

Benchmark activation experiment of various foil samples using the ESS accelerator dump line

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Agenda



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#1

Introduction

ESS status, transition to operations and future needs



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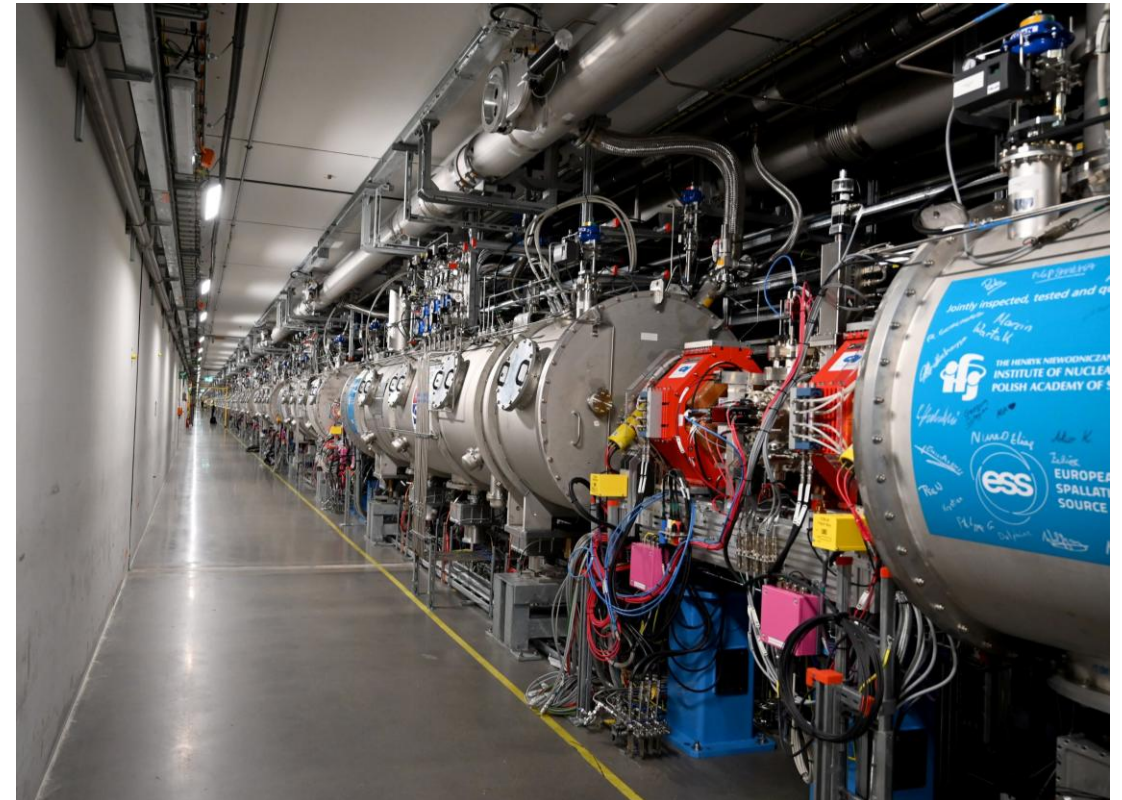


Introduction

ESS status & future needs

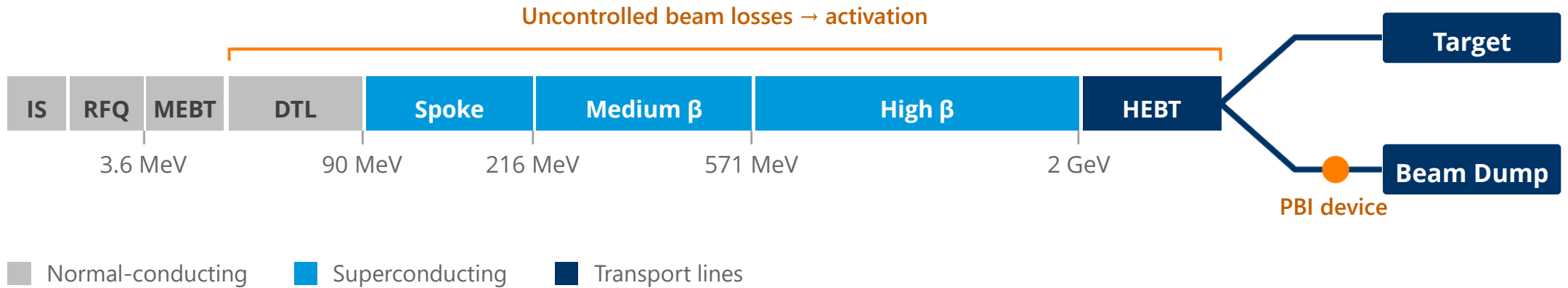


- **Accelerator commissioned**
Beam on Dump milestones reached last year, tuning tests running
- **MRP2 installed**
New Moderator Reflector Plug in place after last year's incident
- **Beam on Target: early 2027**
Transition to operations



