UK Atomic Energy Authority

UKAEA

Advanced application: Activation calculations for spectrum unfolding and neutron diagnostics

C.R. Nobs

Applied Radiation Technology Group

Outline

UK Atomic Energy Authority

- Overview of neutron activation and transmutation
- Introduction to neutron spectrum unfolding
- Using FISPACT-II to calculate high-resolution gamma spectra
- UKAEA's unfolding code suite
- Current and future developments

This talk will focus a lot on fusion applications, though the processes and analysis is transferrable to fission and any field where neutrons are relevant.

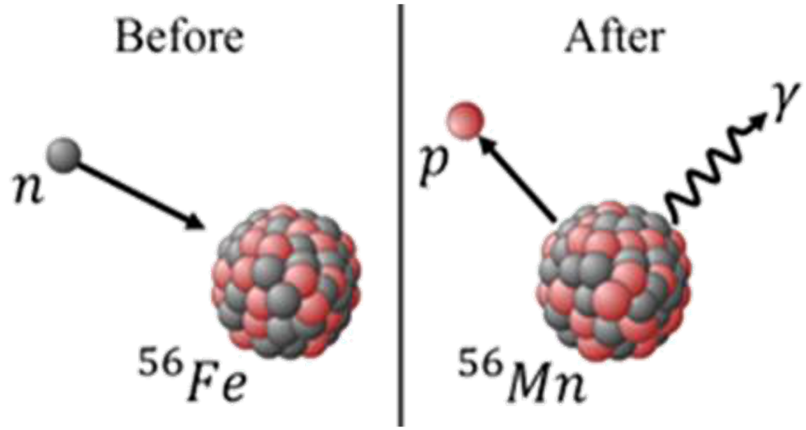
Neutron activation

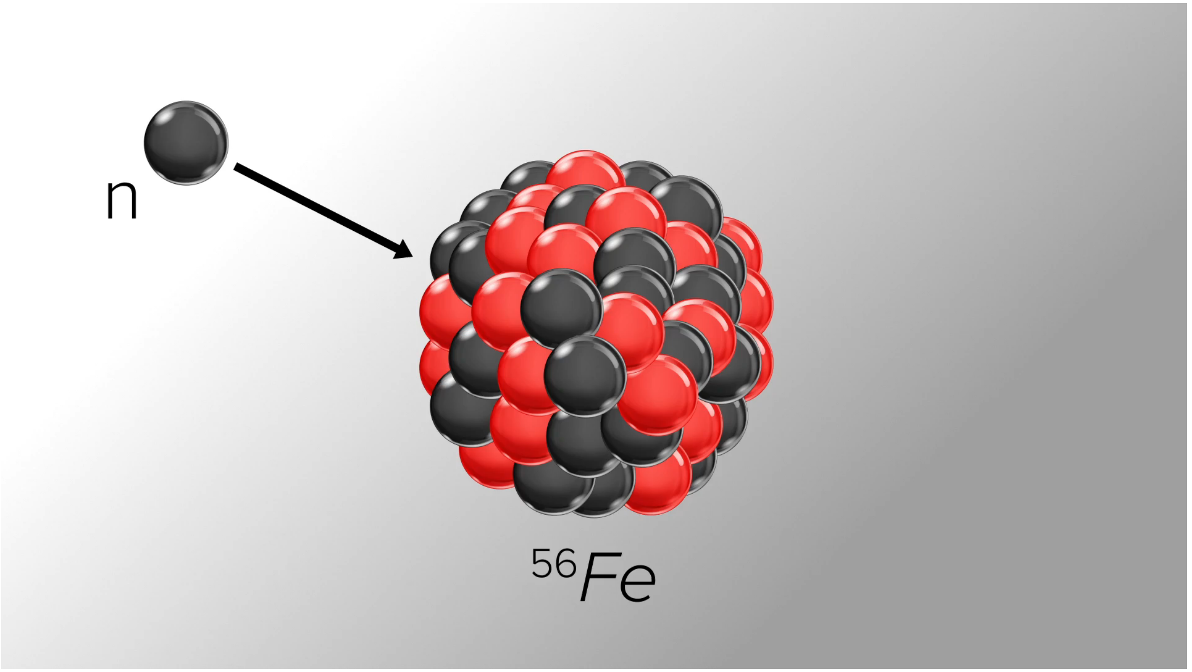
- Neutrons collide with anything in range

  e.g. structural material coolant

- With sufficient energy the neutrons can change materials and make them radioactive
- Probability of a reaction taking place is known as the cross-section

Fe56(n,p)Mn56



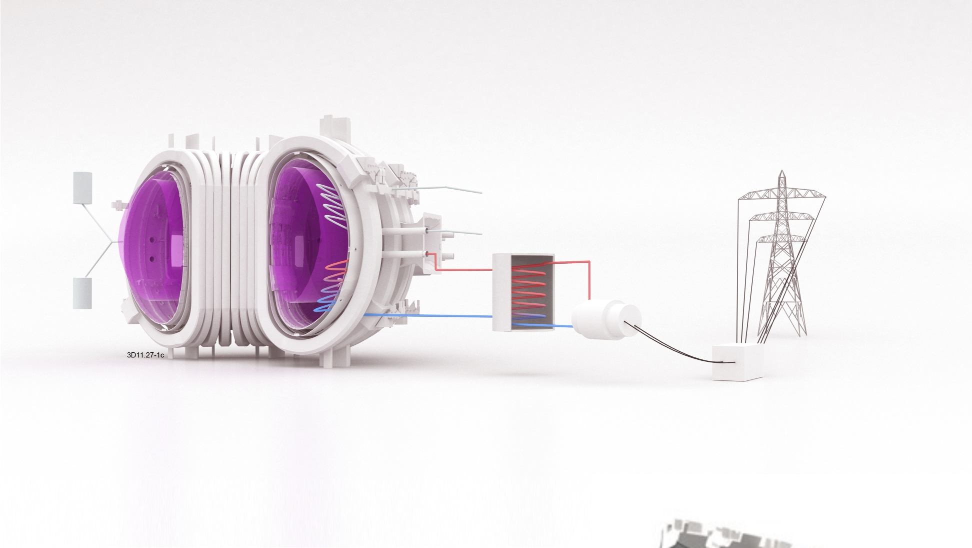


The importance of neutron monitoring

It is important to understand the neutron energy spectrum:

