Measurement of fast ion losses from JET: preliminary results

K. W. Hill,¹ D. Darrow,¹ F. E. Cecil,² R. Budny,¹ V Kiptily,³ M. Reich,⁴ T. Johnson,⁵ A. Salmi,³ and JET-EFDA contributors

¹ PPPL, Princeton, NJ, USA
² Colorado School of Mines, Golden, CO, USA
³ EURATOM/UKAEA Fusion Association, Culham Science Centre, UK
⁴ Max-Planck-Institut fur Plasmaphysik, EURATOM Association, Germany
⁵ Assoc. EURATOM-VR, Alfven Laboratory, Royal Institute of Technology, Stockholm, Sweden
Outline

Introduction

- Motivation
- Faraday Cups - energy, radial, poloidal, good time resolution
- Scintillator Probe - pitch angle, gyroradius, modest time resolution

Analysis of losses in TF Ripple Experiments

- NB fast ion studies
- TF Ripple Plasma Commissioning
- H-mode Ripple studies
- TF Ripple in Advanced Tokamak scenarios

Summary
Fast ion loss measurements are important

- Most auxiliary heating involves fast ions
  - NBI: < 160 keV
  - ICH tail: < 5 MeV
  - $\alpha$ particles: 3.5 MeV
- Loss means inefficient heating
- Concentrated loss may damage first wall
- Features of loss reveal details of physics within plasma
- Important to measure losses in ITER -> Faraday cups
  - Bakeable
  - Radiation hard
  - Low radiation noise
  - Large dynamic range
A Faraday-Cup array was installed in JET (Octant 7)
Faraday cups are positioned poloidally and radially

- Curved beam mounted on vessel wall below midplane
- 5 “Pylons” mounted on beam - poloidal resolution
- Each pylon contains up to 3 Faraday cup modules - radial resolution
FC detector orientation

Plasma moves along $\mathbf{B}$ much more rapidly than normal to $\mathbf{B}$

$\mathbf{B}$ nearly parallel to plane of foils, so no path exists for plasma streaming onto surface of foils

View radially outward

$\theta = 0 - 20^\circ$

$15 - 20^\circ$

$\mathbf{B}$

Detector

Beam
Thin foil Faraday cups allow energy resolution

Detector composed of multiple thin metal foils

- Metal foils separated by mica foils
- Ion energy determines deposition depth
- Ion current measured for each foil individually
- Current vs. depth gives energy distribution ($\Delta E \approx 30-50\%$)
Log amplifiers allow 9-decade current-measurement  100 pA - 10 mA

- Response of log amp to 9-decade calibration current source
Deuterons with $E < 0.78$ MeV don’t reach 2nd foil

## Energy ranges (MeV) for Ions in JET KA-2 foils

<table>
<thead>
<tr>
<th>Ion</th>
<th>proton</th>
<th>deuteron</th>
<th>triton</th>
<th>Helium - 3</th>
<th>alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard detector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (2.5 um)</td>
<td>0.0 - 0.50</td>
<td>0.0 - 0.54</td>
<td>0.0 - 0.53</td>
<td>0.0 - 1.58</td>
<td>0.0 - 1.58</td>
</tr>
<tr>
<td>2 (2.5 um)</td>
<td>0.68 - 0.98</td>
<td>0.78 - 1.18</td>
<td>0.78 - 1.25</td>
<td>2.26 - 3.49</td>
<td>2.35 - 3.68</td>
</tr>
<tr>
<td>3 (4.0 um)</td>
<td>1.15 - 1.52</td>
<td>1.35 - 1.83</td>
<td>1.45 - 2.21</td>
<td>4.00 - 5.42</td>
<td>4.24 - 5.87</td>
</tr>
<tr>
<td>4 (2.5 um)</td>
<td>1.65 - 1.83</td>
<td>2.00 - 2.26</td>
<td>2.24 - 2.53</td>
<td>5.81 - 6.57</td>
<td>6.32 - 7.17</td>
</tr>
</tbody>
</table>

