Technology exploitation at JET: recent and planned activation experiments, and supporting analysis using TENDL

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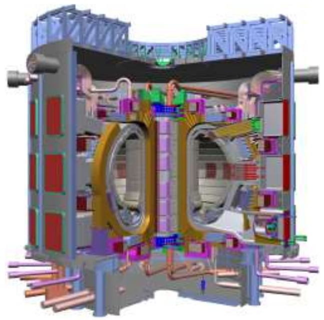
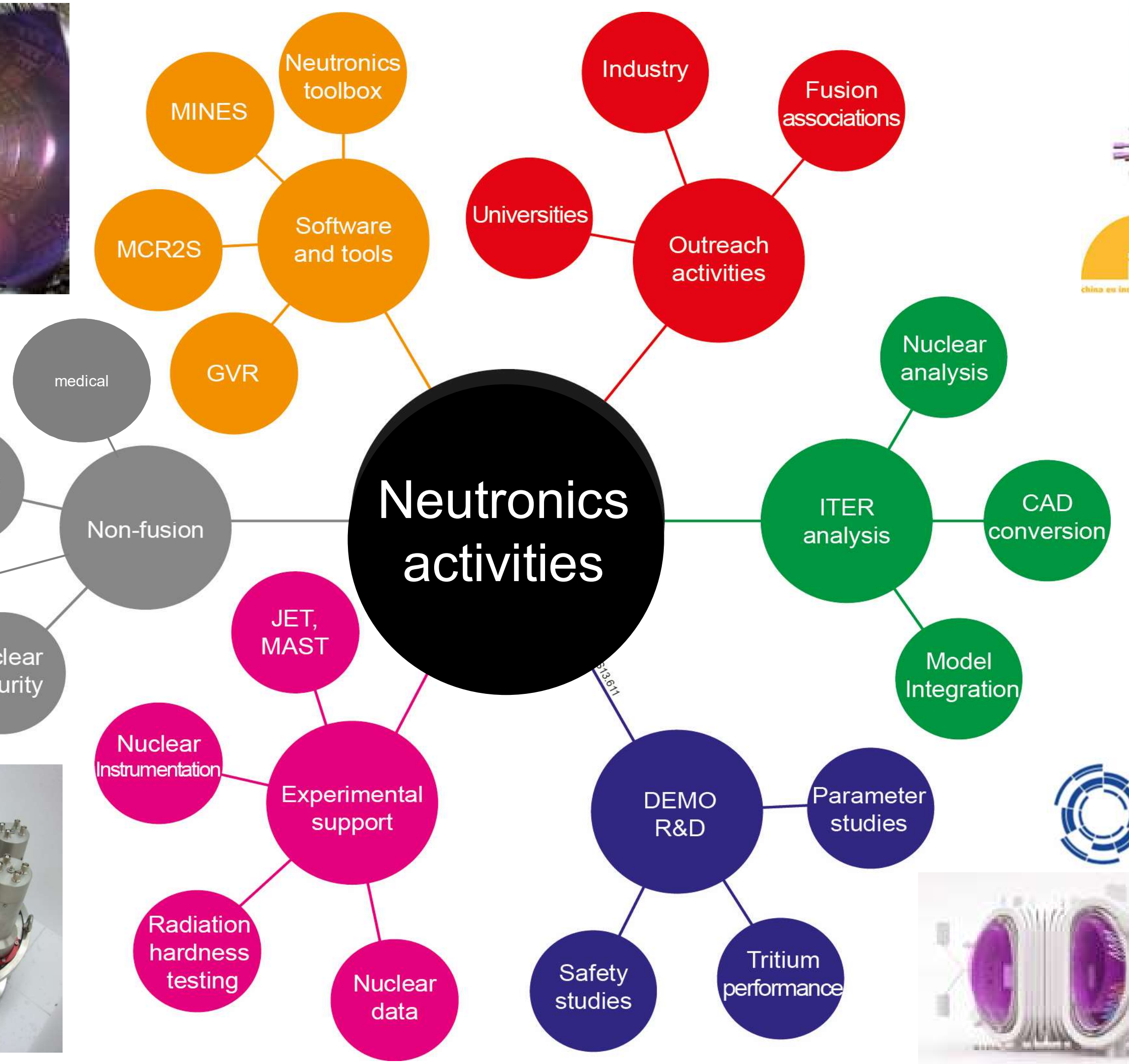
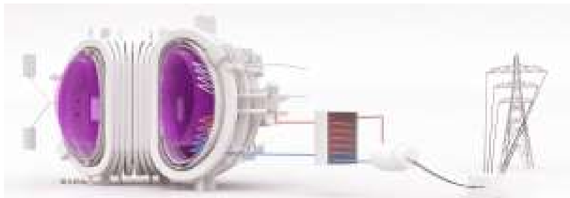
* X. Litaudon et al. to be published in Nuclear Fusion Special issue: Overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016.)

Neutronics areas







EFDA JET

iter

FUSION FOR ENERGY

NNUF National Nuclear User Facility

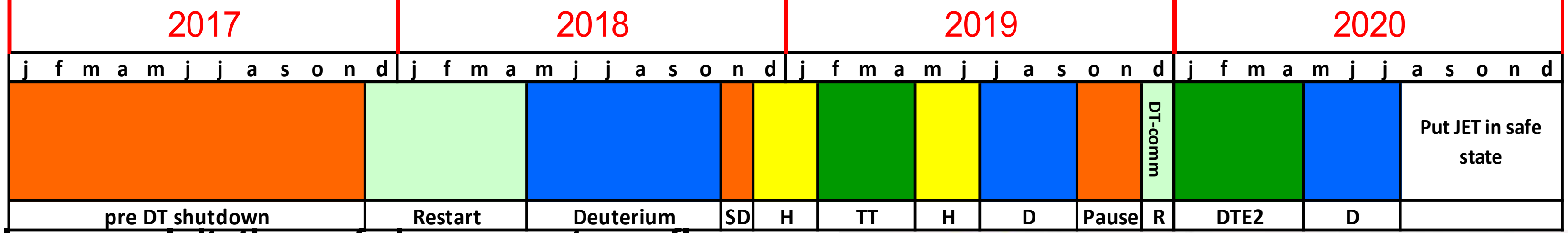
EUROfusion

Research Councils UK Energy For a Low Carbon Future

UK Atomic Energy Authority

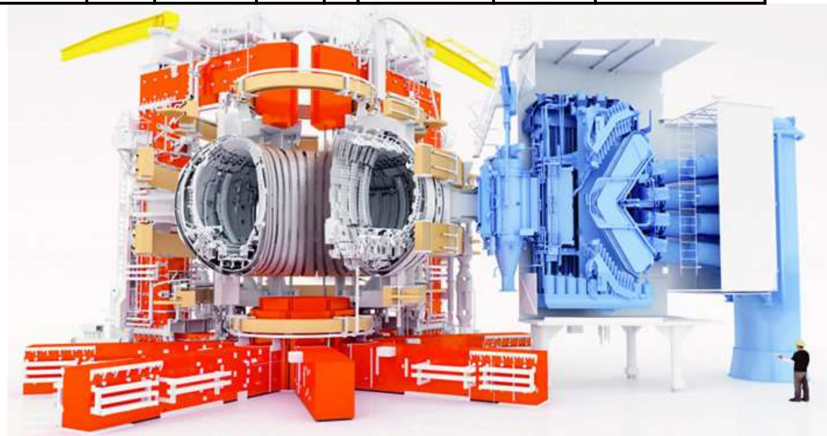
CCFE CULHAM CENTRE FOR FUSION ENERGY

Introduction –WPJET3



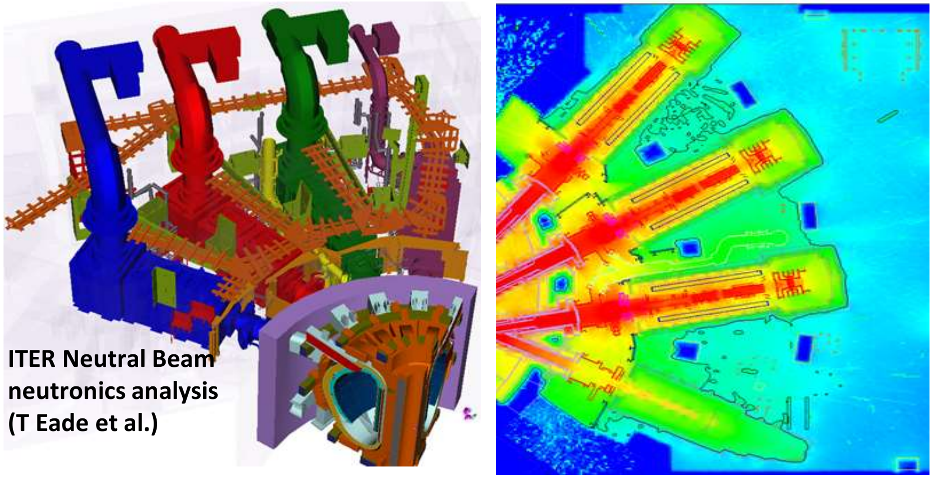
Technology exploitation of large neutron fluxes generated at JET

- DTE2 is expected to produce large neutron yields, >1.55e21 14 MeV neutron budget (DTE1 neutron budget 0.3e21)
- The scientific objectives of the campaign are linked with a technology programme, WPJET3 – exploitation of technology via the high neutron fluxes predicted in and around the JET machine.



Relevance to ITER

- Accurate neutron source measurements
  - Links to fusion power, tritium accountancy
- Radiation field characterization inside and outside the biological shield
- Radiation load on materials and components
- Occupational radiation exposure
- Waste production
- **ITER nuclear design requires experimental validatation by accurate measurements**



ITER Neutral Beam neutronics analysis (T Eade et al.)

Role of simulation tools: predicting radiation environments

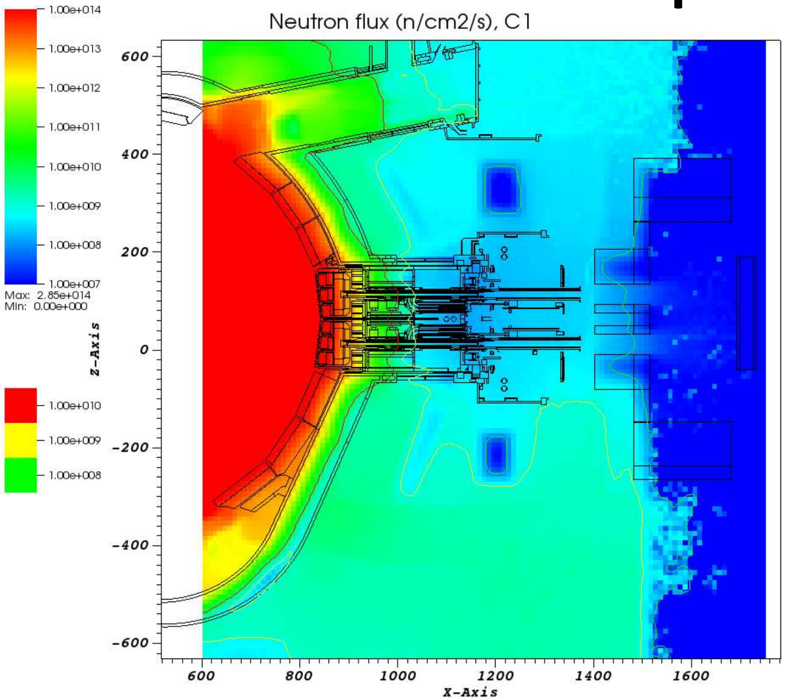
Simulations inform on environment – to guide development of suitable technologies

Need to predict:

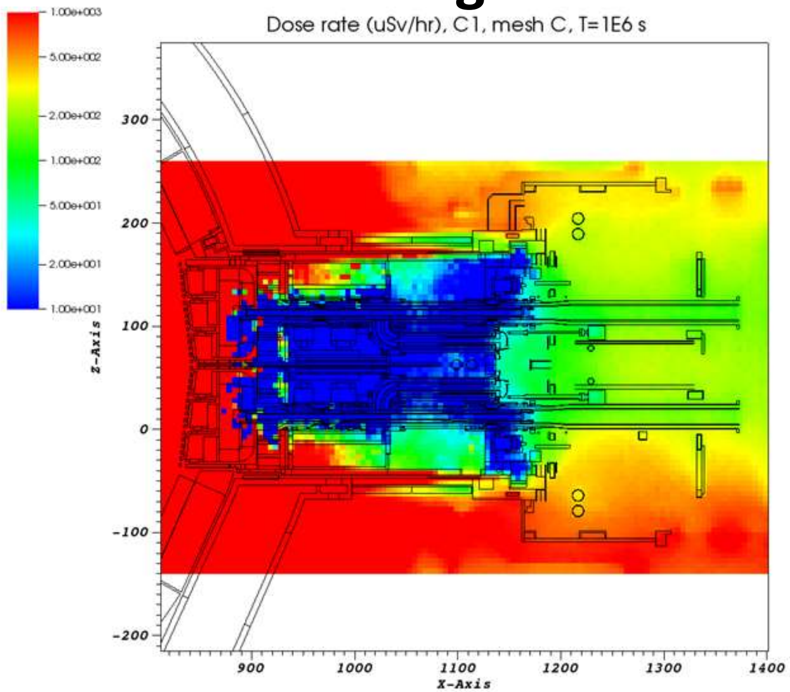
- Neutron/gamma fields, nuclear heating, damage, gas production
- Activation levels during and after operations, and for decommissioning considerations

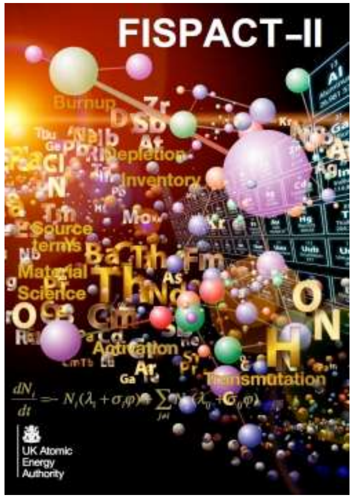
Benchmarking important; DT facilities, JET, SINBAD, validated ND

Neutron flux map



Activation gamma dose map

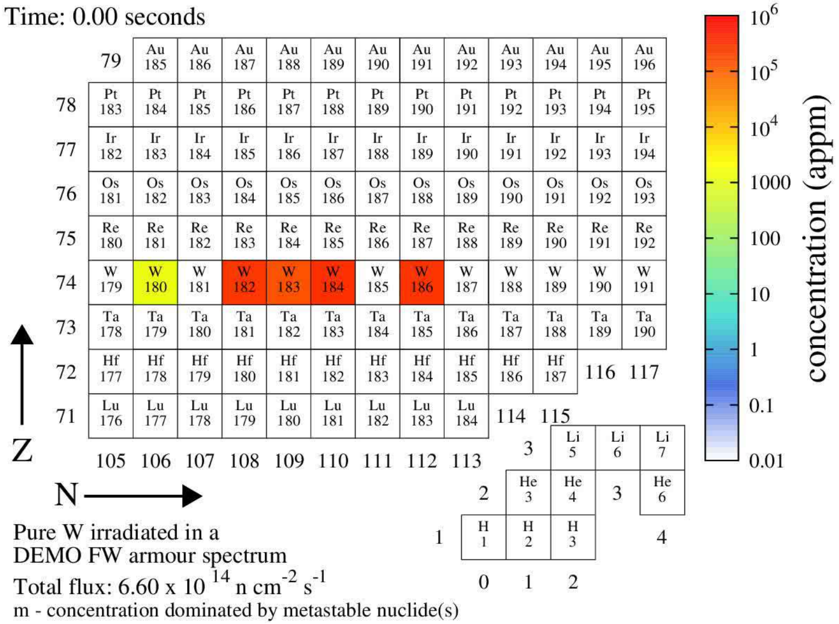


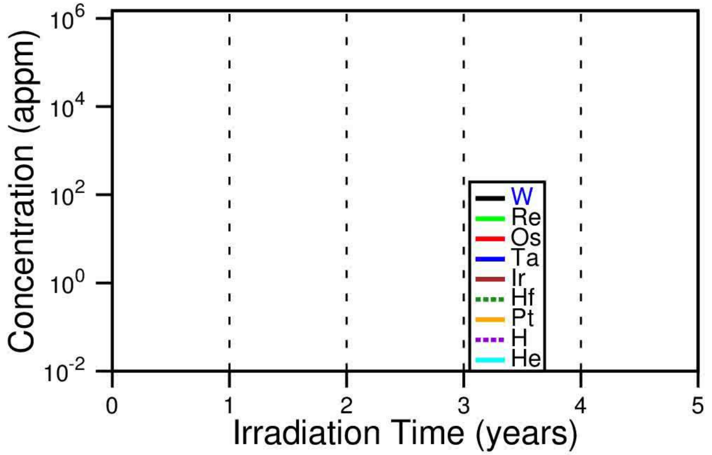


Neutron-induced activation processes

FISPACT-II inventory code has been developed by UKAEA to provide nuclear observables, using the most advanced nuclear reaction physics, for a wide variety of applications.

https://fispact.ukaea.uk/





M. R. Gilbert et al., *Nucl. Sci. Eng* **171** (2014) 291-306

See Gilbert, Packer, Sublet, Forrest, NSE 177 (2014) 291–306

WPJET3 subprojects

- Activation measurements for ITER material & data validation - ACT
- Neutron detector calibration at 14-MeV neutron energy - NC14
- Experiments for neutron transport & activation code validation – NEXP
- Test of detectors for tritium breeder blankets – TBMD
- Functional material damage studies - RADA
- Operational experience on occupational dose – NSAF
- Measurement of T permeation, retention, outgassing and of airborne T - TRI
- Waste production and characterization - WPC
- DEMO-relevant studies, including Fuel cycle – DFC

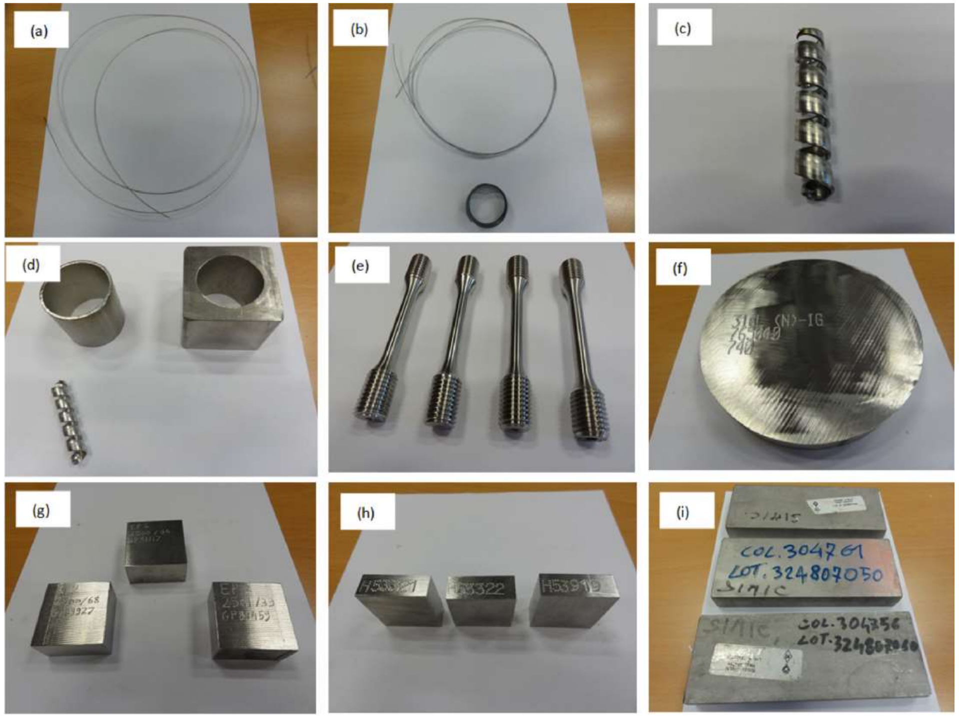
ACT

Activation measurements for ITER material & data validation

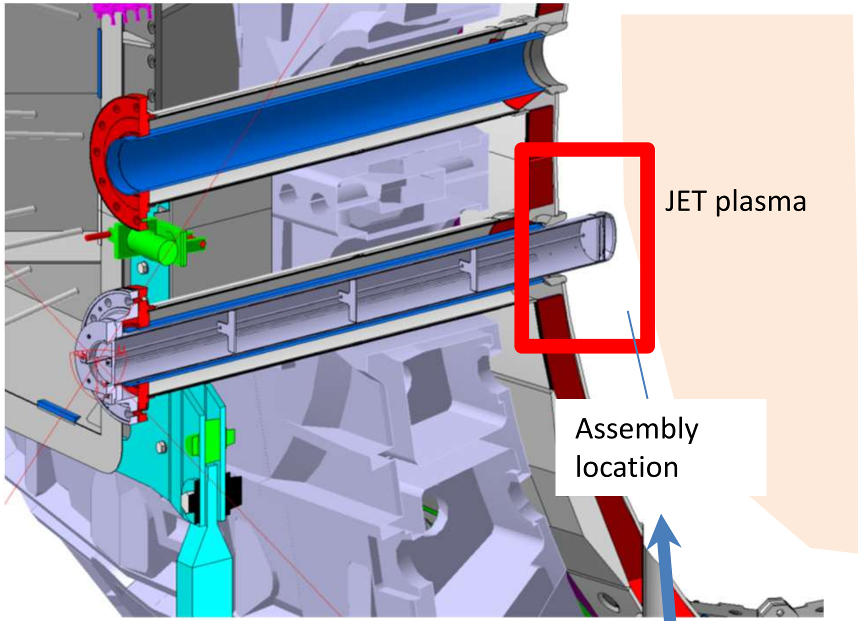
The 'ACT' subproject: Irradiation of ITER materials

