Numerical Studies on Saturated Kink and Sawtooth Induced Fast Ion Transport in JET

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*See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

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Remote

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Distinction Between Resonant vs. Non-Resonant Fast Ion Transport in Kinks and Sawteeth

- Kink modes and sawtooth crashes are ubiquitous in fusion plasmas
  - Sometimes coexist e.g. kinks precursors to ST-crashes
  - Sometimes enforced e.g. induce sawteeth as q-profile constraint

- Competition between resonant and non-resonant energetic particle (EP) transport
  - EP mode-resonant transport with kinks and sawteeth[a-c]
  - EP phase-space redistribution/stochastization[d–e]
  - Dependencies on pitch and energy

[a] *Kolesnichenko Phys. Plasmas 1998*
[b] *Kolesnichenko Nucl. Fusion 2000*
[c] *Farengo Nucl. Fusion 2013*
[d] *Kim Nucl. Fusion 2018*
[e] *Kim Nucl. Fusion 2019*

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  - Dependencies on pitch and energy

1. Which transport process is dominant/how do they differ?
2. Can we experimentally constrain/measure the associated transport?
3. Can we tie experimental EP diagnostics to our integrated modeling?
4. How are different EPs affected (beam vs. fusion, DT-relevant)?

[a] *Kolesnichenko Phys. Plasmas 1998*
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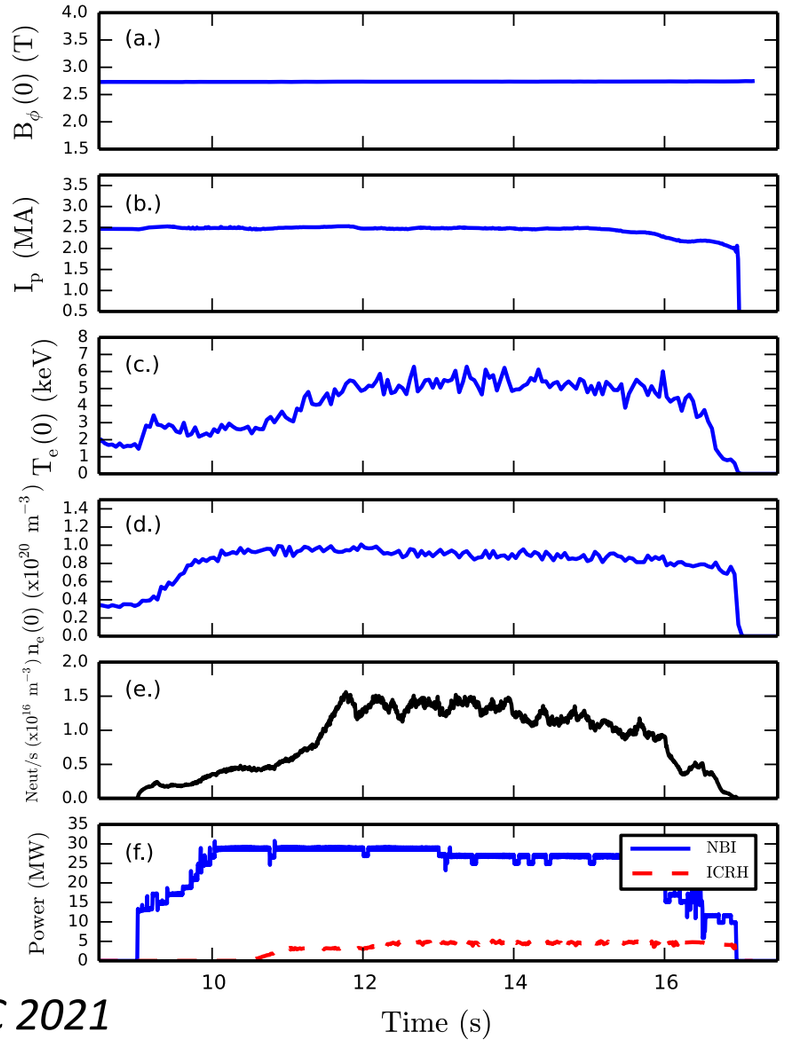
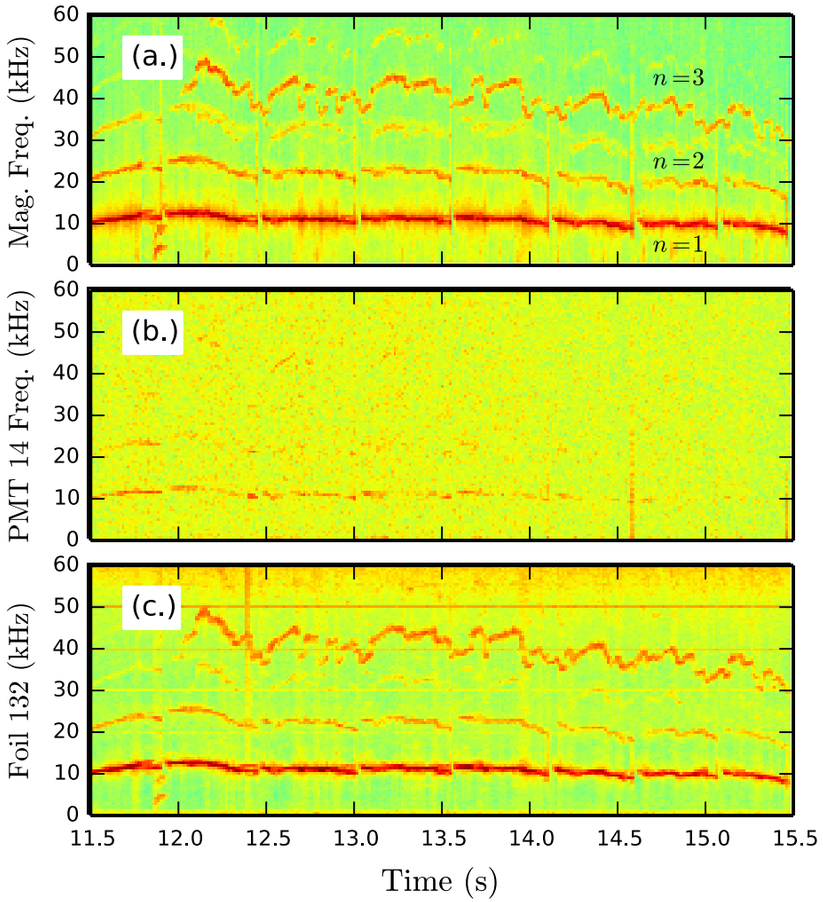
[e] *Kim Nucl. Fusion 2019*

Reference Case: D-Plasma with D-NBI+ICRH and Low Frequency MHD

- Shot: 97493 a JET high performance, Ne seeded, ITER-like discharge[a]
- Heating: 25 MW NBI, 6 MW ICRH
- Fast ions: deuterons, DD-tritons, DD-protons, (minority fraction <1% not focus)
- Long-lived, low freq. modes observed in magnetics, scintillator probe FILD, and Faraday cup FILD
- Intermittent ST-crashes as observed in breaks in the long-lived modes and drops in neutron rate





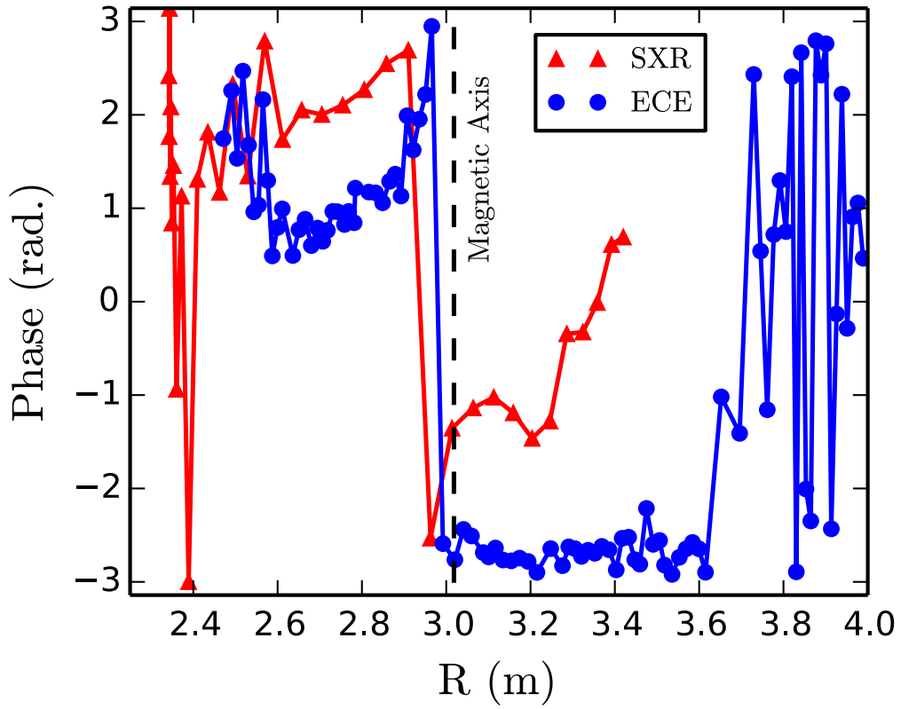
(a.) Magnetic Coil (b.) Scintillator FILD
(c.) Faraday Cup Foil