| **15 MeV p detector** |        |          |        |            |       |
| 1 (2.5 um) | 0.0 - 0.50 | 0.0 - 0.54 | 0.0 - 0.53 | 0.0 - 1.58 | 0.0 - 1.58 |
| 2 (2.5 um) | 0.68 - 0.98 | 0.78 - 1.18 | 0.78 - 1.25 | 2.26 - 3.49 | 2.35 - 3.68 |
| 3 (4.0 um) | 1.15 - 1.52 | 1.35 - 1.83 | 1.45 - 2.21 | 4.00 - 5.42 | 4.24 - 5.87 |
| 4 (2.5 um) | 1.65 - 1.83 | 2.00 - 2.26 | 2.24 - 2.53 | 5.81 - 6.57 | 6.32 - 7.17 |
| 5 (25 um)  | 1.94 - 3.51 |        |        |            |       |
| 6 (75 um)  | 3.74 - 6.73 |        |        |            |       |
| 7 (500 um) | 6.76 - 17.83 |        |        |            |       |
| 8 (100 um) | 17.85 - 19.46 |        |        |            |       |

| **Hi E res** |        |          |        |            |       |
| 1 (1 um)    | 0.0 - .22 |        |        |            |       |
| 2 (1 um)    | 0.46 - 0.67 |        |        |            |       |
| 3 (1 um)    | 0.78 - 0.91 |        |        |            |       |
| 4 (1 um)    | 1.05 - 1.15 |        |        |            |       |
| 5 (1 um)    | 1.29 - 1.39 |        |        |            |       |
| 6 (1 um)    | 1.50 - 1.59 |        |        |            |       |
| 7 (1 um)    | 1.70 - 1.78 |        |        |            |       |
| 8 (1 um)    | 1.87 - 1.95 |        |        |            |       |
Some Faraday cups have special configurations

<table>
<thead>
<tr>
<th>$\Theta_{pol}, Z$</th>
<th>Inner (R)</th>
<th>Middle (R)</th>
<th>Outer (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$9^\circ$</td>
<td>standard configuration</td>
<td>standard</td>
<td>standard</td>
</tr>
<tr>
<td>$Z = -10 \text{ cm}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>standard</td>
<td>T/C*</td>
<td></td>
</tr>
<tr>
<td>$Z = -11 \text{ cm}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$21^\circ$</td>
<td>standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z = -31 \text{ cm}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$27^\circ$</td>
<td>15-MeV protons</td>
<td>standard</td>
<td>standard</td>
</tr>
<tr>
<td>$Z = -50 \text{ cm}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$33^\circ$</td>
<td>High E resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z = -68 \text{ cm}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total: 44 signals. Conduit can accommodate up to 46 wires. *T/C designates a position with a single foil and thermocouple.
Only front foils respond to NBI ion loss

- NBI only
- Deeper foils respond at noise level
- Proton E>~0.7 MeV required to penetrate to 2\textsuperscript{nd} foil
- Loss signal increases with $P_{nbi}$
Sawteeth modulate ICRH ion loss

- 3 MW ICRH
- Energetic ions penetrate to deeper foils
- Some log amplifiers saturated by large currents
Scintillator Probe in JET (Oct.4)

SP located in the lower limiter guide tube; coordinates of the SP: $R = 3.834\,\text{m}$, $Z = -0.277\,\text{m}$
Scintillator probe provides pitch-angle and gyroradius resolution

Ion selection is defined by the slit-geometry and magnetic field
- energy range selection
- pitch-angle range selection

Particle energy is linked to gyroradius of fast ions:

\[ r \propto \sqrt{mE_\perp / B_T Z} \]

Observation of lost ions:
- particles hit surface of the scintillating material (P56, \( \tau = 2 \) ms)
- light emission (611nm) allows to use conventional CCD camera (512x512 pixel, 10-50 Hz) and PMT detectors (4x4 PMT array, rate >1 kHz)

