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Nuclear analysis and measurement experience derived from JET DT operations

EUROfusion

Lee Packer, P. Batistoni, C. Bearcroft, S. C. Bradnam, T. Eade, E. Eardley, L. J. Evitts, M. Fabbri, N. Fonnesu, M Gilbert, Z. Ghani, K. Gorzkiewicz, C. Grove, J. Hagues, P. Kanth, R. Kierepko, E. Laszynska, I. Lengar, X. Litaudon, S. Loreti, J.W. Mietelski, S. I. Muldrew, M. Pillon , M. I. Savva, C.R. Shand, I.E. Stamatelatos, A. Turner, A. N. Turner, T. Vasilopoulou, A Valentine, R. Villari, A. Wójcik-Gargula, A. Zohar and JET Contributors*

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

Main areas to discuss

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1. UK context and fusion strategy
2. Neutronics tools: development, validation, applications to ST concepts
3. Nuclear activities associated with JET operations
   - JET studies - waste predictions, prompt and residual dose rate analysis

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4. Highlight recent EUROfusion neutronics activities at JET
   - Preparation for ITER Operations (PL: X. Lituadon, CEA; Neutronics WP leader: R. Villari, ENEA)
   - Activation of ITER materials at JET
   - Validation of approaches for long pulse operations and for nuclear technology aspects in view of ITER and fusion machines

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Context: UK fusion strategy

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‘Pillars’ of UK fusion strategy announced at IAEA Fusion Energy Conference, London, October 2023

“Overarching goals of the fusion strategy

1. For the UK to demonstrate the commercial viability of fusion by building a prototype fusion power plant in the UK that puts energy on the grid

2. For the UK to build a world-leading fusion industry which can export fusion technology around the world in subsequent decades”


Department for Energy Security & Net Zero

Towards Fusion Energy 2023

The next stage of the UK’s fusion energy strategy

October 2023

Fusion Futures programme - £650m of new investment, subject to business case approval, between now and 2027 on top of the existing fusion programmes.

Spherical Tokamak for Energy Production

- Mission: “Deliver a UK prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion.”
- Predictable net electricity production
- Lower capital cost than other fusion power plant designs
- Site: West Burton, Nottinghamshire
- UKIFS – standing up in November 2024
- UKAEA – Fusion Partner

Neutronics: an enabling capability for the development of fusion

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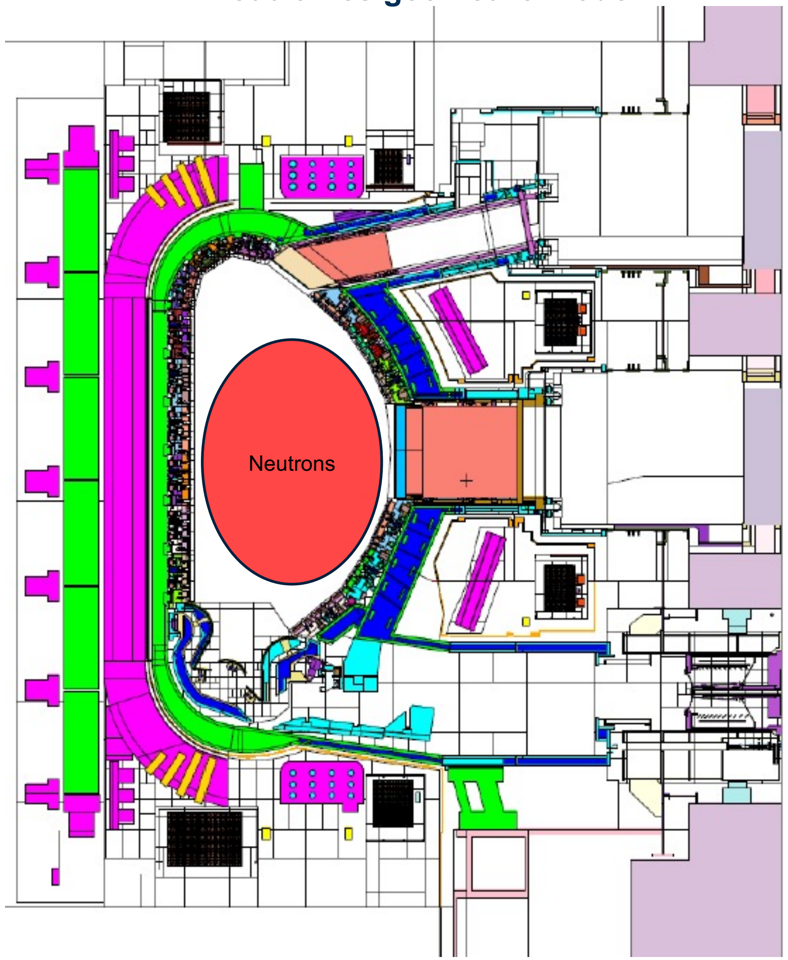
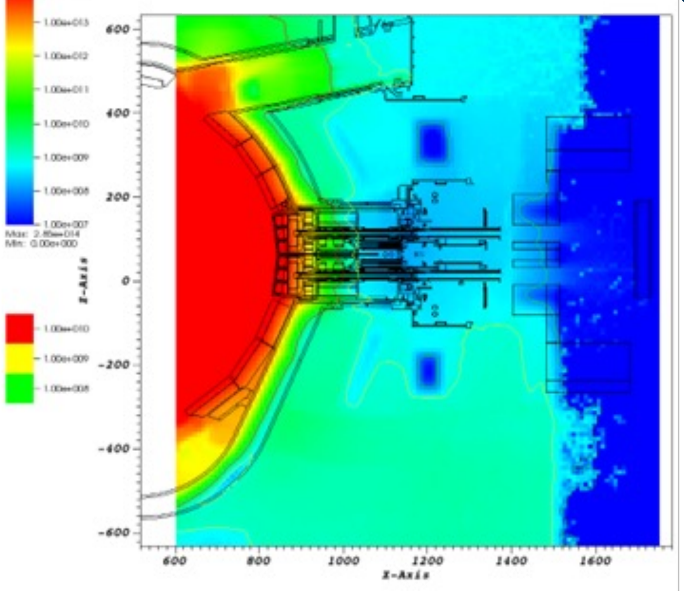
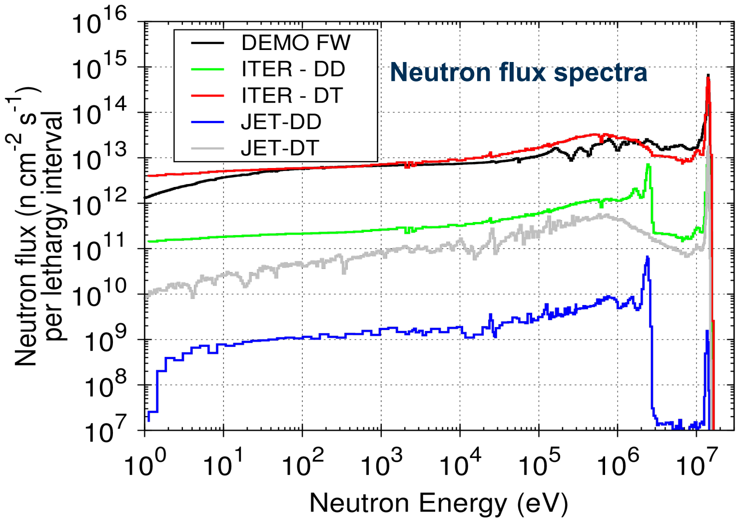
- Fusion power based on DT is mostly **neutron** power
- Aims to increase performance in experiments - long pulse operations, increased fusion product -> **neutrons**
- Neutronics directly contributes to critical areas of fusion plant design & safety
    - nuclear heating to components
    - tritium breeding
    - activation of in-vessel components
- Neutronics provides nuclear information to other disciplines
    - Radiation damage
    - Lifetime of components
    - Radiological dose, safety scenarios
    - Diagnostics

ITER neutronics geometric model

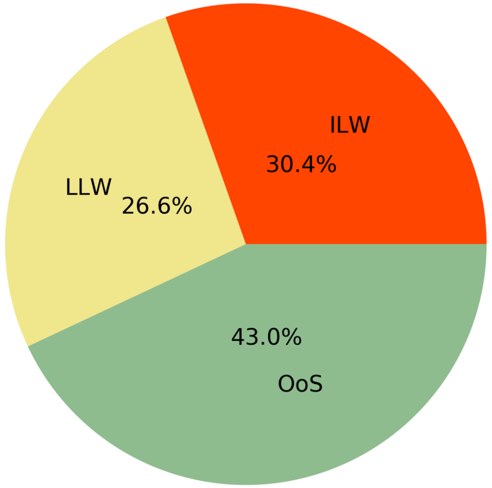


Neutron flux n cm^{-2} s^{-1}





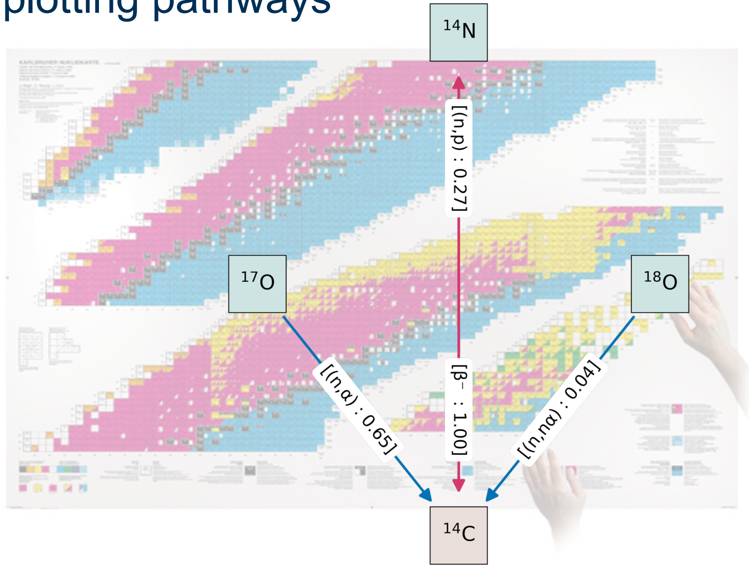
Predicting activation, transmutation and radioactive decay processes

