Critical Gradient Behavior of Fast-Ion Transport from Alfvén Eigenmodes Guides Predictive Models for Burning Plasmas

Cami Collins[1]

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M. A. Van Zeeland[1], R.B. White[3],
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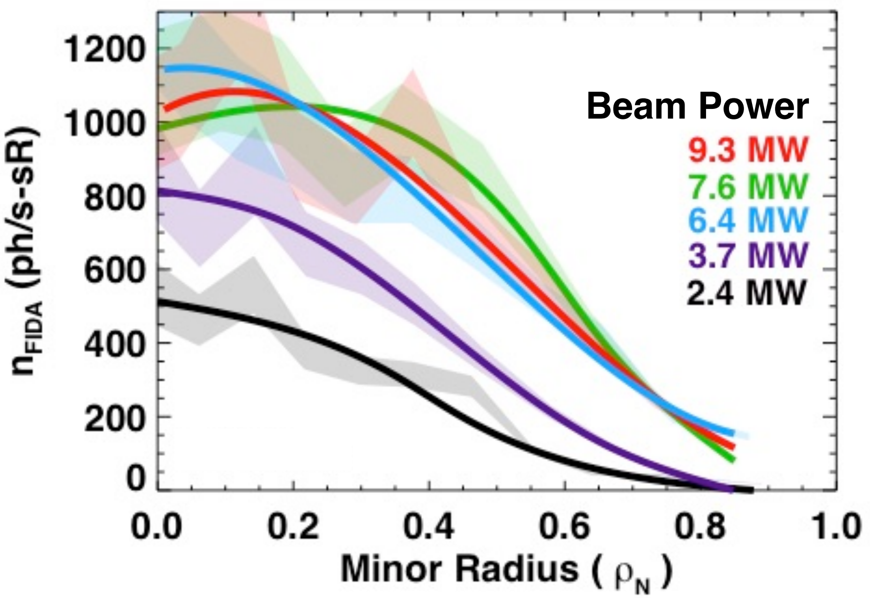
[2]University of California, Irvine
[3]Princeton Plasma Physics Laboratory

Fast-Ion Density Profiles



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Kyoto, Japan
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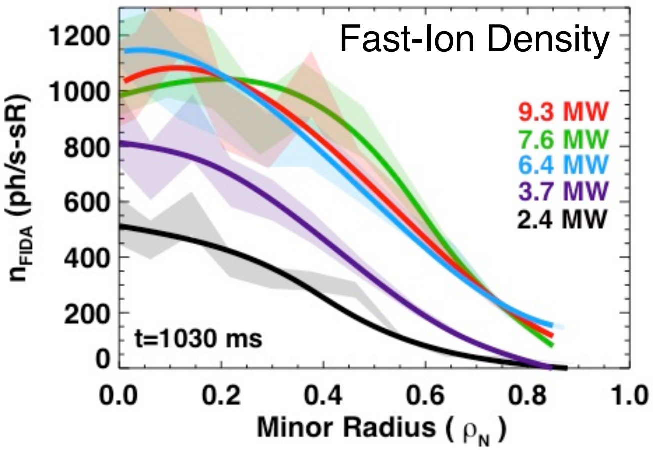
DIII-D NATIONAL FUSION FACILITY PPPL UCIrvine UNIVERSITY OF CALIFORNIA, IRVINE

Critical Gradient Behavior of Alfvén Eigenmode (AE) Induced Fast-Ion Transport Has Been Observed in DIII-D

- **Key features of critical gradient phenomenon:**

1.
Density profiles become 'clamped'
(profile resiliency)



[Collins *et al.*, PRL 116 (2016)]

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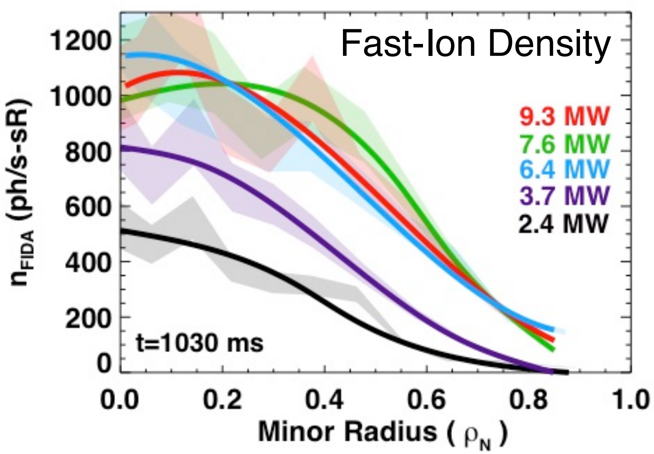
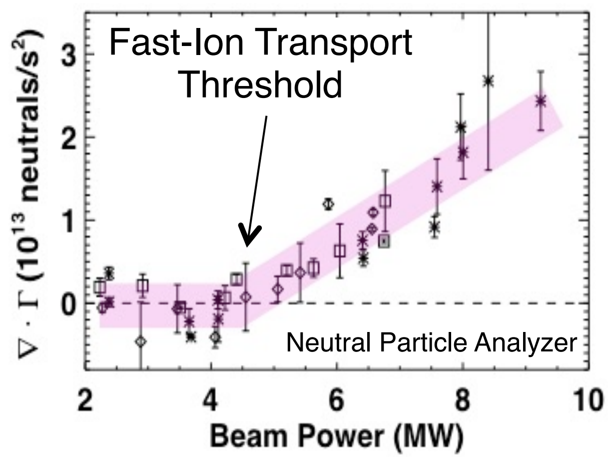


2.
Sudden increase in transport at a threshold
(stiff transport)



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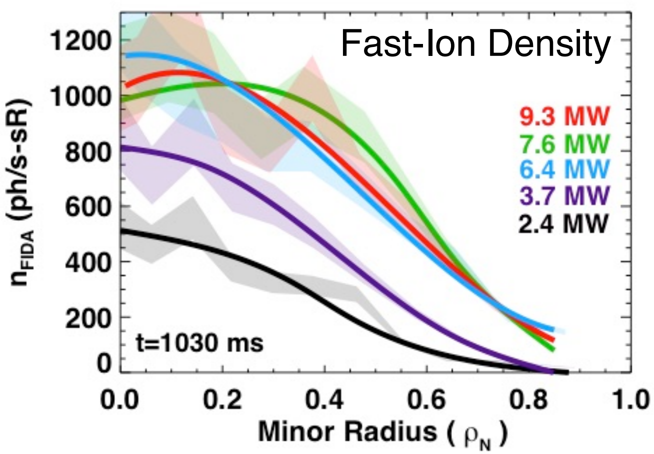

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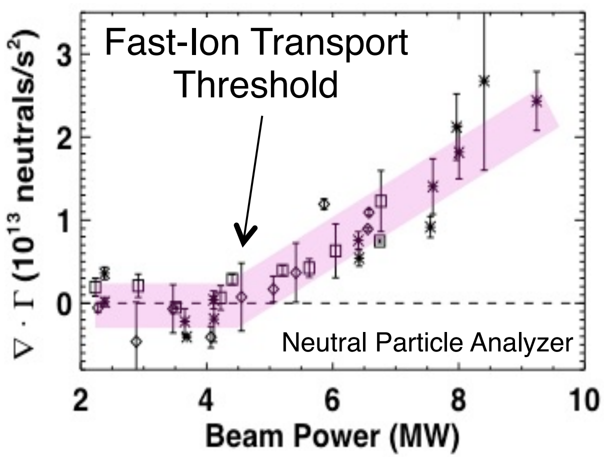
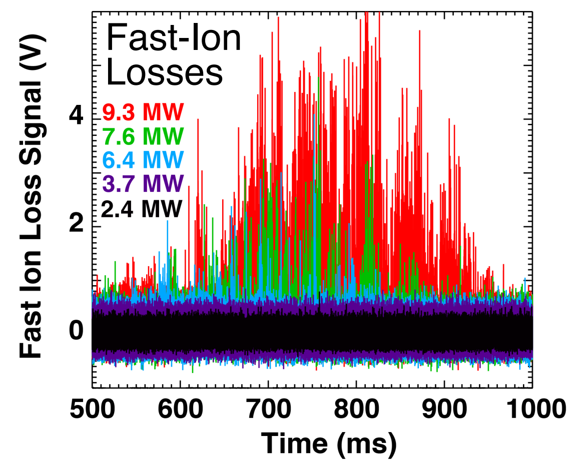


3.
Transient bursts of fast-ion losses
(intermittency)



- **Recent experiments at DIII-D show that fast-ion transport becomes stiff when AEs cause fast-ion orbits to become stochastic.**

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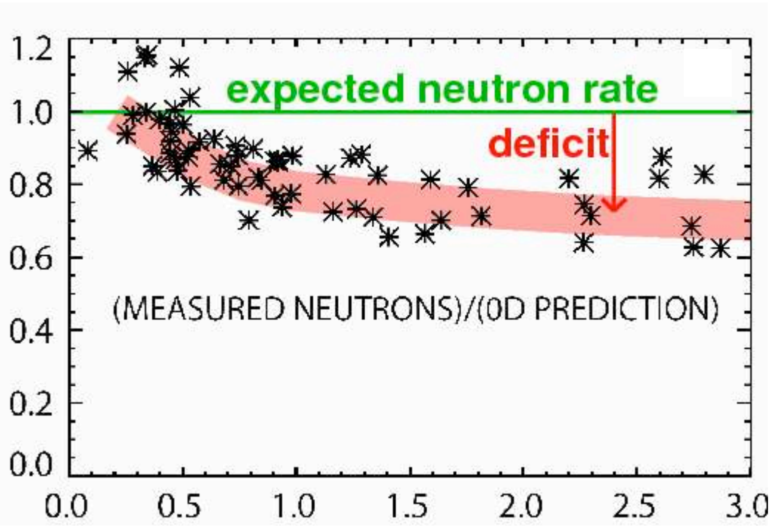
[Collins *et al.*, PRL 116 (2016)]

Attractive Steady-State Tokamak Operation Requires Confined Energetic Particles

- **AEs can cause transport that reduces:**
  - absorbed beam heating power
  - current drive
  - achievable β_N

AEs degrade fusion performance by 40% in DIII-D steady state scenarios



AE Amplitude (a.u.)

[Heidbrink *et al*., PPCF 56 (2014)]
[Holcomb *et al*., Phys. Plasmas 22 (2015)]

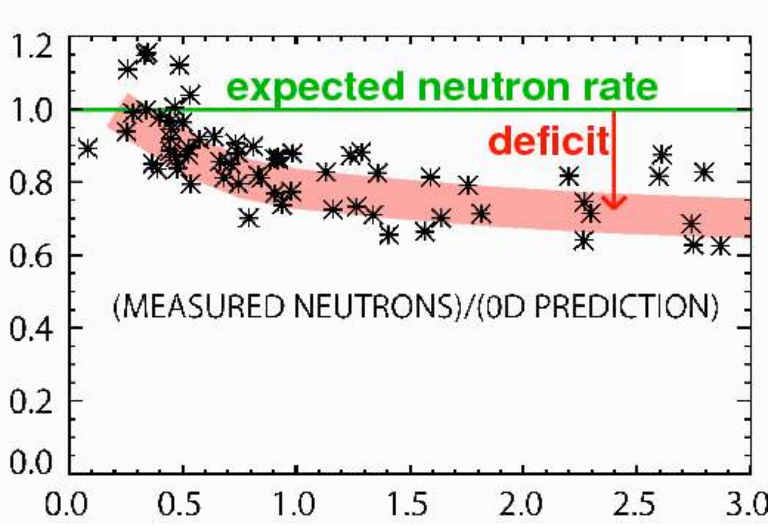
Attractive Steady-State Tokamak Operation Requires Confined Energetic Particles

- **AEs can cause transport that reduces:**
  - absorbed beam heating power
  - current drive
  - achievable β_N

- **AEs are driven by gradients in EP profiles & are predicted to be unstable in ITER**

- **Important questions:**
  - When is transport significant?
  - How can we effectively predict EP profiles, beam ion profiles, and losses to optimize scenarios?

AEs degrade fusion performance by 40% in DIII-D steady state scenarios



AE Amplitude (a.u.)

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[Heidbrink *et al*., PPCF 56 (2014)]
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Outline

- DIII-D critical gradient experiment & analysis technique.
- Critical gradient transport varies in phase-space.
- Theoretical analysis indicates stochasticity sets threshold.

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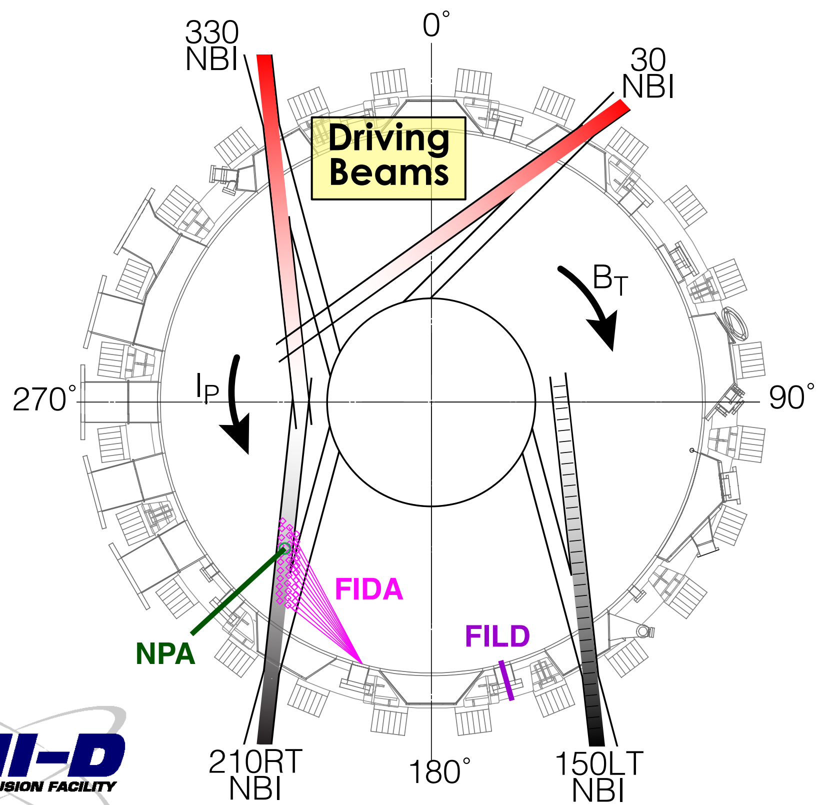
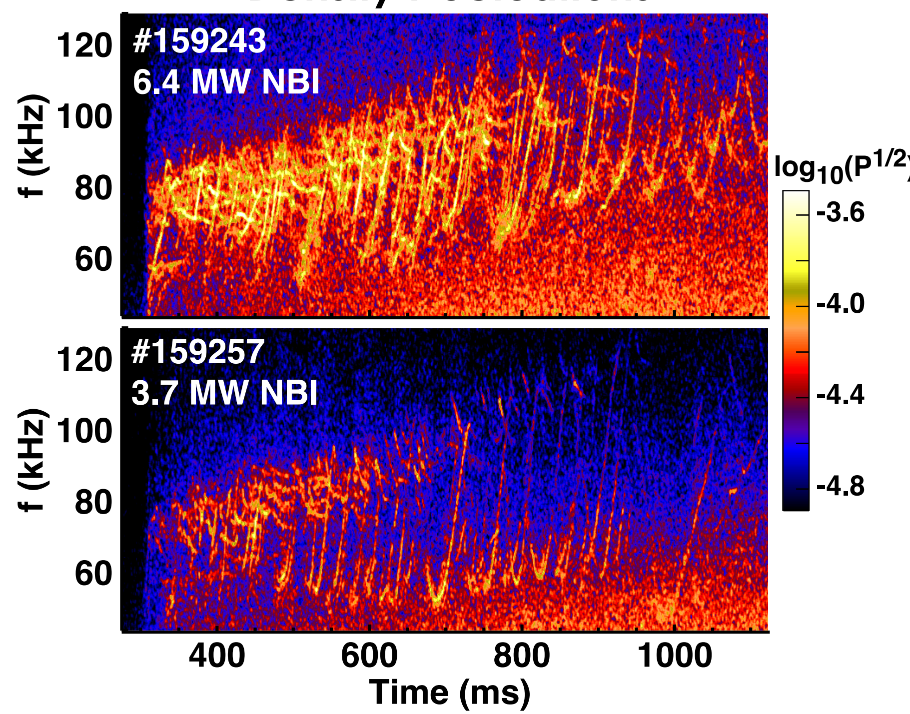
The Experiment: Use NBI Power to Manipulate AEs & Beam Modulation to Measure Fast-Ion Transport