Introduction

ESS status & future needs



1 Beam losses

Protons lost on beam pipe, magnets and cavities, and beam fully stopped in the dumps.

2 Activation

Protons and secondary neutrons build up activation in accelerator components and surrounding equipment.

3 Operational impact

Residual dose rates for maintenance and classification of radioactive waste.

4 Validated predictions

Transport and activation codes benchmarked against measurements in ESS conditions.

#2

Methods

Foil irradiation at the PBI, gamma spectrometry and simulations



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Experiment design

Irradiation over the PBI device

Proton beam imaging device

The PBI is located in the dump line, just before the beam dump

Foils on the top flange

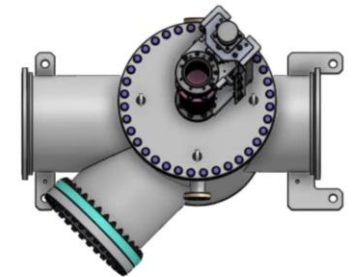
Six pure-element foils positioned onto the flange around the actuator

Tuning test beam

Irradiated during the beam-on-dump commissioning runs



Side view



Top view

Experiment design

Foil samples

Foil	Thickness	Mass
Al	0.762 mm	0.264 g
Fe	0.127 mm	0.126 g
Ni	0.254 mm	0.283 g
Cu	0.127 mm	0.141 g
Nb	2 mm	2.17 g
Bi	2 mm	2.47 g

Discs of 12.7 mm diameter.



