Measurement and Modeling of Fast Ion Losses in JET Plasmas

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*See the author list of E. Joffrin et al. 2019 Nucl. Fusion **59** 112021

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JET Will Conduct a DT-Campaign Next Year

- Confinement of DT fusion born alphas is critical for self-heating of the plasma and achieving a burning reactor plasma
- The last DT-campaign was on JET in 1997 while ITER DT-operations are estimated for 2035!
- There is still much to learn about the confinement and transport of a fusion born alpha population which differs significantly from an externally heated ion population

- Goals:
    1. Prepare fast ion diagnostics on JET and evaluate their performance for alpha measurements
    2. Use discharges in the JET D-campaign for validity testing for predictive fast ion models
    3. Develop a framework for modeling alpha transport and losses (i.e. synthetic diagnostic)

Overview

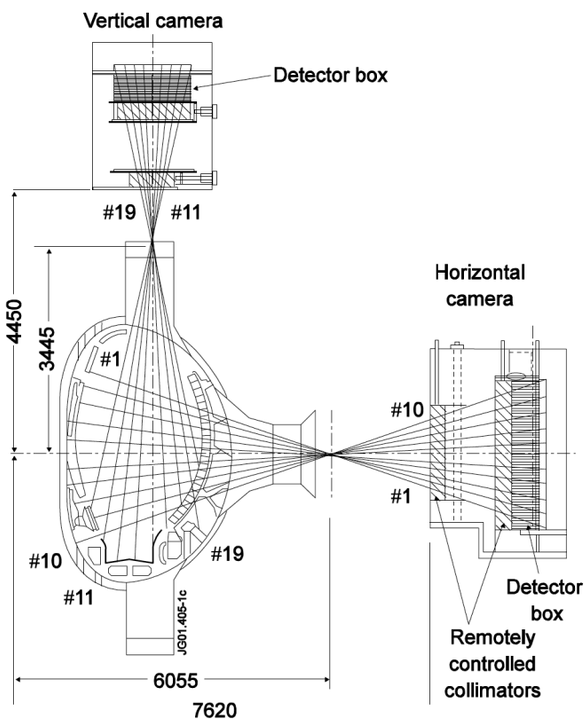
- Measurement
  - Faraday cup fast ion loss detector array
  - Recent upgrades and results

- Modeling
  - Overall Methodology
  - Integration of synthetic detector measurements

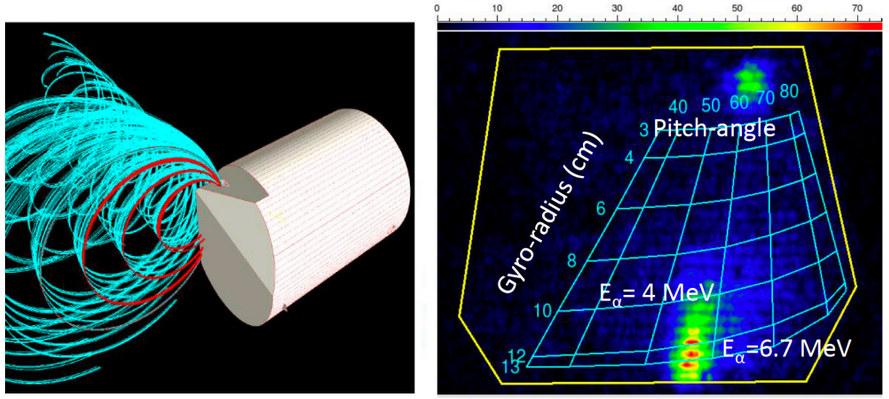
- Conclusion & Ongoing/Future Work

JET Possesses an Advanced Diagnostic Suite for Measuring Energetic Particle Activity

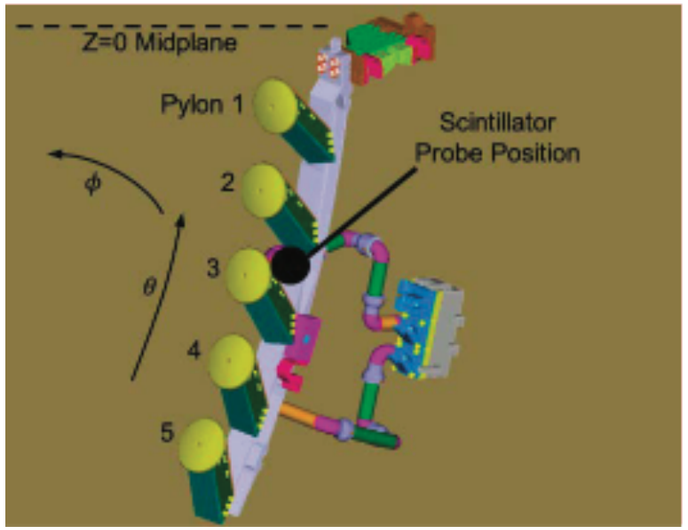
Neutron and Gamma Cameras and Spectroscopy



Scintillator Fast Ion Loss Detector

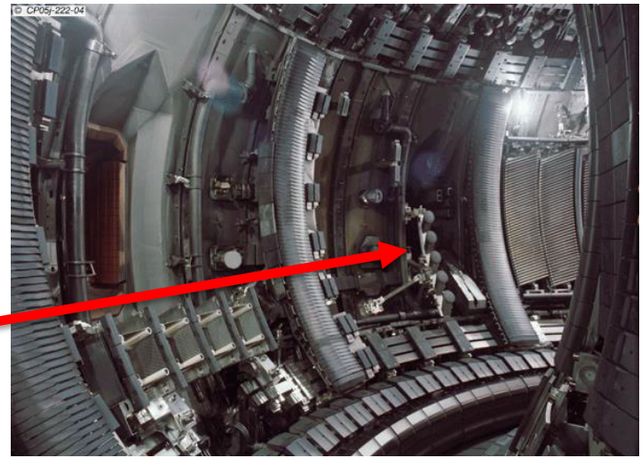


Faraday Cup Fast Ion Loss Detector Array*



Other Useful JET Diagnostics

- Neutral particle analyzers
- TAE antennae
- Edge magnetic coils
- Reflectometry
- Interferometry
- SXR
- ECE



Faraday Cups

**Darrow RSI 2004, 2006, 2010*

PPPL is Responsible for an Array of 5 Faraday Cup Fast Ion Loss Detectors*

General

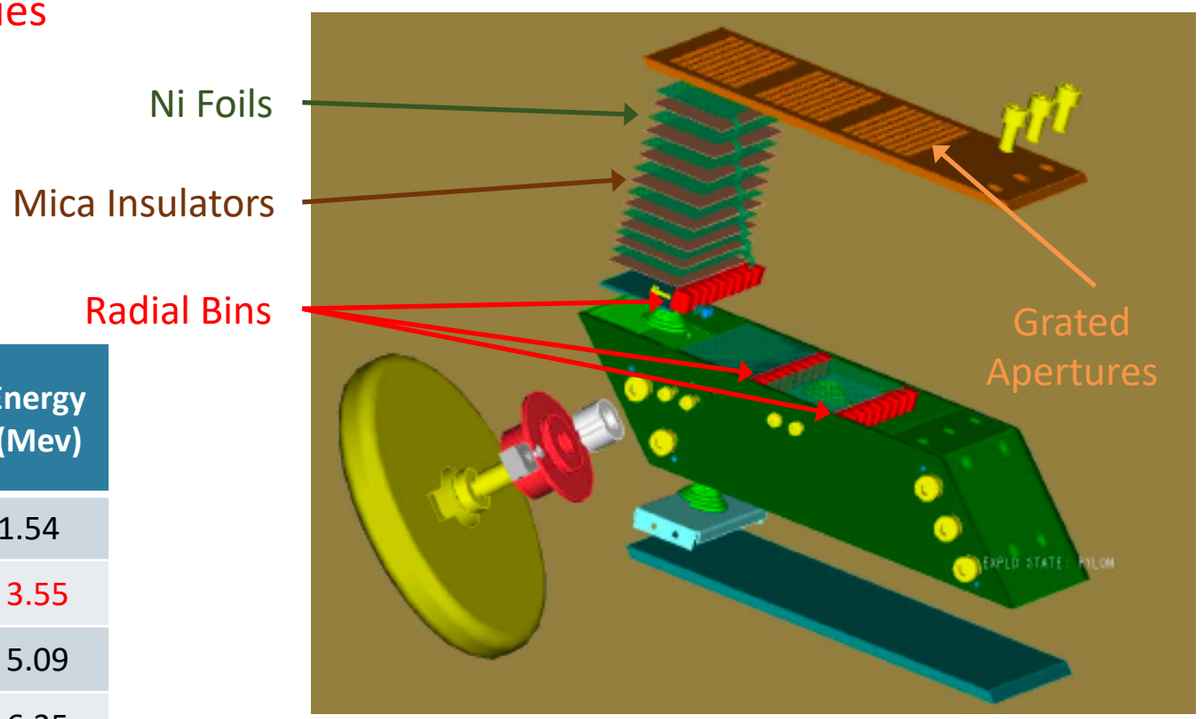
- Foil stacks are alternating layers of Ni and mica
- Ion energy determines deposition depth → Can't identify ion species
- Only way to differentiate ions is through modelling
- Nomenclature: Signal ID = Pylon #, Bin #, Foil #
  e.g. 213 = 2nd pylon from top, 1st radial bin, 3rd foil deep

Energy 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)



**Darrow RSI 2004, 2006, 2010*

Previous Measurements have been Fruitful but Severe Hardware Limitations have Hindered Advanced Analysis

Detector Limitations

1. Large amount of foil-to-foil and foil-to-machine shorts
2. High freq. noise pickup from ambient surroundings
3. Amplifier noise and breaking
4. Limited analysis -> 5 kHz sampling rate

Old Acquisition

- 16-bit, bipolar linear amps
- $\pm$ 200 μA range
- 5 kHz sampling rate ADC

Recent Hardware Upgrades have been Performed to Remediate Past Issues

Detector Limitations

1. Large amount of foil-to-foil and foil-to-machine shorts
2. High freq. noise pickup from ambient surroundings
3. Amplifier noise and breaking
4. Limited analysis -> 5 kHz sampling rate

Recent Upgrades*

1. Installed thicker foils in a 4-stack design to prevent foil-to-foil shorts
2. Installed superscreen cabling to hinder ambient noise pickup

3.–4. New 200 kHz ADC and amplifiers

Old Acquisition

- 16-bit, bipolar linear amps
- $\pm$ 200 μA range
- 5 kHz sampling rate ADC

New Acquisition

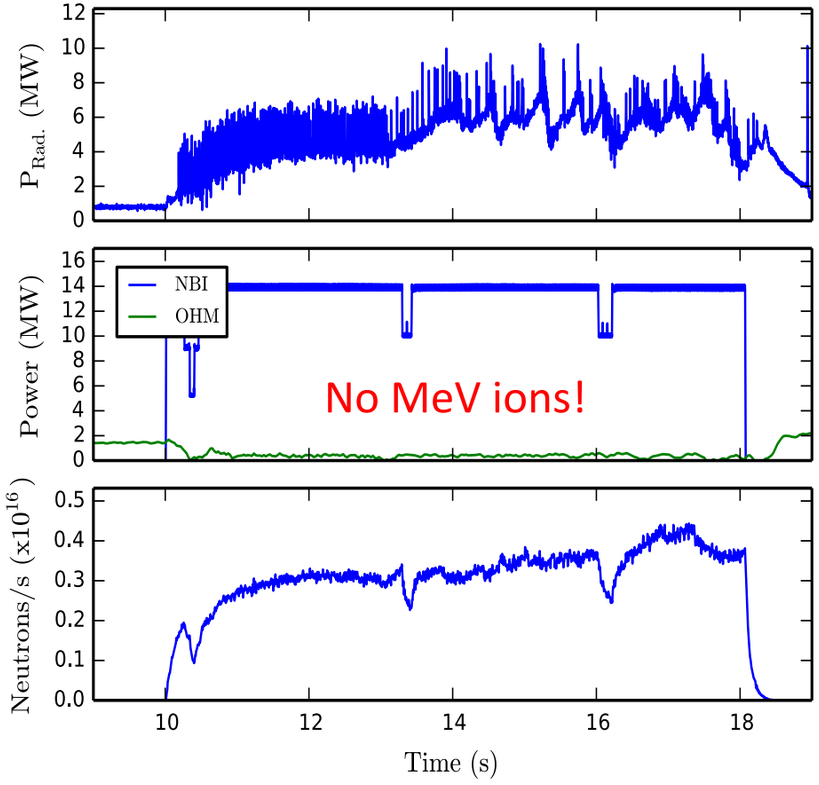
- 16-bit, bipolar linear amps
- $\pm$ 2000 μA range
- 200 kHz sampling rate ADC
- Each channel is fully controllable via software

