EUROfusion

Neutronics using FENDL data: Experimental benchmarking at JET in DTE2 with ITER materials

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**See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al 2022 Nucl. Fusion 62 042026*

FENDL meeting 10th October – 2nd November 2023

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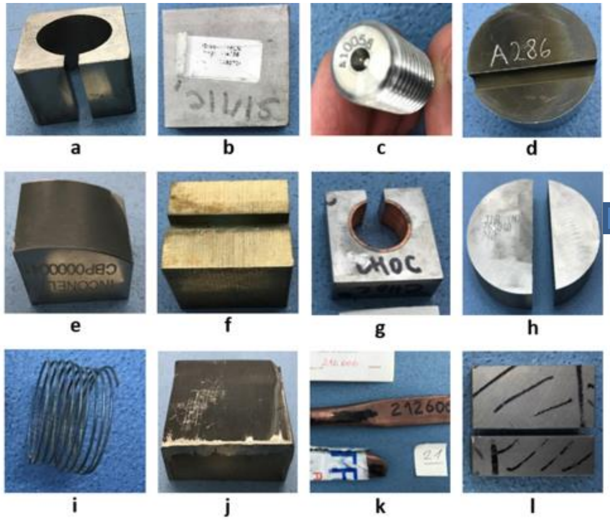
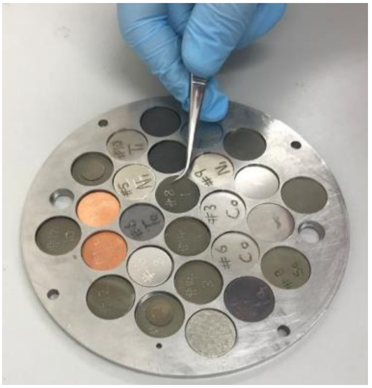
Why irradiate ITER materials within the JET nuclear environment?

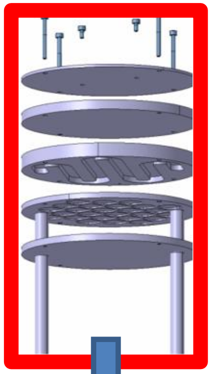
- Take advantage of the large 14 MeV neutron fluence during JET DTE2 to irradiate samples of real ITER materials used in the manufacturing of the main in-vessel tokamak components.
- The materials considered include: SS316L steels from a range of manufacturers, SS304B, Alloy 660, W, CuCrZr, XM-19, Al bronze, Nb_3Sn, NbTi and EUROFER for example.

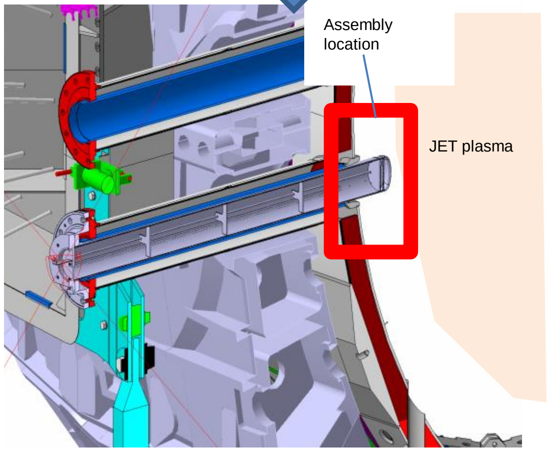


ITER materials sample prep.



Long-term irradiation station assembly (LTIS)





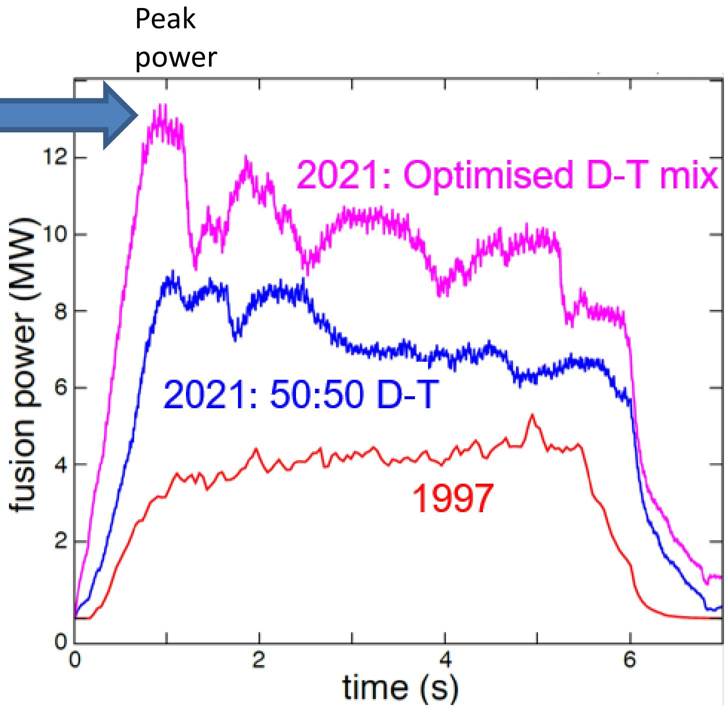
Motivation

- Improve confidence in post-irradiation nuclide predictions and residual radiation fields – relevant to operations, maintenance and decommissioning activities
- Explore deviations in elemental and impurity composition of materials between different suppliers using nuclear techniques
- Explore limited aspects of damage phenomena (not discussed in detail here, analysis ongoing with Czech collaborator NPI)

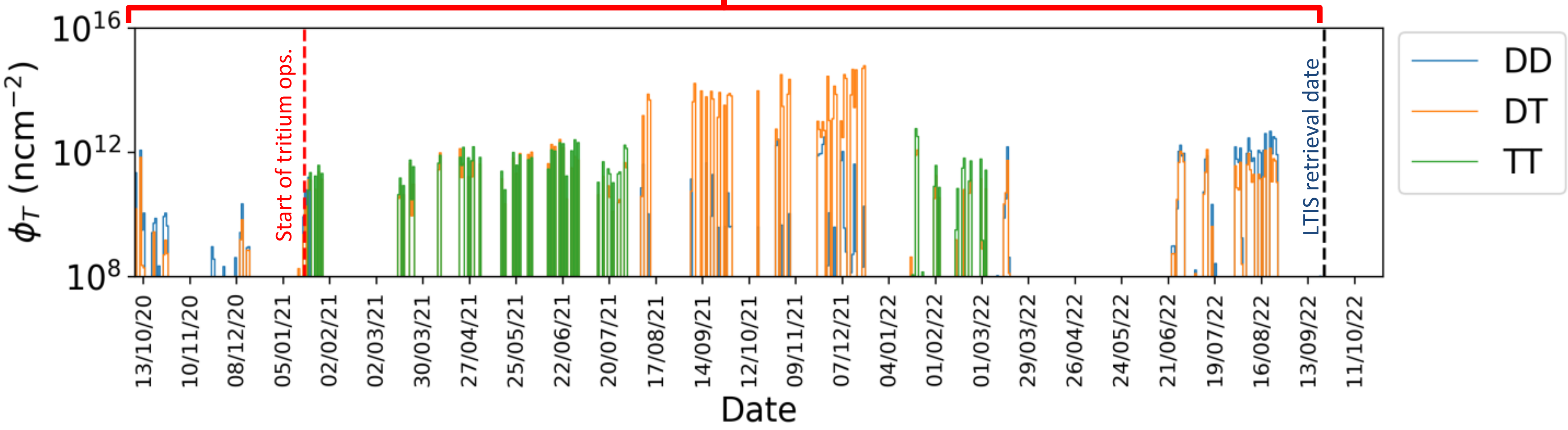
Fusion conditions in JET in the LTIS

LTIS (Long-Term Irradiation Station)