- predict radioactivity in future waste
- Monitor the nuclear performance of the plasma
- Measure key nuclear parameters
  - Tritium breeding ratio
  - Nuclear heating of components

Feeds into decommissioning and design



Neutron diagnostics in fusion

Direct methods

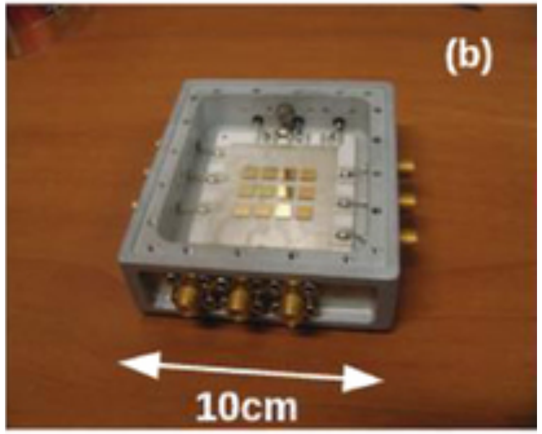
- Scintillators require sensitive electronics
- Diamond detectors have limited dynamic range
- Fission chambers are challenging to calibrate and won’t provide the energy spectrum

Scintillators

Indirect methods

Activation foils are robust and cheap but cannot provide real-time measurement and require an ancillary gamma-spectroscopy lab.

Diamond detectors



Fission chambers

Activation foil diagnostics

Activation foils: high-purity material samples

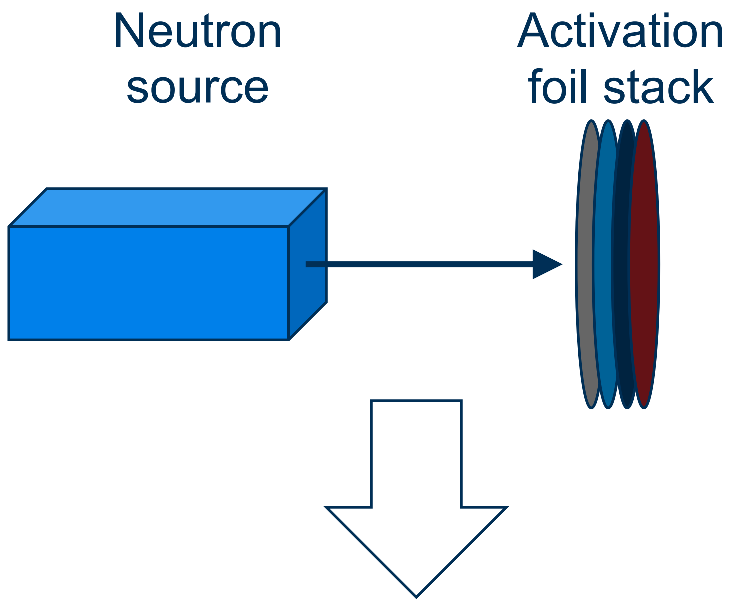
Selected based on the irradiation environment and activation characteristics:

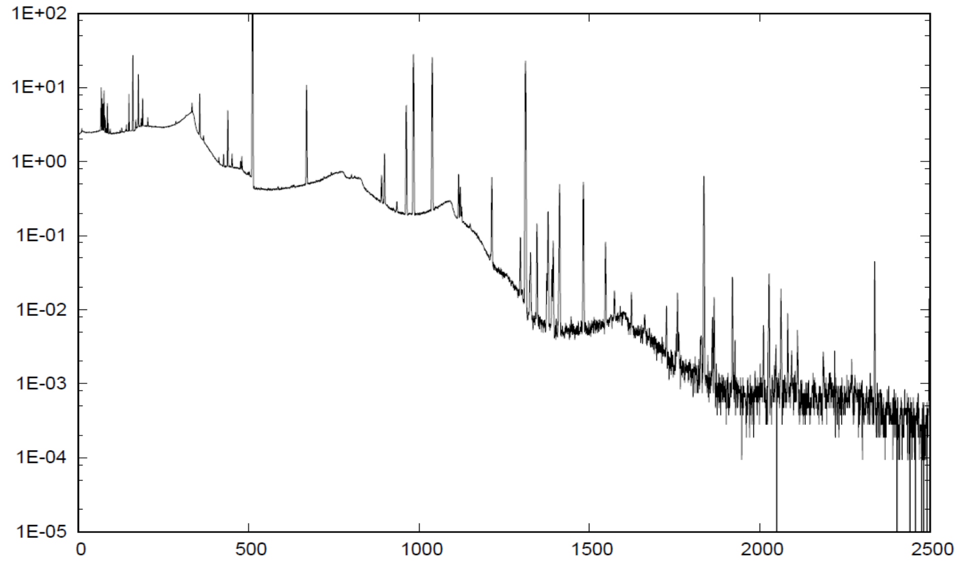
- Do they need to survive fusion environments?
- Are the half-lives long enough to provide reasonable statistics?
- Do the gamma-peaks overlap?
- Do the materials undergo threshold and capture reactions?

Following irradiation foils are extracted and activity is measured using an HPGe detector.

$$M_{0n} = \frac{A_n}{1 - \exp(-\lambda_n T)}$$

A_n - measured activity (decay corrected)
λ_n - product nuclide decay constant
T – total irradiation time