**Bonofiglo RSI 2020*

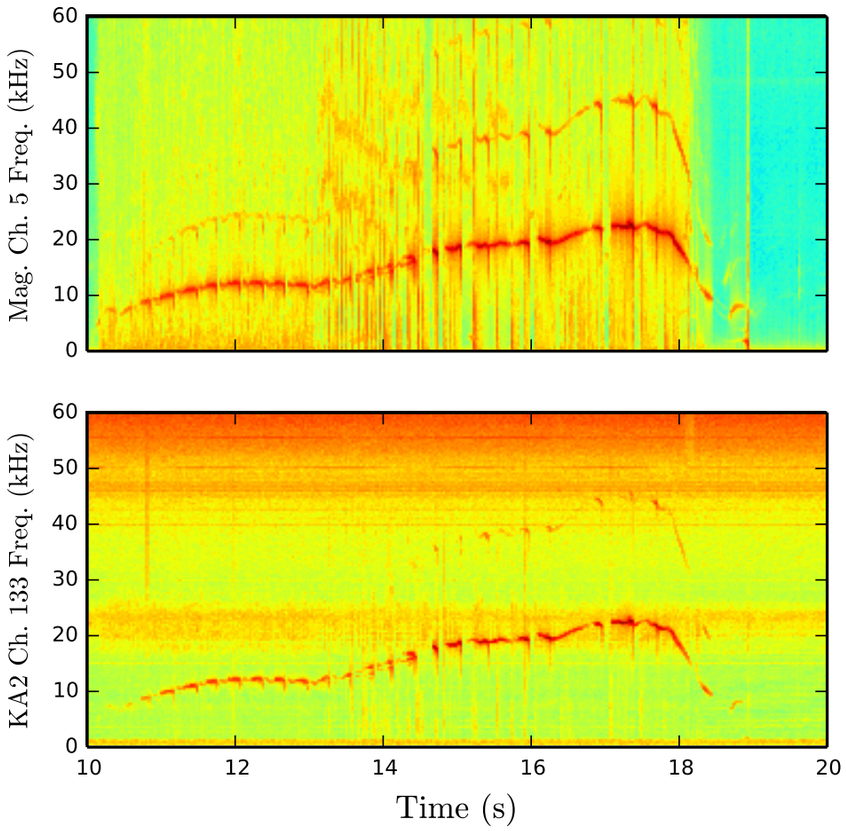
The Foil Stacks are Susceptible to Capacitive Plasma Pickup

- The front foil is plasma facing and couples to MHD activity*. The foils can then capacitively couple to one another allowing noise pickup to traverse the stack
- Impossible to distinguish resonant fast ion losses from pickup noise
- We assume dominant coupling is on first foil and subtract it from deeper signals

NBI only Discharge

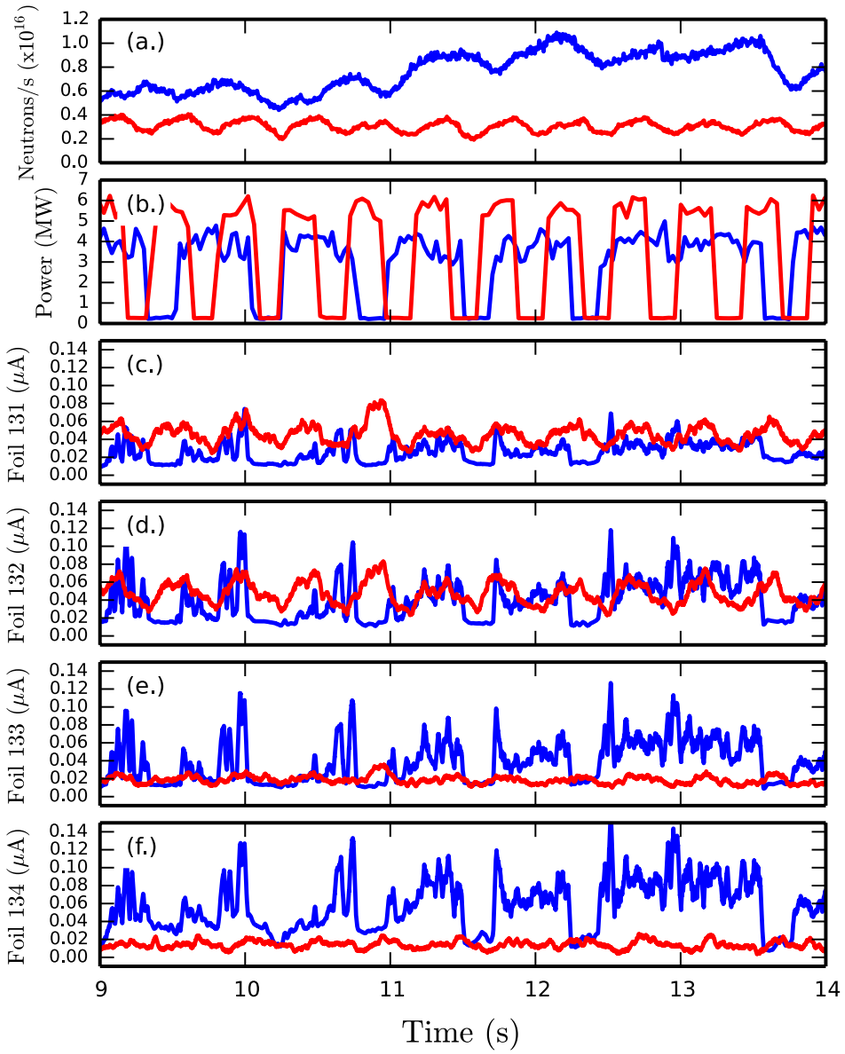


Spectrograms



Darrow RSI 2010, Cecil 2010 RSI

Faraday Cup Signals are Strongly Correlated with Modulated ICRH Input power

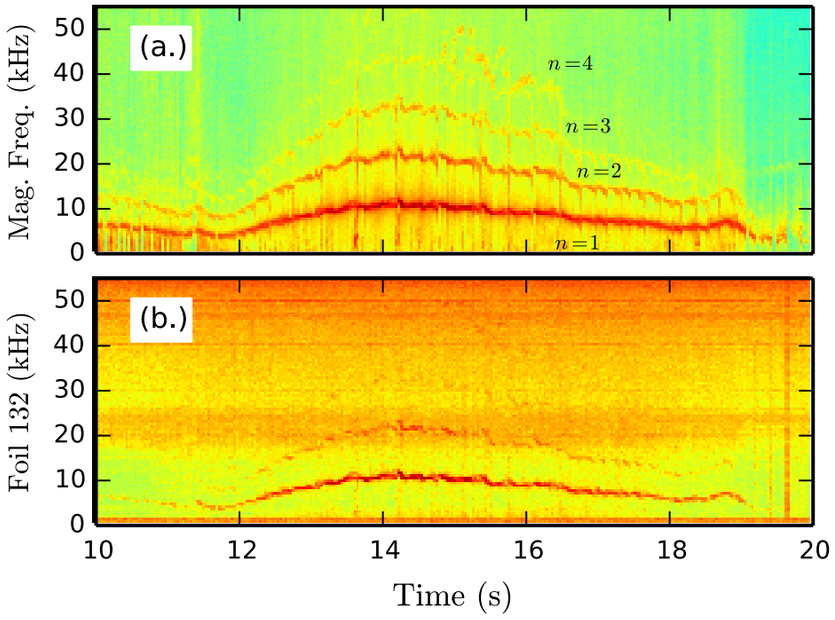


- MeV scale ICRH heated deuterium NBI ions (as well as DD fusion products) act as a proxy for fusion born DT alpha particles in deuterium plasmas
- The Faraday cup signals (left) are correlated with modulated ICRH input power indicative of heated deuteron losses
- Visible in old and upgraded detector array

Shot 94083 – Without upgrades
Shot 96536 – With upgrades

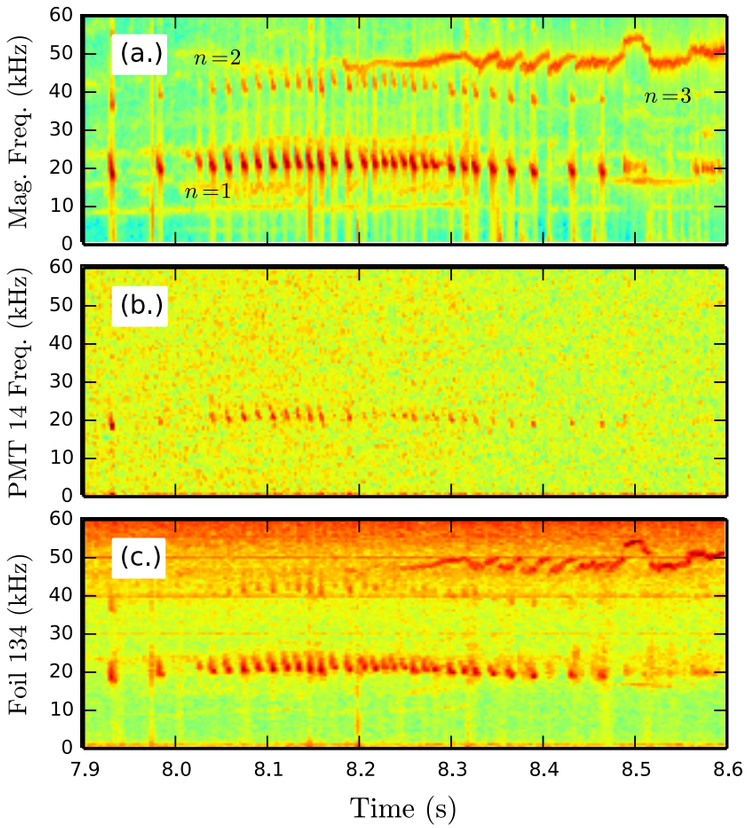
Diagnostic Upgrades have Resulted in Enhanced Measurements of Fast Ion Losses*

Kink Losses



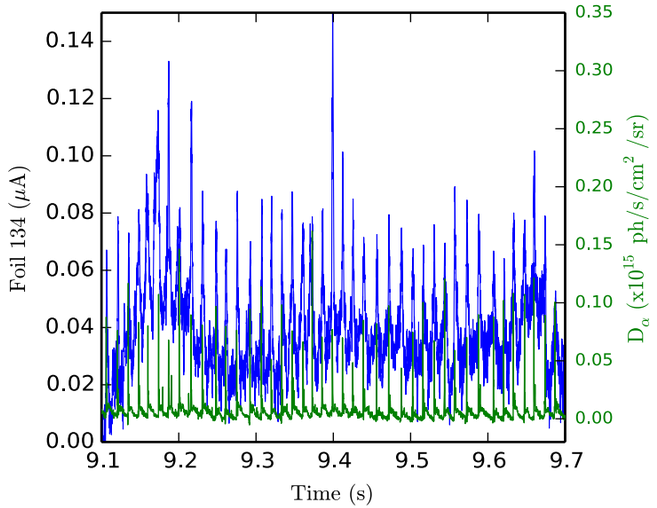
(a.) Magnetic Mirnov coil
(b.) Faraday cup foil

