$. 

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

\textsuperscript{2} W.W. Heidbrink, Comm. Comp. Physics (2011)
\textsuperscript{3} X.Du, Comm. Comp. Physics In Preparation (2019)
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)

Details were reported in P1-8 by D. Lin et al.
INPA Images In MHD Quiescent Plasmas In Agreement With Modeling Using Classical TRANSP Distribution Functions

- 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

Details were reported in P1-8 by D. Lin et al
The Localized Weight Function and Large Number of Channels Make INPA Data ‘Tomography-Friendly’

- Each pixel measures a localized region of phase space
  - Each circle represents a range of particles which contributes 1/e of the total signal at each pixel
  - Typical of NPA weight functions
- The $4 \times 10^4$ 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

- Raw INPA images do not resolve two neutral beams with voltages of ~81keV and ~78keV (Energy res. ~7.5keV)
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- 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
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)

Classically

Neutral Beam

INPA signal from 1 pixel

- 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
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)

Classically

With AE Induced Transport

- 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
- 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 preferred
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

- As expected, the modulated waveform in the high power case shifts up
- Ratio of signal $\Delta A / \Delta B$ is close to 1 over all phase space
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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 $R=2.2m$

1. **P1**: During the RSAE & TAE dominant phase
   - Small deficit at 70kV and $R=2.2m$

2. **P2**: RSAE dominant phase with weakened TAE
   - Signal exceeds the classical expectations

3. **P3**: BAAE dominant phase with weakened RSAE
   - Nearly classical
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 q_{min} location
  - Potential issue for advanced tokamak operation scenario

**Fractional Deficit**

At the injection energy of 81 keV

<table>
<thead>
<tr>
<th>R [m]</th>
<th>TIME [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>0.4</td>
</tr>
<tr>
<td>2.1</td>
<td>0.6</td>
</tr>
<tr>
<td>2.0</td>
<td>0.8</td>
</tr>
<tr>
<td>1.9</td>
<td>1.0</td>
</tr>
<tr>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- Fractional Deficit (deficit/classical)
• 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

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

ECE

Difference from Classical 965ms, 179415

90-250kHz, 0.93-1.0s, 179415

DIII-D National Fusion Facility San Diego
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 $q_{\text{min}}$
  - Significant transport aligns with the RSAE locations

- A portion of phase space outside $R \sim 2.1m$ now exceeds classical levels
  - Clear redistribution in phase space is observed

- The transport in the plasma core $R \sim 1.7m$ is reduced
The plasma is dominated by the RSAE – TAE amplitude is reduced

The transport region moves inward with $q_{\text{min}}$ – Significant transport aligns with the RSAE locations

A portion of phase space outside $R \sim 2.1m$ now exceeds classical levels – Clear redistribution in phase space is observed

The transport in the plasma core $R \sim 1.7m$ is reduced
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
A Smooth Transition Across Each Stage Is Measured By The INPA

- **Phase 1 (TAE, RSAE dominant phase):**
  - AE modes overlap around $q_{\text{min}}$
  - 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 \(q_{\text{min}}\) 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

- 2\textsuperscript{nd} INPA to measure trapped particles underway
- Adding large bandwidth capability to see fluctuations

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