UK Atomic Energy Authority

Neutron spectrum unfolding: at a glance

UK Atomic Energy Authority

Linear least square method

- STAY'SL, LSL, MSITER(MINCHI), DIFBAS, DIFMAZ and LEPRICON

Non-linear least square method

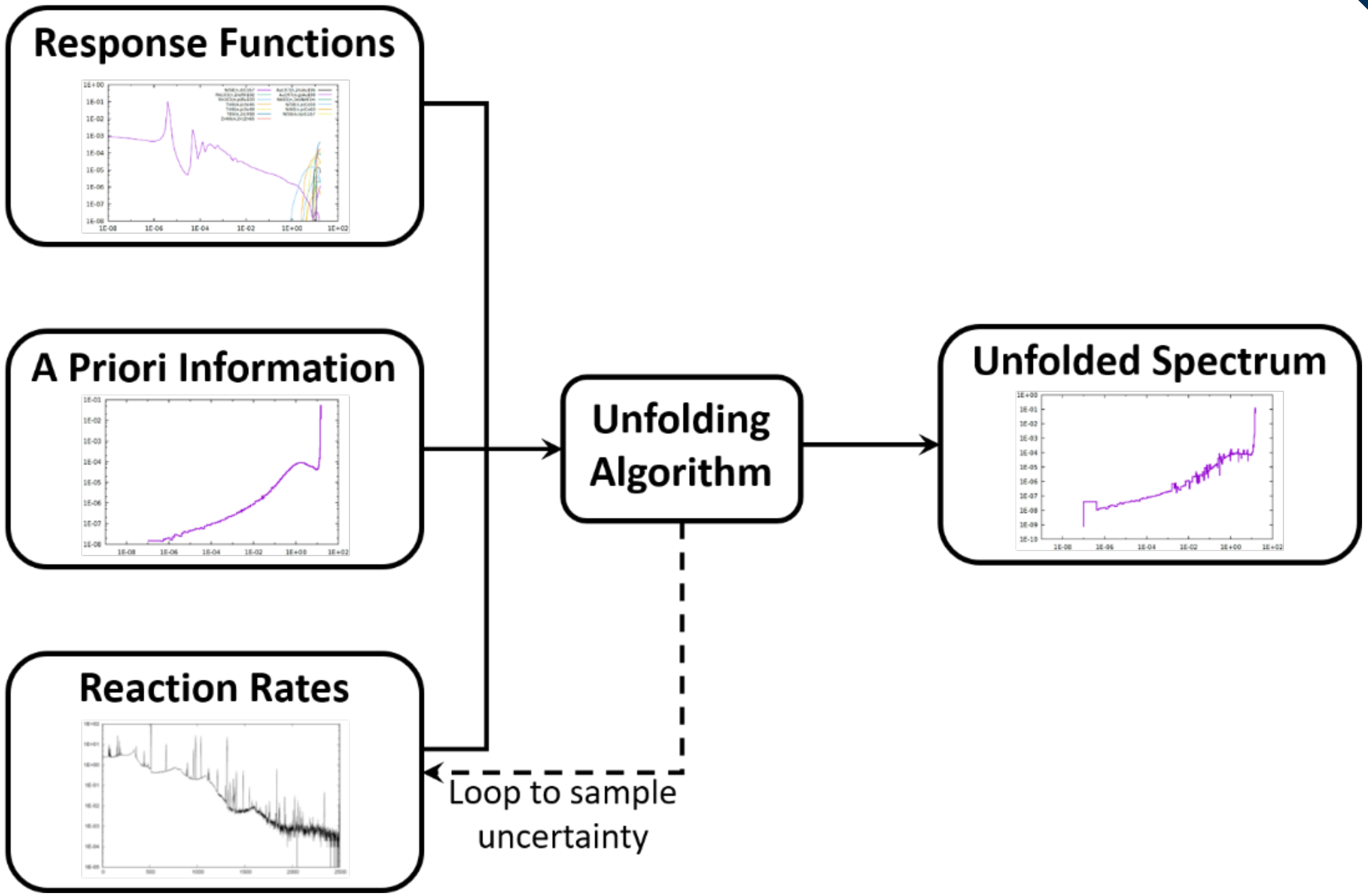
- SAND-II, LSL-M2, BUNKI(SPUNIT), LOUHI and GRAVEL /GRAVELW(SAND-II)

Maximum entropy method

- MAXED, UNFANA and MIEKE

Machine learning

- BUGS (NN) and BONDI-97 (GA)

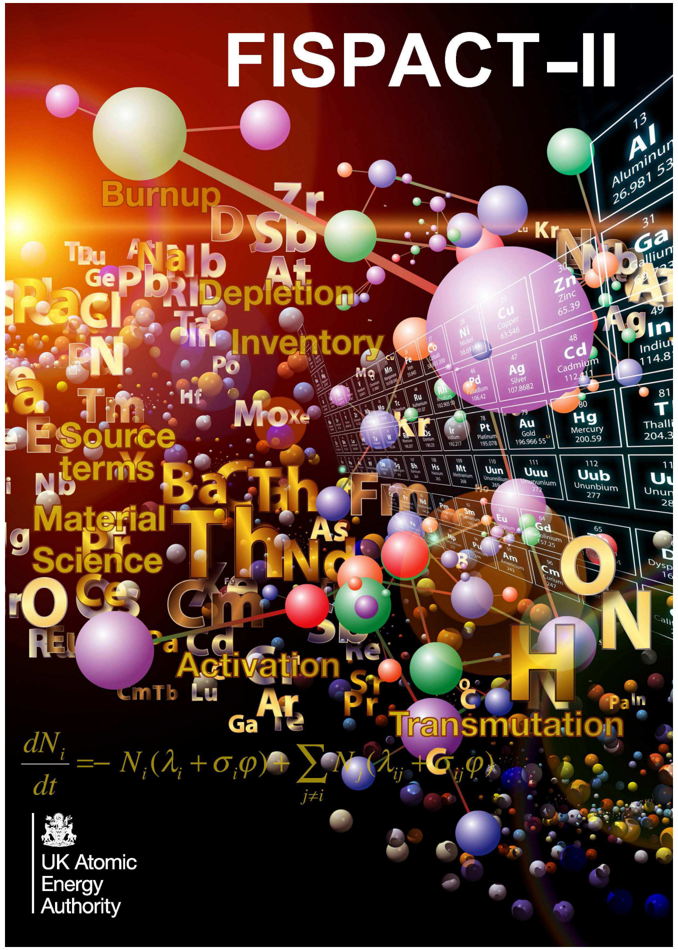


FISPACT-II

- Foil selection
  - Allows us to practice the experiment
  - Selecting foils based on half-life, reaction cross-section, gamma-lines

- Comparison between experiment and calculation
  - Outputting the gamma-spectra in fine energy group structure allows direct comparison with measured spectra