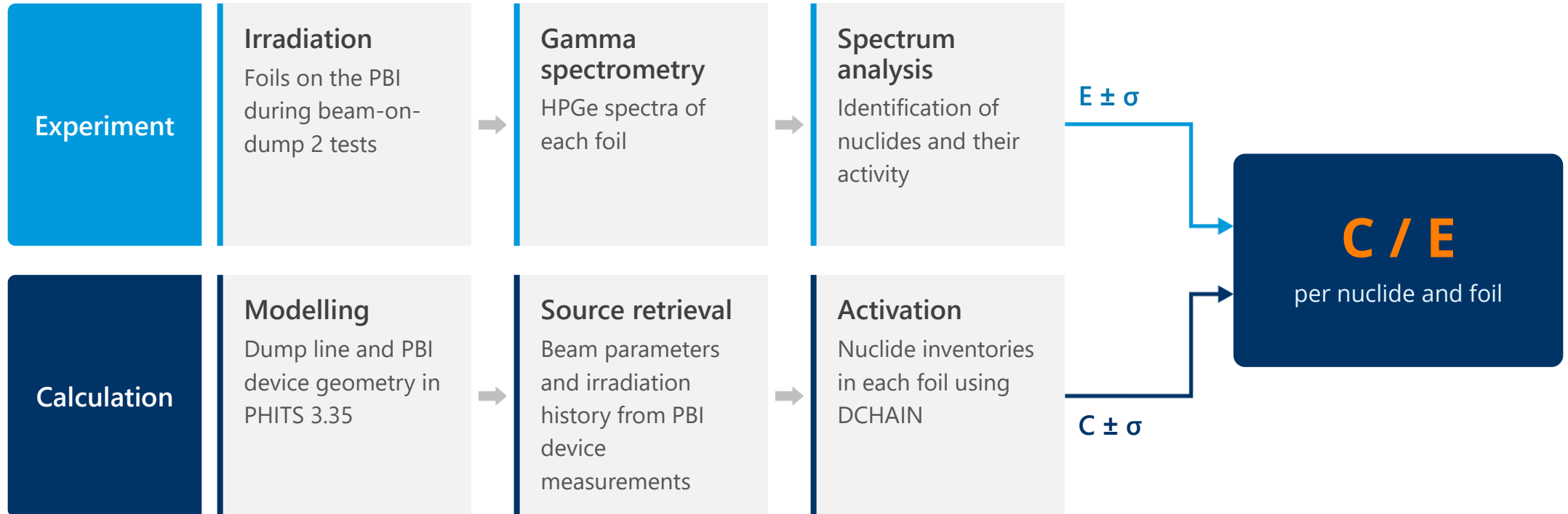
Positions on the PBI top flange



Samples before irradiation

Benchmark workflow

Experimental and computational chains



Experimental work

Gamma spectrometry

Detector

Canberra broad-energy HPGe (BE3830P) from the ESS RP Lab

Measurements

One fixed counting position per sample, 4-hour long measurements

Analysis

Acquisition, Analysis and Corrections using Genie2K



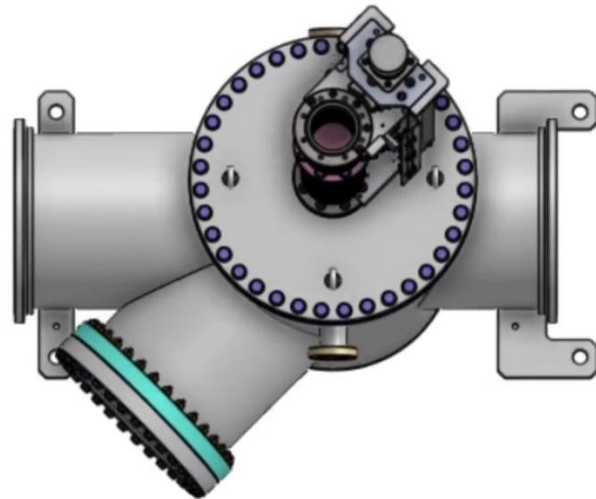
BE3830P Detector



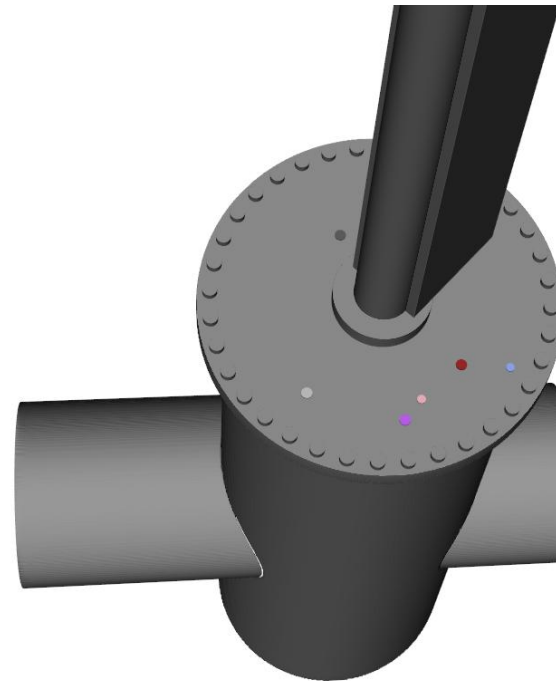
Foils after irradiation

Computational work

Simulation model



Engineering CAD, top view



Transport model – *PHITS 3D*

Geometry

PBI vessel, top flange and the foils in PHITS 3.35

Source

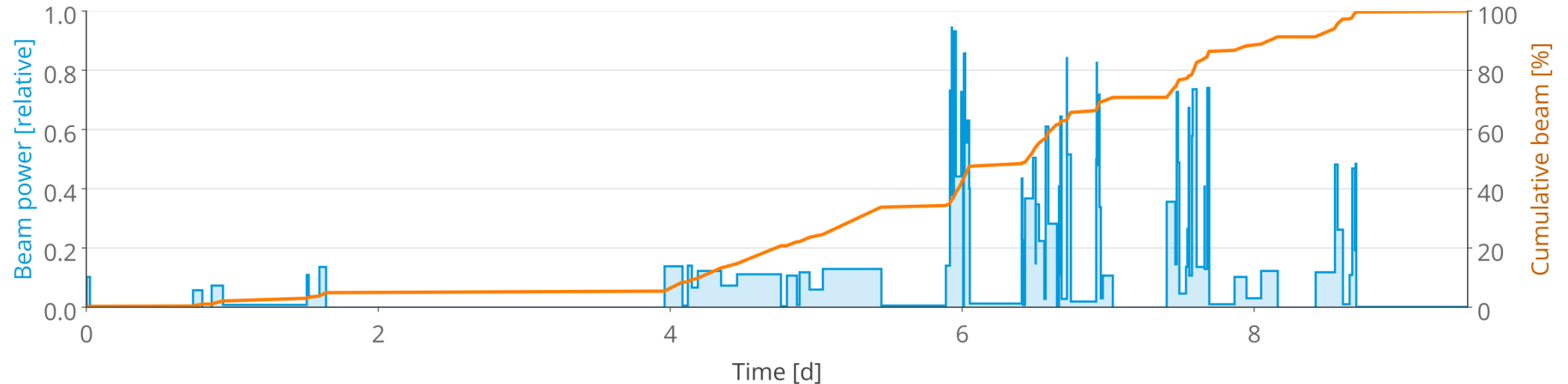
Proton beam to the beam dump, with measurements from the device