[a] *Giroud and Brezinsek IAEA-FEC 2021*

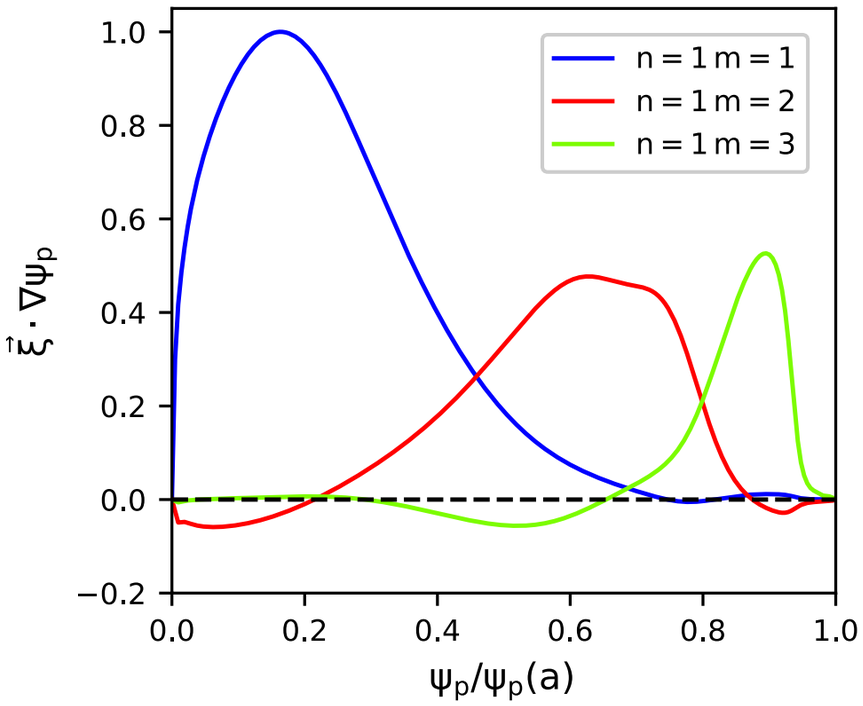
Representative Kink Mode Structure was Found with the NOVA[a] Code

- Mode was identified as a kink mode via EXE and SXR phase inversion, low mode numbers, & sawtooth precursors
- Only the n=1 mode is considered: dominant m=1 with subdominant m=2-3 poloidal harmonics

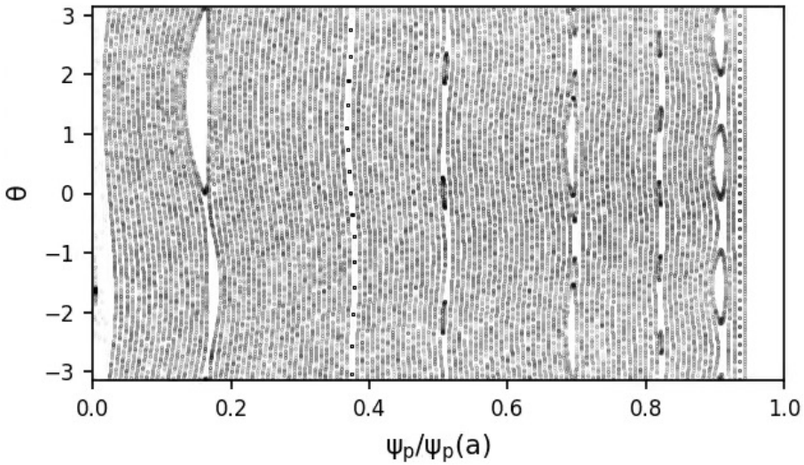
ECE and SXR Phase at n=1 Mode Frequency



Normalized Radial Displacement Vector



Poincaré Plot

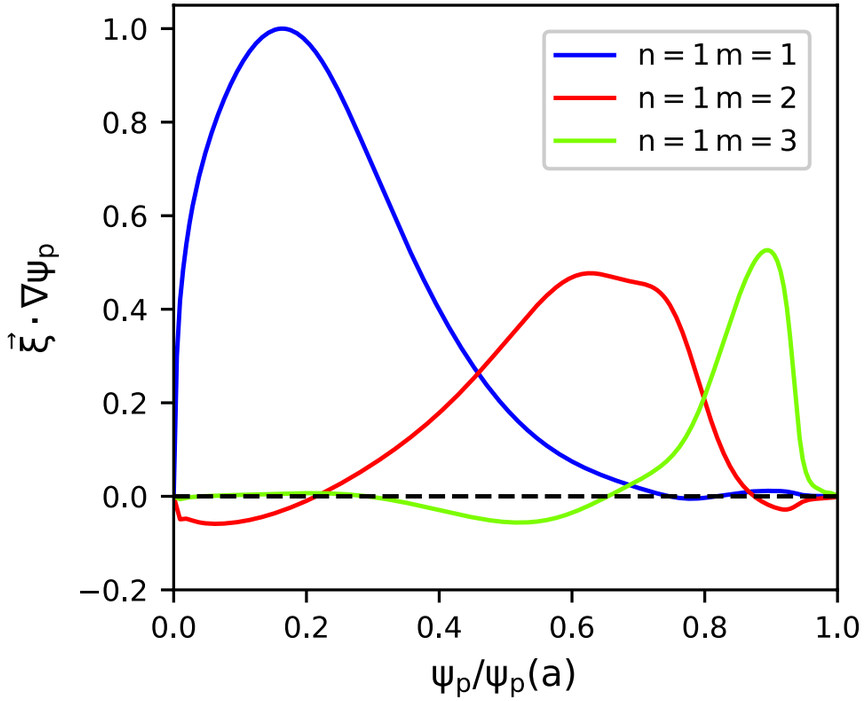


[a]*Cheng Phys. Fluids 1986*

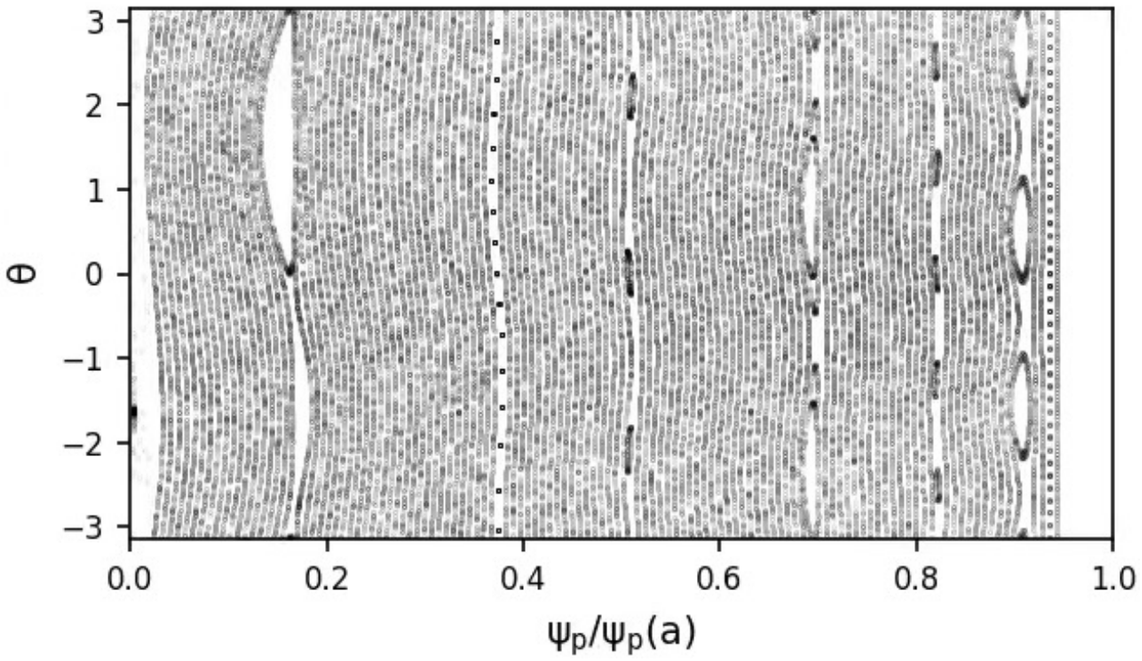
Kink Mode Structure Radially Extends from the Plasma Core to the Edge

- Only the n=1 mode is considered: dominant m=1 with subdominant m=2-3 poloidal harmonics
- m=1 is core-localized, m=2 is mid-radius, and m=3 is near the plasma edge
- Magnetic Poincaré plot made with ORBIT