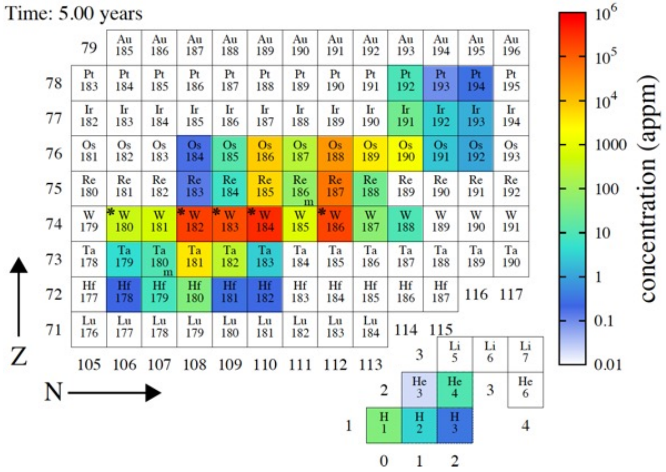


Waste categorisation categories 50 years after reactor shutdown (with 99% tritium removal) for DEMO with HCPB blankets using the UK regulation framework

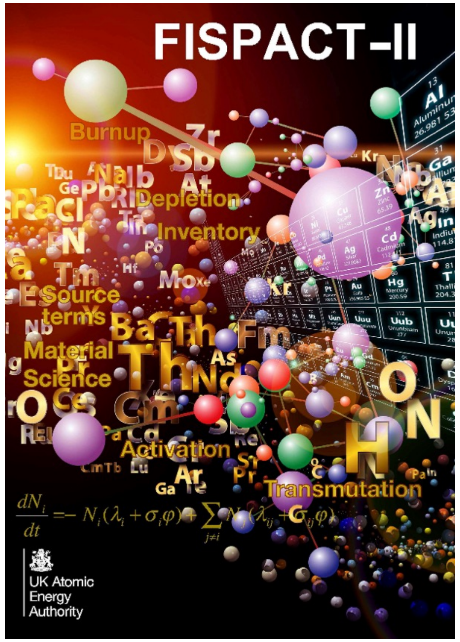
FISPACT-II workshops

PATHFINDER: A Tool for creating and plotting pathways





Burnup and time dependent nuclide inventory prediction: Tungsten irradiation in DEMO FW



A multi-physics platform developed at UKAEA for predicting the inventory changes in materials under both neutron and charged-particle interactions

Website and documentation: *https://fispact.ukaea.uk*

Sublet et al., Nucl. Data Sheets 139(2017) 77-137

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3D activation: Integration of neutronics with activation through MCR2S and N1S methods

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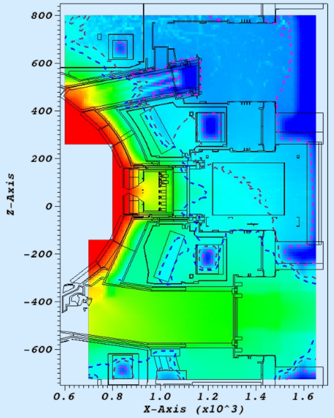
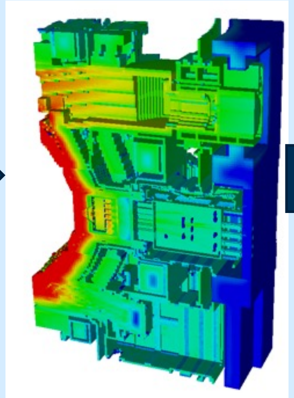
- MCR2S and N1S couples various neutronics codes with inventory codes
- Inventory analysis (e.g. FISPACT-II or derived from decay data)
- **Full 3D activation and shutdown dose analysis tool**

Onload: Neutron Flux and Spectra

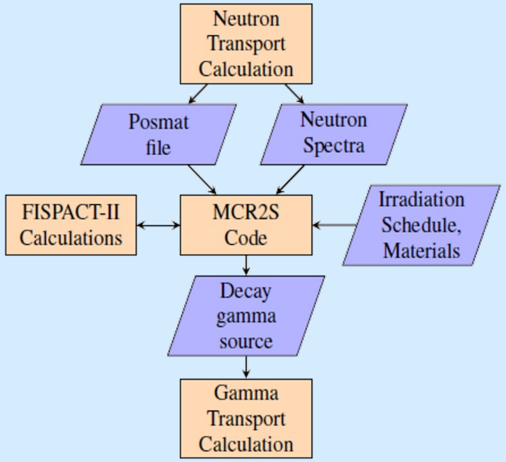


Activation: Gamma source term



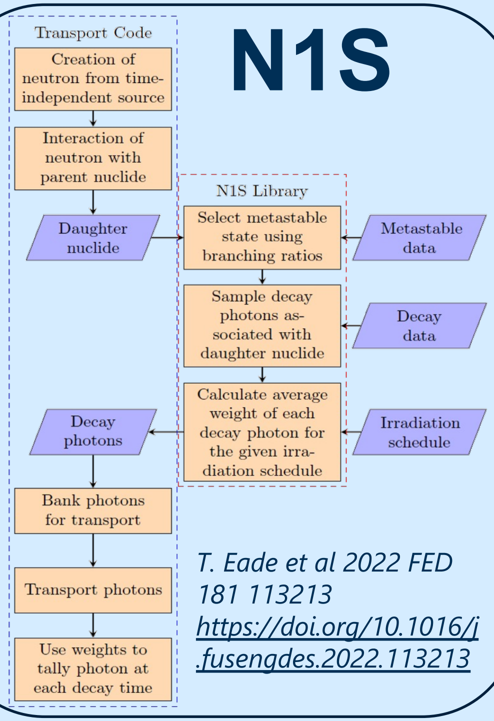
Offload: Shutdown gamma dose

MCR2S



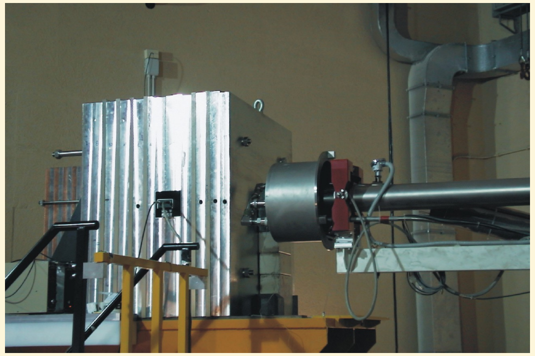
T. Eade et al 2020 Nucl. Fusion 60 056024
https://iopscience.iop.org/article/10.1088/1741-4326/ab8181/meta

N1S



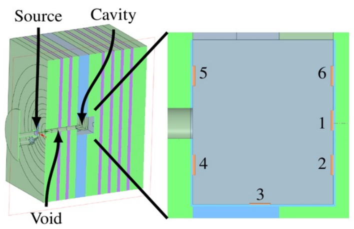
T. Eade et al 2022 FED 181 113213
https://doi.org/10.1016/j.fusengdes.2022.113213

Validation: shutdown gamma benchmark experiment at the Frascati 14 MeV Neutron Generator

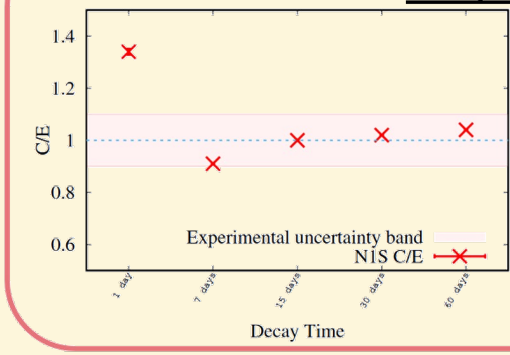


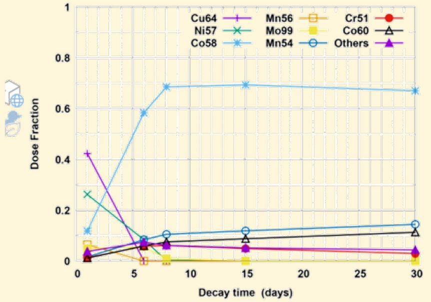
Geometry

- Steel and water layers with cavity



Campaign 1





ST neutronics

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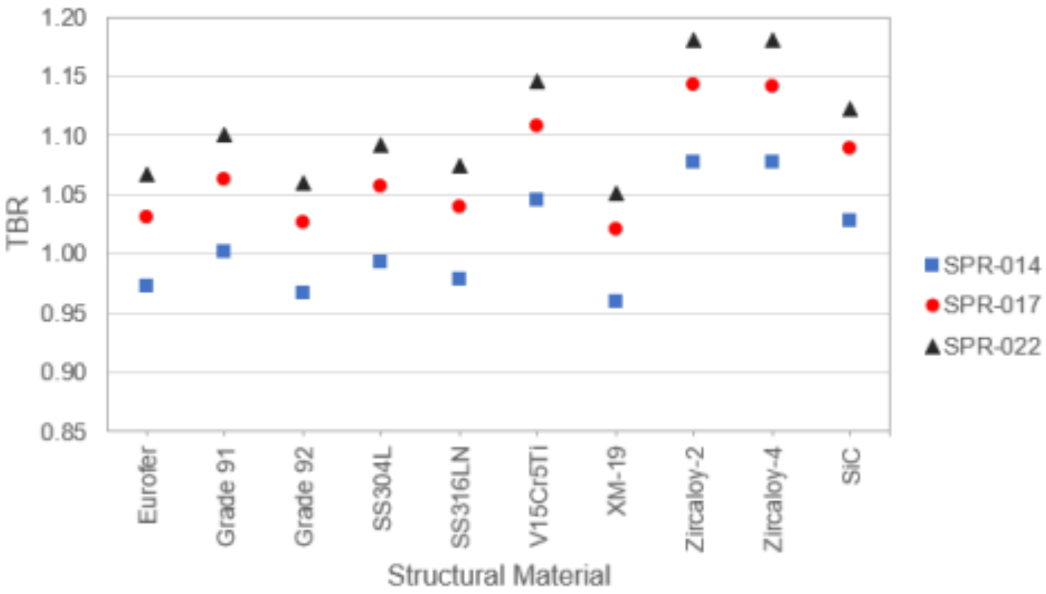
Stuart I. Muldrew et al, Conceptual design workflow for the STEP Prototype Powerplant, Fusion Engineering and Design ***201*** *(2024)*