- Take advantage of the large 14 MeV neutron fluence expected during JET DTE2 to irradiate samples of real ITER materials
- The materials considered include: SS316L steels from a range of manufacturers, SS304B, Alloy 660, Be, W, CuCrZr, OF-Cu, XM-19, Al bronze, Nb_3Sn, NbTi and EUROFER.
- Measurement of nuclide activities for each material and comparison against the predicted quantities through calculation with the FISPACT-II inventory code.
- Current focus on characterising irradiation positions in JET using a range of dosimetry foils
- Next campaign will irradiate some ITER materials

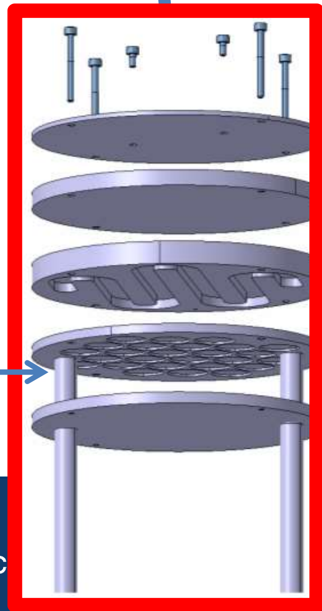
ITER materials selected for irradiation



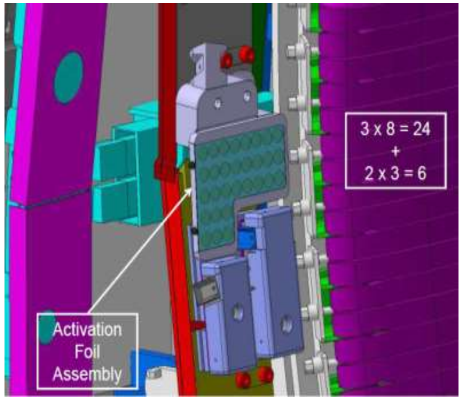
Images of some of the ITER materials that have been selected. (a,b) PF and TF Nb3Sn strands; (c) TF cooling spiral (316L steel); (d): TF jacket (316L(N)), top left, PFjacket (316L), top right, TF cooling spiral (316L), bottom; (e–i) various 316L(N) steel specimens from TF and PF components and 316L(N)-IG VV forged block.

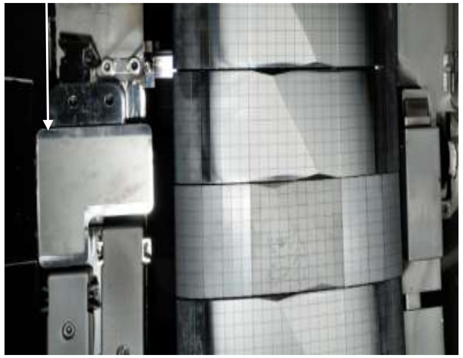


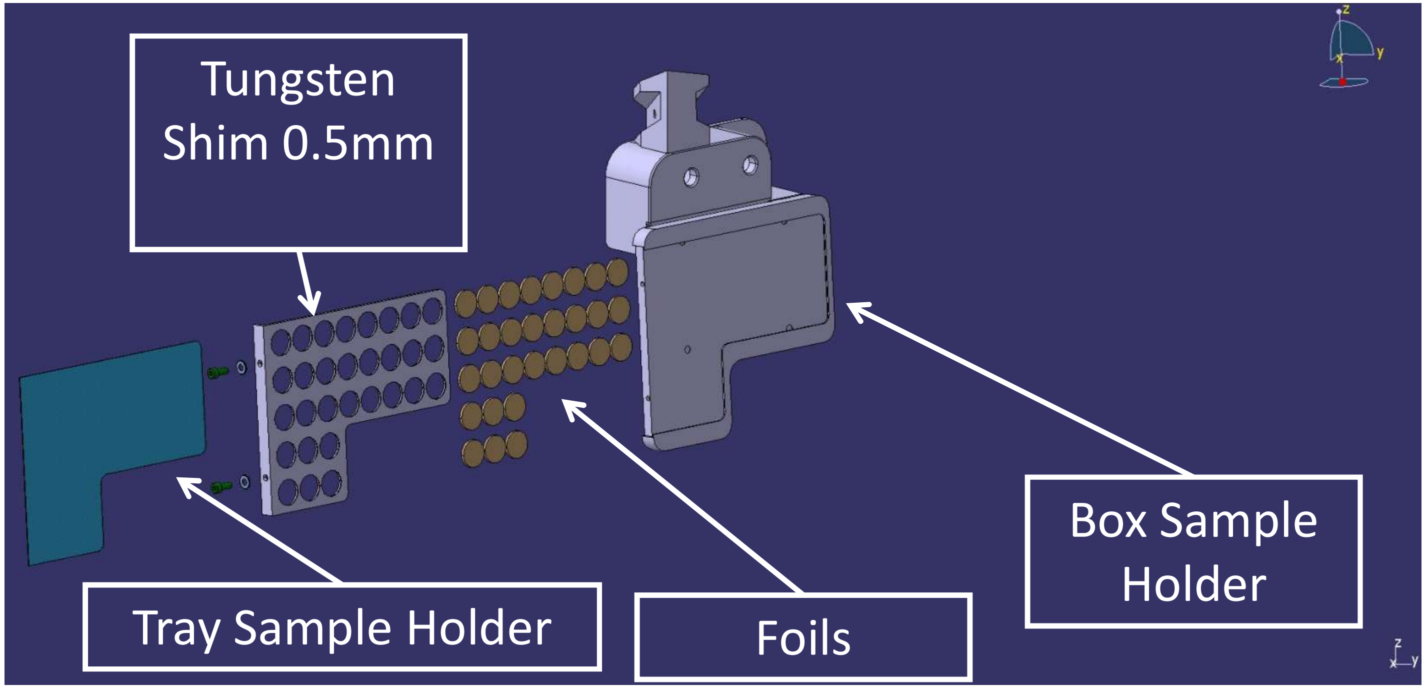
New long-term irradiation assembly



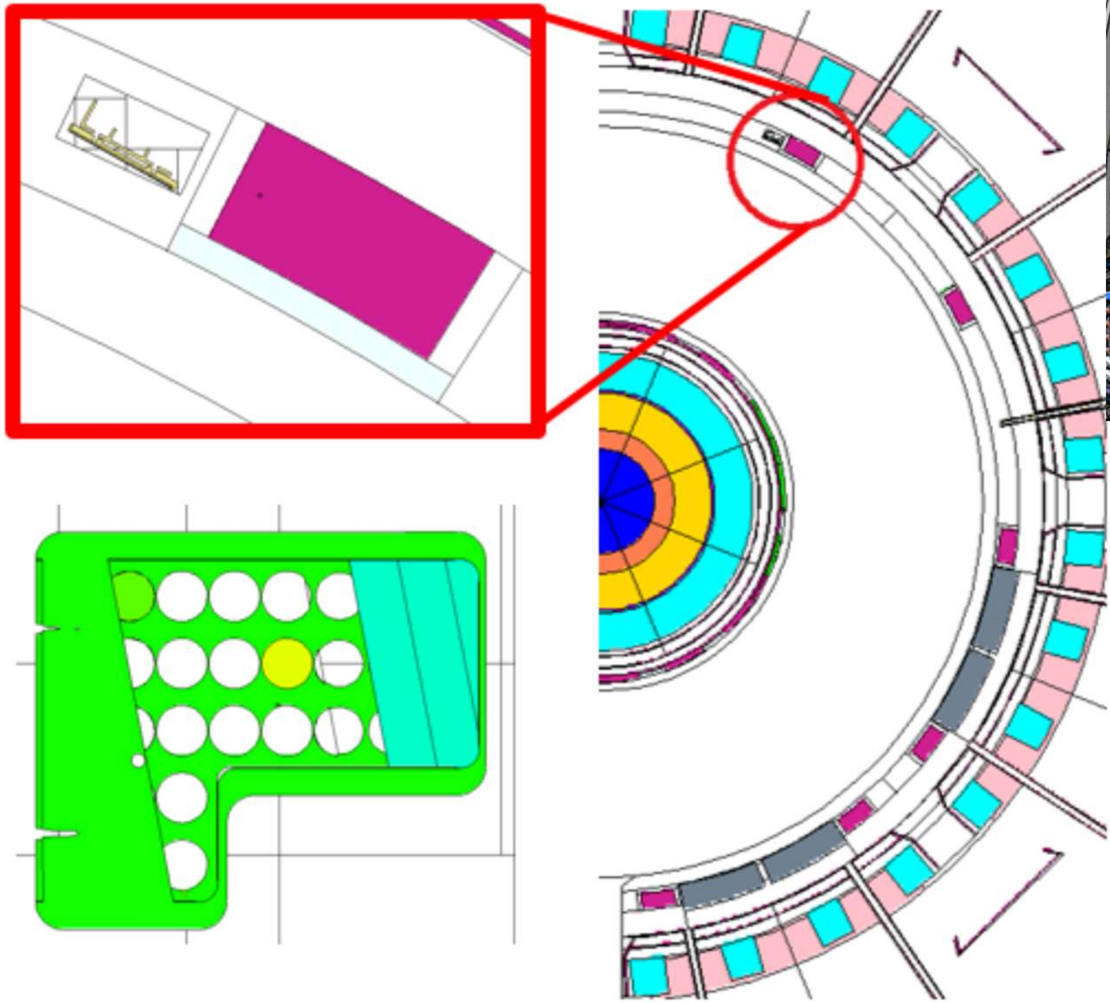
Long term irradiation station at JET used for previous campaign

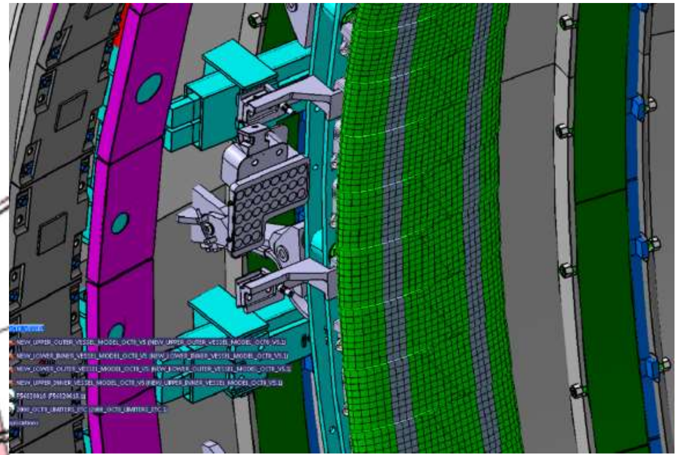






JET MCNP model and LTIS assembly



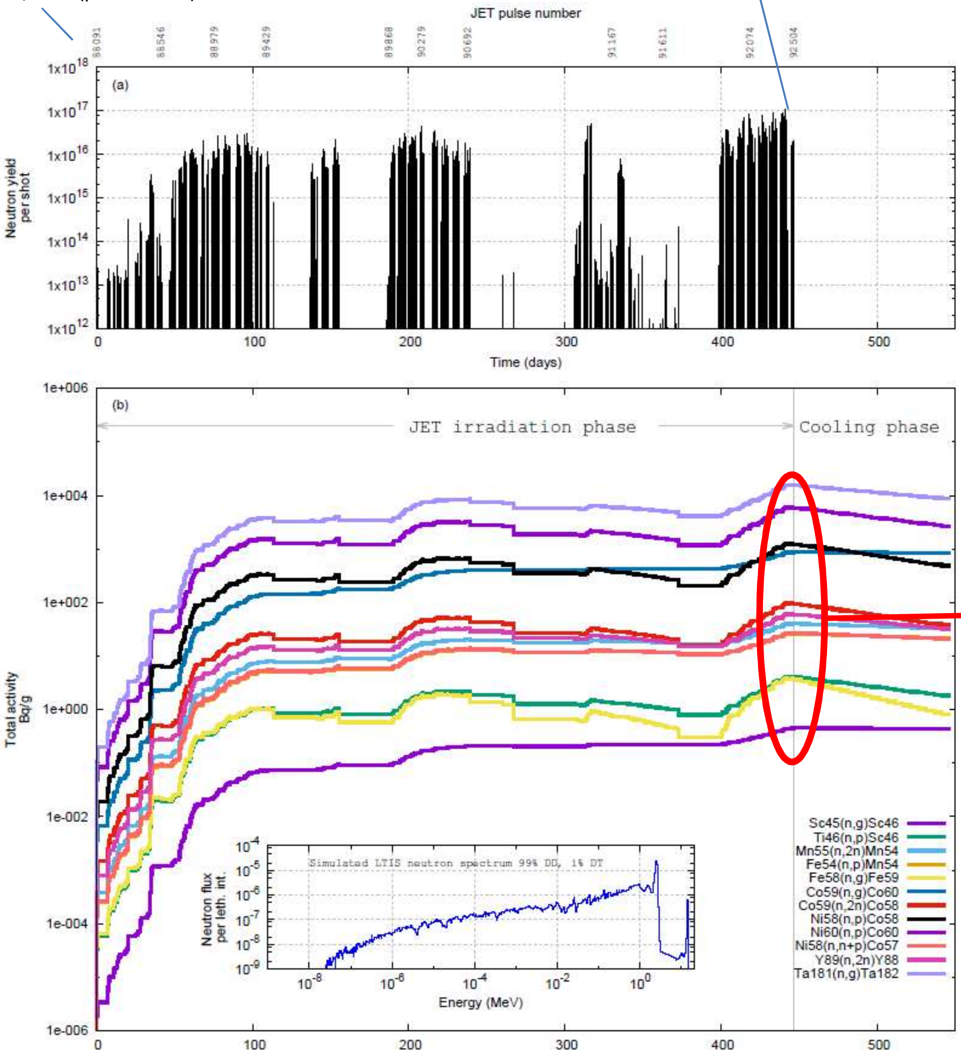


MCNP model x-y slice section of JET showing the location of the octant 8 LTIS assembly (expanded section); left-hand bottom gure shows the LTIS with cutaway section revealing some of the foil cavities.

Characterisation of irradiation locations at JET: simulation results

The first neutron shot that the foils 'saw' was 27/08/2015 (pulse 88091)

The last neutron shot that the foils 'saw' was 15/11/2016 (pulse 92504)

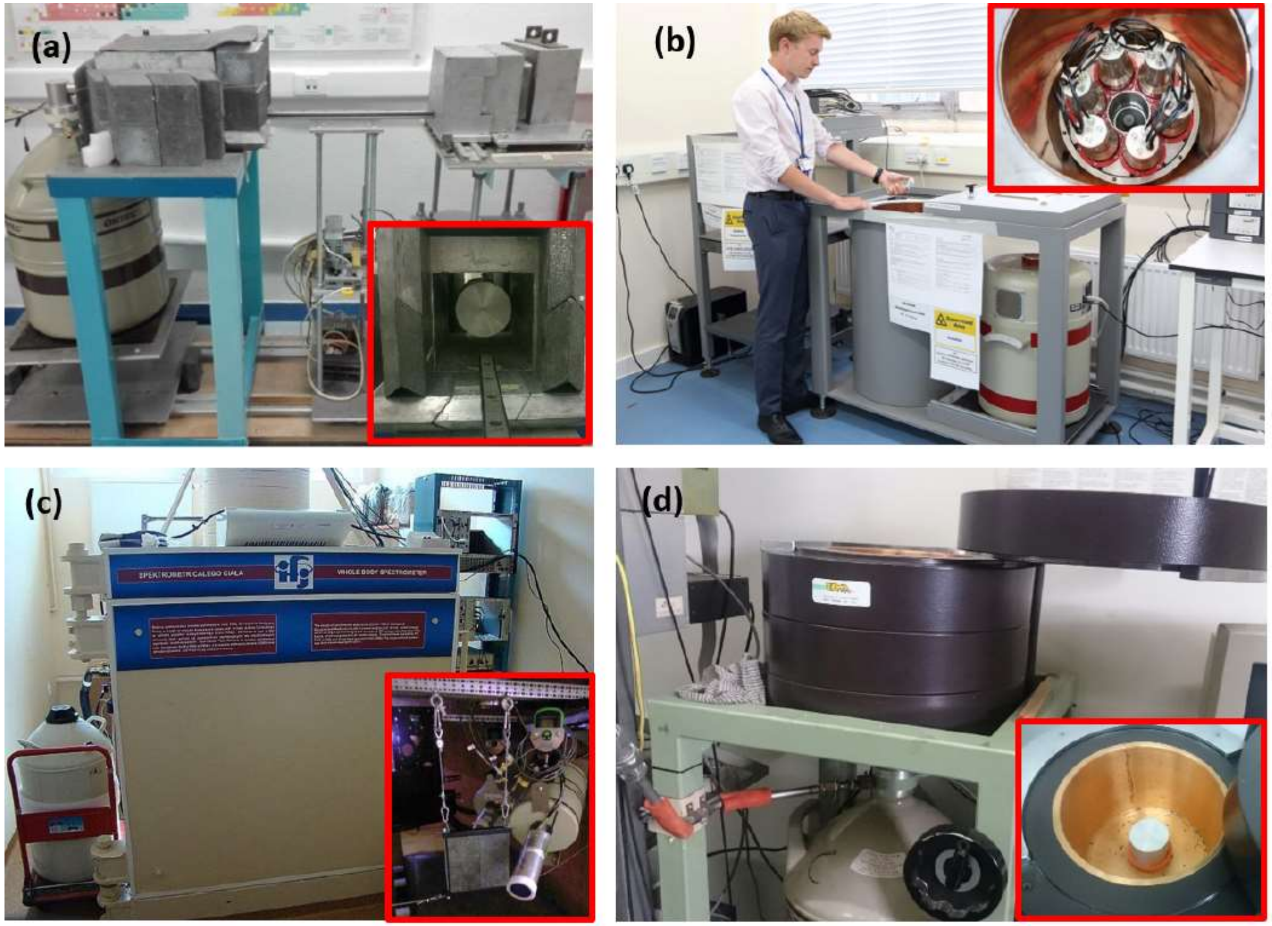


- Installation of the LTIS assembly was May 2015
- Assembly was removed in January 2017
- Active dosimetry foils distributed to Poland, Greece and Italy (and some stayed in UK) for gamma measurements
- Foil predicted activities to be compared to those measurements (analysis ongoing, but some spectra shown)

Table 1: Predicted specific activities at the reference time.