Normalized Radial Displacement Vector



Poincaré Plot

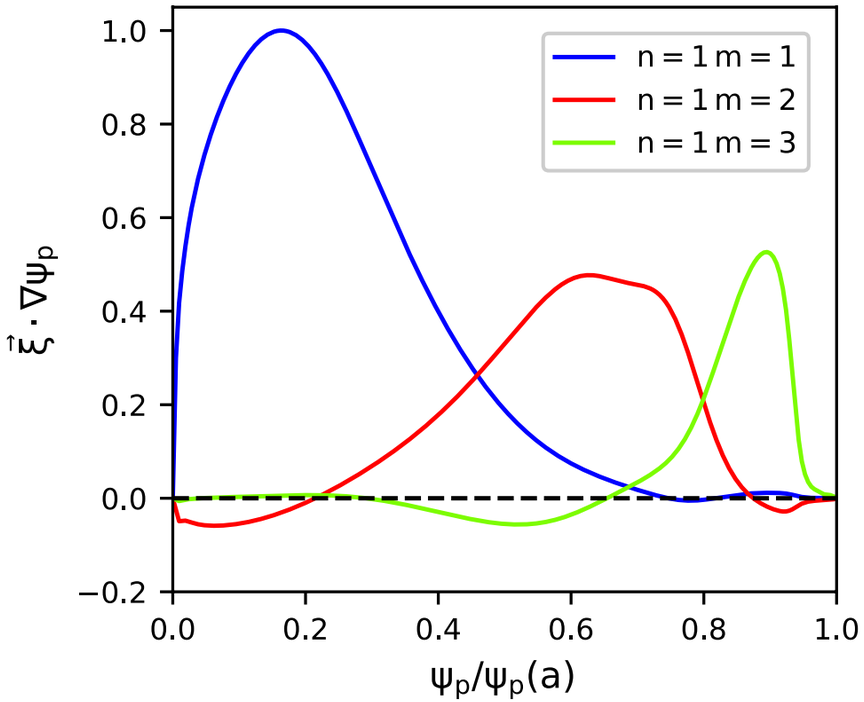


[a]*Cheng Phys. Fluids 1986*

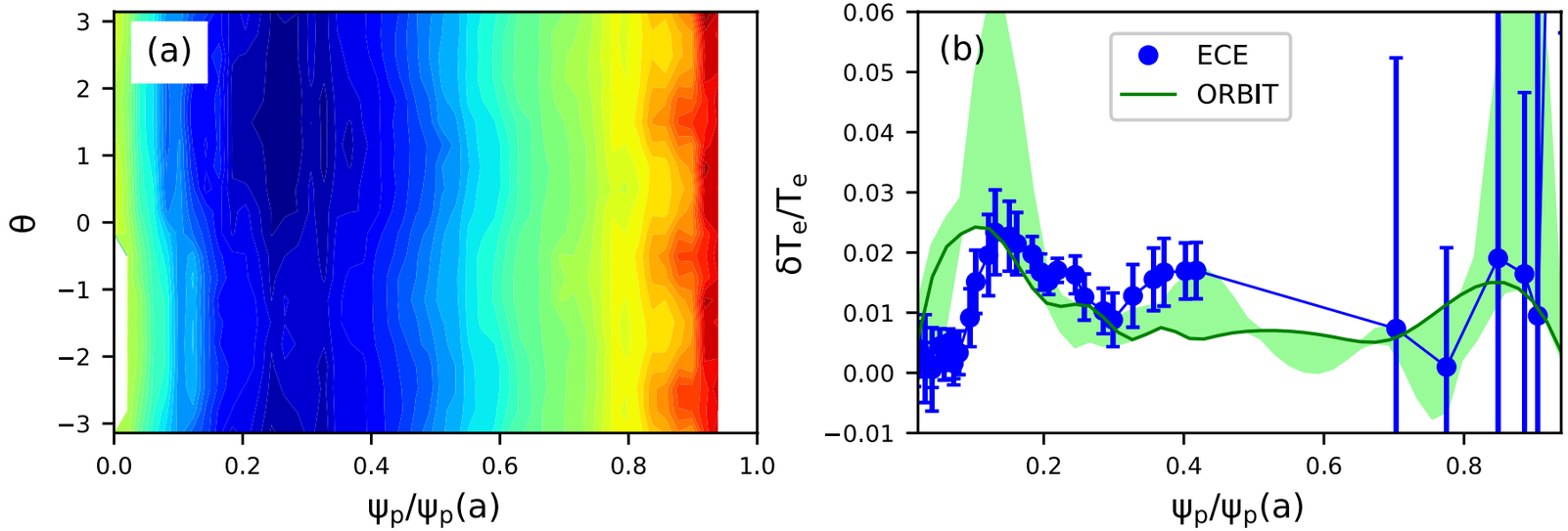
ECE and ORBIT T_e Fluctuations can Constrain Mode Amplitude

- ORBIT calculated T_e fluctuations are found via electron Poincaré mapping in a similar manner to [a,b]
  - Electron position tied to initial T_e profile and motion monitored from supplied mode
- Decent agreement between ORBIT and ECE measurements is found for $\tilde{b}/_{B} \sim 10^{-3}$

Normalized Radial Displacement Vector



T_e Fluctuations from ECE and ORBIT



(a) 2D δT_e fluctuations found in ORBIT from NOVA mode structure
(b) RMS δT_e fluctuations from ORBIT and ECE measurements

[a]*Podestà PPCF Accepted 2021*
[b]*Perez von Thun NuclFus 2010*

JET Maintains an Array of 5 Faraday Cup Fast Ion Loss Detectors[a]

General

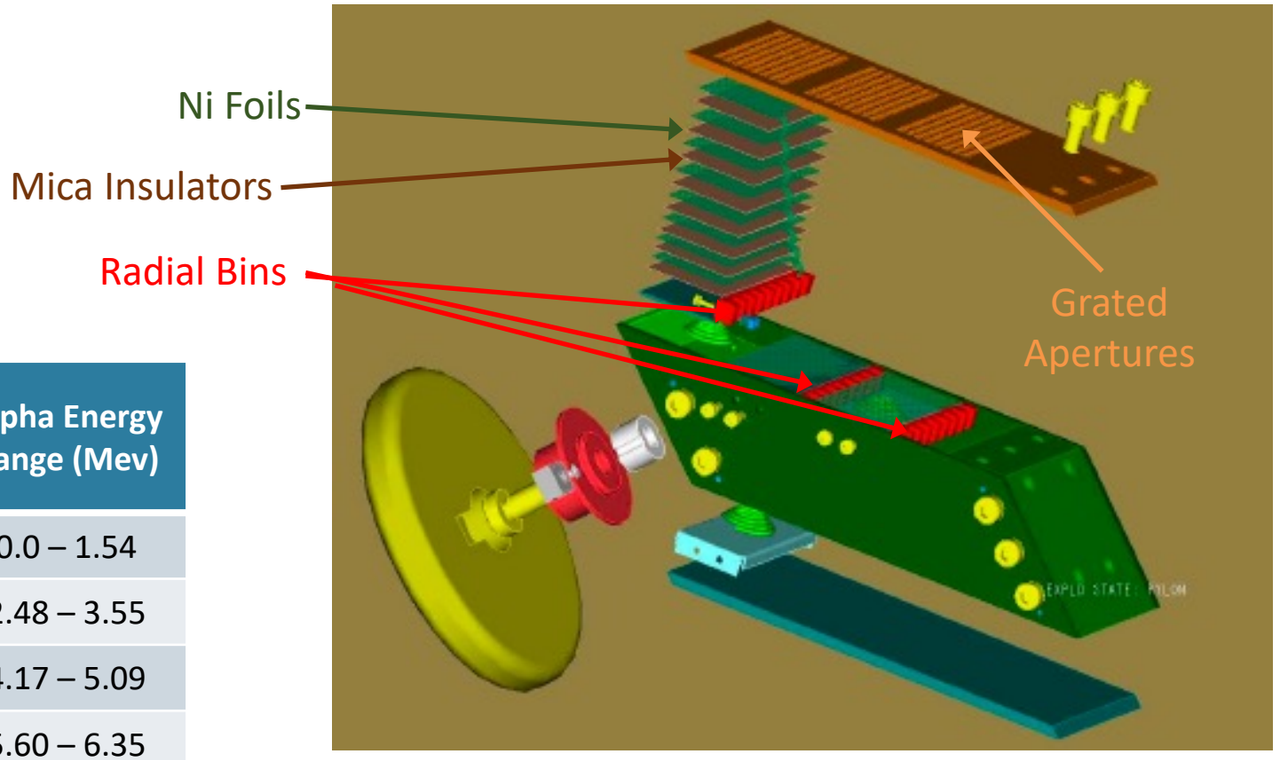
- Foil stacks are alternating layers of Ni and mica
- Ion energy determines deposition depth
  - Sensitive to MeV range ions and low pitch
- Use experimental measurements to verify/validate our quantitative studies

Energy Deposition Range per Foil[†]

Depth (μm)	Proton Energy Range (Mev)	Deuteron Energy Range (Mev)	Triton Energy Range (Mev)	He3 Energy Range (Mev)	Alpha Energy Range (Mev)
0.0 – 2.5	0.0 – 0.49	0.0 – 0.49	0.0 – 0.50	0.0 – 1.55	0.0 – 1.54
5.0 – 7.5	0.68 – 0.96	0.79 – 1.10	0.84 – 1.20	2.30 – 3.35	2.48 – 3.55
10.0 – 12.5	1.10 – 1.32	1.35 – 1.60	1.48 – 1.76	3.90 – 4.70	4.17 – 5.09
15.0 – 17.5	1.45 – 1.65	1.78 – 2.00	2.00 – 2.25	5.20 – 5.80	5.60 – 6.35

[†]*Found via SRIM code*

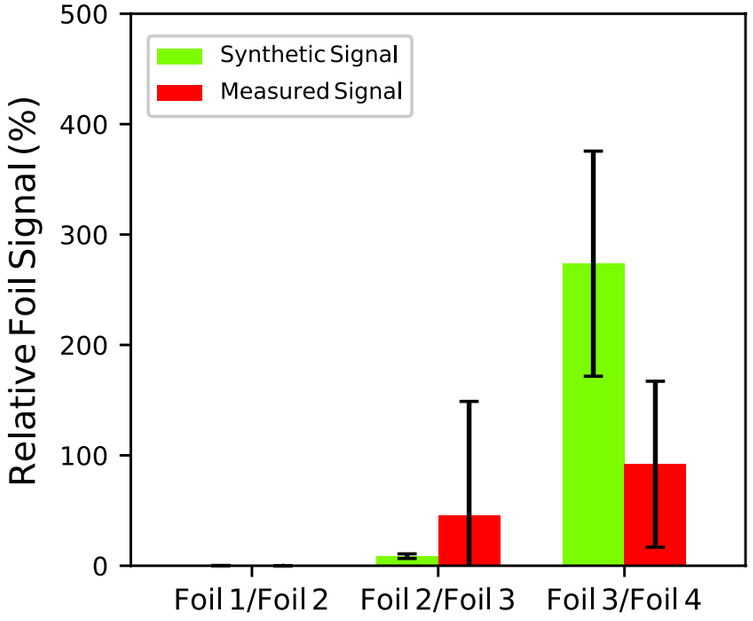
Faraday Cup Assembly (Old 8-stack Design)



[a]*Darrow RSI 2004, 2006, 2010*

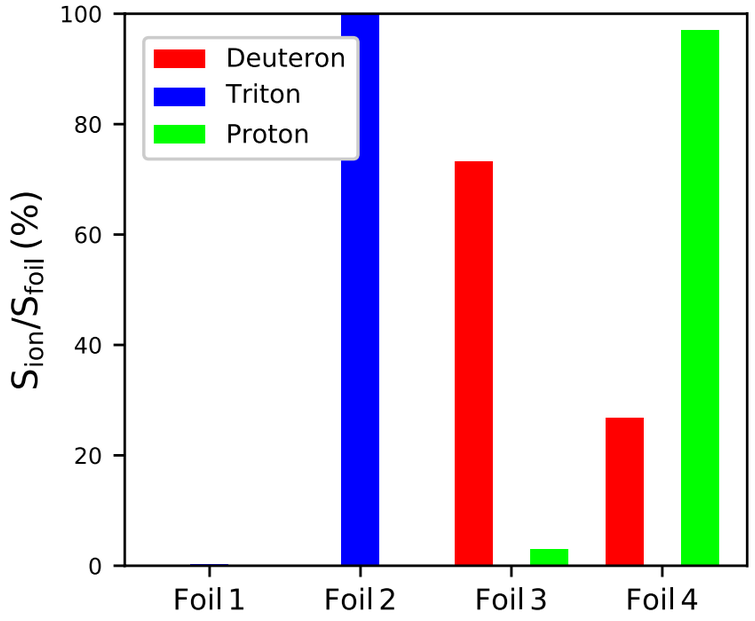
A Synthetic Fast Ion Loss Model[a] Validates Experimental Measurements