Fishbone + Long-lived Mode Losses

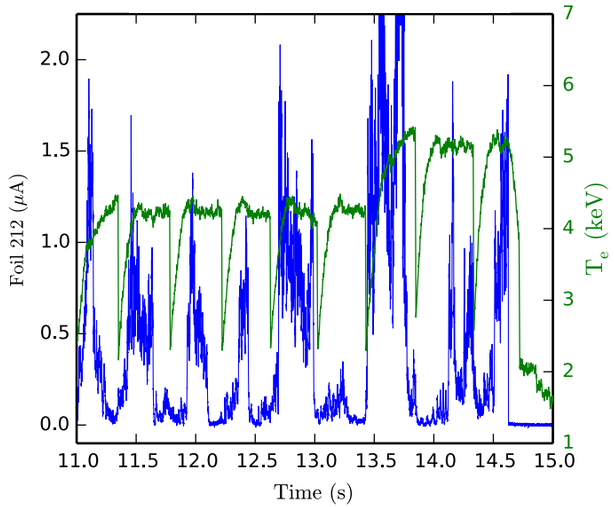


(a.) Magnetic Mirnov coil
(b.) Scintillator probe PMT
(c.) Faraday cup foil

ELM Losses



Sawtooth Losses



Bonofiglo RSI 2020

Midway Overview

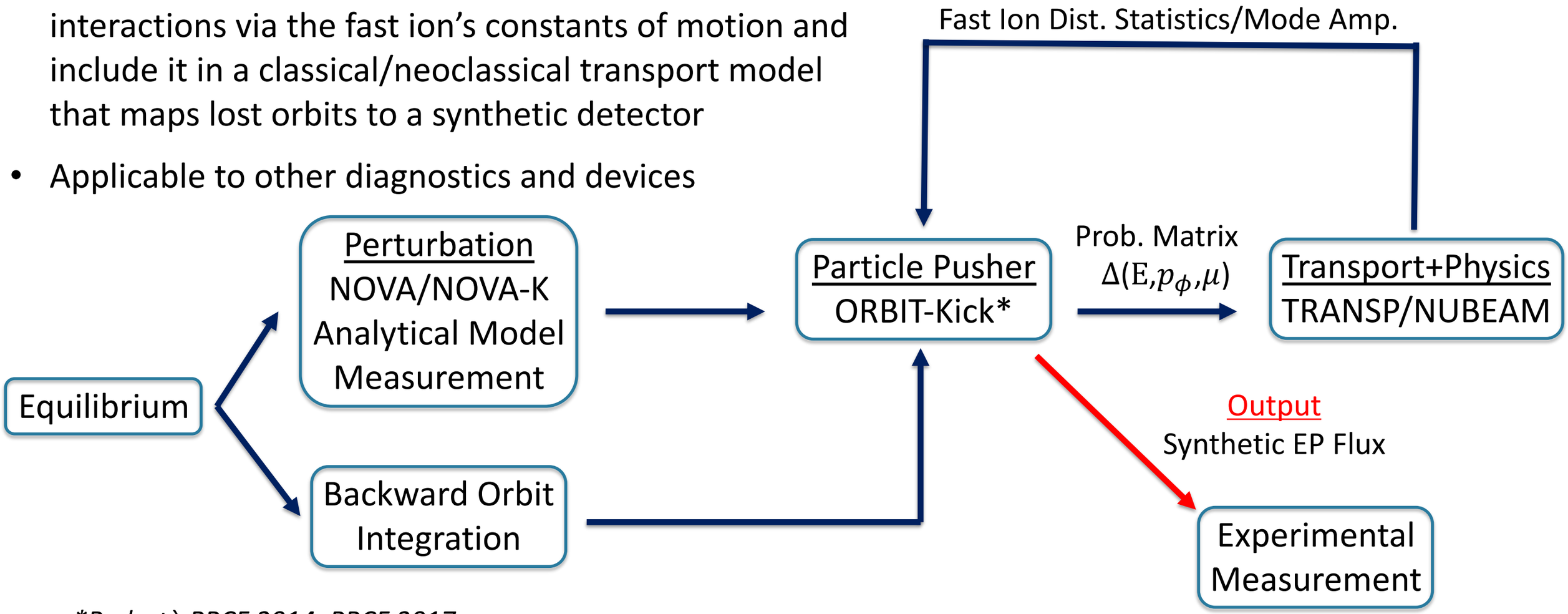
- Measurement
  - Faraday cup fast ion loss detector array
  - Recent upgrades and results

- Modeling
  - Overall Methodology
  - Integration of synthetic detector measurements

- Conclusion & Ongoing/Future Work

Can Combine Existing Codes to Form a Fully Integrated Model for Fast Ion Transport Validated by Experimental Measurements

- Encode the effect of resonant wave-particle interactions via the fast ion's constants of motion and include it in a classical/neoclassical transport model that maps lost orbits to a synthetic detector
- Applicable to other diagnostics and devices



**Podestà PPCF 2014, PPCF 2017*

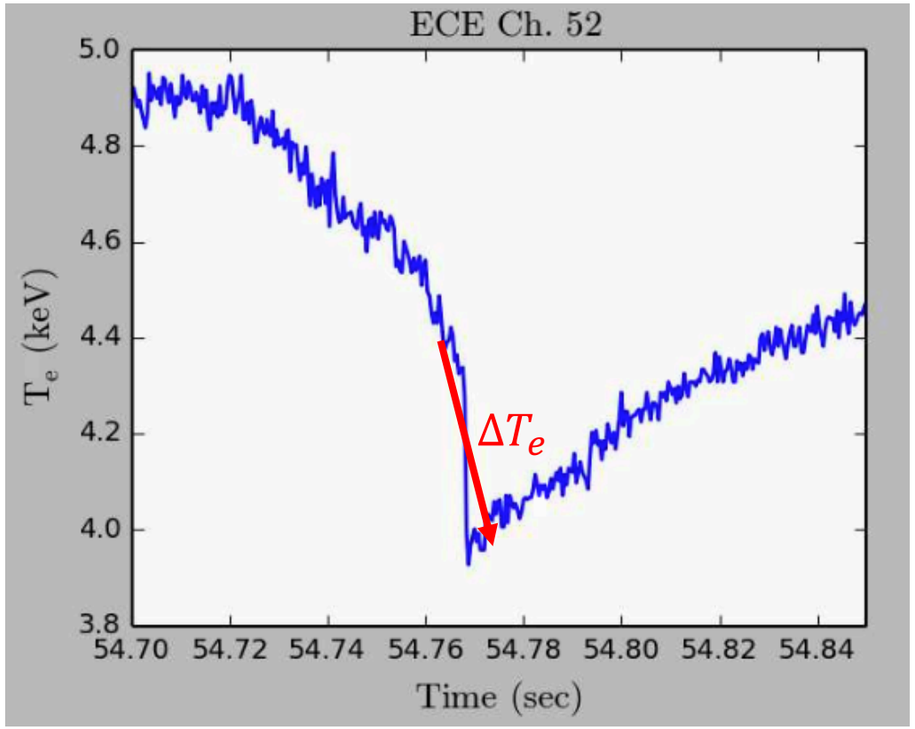
Equilibrium is Provided by EFIT but Often Needs Further Constraining

- Standard equilibrium is pressure constrained EFIT
- MSE available but not on every discharge…
- Often need to better constrain the EFITs with measurements, TRANSP analysis, or other models

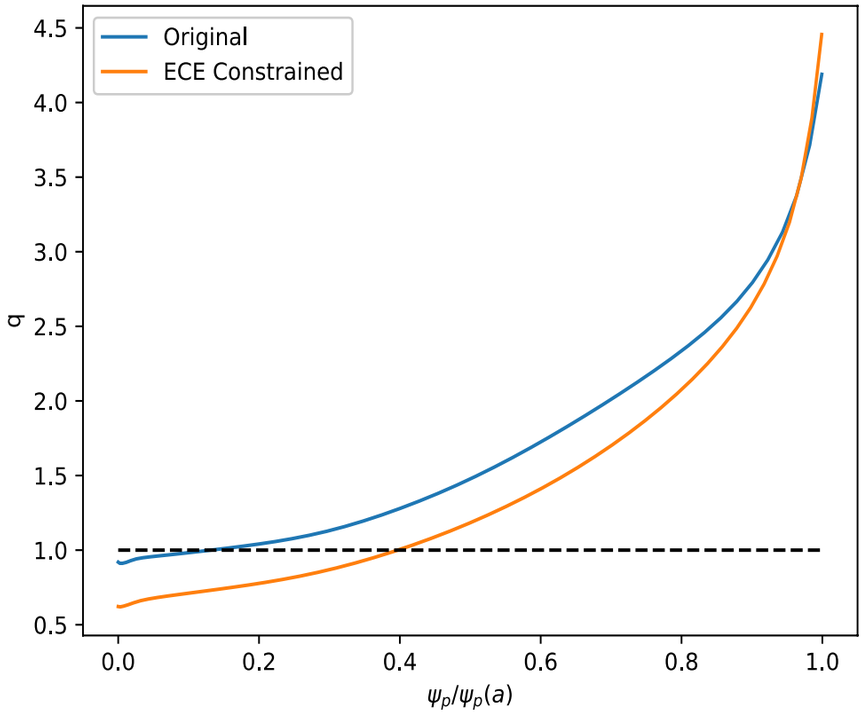
Shot 96133 Example w/ ST

1. ΔT_e calculated across crash for every ECE and SXR channel
2. Map inversion radius (ΔT_e=0) to pol. flux
3. Adjust initial q-profile in TRANSP to match

Example Te from ECE Channel during ST-Crash



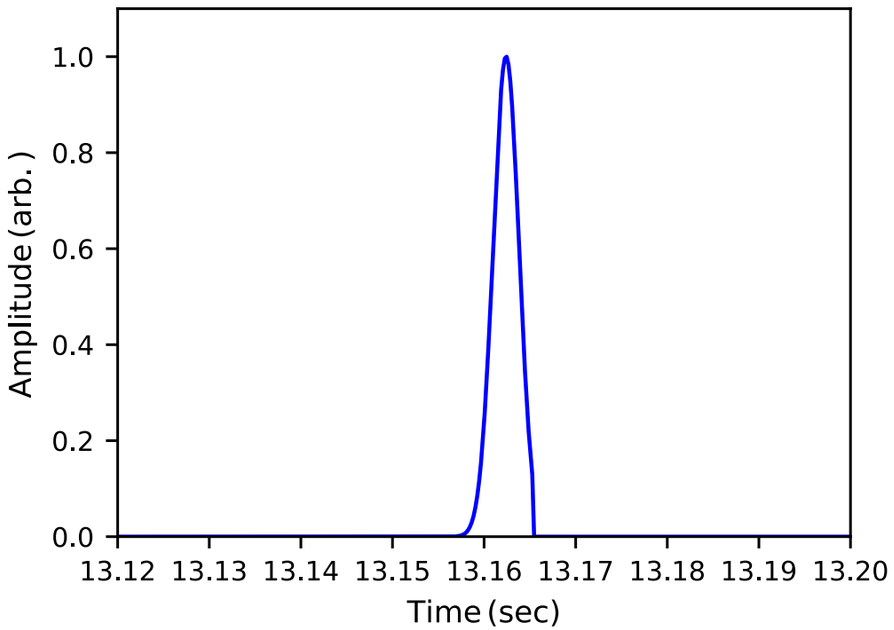
Constrained q-Profile Comparison



Perturbations Follow Analytical Models Constrained by Measurements and ORBIT Calculations

- ORBIT takes displacement vector as input
- Structure is up to best known interpretation…
- Mode amplitude found by adjusting ORBIT calculated kicks to match measured neutron rate