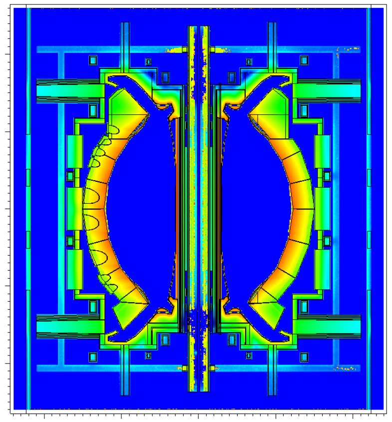
Neutronics plays one of the most important roles in a DT fusion machine:

- Tritium production performance
- Nuclear heating
- Sensitive superconducting magnets -> protected from neutron damage
- Neutron activation fields relevant to safety and maintenance activities

Impact of Blanket Structural Material on TBR



Nuclear Heating (W cm^{-3})



Neutron Flux (n cm^{-2} s^{-1})

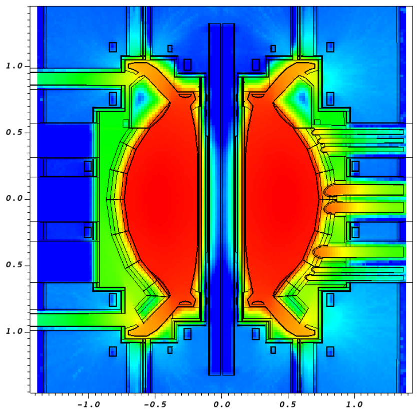
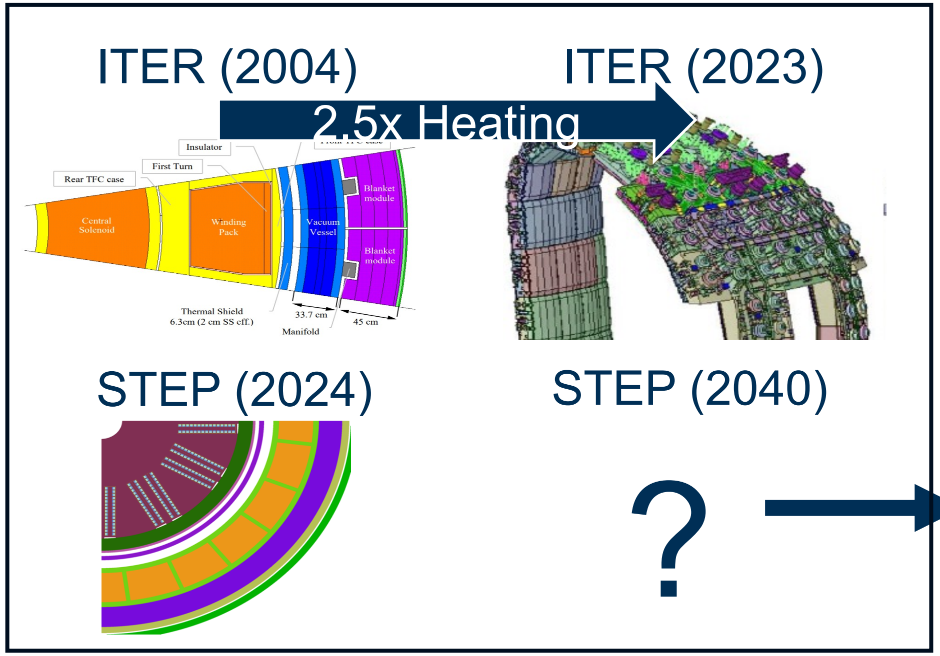


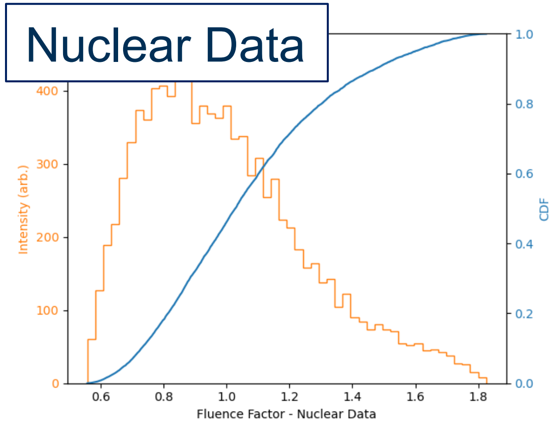
Table 1
The point design parameters for the 2023 CML4 STEP Prototype Powerplant.

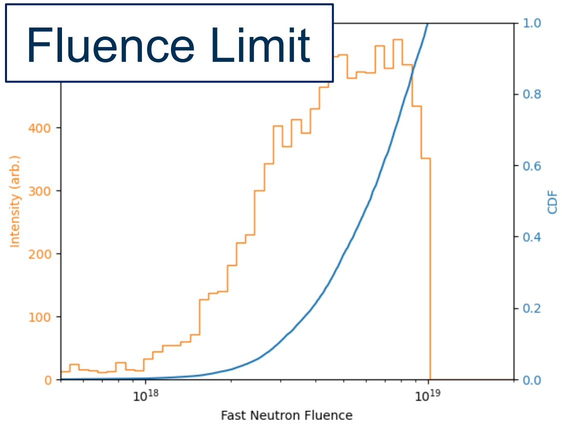
Triangularity (Sign)	Positive
Plasma edge	Edge Pedestal
Heating & current drive mix	Electron Cyclotron & Electron Bernstein Waves
Primary divertor configuration	Dynamic Double-null
Secondary divertor configuration (Inboard)	Flat Top: X Type Ramp Up: Perpendicular
Secondary divertor configuration (Outboard)	Extended Leg
Toroidal field conductor type	REBCO
Tokamak morphology (Radial Build)	Plasma/Wall/Blanket/Vessel
Primary maintenance access route	Vertical
Remountable toroidal field coils	16 TF coils 3 Remountable Joints per TF
Peak steady state divertor heat flux	<20 MW/m^2
Tritium breeder material	Liquid Lithium
Centre column coolant	Water
Divertor coolant	Water
Outboard first wall, blanket, outboard limiter coolant	Helium
Blanket coolant outlet temperature	600 °C
Direct or indirect cycle	Indirect
Fusion power	1.6–1.8 GW
Net electric output	100–200 MW$_e$
Inboard build	1.6 m
Major radius	3.6 m
Toroidal field	3.2 T
Elongation	2.93
Triangularity	0.5

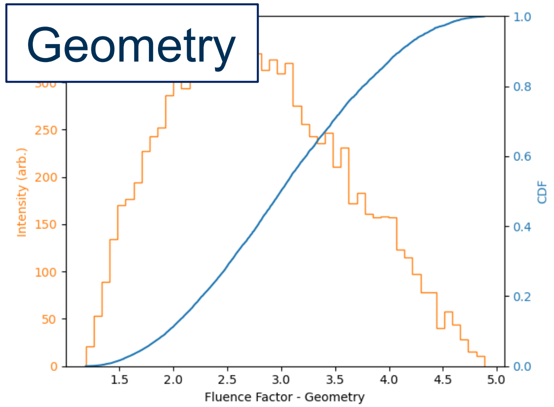
Uncertainty Quantification in Nuclear Analysis

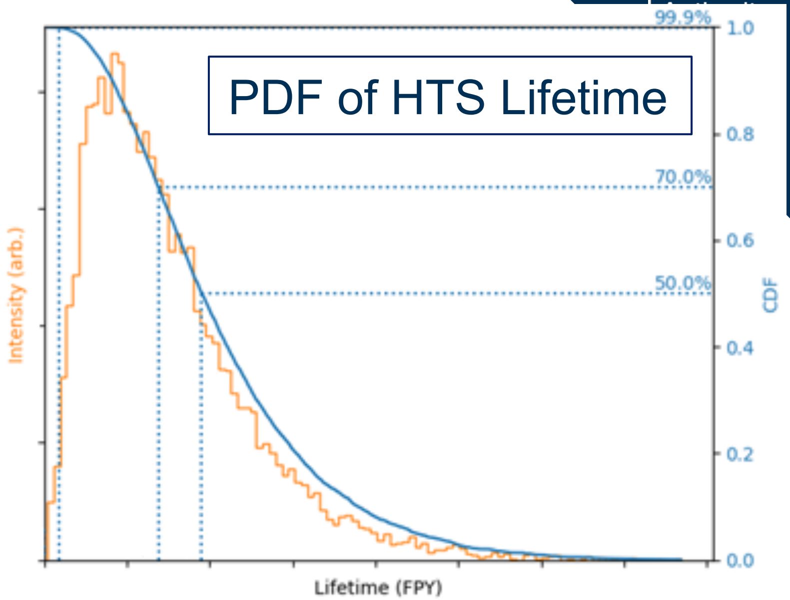
Monte Carlo error analysis developed, using known uncertainties, to provide confidences on certain tallies e.g., inboard magnet (HTS) lifetimes. Confidences inform on risk during concept design phase.