Comparison of Synthetic Loss Model and Measurement



- Ratio of signals compared due to lack of absolute calibration
- Foil 1 discarded due to capacitive plasma pickup in experiment[b]
- Model lower energy limit taken as 150 keV

Distribution of Synthetic Lost Ion Signals Across Foils

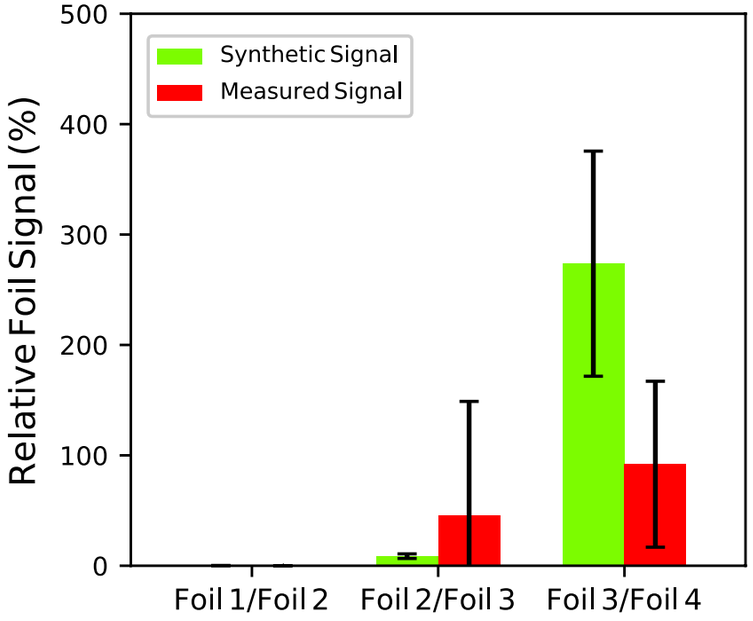


- Deuteron component of the signal dominates each respective foil measurement because $n_{NBI} \gg n_{fus}$ (marker weights)
- DD-triton birth energy lies in Foil 2; DD-proton birth energy >> Foil 4
- Very useful information for multi-ion species plasmas such as DT-ops

[a]Bonofiglo NuclFus Submitted 2021 [b]Bonofiglo RSI 2020

A Synthetic Fast Ion Loss Model[a] Validates Experimental Measurements

Comparison of Synthetic Loss Model and Measurement



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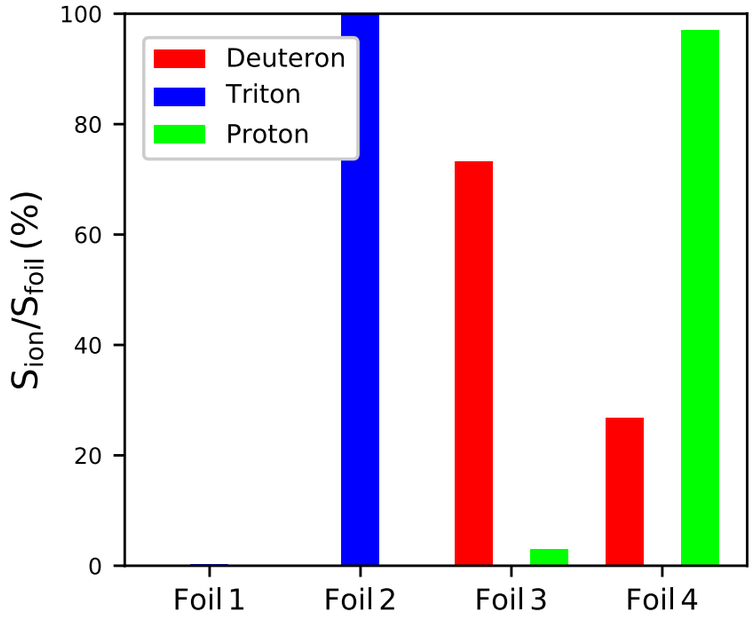


Integrated EP Transport Model is Now Constrained/Verified Against Measured Losses

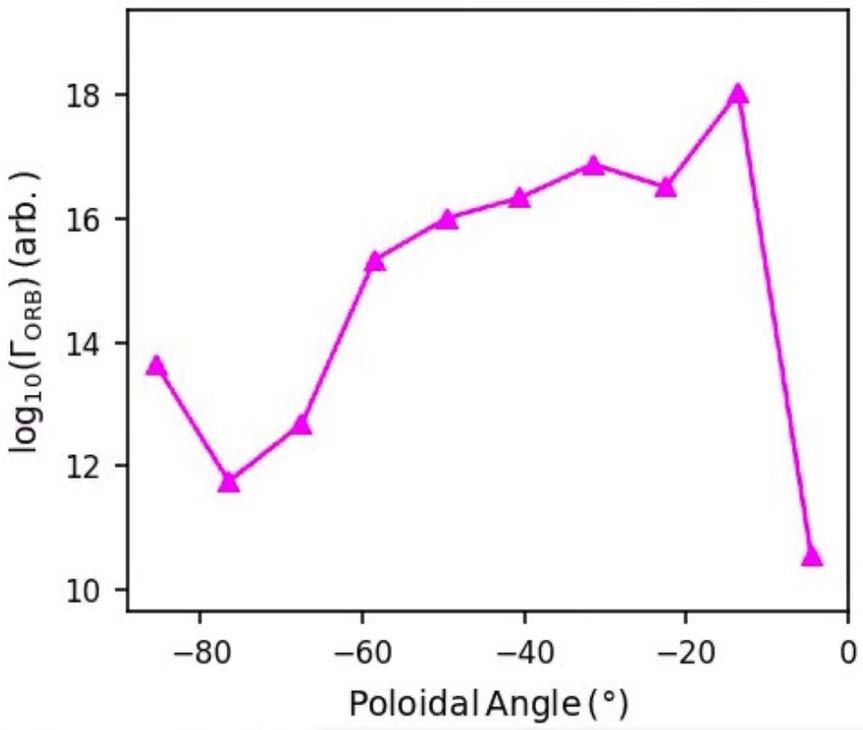
- Model confirms mode amplitude and structure
- Very useful information for multi-ion species plasmas such as DT-ops
- Foil 1 signal absent in model? → Physical difference for lower energy particles?

[a]Bonofiglo NuclFus Submitted 2021 [b]Bonofiglo RSI 2020

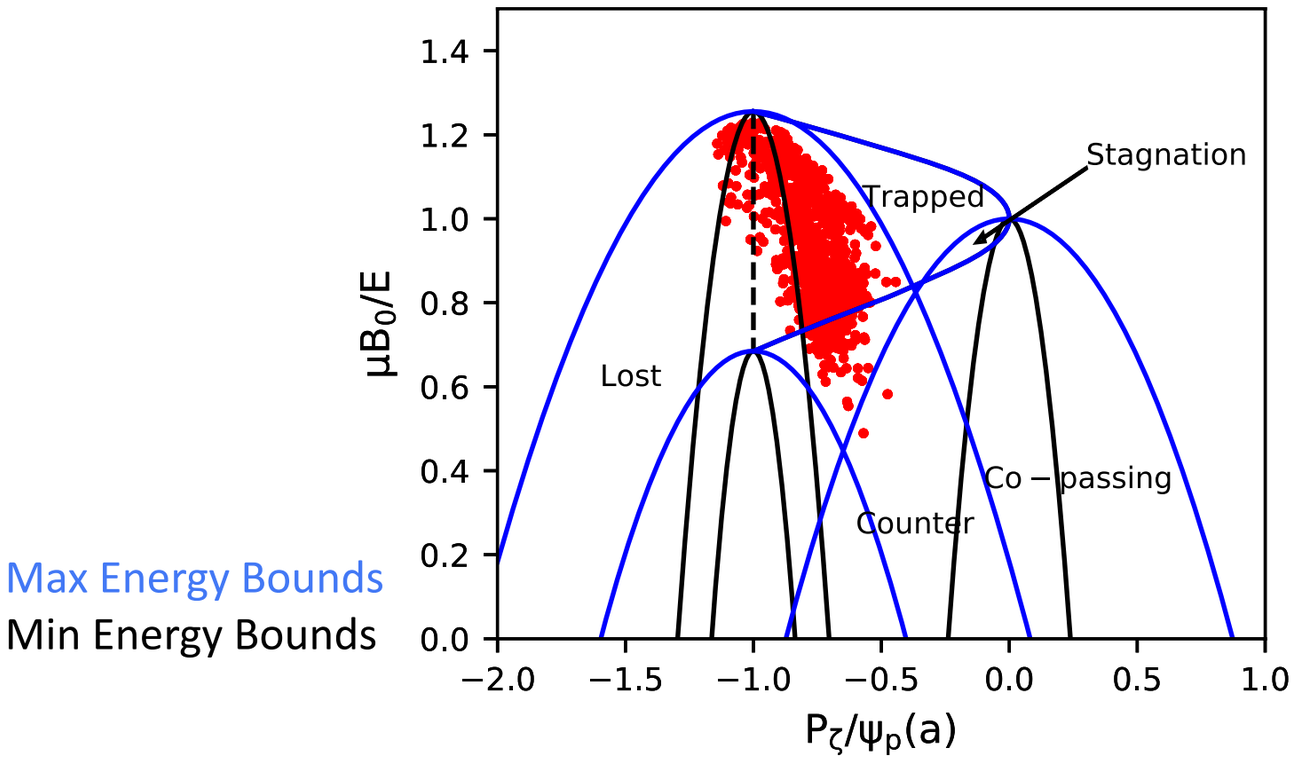
The Validated Loss Model can Give Additional Information on EP Transport Absent in Experiment

- Spatial sensitivity of losses: larger near the midplane and reduce near the divertor region
- Most detector sensitive losses occur from counter-passing and trapped orbits
  - Predominantly from mid-radius to the edge plasma region