- Peak neutron flux: **2×10^{13} n/cm²/s -** One order of magnitude less than flux at ITER FW @ 500 MW

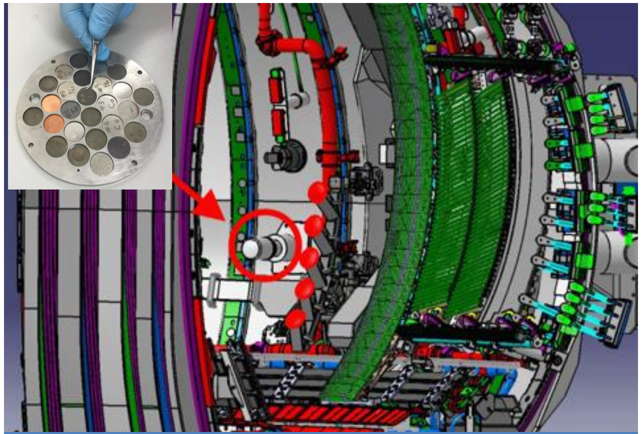


- Neutron fluence over 715 days **5×10^{15} n/cm²**



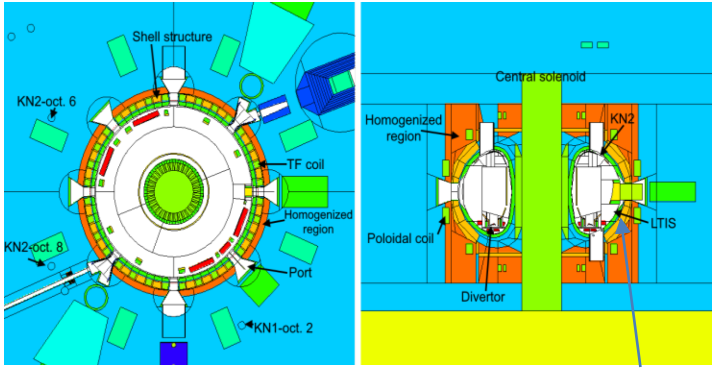
Total neutron yield over 715 days: **8.67×10^{20} n**

Neutronic simulations of the JET nuclear environment: activity predictions for ITER materials

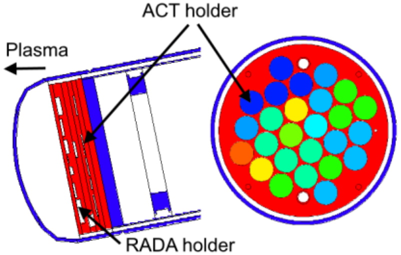


Irradiation assembly and location of installation in JET

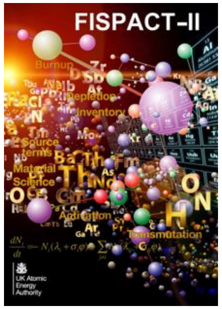
JET 360 degree reference neutronics model (JSI)



MCNP model of detailed LTIS assembly containing samples

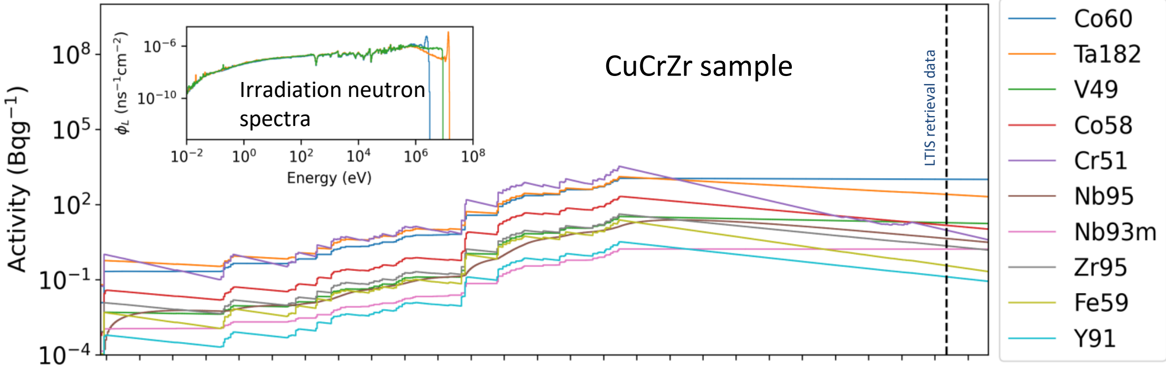


MCNP6 +

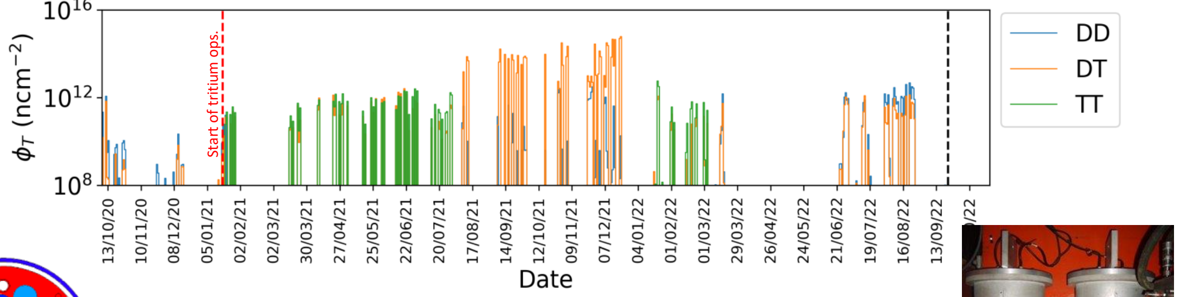


Nuclear data for radiation transport: FENDL 3.2b
Nuclear data for activation (priority order):
1) IRDFF-II → JEFF-3.3 → TENDL-2017
2) TENDL-2017