	Activity (Bq/g)
	Reference time (15/11/2016 19:14:37)
Total irradiation days (cumulative)	4.4639E+02
Sc45(n,g)Sc46	1.6730E+04
Ti46(n,p)Sc46	3.9220E+00
Mn55(n,2n)Mn54	4.3800E+01
Fe54(n,p)Mn54	2.6225E+01
Fe58(n,g)Fe59	1.1321E+01
Co59(n,g)Co60	1.0298E+04
Co59(n,2n)Co58	8.9850E+01
Ni58(n,p)Co58	1.3449E+03
Ni60(n,p)Co60	4.5940E-01
Y89(n,2n)Y88	6.0640E+01
Ta181(n,g)Ta182	2.0536E+05

Post-irradiation gamma spectrometry measurements at EU laboratories

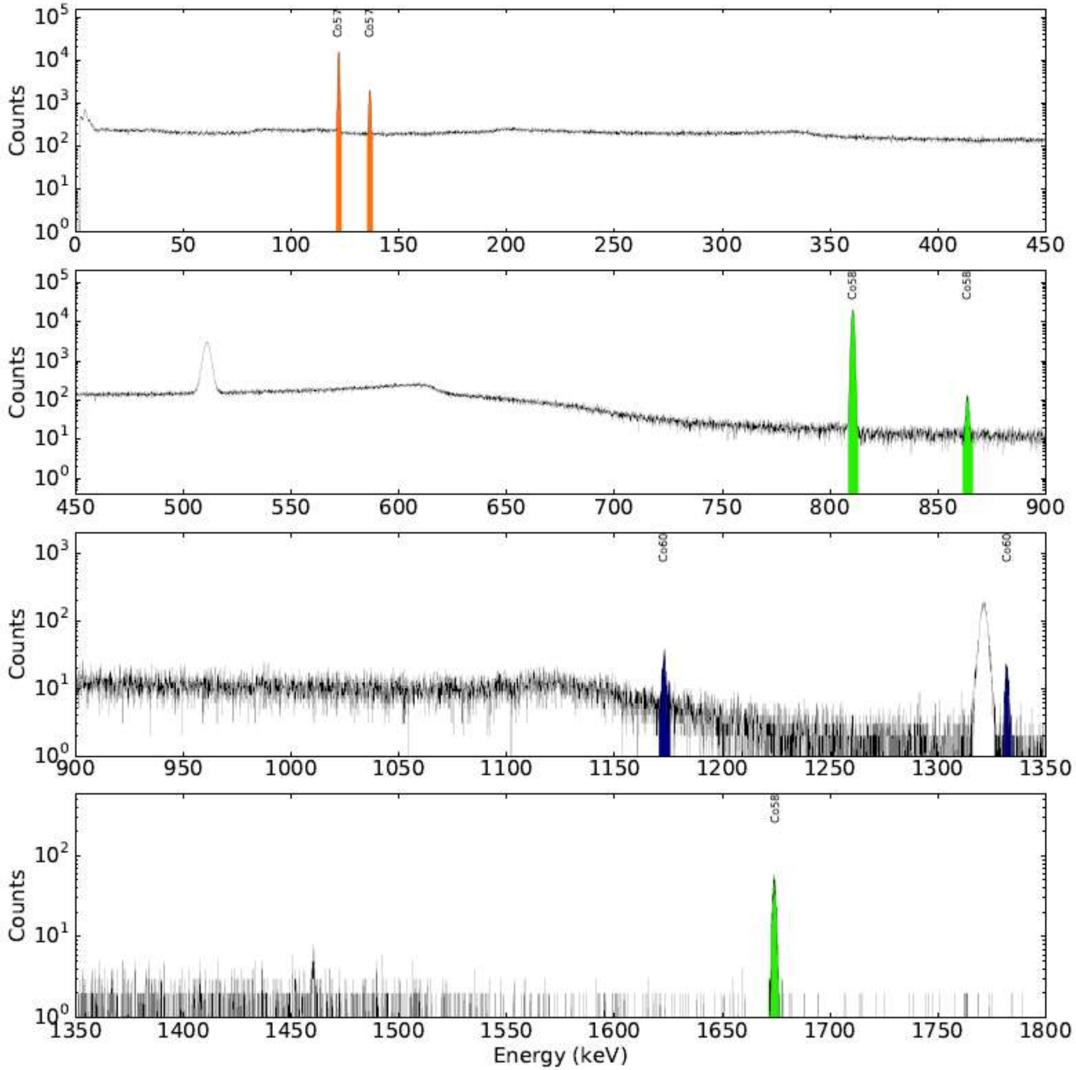


(a) NCSRD 85% relative efficiency HPGe coaxial detector and (inset) detector shown inside low background configuration; (b) CCFE BEGe detector and cryogenic recycler with (inset) NaI Compton suppression ring inside a Pb/Sn/Cu low background shield; (c) Whole-body spectrometer at IFJ PAN view from outside low background shielding, and (inset) a pair of 30% relative efficiency HPGe detectors inside the shielding separated by a suspended lead shield; (d) ENEA HPGe detector inside low background shield.

LTIS assembly tray post-irradiation, with some dosimetry foils removed

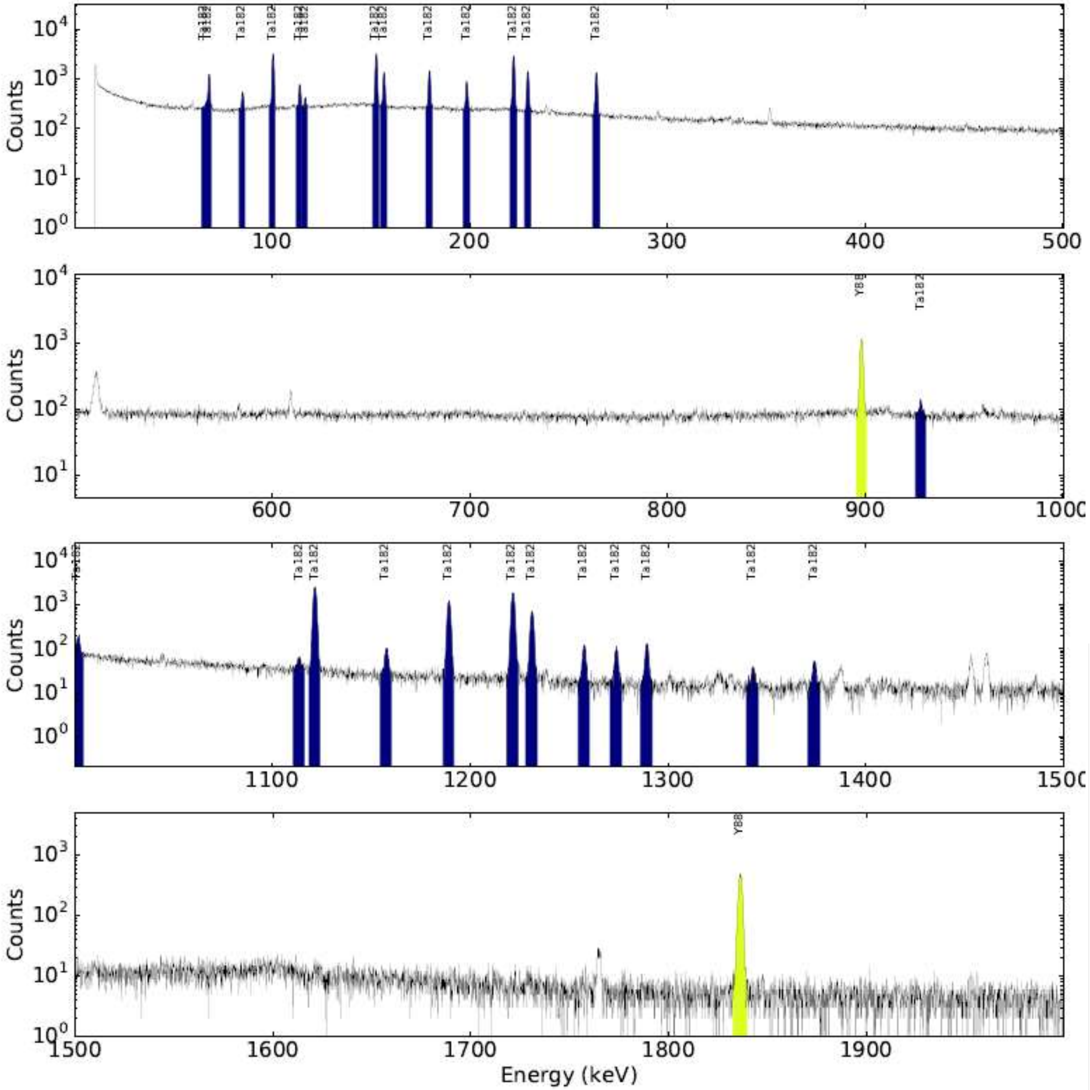
Collected activated dosimetry foil samples from 4D, prior to distribution and measurement analyses.

Example measurements: Ni foils

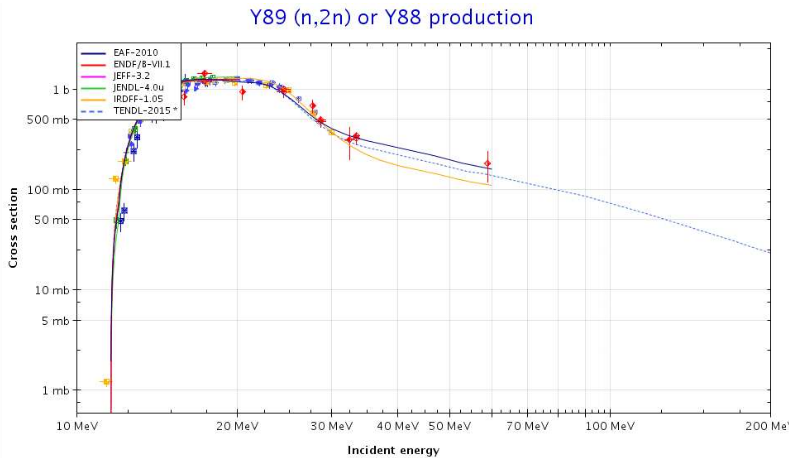


HPGe measurement taken from an Ni foil `NICCFE2', showing characteristic peaks from Co-57, Co-58 and Co-60. The two unmarked peaks are the characteristic annihilation peak at 511 keV, and at approximately 1321.8 keV, a Co-58 true coincidence peak for positron annihilation at 511 keV summed with the 810.8 keV emission.

Example measurements: Y foils

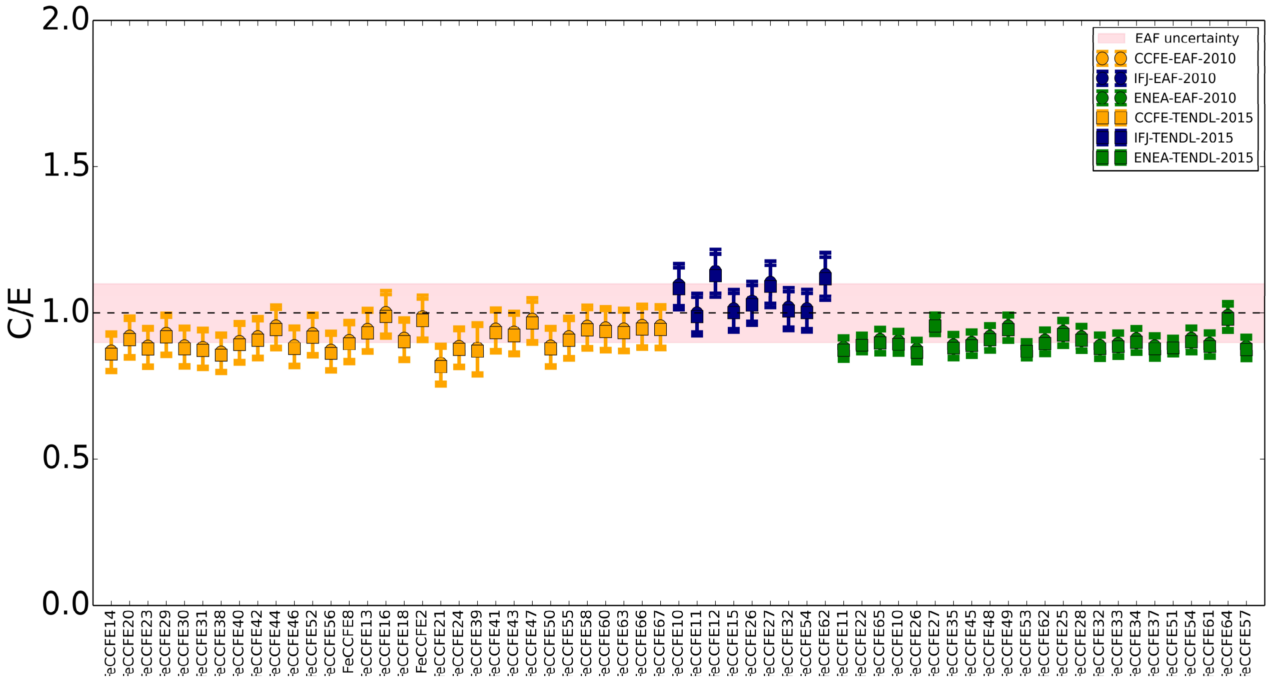


HPGe measurement taken from an Y foil `YCCFE1', showing showing characteristic gamma lines from Y-88 and Ta-182, the latter isotope being measured due to neutron activation of Ta impurities in the Y foil. The unmarked peaks are due to background environmental lines.



Threshold reaction C/E results

Preliminary C/E: Fe foil Mn54 production



Calculated specific activities, C, at the reference time

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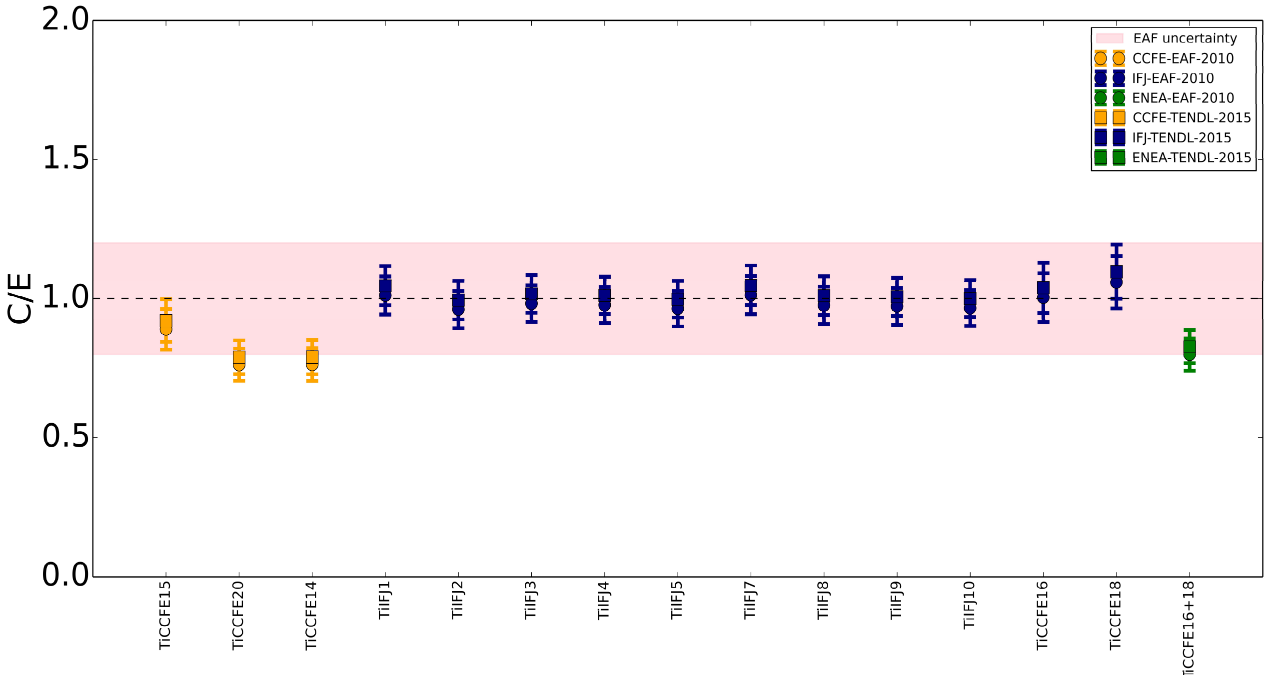
Mn55(n,2n)Mn54	4.3800E+01
Fe54(n,p)Mn54	2.6225E+01
Fe58(n,g)Fe59	1.1321E+01
Co59(n,g)Co60	1.0298E+04
Co59(n,2n)Co58	8.9850E+01
Ni58(n,p)Co58	1.3449E+03
Ni60(n,p)Co60	4.5940E-01
Y89(n,2n)Y88	6.0640E+01
Ta181(n,g)Ta182	2.0536E+05

Preliminary C/E: Ti foil Sc46 production



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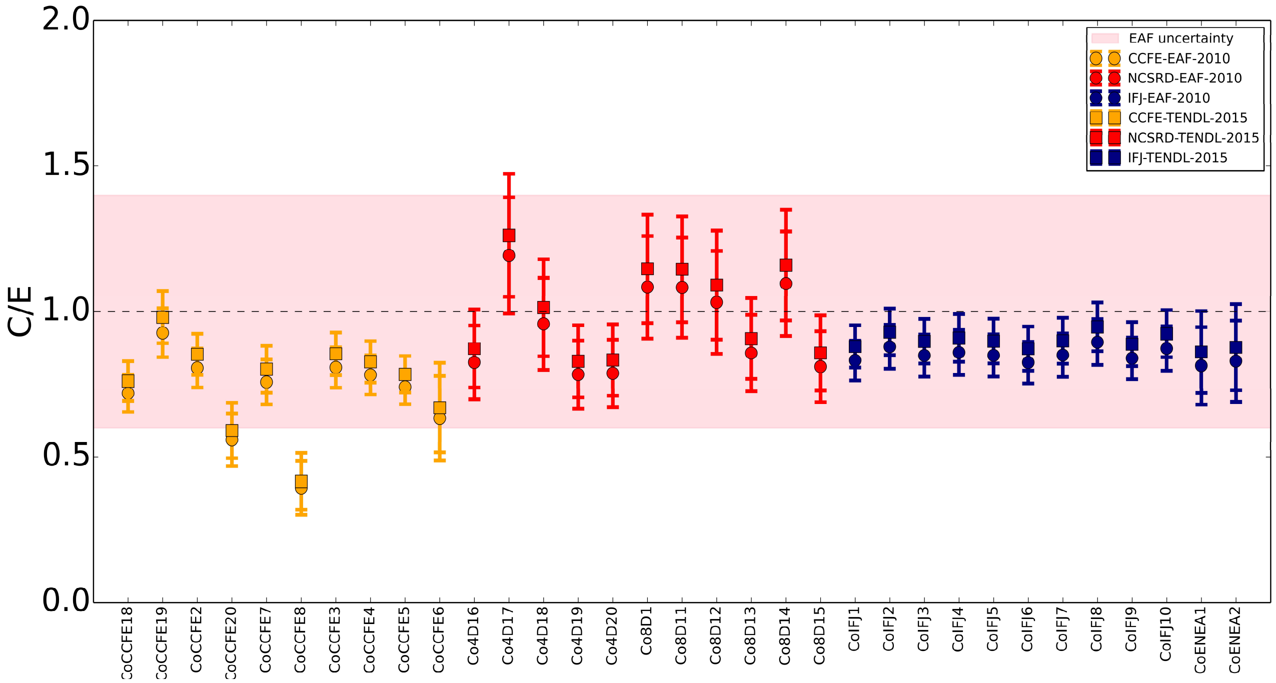
Ni60(n,p)Co60	4.5940E-01
Y89(n,2n)Y88	6.0640E+01
Ta181(n,g)Ta182	2.0536E+05