Poloidal Dependence of Lost EP Flux

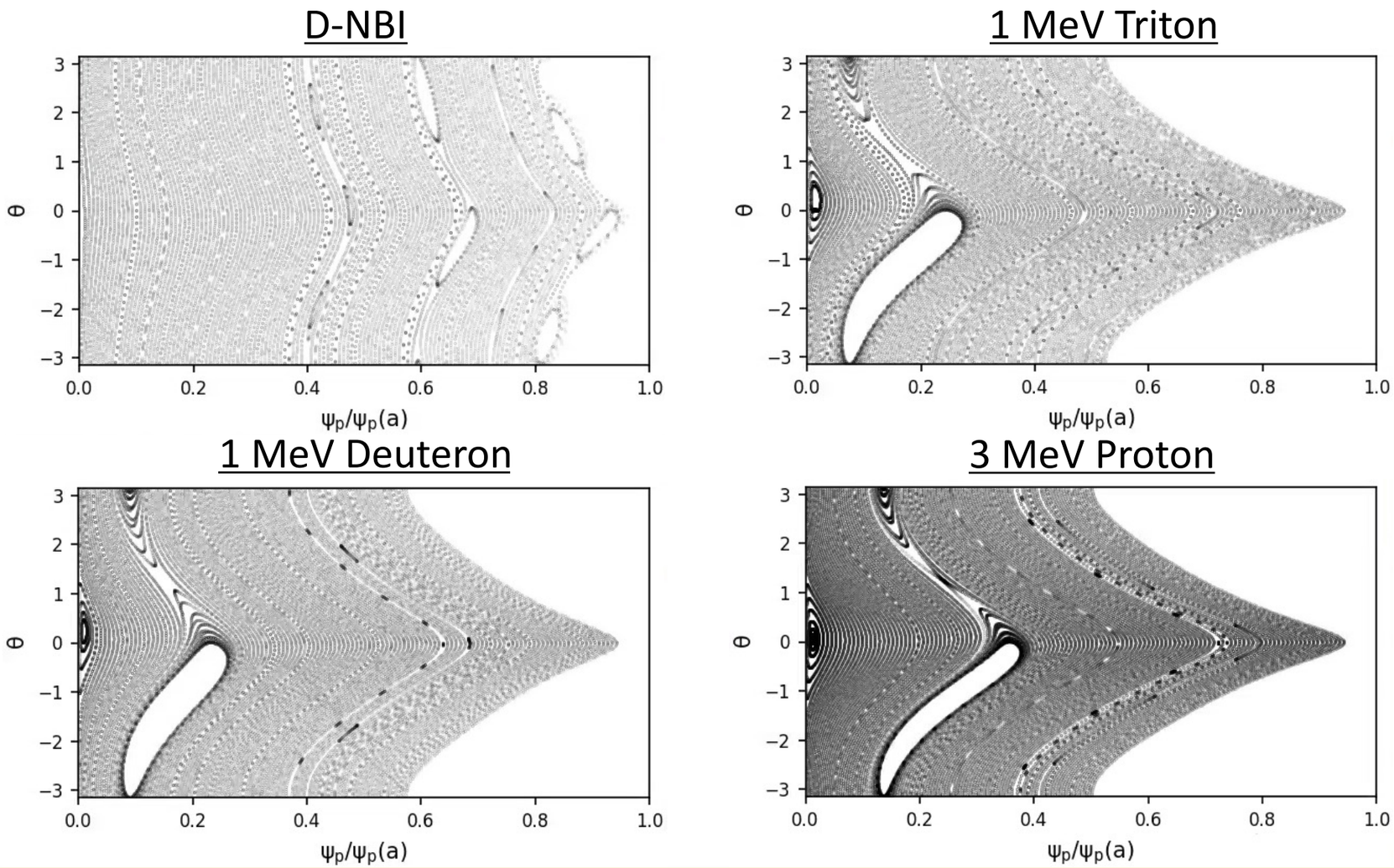


Initial Loss Orbits



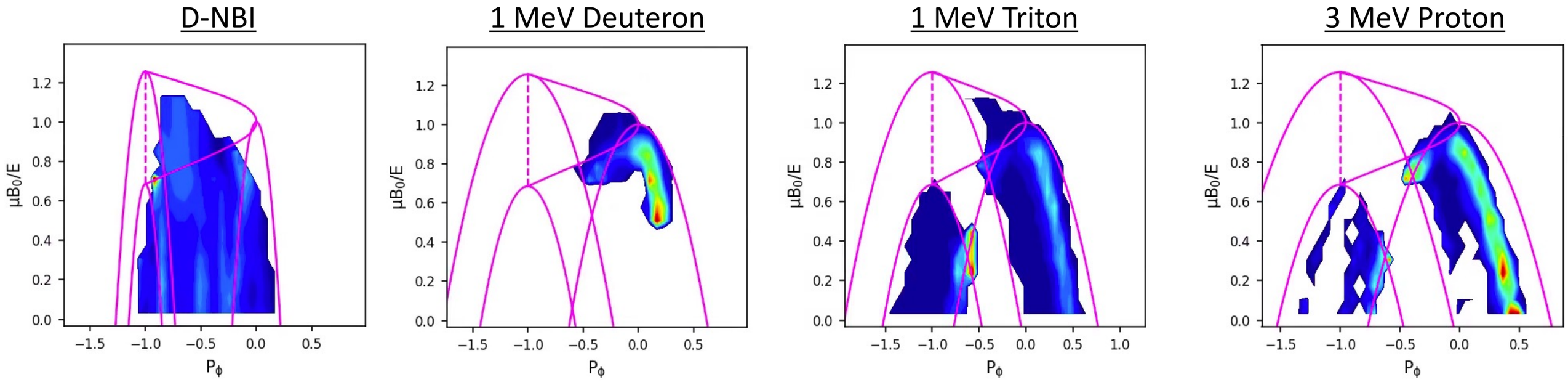
Saturated Kink has Stronger Affect on Higher Energy Particles

- Using mode structure and amplitude validated with loss model
- Kinetic Poincaré visualize fast ion resonances with the kink mode
- Beam-born ions are unaffected near the core
- RF-heated deuterons and fusion products feel strong effect from m=1 component
- All plots taken at $^{\mu B_0}/_{E} = 0.7$



Wave-Particle Interactions are Stronger for Fusion Products and RF-Tail Populations

- Resonances calculated from ORBIT-kick code[a] from TRANSP/NUBEAM[b] fast ion distribution
- Fusion products and high energy deuterons have stronger resonances
- Beam+slowing population resonances cover a larger area in fast ion phase-space but are much weaker
- Most effected population are co-passing ions near the core with middling interactions of trapped, stagnation, and counter-passing orbits

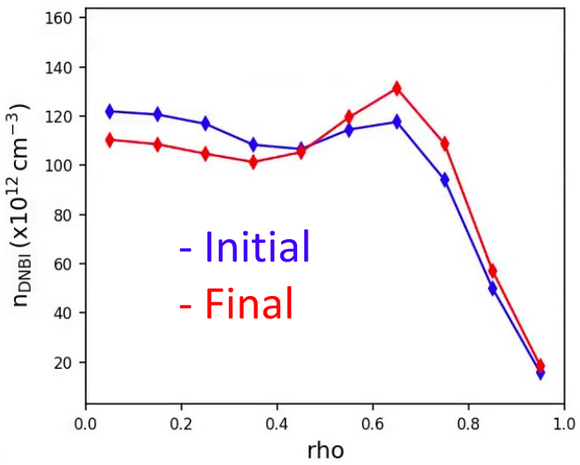


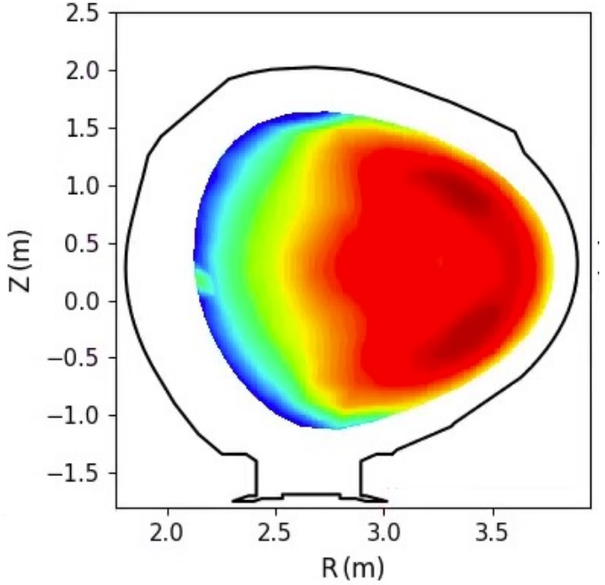
[a]Podestà PPCF 2014, 2017 [b]doi:10.11578/dc.20180627.4

High Edge Density Produces Broad Beam-Born Distribution

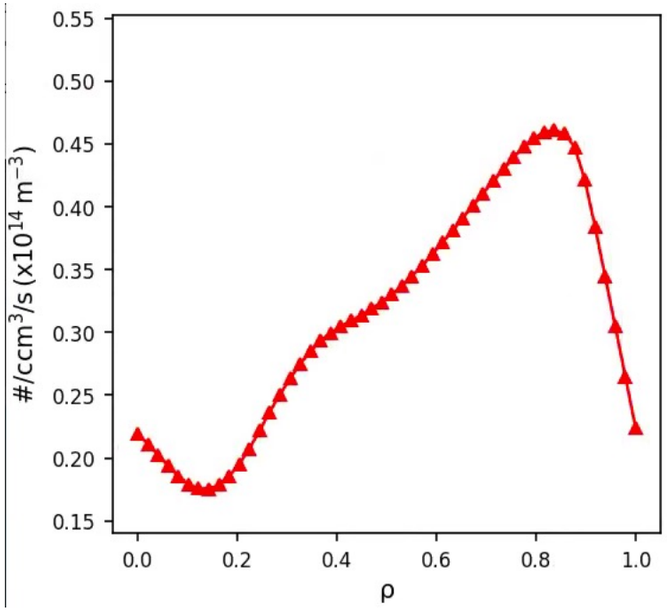
- High edge density produces a broad, and somewhat hollow, deuteron distribution as NBI deposition occurs mainly near the edge (as well as the off-axis RF-resonance) near the m=2-3 components
- Beam-born ions experience edge transport/losses with minor core-localized transport

