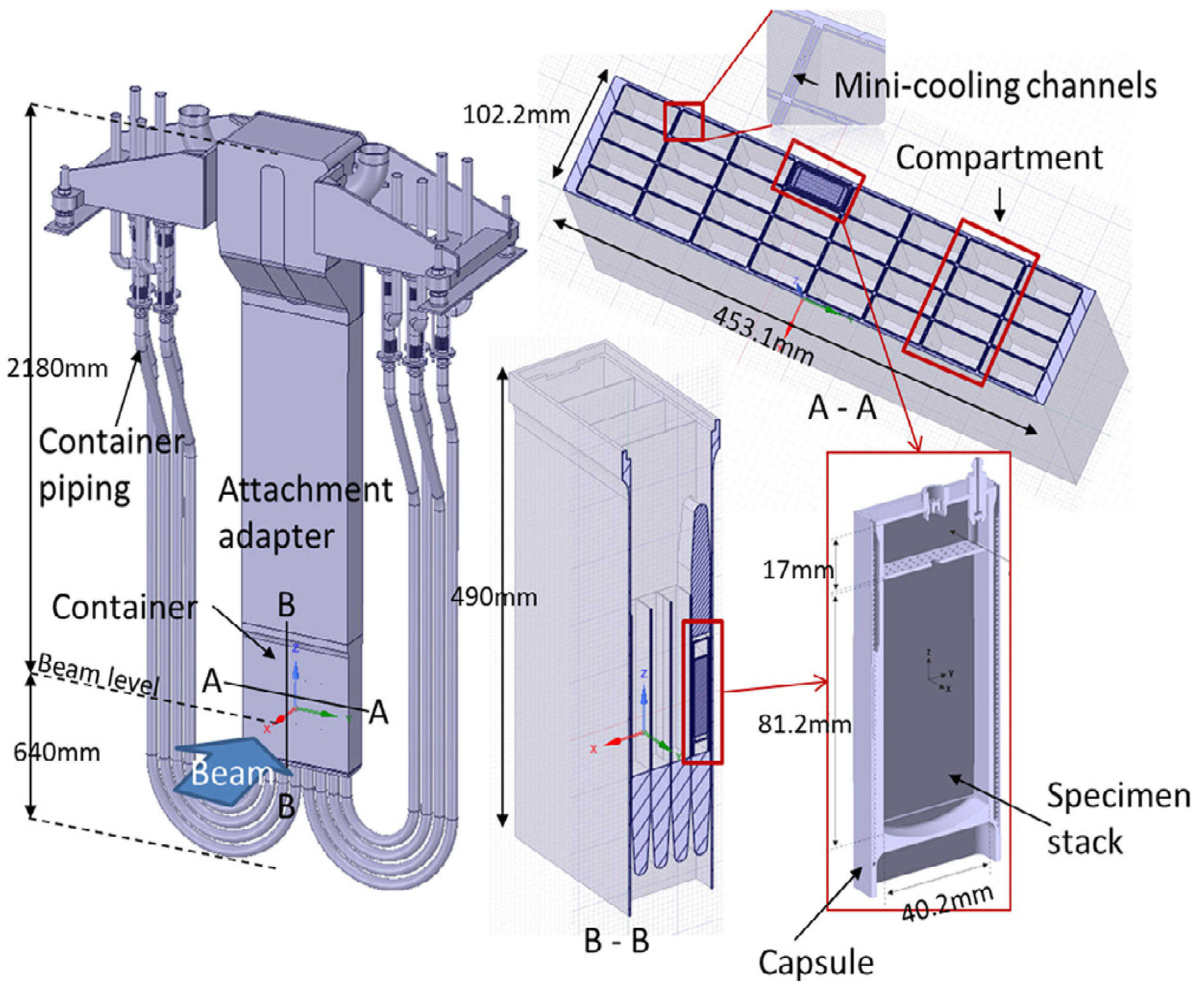
Karlsruhe Institute of Technology

Institute for Neutron Physics and Reactor Technology
Fusion Neutronics
Hermann-von-Helmholtz-Platz 1
D-76344 Eggenstein-Leopoldshafen
http://www.inr.kit.edu