Preliminary C/E: Co foils Co58 production



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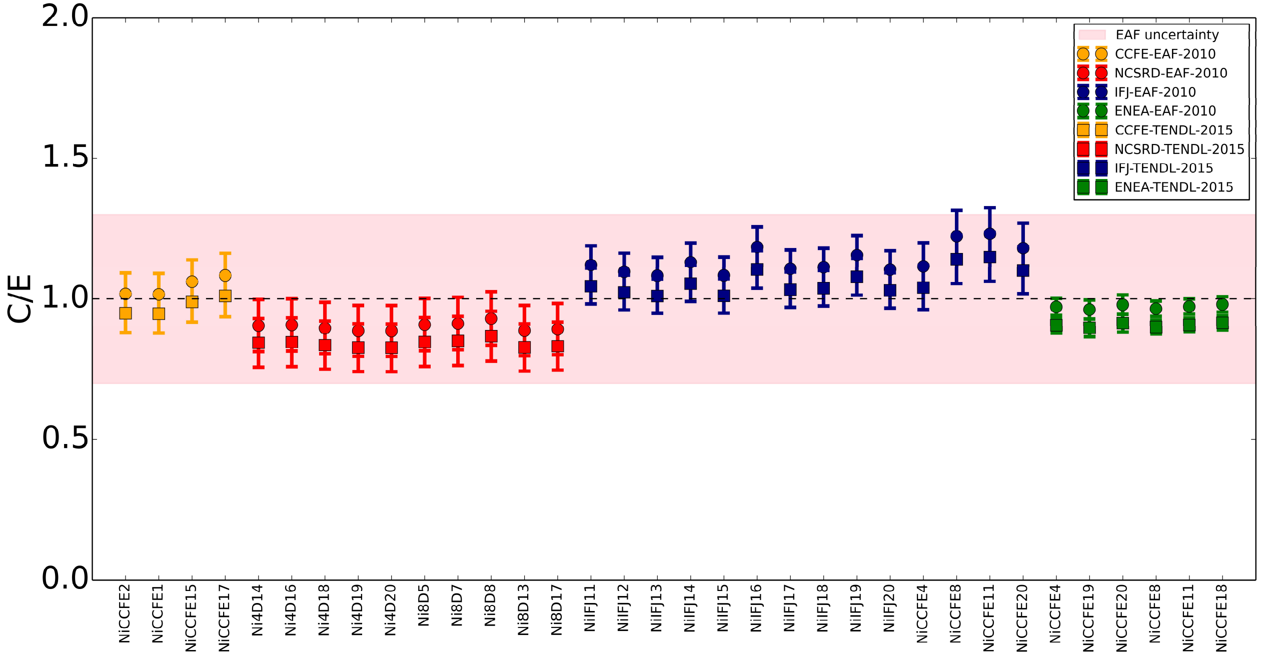
Ni60(n,p)Co60	4.5940E-01
Y89(n,2n)Y88	6.0640E+01
Ta181(n,g)Ta182	2.0536E+05

Preliminary C/E: Ni58(n,p)Co58



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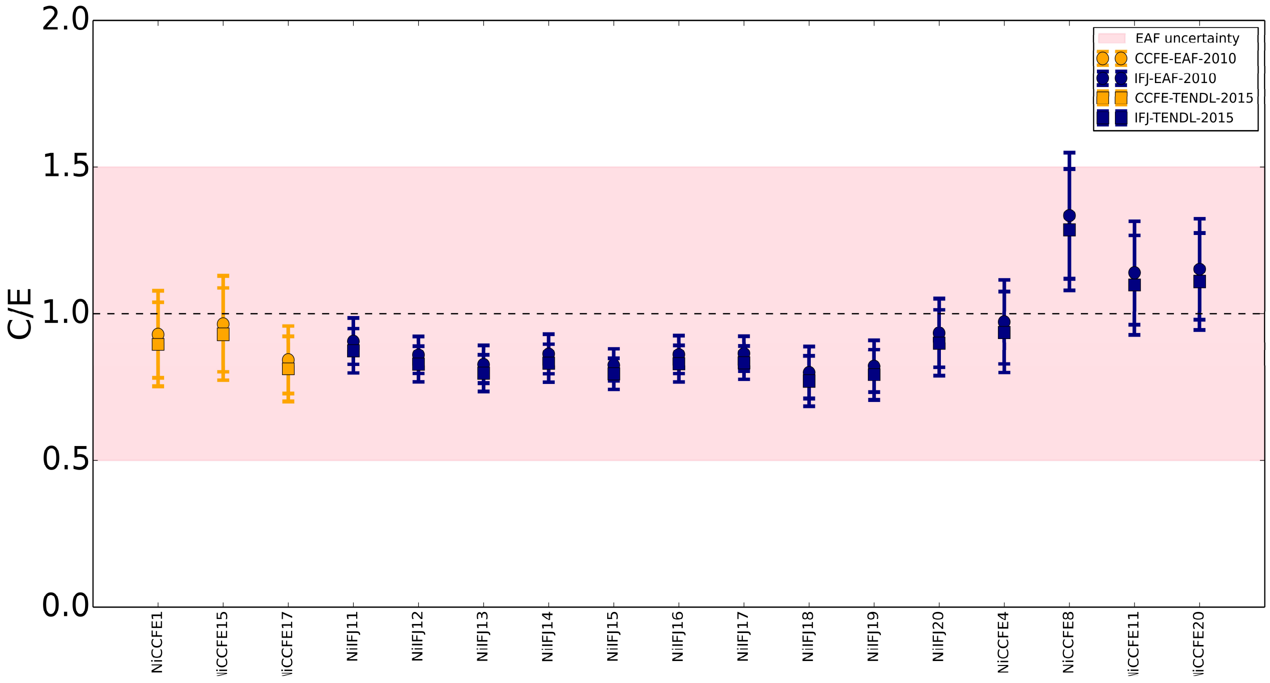
Ni58(n,p)Co58	1.3449E+03
Ni60(n,p)Co60	4.5940E-01
Y89(n,2n)Y88	6.0640E+01
Ta181(n,g)Ta182	2.0536E+05

Preliminary C/E: Ni foil Co60 production



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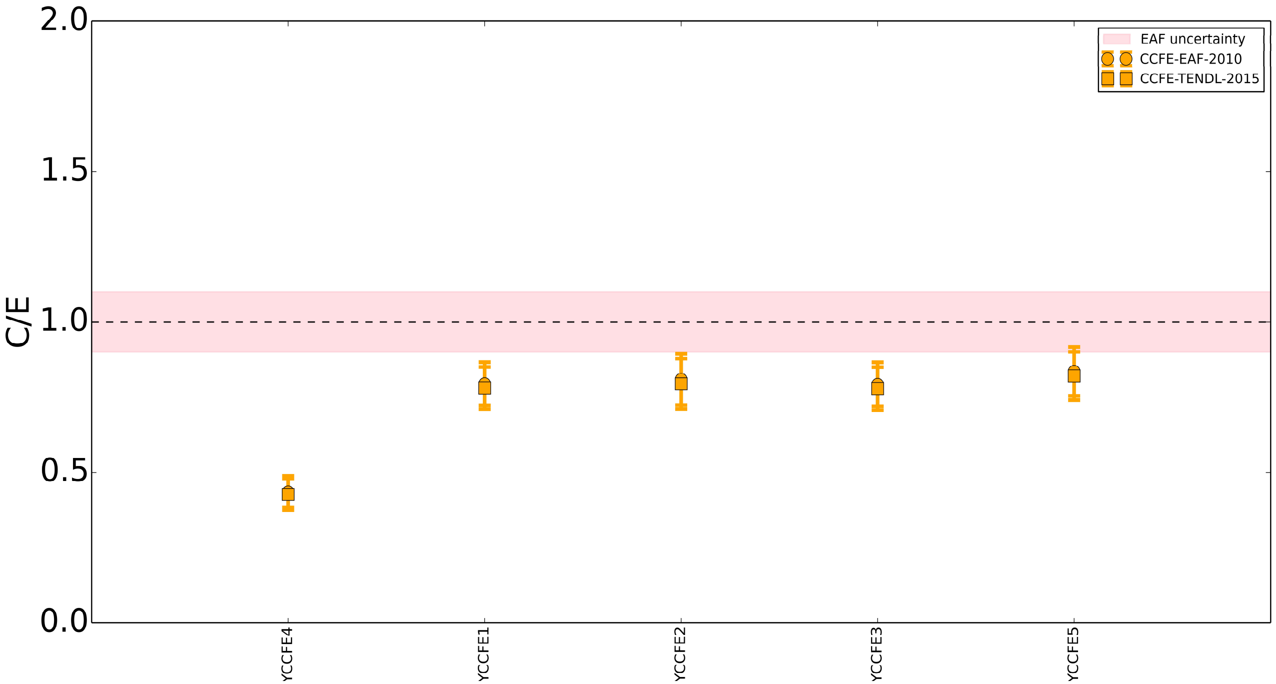
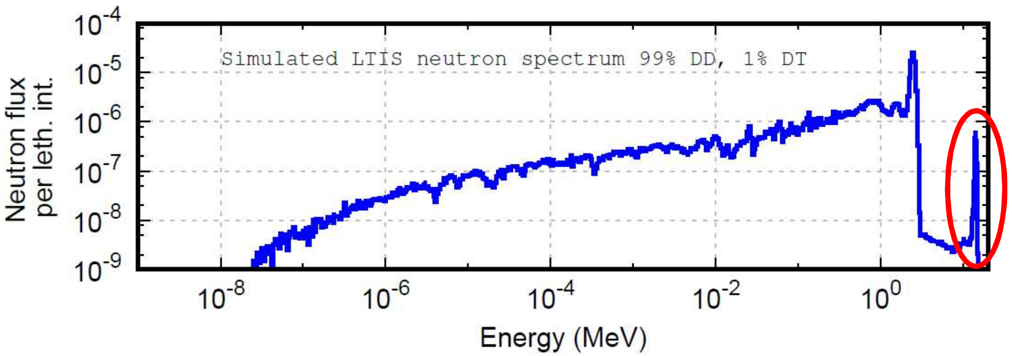
Ni60(n,p)Co60	4.5940E-01
Y89(n,2n)Y88	6.0640E+01
Ta181(n,g)Ta182	2.0536E+05

Preliminary C/E: Y89(n,2n)Y88





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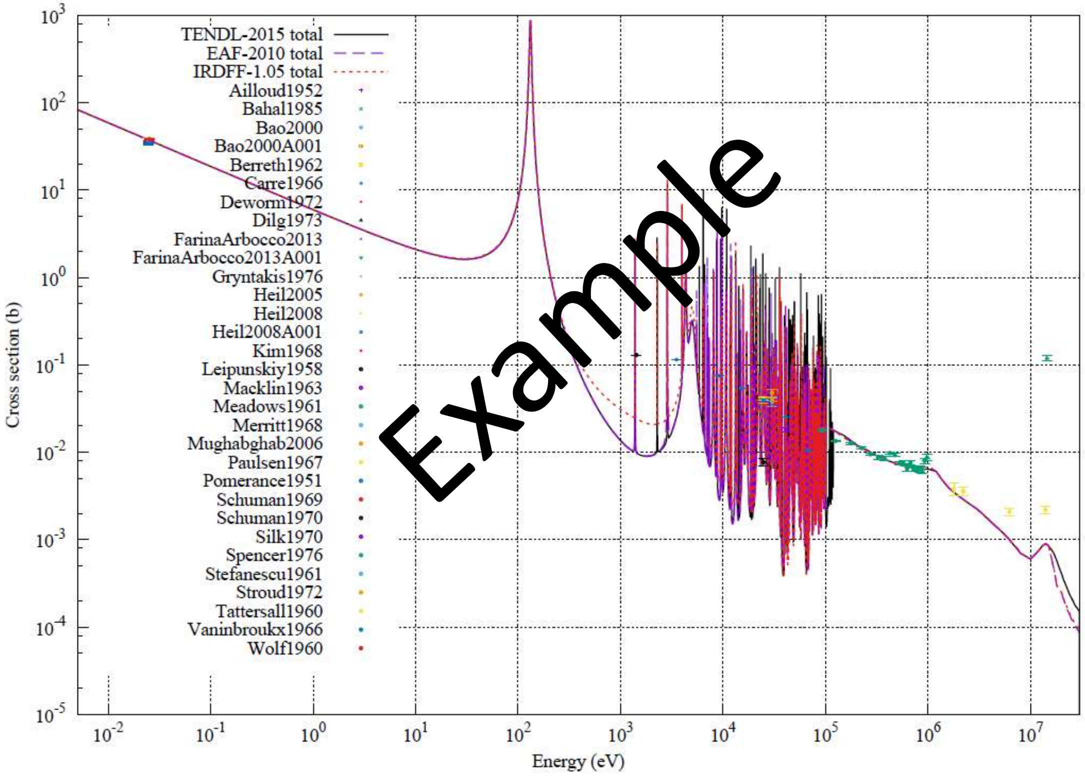
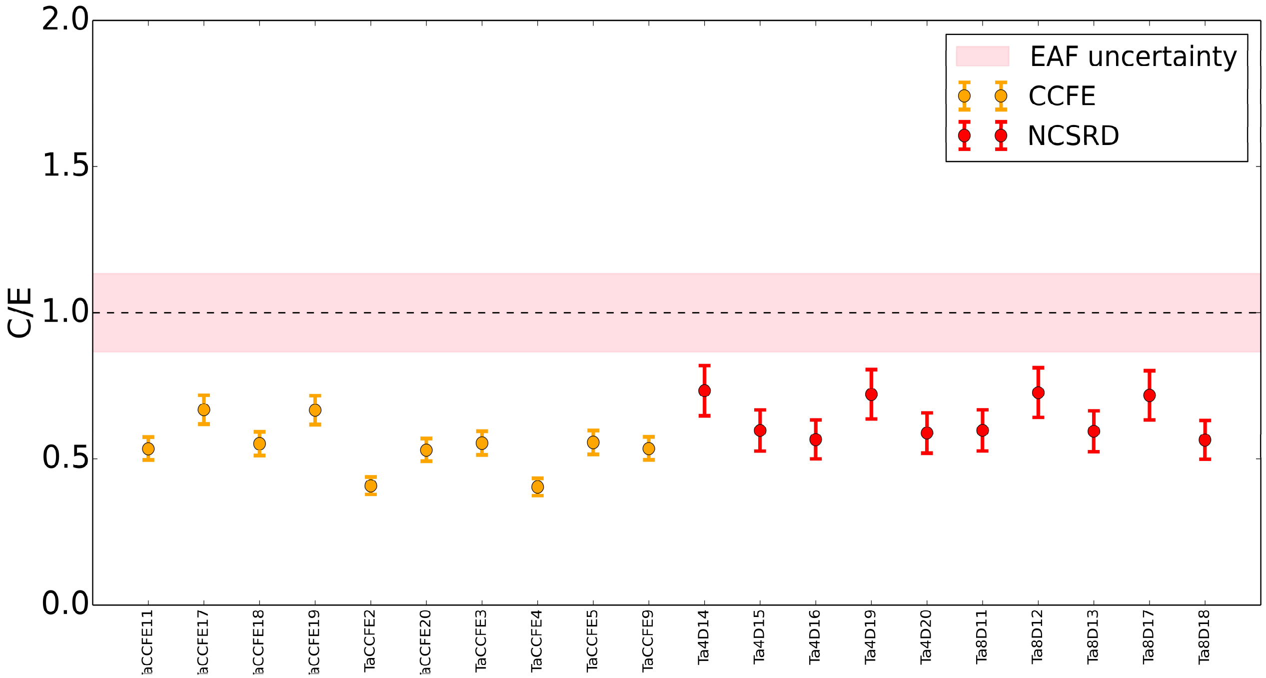
Capture reaction C/E results



The following results for capture reactions were calculated using PW IRDFF1.05 library

Preliminary C/E: Ta-181(n,g)Ta-182



Reaction rate calculated in MCNP using IRDFFv1.05 pointwise data

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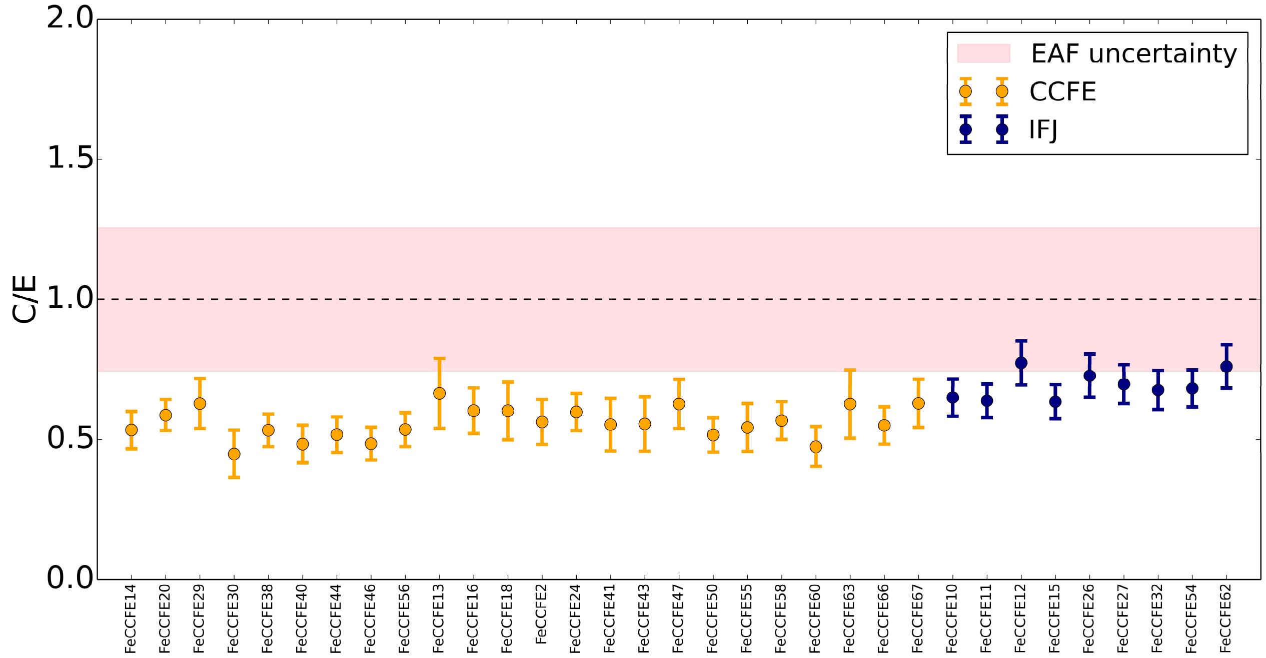
Preliminary C/E: Fe-58(n,g)Fe-59



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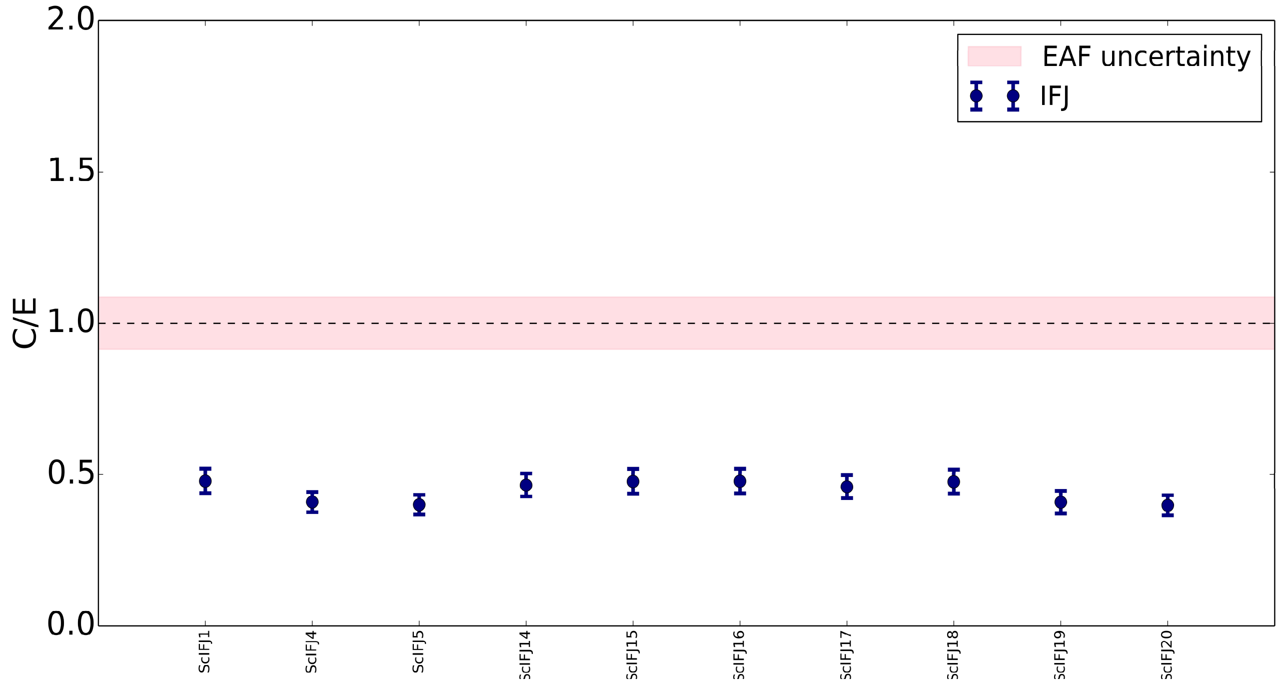
Preliminary C/E: Sc-45(n,g)Sc-46