Deuteron Distribution

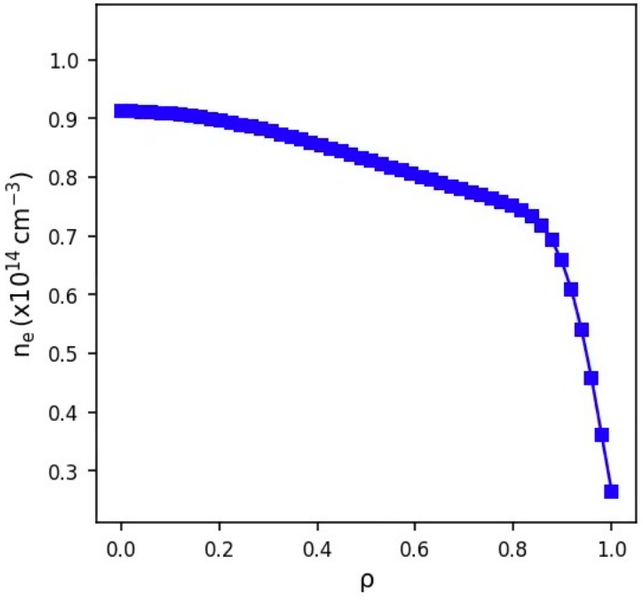




NB Deposition- TRANSP



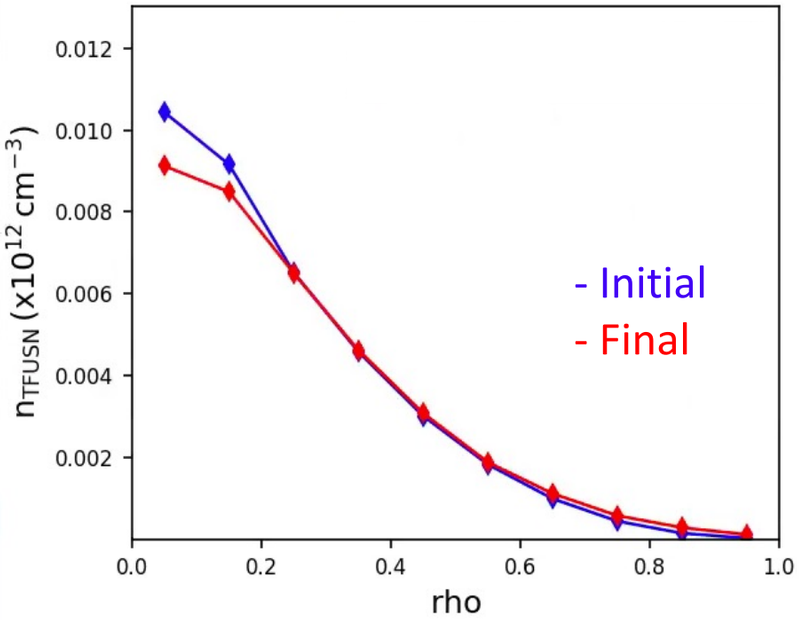
Electron Density - TRANSP



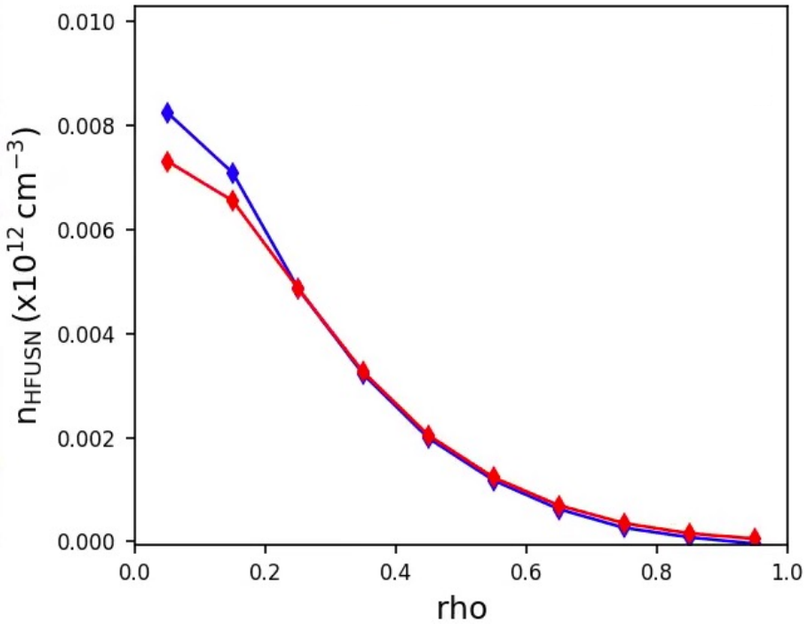
Fusion Products are Core-Peaked and Experience More Transport

- Fusion products are core-localized and subject to the effects of the stronger m=1 component
- Consistent with Poincaré plots shown earlier
- Explains why synthetic loss model observed no losses to front most foil (lowest energies)

Triton Distributon



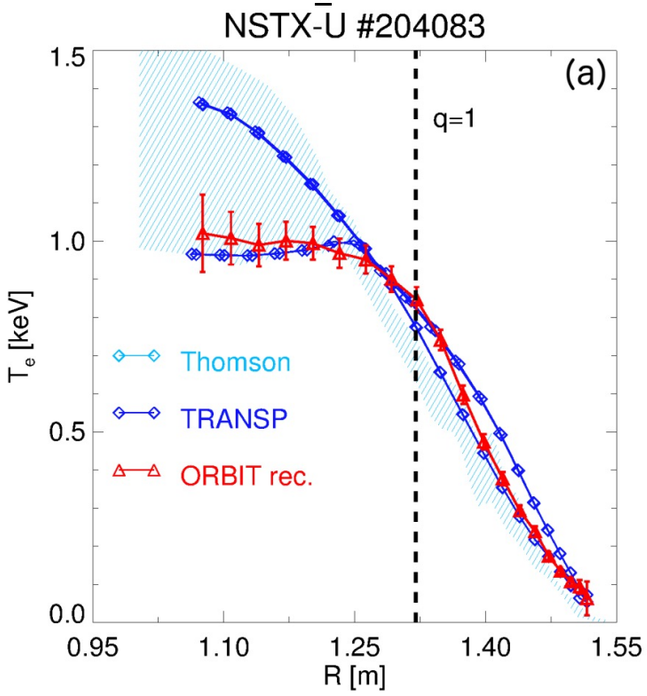
Proton Distribution



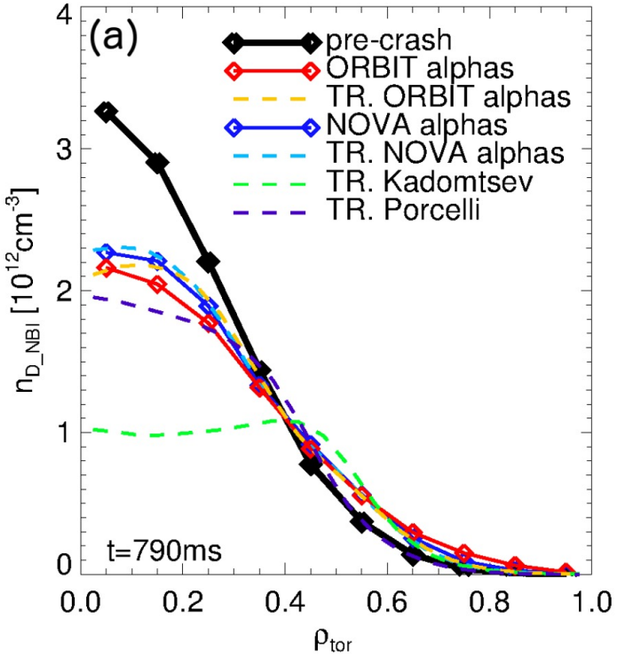
A Reduced Model for Sawtooth Induced EP Transport[a] has been Recently Tested on NSTX-U

- Uses an analytic representation for the mode structure (good agreement with NOVA for NSTX-U case)
- Mode amplitude is varied in time as an exponential growth followed by a rapid decay
- Peak mode amplitude is found when electrons from q=1 mix to the core[b] e.g. full reconnection in Kadomtsev
- In good agreement with NSTX-U discharge