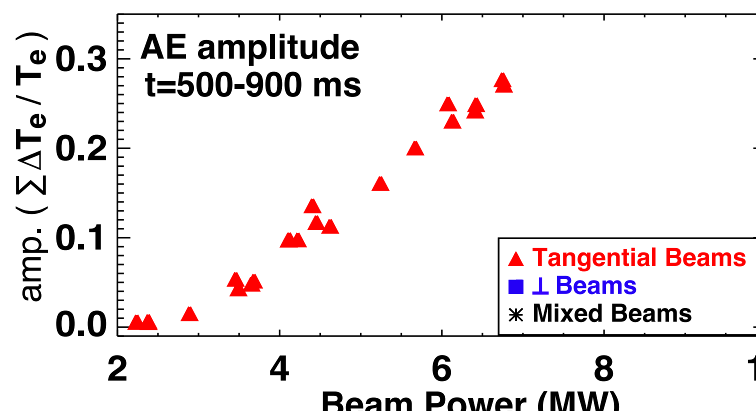
- **Control AE activity with NBI power & geometry during the current ramp**

  (reverse-shear, L-mode plasma)



Density Fluctuations





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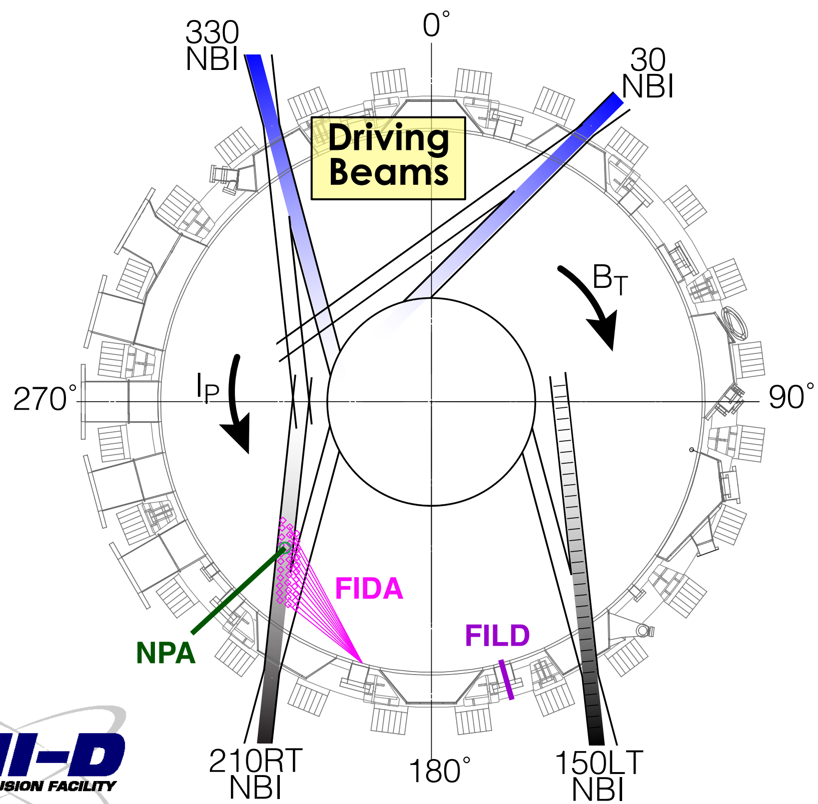

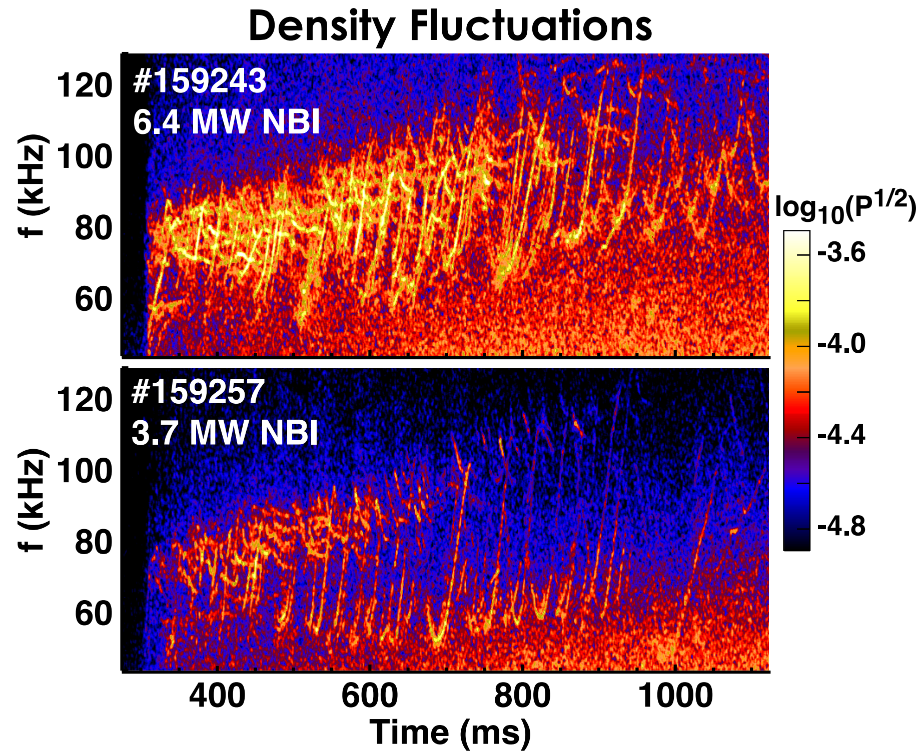

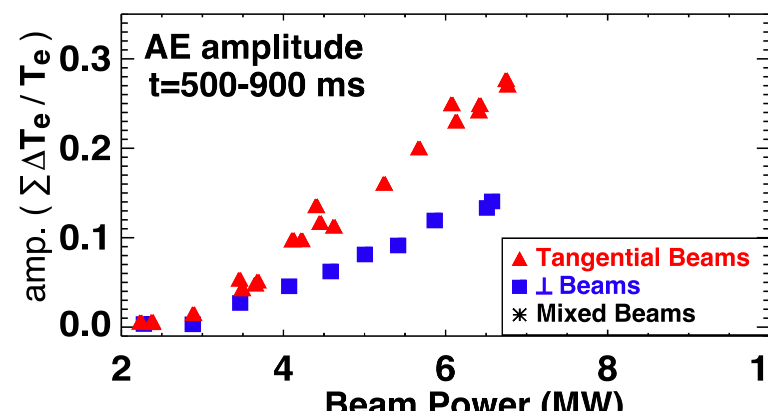

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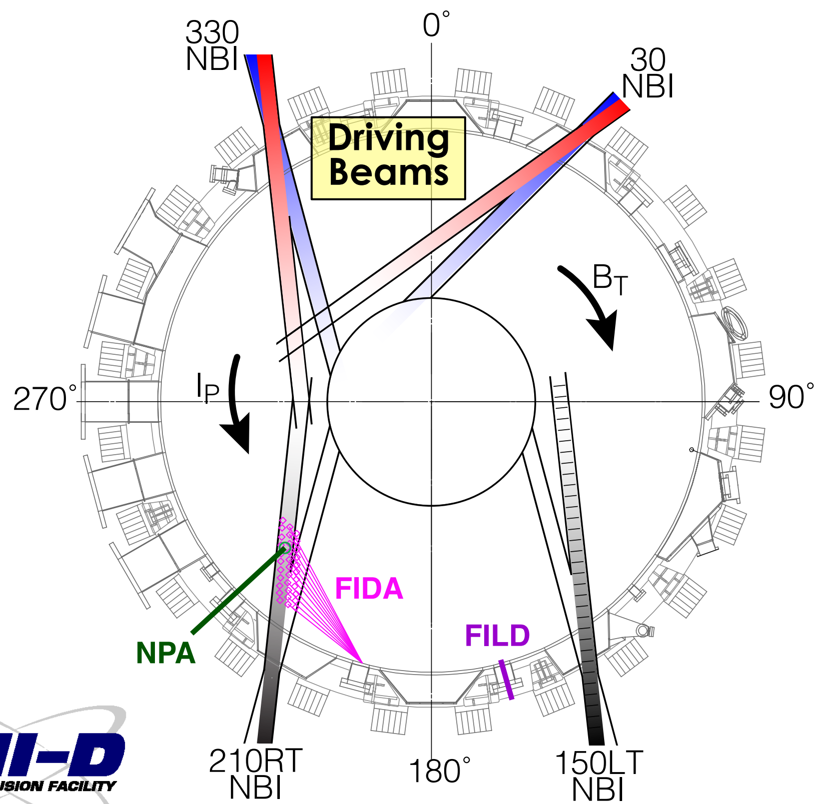

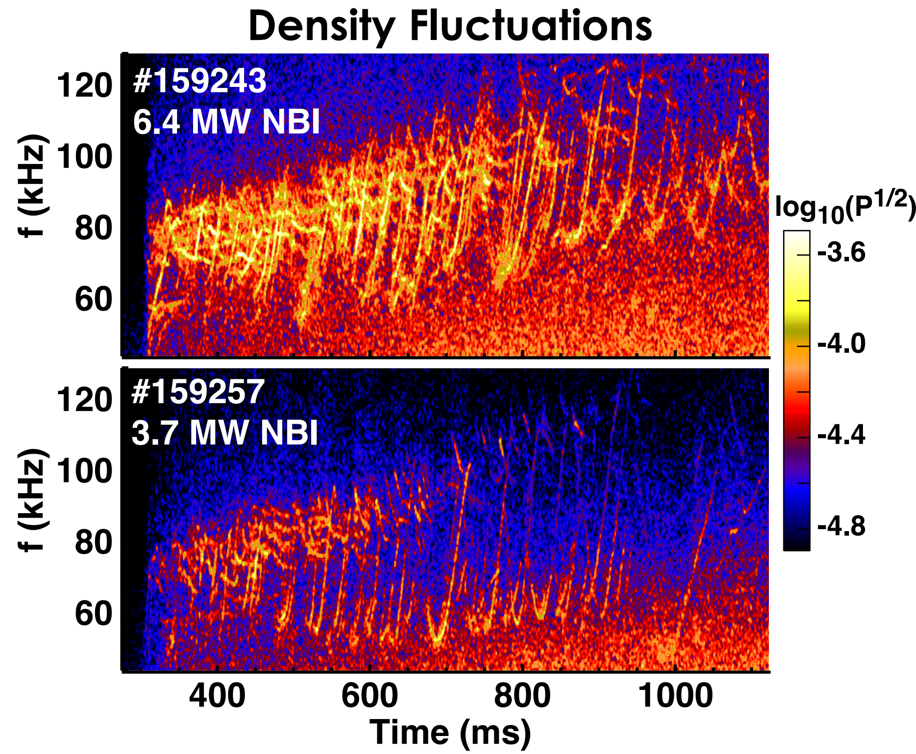

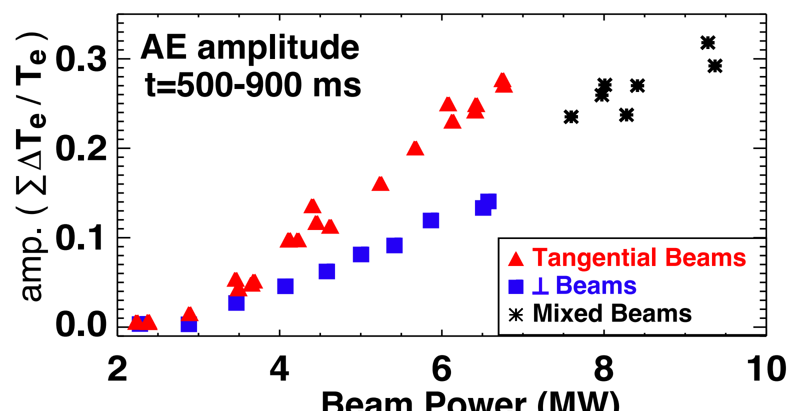

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The Experiment: Use NBI Power to Manipulate AEs & Beam Modulation to Measure Fast-Ion Transport

- **Control AE activity with NBI power & geometry during the current ramp**
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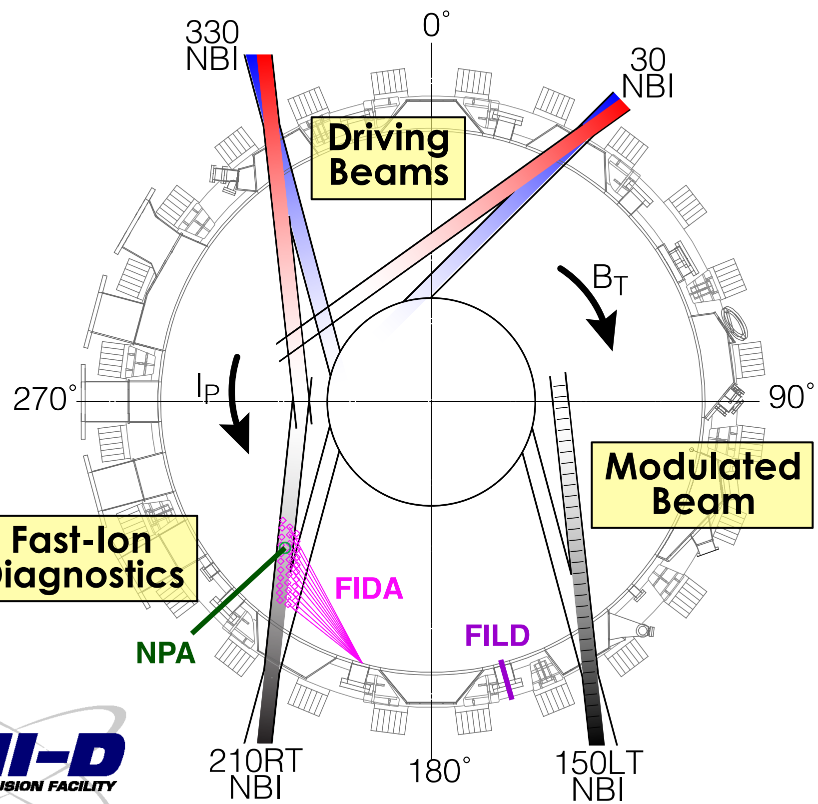
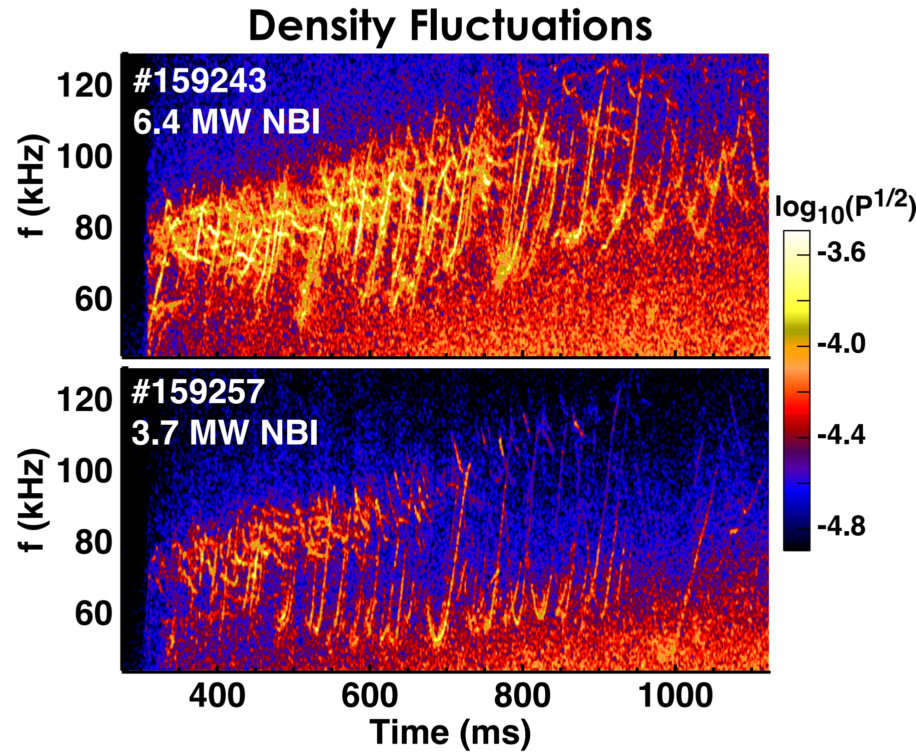
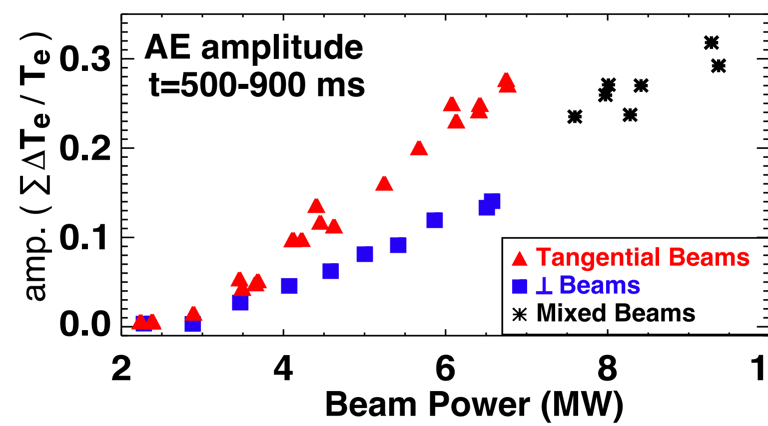
- **Measure transport by modulating the fast-ion pressure profile with off-axis neutral beam injection (150LT)**