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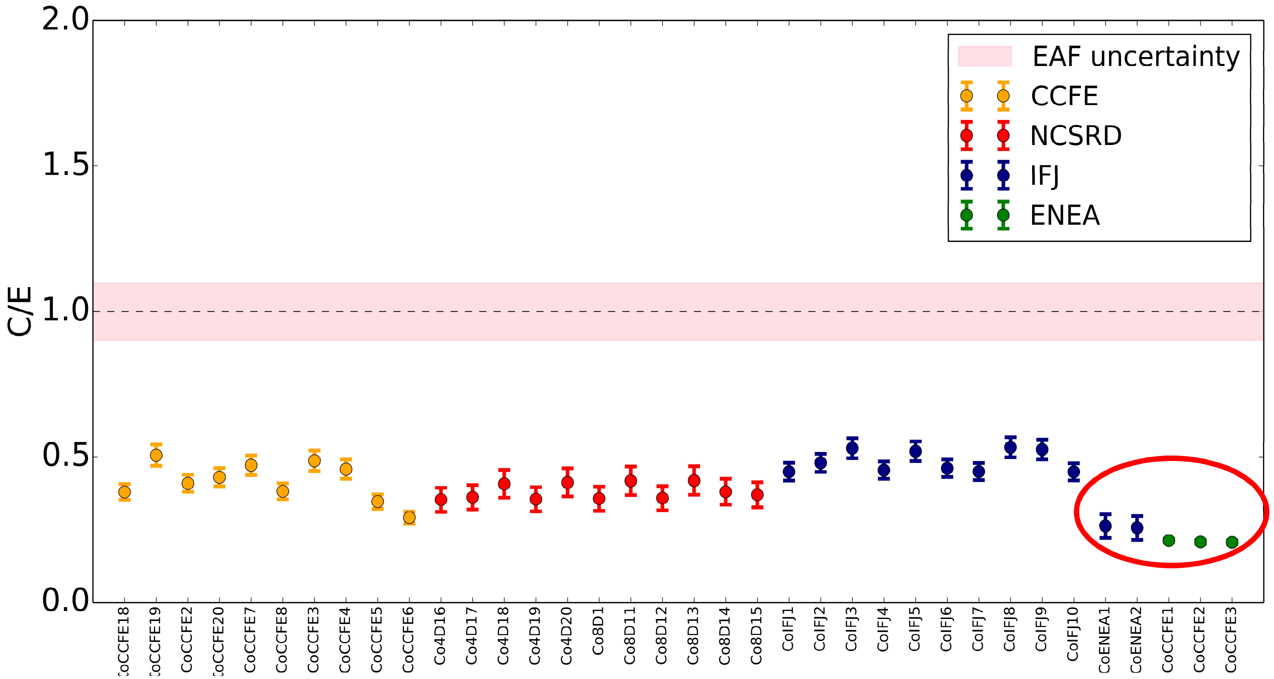
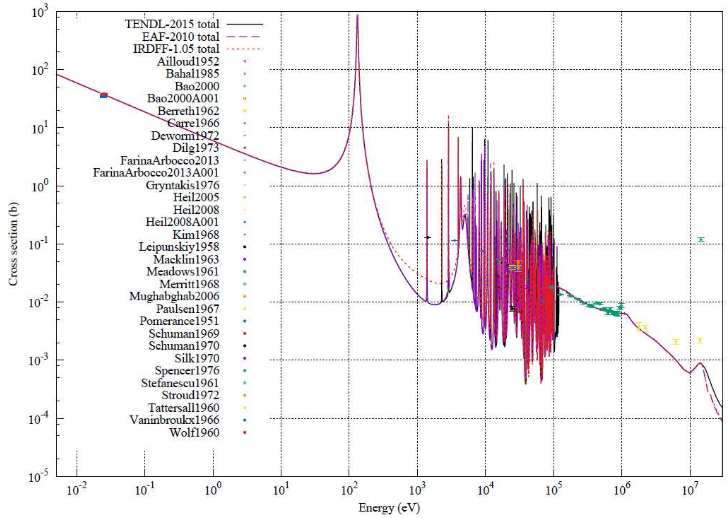
Mn55(n,2n)Mn54	4.3800E+01
Fe54(n,p)Mn54	2.6225E+01
Fe58(n,g)Fe59	1.1321E+01
Co59(n,g)Co60	1.0298E+04
Co59(n,2n)Co58	8.9850E+01
Ni58(n,p)Co58	1.3449E+03
Ni60(n,p)Co60	4.5940E-01
Y89(n,2n)Y88	6.0640E+01
Ta181(n,g)Ta182	2.0536E+05

Preliminary C/E: Co-59(n,g)Co-60



Reaction rate calculated in MCNP using IRDFFv1.05 pointwise data



Thinner Co foils (0.05 mm) – resonance self shielding correction factors were applied for 0.5 mm thickness …..calculations are ongoing….!

Calculated specific activities, C, at the reference time

	Activity (Bq/g)
	Reference time (15/11/2016 19:14:37)
Total irradiation days (cumulative)	4.4639E+02
Sc45(n,g)Sc46	1.6730E+04
Ti46(n,p)Sc46	3.9220E+00
Mn55(n,2n)Mn54	4.3800E+01
Fe54(n,p)Mn54	2.6225E+01
Fe58(n,g)Fe59	1.1321E+01
Co59(n,g)Co60	1.0298E+04
Co59(n,2n)Co58	8.9850E+01
Ni58(n,p)Co58	1.3449E+03
Ni60(n,p)Co60	4.5940E-01
Y89(n,2n)Y88	6.0640E+01
Ta181(n,g)Ta182	2.0536E+05

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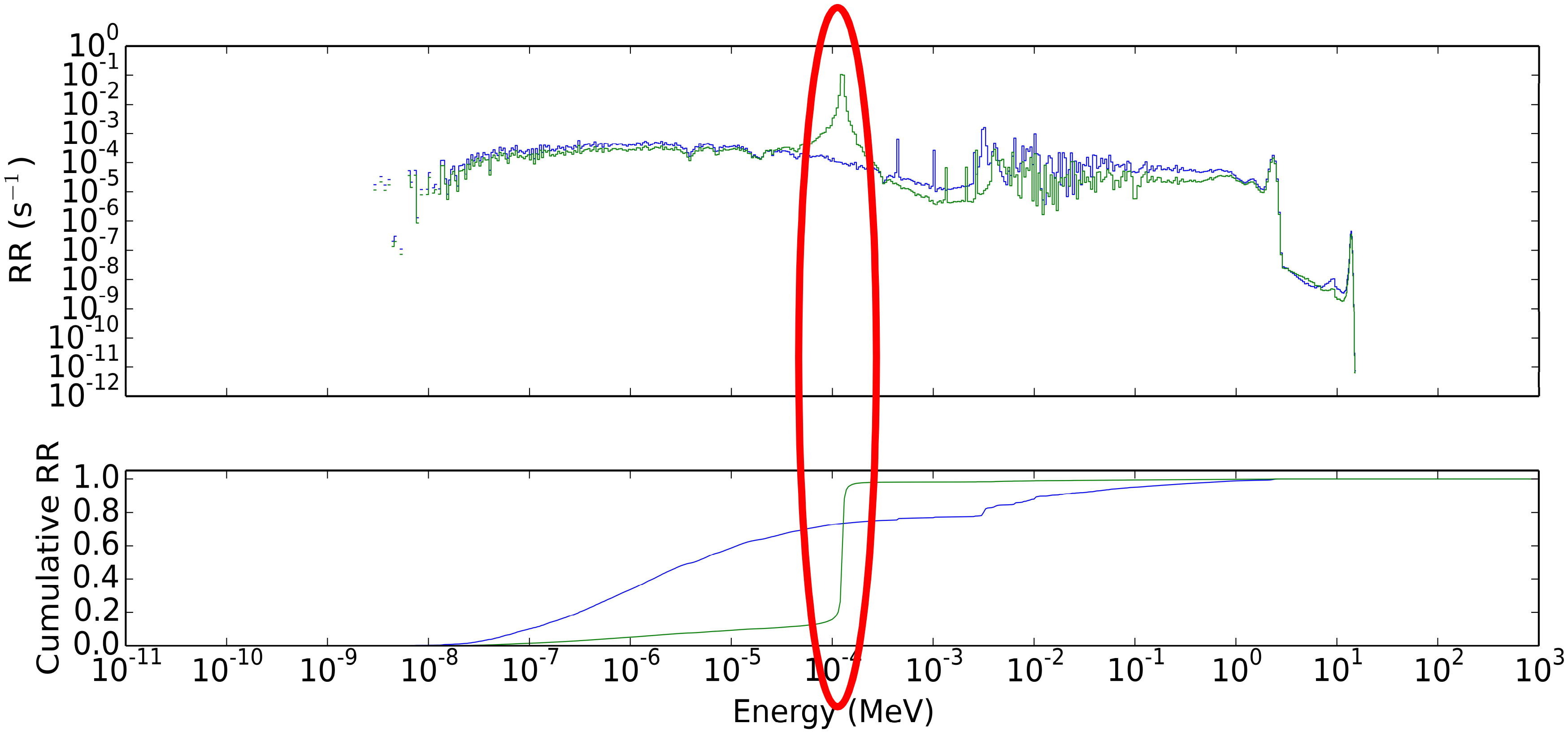
Contrasting Co-59(n,g)Co-60 and Sc-45(n,g)Sc-46 RRs in 709 group format



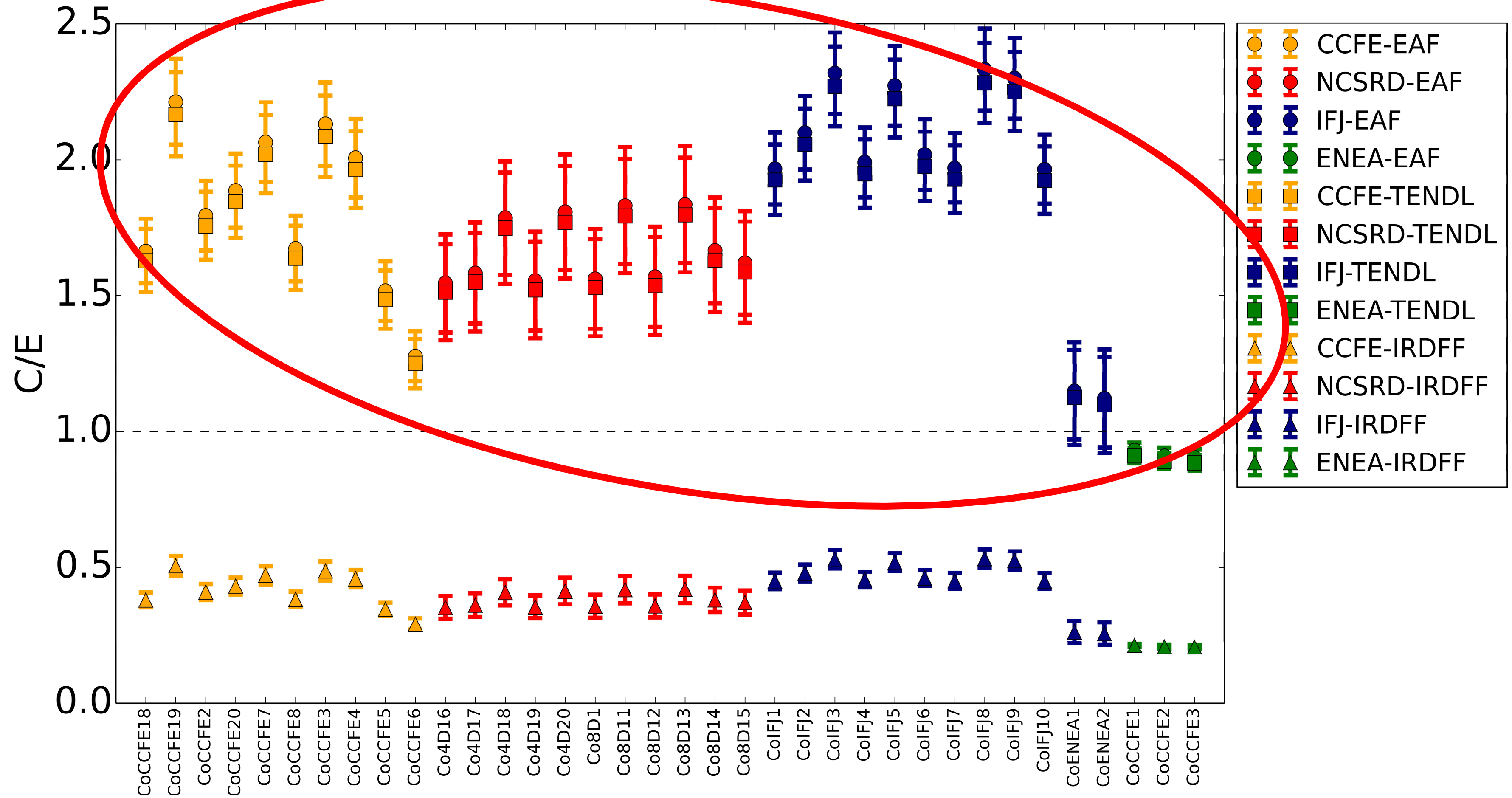
To be done: FISPACT-II with SSF treatment with 709 multigroup spectra – potentially a convenient way to treat capture reactions.

Concluding remarks

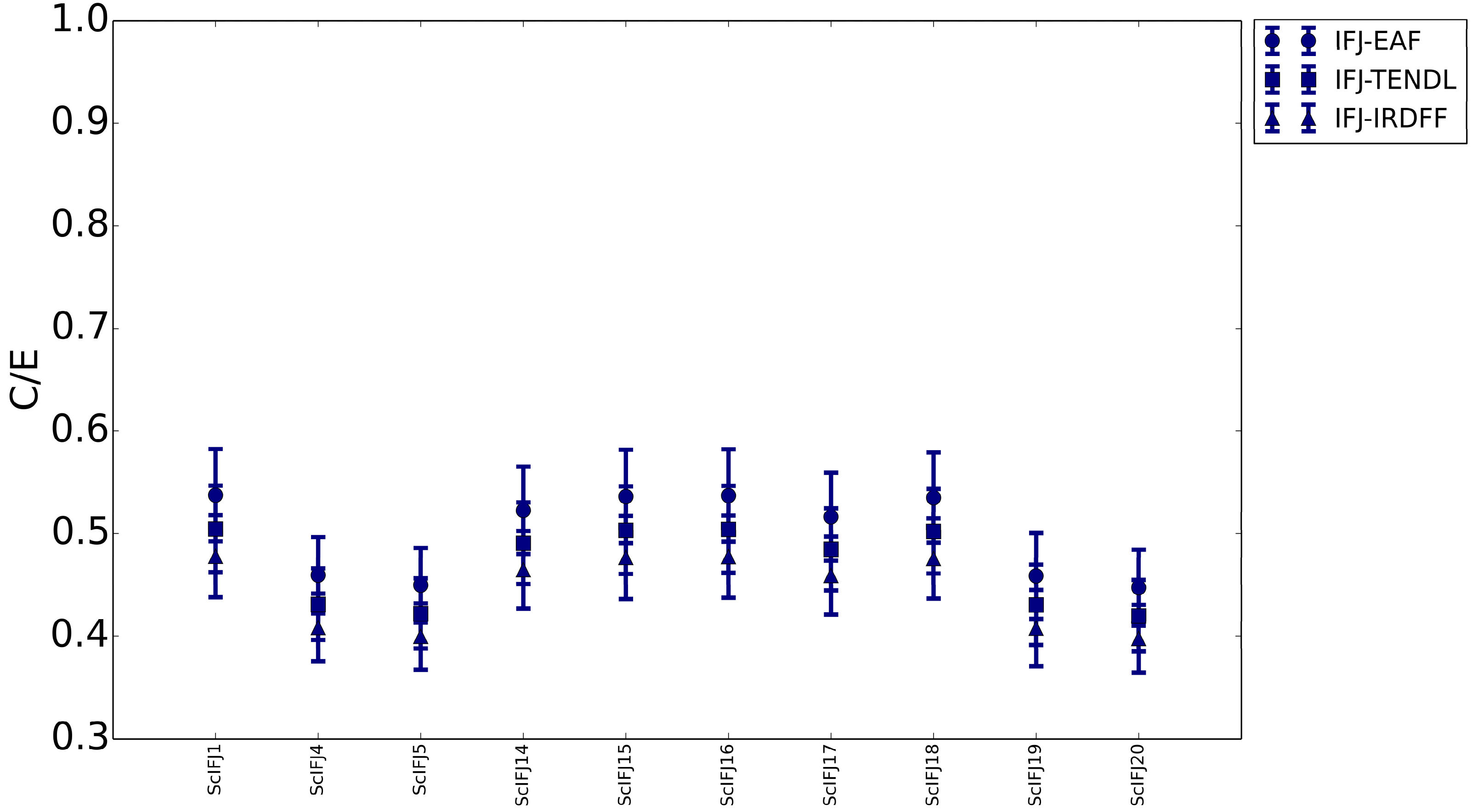
- Preliminary activation results, particularly threshold reactions broadly agree with what has been predicted using FISPACT-II with TENDL-2015, EAF-2010 and IRDFF-1.05 – indicates a reasonable understanding of the irradiation location through modelling predictions at higher neutron energy.
- However, the current MCNP model appears to slightly under-predict the low energy neutron flux – seen across 4 capture reactions.
- Higher fidelity modelling expected in new work to try to capture thermal field better…
- FISPACT-II using IRDFF1.05 pointwise currently necessary to compare capture reactions, but TENDL-2015 709 groups with benefits of SSF treatment are being explored…
- For more information on ACT, see: L.W. Packer et al., ‘Status of ITER material activation experiments at JET’, Fus. Eng. Des., available online February 2017 https://doi.org/10.1016/j.fusengdes.2017.01.037