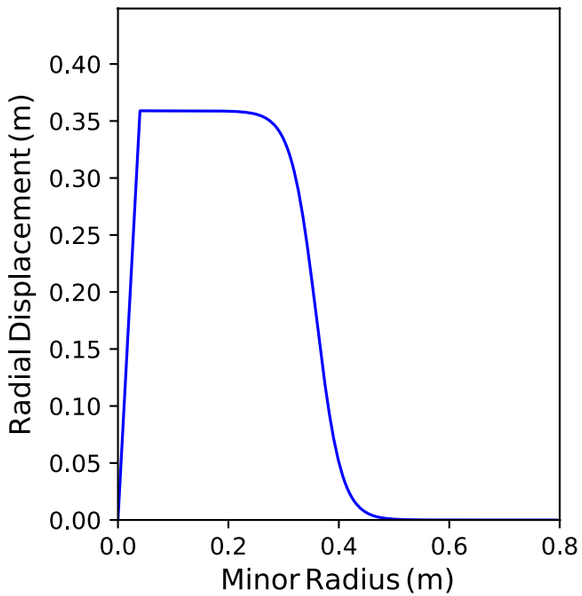
Sawtooth Temporal Structure

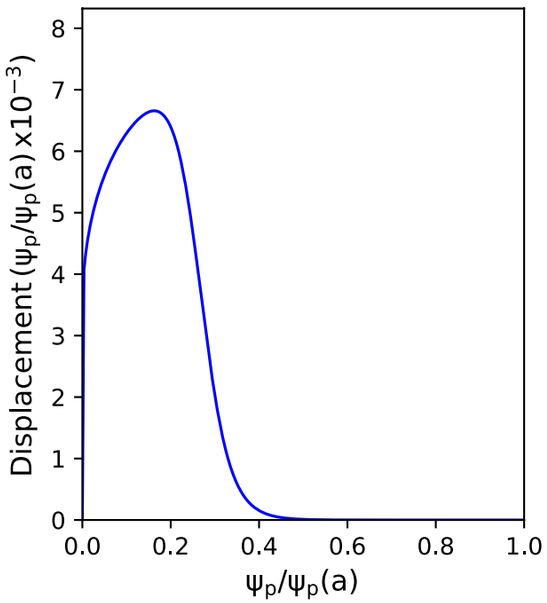


Sawtooth Radial Structure*

$$f_{11}(x) = \frac{1}{2}\{1 - \tanh[\delta(x - x_s)]\},$$

$$f_{22}(x) = \begin{cases} \cos^2\left[\frac{\pi}{2}\left(\frac{x - x_{22}}{x_{22}}\right)\right] + \frac{e^{-x^2/x_{22}^2}}{4}, & x \leqslant 2x_{22}, \\ 0, & x > 2x_{22}, \end{cases}$$

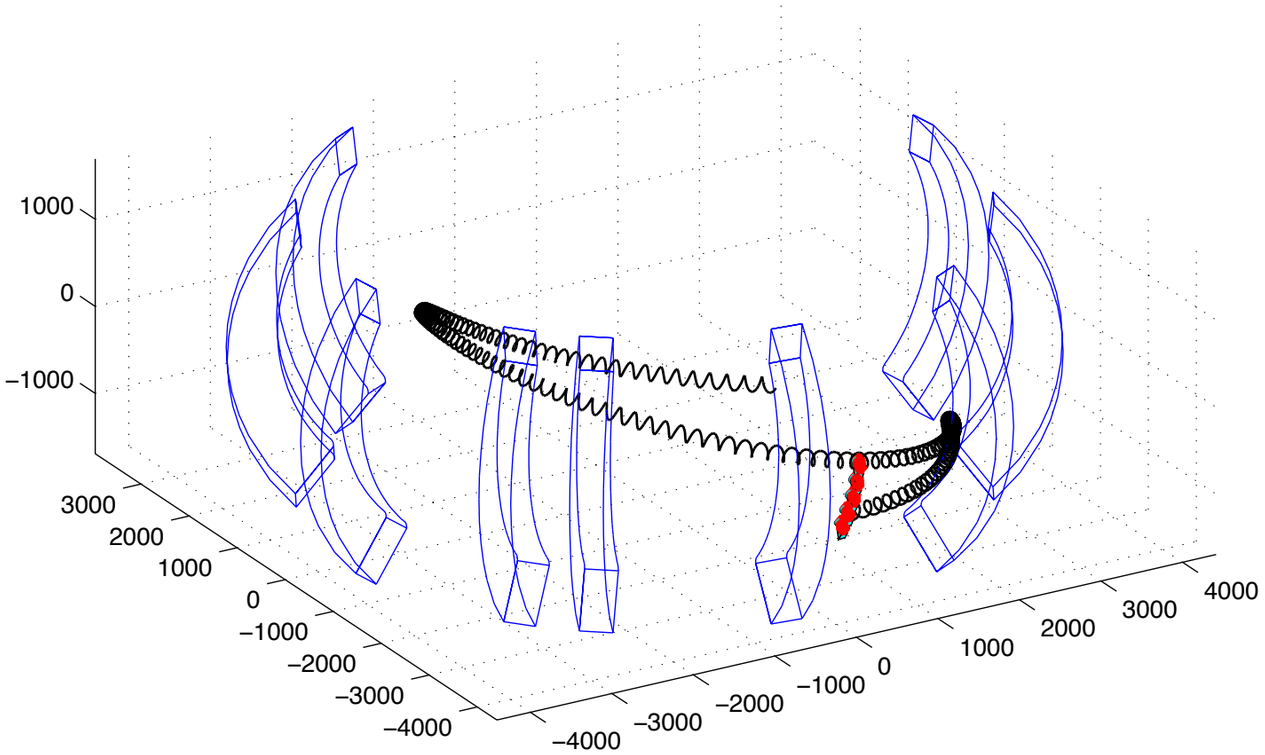


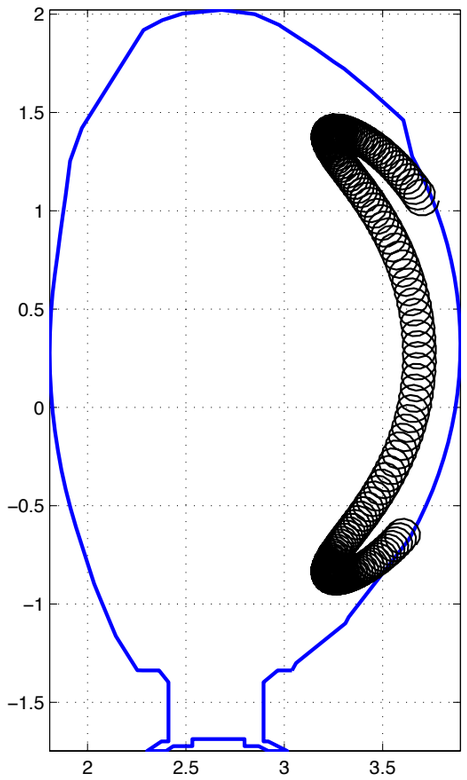


**Farengo NucFus 2013, Kim Nucfus 2018*

Detector Measurements are Connected to the Model by Integrating Loss Orbits Backward*

0.95 MeV Lost Deuteron Orbit.

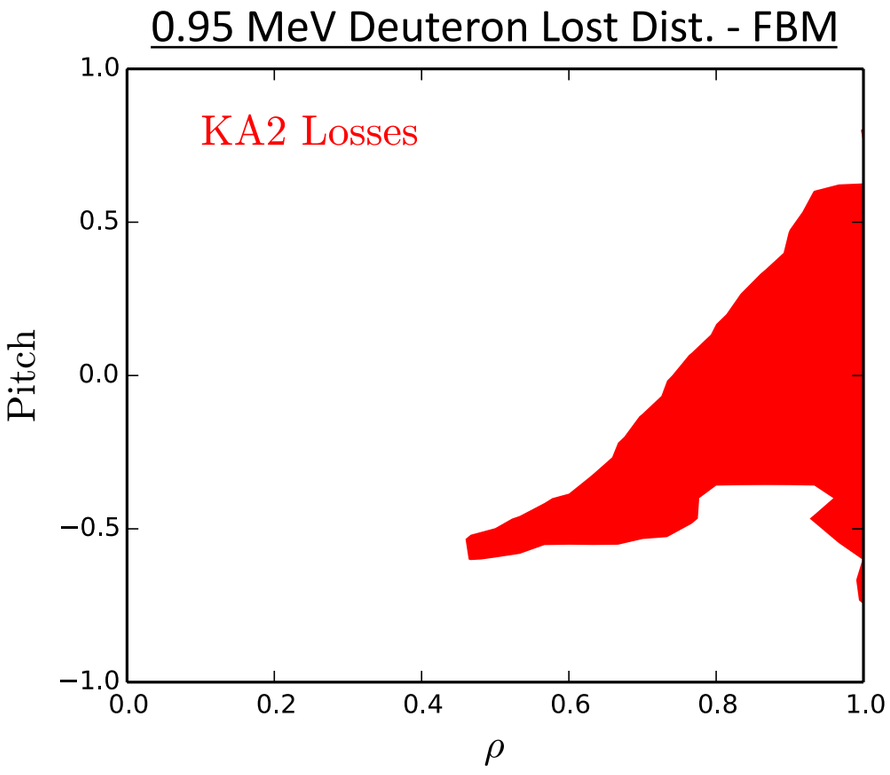


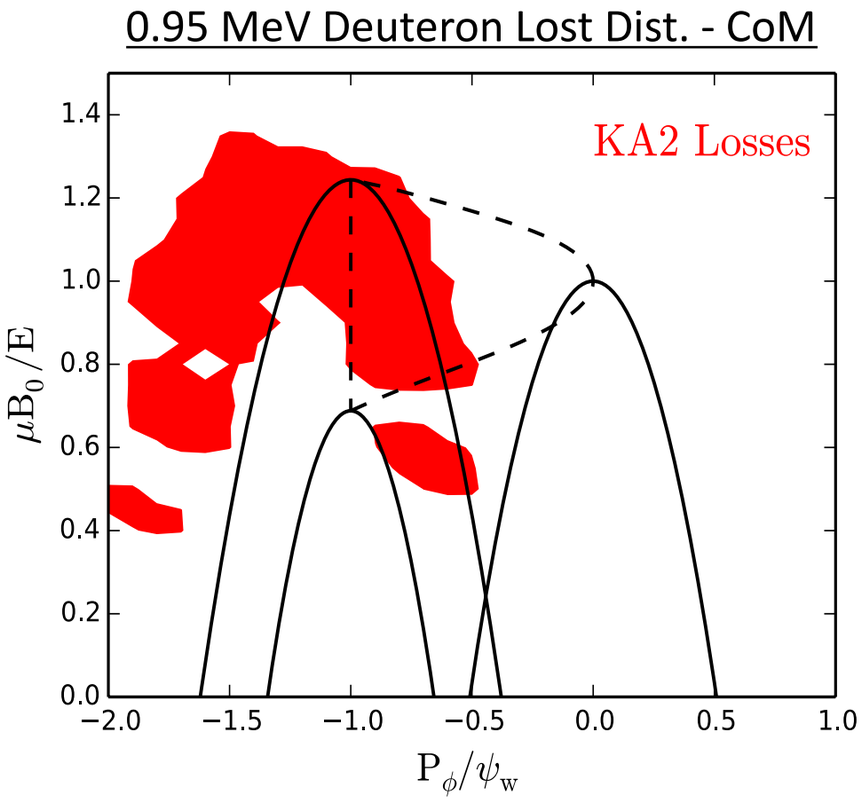


- Initial conditions: equilibrium, Faraday cup, energy, mass, charge, launch angle