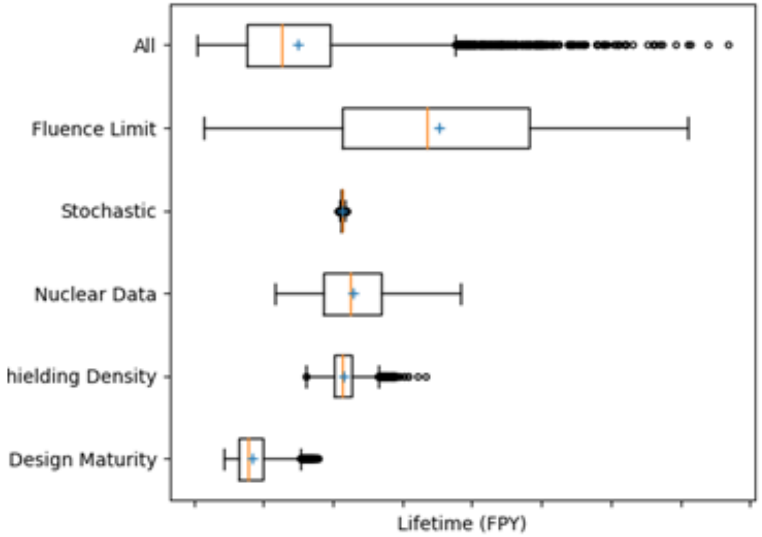








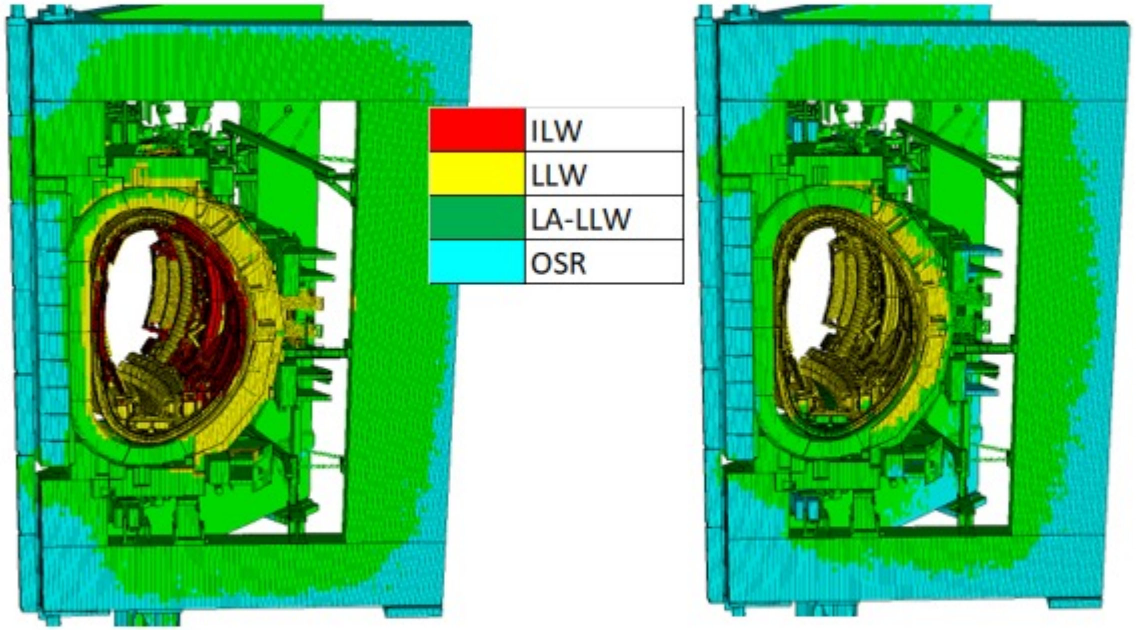




JET - spatial, component and global mass-based waste analysis

Specific activity of individual components

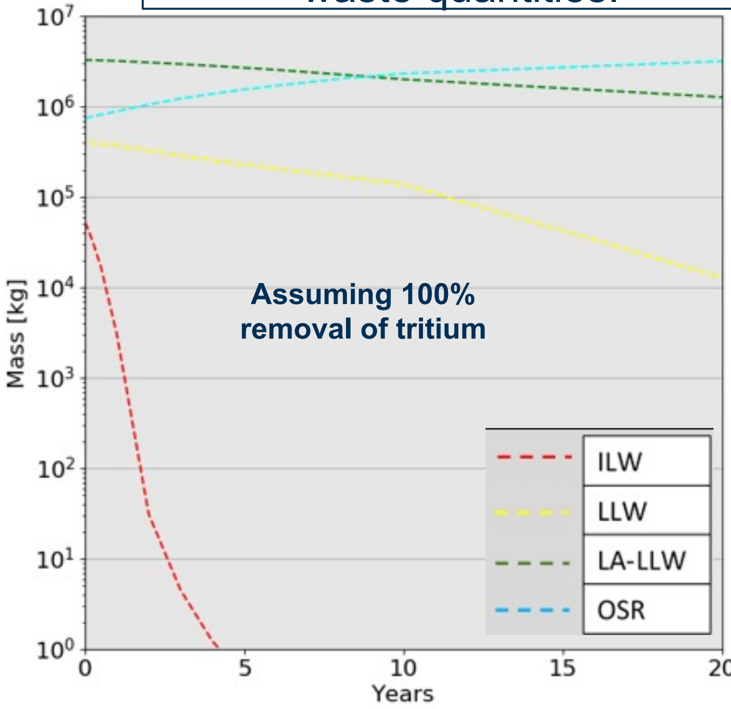
Waste type spatial distributions (to inform segregation and cutting)



At shutdown

5 years cooling time

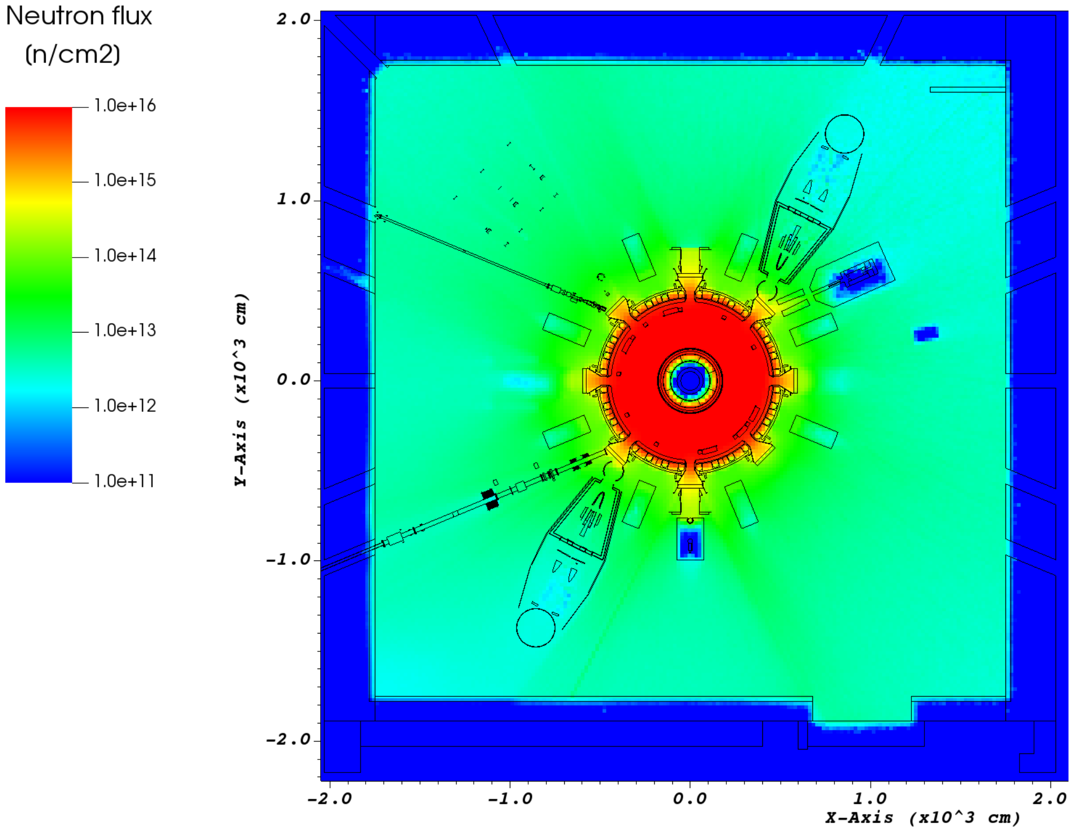
Global analysis of radioactive waste quantities:



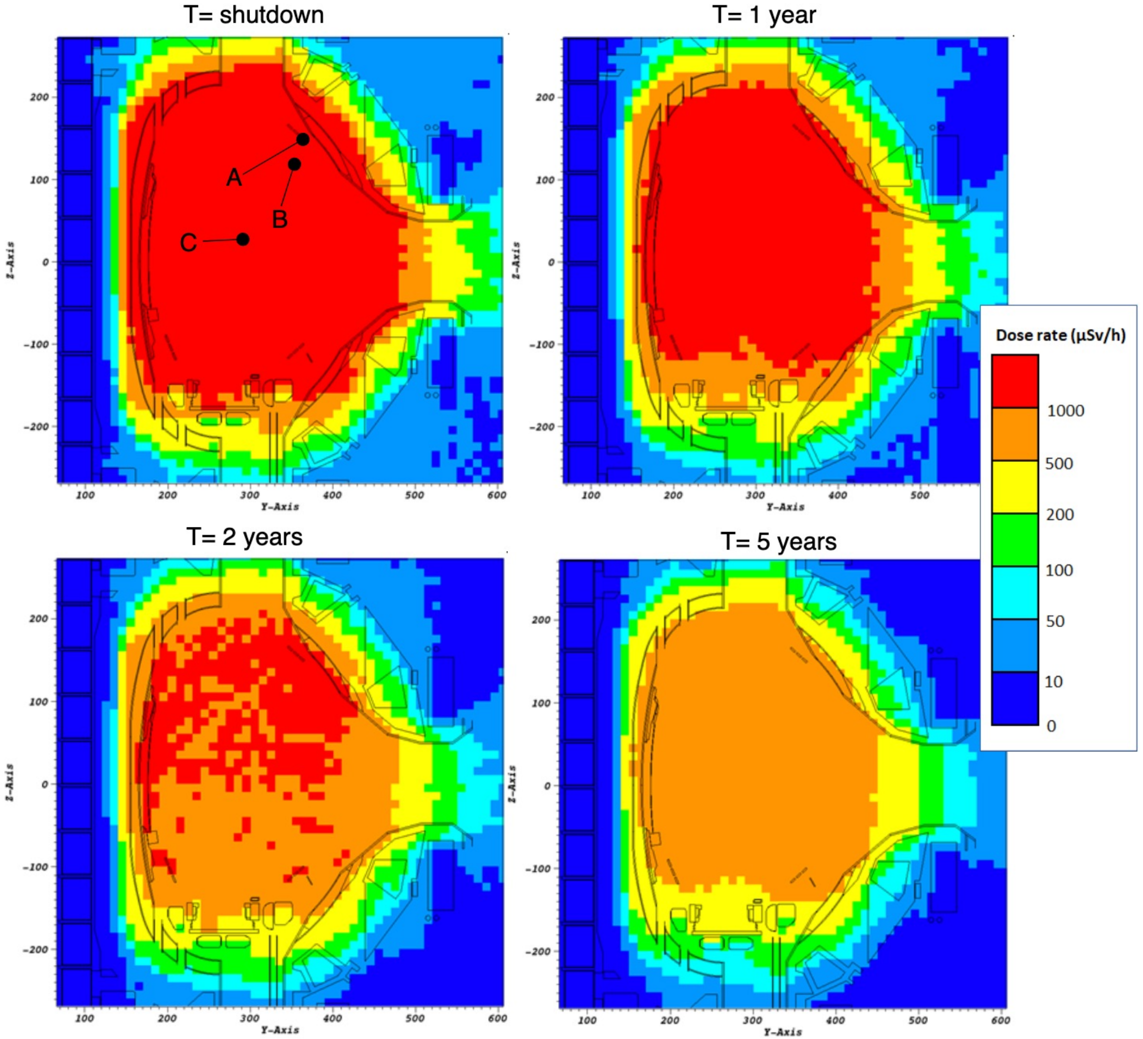
	HLW	ILW	LLW	LA-LLW	OSR
	High level waste	Intermediate level waste	Low level waste	Low activity low level waste[1]	Out of scope of regulations
Specific activity	> 12 GBq/t or > 4 GBq/t [a]		< 12 GBq/t and < 4 GBq[a]/t	< 200 Bq/g	See summation rule criteria for nuclides in [1]
Heat:	> 2 kW/m^3	< 2 kW/m^3			

