Status of the JET Faraday cup lost alpha particle diagnostic KA-2

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*Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA Fusion Energy Conf. 2010, Daejeon, Korea
The JET lost alpha particle diagnostic KA-2 was installed in JET in 2005 to investigate lost energetic ions in general and lost alpha particles from possible future d-t plasmas in particular. We will summarize our operational experience with this diagnostic over the past six years. In particular we will describe the response of KA-2 to ICRH, scattered UV, Langmuir type behavior and various machine magnetic fields. We will also summarize the measurement of lost energetic ions during ICRH heated deuterium/helium plasmas during the 2009 JET campaign. Finally we will discuss the theoretical and experimental evidence for the insensitivity of this diagnostic to intense fluxes of fast neutrons as the basis for the consideration of such a device as a lost alpha diagnostic for ITER and other future burning plasma experiments.

This work supported in part by PPPL subcontract S010140-F and the U.S. Department of Energy and by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
(1) Conceptual design of KA2 Faraday Foil lost alpha diagnostic

(2) Measured and calculated responses of a set of thin Faraday foils as a lost alpha particle diagnostic for high yield d-t plasmas to:
   (a) Fast neutrons
   (b) Energetic gamma rays
   (c) UV radiation/Langmuir
   (d) ICRH
   (e) Time varying magnetic fields

(3) Recent observations on JET
   (a) Lost $\alpha$’s / d’s with energies up to 7 MeV during ICRH $^4$He plasmas
   (b) Energetic $^3$He/d’s during mode conversion plasmas
   (c) Rough calibration of KA3 PMT current during ICRH $^4$He plasmas
(1) Conceptual design JET Lost Alpha Diagnostic KA-2; 2005

2.5 um x 25 mm x 75 mm Ni foil

6.3-7.2 MeV alphas
1.7-2.5 MeV p, d, t

4.2-5.9 MeV alphas
1.1-2.2 MeV p, d, t

2.3-3.8 MeV alphas
0.7-1.2 MeV p, d, t

0-1.6 MeV alphas
0.5 MeV p, d, t

58Ni(n,p)

Schematic diagram of poloidal distribution of 5 sets of foils
Response (a): Fast neutrons

Calculation of fast neutron induced currents

\[ \varphi = \text{Neutron flux} = 6 \times 10^13 \text{ /cm}^2 \text{- s}; \]
\[ \sigma = \text{Cross section} = 6 \times 10^{-25} \text{ cm}^2; \]
\[ n = \text{Target density} = 2.1 \times 10^{19} \text{ /cm}^2; \]
\[ \text{reaction rate density} = \varphi \times \sigma \times n = 7.4 \times 10^8 \text{ /cm}^2 \text{- s} \]
\[ \text{predicted current} = -0.12 \text{nA/cm}^2 \]

Measurements of fast neutron induced currents (per cm² target)

<table>
<thead>
<tr>
<th>Machine</th>
<th>Flux(n/cm²/s)</th>
<th>Msd current</th>
<th>Pred current</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFTR(95)</td>
<td>1E12</td>
<td>&lt; 100 nA</td>
<td>0.1 nA</td>
</tr>
<tr>
<td>JET(97)</td>
<td>3E12</td>
<td>&lt;5 nA</td>
<td>0.3 nA</td>
</tr>
<tr>
<td>TRIGA(03)</td>
<td>1E13</td>
<td>1.2 nA</td>
<td>0.5 nA</td>
</tr>
<tr>
<td>JAERI(01)</td>
<td>3E14</td>
<td>30 nA</td>
<td>n/a</td>
</tr>
<tr>
<td>ITER</td>
<td>6E13</td>
<td></td>
<td>6 nA</td>
</tr>
</tbody>
</table>

Refs: a RSI 68, p. 363, b RSI 70, p. 1151, c RSI 74, p. 1749, d FED 56, p. 907
Response (b): Energetic gamma rays

Calculation of gamma ray induced currents (per cm\(^2\) target)

Attenuation coefficient at 5 MeV = 0.03 cm\(^2\)/gm

Thickness of 2.5 micron Ni foil = 0.002 gm/cm\(^2\)

Gamma ray flux = \(6 \times 10^{13}\) /cm\(^2\) - s;

Number absorbed = \(6 \times 10^{13} \left(1 - e^{-\text{Atten} \times \text{Thk}}\right)\)

= \(4 \times 10^{13}/\text{cm}^2\cdot\text{s} = 0.6\) nA/cm\(^2\)

Measurement of gamma ray induced currents (per cm\(^2\) target)

Induced charge from 2.5 micron foil \(\sim 2.5 \times 10^{-23}\) Coulomb/(\(\gamma\)/cm\(^2\))\(^a\)

Measured current for \(\gamma\) flux of \(6 \times 10^{13}\) /cm\(^2\) - s \(\sim 1.2\) nA/cm\(^2\)