**Code courtesy of V. Goloborodko*

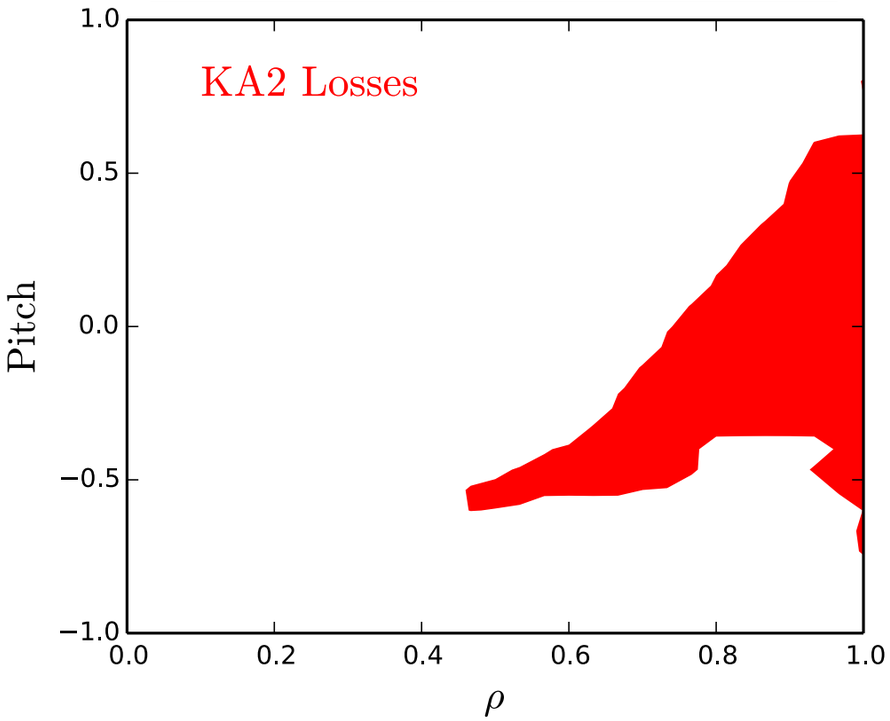
The Loss Detector is Sensitive to Trapped and Counter-Passing Orbits



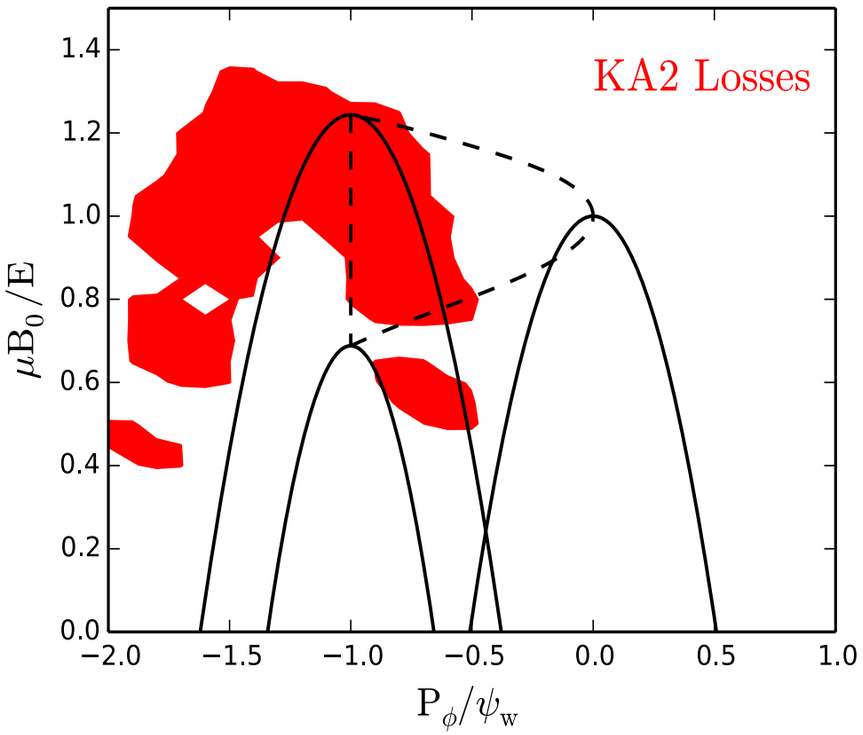


The Loss Detector is Sensitive to Trapped and Counter-Passing Orbits

0.95 MeV Deuteron Lost Dist. - FBM



0.95 MeV Deuteron Lost Dist. - CoM

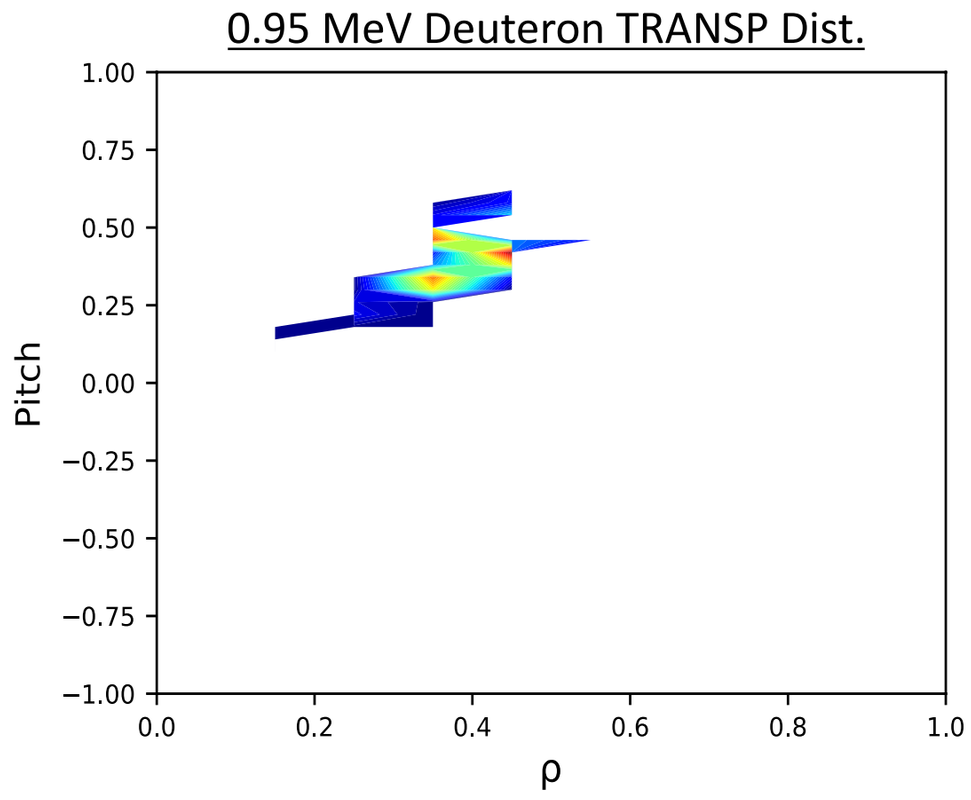


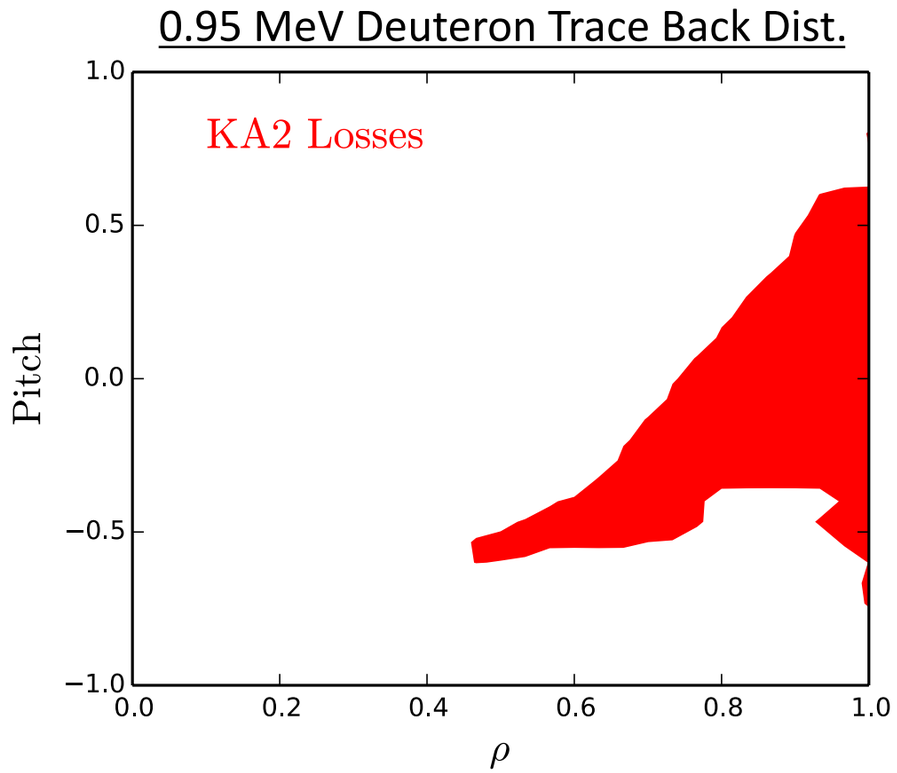
Caveats

1. Full orbit
2. No perturbations
3. Dist. is naturally in the lost region outside of the scope of NUBEAM

TRANSP Produced Fast Ion Distributions Lack Sufficient Statistics for the Energy Ranges of Interest

- RF-tail produced by NUBEAM/TORIC+RFkick is very small (run with 64000 particles)
- TRANSP distribution must be built up for any meaningful biasing from the reverse integrated dist.

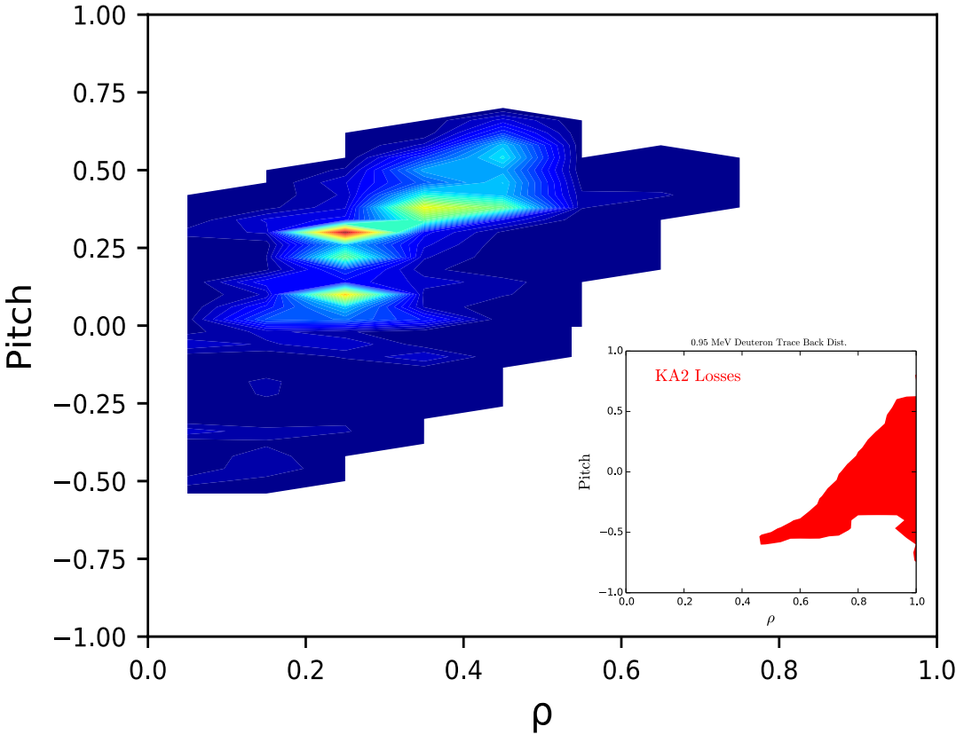




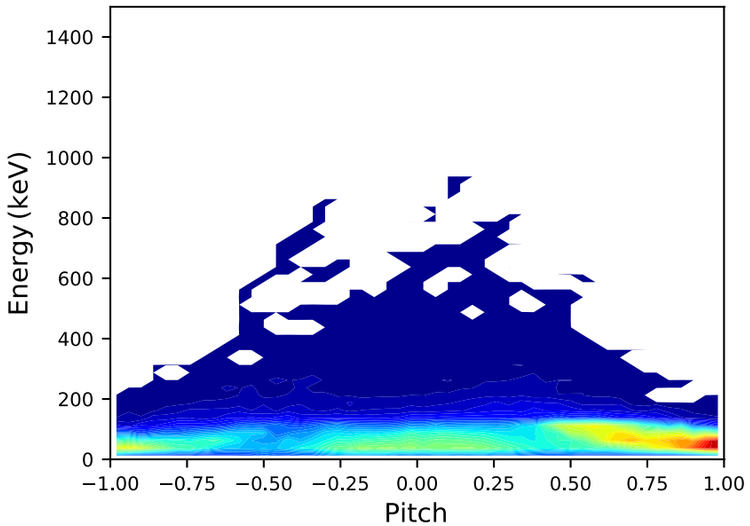
TRANSP Fast Ion Distributions are Improved by Running Stand-Alone NUBEAM/TORIC