- Experimental safety
  - Dose rate predictions



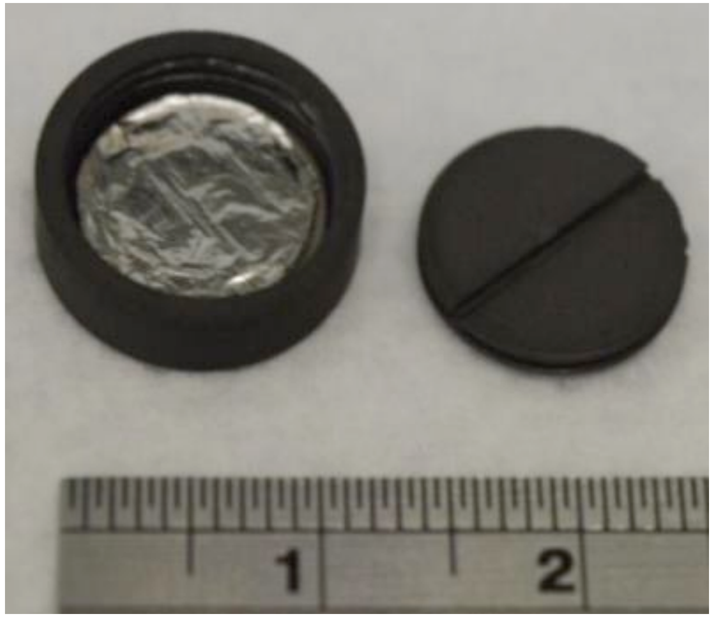
Example

Work performed under: *EUROfusion Consortium*
WP-ENR: Enabling Research
Project: AWP17-ENR-MFE-NCSRD-02

VERDI Project – Novel Neutron Detector for Fusion

Aim

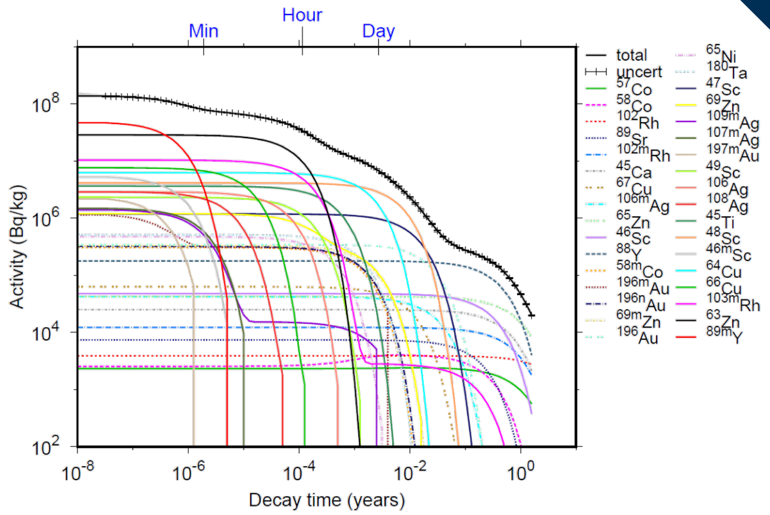
Develop a robust detector to accurately monitor neutrons and withstand the harsh conditions of the fusion environment.

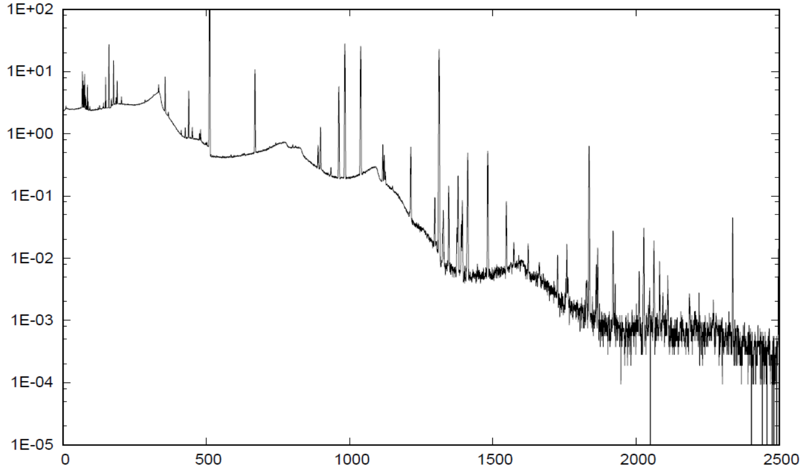


Activation foil technique can be limited by melting points, material properties (powder, brittleness).

Key novelty: Low activation matrix capsule and selection of activation foils (Au, Nb, Ni, Rh, Ti, Zn, Y_2O_3 powder)

- High intensity gamma lines
- Minimal interference between gamma lines
- High cross section
- High melting point (>800^{o}C)