Decreasing activity

JET radiation maps: prompt and residual fields



Integrated prompt neutron fluence – projections at end of operations



Post operation SDDR using ‘JET23’ schedule

Not ‘actual’ schedules

Learnings from neutron activation studies on ITER materials at JET

Lee Packer, P. Batistoni, C. Bearcroft, S. C. Bradnam, E. Eardley, M. Fabbri, N. Fonnesu, M Gilbert, Z Ghani, K. Gorzkiewicz, C. Grove, R. Kierepko, E. Laszynska, I. Lengar, X. Litaudon, S. Loreti, J.W. Mietelski, M. Pillon , M. I. Savva, C.R. Shand, I.E. Stamatelatos, A. N. Turner, T. Vasilopoulou, R. Villari, A. Wójcik-Gargula, A. Zohar and JET Contributors*

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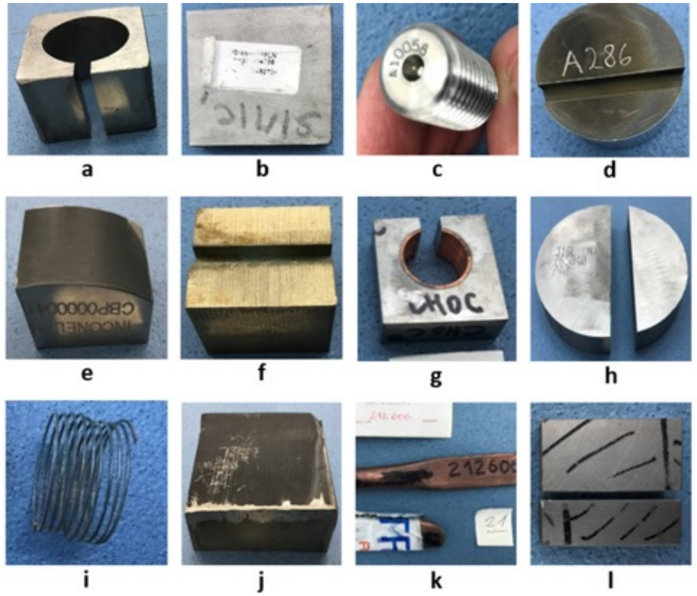
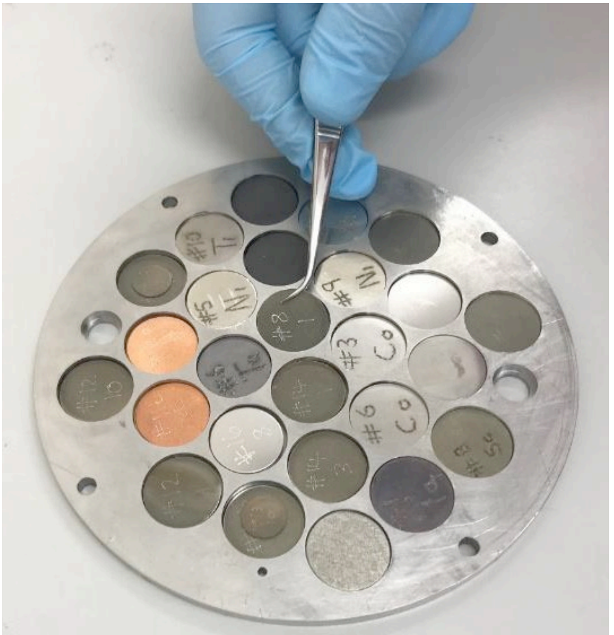
Why irradiate ITER materials within the JET nuclear environment?

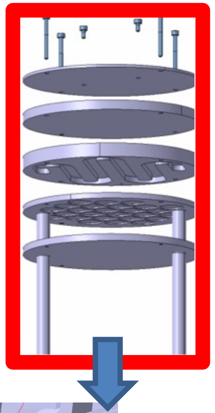
- Take advantage of the large 14 MeV neutron fluence during JET DT operations to irradiate samples of real ITER materials used in the manufacturing of the main in-vessel tokamak components.
- Broader activities within PrIO covered in *X. Litaudon et al 2024 Nucl. Fusion **64** 112006.*
- The materials considered include: SS316L steels from a range of manufacturers, SS304B, Alloy 660, W, CuCrZr, XM-19, Al bronze, NbTi and EUROFER for example.

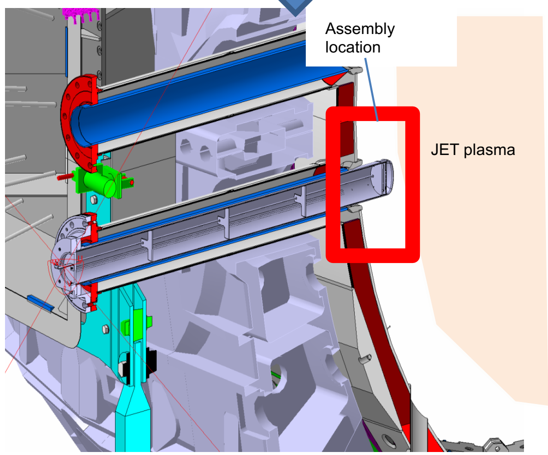


ITER materials sample prep.



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)

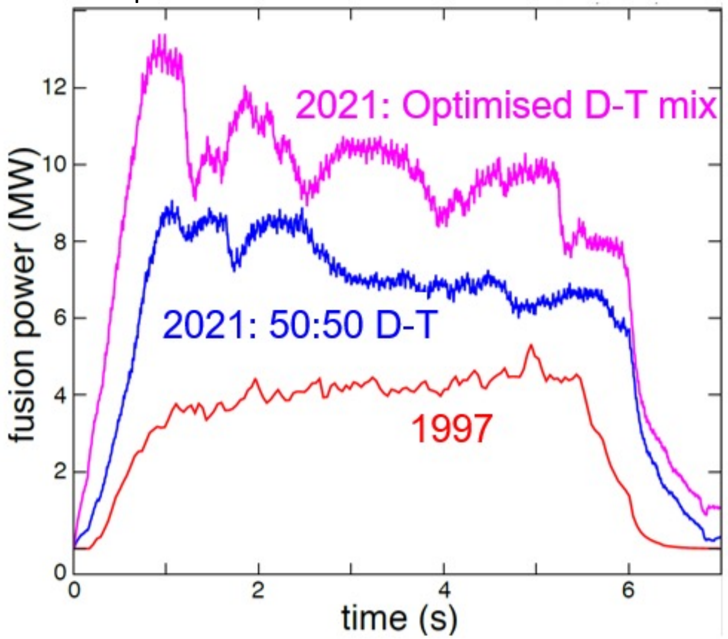
Fusion conditions in JET in the LTIS

LTIS (Long-Term Irradiation Station)

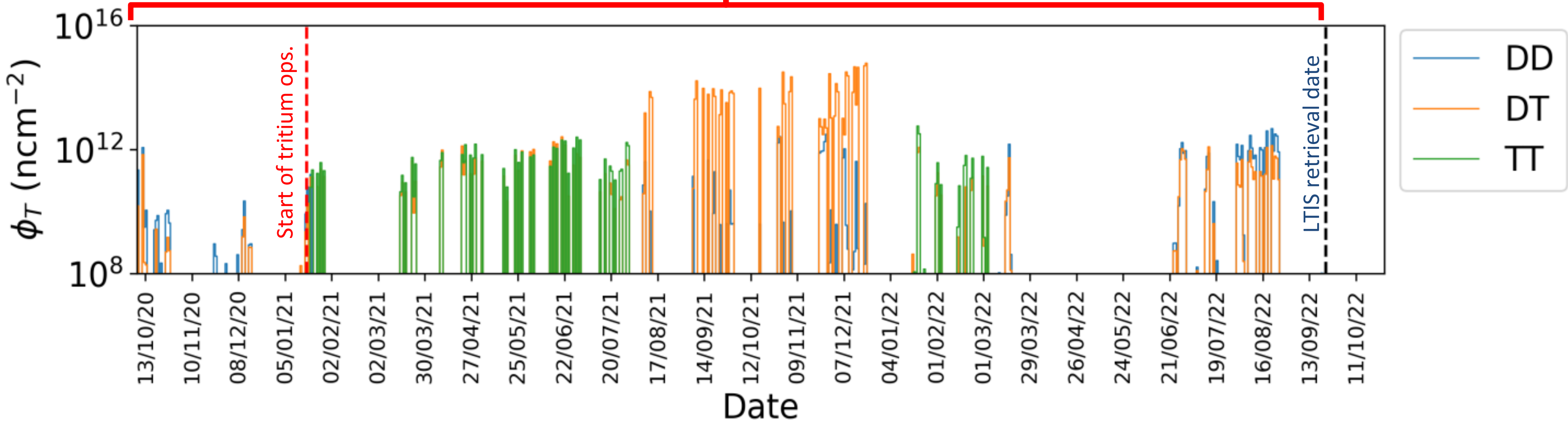
- Peak neutron flux: **$2x10^{13}$ n/cm^2/s** - One order of magnitude less than flux at ITER FW @ 500 MW