Scoring

Fluence and production from models are passed to DCHAIN

Computational work

Irradiation history



99 steps over 9.5 days

Time evolution & distribution captured from the PBI device

Normalization

Source energy of **800 MeV**, current known for each frame

Source definition

A Gaussian distribution was fitted to each period's mean source

#3

Results

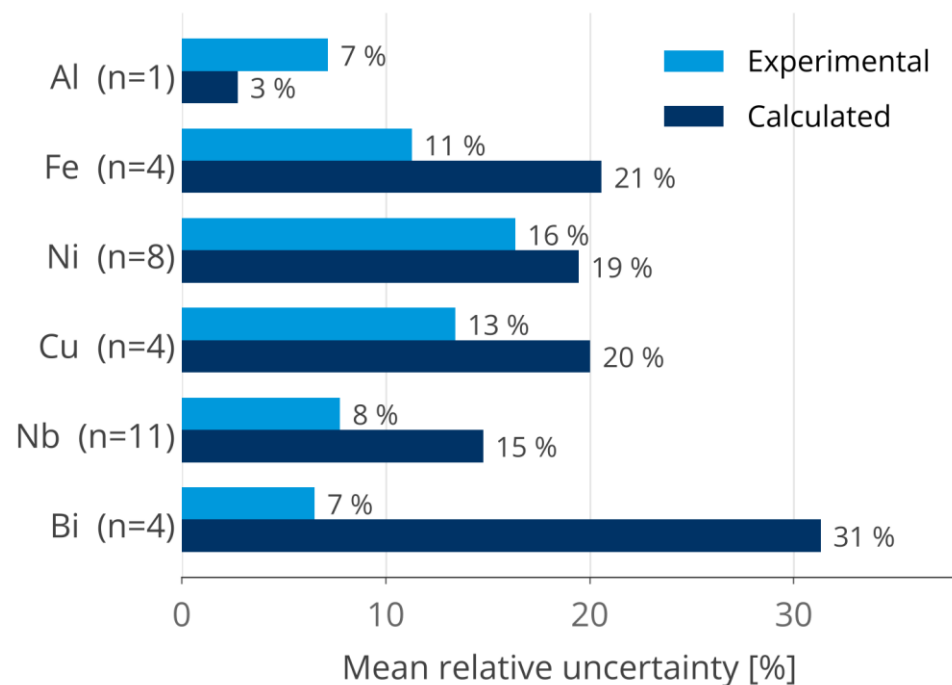
Measured activities and calculated-over-experimental ratios



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Considerations

Uncertainties



n = nuclides measured per foil; metastable Pb isotopes excluded of the comparison due to large uncertainties in the decay chain

Contributor	On	Mean (range)
Gamma spectrometry	E	11 % (2–54 %)
Simulations	C	19 % (1–56 %)
Beam history	C	5 %
Combined	C/E	22 % (7–59 %)

Peaks with **medium/low** identification confidence: 19 % mean unc.

Peaks with **high** identification confidence: 8.5 % mean unc.