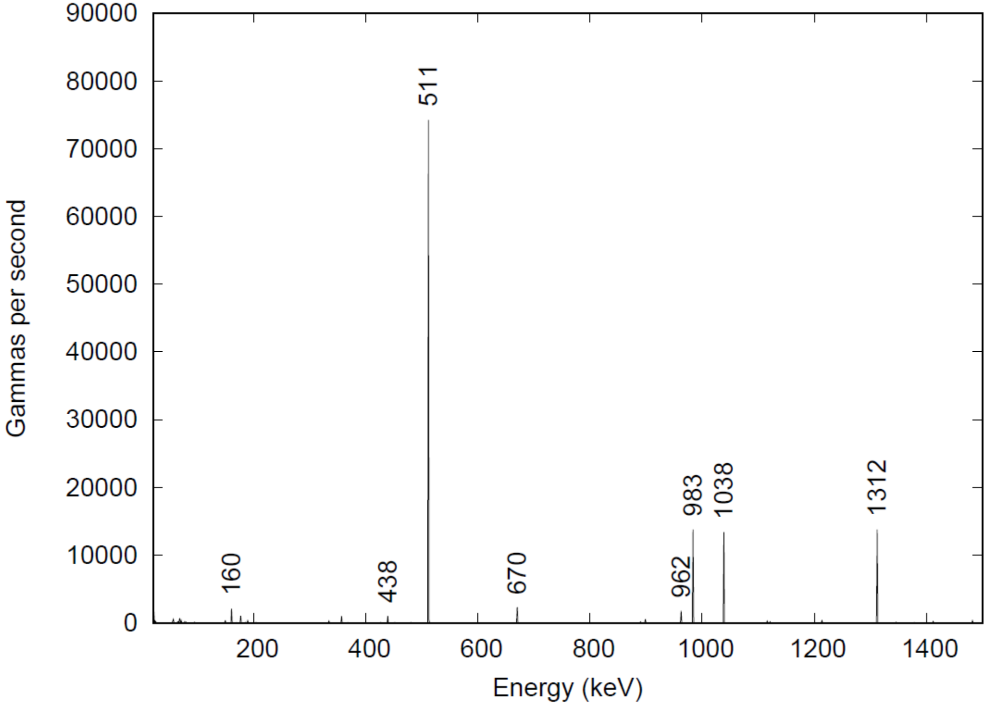




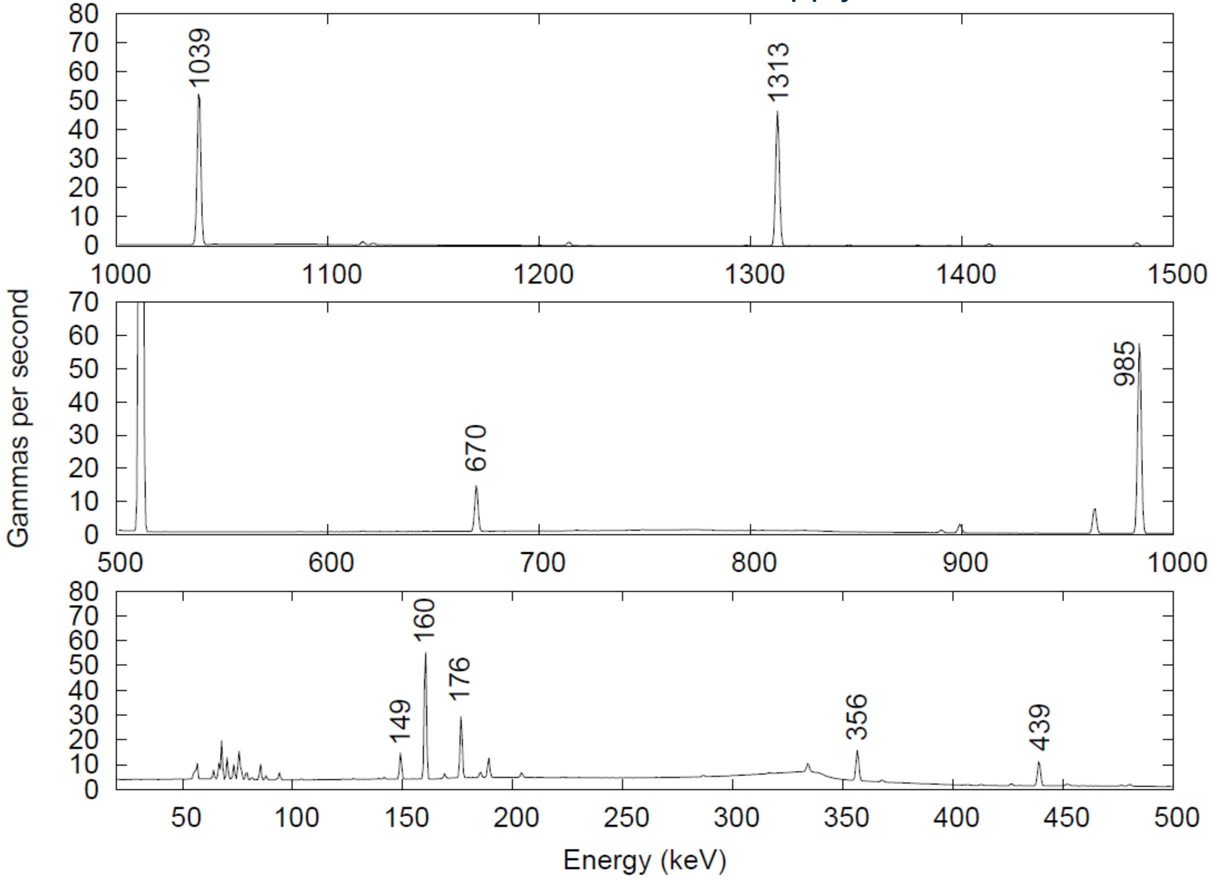
Fine gamma group structure

Outputting to fine energy bin structure – check for overlaps, put through detector model to generate efficiencies and GEB and ascertain whether foils will have enough activity

Instantaneous spectrum – FISPACT-II



MCNP detector model to apply GEB



Pathways analysis

Really useful tool for planning and pre-analysis.

Support post-analysis and nuclide identification.

```
Target nuclide Y  89m     99.988% of inventory given by  1 path
--------------------

path  1  99.988% Y  89 ---(R)--- Y  89m---(S)---
                   100.00%(n,n)

Target nuclide Zn 63    100.000% of inventory given by  1 path
--------------------

path  1 100.000% Zn 64 ---(R)--- Zn 63 ---(S)---
                   100.00%(n,2n)

Target nuclide Ti 45     99.969% of inventory given by  1 path
--------------------

path  1  99.969% Ti 46 ---(R)--- Ti 45 ---(L)---
                   100.00%(n,2n)

Target nuclide Sc 48    100.000% of inventory given by  2 paths
--------------------

path  1  99.215% Ti 48 ---(R)--- Sc 48 ---(L)---
                   100.00%(n,p)

path  2   0.790% Ti 49 ---(R)--- Sc 48 ---(L)---
                    62.00%(n,np)
                    38.00%(n,d)

Target nuclide Sc 50    100.000% of inventory given by  2 paths
--------------------

path  1  87.094% Ti 50 ---(R)--- Sc 50 ---(S)---
                   100.00%(n,p)

path  2  12.906% Ti 50 ---(R)--- Sc 50m---(d)--- Sc 50 ---(S)---
                   100.00%(n,p)    100.00%(IT)

Target nuclide Cu 66     99.988% of inventory given by  2 paths
--------------------

path  1  93.042% Zn 66 ---(R)--- Cu 66 ---(S)---
                   100.00%(n,p)

path  2   6.946% Zn 67 ---(R)--- Cu 66 ---(S)---
                    84.63%(n,np)
                    15.37%(n,d)
```