Scintillator probe provides 2D lost-ion images (pitch-angle & gyroradius)

KA3 detects particles with gyro-radius from 30 mm to 140 mm

Entrance aperture 1-m Au foil stop slow-energy ions (e.g. NBI): H, D < 150 keV; He < 250 keV
Grid lines indicate pitch angle and gyroradius

Collimator shape optimized in iterative process between CAD-design and orbit calculations using real model co-ordinates. 1-μ Au foil is installed to stop NBI-ions.

Scintillator probe

3D model

Gridlines indicate mesh of particle impact positions where they have constant pitch angle and gyro-radius respectively.

Development of the software for data evaluation and PPF generation is almost finished. (M.Reich, IPP)
Ion losses were analyzed in TF Ripple Experiments

- The 1\textsuperscript{st} foil signals of the FC system were used for analysis of NBI and low-energy ion losses in the following experiments
  - TF Ripple Plasma Commissioning
  - TF Ripple effect on NB fast ions
  - H-mode Ripple studies in low triangularity plasmas

- The 1\textsuperscript{st} foil currents were integrated over 1-s interval

- Fusion products and MeV-ion losses were analyzed with Scintillator Probe in experiments on ripple effects in Advanced Tokamak scenarios
Analysis of four experiments was done

<table>
<thead>
<tr>
<th>Commissioning - Restart TF</th>
<th>t=57-58s</th>
</tr>
</thead>
<tbody>
<tr>
<td>delta I imbalance(kA)</td>
<td></td>
</tr>
<tr>
<td>69178</td>
<td>42</td>
</tr>
<tr>
<td>69179</td>
<td>42 63.8/22.1</td>
</tr>
<tr>
<td>69180</td>
<td>0 42.5/43</td>
</tr>
<tr>
<td>69181</td>
<td>27</td>
</tr>
<tr>
<td>69186</td>
<td>27</td>
</tr>
<tr>
<td>69187</td>
<td>0</td>
</tr>
<tr>
<td>69198</td>
<td>0</td>
</tr>
<tr>
<td>69197</td>
<td>27</td>
</tr>
<tr>
<td>69199</td>
<td>0</td>
</tr>
<tr>
<td>69200</td>
<td>27</td>
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<table>
<thead>
<tr>
<th>H-mode - S1</th>
<th>t=60-62s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imax/Imin delta</td>
<td></td>
</tr>
<tr>
<td>69625</td>
<td>42/42</td>
</tr>
<tr>
<td>69631</td>
<td>0.73</td>
</tr>
<tr>
<td>69632</td>
<td>0.73</td>
</tr>
<tr>
<td>69633</td>
<td>0.64</td>
</tr>
<tr>
<td>69635</td>
<td>0.52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NB fast ions-H/M</th>
<th>t= 57-58s, 59.5-60.5s, 62.5-63.5s</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_max/I_min delta</td>
<td></td>
</tr>
<tr>
<td>69605</td>
<td>43/42 0.03 42.3/42.8</td>
</tr>
<tr>
<td>69606</td>
<td>47/38 0.4 47/38</td>
</tr>
<tr>
<td>69607</td>
<td>52/33 0.8 51.7/33.4</td>
</tr>
<tr>
<td>69608</td>
<td>56.6/29 1.1</td>
</tr>
<tr>
<td>69610</td>
<td>61/24 1.5 61.4/24.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AT scenarios - S2</th>
<th>t=45.025s</th>
</tr>
</thead>
<tbody>
<tr>
<td>no ripple</td>
<td></td>
</tr>
<tr>
<td>69685</td>
<td>1</td>
</tr>
<tr>
<td>69687</td>
<td>0.5</td>
</tr>
<tr>
<td>69689</td>
<td>1</td>
</tr>
<tr>
<td>69690</td>
<td>0.5</td>
</tr>
</tbody>
</table>