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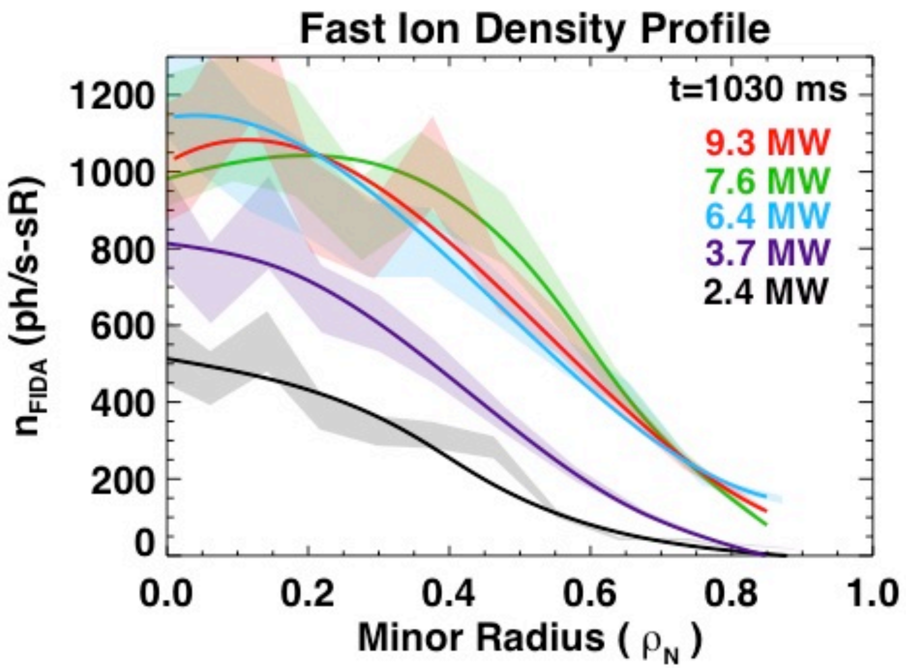
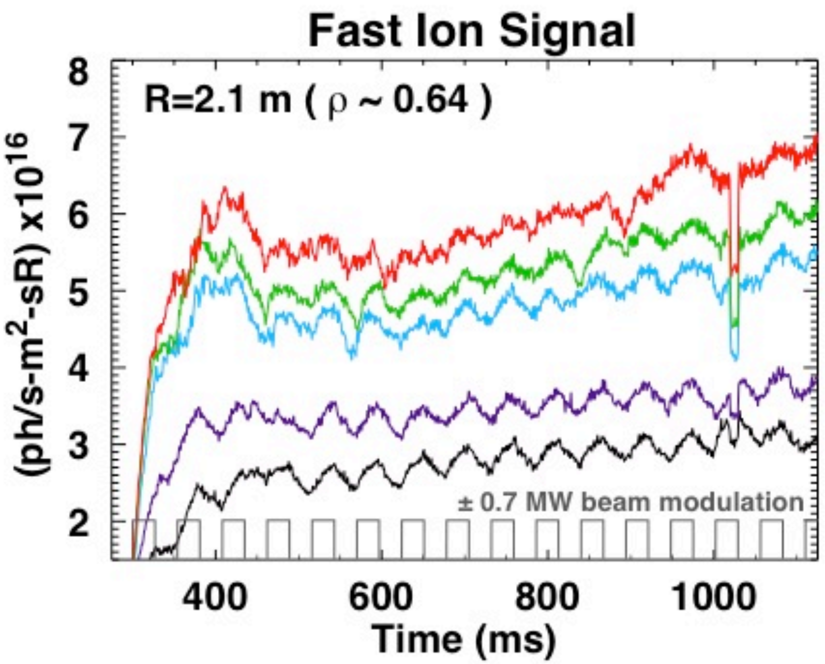
Stiff Transport Causes Clamped Equilibrium Density Profiles and Distortions In Modulated Signals





- Profile resilience has also been observed in off-axis beam injection experiments.
  [Heidbrink et al.,Nucl. Fusion 53 (2013)]

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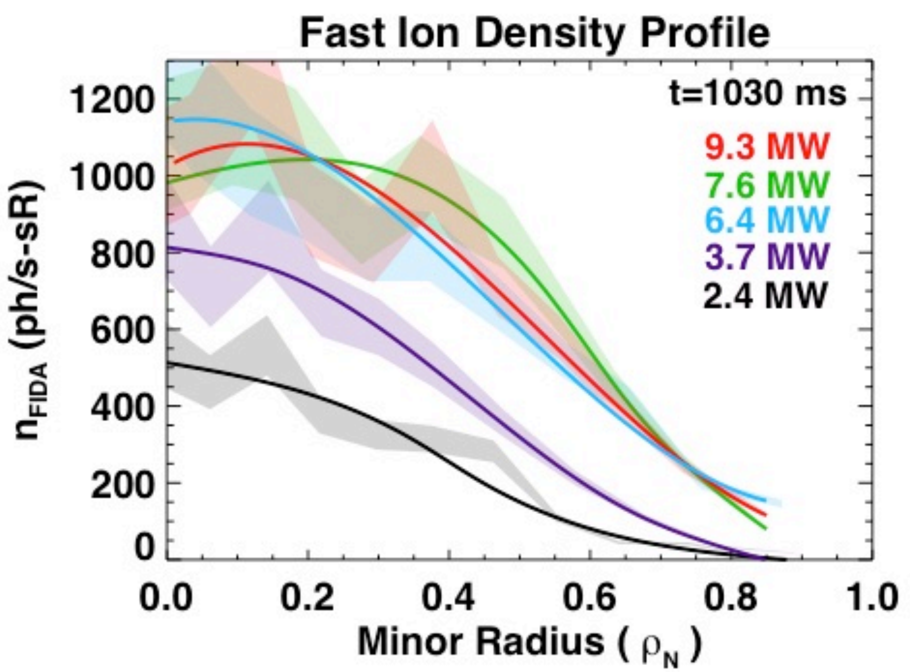

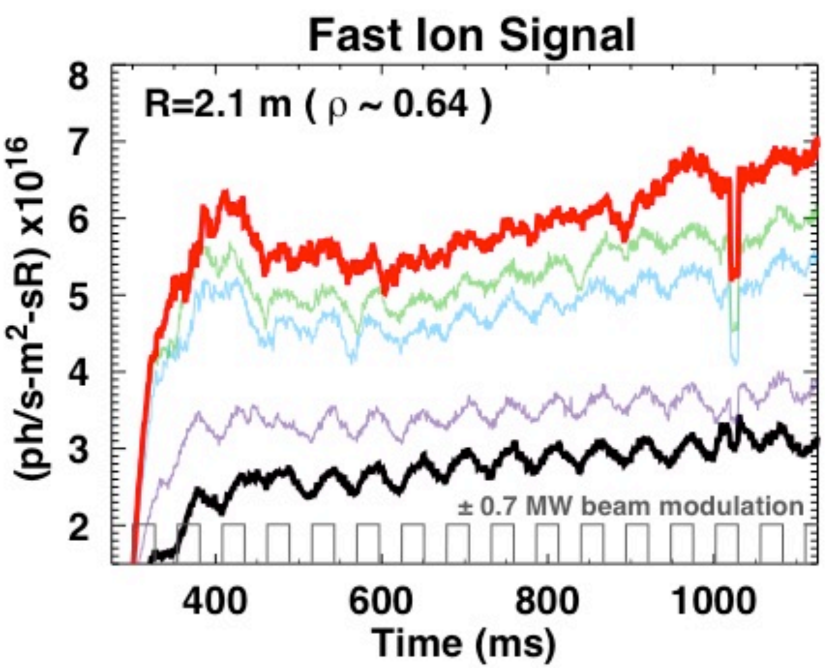

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Technique: Use Particle Balance To Calculate Transport

$$\frac{\partial \tilde{n}}{\partial t} = \tilde{S} - \frac{\tilde{n}}{\tau} - \nabla \cdot \tilde{\Gamma}$$

source (modulated beam)

Sink term (modulated particles thermalize)

Divergence of Flux (transport) due to interaction with AEs

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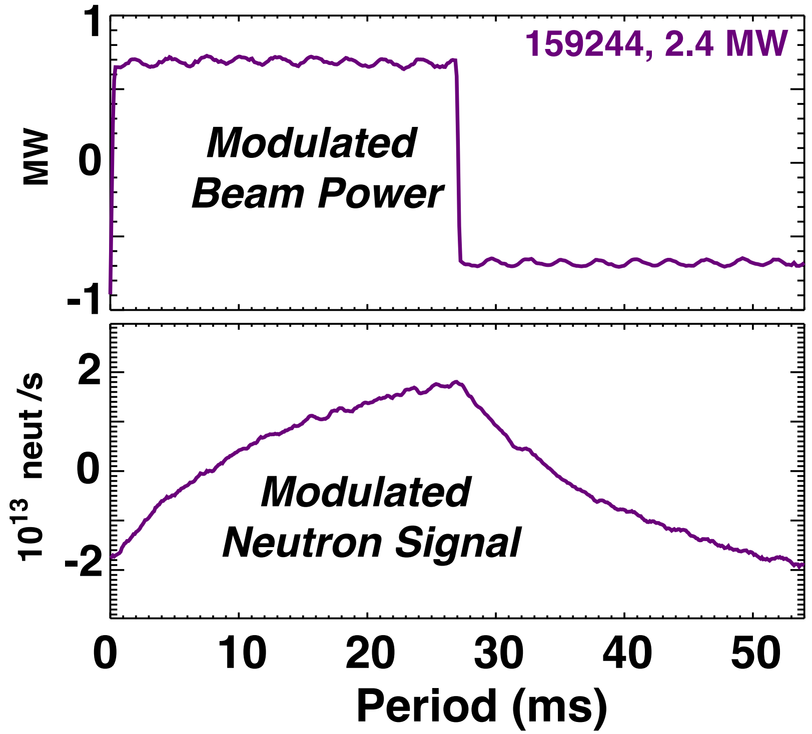

1. **Modulate the fast-ion source with off-axis neutral beam injection (150LT)**

$$S = S_0 + \tilde{S}$$

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Divergence of Flux (transport) due to interaction with AEs

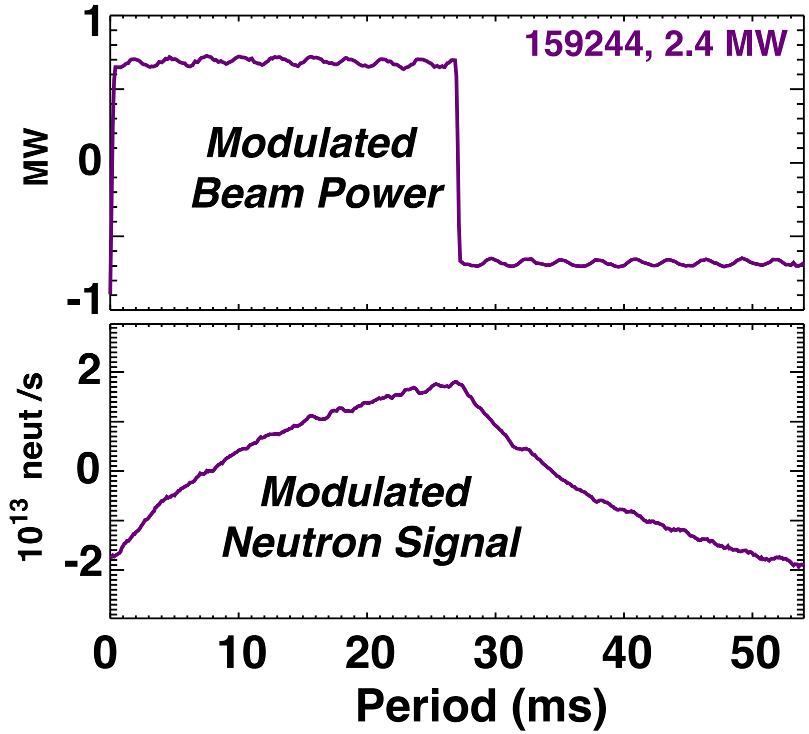
1. **Modulate the fast-ion source with off-axis neutral beam injection (150LT)**

$$S = S_0 + \tilde{S}$$

2. **Measure fast-ion evolution:**

$$n = n_0 + \tilde{n}$$

- fast-ion Dα (FIDA) spectroscopy
  - density profiles
- solid-state neutral particle analyzer (NPA)
  - fast neutrals from charge-exchange
- neutron emission (mostly beam-plasma)
  - proxy for volumetric fast-ion population



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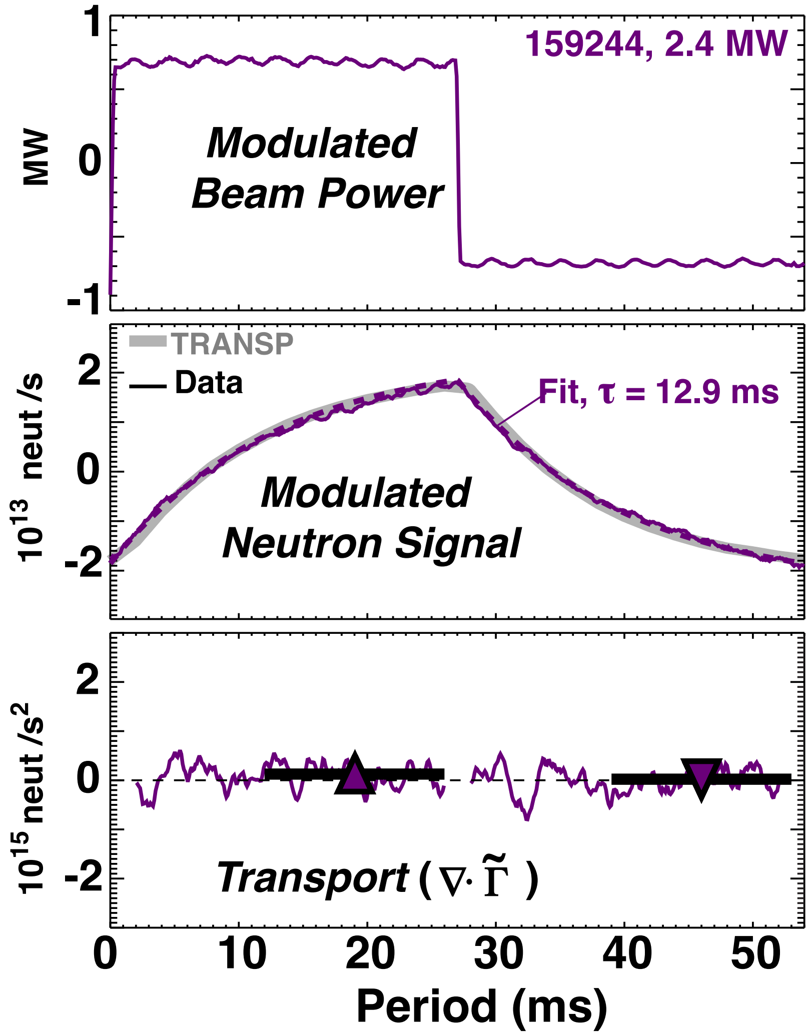
Technique: Use Particle Balance To Calculate Transport

$$\nabla \cdot \tilde{\Gamma} = -\frac{\partial \tilde{n}}{\partial t} + \tilde{S} - \frac{\tilde{n}}{\tau}$$