Experimental testing

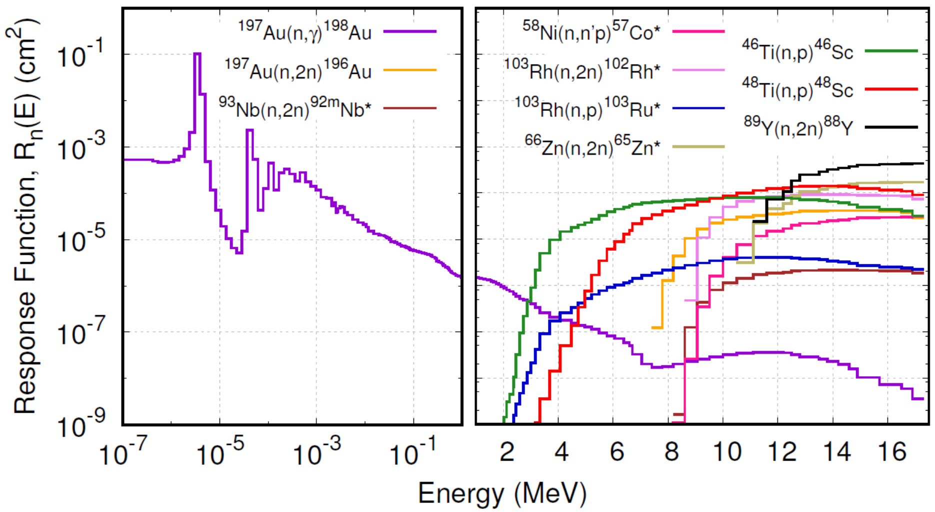
UK Atomic Energy Authority

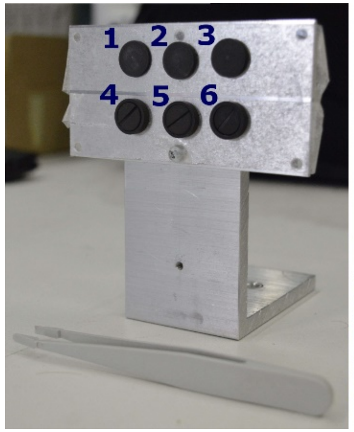
Testing of prototype detectors:

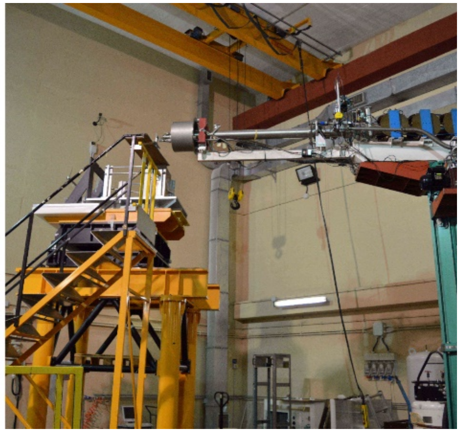
- Irradiated under a 14 MeV neutron field at FNG for ~3 hours
  Activity measured ~10 days after end of irradiation at NCSRD, using HPGe detector.
- Activity measurements compared with MCNP simulations and FISPACT-II calculations, an average C/E value of 1.05±0.13 was achieved (spectrum fluence a factor of 1.05 higher than the *a priori* spectrum.

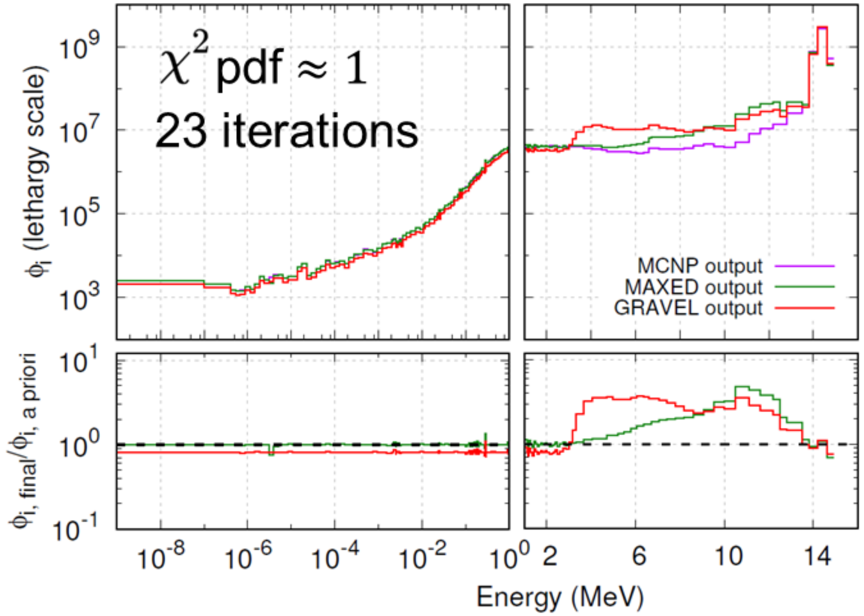
$$R_n(E) = N_d V \sigma_n(E)$$

N_d - number density
V – volume of activation foil
$\sigma_n(E)$ – cross-section









C.R. Nobs *et al.*, Neutron Spectrum Unfolding for the Development of a Novel Neutron Detector for Fusion, Fus. Eng. Des., **146** 2019
M.I. Savva *et al.*, VERDI detector benchmark experiment at the ENEA 14 MeV Frascati Neutron Generator, Fus. Eng. Des., **146**, 2019