MCNP + FISPACT-II calculations used to predict activity in each ITER sample

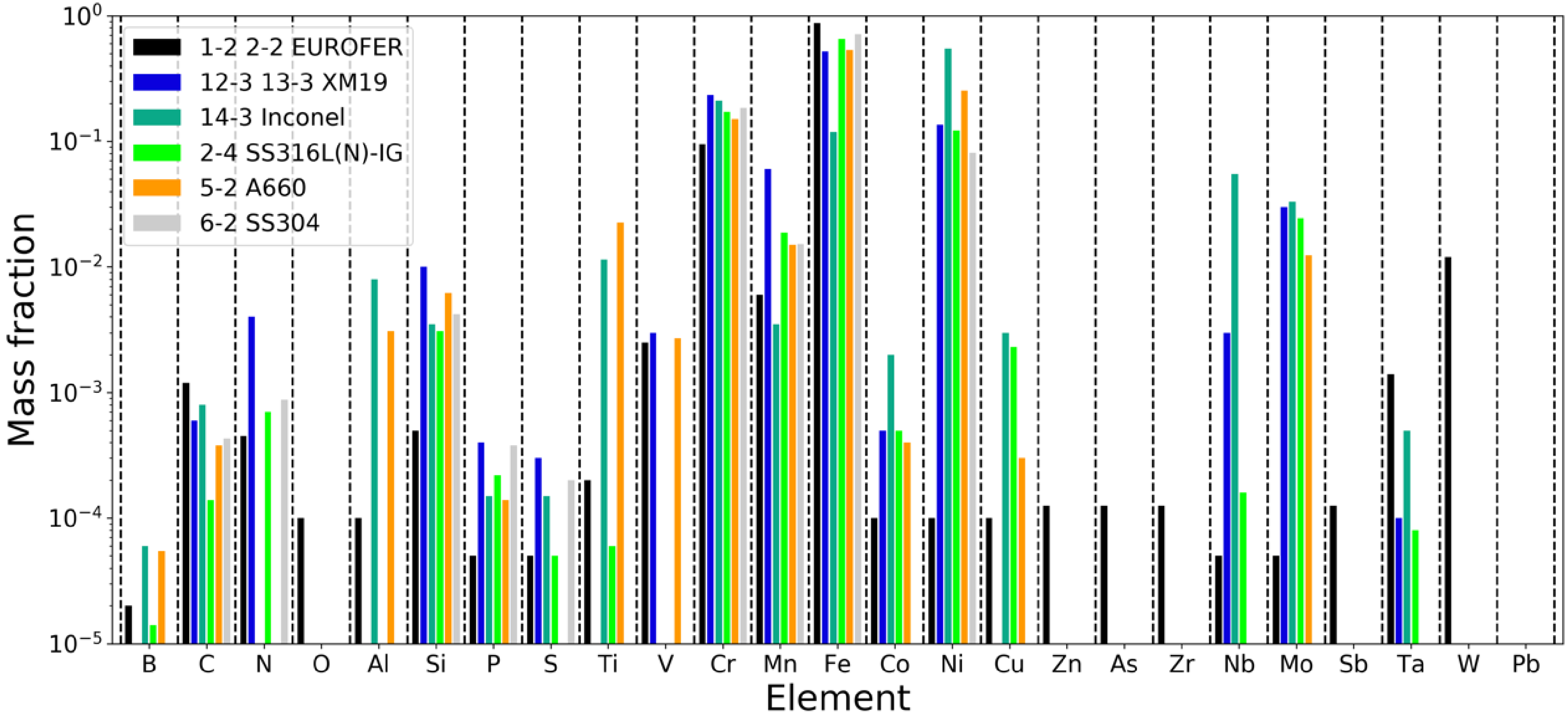


Temporal daily neutron fluence at the irradiation assembly location



KN1 neutron diagnostic (provided temporal neutron yield data)

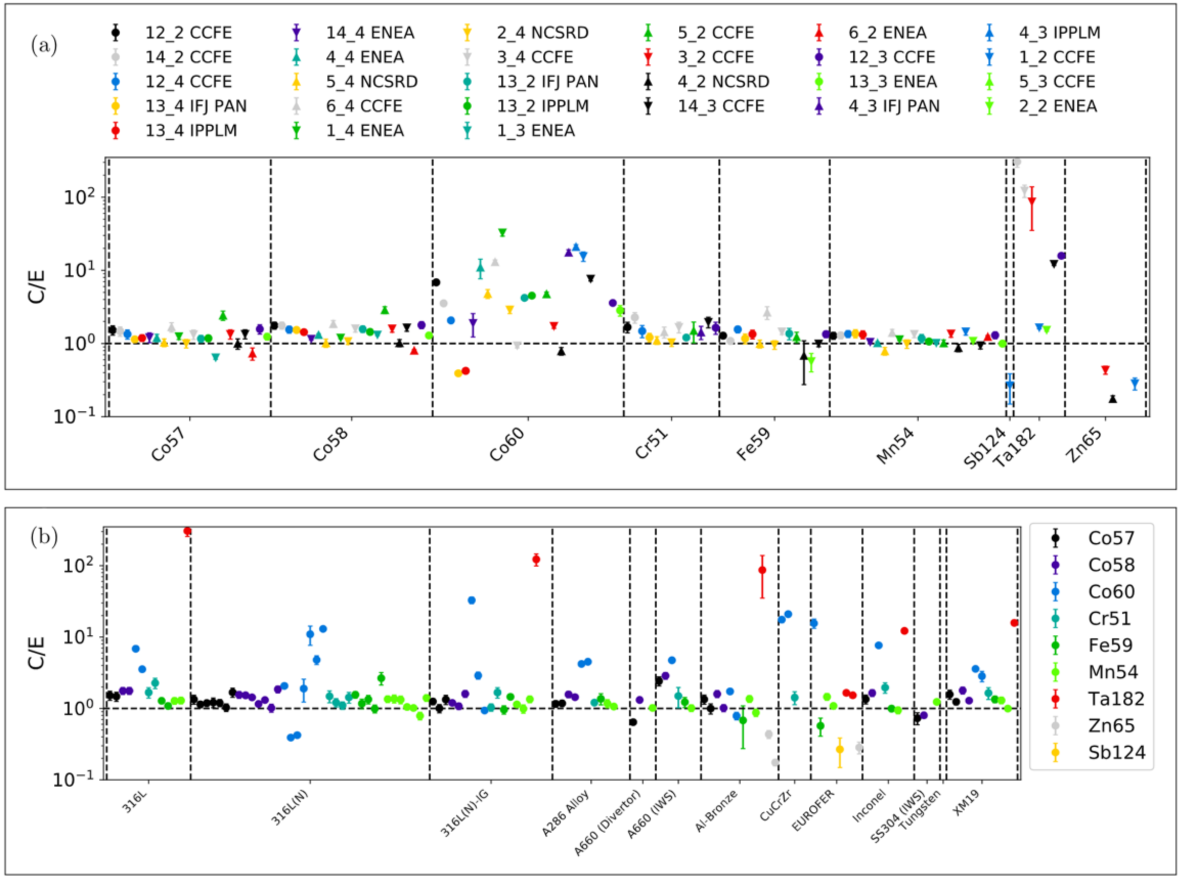
Inputs to simulations: ITER material elemental composition certificates

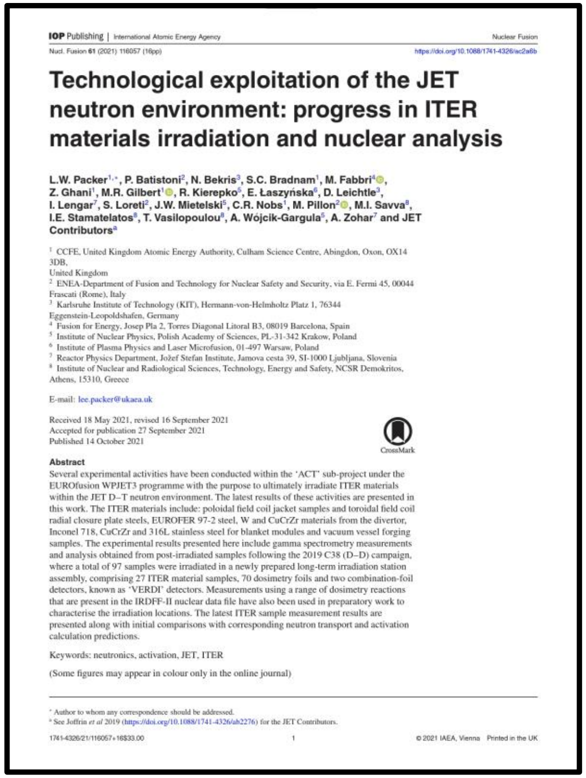


Upper bounds for impurities ranges assumed, where ranges were specified

Subset of material elemental compositions

Previous work: irradiation of ITER materials during JET DD (C38) campaign





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Technological exploitation of the JET neutron environment: progress in ITER materials irradiation and nuclear analysis

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Abstract

Several experimental activities have been conducted within the 'ACT' sub-project under the EUROfusion WPJET3 programme with the purpose to ultimately irradiate ITER materials within the JET D–T neutron environment. The latest results of these activities are presented in this work. The ITER materials include: poloidal field coil jacket samples and toroidal field coil radial closure plate steels, EUROFER 97-2 steel, W and CuCrZr materials from the divertor, Inconel 718, CuCrZr and 316L stainless steel for blanket modules and vacuum vessel forging samples. The experimental results presented here include gamma spectrometry measurements and analysis obtained from post-irradiated samples following the 2019 C38 (D–D) campaign, where a total of 97 samples were irradiated in a newly prepared long-term irradiation station assembly, comprising 27 ITER material samples, 70 dosimetry foils and two combination-foil detectors, known as 'VERDI' detectors. Measurements using a range of dosimetry reactions that are present in the IRDFF-II nuclear data file have also been used in preparatory work to characterise the irradiation locations. The latest ITER sample measurement results are presented along with initial comparisons with corresponding neutron transport and activation calculation predictions.