3. Calculate $\tilde{S}$ and τ, solve for $\nabla \cdot \tilde{\Gamma}$

- Use TRANSP/FIDASIM to calculate source from classical signal [Heidbrink et al., NF 2016]



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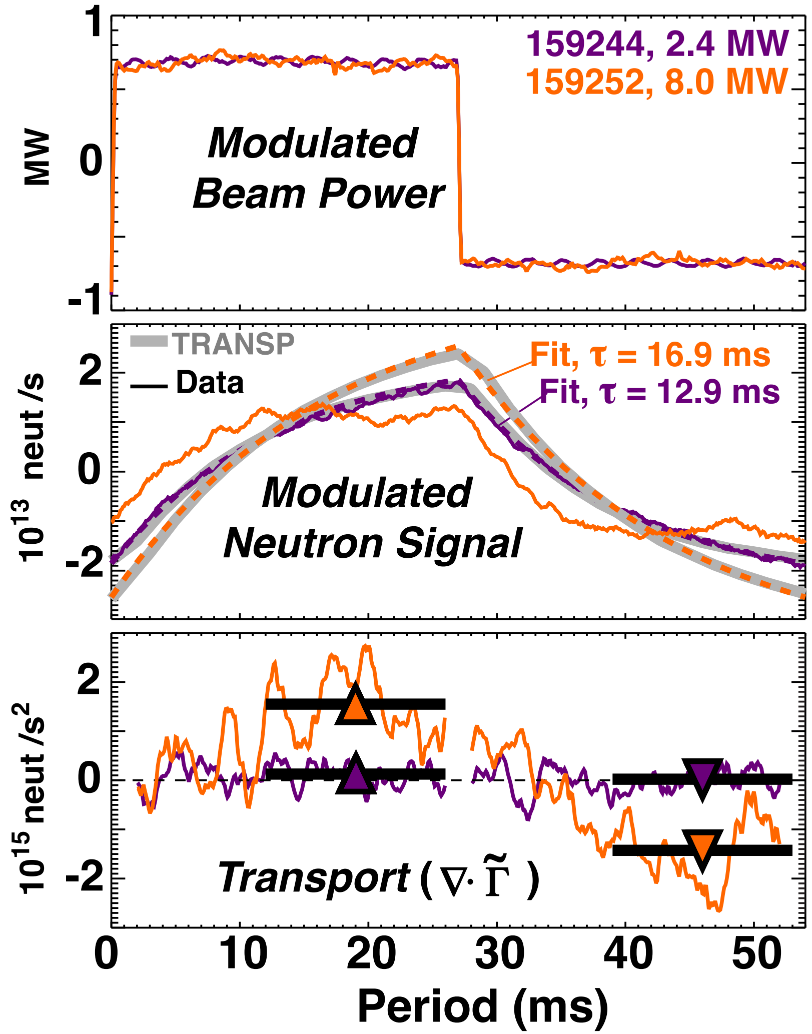

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Technique: Use Particle Balance To Calculate Transport

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3. Calculate $\tilde{S}$ and τ, solve for $\nabla \cdot \tilde{\Gamma}$

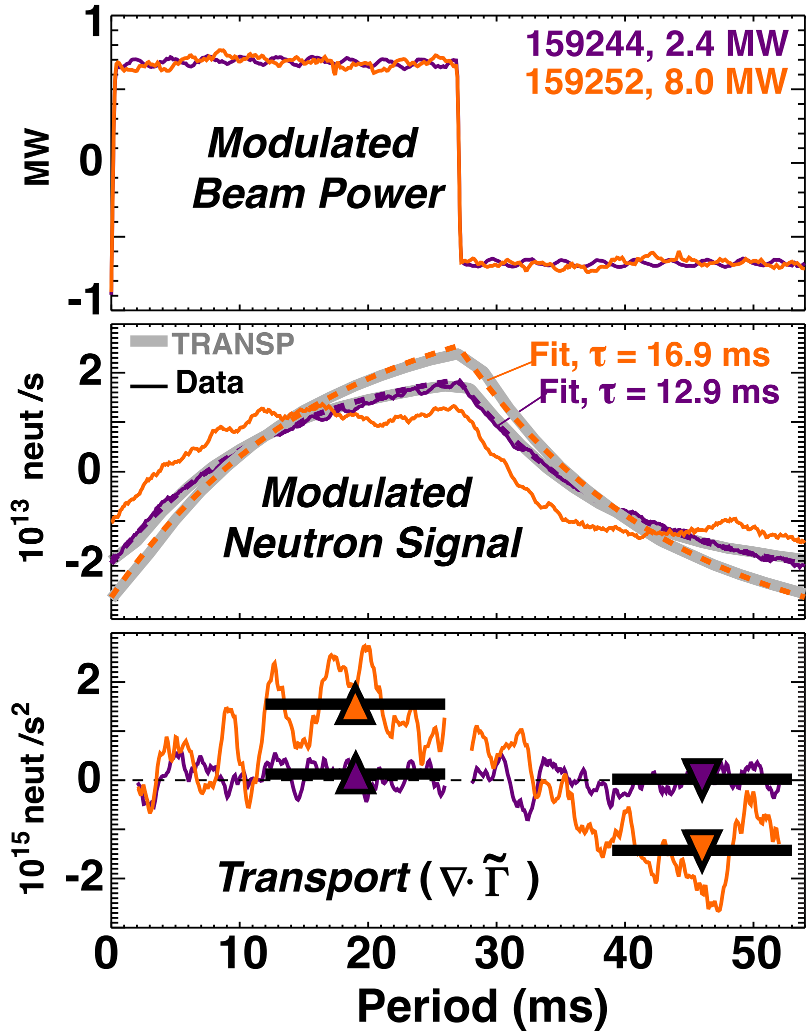
- Use TRANSP/FIDASIM to calculate source from classical signal [Heidbrink et al., NF 2016]
- Transport analysis is complicated because fast-ion 'density' is phase-space dependent:

$$\tilde{n} = \int \int \int \tilde{f}(\mathrm{E}, \mathrm{p}, \mathbf{x}) W(\mathrm{E}, \mathrm{p}, \mathbf{x}) d\mathrm{E} d\mathrm{p} d\mathbf{x}$$

Modulated distribution function ($\tilde{f}$) — Diagnostic sensitivity (W)

→ Flux is not a function of radius alone

$$\tilde{\Gamma} \neq -D \nabla \tilde{n} + V \tilde{n}$$



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Outline

- DIII-D critical gradient experiment & analysis technique.
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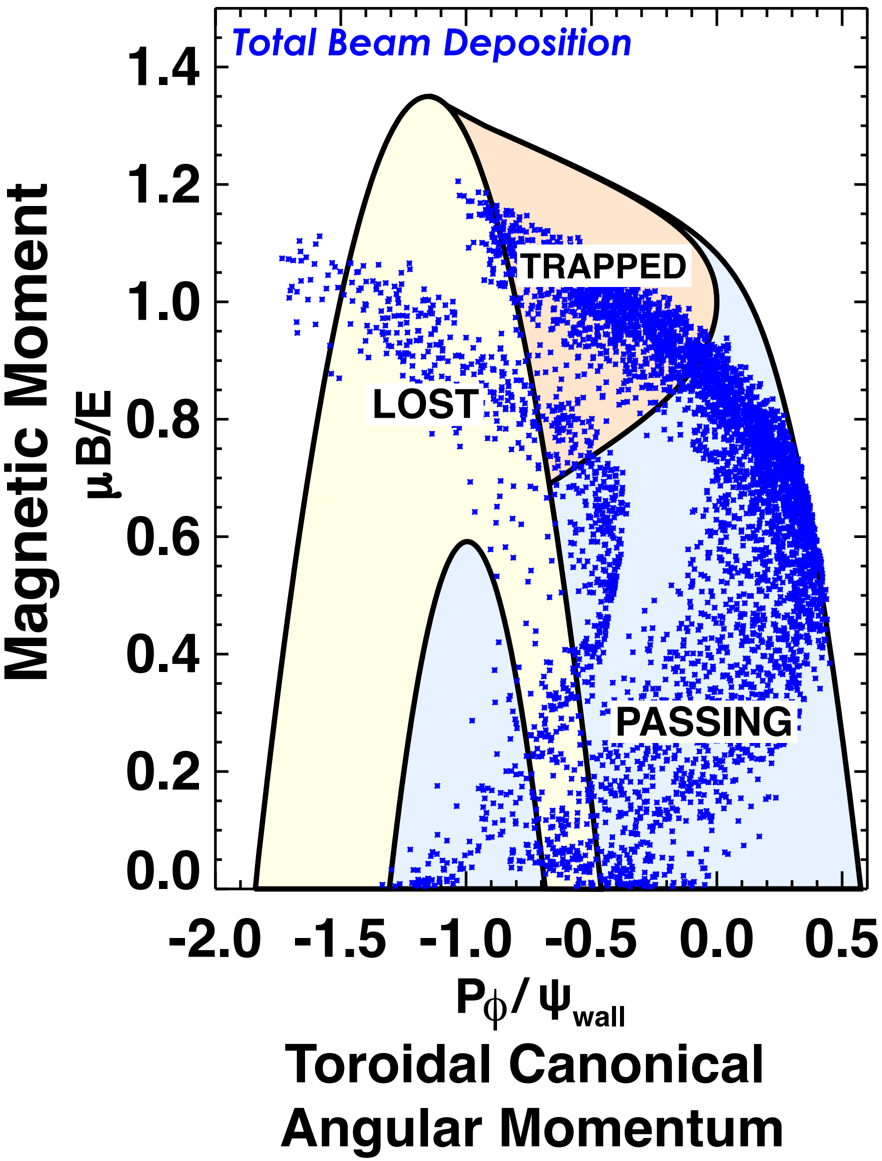
Probing Localized Transport in Phase Space



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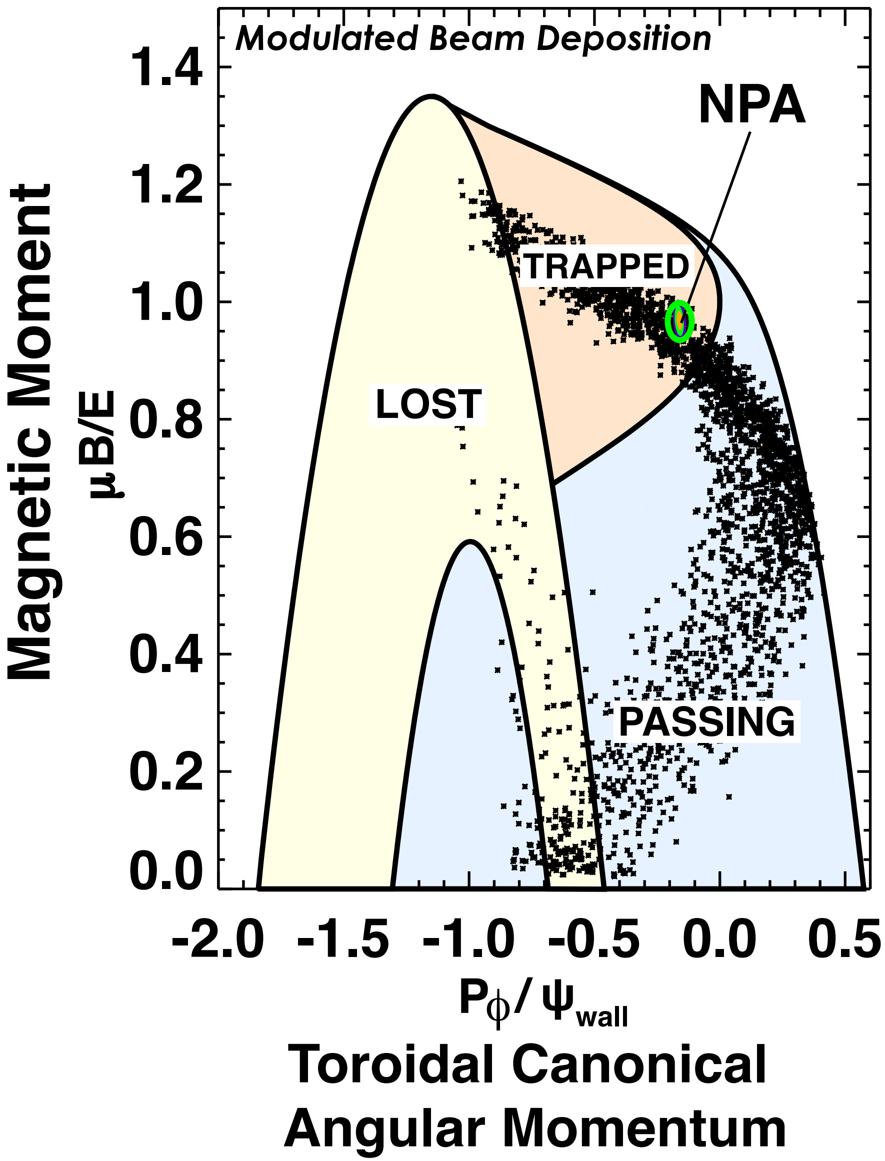
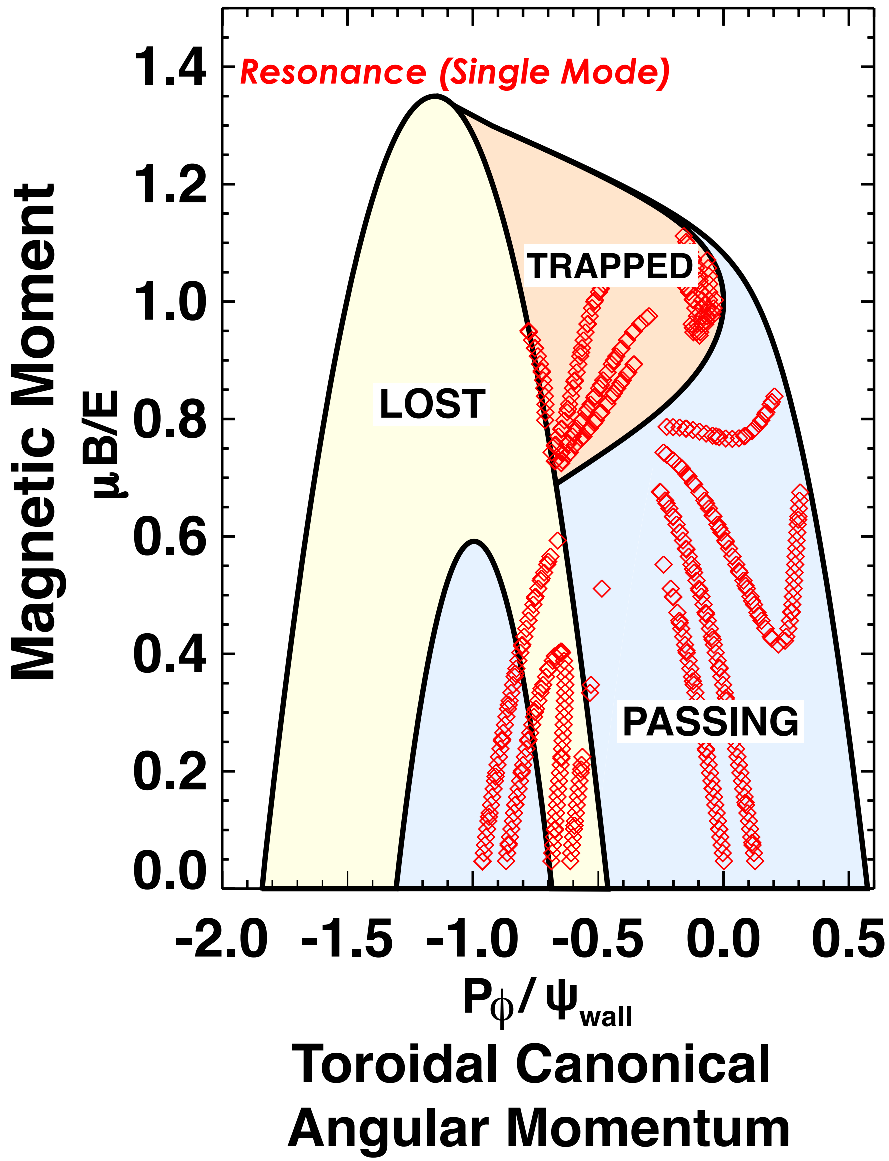
Probing Localized Transport in Phase Space