Experimental testing

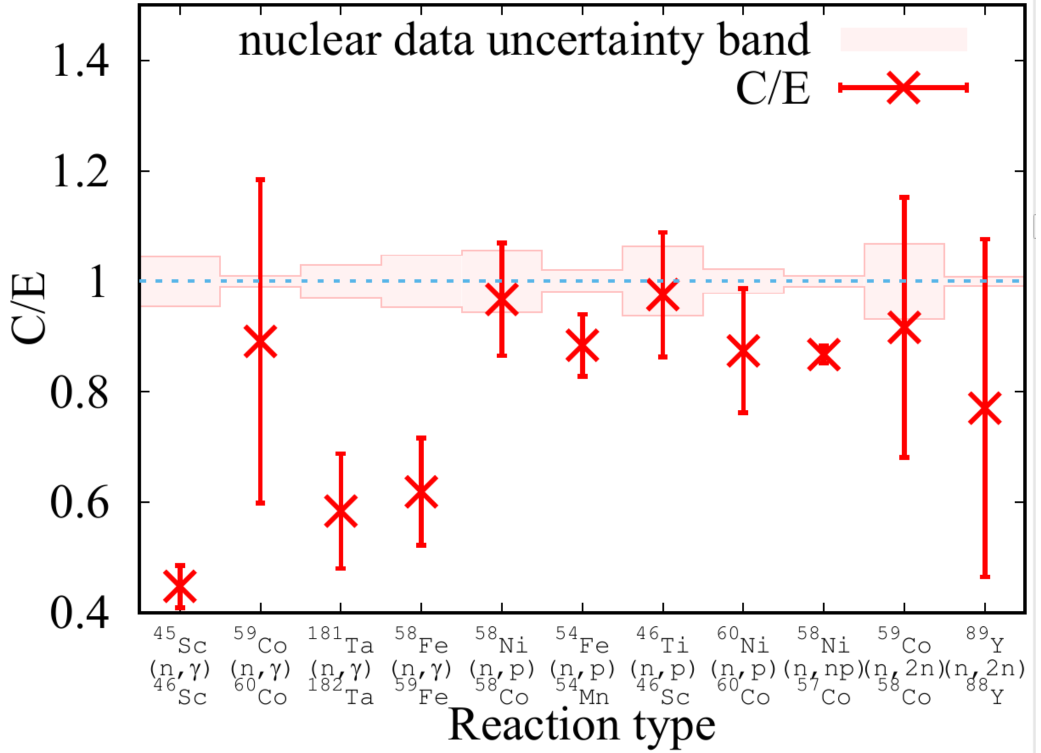
JET activation project

Objective:
To characterise irradiation locations at JET

Activation foils installed in sample holder which was installed inside the JET vessel at the long-term irradiation station

Diagnostic foils (Ti, Co, Ni, Y, Fe, Sc, Ta) irradiated in recent JET DD operations, with 99% DD and 1% DT neutrons