Peak power

DTE2

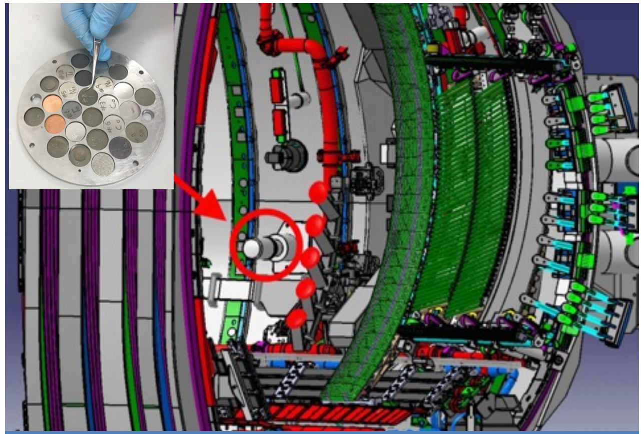


- Neutron fluence over 715 days **$5x10^{15}$ n/cm^2**



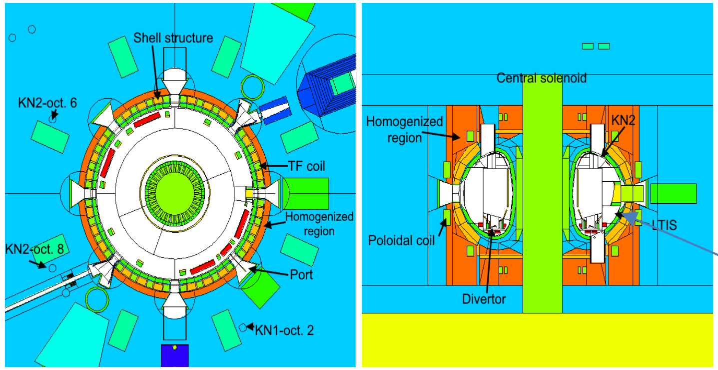
Total neutron yield over 715 days: **8.67 x 10^{20} n**

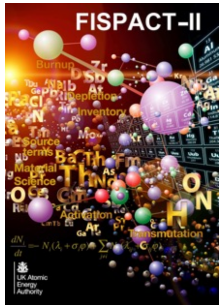
Neutronic simulations of the JET nuclear environment: activity predictions for ITER materials



Irradiation assembly and location of installation in JET

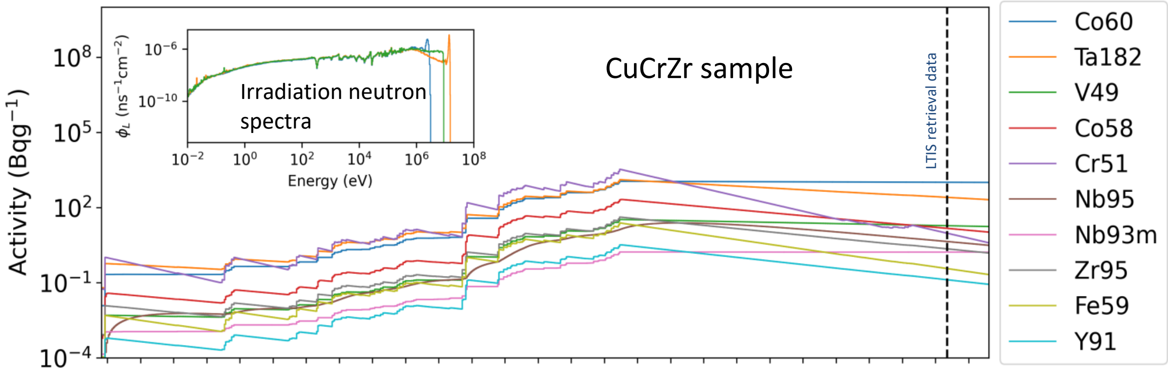
JET 360 degree reference neutronics model (JSI)



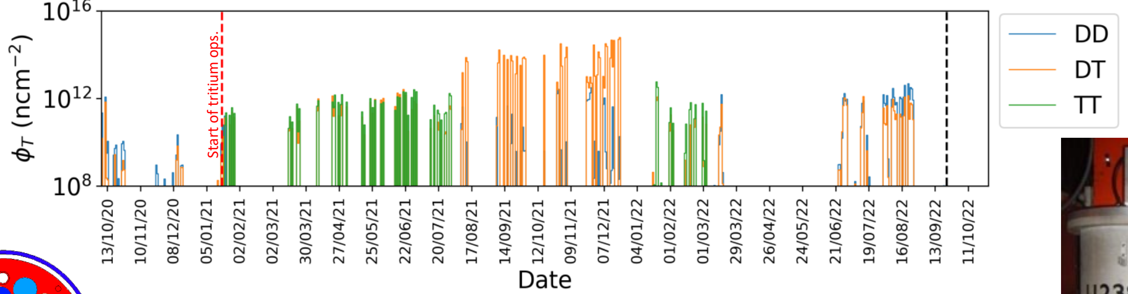
MCNP6 + 

Nuclear data for radiation transport: FENDL 3.1d
Nuclear data for activation (priority order):
IRDFF-II → JEFF-3.3 → TENDL-2017

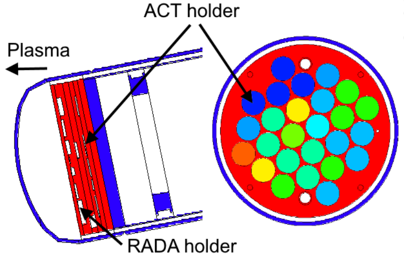
MCNP + FISPACT-II calculations used to predict activity in each ITER sample



Temporal daily neutron fluence at the irradiation assembly location

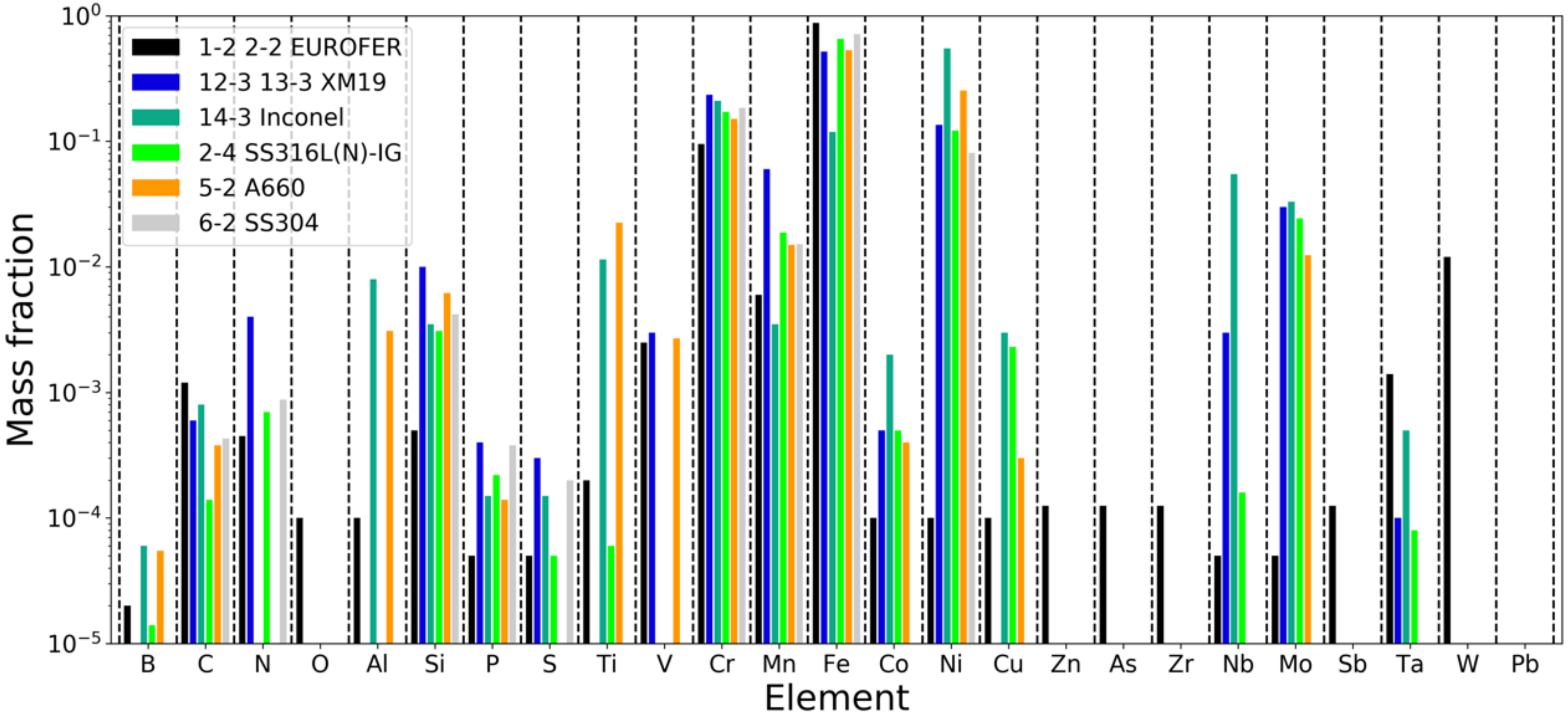


MCNP model of detailed LTIS assembly containing samples



KN1 neutron diagnostic (provided temporal neutron yield data)