12th US-EU TTF Workshop, San Diego, CA, Apr 18, 2007
ELM amplitude reduced by ripple

Ripple plasma commissioning

Ripple $\delta = 0.1.5\%$

$\delta = \frac{B_{\text{max}} - B_{\text{min}}}{B_{\text{max}} + B_{\text{min}}}$

Low triangularity

H mode

Ripple $\delta = 0.1.0\%$

time (s)
TF Ripple - NB fast ion studies (Ian Jenkins)

\[ B_t = 2.2 \text{ T}, \quad I_p = 2.1 \text{ MA}, \quad \delta = 0 - 1.5\% \]
Front foils respond to NBI injection

- NB-fast-ion loss experiments
- No ELMs
- Ripple $\delta = 1.5\%$

MHD $n=1$

$S_x$, $D\alpha$, $P_{nb}$

time (s)
TF Ripple - NB fast ion studies (2)

Delayed losses relative to sawtooth crashes

On-axis NBI
80-keV, normal bank

Off-axis NBI
80-keV, normal bank

On-axis NBI
130-keV, tangential

The fast-ion signal peaks ≈20 ms after the sawtooth crash
In the off-axis NBI, the ST frequency monotonically increases with \( \delta \).

In the on-axis NBI (normal and tangential banks) that is not the case.
NB ion losses depend on ripple value.

In the case of the normal bank 80-keV NBI the losses are a bit higher than for the tangential bank 130-keV NBI. In the off-axis case the losses are intermediate.
TF Ripple - NB fast ion studies (5)

Losses show a poloidal dependence

![Graphs showing poloidal dependence of average ion flux.](image)
Marked front-foil signal and ELMS during NBI

- Ripple plasma commissioning experiments
- ELMs
- $I_{\text{max}}/I_{\text{min}} = 64/22$ kA
- Ripple $\delta = 1.5\%$

**Foil currents (A)**

- $P_{\text{nb}}$
- $D\alpha$
- $sx$
- MHD $n=1$

**time (s)**

12th US-EU TTF Workshop, San Diego, CA, Apr 18, 2007
Anomalies were observed for the shots with max/min injected NBI power (ELMs vs. ripple-loss competition?)

Losses monotonically decrease with ripple value.

Average ion flux, $\text{cm}^{-2} \text{s}^{-1}$

Imbalance, $\text{kA}$
TF Ripple Plasma Commissioning

**Losses monotonically increase with NBI power**

![Graph showing the relationship between NBI power and average ion flux with anomalies observed for shots with \( I_{imb} = 0 \).](image)

Anomalies were observed for the shots with \( I_{imb} = 0 \).

\[
\begin{align*}
Z &= -31 \text{ cm} \\
Z &= -50 \text{ cm}, R = 380 \text{ cm} \\
Z &= -54 \text{ cm}, R = 382 \text{ cm} \\
Z &= -57 \text{ cm}, R = 384 \text{ cm} \\
Z &= -68 \text{ cm}
\end{align*}
\]
Losses Increase with $D\alpha$
D$\alpha$ signal decreases with ripple amplitude.
Ion losses higher during ELM event

- Analyze losses during vs between ELMs
Front foils respond to NBI and ELMs - H-mode

- Low triangularity H-mode studies
- ELMs
- Ripple $\delta=0.5\%$
H-mode Ripple studies (low triangularity)

Poloidal and radial dependencies of losses

The losses decrease with ripple amplitude except for the measurements with largest ripple:

ELMs vs. Ripple loss (?)
TF Ripple in AT scenarios (4)

Scintillator Probe results

NBI on-axis
\[ P_{\text{NBI}} = 8.4 \text{ MW} \& 13 \text{ MW} \]
\[ P_{\text{ICRF}} = 3.0 \& 3.5 \text{ MW} \]

Fusion protons
\[ \langle E_p \rangle \sim 2.8 \text{ MeV} \]

Tail protons
\[ \langle E_p \rangle \sim 1.6 \text{ MeV} \]
and deuterons
\[ \langle E_d \rangle \sim 0.8 \text{ MeV} \]

Ripple: \( I_{\text{min}} / I_{\text{max}} = 0.5 \)

No ripple

Ripple effect?