Core T_e Flattening



Core EP Transport

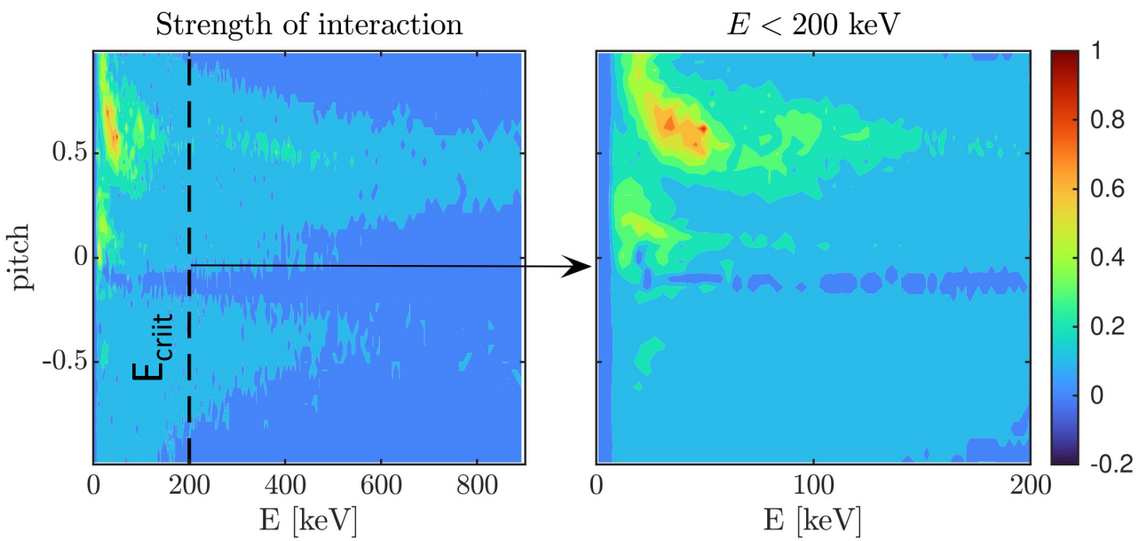


[a]*Podestà PPCF Accepted 2021*
[b]*Perez von Thun NuclFus 2010*

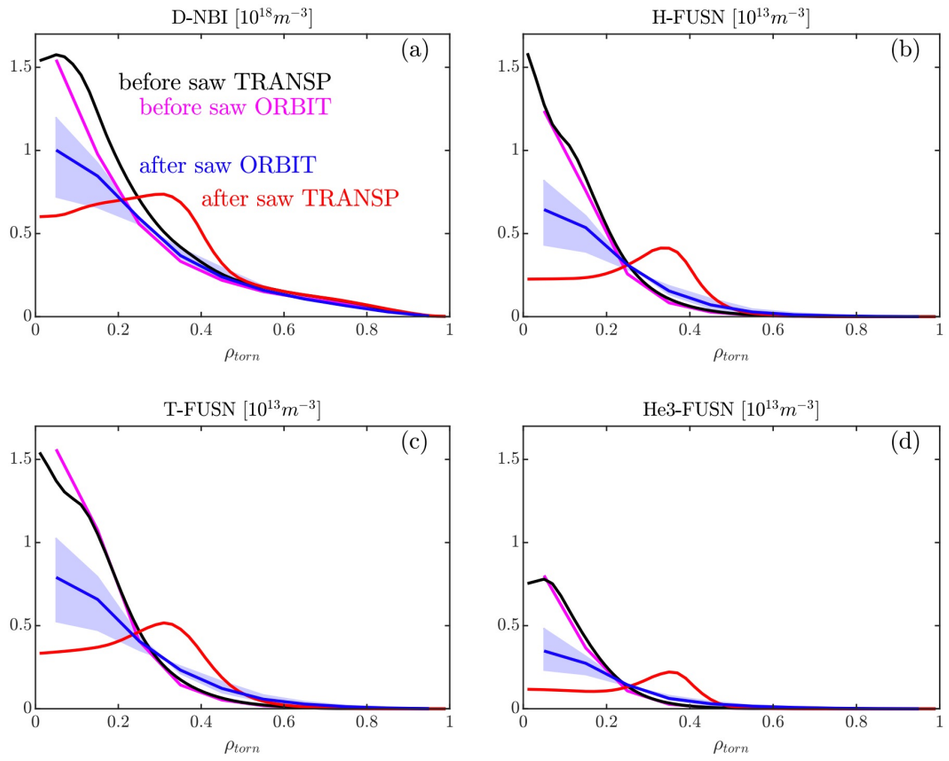
Recent JET Analysis[a] Shows Resonant Transport with $E>E_{crit}$ for Sawtooth is Important

- Comparisons among TRANSP and ORBIT altered fast ion distributions show that EP transport extends beyond the standard Kadomtsev model within TRANSP
- Differences between resonant and non-resonant transport observed in beam(+RF) and fusion products in energy and radial coordinates

Resonant Intereaction Strength



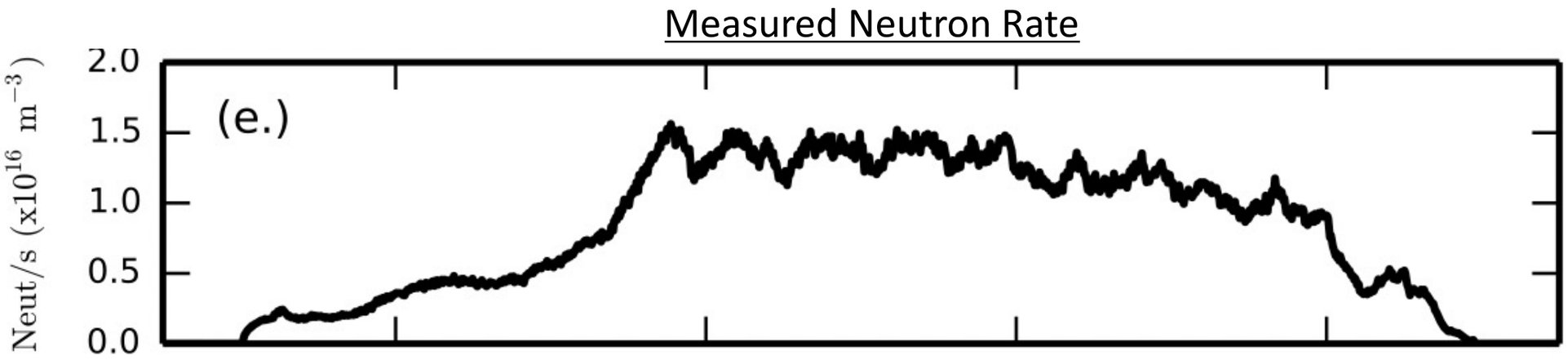
Change in EP Profiles



[a]*Teplukhina Nucl. Fusion 2021*

Sawtooth Induced Fast Ion Transport is Readily Implied by Drops in the JET Measured Neutron Rate

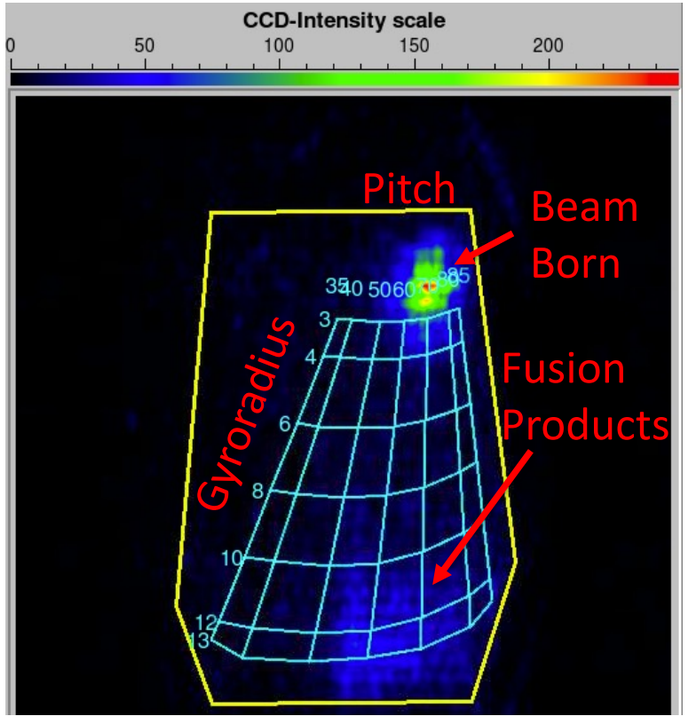
- Neutron rate is dominated by beam-thermal interactions:
  - Drops in neutron can be attributed to thermal and EP redistribution (can confirm with EP loss measurements)
  - Fusion product vs. beam-born ion associated transport → Energy dependence?



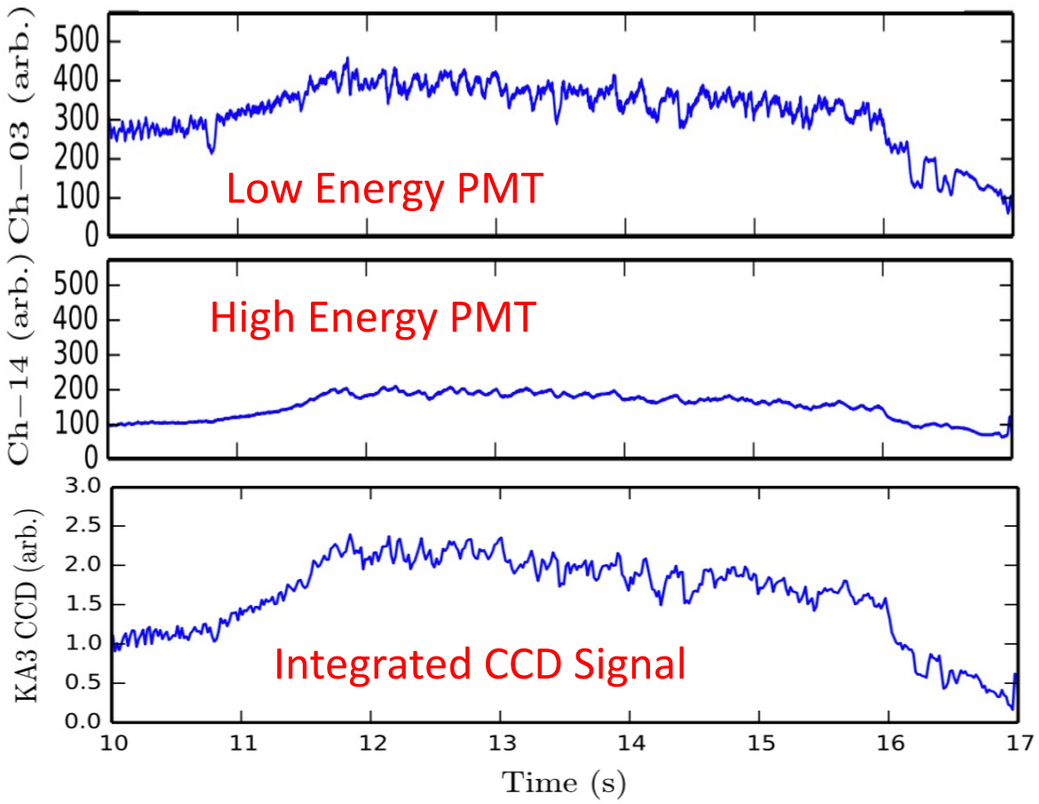
JET FILD Measured Sawtooth Losses are Dominated by Lower Energy (NBI-born) Particles

- Scintillator FILD losses show strong beam-born ions on edge of CCD along with weak fusion product losses in a time immediately after a ST-crash
- Faraday cup beam-born losses are inconclusive due to plasma pickup noise

