Measurement and Modeling of Fast Ion Losses in JET Plasmas

P. J. Bonofiglo
Princeton Plasma Physics Laboratory, Princeton, NJ - USA

Acknowledgements: M. Podestà, V. Kiptily, R. Ellis, A. Horton, P. Beaumont, V. Goloborodko, F. E. Cecil, and JET Contributors*

EP Group Meeting
August 19, 2020
Princeton Plasma Physics Laboratory, Princeton, NJ - USA

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

Other Useful JET Diagnostics
- Neutral particle analyzers
- TAE antennae
- Edge magnetic coils
- Reflectometry
- Interferometry
- SXR
- ECE

*Darrow RSI 2004, 2006, 2010

Measurement and Modeling of Fast Ion Losses in JET Plasmas
(Bonofiglo, EP Group Meeting)
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 = 2\(^\text{nd}\) pylon from top, 1\(^\text{st}\) radial bin, 3\(^\text{rd}\) foil deep

**Energy Range per Foil†**

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

†Found via SRIM code

*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
• ± 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

<table>
<thead>
<tr>
<th>Old Acquisition</th>
<th>New Acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 16-bit, bipolar linear amps</td>
<td>• 16-bit, bipolar linear amps</td>
</tr>
<tr>
<td>• ± 200 𝜇A range</td>
<td>• ± 2000 𝜇A range</td>
</tr>
<tr>
<td>• 5 kHz sampling rate ADC</td>
<td>• 200 kHz sampling rate ADC</td>
</tr>
<tr>
<td></td>
<td>• Each channel is fully controllable via software</td>
</tr>
</tbody>
</table>

*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.

*Darrow RSI 2010, Cecil 2010 RSI

Measurement and Modeling of Fast Ion Losses in JET Plasmas
(Bonofiglo, EP Group Meeting)
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

Fishbone + Long-lived Mode Losses

Sawtooth Losses

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

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

*Bonofiglo RSI 2020

Measurement and Modeling of Fast Ion Losses in JET Plasmas
(Bonofiglo, EP Group Meeting)
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. $\Delta T_e$ calculated across crash for every ECE and SXR channel
2. Map inversion radius ($\Delta T_e=0$) 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 Radial Structure*

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

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

*Sawtooth Temporal Structure*

*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

0.95 MeV Deuteron Lost Dist. - FBM

0.95 MeV Deuteron Lost Dist. - CoM

KA2 Losses

\(\rho\)

\(P_{\psi}/\psi_w\)

\(\mu B_0/E\)
The Loss Detector is Sensitive to Trapped and Counter-Passing Orbits

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

Measurement and Modeling of Fast Ion Losses in JET Plasmas
(Bonifiglo, EP Group Meeting)
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
Can Examine the Differences in Resonances between Fast Ion Species with ORBIT-kick

Measurement and Modeling of Fast Ion Losses in JET Plasmas
(Bonfiglio, EP Group Meeting)
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: \( D+D \rightarrow H^3(1.01 \text{ MeV}) + p(3.02 \text{ MeV}) \) and \( D+\text{He}^3 \rightarrow \text{He}^4(3.54 \text{ MeV}) \)

**Fusion Product Losses**

**Sawtooth Losses**

**TAE Losses**

- Triton Sawtooth Losses
- Alpha Losses
- EAE losses post Sawtooth
- 1 Foil Deeper than Above
- New Pylon

8/19/20

Measurement and Modeling of Fast Ion Losses in JET Plasmas
(Bonofiglo, EP Group Meeting)
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 $\psi_p$ given by TRANSP equilibrium from (R,Z) coordinates
- Inversion radius $\to 0.4$
- Mixing radius $\to 0.5$-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

*Podestà NucFus 2019*
Can Examine the Differences in Resonances between Fast Ion Species with ORBIT-kick

Triton Kicks

E=898.750keV

E=1016.25keV

E=1133.75keV

E=1251.25keV

E=1368.75keV

E=1486.25keV

E=1603.75keV

E=1721.25keV

E=1838.75keV

E=1956.25keV

E=2073.75keV

E=2191.25keV

E=1016.25keV, max=44980, tot=154595

E=1251.25keV, max=20449, tot=154595

E=1603.75keV, max=22749, tot=154595

E=1956.25keV, max=24229, tot=154595

Measurement and Modeling of Fast Ion Losses in JET Plasmas
(Bonfiglio, EP Group Meeting)