Experimental results

Nuclides identified per foil



Foil	Nuclides identified	n
Al	Na-24	1
Fe	Sc-47, Cr-51, Mn-52, Mn-54	4
Ni	Cr-51, Mn-52, Mn-54, Co-56, Mn-56, Co-57, Ni-57, Co-58	8
Cu	Mn-52, Mn-56, Co-57, Co-58	4
Nb	Rb-83, Sr-83, Sr-85, Y-87, Y-87m, Y-88, Y-89, Zr-88, Zr-89, Nb-90, Nb-92m	11
Bi	Tl-201, Tl-202, Pb-204m, Bi-205, Pb-205m, Bi-206	6

34

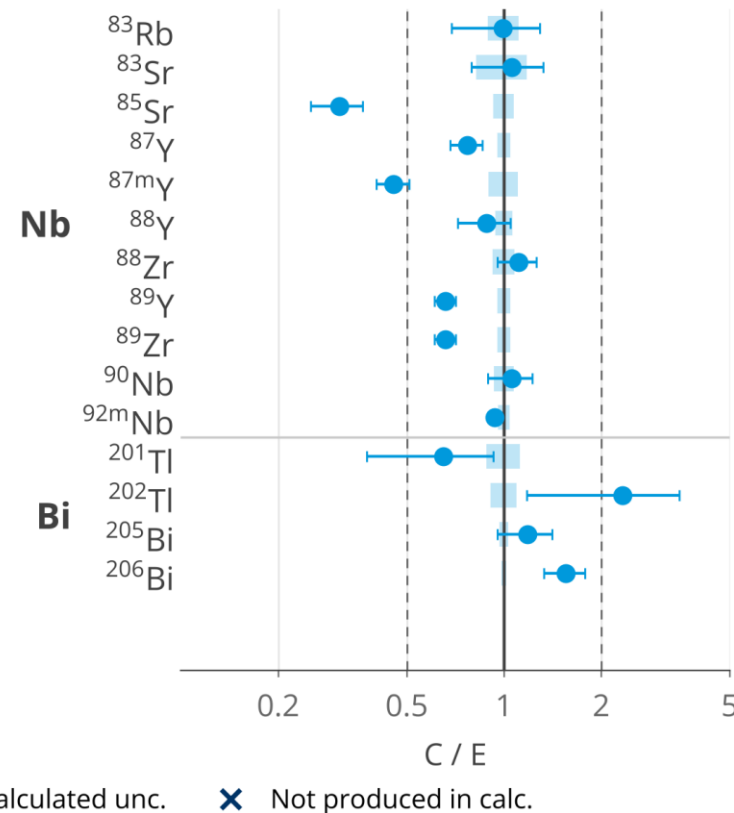
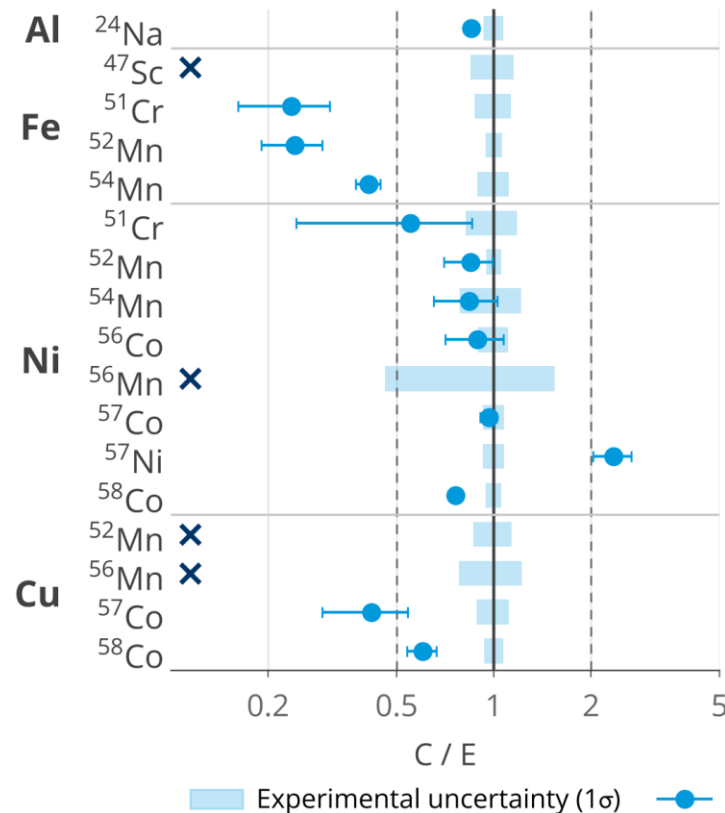
nuclides identified in six foils

76 %

with high confidence

Benchmark results

Calculated over experimental activities



71%

within a factor of 2

14 / 28

compatible with $C/E = 1$ at 1σ

4

measured but not produced in the simulations

#4

Conclusions

Discussion and future work



Conclusions

Discussion & future work



Satisfactory agreement

20 of 28 nuclides C/E within a factor of 2. Al, Ni and Nb close to unity.