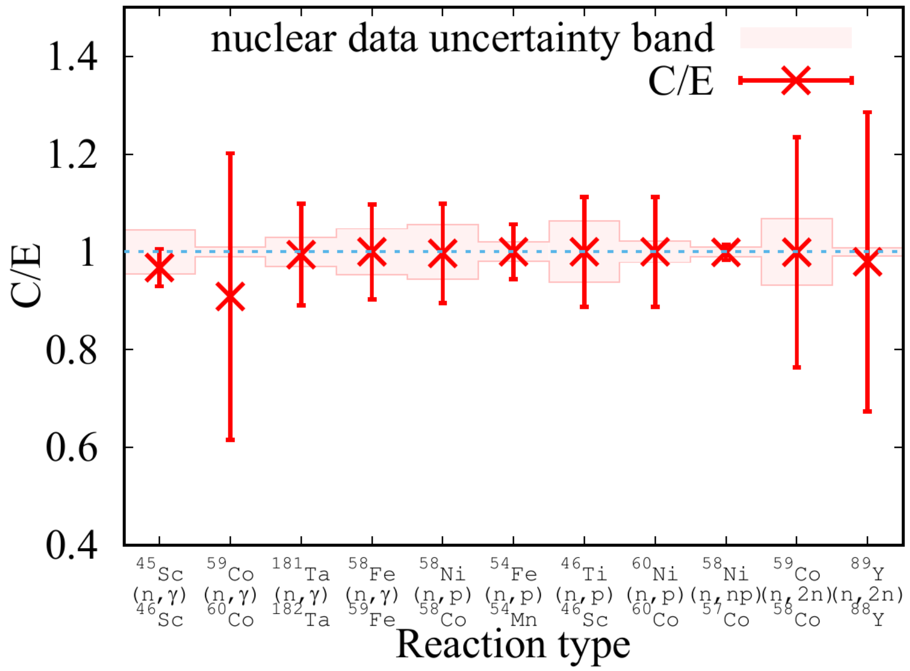
Cumulative irradiation time 446 days

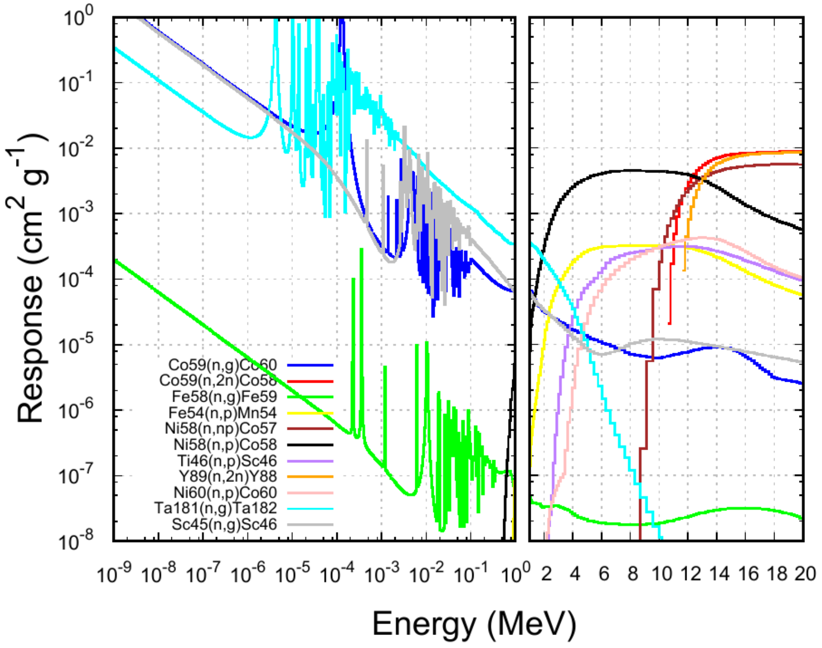


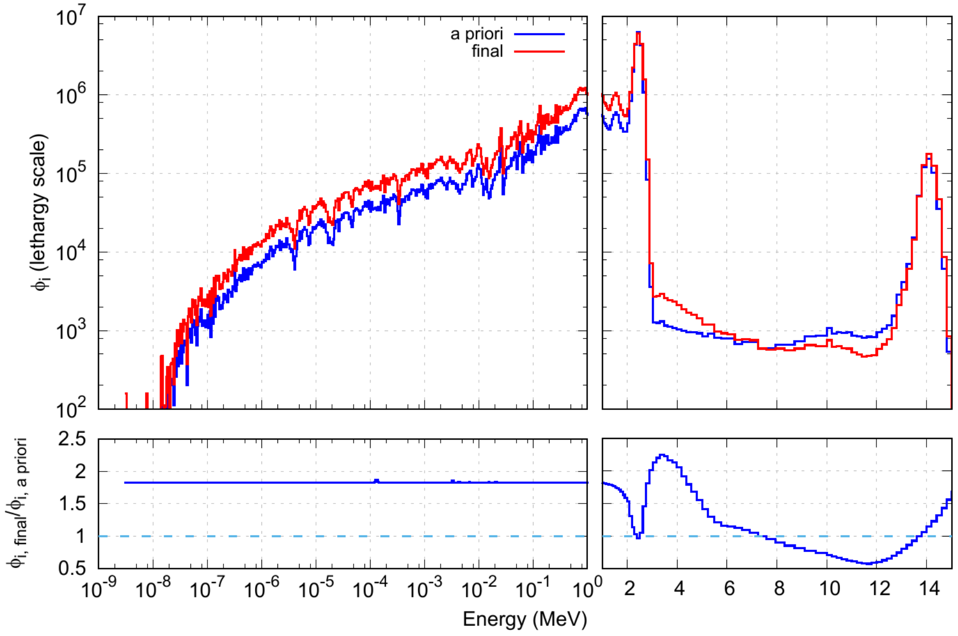
Full details: L.W. Packer *et al.* Nuclear Fusion 58 (9) 2018 096013

Experimental testing

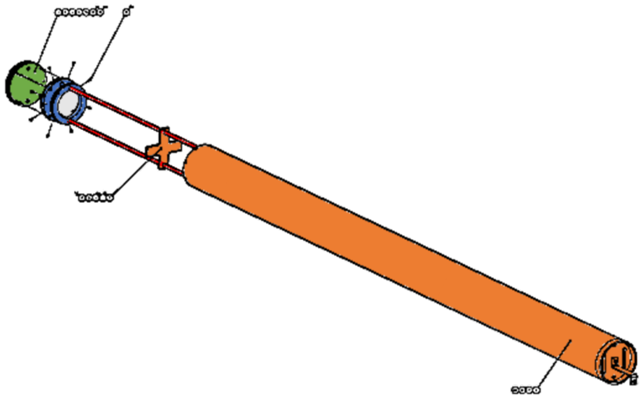
Final spectrum fluence: a factor of 1.57 higher than the *a priori* spectrum. Corresponding to 1.82 between 0-2 MeV, 1.08 between 2-10 MeV and 1.1 above 10 MeV.

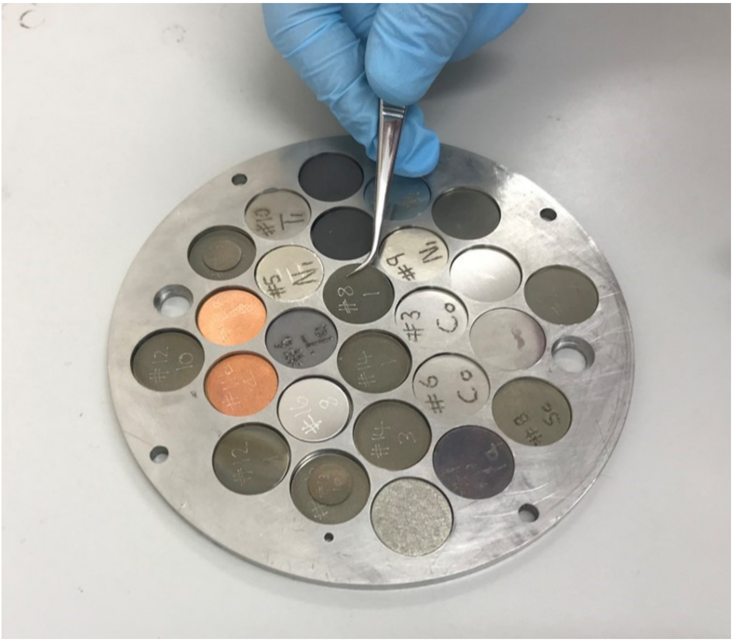






Upcoming experiments





FISPACT-II equations used for the semi-infinite slab model to calculate the contact dose rate of the cassette and samples.

Contact dose rate measured = 65 uSv/hr
Contact dose rate calculated = 93 μSv/hr

Point source model used to calculate dose rate at a distance.

Neutron yield (14 MeV)	DTE2 contact dose rate (μSv/hr) @ 180 days cooling time (Irradiation schedule: neutrons all in one shot)		
	Contact dose rate*	Dose rate at 30 cm **	Dose rate at 100 cm **
3×10^{20}	821	35.7	1.1
7×10^{20}	1918	83.4	2.6
1×10^{21}	2738	119.2	3.7
1.3×10^{21}	3560	155	4.8
1.7×10^{21}	4655	202.7	6.3

ADRIANA gamma-spectroscopy lab

Advanced Digital Radiometric Instrumentation for Applied Nuclear Activities

Trans-SPEC Portable HPGe detector

SAGe well detector

BEGe detector with NaI Compton suppression

190% RE coaxial HPGe detector

State of the art equipment for measurement and characterisation of radioactive material.

A range of high-specification, low background, high-resolution gamma spectrometry systems are available to academia and industry.

NNUF
National Nuclear User Facility

Summary

- Neutron monitoring is a vital tool for fusion research
- Relies heavily on the capabilities provided by FISPACT-II
- FISPACT-II can be used for pre-analysis and experimental preparation, planning for safety requirements, and supporting post-analysis for activation foil based neutron monitoring
- Lots of useful keywords that provide important user definitions for gamma spectra