Extra slides

Groupwise EAF-2010 and TENDL-2015 versus PW IRDFF1.05: Co-59(n,g)Co-60



Groupwise EAF-2010 and TENDL-2015 versus PW IRDFF1.05: Sc-45(n,g)Sc-46

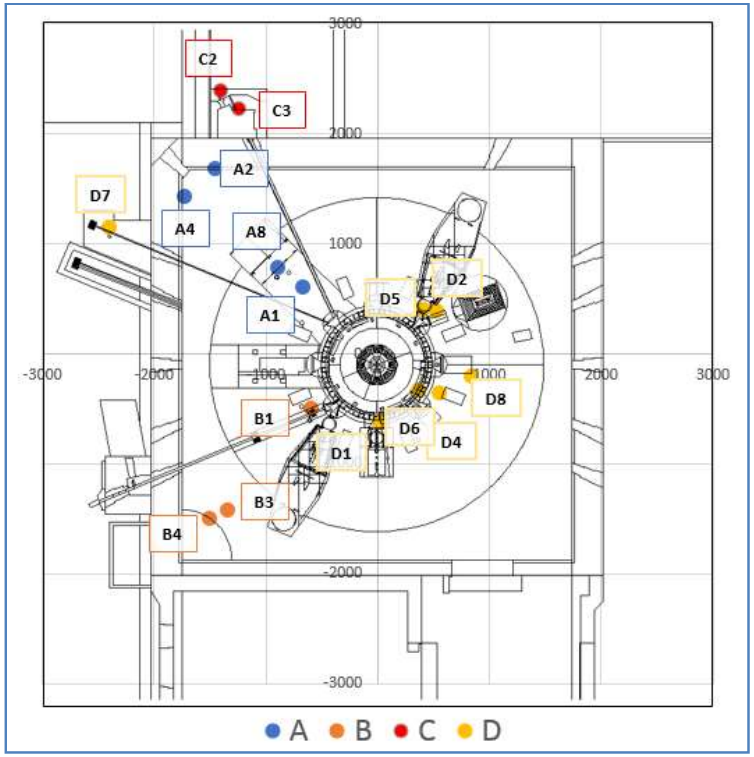


NEXP

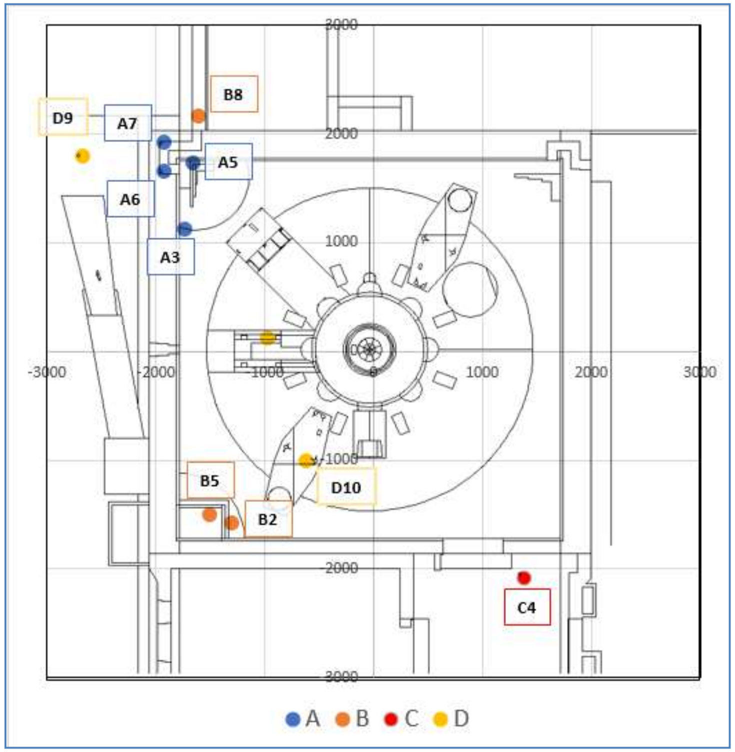
Experiments for neutron transport & activation code validation

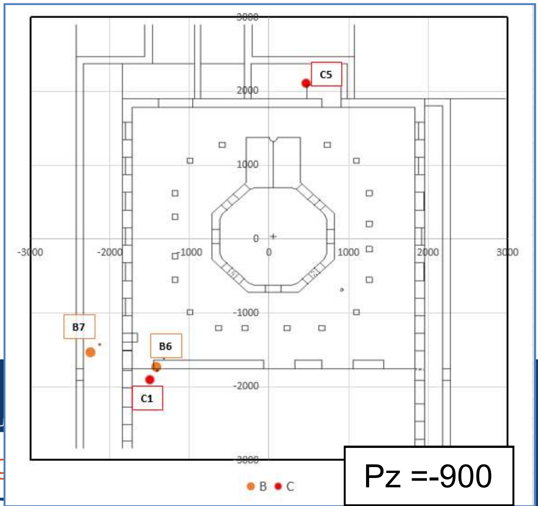
Measurement of neutron flux around JET using TLDs

Pz =0

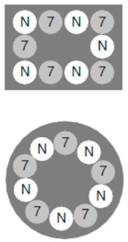


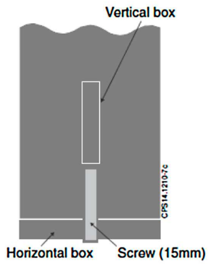
Pz =-590





31 locations have been measured using TLDs (inside polyethylene moderators)

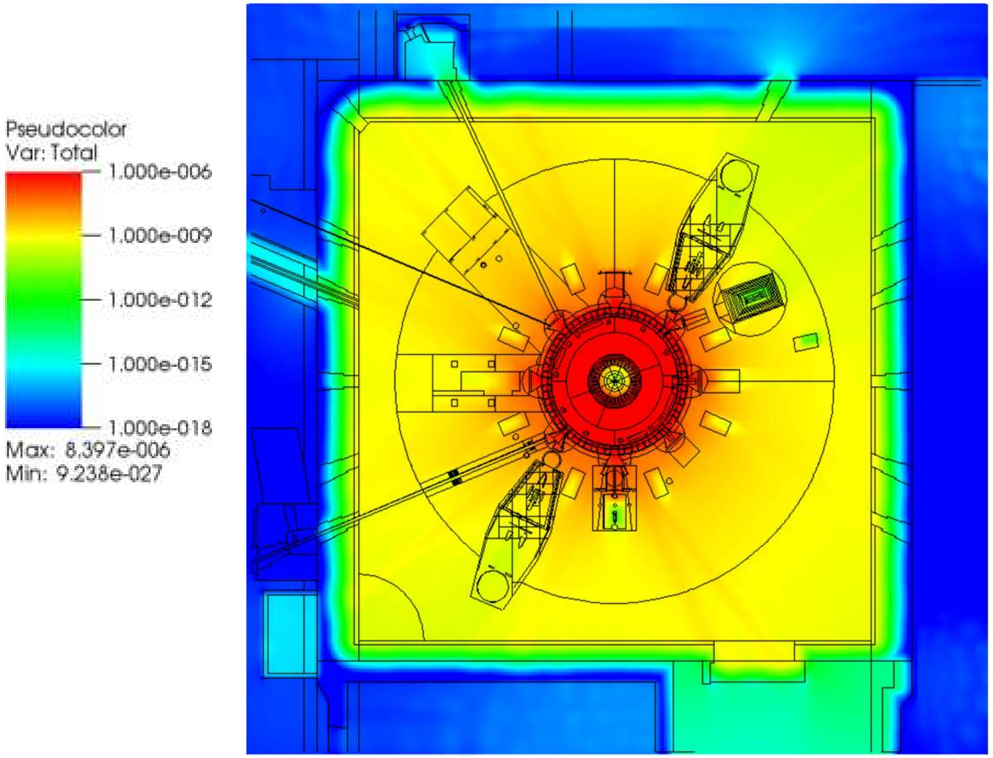




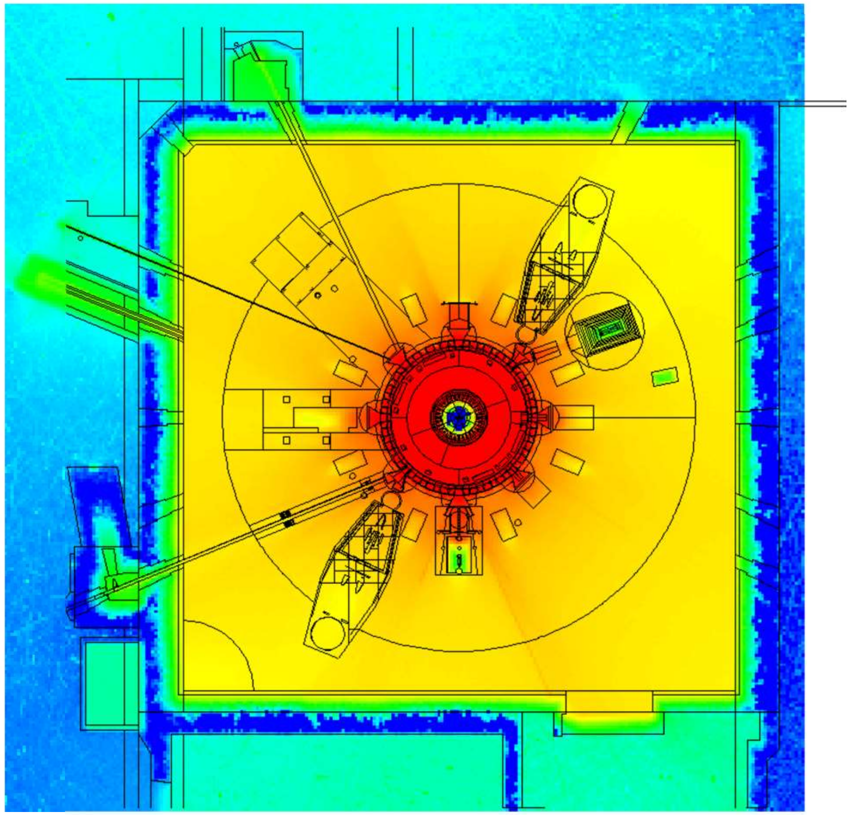
Also see: R. Villari et al, ITER oriented neutronics benchmark experiments on neutron streaming and shutdown dose rate at JET, In Fusion Engineering and Design, 2017,

Complementary calculations: deterministic versus Monte Carlo approaches

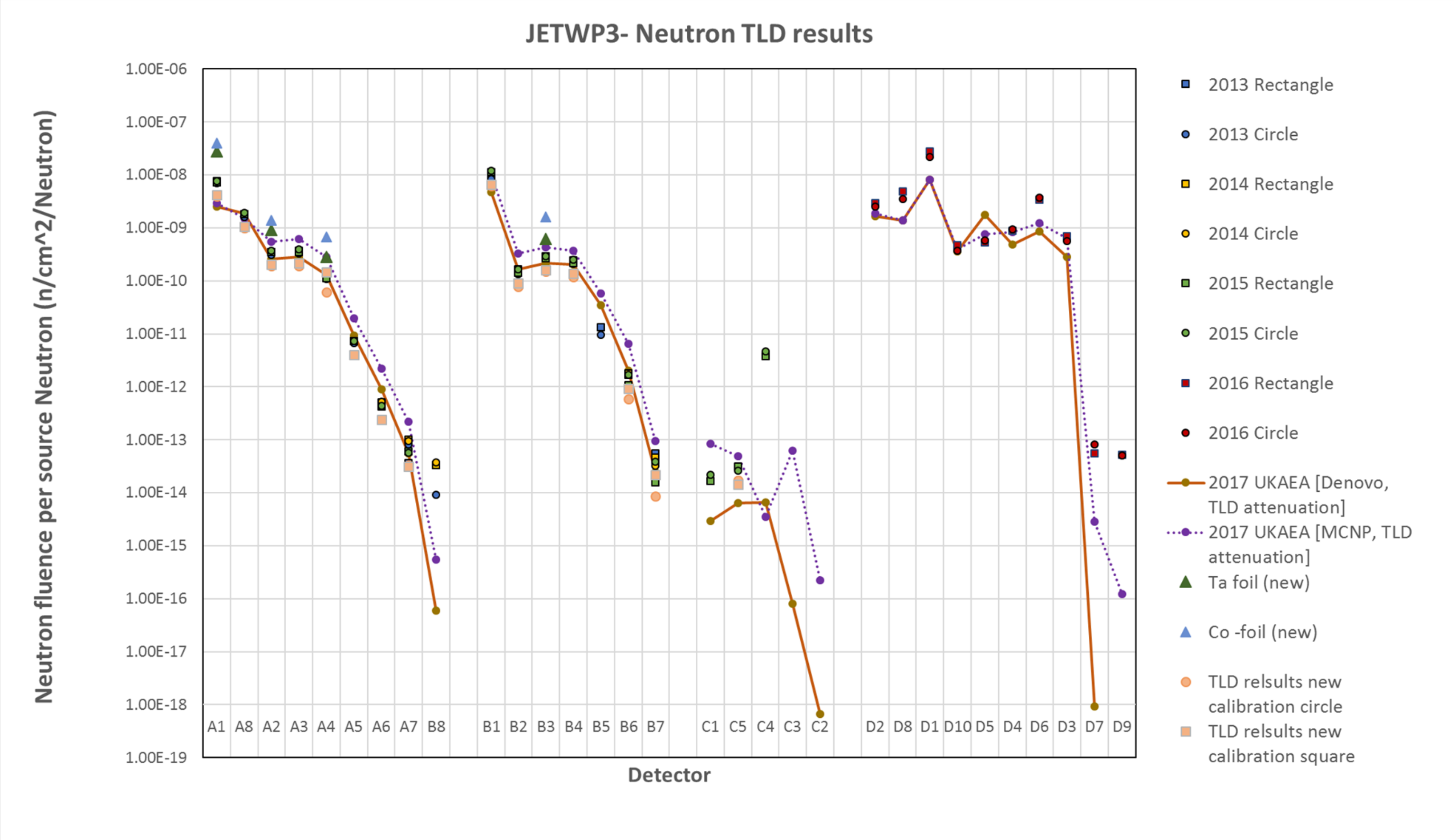
DENOVO (MCNP geometry superimposed)



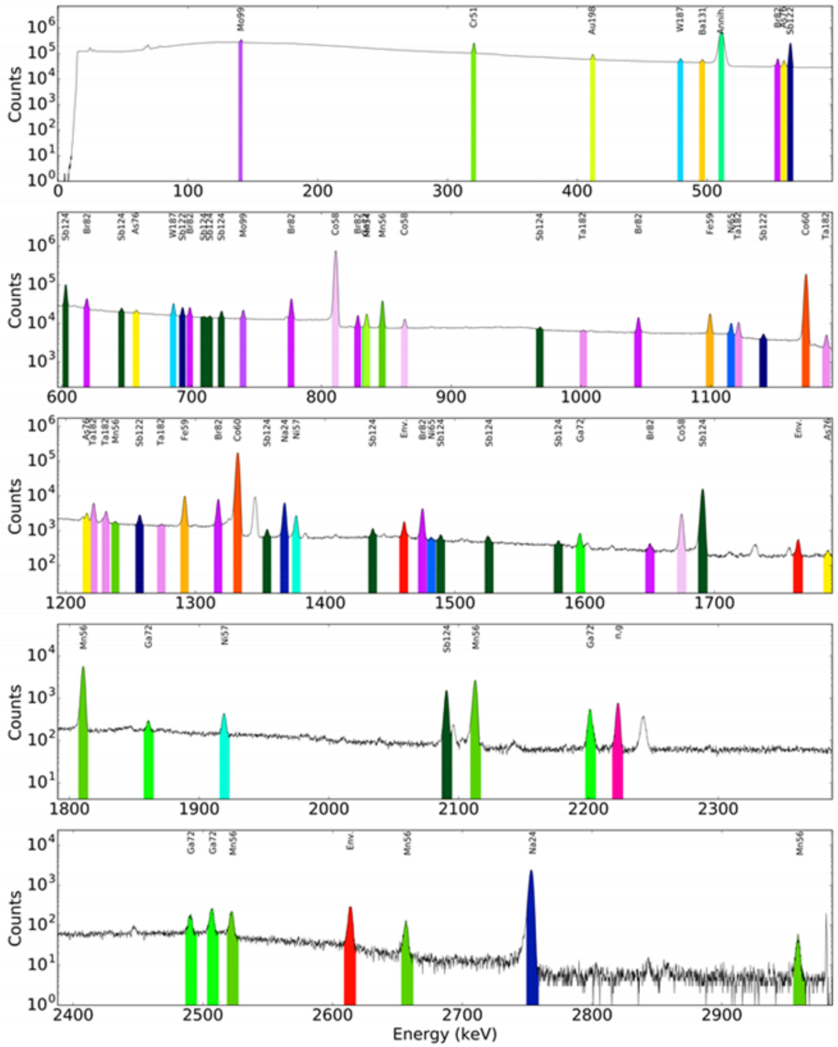
MCNP



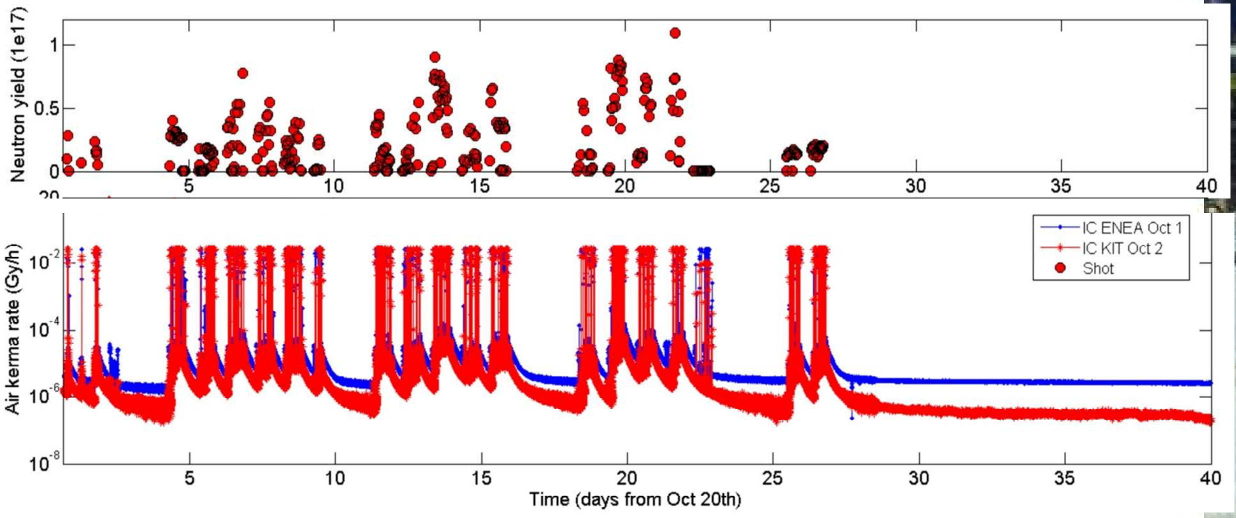
Comparisons of modelling against experimental results