- **Diagnostics measure a portion of fast-ions**
  - NPA measures narrow band of trapped fast-ions



Probing Localized Transport in Phase Space

- AEs are driven by bulk population of fast-ions
- Energy exchange occurs when orbits are in **resonance with AE modes**



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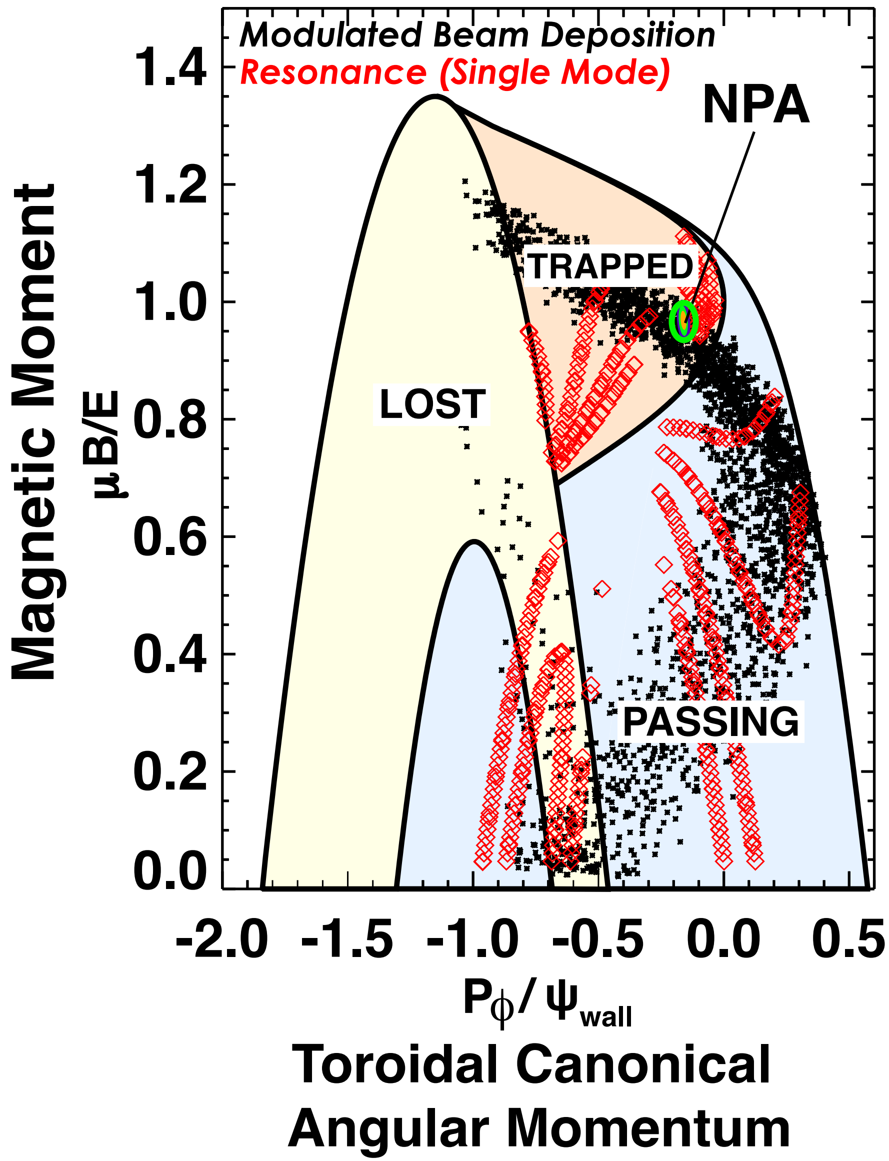
Probing Localized Transport in Phase Space

- **Expect to measure transport at intersection of:**
  - Diagnostic sensitive space
  - Modulated beam orbits
  - AE resonance



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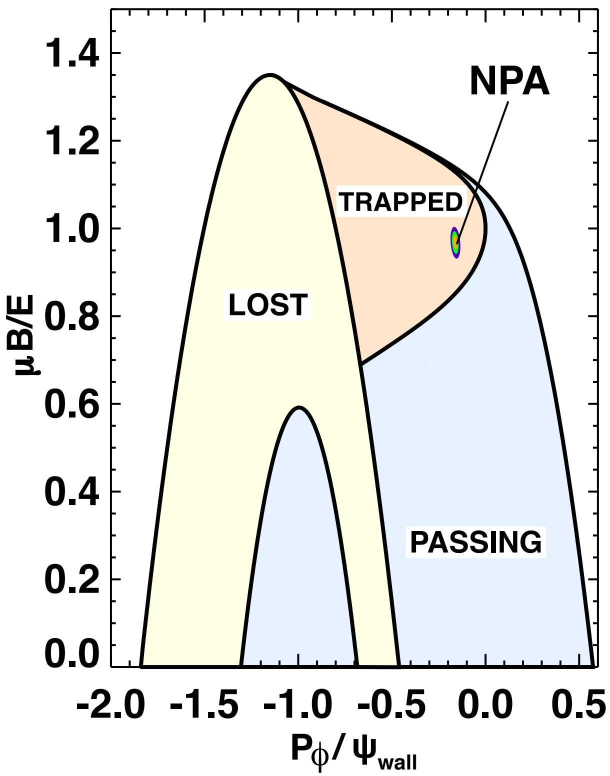
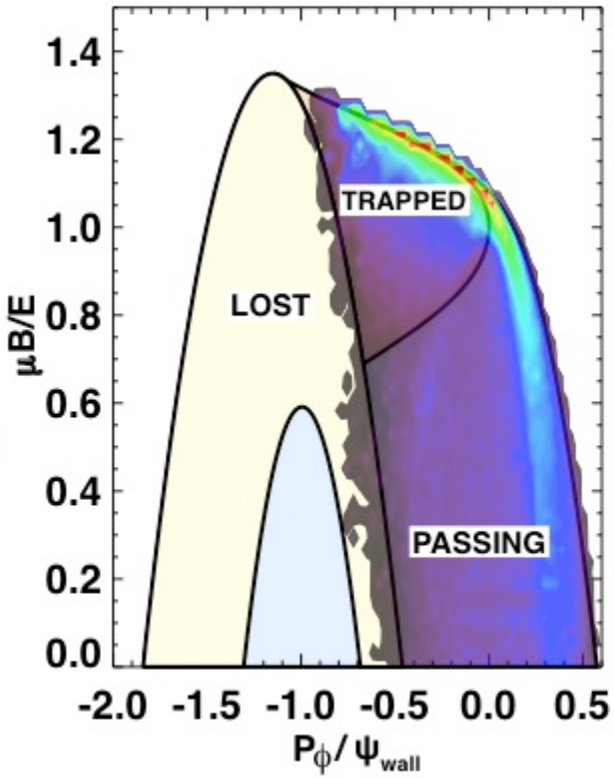
Different Diagnostics Provide Comprehensive Survey of Fast-Ion Orbit Topology Space

Neutral Particle Analyzer



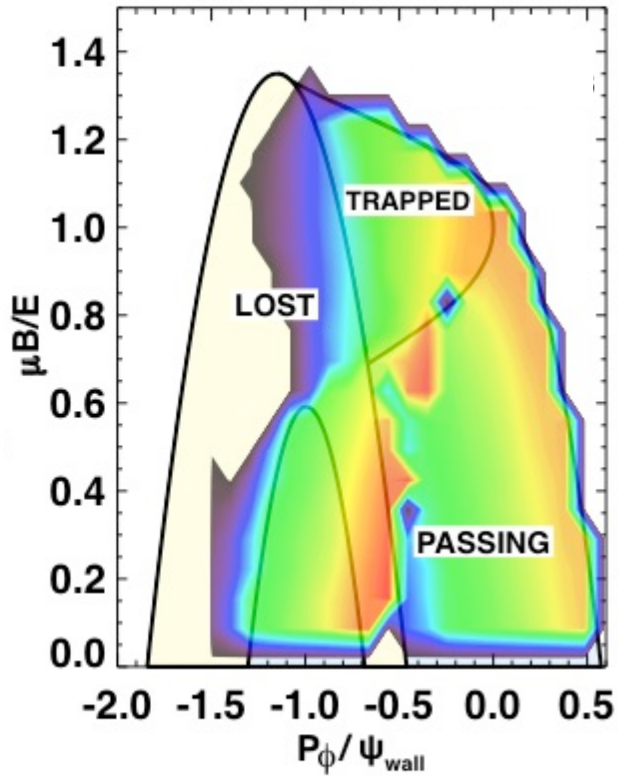
Trapped fast ions ($v_{||}/v < 0.3$)

Fast Ion Dα Spectroscopy



Co-passing fast ions ($v_{||}/v > 0.3$)

Neutron Diagnostic



High energy, volume-averaged

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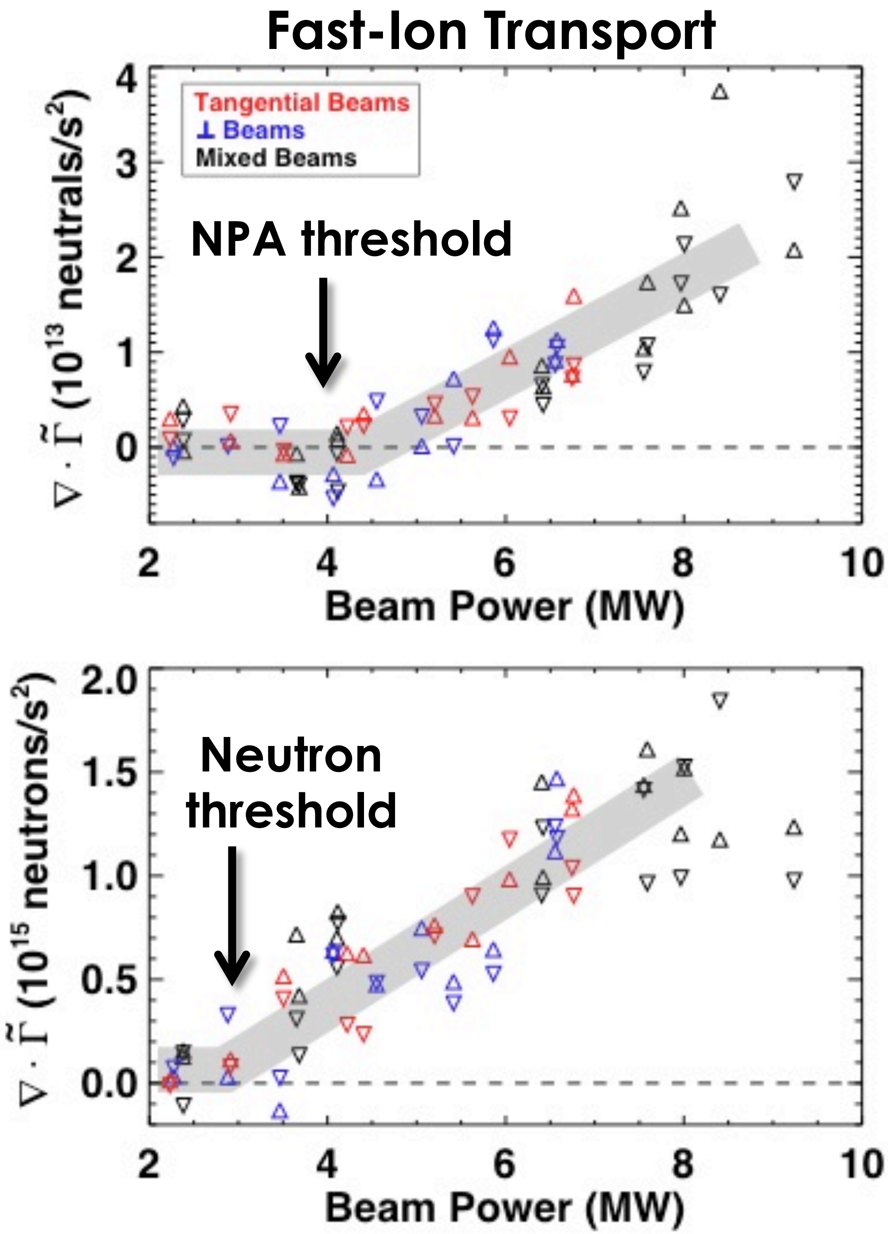
Onset Threshold for Transport Differs Between Various Fast-ion Diagnostics



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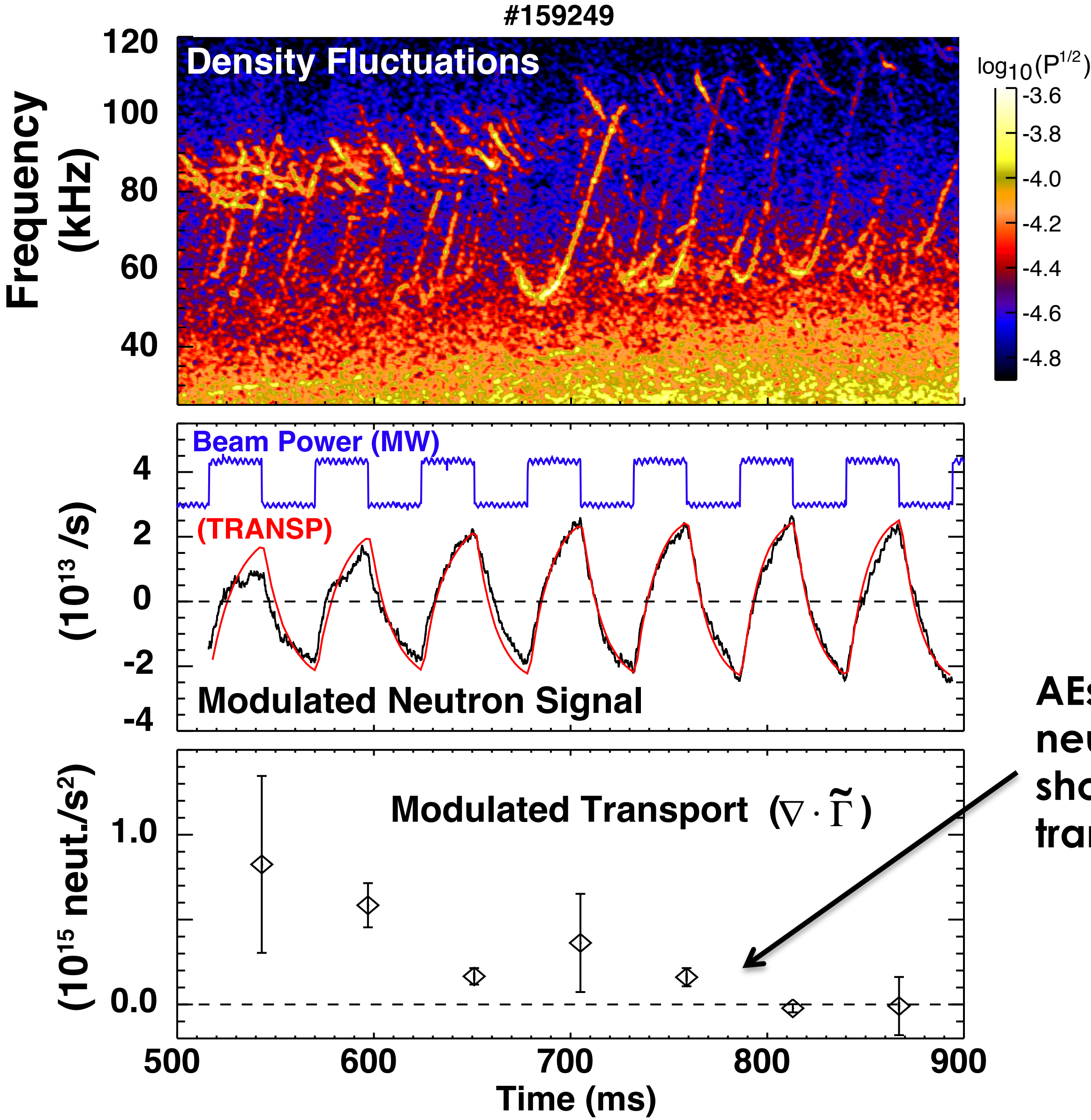
Threshold for Significant Transport Is Clearly Beyond AE Linear Stability Threshold