Open questions

Fe and Cu products underestimated; Mn isotopes not produced or underestimated.



Ongoing: neutron spectrum

Characterizing the neutron spectrum at the position using foil irradiation of Au (Cd), Sc, Ti, Bi, and Nb.

Thank you!

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Appendix

Activities and C/E: Al, Fe, Ni, Cu



Foil	Nuclide	E [unit]	C (rel.)	C/E
Al	Na-24	0.287 ± 0.021	0.244 (3 %)	0.85 ± 0.07
Fe	Sc-47	0.064 ± 0.010	not produced	—
Fe	Cr-51	0.74 ± 0.09	0.17 (31 %)	0.24 ± 0.08
Fe	Mn-52	0.382 ± 0.022	0.093 (21 %)	0.24 ± 0.05
Fe	Mn-54	0.241 ± 0.027	0.099 (9 %)	0.41 ± 0.06
Ni	Cr-51	0.31 ± 0.06	0.17 (56 %)	0.55 ± 0.32
Ni	Mn-52	0.281 ± 0.015	0.237 (17 %)	0.85 ± 0.15
Ni	Mn-54	0.046 ± 0.010	0.039 (22 %)	0.84 ± 0.26
Ni	Co-56*	0.311 ± 0.033	0.276 (20 %)	0.89 ± 0.20

Foil	Nuclide	E [unit]	C (rel.)	C/E
Ni	Mn-56*	0.17 ± 0.09	not produced	—
Ni	Co-57	0.808 ± 0.062	0.779 (6 %)	0.96 ± 0.09
Ni	Ni-57	0.356 ± 0.027	0.836 (14 %)	2.35 ± 0.37
Ni	Co-58	3.80 ± 0.21	2.89 (1 %)	0.76 ± 0.04
Cu	Mn-52*	0.023 ± 0.003	not produced	—
Cu	Mn-56*	0.087 ± 0.019	not produced	—
Cu	Co-57	0.036 ± 0.004	0.015 (30 %)	0.42 ± 0.13
Cu	Co-58	0.197 ± 0.013	0.118 (11 %)	0.60 ± 0.08

* medium or low identification confidence. C/E in orange: outside a factor of 2.

Appendix

Activities and C/E: Nb, Bi



Foil	Nuclide	E [unit]	C (rel.)	C/E
Nb	Rb-83*	0.54 ± 0.06	0.53 (30 %)	0.99 ± 0.32
Nb	Sr-83*	0.82 ± 0.15	0.87 (25 %)	1.06 ± 0.32
Nb	Sr-85	1.88 ± 0.14	0.58 (18 %)	0.31 ± 0.06
Nb	Y-87	11.9 ± 0.6	9.17 (11 %)	0.77 ± 0.09
Nb	Y-87m	0.462 ± 0.048	0.211 (12 %)	0.46 ± 0.07
Nb	Y-88	0.622 ± 0.038	0.549 (19 %)	0.88 ± 0.17
Nb	Zr-88	1.41 ± 0.11	1.56 (14 %)	1.11 ± 0.18
Nb	Y-89	18.4 ± 0.9	12.1 (7 %)	0.66 ± 0.06
Nb	Zr-89	18.5 ± 0.9	12.1 (7 %)	0.66 ± 0.06

Foil	Nuclide	E [unit]	C (rel.)	C/E
Nb	Nb-90*	0.609 ± 0.043	0.643 (16 %)	1.06 ± 0.18
Nb	Nb-92m	26.2 ± 1.1	24.6 (2 %)	0.94 ± 0.04
Bi	Tl-201	3.97 ± 0.47	2.58 (42 %)	0.65 ± 0.29
Bi	Tl-202	0.416 ± 0.038	0.971 (50 %)	2.33 ± 1.18
Bi	Pb-204m*	0.187 ± 0.030	0.0018 (10 %)	0.009 ± 0.002
Bi	Bi-205	7.90 ± 0.26	9.33 (19 %)	1.18 ± 0.23
Bi	Pb-205m	0.25 ± 0.09	1.26 (19 %)	5.08 ± 2.15
Bi	Bi-206	12.4 ± 0.2	19.3 (14 %)	1.55 ± 0.23

* medium or low identification confidence. C/E in orange: outside a factor of 2. Metastable Pb not included in the C/E figure.