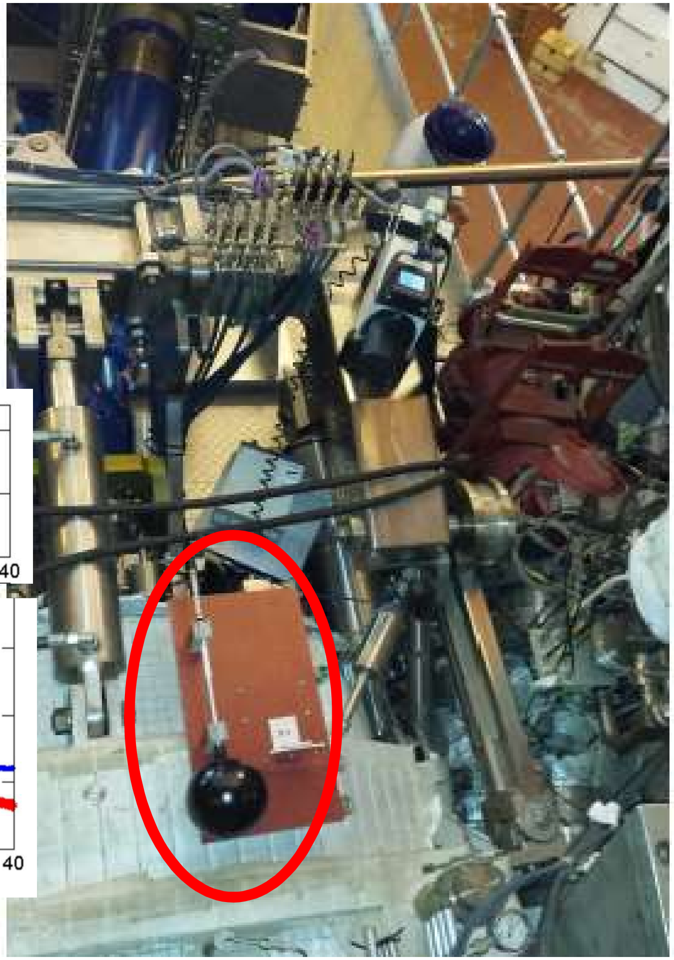


Gamma spectrometry measurements following JET shutdown



Ion chamber measurements during and following JET shutdown



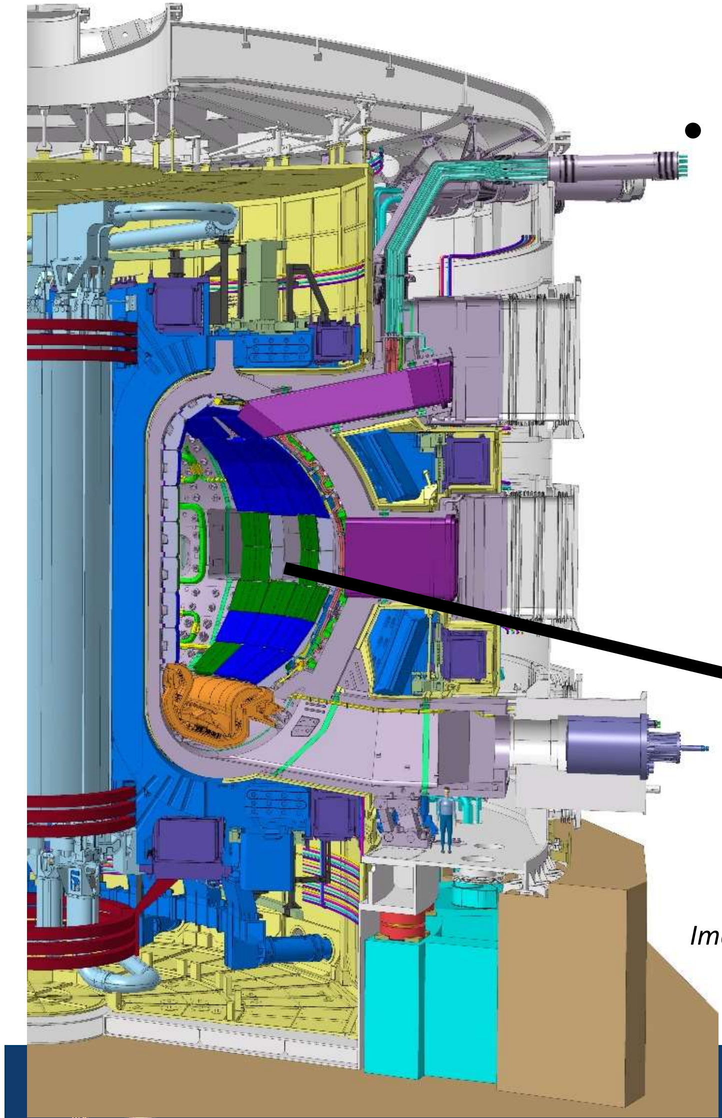


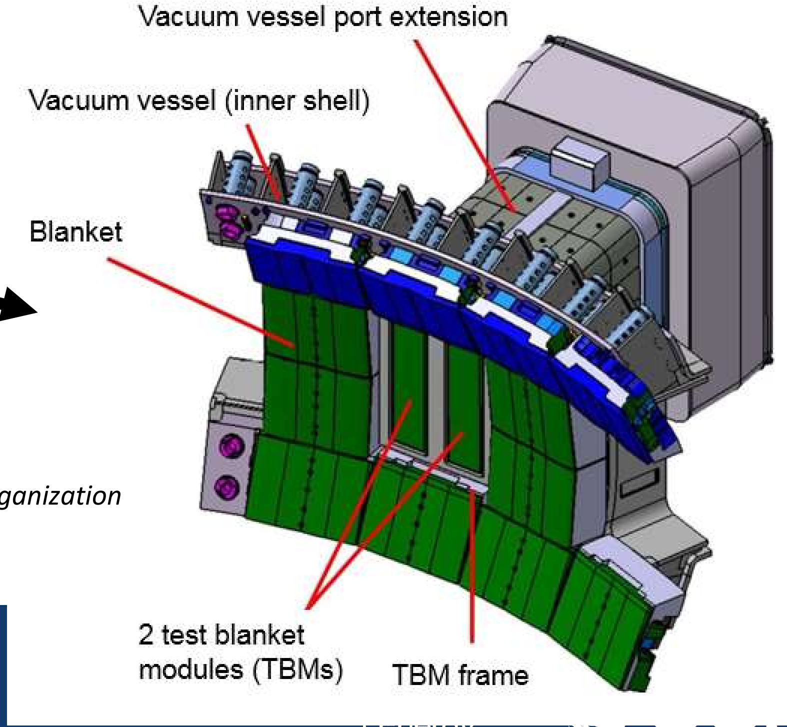
TBMD

Test of detectors for tritium breeder blankets

Activation foil-based spectrometer

- Potential 'radiation hard' system to evaluate radiation field inside a TBM
- Using a set of high-purity dosimetry foils within the TBM.
  - Reactions previously proposed (include a number of energy threshold and non-threshold reactions) using high-purity Ce, Al, Cr and Nb.





Images courtesy of ITER Organization

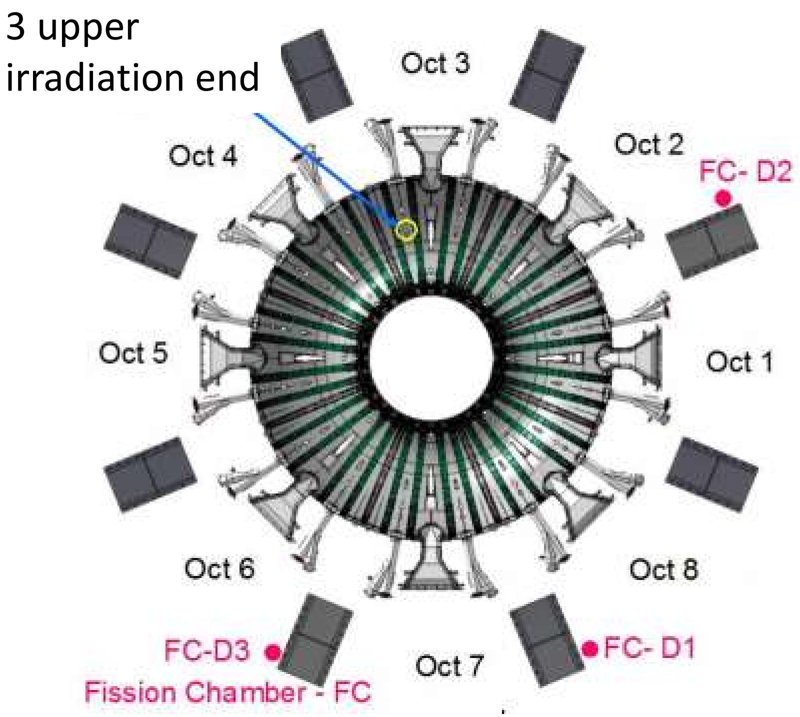
Activation foil-based spectrometer

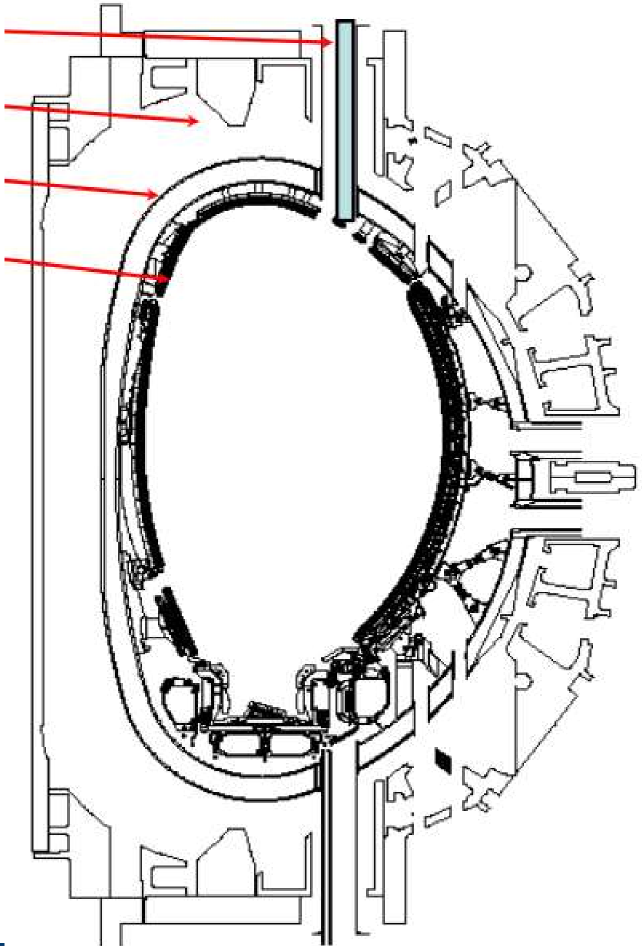
- Reactions previously proposed by A.Klix using high-purity Ce, Al, Cr and Nb.

Foil	Reaction	Product half-life (s)	Approx. energy threshold (MeV)	Gamma line energy (MeV)
Al	$^{27}Al(n,\gamma)^{28}Al$	134.46	-	1.7787
	$^{27}Al(n,p)^{27}Mg$	567.48	4.5	0.8437
Cr	$^{52}Cr(n,p)^{52}V$	224.7	5.5	1.4341
	$^{53}Cr(n,p)^{53}V$	97.2	6	1.0063
	$^{54}Cr(n,p)^{54}V$	49.8	11	0.8348
	$^{54}Cr(n,\alpha)^{51}Ti$	348.0	8.2	0.3201
Nb	$^{93}Nb(n,\gamma)^{94m}Nb$	375.6	-	0.871
	$^{93}Nb(n,\alpha)^{90m}Y$	11484	6.9	0.2025
	$^{93}Nb(n,n'\alpha)^{89m}Y$	15.663	12.5	0.909
	$^{93}Nb(n,2n)^{92m}Nb$	876960	9.5	0.9345

Testing and deployment on JET

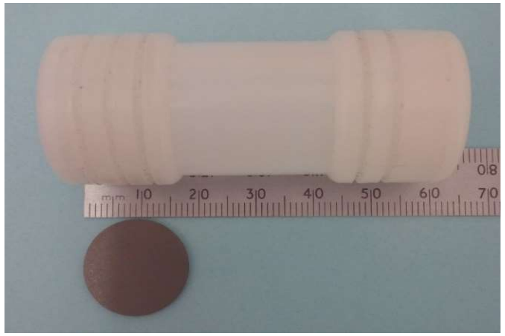
Octant 3 upper irradiation end using KN2 transfer system

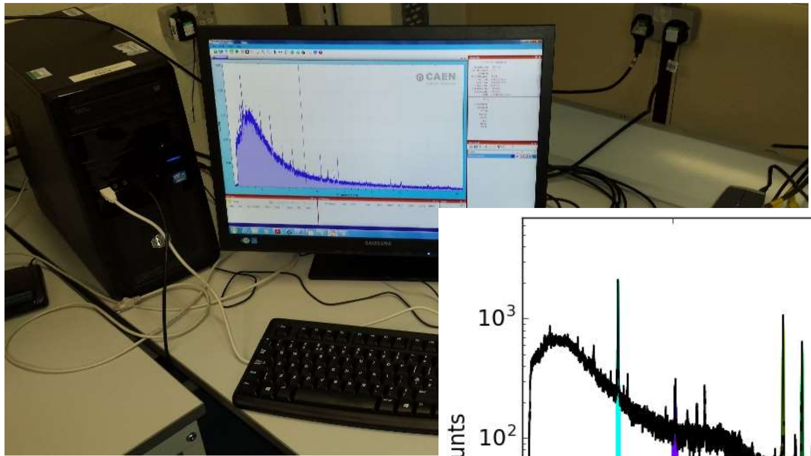


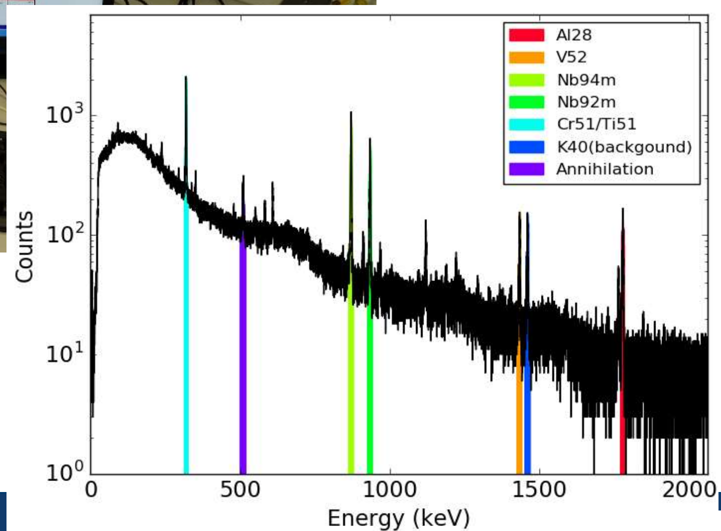


Testing at JET KN2

- Testing of foil-based spectrometry system performed during JET D-D shots
- Provided important functional and development testing of experimental setup and post-processing







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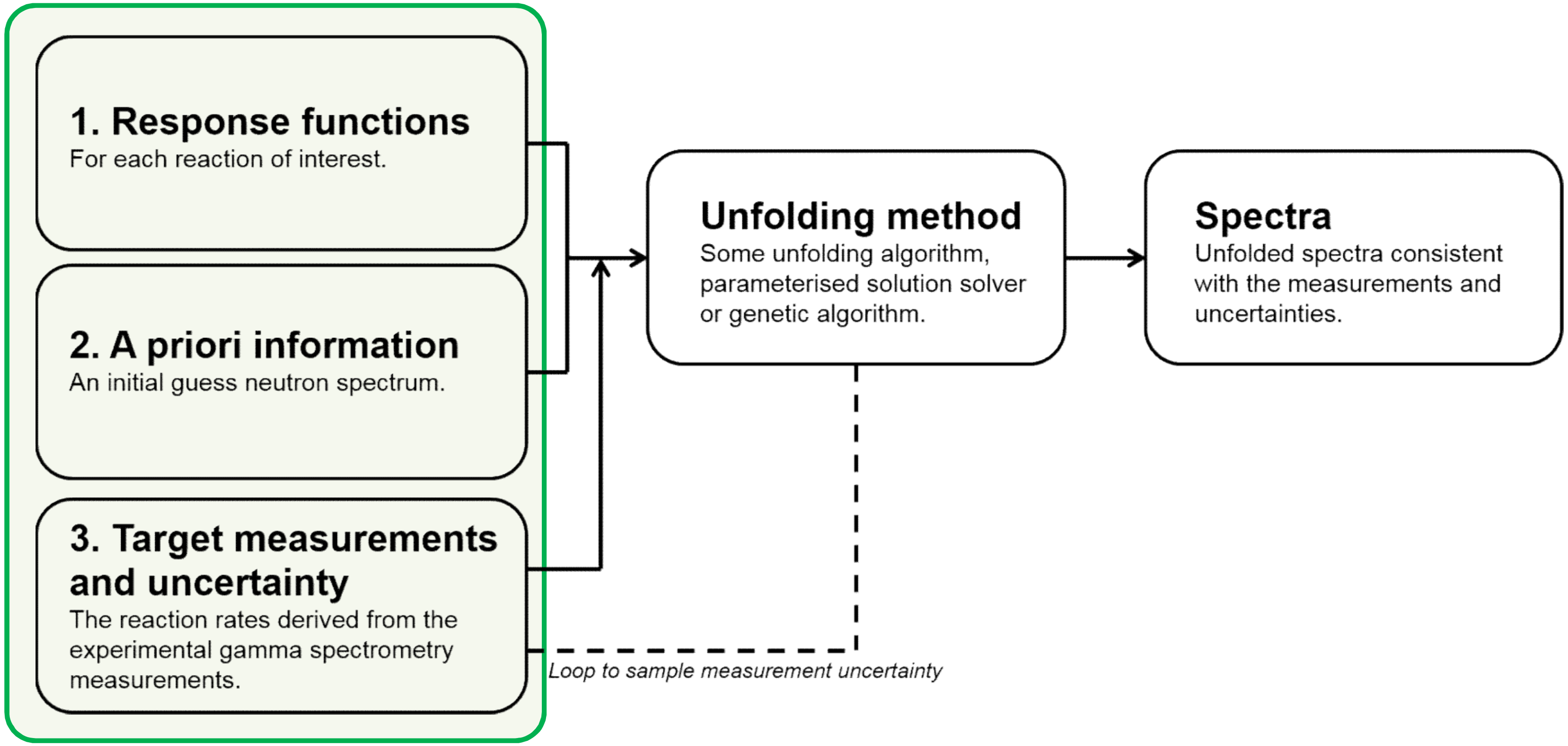
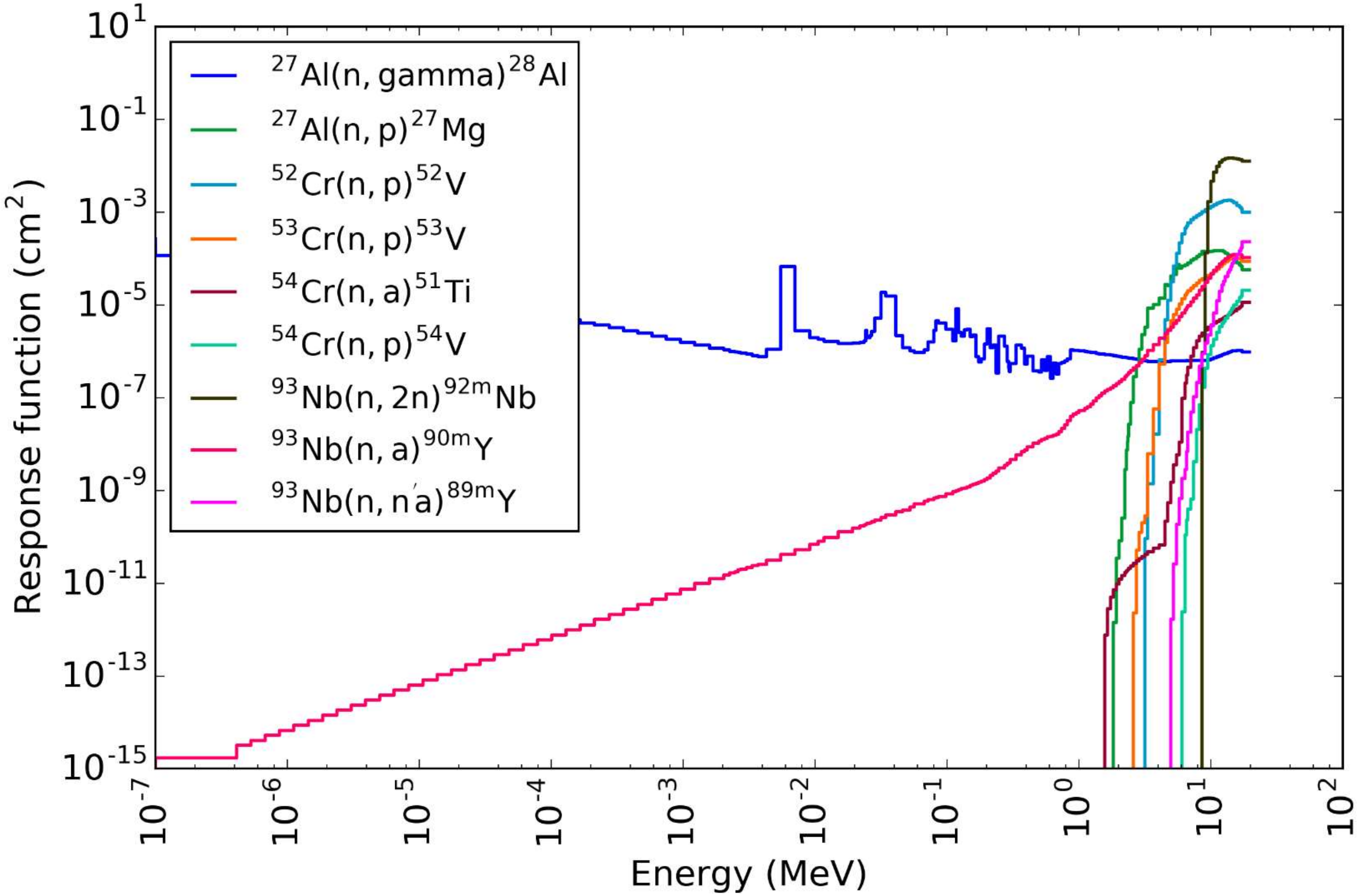
Neutron spectrum unfolding