Keywords: neutronics, activation, JET, ITER

(Some figures may appear in colour only in the online journal)

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[a] See Joffrin *et al* 2019 (https://doi.org/10.1088/1741-4326/ab2276) for the JET Contributors.

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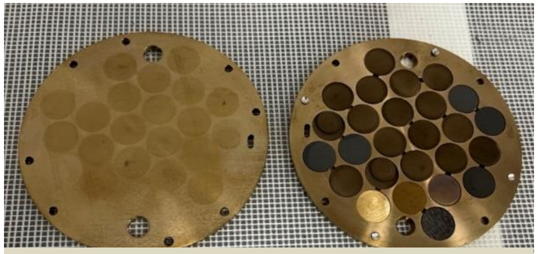
- ^{57}Co, ^{58}Co, ^{51}Cr, ^{59}Fe and ^{54}Mn are observed to be closest to 1, with averaged values per nuclide within the range 1.08–1.39
- ^{60}Co has a high average C/E of 6.55
- Discrepancies observed included ^{65}Zn and ^{182}Ta in some samples

See L.W. Packer, et al, Technological exploitation of the JET neutron environment: progress in ITER materials irradiation and nuclear analysis, Nuclear Fusion (2021) **61** 116057, https://doi.org/10.1088/1741-4326/ac2a6b

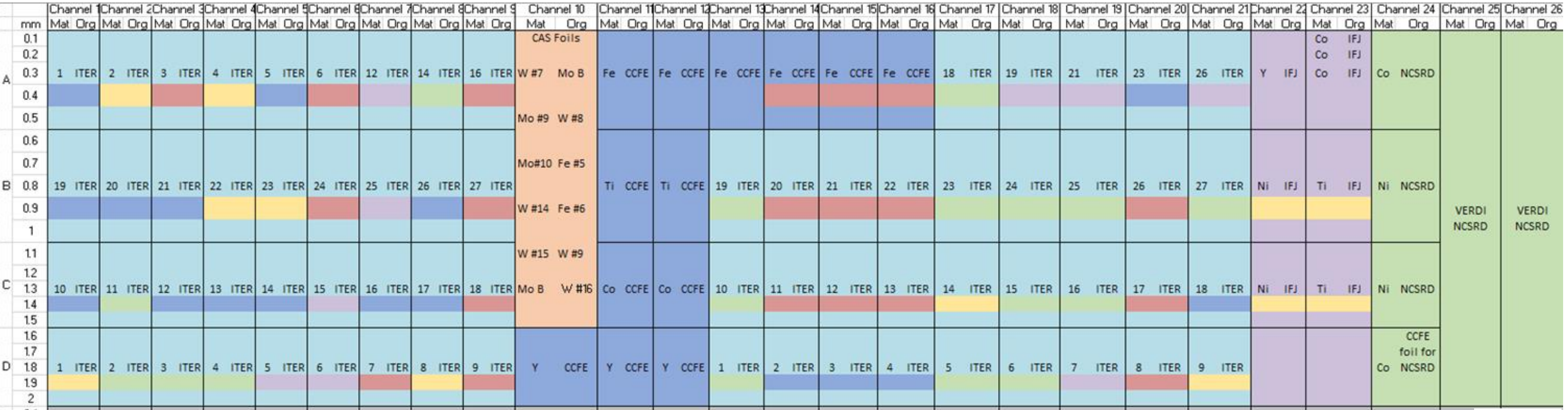
Current work: ITER materials LTIS configuration for DTE2 exposure

- ITER samples, dosimetry foils and PALS samples were irradiated in DTE2 within an assembly ‘ACT holder’
- The ACT holder was retrieved from JET on 25/09/2022
- Transferred to the UKAEA Materials Research Facility for extraction of samples
- Measured contact dose rate: 660 μSv/hr [calculated 673±75 μSv/hr]
- The samples were then distributed to various labs: NCSRD, ENEA, IFJ-PAN, IPPLM



Post-irradiated ACT holder containing the samples

Gamma spectrometry measurement of the ACT holder



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	0.1																			CAS Foils							
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A	0.3	1	ITER	2	ITER	3	ITER	4	ITER	5	ITER	6	ITER	12	ITER	14	ITER	16	ITER	W #7	Mo B	Fe	CCFE	Fe	CCFE	Fe	CCFE
	0.4	🟦	🟦	🟨	🟨	🟥	🟥	🟨	🟨	🟦	🟦	🟥	🟥	🟪	🟪	🟩	🟩	🟥	🟥								
	0.5																			Mo #9	W #8						
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B	0.8	19	ITER	20	ITER	21	ITER	22	ITER	23	ITER	24	ITER	25	ITER	26	ITER	27	ITER			Ti	CCFE	Ti	CCFE	19	ITER
	0.9	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟥	🟥	🟪	🟪	🟦	🟦	🟥	🟥	W #14	Fe #6					🟩	🟩
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D	1.8	1	ITER	2	ITER	3	ITER	4	ITER	5	ITER	6	ITER	7	ITER	8	ITER	9	ITER	Y	CCFE	Y	CCFE	Y	CCFE	1	ITER
	1.9	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟪	🟪	🟪	🟪	🟥	🟥	🟨	🟨	🟥	🟥							🟩	🟩
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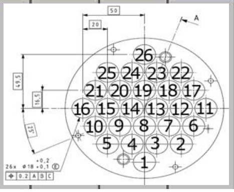
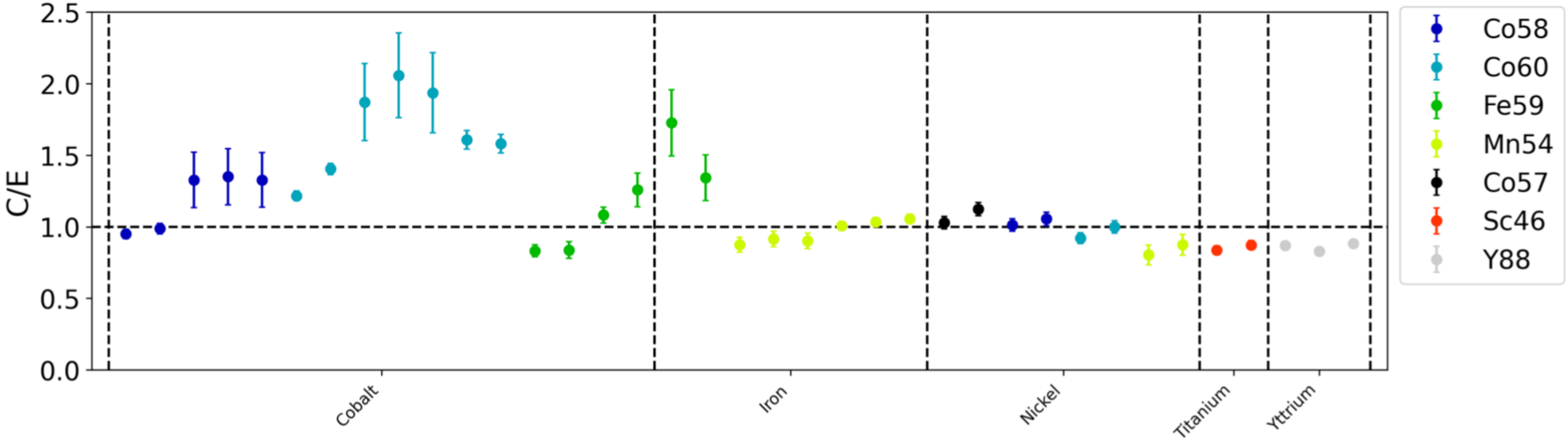
Arrangement of ITER samples and dosimetry foils in the ACT holder