AEs present, but neutron diagnostic shows minimal transport

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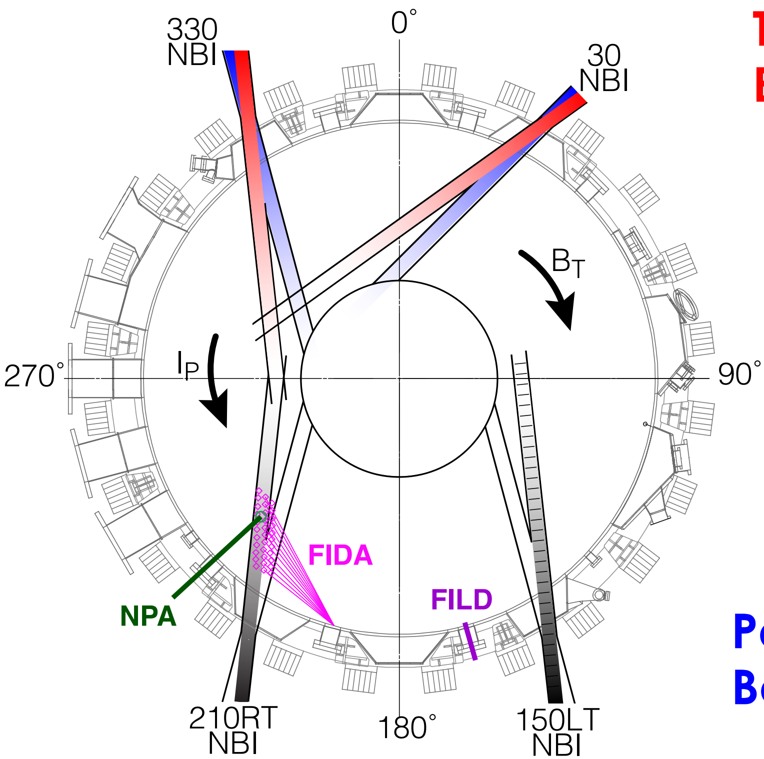
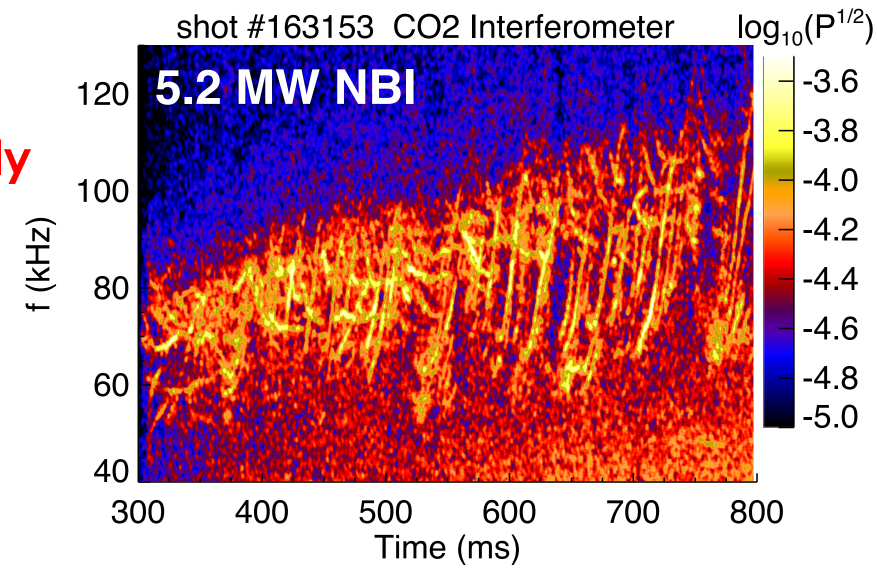
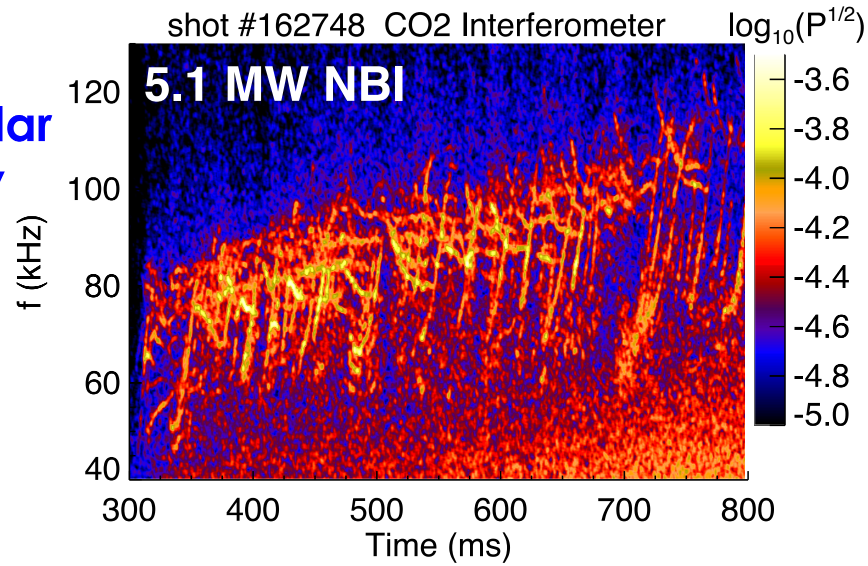
Varied Beam Geometry Used To Drive Different AE Resonances By Changing Bulk Fast-Ion Distribution



Tangential Beams Only



Perpendicular Beams Only



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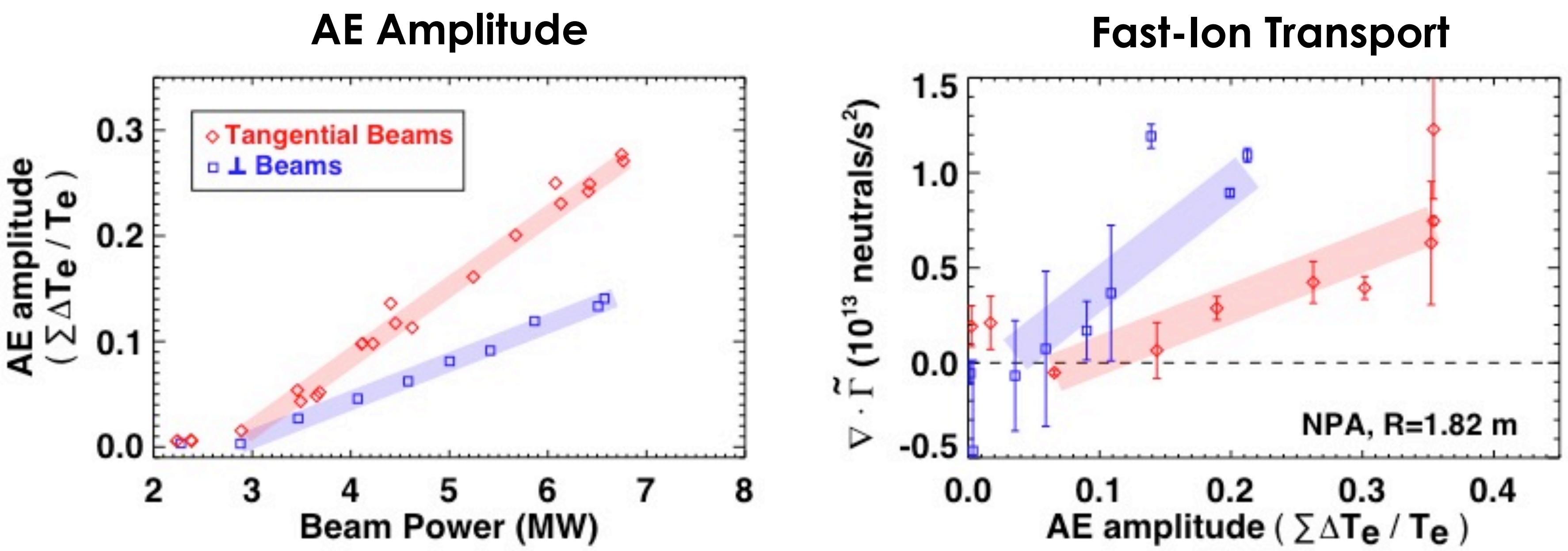
Threshold and Stiffness Change as Beam Deposition Shifts Resonances in Phase-Space



- For a given total beam power, tangential beam injection results in the strongest total AE amplitude.
- However, perpendicular beam injection drives modes that are more efficient at transporting the trapped particle population.

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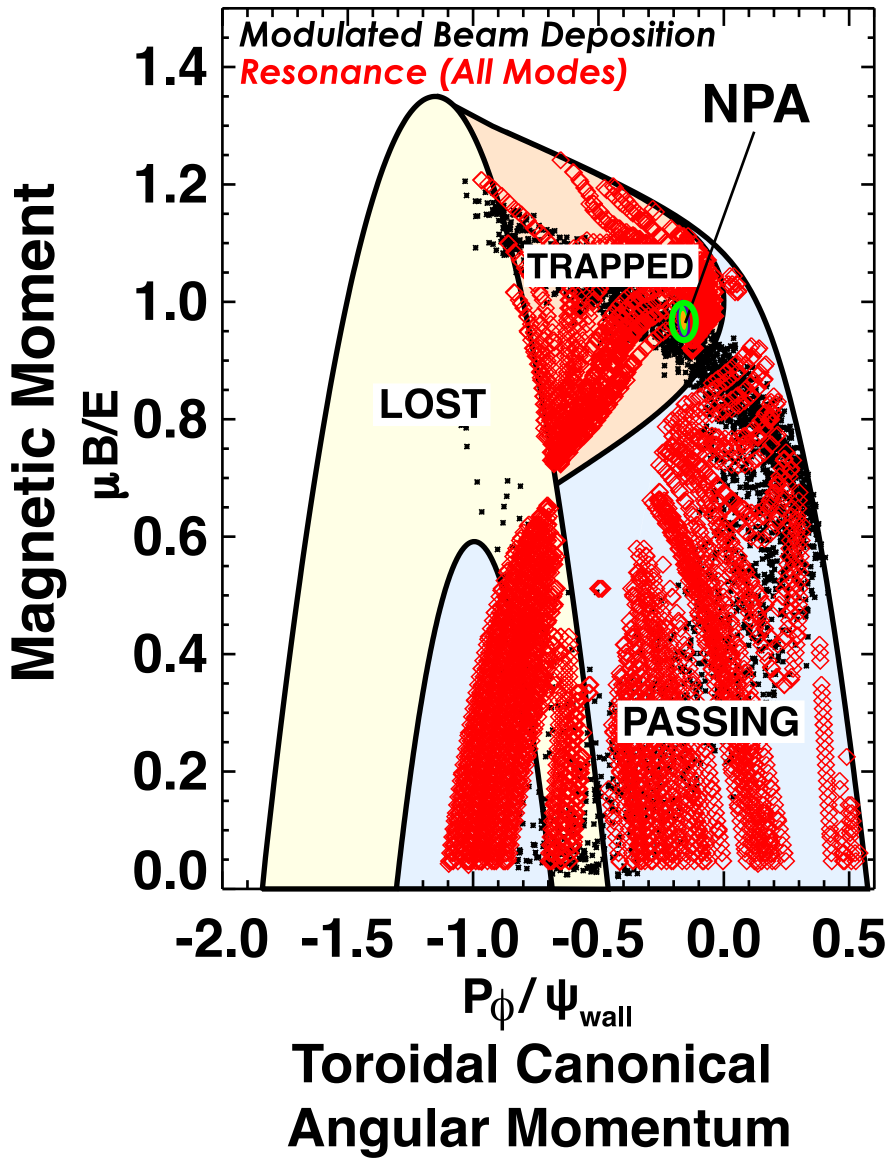
Outline

- DIII-D critical gradient experiment & analysis technique.
- Critical gradient transport varies in phase-space.
- **Theoretical analysis indicates stochasticity sets threshold.**

Probing Localized Transport in Phase Space

- **Expect to measure transport at intersection of:**
  - Diagnostic sensitive space
  - Modulated beam orbits
  - AE resonance

- **Theoretical analysis shows multiple, overlapping AEs cause *stochastic* orbits**



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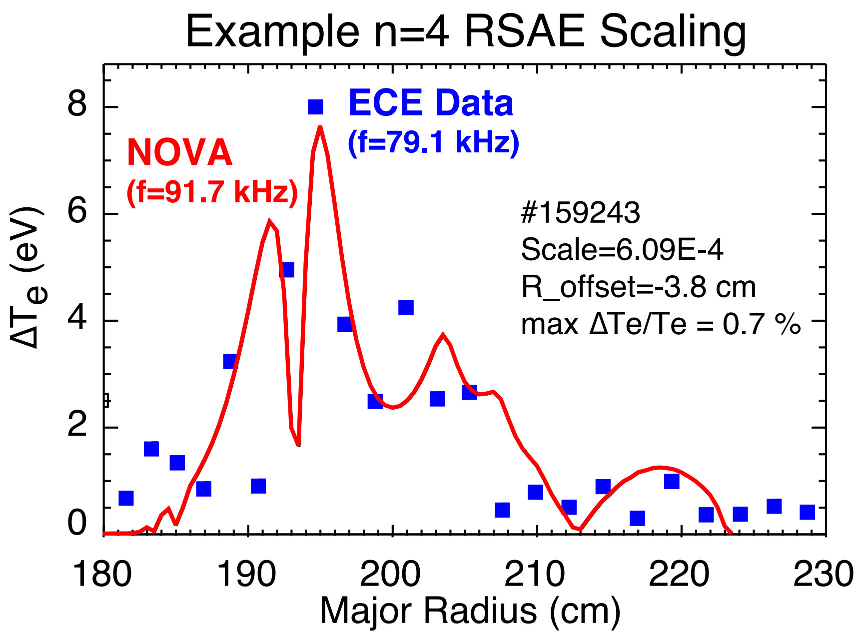
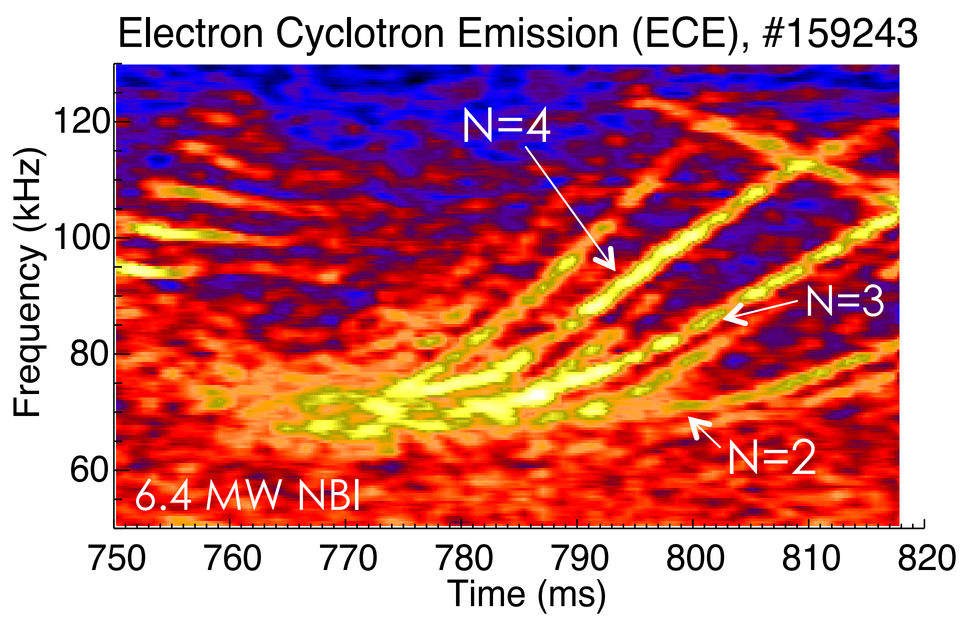
NOVA AE Mode Amplitudes are Matched to Experiment