Scintillator Probe Signal Post ST-Crash



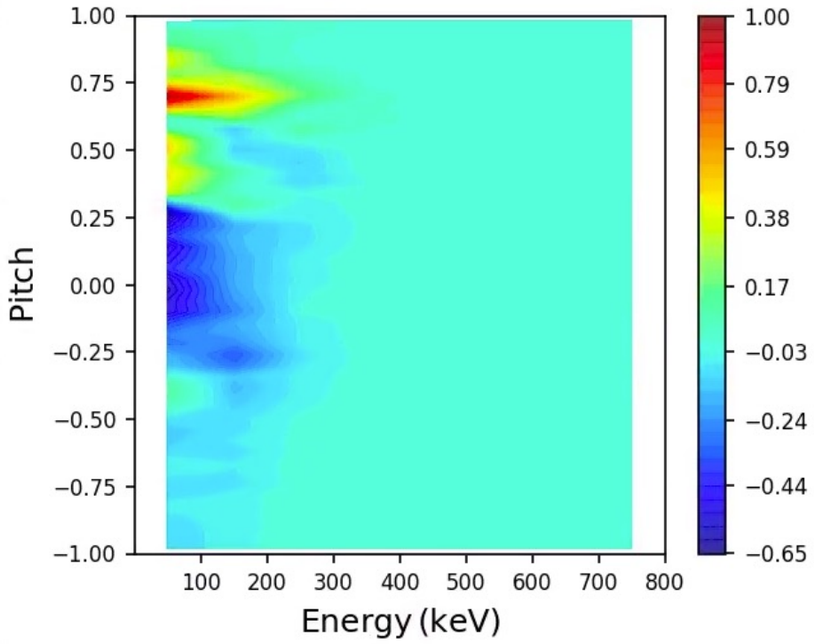
PMT and CCD Signals



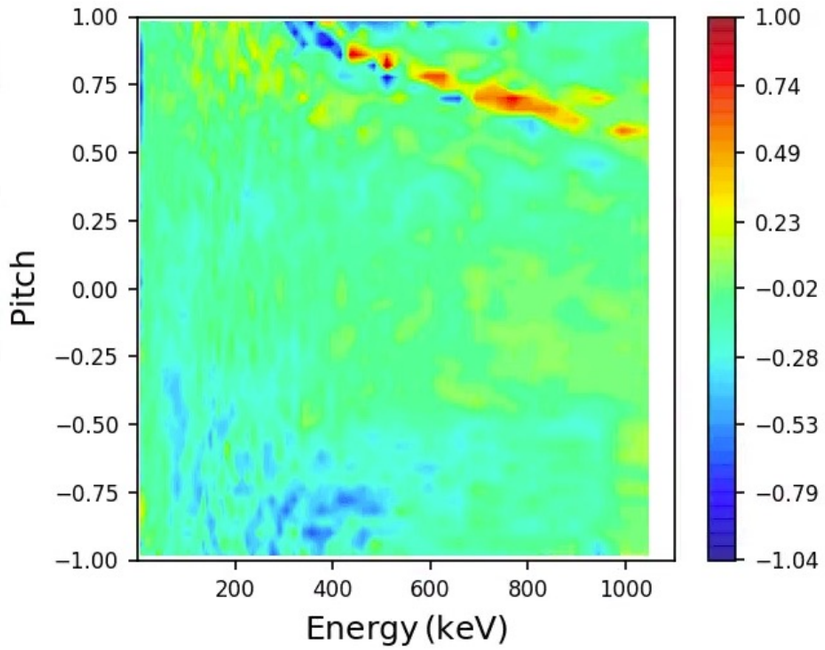
ORBIT Calculated EP Distribution Changes Show Interaction at High Energies and Pitch

- Redistribution observed in pitch and energy → Bigger at lower energies for beam-born particles
- Extends to high energies above typical critical energy (~200-300 keV)
- Consistent with A. A. Teplulkhina *et al.* shown on slide 17

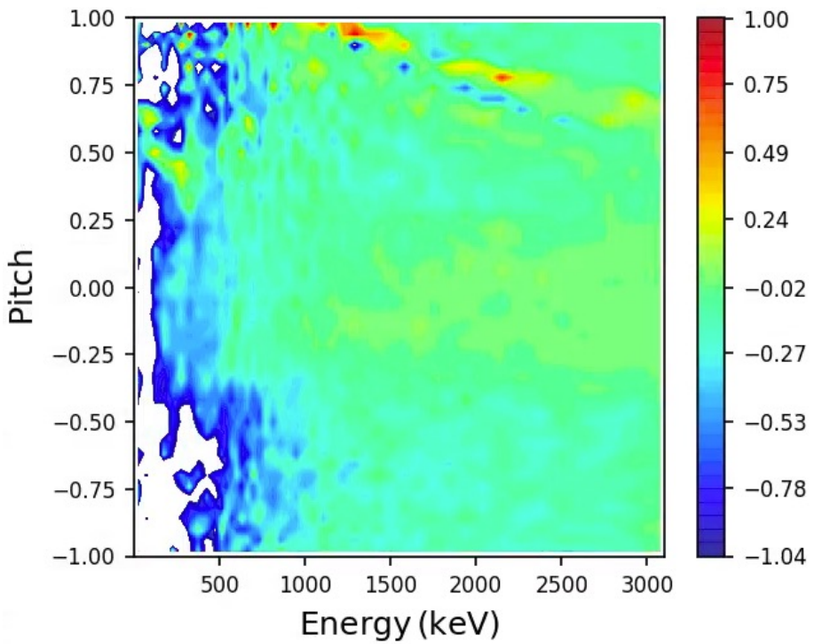
Change in Deut. Dist



Change in Trit. Dist



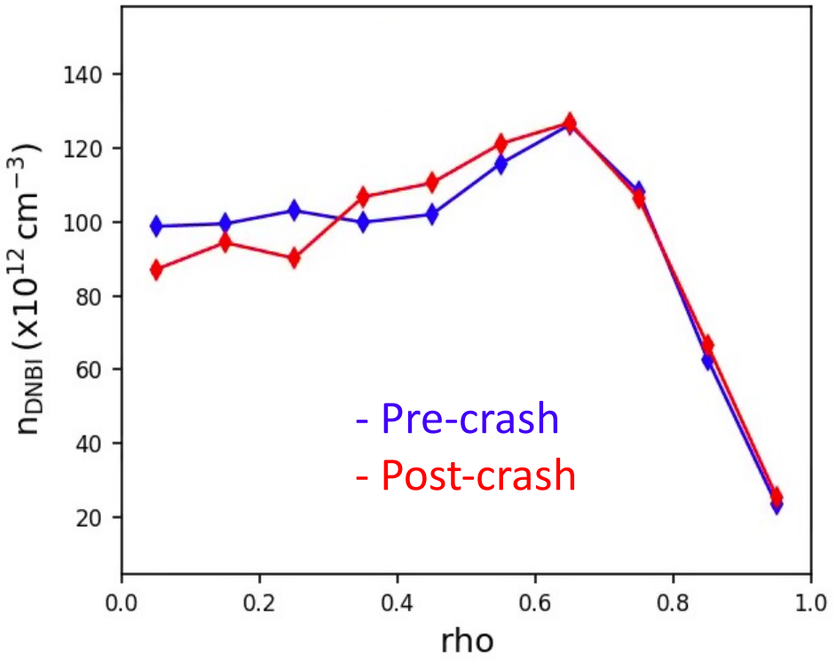
Change in Prot. Dist



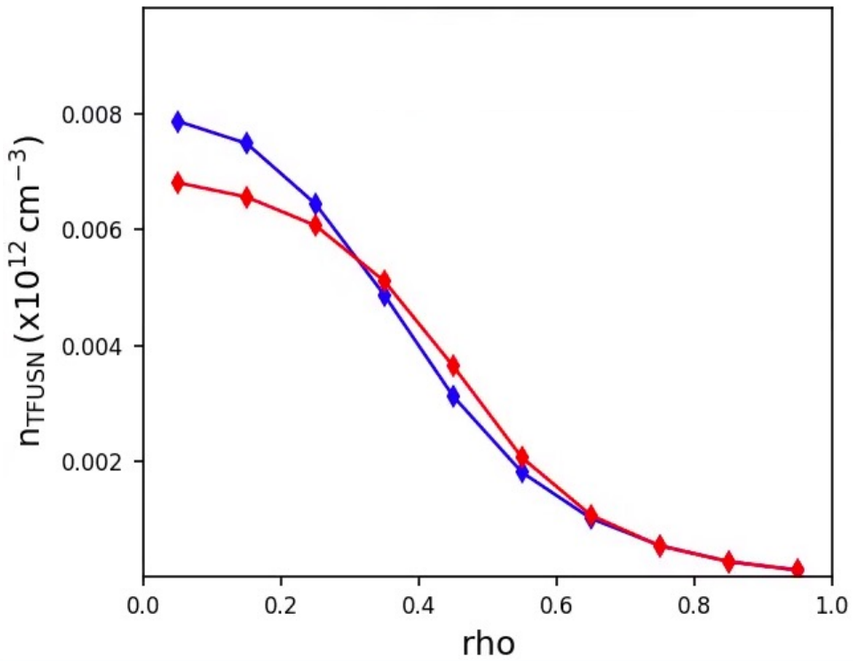
ORBIT Sawtooth Model Produces Expected Redistribution within q=1

- Below q=1 is approximately rho=0.35
- Not as drastic as Kadomtsev model with core flattening (see slides 16-17)
- Consistent with A. A. Teplukhina *et al.* shown on slide 17
- Future test: Calculate resonant vs. non-resonant transport matrices in ORBIT for use in TRANSP and observe relative change in neutron rate

Deuteron Dist.



Triton Dist.



Conclusions

- Saturated kink modes and sawtooth crash induced EP transport has been analyzed in a JET deuterium discharge with D-NBI+RF heating:
  - Kink mode is modeled with NOVA and constrained against fast ion loss measurements with a synthetic fast ion detector model
  - Sawteeth are modeled analytically with a mode amplitude and time evolution dictated by a new integrated workflow in ORBIT

- Saturated kink acts fusion products:
  - Beam born energies are relatively unaffected due to high edge deposition and flat profiles
  - High energy (>> NBI injection) and fusion products are sensitive to resonant core m=1 kink component which causes larger radial transport

- Sawteeth act on beam-born ions:
  - Resonant sawtooth interaction is important in addition to phase-space stochastization