Key
🟦 UKAEA
🟩 NCSRD
🟥 ENEA
🟪 IFJ
🟨 IPPLM
🟧 CAS

Nuclear characterisation of the LTIS: Dosimetry foil-based measurements



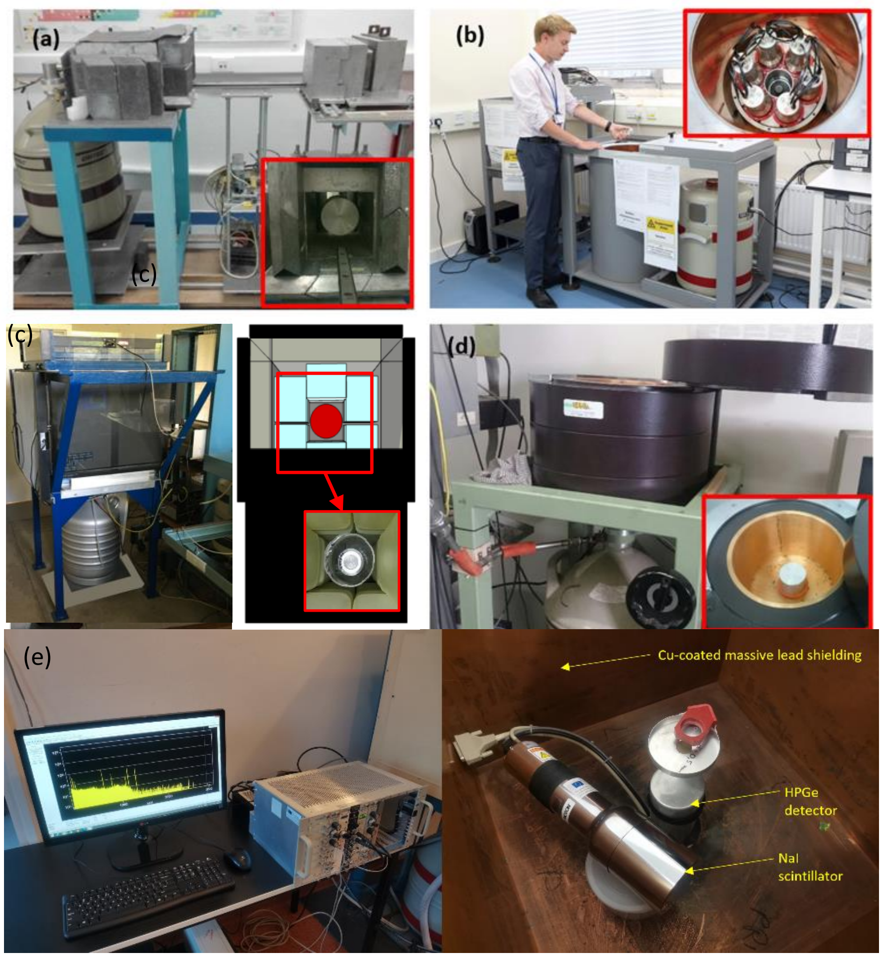
(C/E – calculated to experimental ratio)

- **The weighted average C/E across all dosimetry foil diagnostic measurements was 0.986 ± 0.01**

- The uncertainty in the KN1 neutron yield diagnostic is reported as 10 % and so the fast neutron fluence value is consistent (within uncertainties) with measurement
- May indicate a slight overestimate of the thermal neutron flux within the LTIS. The discrepancy could also potentially originate from factors such as self-shielding effects from adjacent materials or unaccounted-for details in the model.

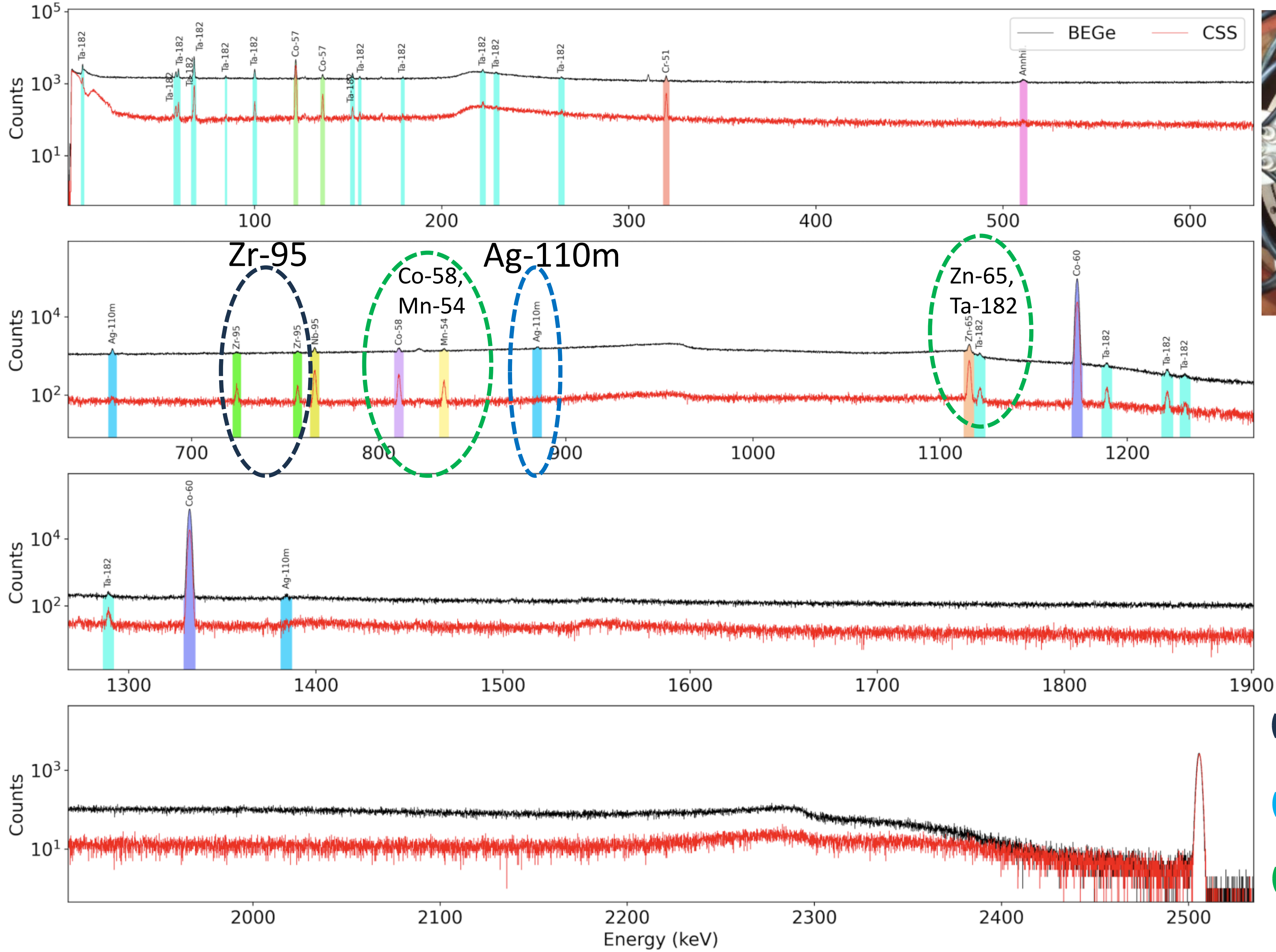
Post DTE2 irradiation gamma spectrometry measurements