Combined observed neutron/gamma insensitivity

Example: KA-1 on JET for 16 MW d-t pulse

**Total neutron yield JPN42976**

Neutrons/sec

-10 -5 0 5 10 15

Time (sec)

**KA1 f2-f4 JPN42976**

Net foil current (nA)

-10 -5 0 5 10 15 20

Time (sec)
Response (c): Scattered UV/Langmuir

Observation of significant (µA) current during Ohmic heating
Observed strong correlation with bolometer which is a good measure of UV/Langmuir.
Comparison of front foil current and bolometric power

Conclusion ~ 6 µA front foil current per MW total bolometric power:

Solution: 1) Install very thin (0.1 µm) Ni foil to suppress UV/low energy ions
2) Measure BOLO and subtract using 6 µA /MW
Response (d): >100 µA of noise during high power (6 MW) ICRH

Solution: reduce noise by >100 with passive filters at amps

Comparison of foil currents for JPN 75699 (with 4.5 MW of RF power) where filters have been installed on KA2-415, 416 and 417 and JPN 74285 with no filters. Note that the currents in these three foils are at the 100 nA level whereas the currents in the unfiltered foils exceed 100 µA.
Response (e): Correlation between KA2 total current density and time derivative of Toroidal magnetic field (but NOT other magnetics)
Solution: subtract induced current by measuring $dI/dt$ and using approximate correlation coefficient $J_{Tot} (A/m^2) \sim 4.5 \times 10^{-8} (s/m^2) dI/\text{dt} (A/s)$
Recent observation of energetic charged particles

Observation (a): Lost alpha particles (or deuterons) with energies up to about 7 MeV (4 MeV) generated during ICRH (up to 6 MW) $^4$He/d plasmas
KA2 112, 113, and 114 (6.3 to 7.2 MeV)

JPN 79171

Alphas ?
2.3-3.7 MeV
4.2-5.9 MeV
6.3-7.2 MeV
deuterons ?
2-2.3 MeV

MW
ICRH
NBI

nA
0
11
60
0
11

s
10
14
18
60
Foil currents at increasing RF power

- k112
- k113
- k114 \times 2

Net Foil Current (nA) vs RF power (MW)
Energy spectra at top detector for different RF powers

Alphas

Net Foil Current (nA) vs. Average energy (MeV)

RF 5.7 MW
RF 4.4 MW
RF 3.7 MW
RF 2.9 MW
Correlation between foil current and electron temperature

- Foil 114 x 10
- Foil 113
- Foil 112
2.24 MeV tail temperature good fit to foil current vs depth

- Pylon 3, first stack; Data averaged over RF pulse duration

\[ T_{\text{eff}} = 2.24 \text{ MeV} \]
Radial scrape off length ~4 cm

- Data from top pylon (near midplane)
- Both energy ranges show similar scrape off length

![Graph showing current (nA) vs. detector distance behind limiter (cm) with two curves. The first curve with lambda = 4.1 cm and E = 2.3–3.7 MeV and the second curve with lambda = 4.3 cm and E = 4.2–5.9 MeV.](image-url)
Observation (b): Poloidal distribution of lost energetic 3He during JPN 79341 mode conversion plasma.

Note very weak correlation between front foil currents and bolometer (recall slide 10 above).
Poloidal distribution front foil currents JPN 79341

Foil current (A)

Angle below machine midplane

-15 -10 -5 0 5 10 15 20 25 30

Foil current (A)

1.E-07 1.E-06 1.E-05 1.E-04

Angle below machine midplane

-15 -10 -5 0 5 10 15 20 25 30

Foil current (A)

1.E-07 1.E-06 1.E-05 1.E-04

Poloidal distribution front foil currents JPN 79341
JPN 79352: Note that peak current occurs at later times for foils closer to machine midplane; rising at about $9^o/\text{sec.}$
Observation (c): Calibration of KA3 PMT during ICRH $^4$He plasmas

Focal plane image of KA3 Scintillator Probe of α’s up to 3.7 MeV or d’s up to 1.9 MeV

Pulse: 79168, time: 14.025 s, field: 1.76018 T

CCD-Intensity scale
Comparison of KA3 total PMT current and KA2 foil 312 during JPN 79168 ICRH $^4$He plasmas
Conclusion: 8 nA of KA3 total PMT current corresponds to about 1E-4 A/m² of KA2 312 current density (same poloidal height as KA3) during ICRH ⁴He plasmas.
Conclusions

• Faraday cup lost ion detector capable of operating in ITER like conditions for alpha currents > 10 nA/cm²

• Lost alpha/deuteron signals measured on JET for ICRH $^4$He d-t simulation plasmas

• Poloidal distributions measured during $^3$He mode conversion experiment

• KA2 data (KA2-312 at same height as KA3) will allow absolute calibration of KA3 scintillator losses