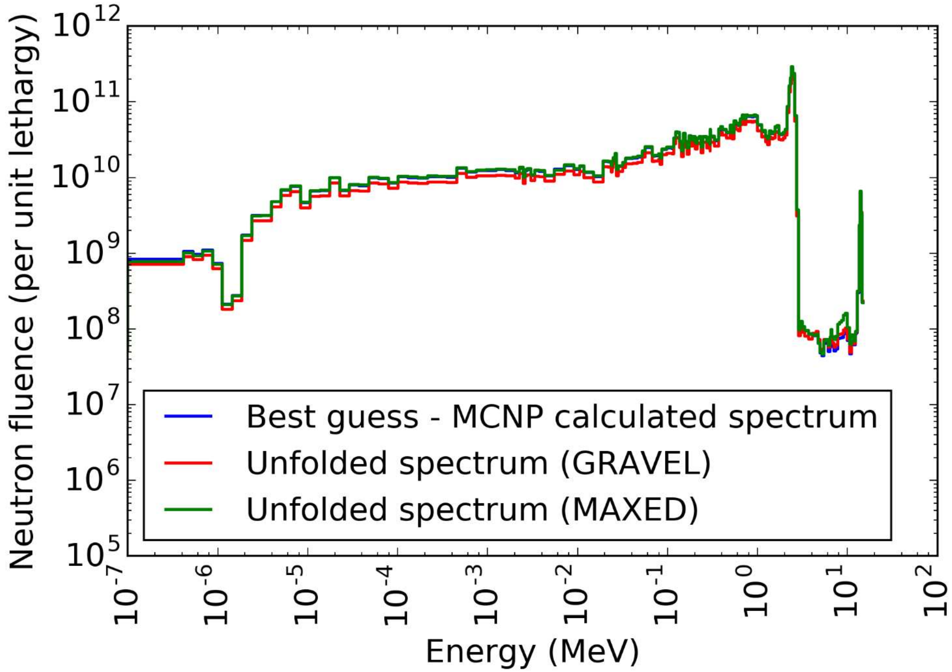


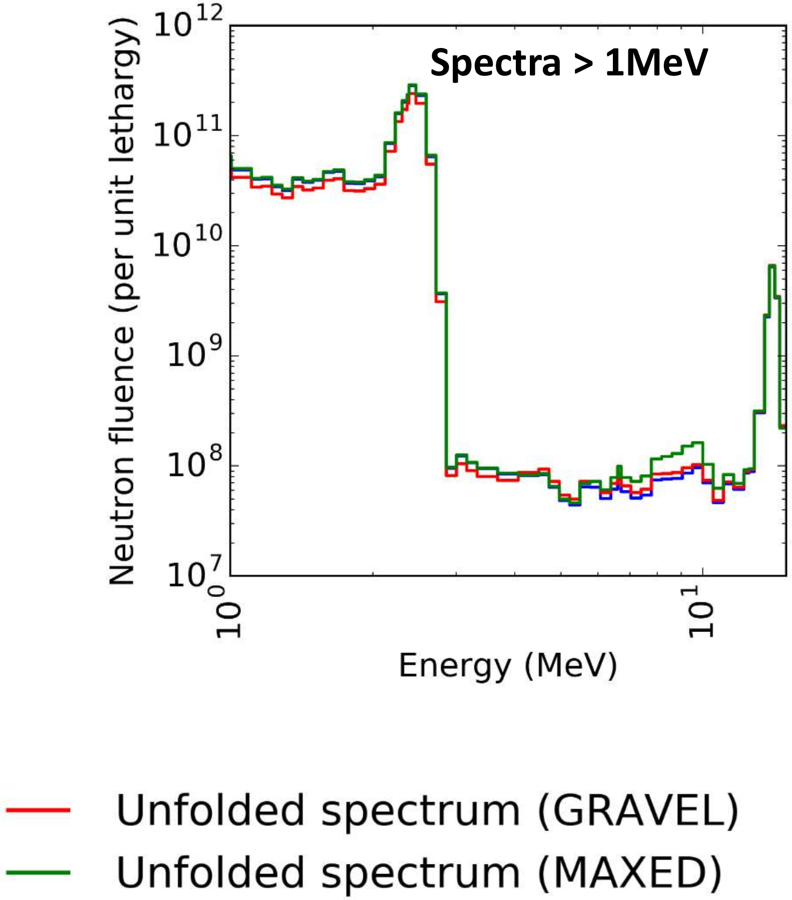
Neutron spectrum unfolding: response functions

Reaction response functions were calculated using particle transport calculation (MCNP) to include foil self-shielding and plastic capsule effects.

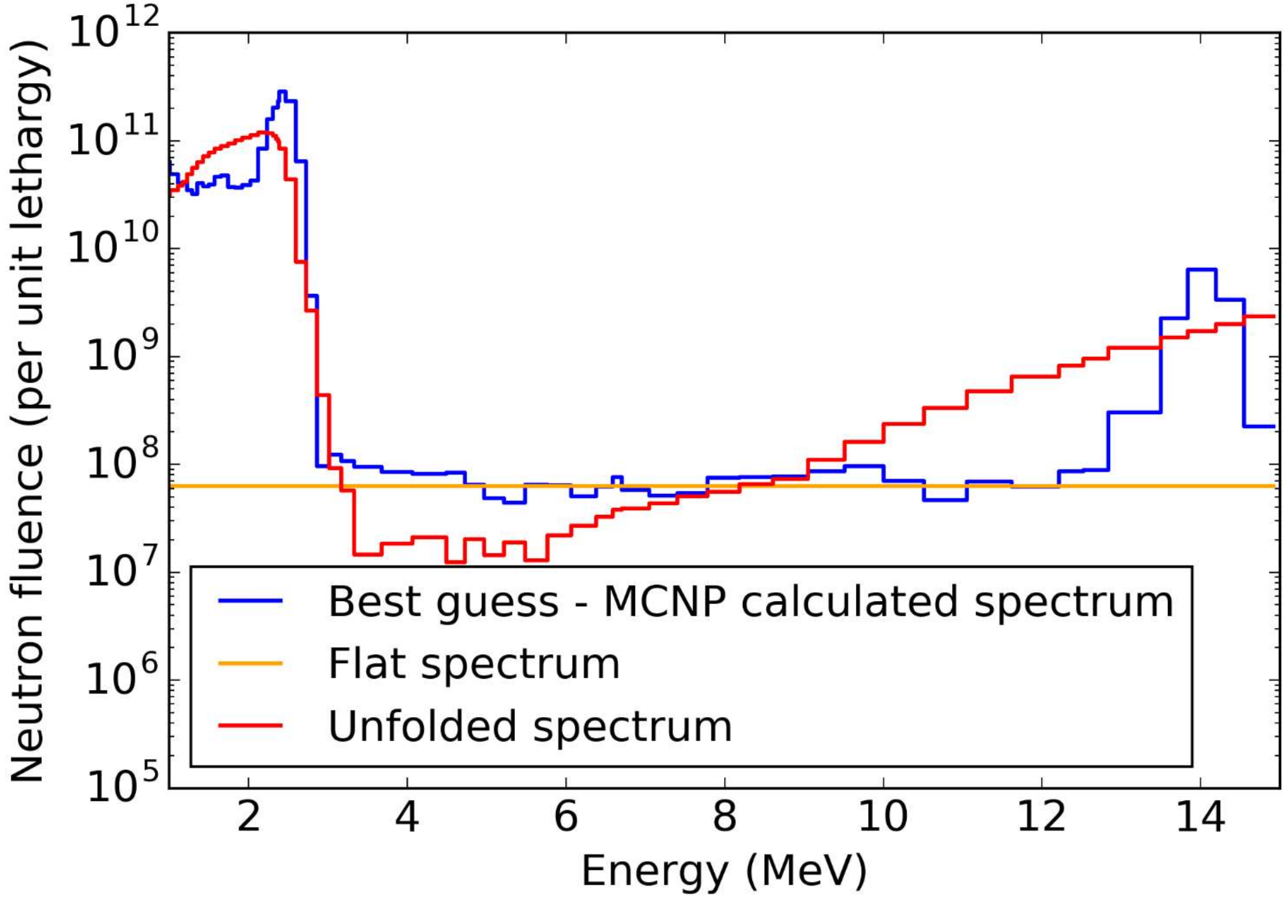


Spectrum unfolding with a good guess





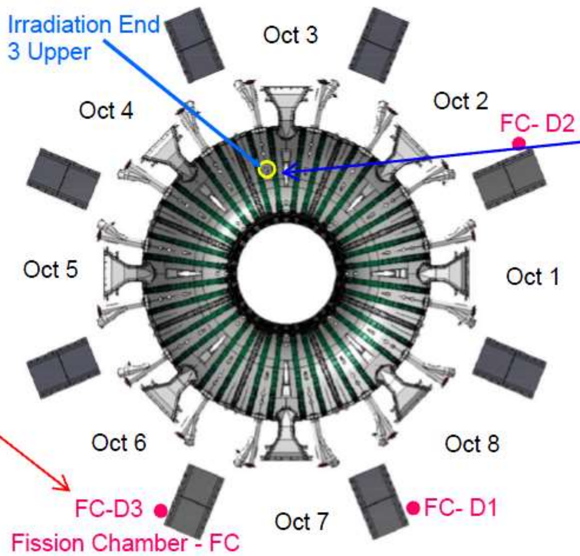
Spectrum unfolding with a poor guess

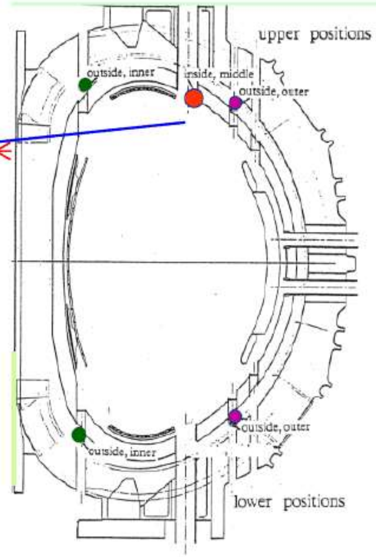


NC14

Neutron detector calibration at 14-MeV neutron energy

Fusion power is measured by neutron detectors: JET neutron yield measurements





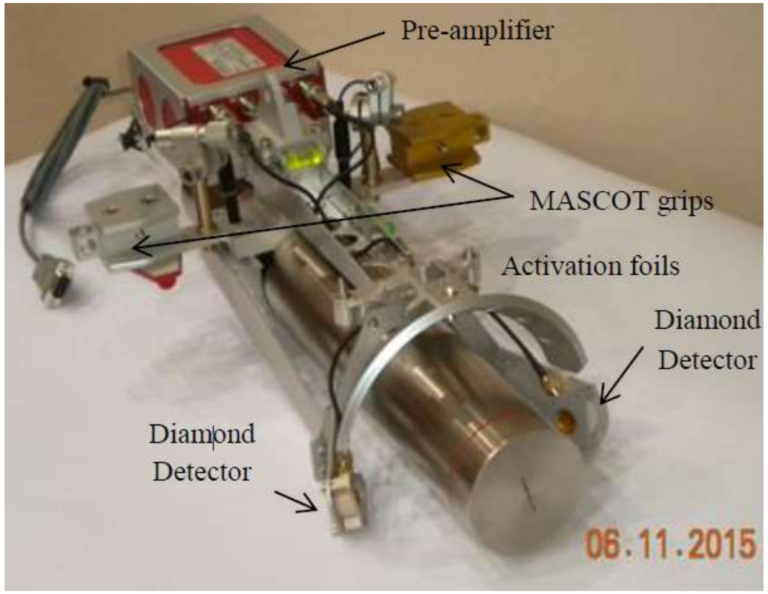
Fission chambers

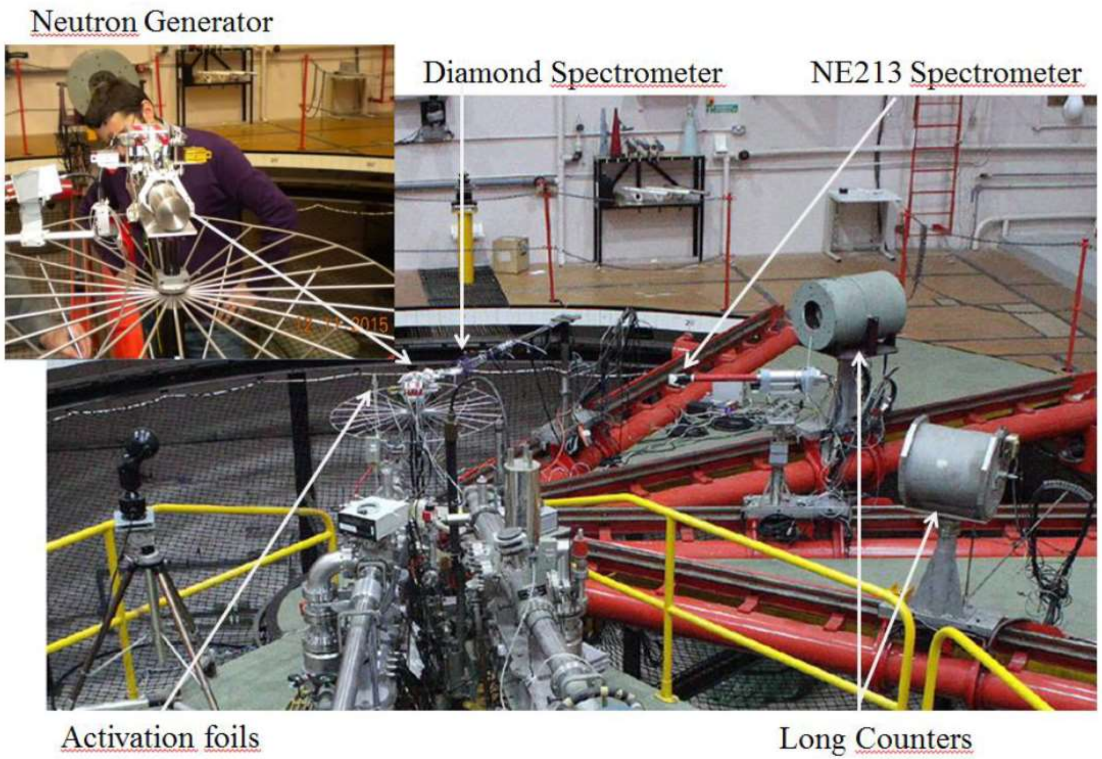
- ^{238}U, ^{235}U pairs
- Located outside the device
- Time-resolved neutron yield
- Measurement range from 10^{10} to 10^{20} n/s
- Moderate sensitivity to neutron energy spectrum
- High sensitivity to environmental changes (new installations, removals of equipment etc.)

Activation system

- 8 Irradiation Ends
- Time integrated neutron yield
- Based on the analysis of neutron induced radioactivity in selected metal samples.
- $^{115}In(n, n')In^{115m}$ for DD plasmas
- $^{28}Si(n,p)^{28}Al$, $^{63}Cu(n,2n)^{62}Cu$, $^{93}Nb(n,2n)^{92m}Nb$ for DT plasmas
- Neutron transport calculations needed to relate the total neutron yield to the neutron fluence at the sample position.

NC14 – experimental activities at NPL





See P. Batistoni et al, 14 MeV Calibration of JET neutron detectors – Phase 1: calibration and characterization of the neutron source, Nuclear Fusion 2018

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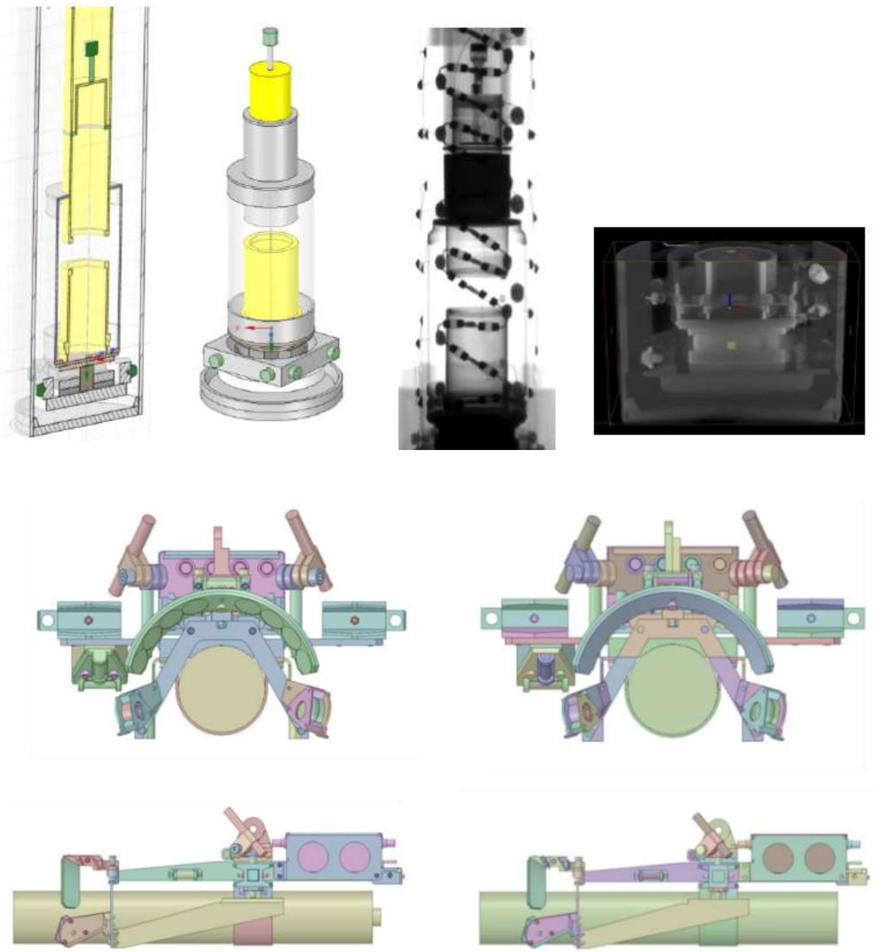
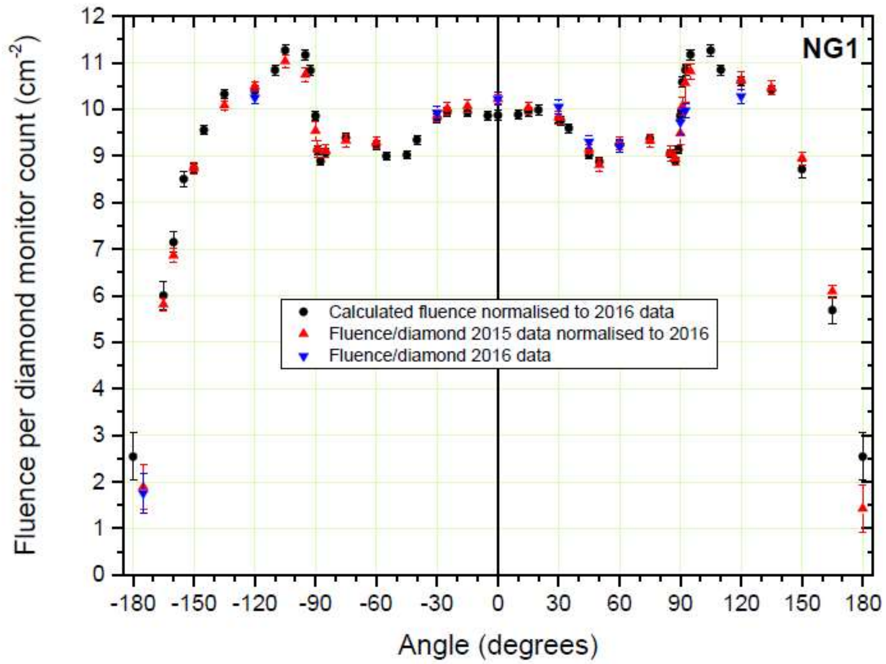
Development of neutron generator neutronics model and associated experimental validation





See P. Batistoni et al, 14 MeV Calibration of JET neutron detectors – Phase 1: calibration and characterization of the neutron source, Nuclear Fusion 2018

Concluding remarks on WPJET3

- WPJET3 programme aims to exploit technologies using large 14 MeV neutron fluences at JET
- A selection of recent results were presented here…
- For more information on the broader WPJET3 activities, see: P. Batistoni et al., ‘Technological exploitation of Deuterium–Tritium operations at JET in support of ITER design, operation and safety’ Fus. Eng. Des, 109–111, November 2016, pp 278-285