- Plasma state file is pulled from TRANSP and ran with the stand-alone version of NUBEAM/TORIC to build the fast ion statistics
- RF-tail is better filled in, but it takes many loops to sufficiently populate higher energies

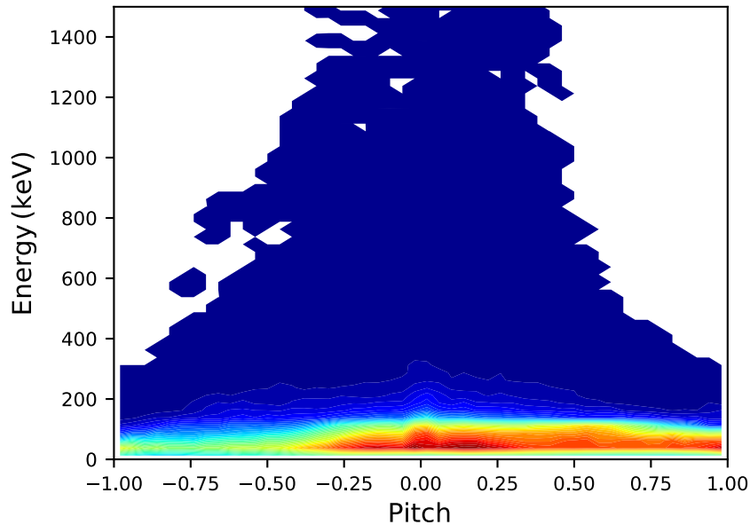
0.95 MeV Deuteron TRANSP Dist. x 21



RF-tail Before



RF-tail After



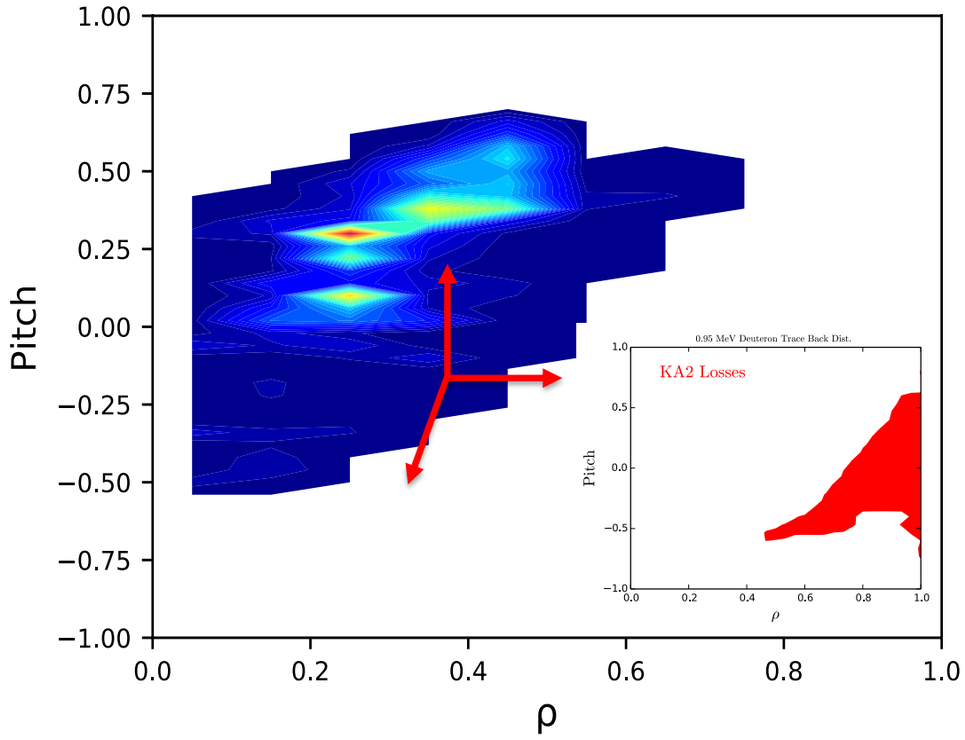
The NUBEAM Produced Dist. Is Biased Against the Reverse Integrated Dist. to Give Marker Weights

- Randomly sample the NUBEAM distribution in (E, pitch, rho) and bias against the lost distribution to give density markers that can be translated to a particle flux on the detector in a time slice analysis
- Treat the reverse integrated distribution in a binary fashion (existence vs. nonexistence of a lost orbit)
- Requires acceptable "smearing" ranges: 1-2 in rho, 5 in pitch, 10 in energy

Method

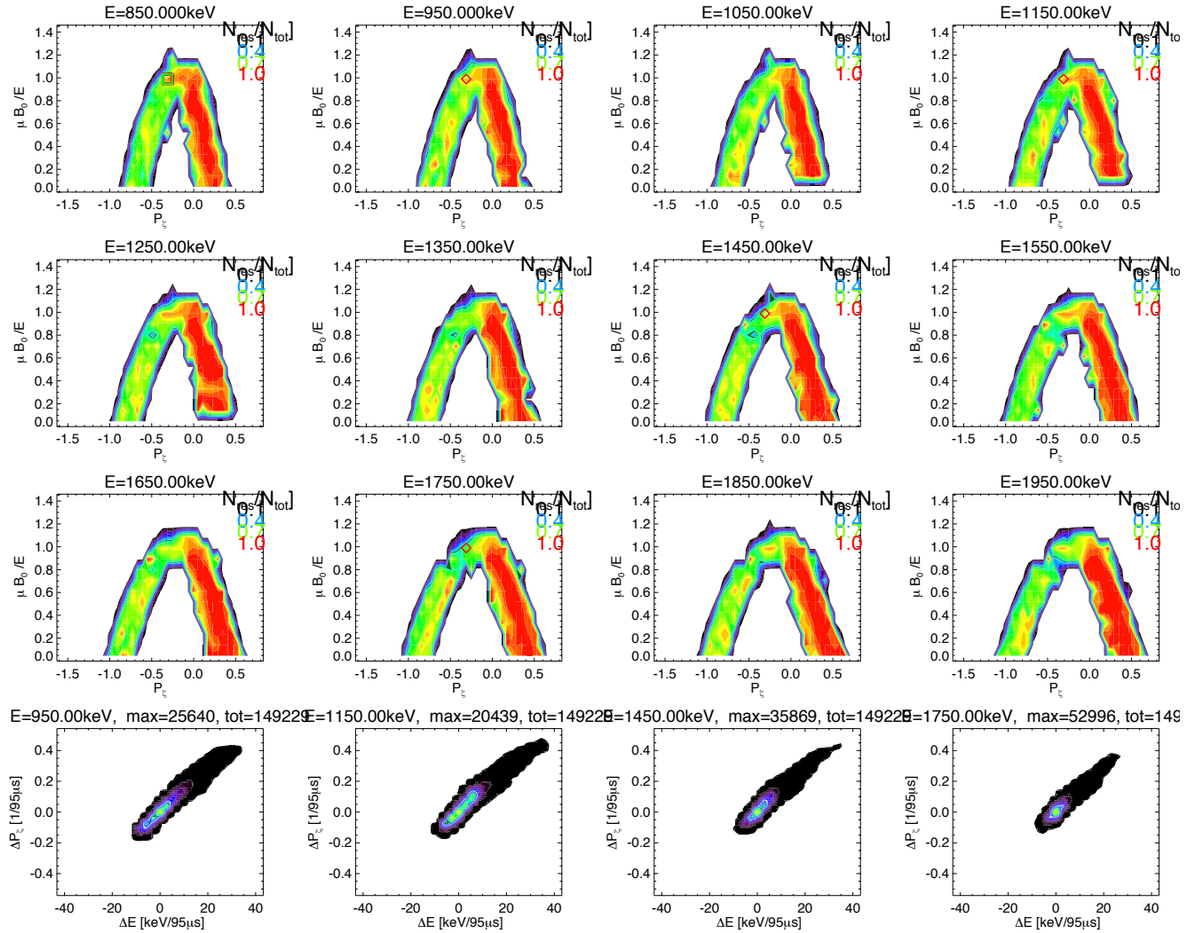
1. Sample NUBEAM distribution
2. Look around the sampled point to reach into the lost region
3. Interpolate selected value
4. Bias against lost distribution (either 1 or 0)
5. Marker weight is noted as density (#/cm^3/eV/dω/4π)
6. Translate weights to particle flux on to detector
7. Perform time slice analysis

0.95 MeV Deuteron TRANSP Dist. x 21

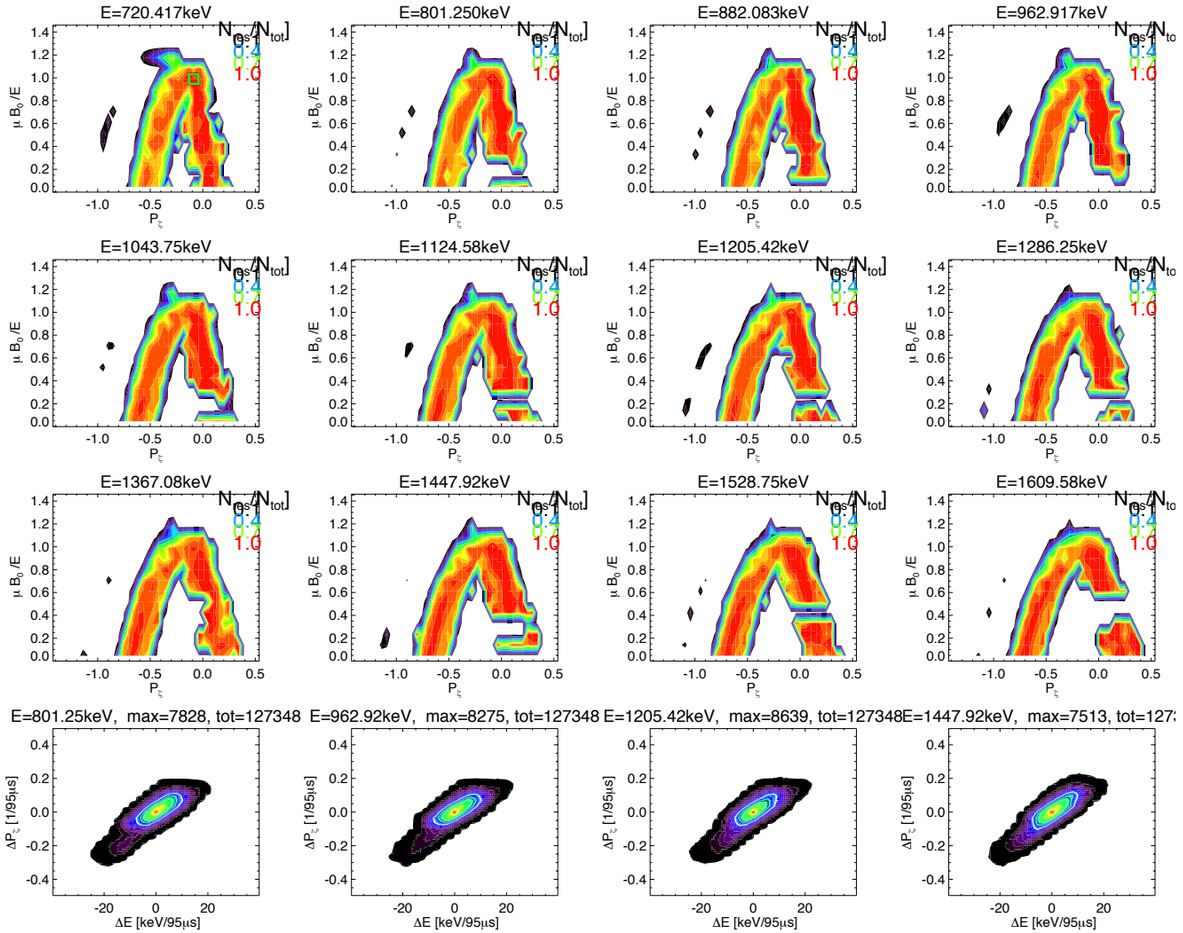


Can Examine the Differences in Resonances between Fast Ion Species with ORBIT-kick