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TF Ripple in AT scenarios (5)

Pulse No. 69689
No ripple
There are no losses with narrow pitch-angle distribution
@ $\theta \approx 55^\circ$ (ICRF power is too low?)

Pulse No. 69688
Ripple: $I_{\text{min}} / I_{\text{max}} = 0.5$
A component with $\theta \approx 75^\circ$ was observed in the off-axis case as well
Summary (1)

• Faraday cup and scintillator probe were used for measurements of fast-ion losses of the keV and MeV-ranges in the JET ripple experiments.

• A significant dependence of losses on $D\alpha$ was found, suggesting that substantial ion losses may take place due to ELMs.

• In the H-mode experiments:
  – ion losses decrease with $\delta$ except at the largest ripple value, where the increase suggests a competition of loss mechanisms (ELMs vs. Ripple).
  – there are significant $z$- and $R$-dependencies of the losses.
  – there is a monotonic increase of the losses with NBI power.
  – losses with normal bank NBI are higher than in the tangential bank case.
Summary (2)

• In the NB fast ion studies
  – the sawtooth frequency depends on the ripple value
  – delayed losses relative to the sawtooth crashes
  – there is an increase of losses with $\delta$
  – there is no strong link with the NB injection type

• In the AT scenarios
  – MeV-ion losses (fusion products and ICRF accelerated ions) were observed
  – there is evidence of MeV-ion redistribution due to the ripple
Future work

- Look at broader range of ion-loss data
  - MHD
  - TAEs
  - ELMs

- Compare ripple-experiment measurements with simulations from TRANSP/ORBIT, ASCOT - R. Budny, R. White, T. Johnson, A. Salmi, others

- Differentiate ELM vs ripple-loss contributions

- Correlate Faraday-Cup data with Scintillator-Probe data

- …
• Backup slides
Without ripple:
Initial torque of 18.4 Nm goes:
to \textit{wall} 0.2 Nm
to plasma through \textit{collisions} 4.8 Nm
to plasma through \textit{JxB force} 13.6 Nm
to \textit{coils} 0 Nm

1\% of ripple induces \(~\sim\~20\%\) of energy losses of NBI mostly outside $\rho_{pol} 0.7$

With ripple:
Initial torque of 18.4 Nm goes:
to \textit{wall} 3.1 Nm
to plasma through \textit{collisions} 4.6 Nm
to plasma through \textit{JxB force} -2.1 Nm
to \textit{coils} 12.8 Nm

1\% of ripple reduces \(~\sim\~85\%\) of the total torque from NBI
TF Ripple in AT scenarios (E. Joffrin)

**Scintillator Probe results**

NBI off-axis

\[ P_{\text{NBI}} = 8.5 \text{ MW } \& \text{ } 9 \text{ MW} \]

\[ P_{\text{ICRF}} = 3.7 \text{ } \& \text{ } 3.8 \text{ MW} \]

Tail protons

\[ <E_p> \sim 1.6 \text{ MeV} \]

and deuterons

\[ <E_d> \sim 0.8 \text{ MeV} \]

Ripple: \[ I_{\text{min}} / I_{\text{max}} = 0.5 \]

No ripple
TF Ripple in AT scenarios (3)

MeV-ion redistribution due to the ripple

Pulse No. 69685
No ripple

There are losses with narrow pitch-angle distribution @ $\theta \approx 55^\circ$ (deuterons?)

Pulse No. 69687
Ripple: $I_{\text{min}} / I_{\text{max}} = 0.5$

Pitch-angle distribution is broader, and a component with $q \gg 75^\circ$ was observed