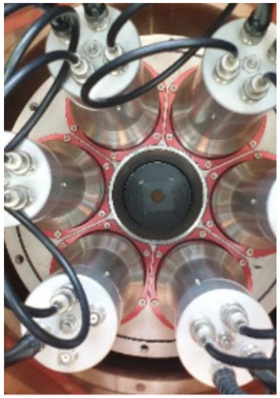
ITER materials were measured using gamma spectrometry techniques at several laboratories to identify and quantify nuclide activities generated through neutron activation



Participating gamma spectrometry laboratories: (a) NCSRD; (b) CCFE; (c) IFJ-PAN; (d) ENEA and (e) IPPLM

Gamma spectrometry measurements: BEGe + Compton suppression system (CSS) for an ITER CuCrZr sample





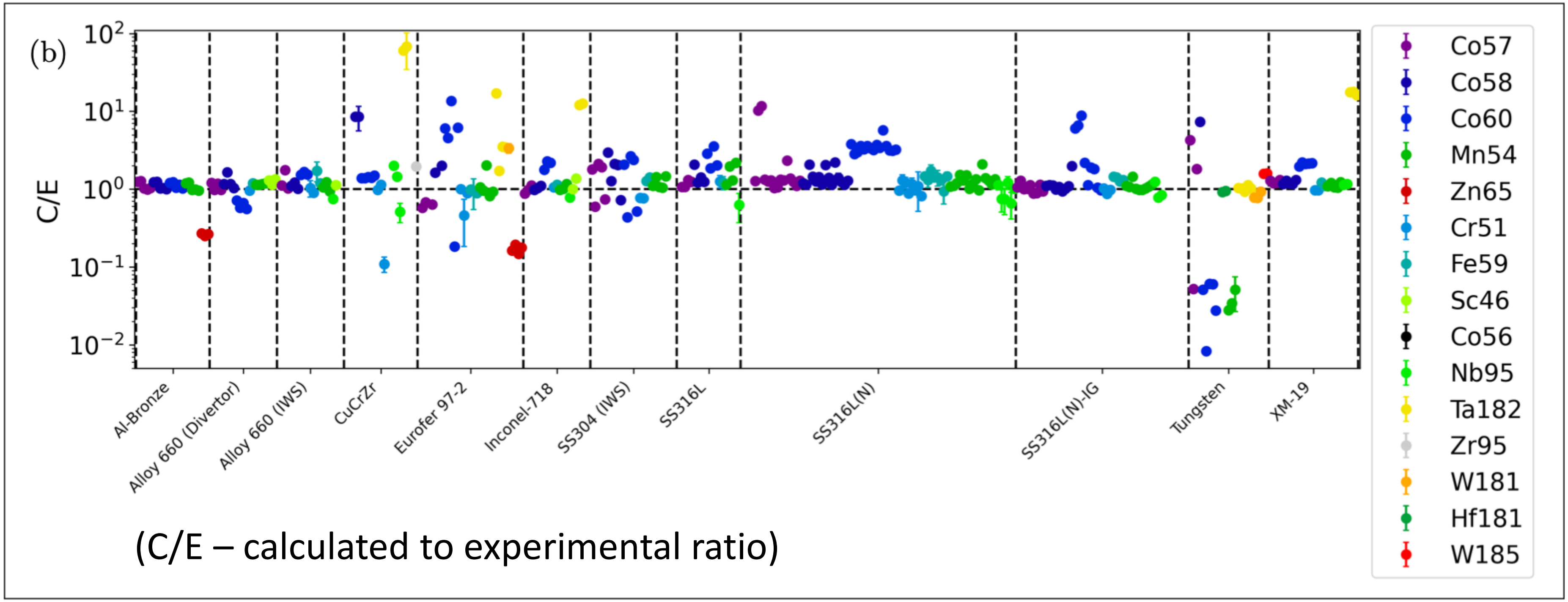
BEGe + Compton suppression system

○ CSS nuclide identification

○ BEGe nuclide identification

○ CSS improves S/B ratio

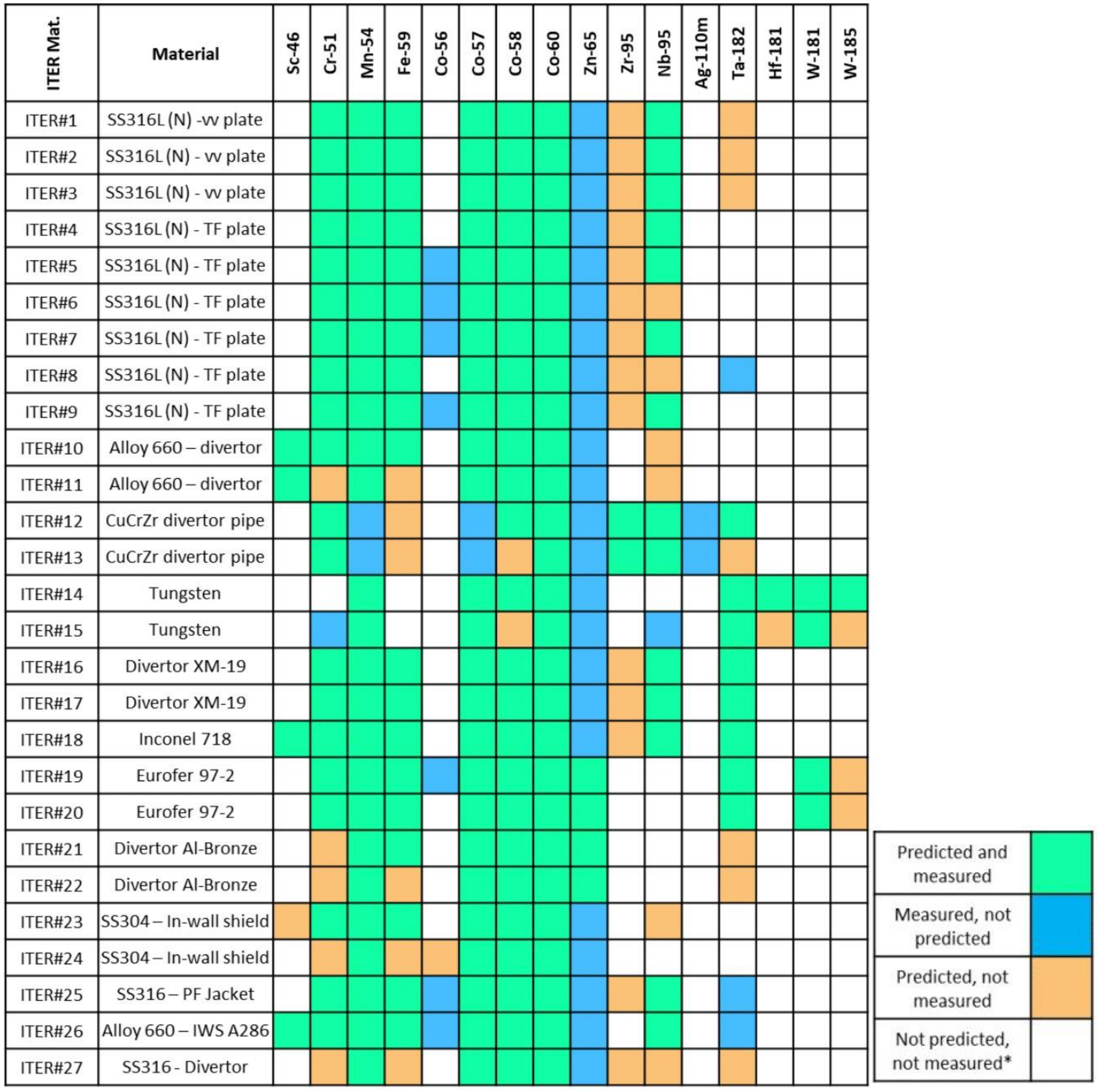
Post DTE2 C/E results – all data grouped by material and isotope