- **The linear ideal MHD code NOVA is used to compute AE frequencies and structures for 159243 at t=790 ms (6.4 MW NBI).**
- **NOVA amplitudes are scaled to match experimental values based on ECE fluctuation measurements.**



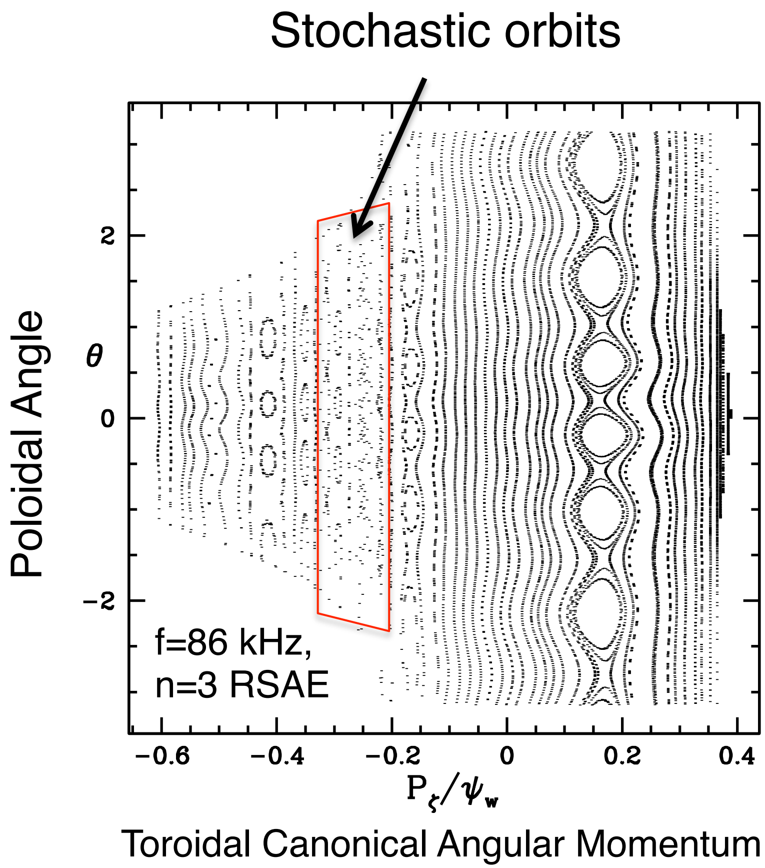


[Cheng, Chang, Phys. Fluids 29 (1986)]

[Van Zeeland, Kramer, Austin *et al.*,PRL 97 (2006)]

Stochasticity is Calculated Using ORBIT

- **ORBIT code determines which portions of fast-ion phase space have orbits that reside in islands or become stochastic due to AE modes.**



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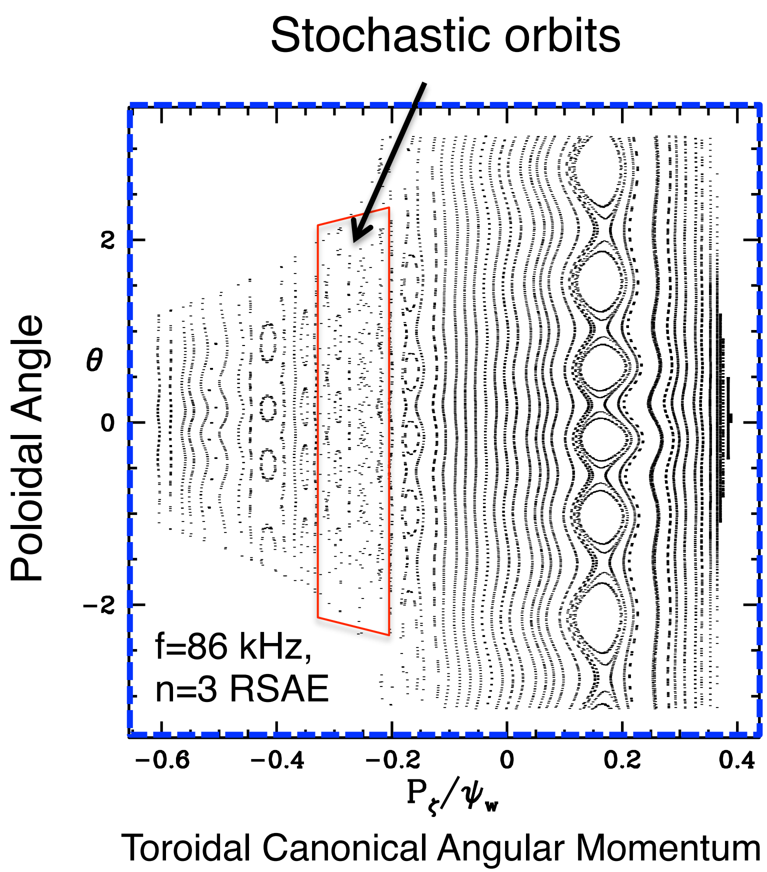
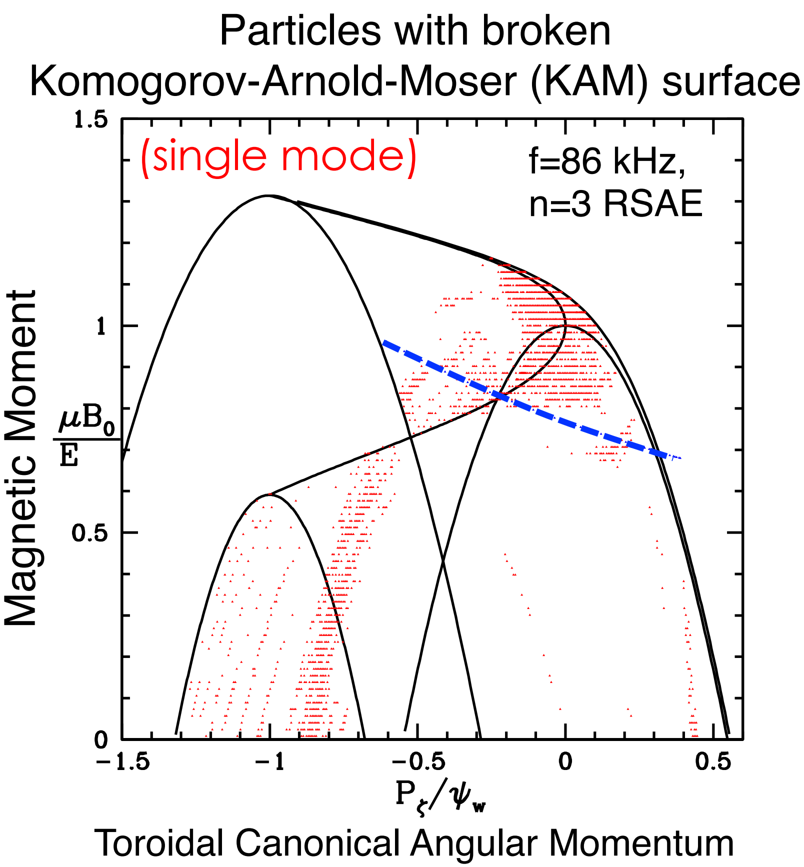
[R. B. White, Com. Nonlin. Sci. Num. Sim. (2012)]

Stochasticity is Calculated Using ORBIT

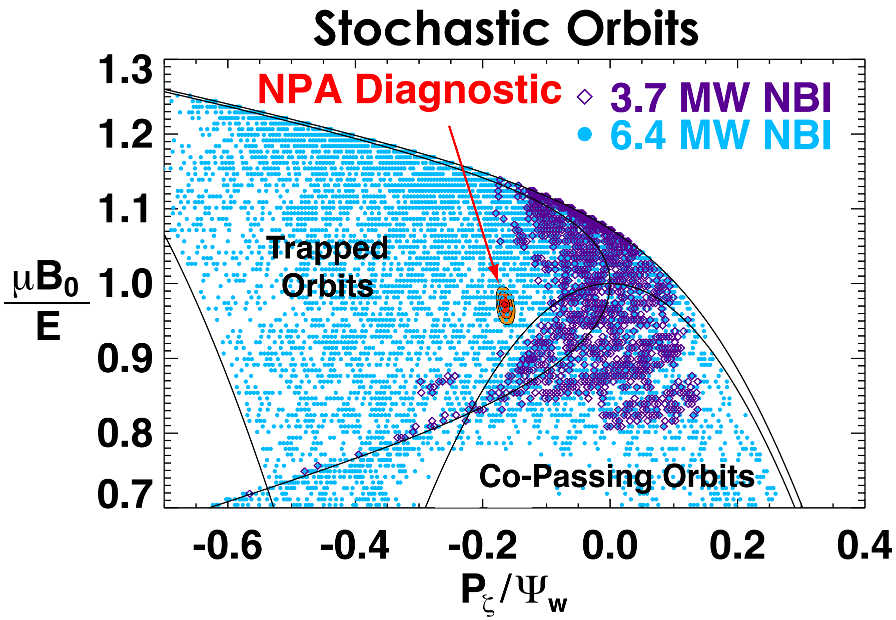
- **ORBIT code determines which portions of fast-ion phase space have orbits that reside in islands or become stochastic due to AE modes.**



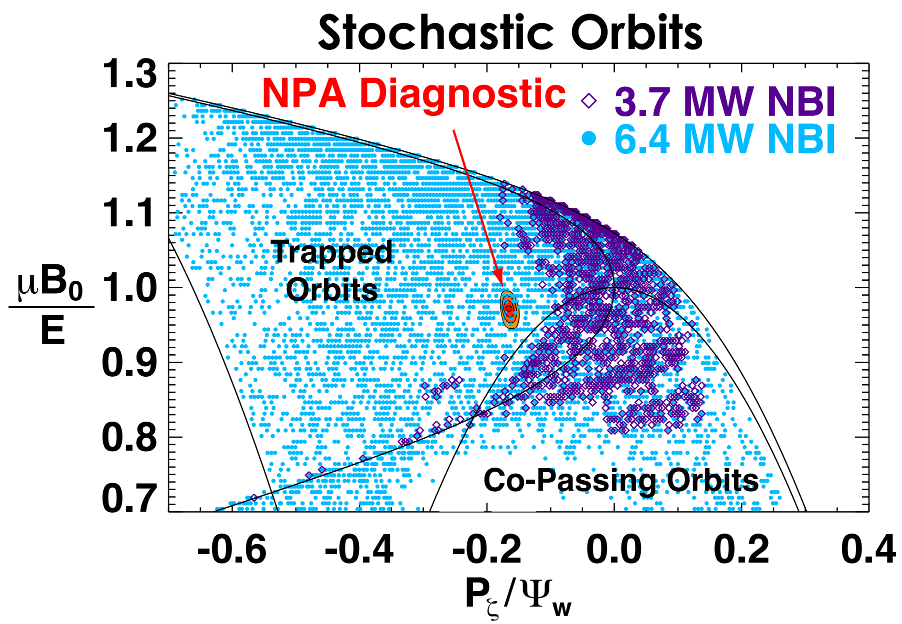


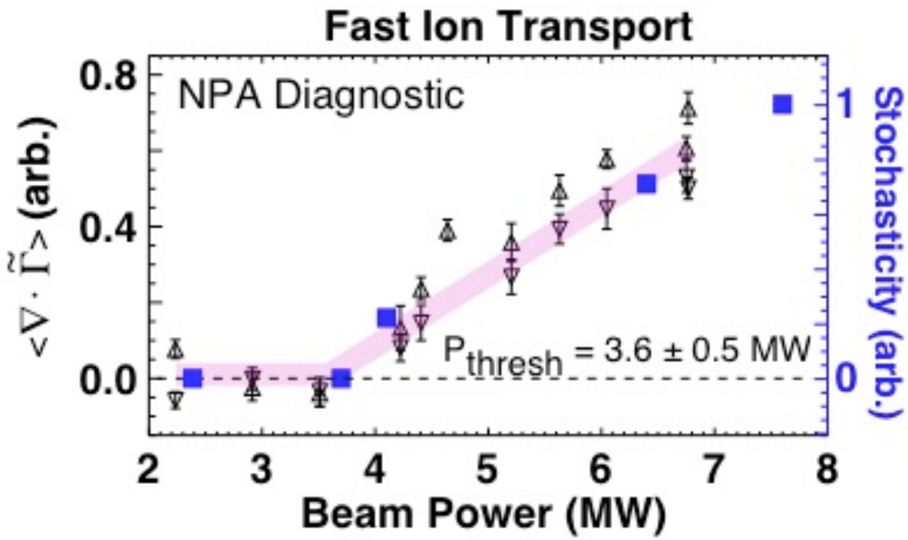
[R. B. White, Com. Nonlin. Sci. Num. Sim. (2012)]

Transport Occurs When Orbits In Diagnostic Sensitive Region Become Stochastic



Transport Occurs When Orbits In Diagnostic Sensitive Region Become Stochastic





- Increase in total number of stochastic orbits in diagnostic region coincides with jump in measured transport.

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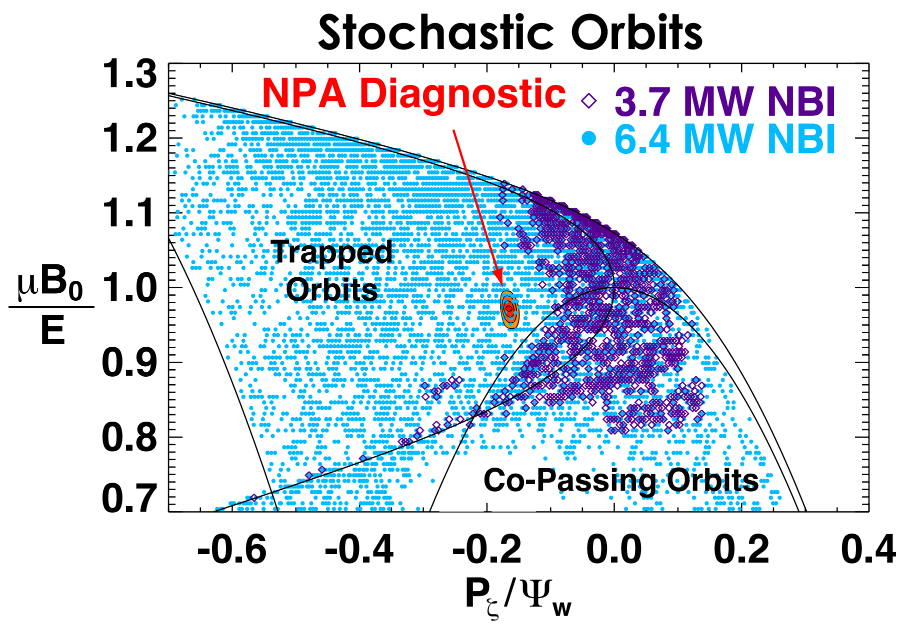
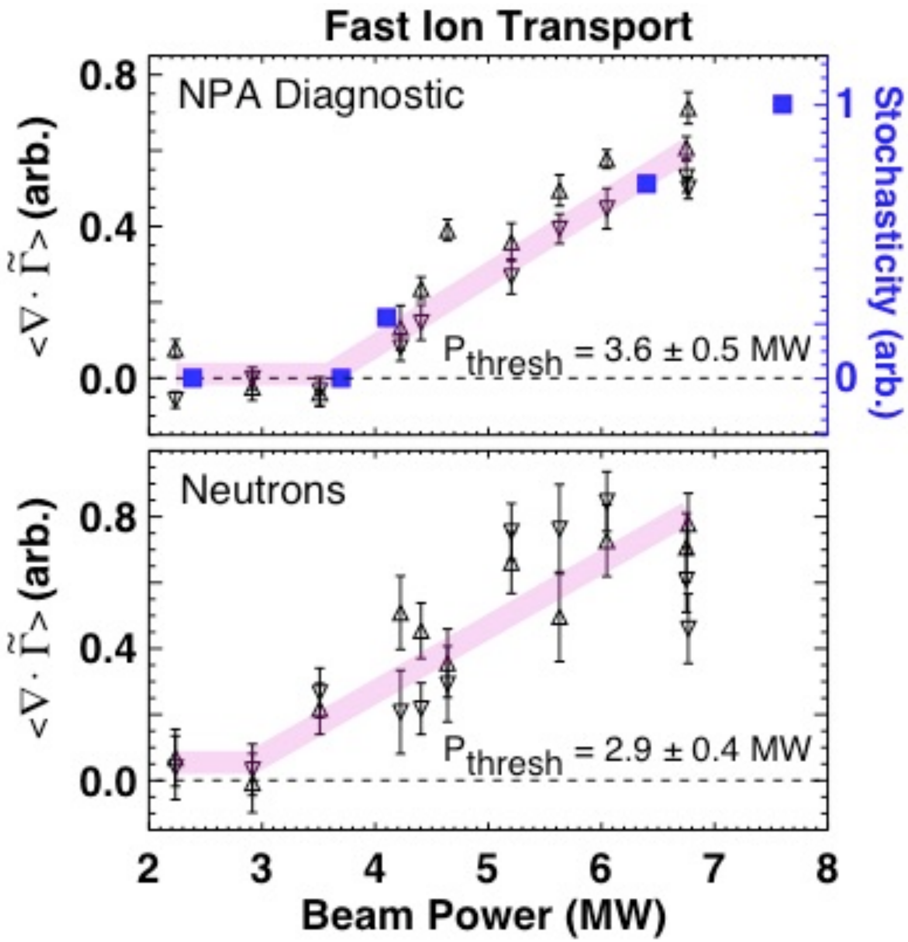
Transport Occurs When Orbits In Diagnostic Sensitive Region Become Stochastic



- Increase in total number of stochastic orbits in diagnostic region coincides with jump in measured transport.