Deuteron Kicks



Proton Kicks



Conclusions

- The Faraday cup fast ion loss detector on JET has undergone recent upgrades that have resulted in improved acquisition and enhanced measurements

- A model for fast ion transport and confinement, to be validated by measurement, is nearing completion:
  - Constrained equilibria and perturbations via measurement
  - Integrated a synthetic loss detector via biasing distributions
  - Solved statistics problems with NUBEAM/TORIC distributions
  - Calculated ORBIT-kicks for the perturbations

Ongoing & Future Work

- Ongoing:
  - Adding statistics to TRANSP distribution
  - Need to perform final ORBIT run that finds weights for test population
  - Calculate fluxes and relate to experimental loss measurements

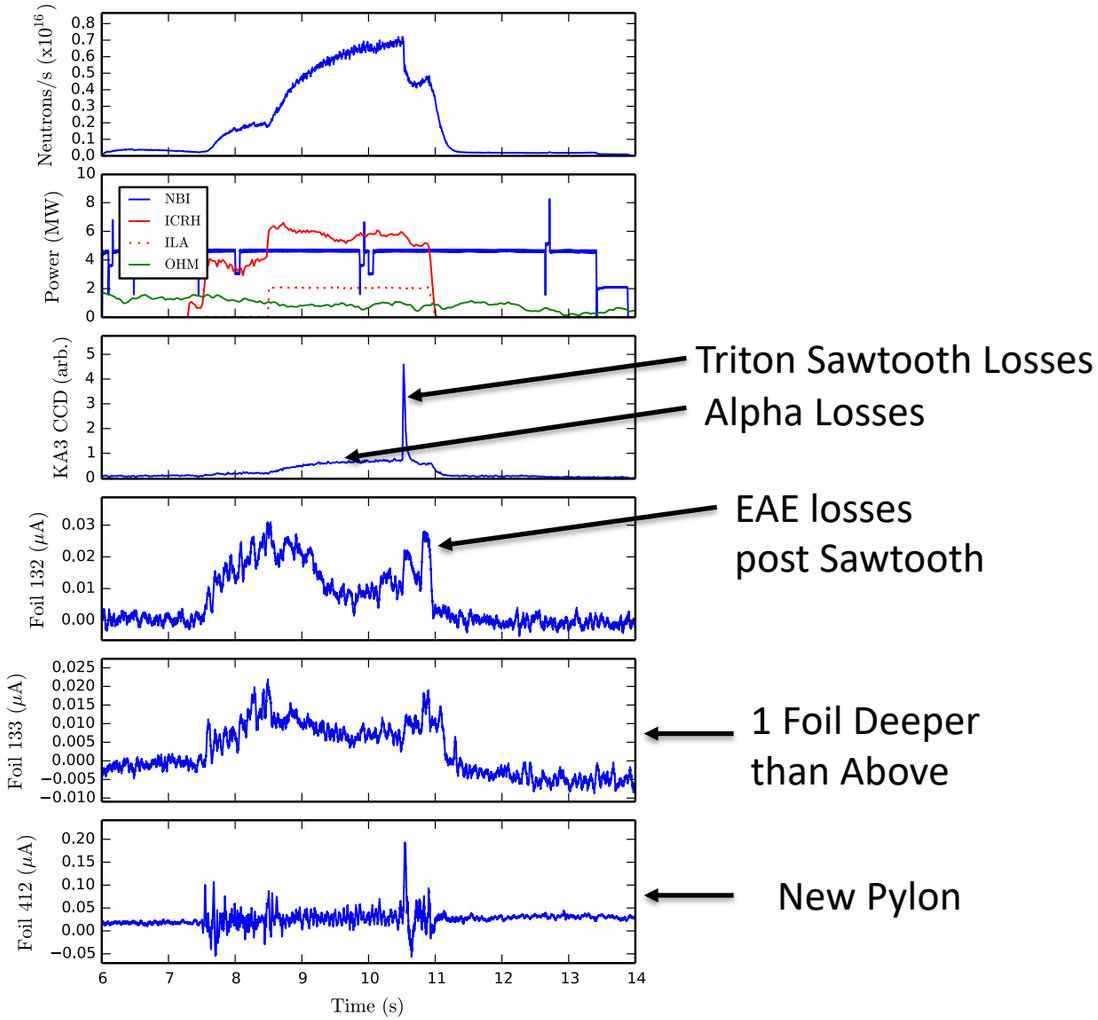
- Future:
  - Predictive alpha losses
  - “Install” Fataday cups in ORBIT beyond the LCFS
  - Extend model to scintillator probe

BACK UP SLIDES

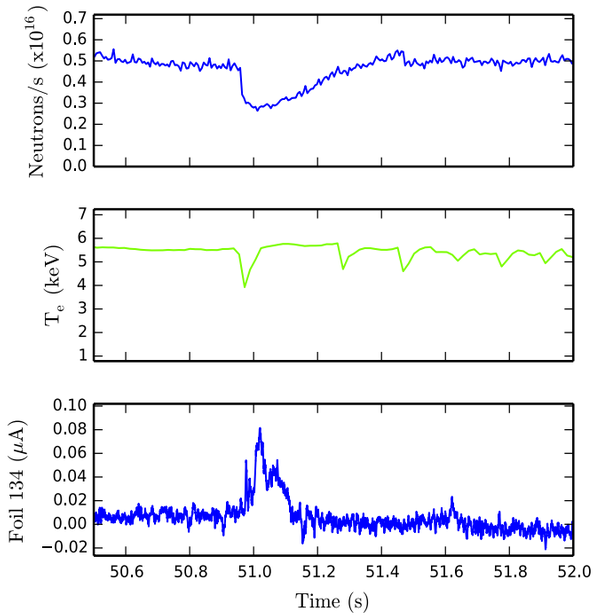
More FILD Loss Measurements

- Deuterium plasmas with MeV scale ICRH heated deuterium NBI ions which act as a proxy for fusion born DT alpha particles
- Fusion products: D+D → H^3(1.01 MeV)+p(3.02 MeV) and D+He^3 → He^4(3.54 MeV)