(C/E – calculated to experimental ratio)

- In general, the isotopes ^{46}Sc, ^{51}Cr, ^{54}Mn, ^{57}Co, ^{59}Fe, ^{95}Nb and ^{181}Hf have C/E values closest to 1 with weighted averages (excluding material outliers) within 25%
- CuCrZr and W monoblock samples showed comparatively more deviations than other samples
- High C/E values were seen in some materials for ^{58}Co (CuCrZr *8.6*, Tungsten *7.3*), ^{60}Co (6 materials e.g. SS316L(N) *3.29*), and ^{182}Ta (CuCrZr *60*, XM-19 *17*, Inconel-718 *13*). These isotopes are important for SDDR, but these results generally show calculations are conservative.
    - Although 4 materials gave ^{60}Co result with C/E<1 (e.g. Eurofer 97-2 *0.3*) - an underestimation in calculations. 2 materials (Al-Bronze and SS316L(N)-IG within 25% of C/E=1).
- Some low C/E values observed, particularly ^{65}Zn and ^{56}Co. ^{110m}Ag observed unexpectedly in CuCrZr. ^{182}Ta observed unexpectedly in Alloy 660 (IWS), SS316L and SS316L(N)

Summary matrix



ITER Mat.	Material	Sc-46	Cr-51	Mn-54	Fe-59	Co-56	Co-57	Co-58	Co-60	Zn-65	Zr-95	Nb-95	Ag-110m	Ta-182	Hf-181	W-181	W-185
ITER#1	SS316L (N) -vv plate	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	🟧	🟩	⬜	🟧	⬜	⬜	⬜
ITER#2	SS316L (N) - vv plate	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	🟧	🟩	⬜	🟧	⬜	⬜	⬜
ITER#3	SS316L (N) - vv plate	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	🟧	🟩	⬜	🟧	⬜	⬜	⬜
ITER#4	SS316L (N) - TF plate	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	🟧	🟩	⬜	⬜	⬜	⬜	⬜
ITER#5	SS316L (N) - TF plate	⬜	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟧	🟩	⬜	⬜	⬜	⬜	⬜
ITER#6	SS316L (N) - TF plate	⬜	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟧	🟧	⬜	⬜	⬜	⬜	⬜
ITER#7	SS316L (N) - TF plate	⬜	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟧	🟩	⬜	⬜	⬜	⬜	⬜
ITER#8	SS316L (N) - TF plate	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	🟧	🟧	⬜	🟦	⬜	⬜	⬜
ITER#9	SS316L (N) - TF plate	⬜	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟧	🟩	⬜	⬜	⬜	⬜	⬜
ITER#10	Alloy 660 – divertor	🟩	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	⬜	🟧	⬜	⬜	⬜	⬜	⬜
ITER#11	Alloy 660 – divertor	🟩	🟧	🟩	🟧	⬜	🟩	🟩	🟩	🟦	⬜	🟧	⬜	⬜	⬜	⬜	⬜
ITER#12	CuCrZr divertor pipe	⬜	🟩	🟦	🟧	⬜	🟦	🟩	🟩	🟦	🟩	🟩	🟦	🟩	⬜	⬜	⬜
ITER#13	CuCrZr divertor pipe	⬜	🟩	🟦	🟧	⬜	🟦	🟧	🟩	🟦	🟩	🟩	🟦	🟧	⬜	⬜	⬜
ITER#14	Tungsten	⬜	⬜	🟩	⬜	⬜	🟩	🟩	🟩	🟦	⬜	⬜	⬜	🟩	🟩	🟩	🟩
ITER#15	Tungsten	⬜	🟦	🟩	⬜	⬜	🟩	🟧	🟩	🟦	⬜	🟦	⬜	🟩	🟧	🟩	🟧
ITER#16	Divertor XM-19	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	🟧	🟩	⬜	🟩	⬜	⬜	⬜
ITER#17	Divertor XM-19	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	🟧	🟩	⬜	🟩	⬜	⬜	⬜
ITER#18	Inconel 718	🟩	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	🟧	🟩	⬜	🟩	⬜	⬜	⬜
ITER#19	Eurofer 97-2	⬜	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟩	⬜	⬜	⬜	🟩	⬜	🟩	🟧
ITER#20	Eurofer 97-2	⬜	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟩	⬜	⬜	⬜	🟩	⬜	🟩	🟧
ITER#21	Divertor Al-Bronze	⬜	🟧	🟩	🟩	⬜	🟩	🟩	🟩	⬜	⬜	⬜	⬜	🟧	⬜	⬜	⬜
ITER#22	Divertor Al-Bronze	⬜	🟧	🟩	🟧	⬜	🟩	🟩	🟩	⬜	⬜	⬜	⬜	🟧	⬜	⬜	⬜
ITER#23	SS304 – In-wall shield	🟧	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟦	⬜	🟧	⬜	⬜	⬜	⬜	⬜
ITER#24	SS304 – In-wall shield	⬜	🟧	🟩	🟧	🟧	🟩	🟩	🟩	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜
ITER#25	SS316 – PF Jacket	⬜	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟦	🟧	🟩	⬜	🟦	⬜	⬜	⬜
ITER#26	Alloy 660 – IWS A286	🟩	🟩	🟩	🟩	🟦	🟩	🟩	🟩	🟦	⬜	🟩	⬜	🟦	⬜	⬜	⬜
ITER#27	SS316 - Divertor	⬜	🟧	🟩	🟧	⬜	🟩	🟩	🟩	🟦	🟧	🟧	⬜	🟧	⬜	⬜	⬜

Predicted and measured	🟩
Measured, not predicted	🟦
Predicted, not measured	🟧
Not predicted, not measured*	⬜