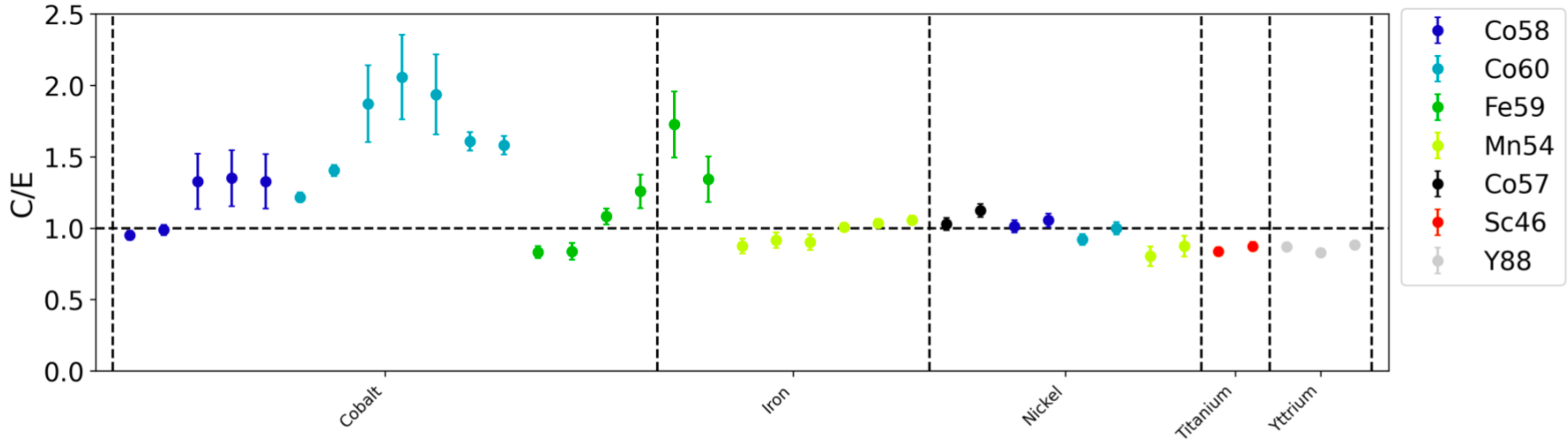
Inputs to simulations: ITER material elemental composition certificates



Upper bounds for impurities ranges assumed, where ranges were specified

Subset of material elemental compositions

Nuclear characterisation of the LTIS: Dosimetry foil-based measurements



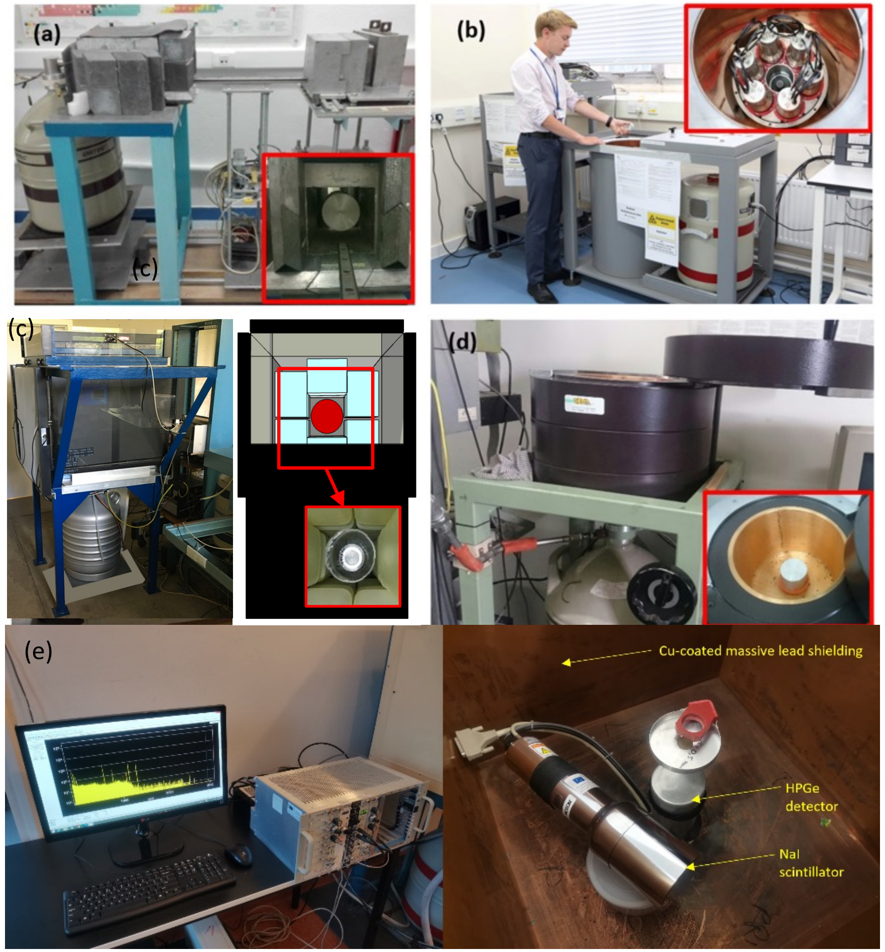
(C/E – calculated to experimental ratio)

- **The weighted average C/E across all dosimetry foil diagnostic measurements was 0.986 ± 0.007**

- 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.

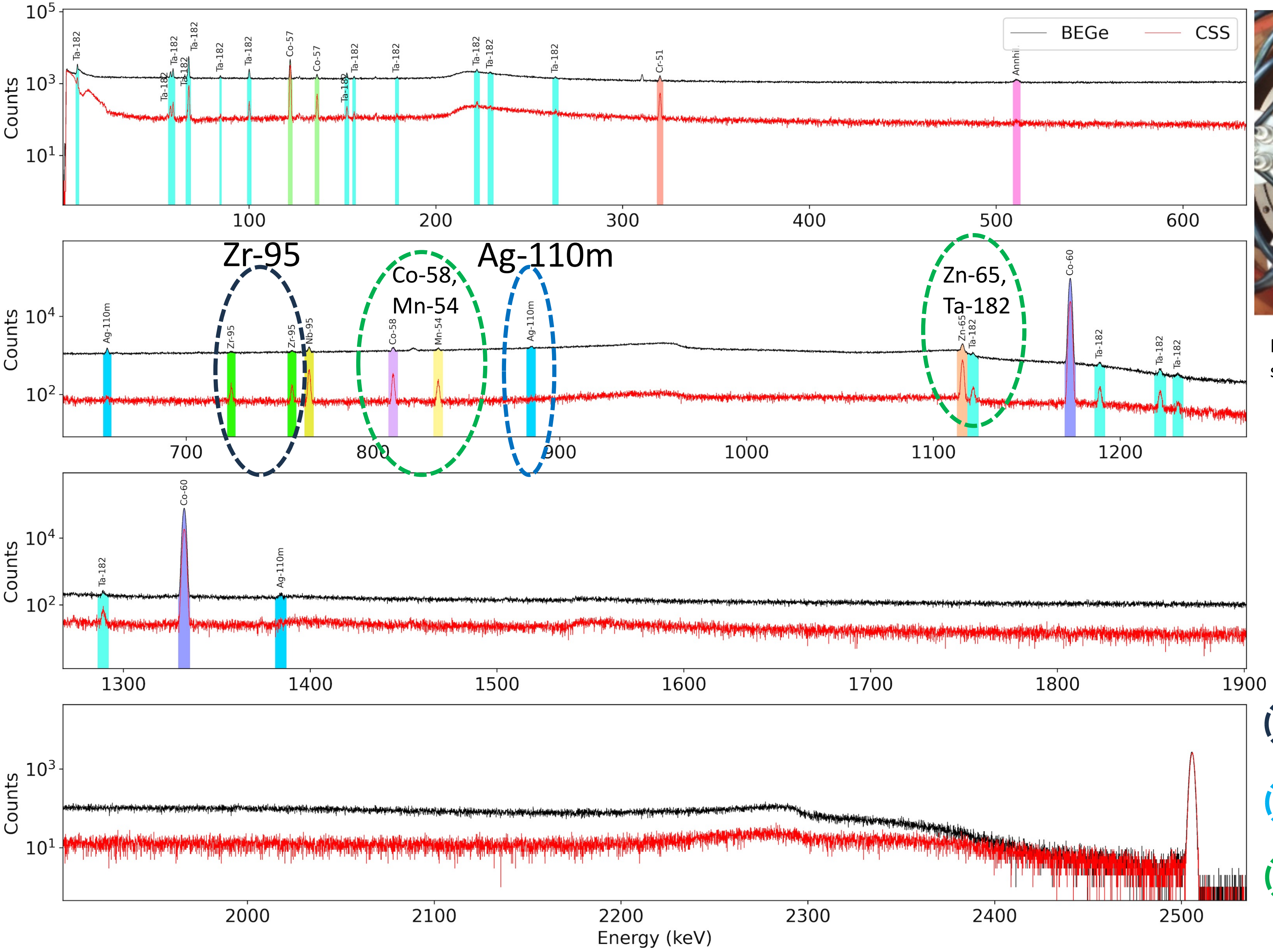
Post DTE2 irradiation gamma spectrometry measurements

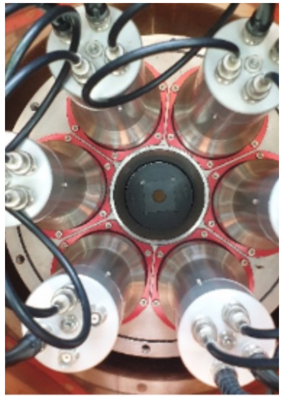
ITER materials were measured using gamma spectrometry techniques at several laboratories to identify and quantify nuclide activities generated through neutron activation



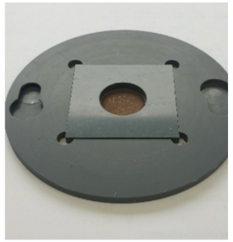
Participating gamma spectrometry laboratories: (a) NCSRD; (b) CCFE; (c) IFJ-PAN; (d) ENEA and (e) IPPLM