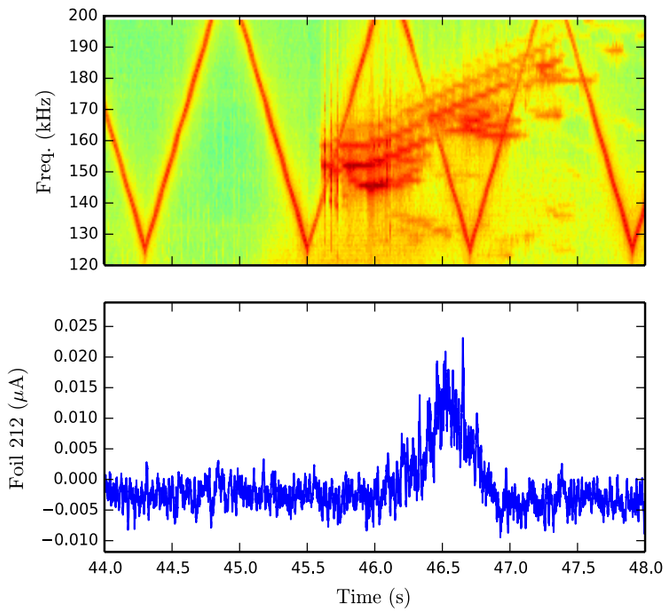
Fusion Product Losses



Sawtooth Losses

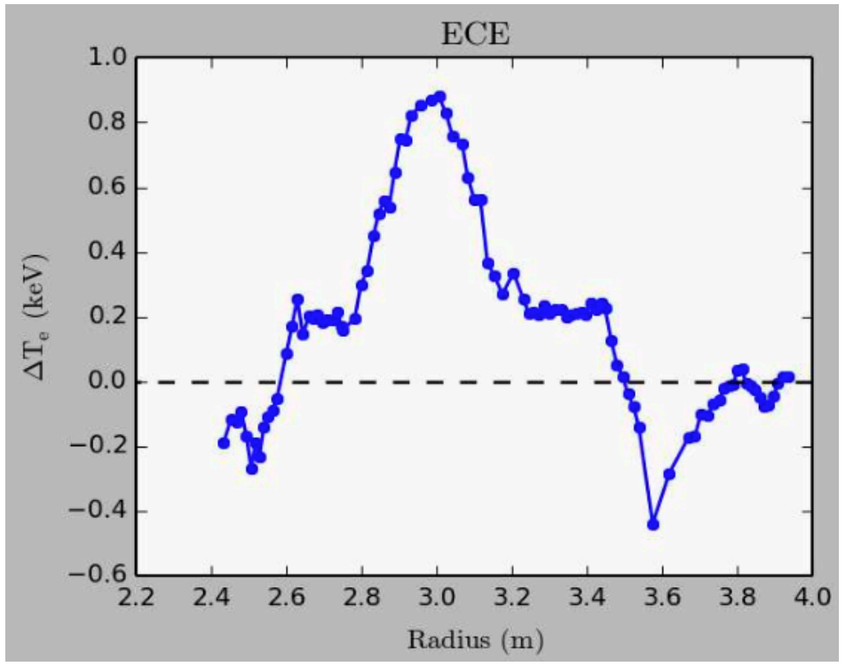


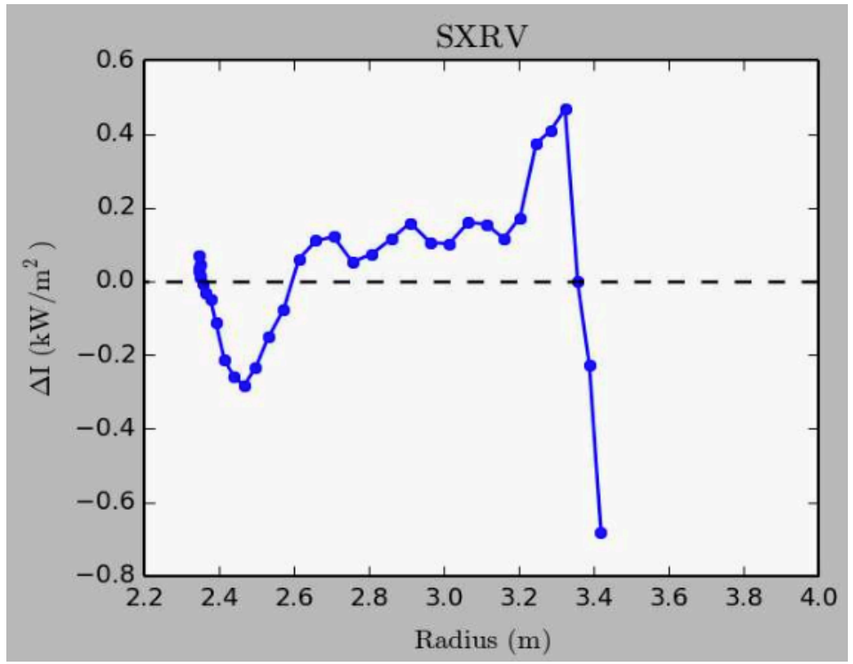
TAE Losses

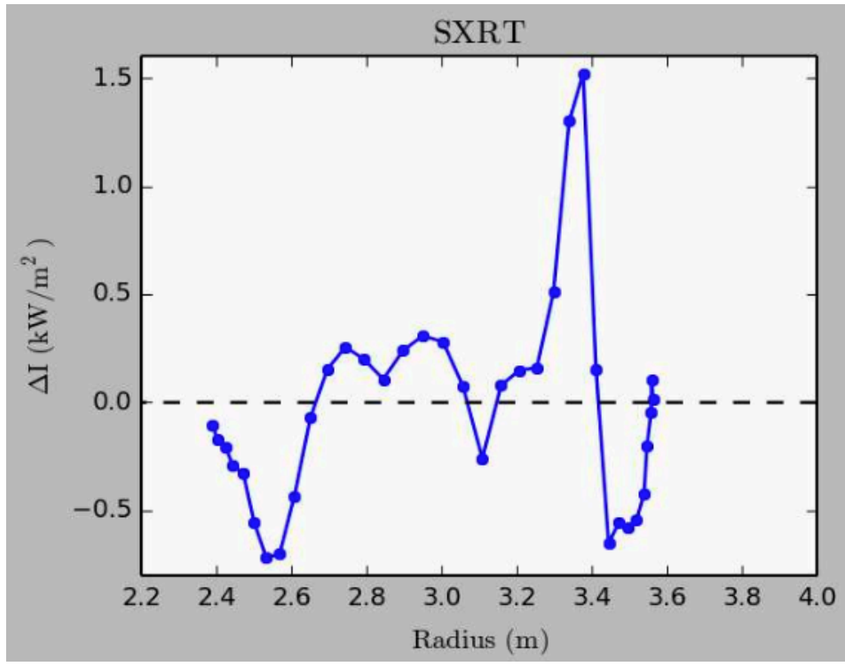


Finding the q=1 Surface - Results

- SXRT and SXRV are toroidally separated by 135°
- Below is for a single sawtooth
- Zero crossings are approximately R=2.6 m and R=3.4-3.5 m -> Inversion radius
- Second zero crossings are approximately R=2.3-2.4 m and R=3.6-3.8 m -> mixing radius
- Trend appears roughly across all 3 diagnostics

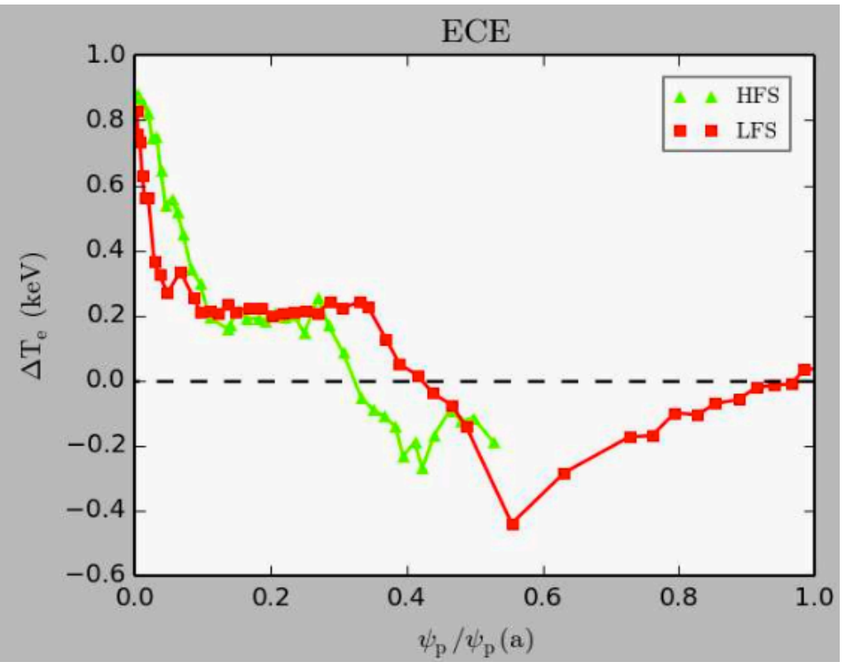


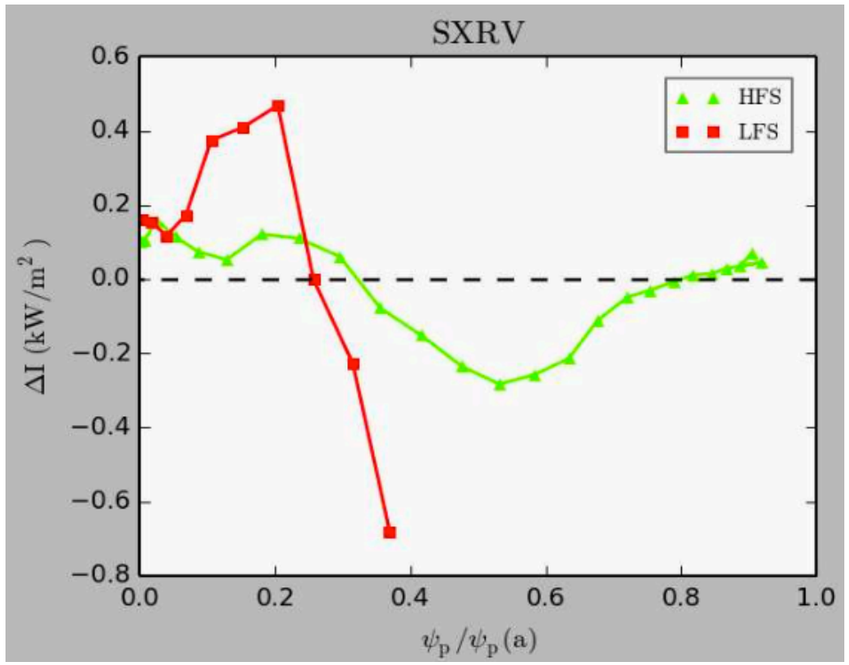


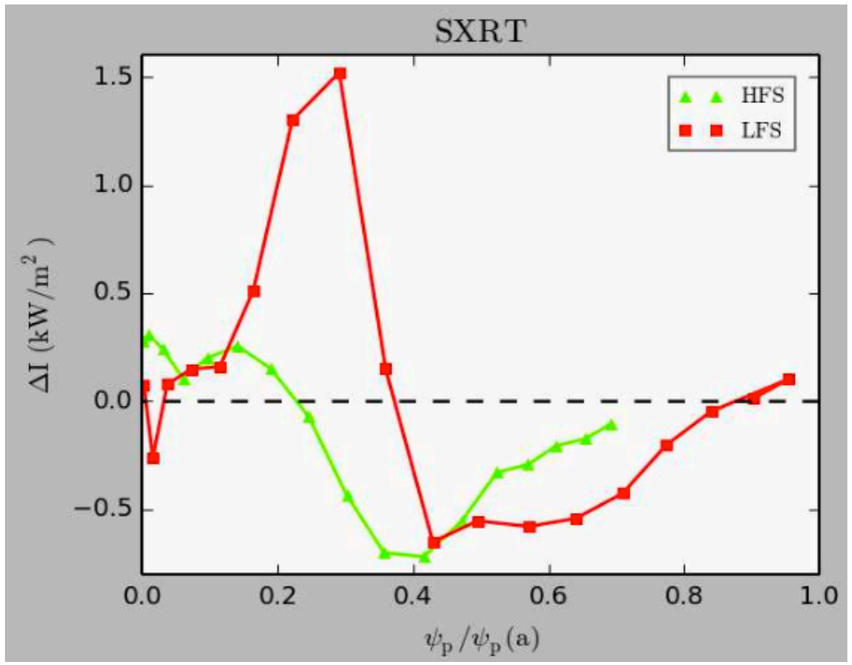


Finding the q=1 Surface – Results Cont.

- Below is for a single sawtooth
- Same results from previous slide translated to ψ_p given by TRANSP equilibrium from (R,Z) coordinates
- Inversion radius -> 0.4
- Mixing radius -> 0.5-0.8 ??
- Using ECE since it's a point diagnostic, there is a big difference between HFS vs, LFS



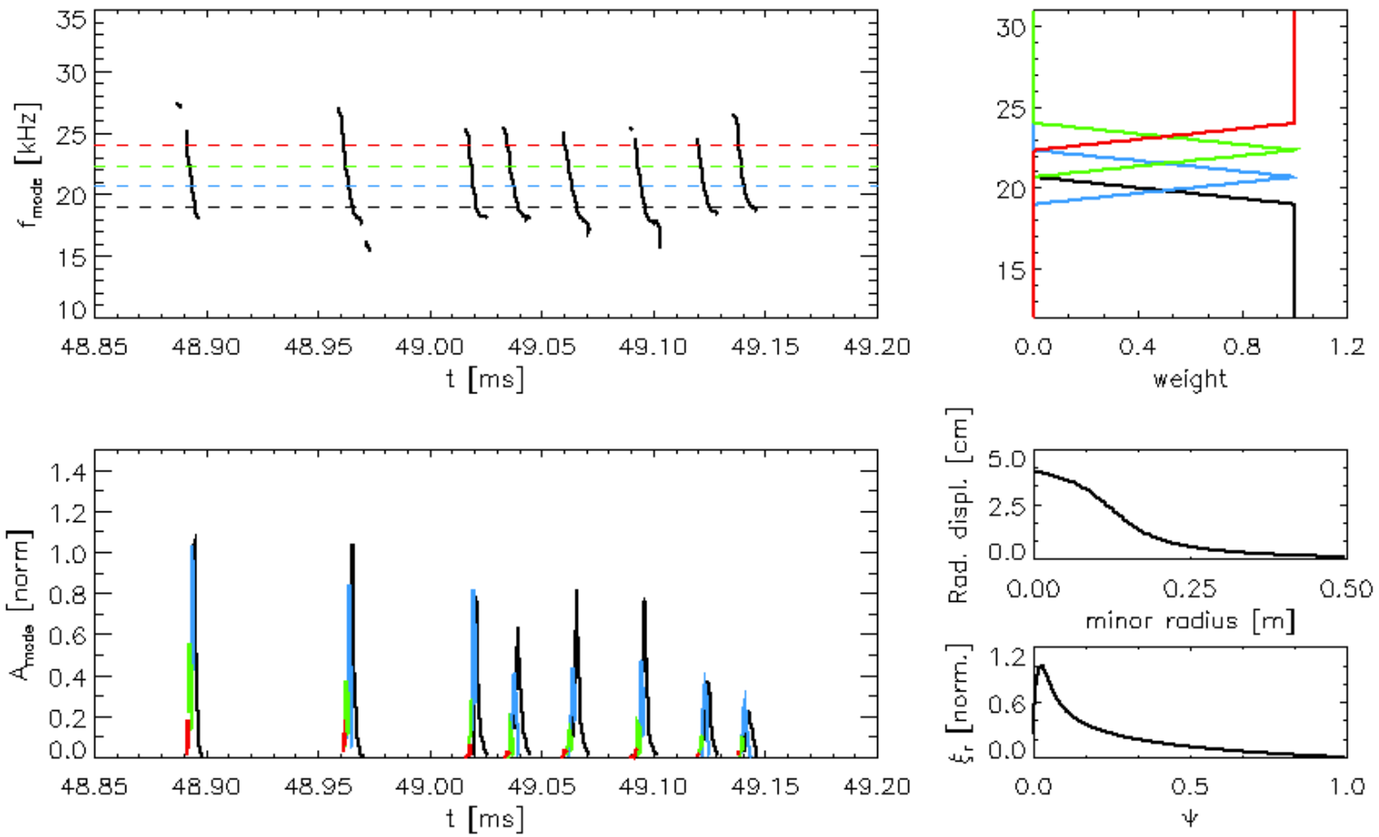




Fishbones are Decompose into Multiple Modes of Different Frequency

- Fishbones displacements are modeled as simple (1,1) kink modes
- The fishbones are broken up into multiple modes of varying frequency
- Frequency and amplitude are weighted by time

Fishbone Decomposition



*Podestà NucFus 2019

Can Examine the Differences in Resonances between Fast Ion Species with ORBIT-kick

Triton Kicks