- Diagnostics like neutrons cover entire area of phase space, therefore include more stochasticity.



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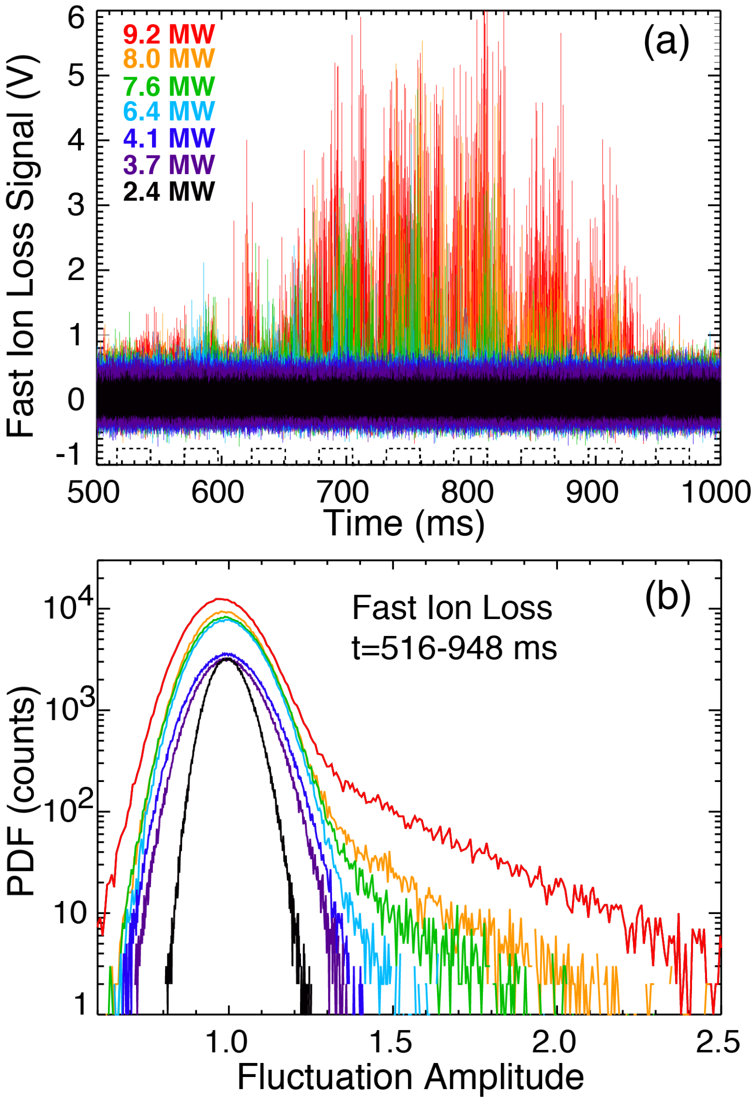
Stiff Transport Causes Bursts of Fast Ion Losses

- In theory, intermittent transport occurs when **overlapping resonances** cause **rapid avalanches** of global redistribution and losses.
- Current critical gradient models **do not account** for this mechanism.
- **ITER must avoid concentrated alpha losses and excessive wall heating.**



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Critical Gradient Transport of Fast Ions Due to Multiple, Overlapping AEs Has Been Observed In DIII-D

1. **Above threshold, fast-ion profiles are clamped and fusion performance is reduced.**
2. **AE-induced transport is a phase-space dependent quantity.**

   -Transport threshold occurs when orbits become stochastic.

   -Transport can be varied by shifting beam deposition to move resonances to different portions of phase space.
3. **Stiff transport causes intermittent losses.**

- **This work provides a basis for understanding how to avoid AE transport in advanced tokamak scenarios.**
  -Some AEs can be tolerated before causing significant transport.
  -Measurements are being used to validate AE-induced transport models for ITER.

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More on Implications for Predicting and Controlling AEs in ITER

R.E. Waltz (TH/P4-14)
A Critical Gradient Model for Energetic Particle Transport from Alfvén Eigenmodes: GYRO Verification, DIII-D Validation, and ITER Projection

G.J. Kramer (TH/P4-5)
Improving Fast-Ion Confinement in High-Performance Discharges by Suppressing Alfvén Eigenmodes

M.A. Van Zeeland (EX/P3-24)
Electron Cyclotron Heating Modification of Alfvén Eigenmode Activity in DIII-D

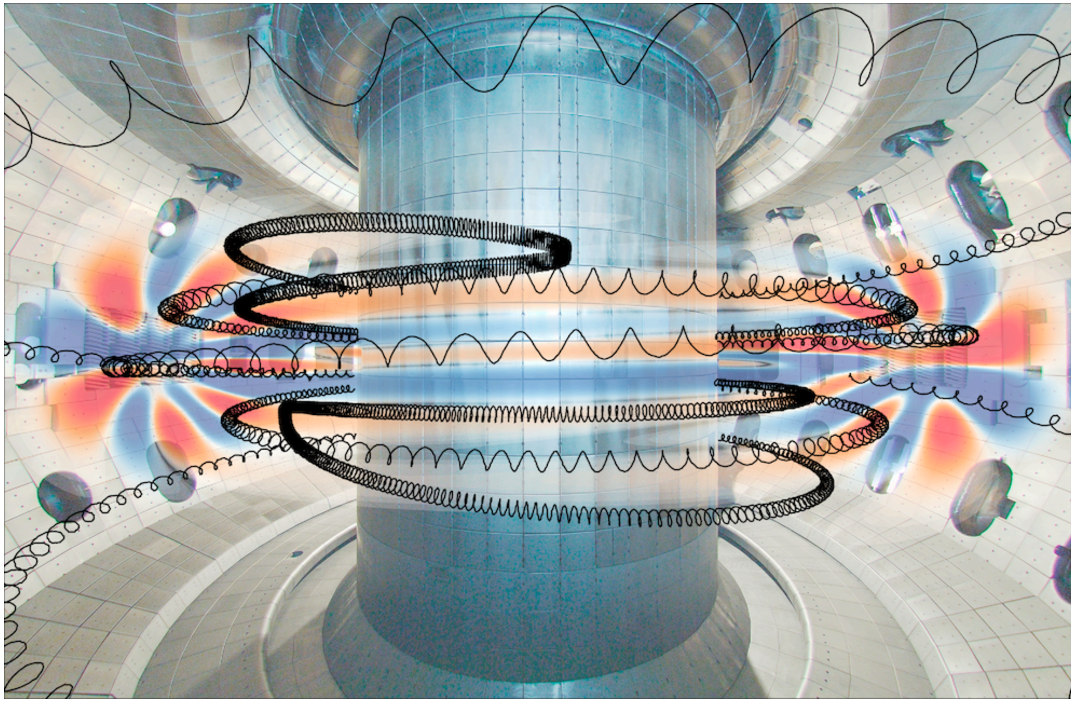

Image credit: Pace et. al.,*Physics Today* (2015)

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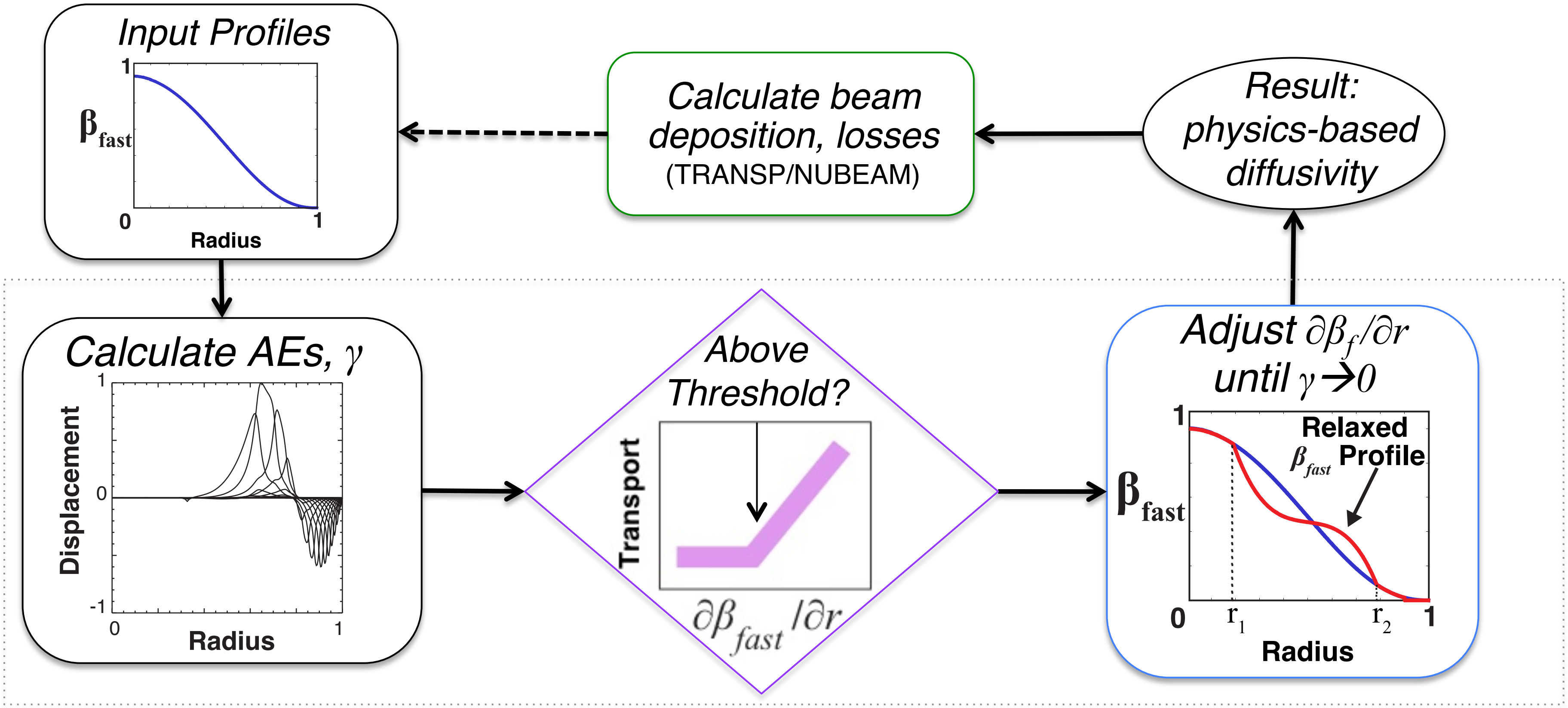
Bonus Slides

Goal: Use Critical Gradient In Reduced Models To Calculate EP Transport & Optimize Scenarios For Future Fusion Reactors

- **Reduced 'critical gradient' models avoid detailed nonlinear calculations of saturated mode amplitudes.**



- **Experiments guide model development:**
  - –When does transport become stiff?
  - –Is an energy-dependent transport calculation necessary?
  - –Does intermittency cause significant transport?

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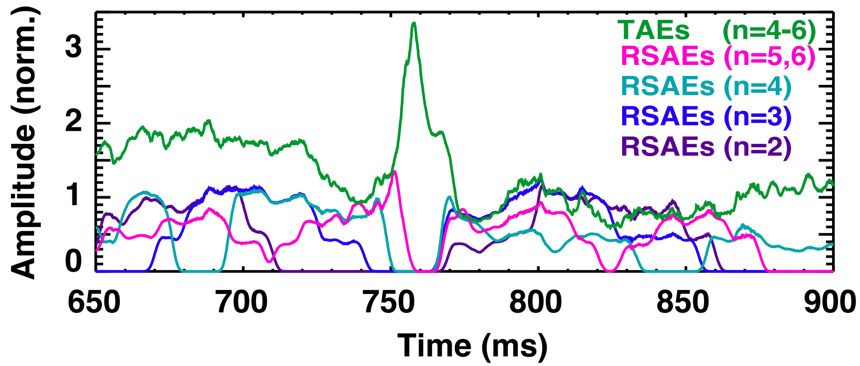
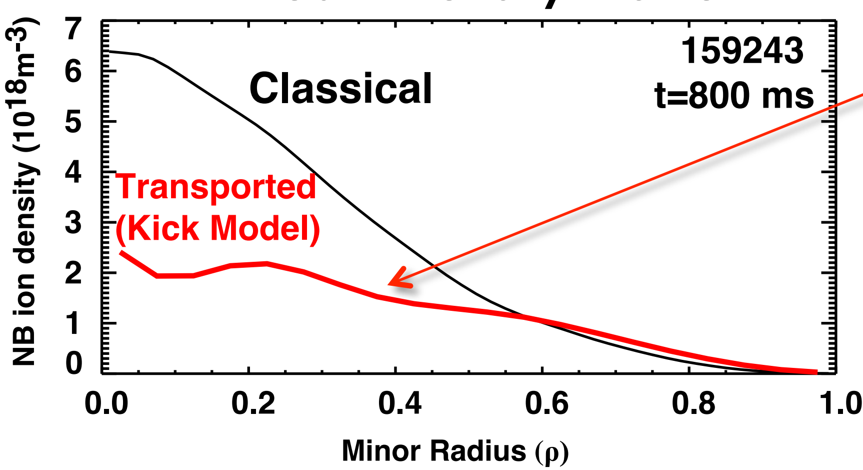
Peak Density Gradient of Kick Model Transported EP Density Profile Agrees with Inferred Value From Experiment

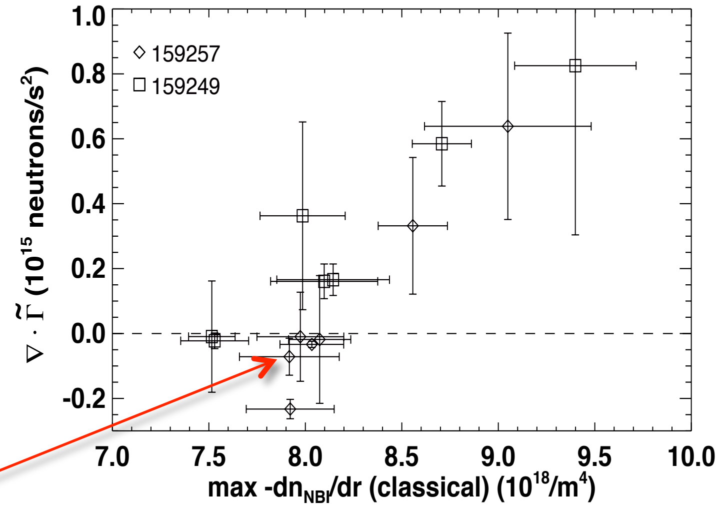
Mode Amplitude Evolution (To Match Measured Neutron Rate)



Beam Density Profile



Measured transport vs. peak classical beam density gradient



- **Peak gradient from model is 8.18×10^{18} m^{-4} ±7%**
- **Future work: implement predictive critical gradient model**

[M. Podestà, PPCF 56 (2014)]