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





BEGe + Compton suppression system

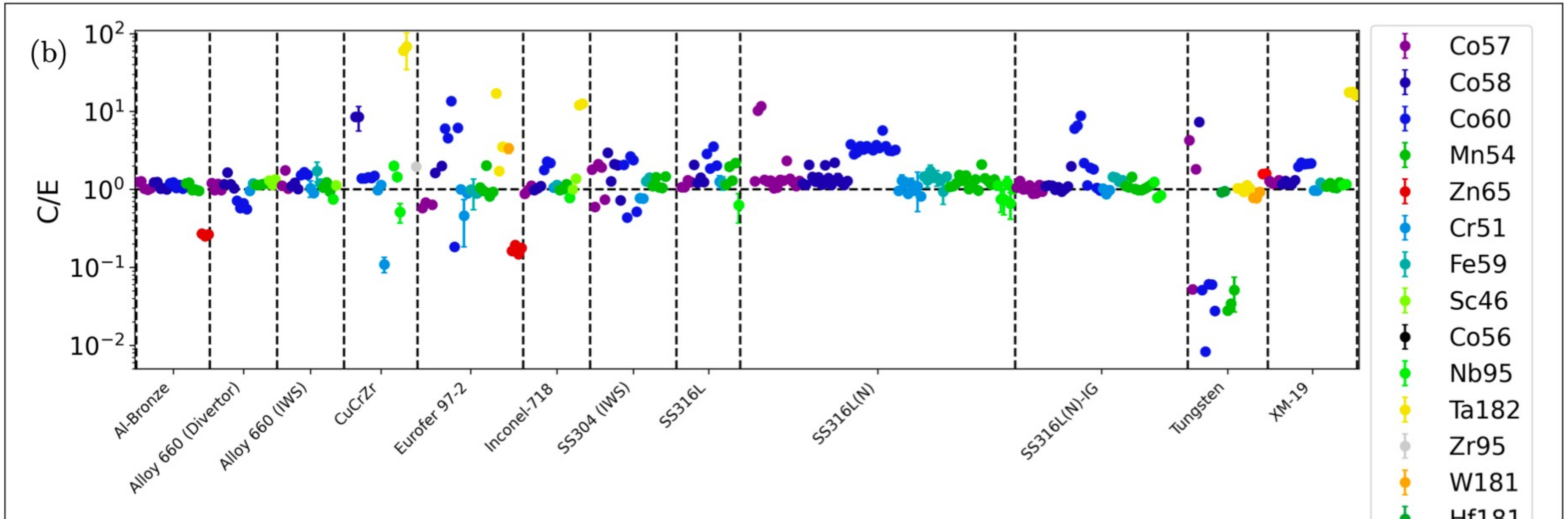


CSS nuclide identification

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

DTE2 analysis publication

nuclear fusion
IAEA

ACCEPTED MANUSCRIPT • OPEN ACCESS

ITER materials irradiation within the D-T neutron environment at JET: post-irradiation radioactivity analysis following the DTE2 experimental campaign

Lee Packer[1], Paola Batistoni[2], Chris Bearcroft[1], Steven Bradnam[1], Edward Eardley[1], Marco Fabbri[3], Nicola Fonnesu[4], Mark R Gilbert[1], Zamir Ghani[1], Krzysztof Gorzkiewicz[5]

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What is an Accepted Manuscript?

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Accepted Manuscript PDF

ITER samples for DTE3

- An 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

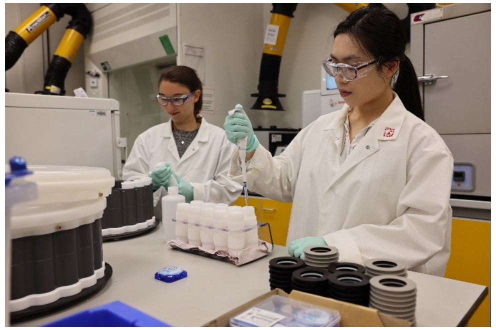
Pre-irradiated ACT holder containing the samples

mm	Channel 1 (Mat / Org)	Channel 2 (Mat / Org)	Channel 3 (Mat / Org)	Channel 4 (Mat / Org)	Channel 5 (Mat / Org)	Channel 6 (Mat / Org)	Channel 7 (Mat / Org)	Channel 8 (Mat / Org)	Channel 9 (Mat / Org)	Channel 10 (Mat / Org)	Channel 11 (Mat / Org)	Channel 12 (Mat / Org)	Channel 13 (Mat / Org)
0.1–0.5	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
0.6–1	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
1.1–1.5	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
1.6–2	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
2.1–3													

mm	Channel 14 (Mat / Org)	Channel 15 (Mat / Org)	Channel 16 (Mat / Org)	Channel 17 (Mat / Org)	Channel 18 (Mat / Org)	Channel 19 (Mat / Org)	Channel 20 (Mat / Org)	Channel 21 (Mat / Org)	Channel 22 (Mat / Org)	Channel 23 (Mat / Org)	Channel 24 (Mat / Org)	Channel 25 (Mat / Org)	Channel 26 (Mat / Org)
0.1–0.5	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
0.6–1	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				
1.1–1.5	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				
1.6–2	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				
2.1–3													

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

Ongoing work - NPL independent elemental analysis



Sample preparation facilities

- Microwave acid digestion
- Anton Paar Multiwave 5000
- Sample weighed at each step to allow calculation of mass fraction in original sample

Sample preparation

- Microwave acid digestion
- Aqueous sample for ICP-MS analysis
- Acid matrix keeps metals suspended in solution
- Dilution to appropriate concentration for ICP-MS

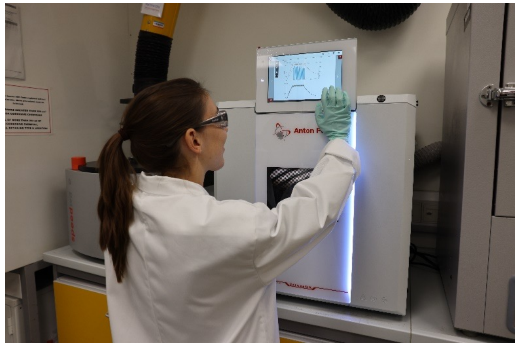
ICP-MS analysis

- Initial measurement of samples to indicate concentration
- Dilute if necessary
- Interference assessment
- Multi-element calibration solution
- QC check

Data processing

- Drift correction
- Blank correction
- XLGENLINE polynomial calibration function
- Results given as mass fraction i.e. $ng.g^{-1}$
- Uncertainty budget analysis

NPL National Physical Laboratory



ICP-MS analysis: Agilent 8800 and 8900

Accredited by UKAS to ISO 17025 to measure V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, and Pb in ambient air particulate matter collected on filters

Instrument detection limits for measurements of ambient particulate matter (PM_{10}, $ng{\cdot}g^{-1}$)

Instrument	V	Cr	Mn	Fe	Ni	Cu	Zn	Cd	Pb	As	Co	Se
8800	0.04	3	0.4	9	0.4	0.9	5	0.004	0.1	0.06	0.08	0.2
8900	0.01	3	0.6	10	0.3	1.1	4	0.003	0.1	0.0	0.05	0.1

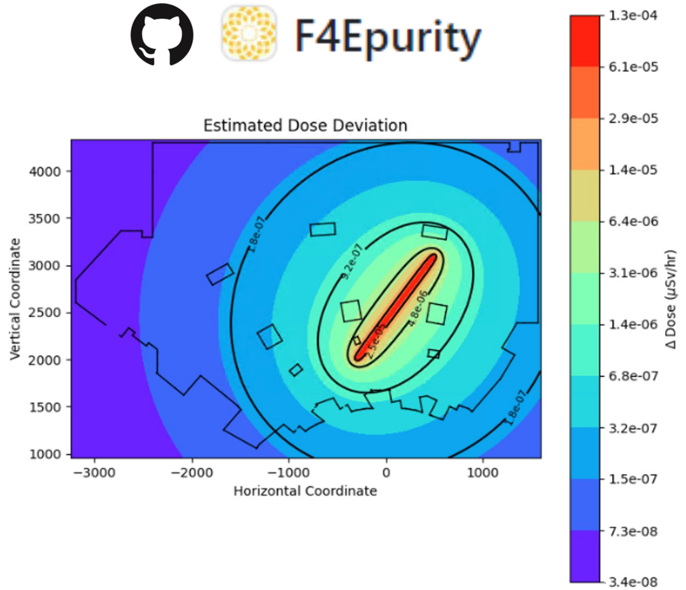
NPL Credit: Emma Braysher & Ben Russell

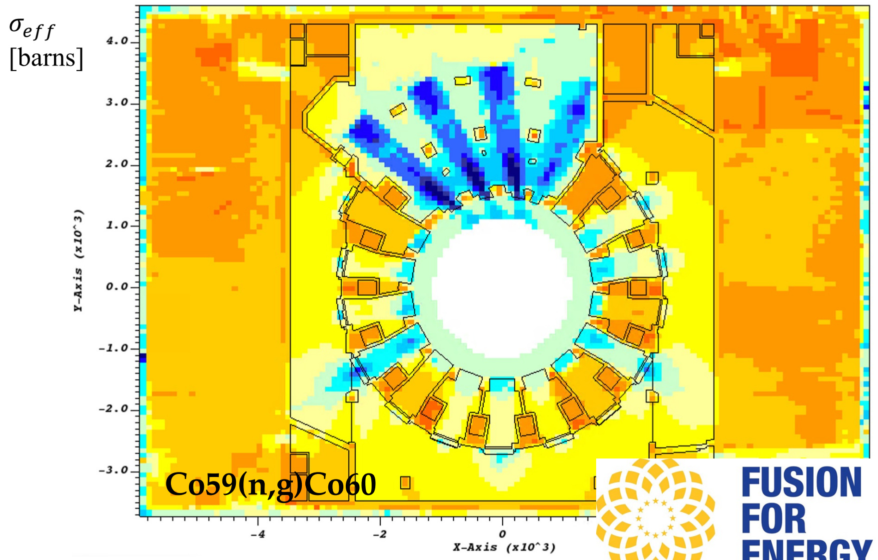
Ongoing work – relevance to ITER DT operations

- Understanding and controlling impurity content in materials is fundamental to the ITER safety case.
- ITER has project requirements controlling the material content of elements such as Cobalt, Niobium and Tantalum. These elements are strong drivers of the shutdown down dose rate.
- UKAEA have developed a tool in collaboration with F4E to provide a quick method for understanding the impact of deviations in impurity content on the local shutdown dose rate.
  - Written in Python with command line interface – can be straightforwardly installed on Linux/Windows/mac. Currently hosted in a private repository on GitHub.
  - Quick estimation of local change in dose due to a change in impurity – output 3D dose map. Support for point and line sources.
  - Produce 3D maps of the effective cross section (collapse of flux with reaction cross section) and activity.
  - Multiple source terms supported. Calculates the change in dose at ITER workstations in different parts of the building.
  - Assumes un-scattered, unshielded conditions.
- There are important lessons from the activation foil results in terms of uncertainty in prediction of the inventory of certain nuclides critical to shutdown dose rates.

UK Atomic Energy Authority

F4Epurity





FUSION FOR ENERGY

JET DTE2 studies: conclusions

- **Unique experience** has been gained in characterisation and neutron activation studies for ITER materials in a tokamak environment operating with significant nuclear conditions.
- **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 (e.g. ICP-OES techniques)
  - 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 advanced tools such as MCNP and FISPACT-II with modern nuclear data libraries 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 analysis following JET DTE3