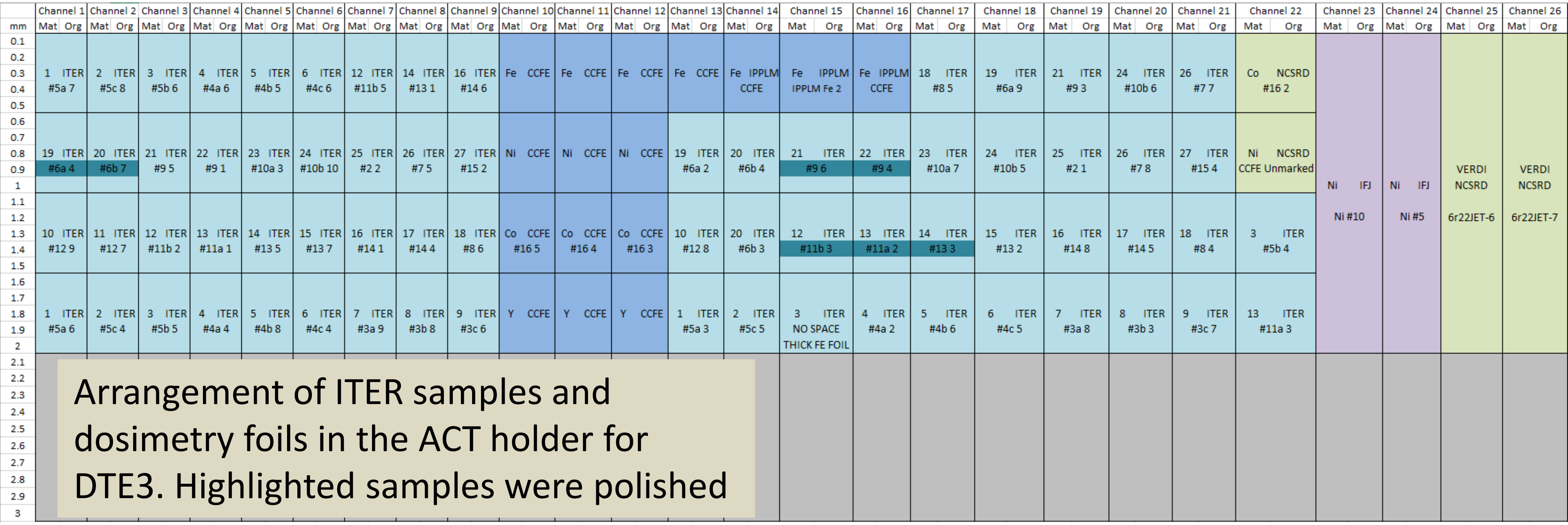
*Note that this subset of nuclides only corresponds to those measured in at least one ITER sample and that other nuclides may be predicted, but not measured in these samples. A nuclide is considered predicted if it was in the top 10 most active nuclides or its activity was >0.5 Bq/g on 28/10/2022 in FISPACT-II calculations.

- The introduction of brass depositions through the electrical discharge machining (EDM) cutting technique explained the discrepancies for ^{65}Zn
- High C/E values were evident in several samples containing ^{182}Ta
- ^{110m}Ag observed in CuCrZr – unexpected
- ^{95}Zr difficult to measure, but aided by CSS techniques for some samples
- Generally good agreement or slightly conservative for important isotopes relevant to SDDR calculations

Next steps: installation of new ITER samples for DTE3

- A ‘new’ unirradiated ACT holder was loaded with some remaining ITER materials & dosimetry foils for irradiation during DTE3.
- A few of the CuCrZr, Tungsten, Eurofer, and Al-Bronze were polished to remove potential surface contaminants from machining/cutting.
- DTE3 started in late Aug
- Explore ultra-sensitive analysis methods to evaluate longer-lived (and other difficult to measure) nuclides

Pre-irradiated ACT holder containing the samples



mm	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7	Channel 8	Channel 9	Channel 10	Channel 11	Channel 12	Channel 13	Channel 14	Channel 15	Channel 16	Channel 17	Channel 18	Channel 19	Channel 20	Channel 21	Channel 22	Channel 23	Channel 24	Channel 25	Channel 26
	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org	Mat Org
0.1 0.2 0.3 0.4 0.5	1 ITER #5a 7	2 ITER #5c 8	3 ITER #5b 6	4 ITER #4a 6	5 ITER #4b 5	6 ITER #4c 6	12 ITER #11b 5	14 ITER #13 1	16 ITER #14 6	Fe CCFE	Fe CCFE	Fe CCFE	Fe CCFE	Fe IPPLM CCFE	Fe IPPLM IPPLM Fe 2	Fe IPPLM CCFE	18 ITER #8 5	19 ITER #6a 9	21 ITER #9 3	24 ITER #10b 6	26 ITER #7 7	Co NCSRD #16 2	Ni IFJ Ni #10	Ni IFJ Ni #5	VERDI NCSRD 6r22JET-6	VERDI NCSRD 6r22JET-7
0.6 0.7 0.8 0.9 1	19 ITER #6a 4	20 ITER #6b 7	21 ITER #9 5	22 ITER #9 1	23 ITER #10a 3	24 ITER #10b 10	25 ITER #2 2	26 ITER #7 5	27 ITER #15 2	Ni CCFE	Ni CCFE	Ni CCFE	19 ITER #6a 2	20 ITER #6b 4	21 ITER #9 6	22 ITER #9 4	23 ITER #10a 7	24 ITER #10b 5	25 ITER #2 1	26 ITER #7 8	27 ITER #15 4	Ni NCSRD CCFE Unmarked				
1.1 1.2 1.3 1.4 1.5	10 ITER #12 9	11 ITER #12 7	12 ITER #11b 2	13 ITER #11a 1	14 ITER #13 5	15 ITER #13 7	16 ITER #14 1	17 ITER #14 4	18 ITER #8 6	Co CCFE #16 5	Co CCFE #16 4	Co CCFE #16 3	10 ITER #12 8	20 ITER #6b 3	12 ITER #11b 3	13 ITER #11a 2	14 ITER #13 3	15 ITER #13 2	16 ITER #14 8	17 ITER #14 5	18 ITER #8 4	3 ITER #5b 4				
1.6 1.7 1.8 1.9 2	1 ITER #5a 6	2 ITER #5c 4	3 ITER #5b 5	4 ITER #4a 4	5 ITER #4b 8	6 ITER #4c 4	7 ITER #3a 9	8 ITER #3b 8	9 ITER #3c 6	Y CCFE	Y CCFE	Y CCFE	1 ITER #5a 3	2 ITER #5c 5	3 ITER NO SPACE THICK FE FOIL	4 ITER #4a 2	5 ITER #4b 6	6 ITER #4c 5	7 ITER #3a 8	8 ITER #3b 3	9 ITER #3c 7	13 ITER #11a 3				
2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3																										

Arrangement of ITER samples and dosimetry foils in the ACT holder for DTE3. Highlighted samples were polished

Conclusions and recommendations

- **Unique experience** has been gained in characterisation and neutron activation studies for ITER materials in a tokamak environment operating with significant nuclear conditions.
- FENDL-3.2d used for radiation transport simulations with TENDL-2017 activation libraries (IRDFF-II for dosimetry foils)
- **Advanced post-irradiation analysis techniques** have helped with identification of radionuclides
- C/E values generally show good agreement, but also some useful and interesting anomalous results were identified leading to several recommendations for ITER and for future work
  - Conducting independent elemental analysis is advisable for materials to improve knowledge of composition prior to supply inputs to neutronics calculation
  - Manufacturing and cutting techniques have implications with respect to surface impurities which lead to the production of additional nuclides in fusion environments
  - Further analysis using ultra-sensitive analysis techniques is advised for these, and future irradiated ITER samples – focus on longer-lived nuclides relevant to fusion wastes
- **A novel and valuable experimental dataset and sample set**
  - Substantial contribution to our comprehension of fusion environments and offers an invaluable means of validation for neutronics methodologies
- Demonstrates that MCNP6.2 with FENDL-3.2d + FISPACT-II with TENDL-2017 can be reliably applied to predict nuclide activation in materials exposed to D-T fusion nuclear environments – **provided that accurate and detailed neutronics models are used and detailed materials certificate information, including impurities, are specified**
- **Further work and results expected** through the ongoing JET DTE3 campaign