Measurement of neutron fluence in the High-Flux Test Module of the Early Neutron Source by neutron activation

Axel Klix[1*], Frederik Arbeiter[1], Mitja Majerle[2], Yuefeng Qiu[1], Milan Štefánik[2]

[1]Karlsruhe Institute of Technology, Eggenstein-Leopoldshafen, Germany [2]National Physics Institute, Řež, Czech Republic



Neutron Activation Method

- Neutron fluence calculated from measured induced activity in activation probes after irradiation
- High fluence → small activation probes (≈mg)
- Possible locations:
  - Outer surface of HFTM
  - Pocket on outer surface of capsule
  - Inside capsule (in hermetic container)

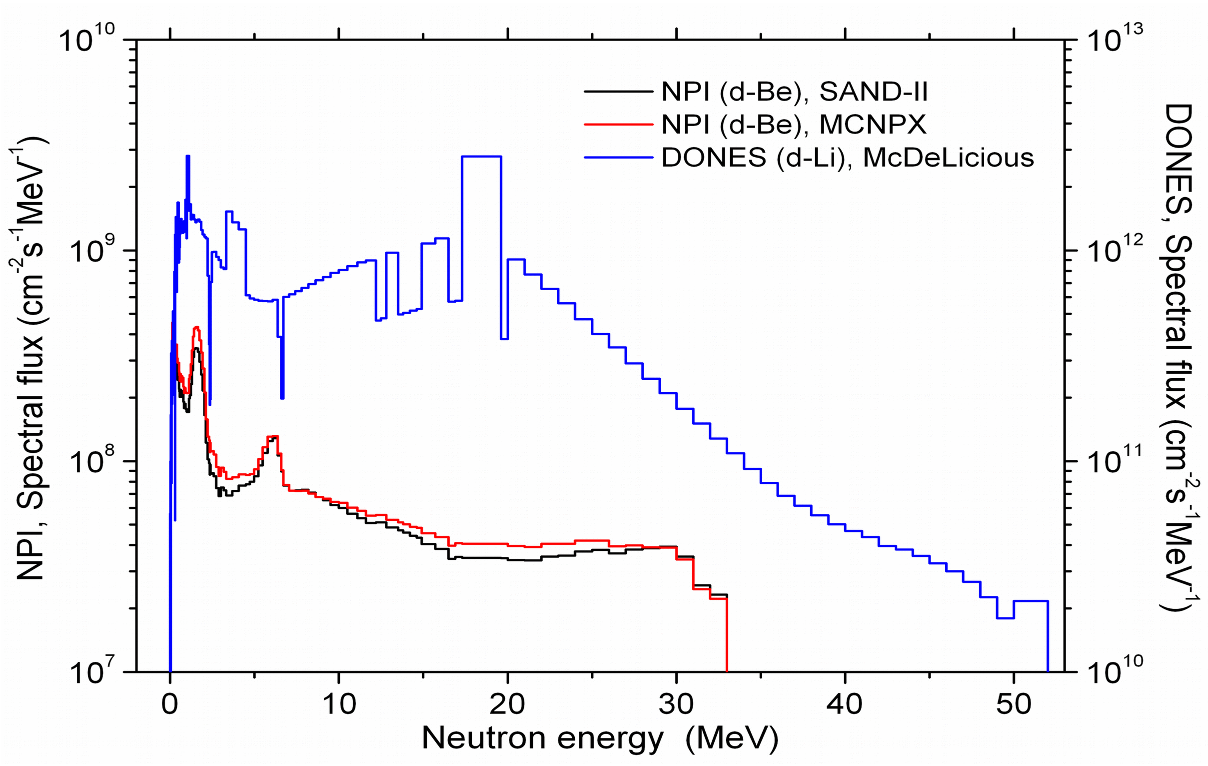
Each location with restrictions on selection of activation foil materials due to unloading schedules:

HFTM duty period ≈ 1 y → Only radio isotopes with long half lives (>100 d)

Location	Expected access time
Outer surface of HFTM	1 week
Pocket on specimen capsule surface	3 weeks
Inside specimen capsule	2-3 months

Experimental test at NPI Rez

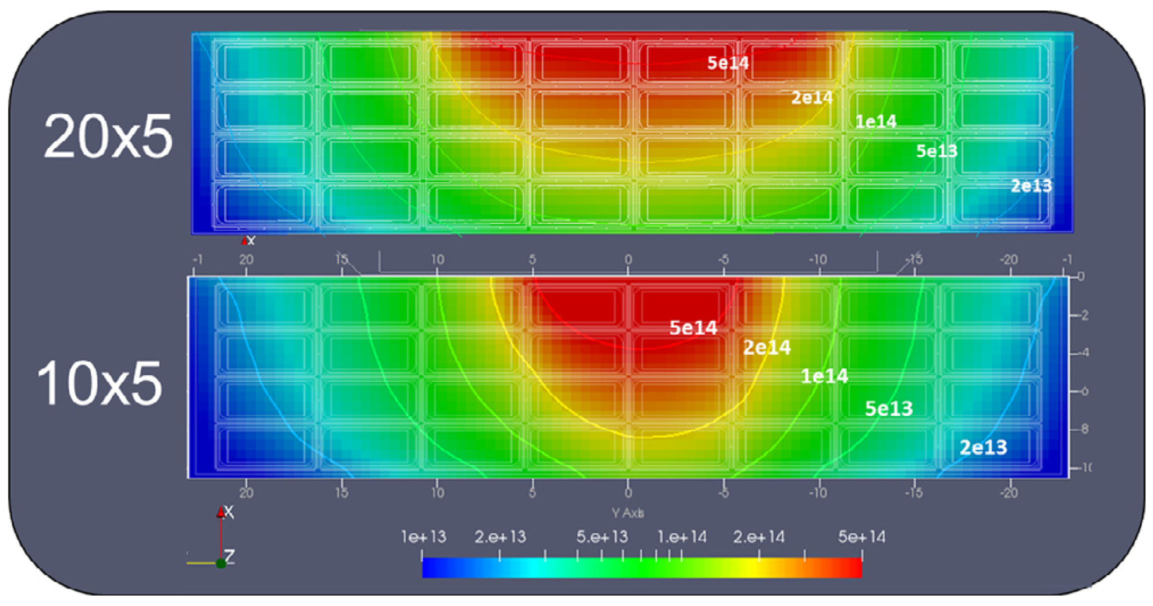
- Irradiation of a set of foils (Ni, Y, Co, Fe, Au) with a cyclotron at NPI Řež
- Position P14, irradiation time 9.5 hrs, proton beam current 11 μA, Be target
- Sample size 2.5×2.5 cm^2, up to 0.5 mm thick
- Neutron fluence 1.71×10^9 s^{-1}cm^{-2}, 5.85×10^{13} cm^{-2}
- This fluence about factor of 10^6 to 10^8 lower than in the specimen capsules of DONES.



Neutron flux spectrum in a center-front specimen box of the HFTM compared wih the neutron flux spectrum at the experimental position at NPI.

Neutron fluence measurement

- Neutron fluence figure required for analysis of specimen irradiation (dpa)
- Neutron flux changes with location:
  10^{13} – 10^{15} cm^{-2}s^{-1}
- Change of an order of magnitude over cm
- Neutron activation method suitable (low cost, simple, robust, no radiation damage issues)
- Activation probes optimized for expected neutron fluence, operation regime, temperature in HFTM, access after irradiation



Neutron flux density (cm^{-2}s^{-1}) distribution in the HFTM calculated with McDeLicious.

Dosimetry reactions

Dosimetry reaction	Melting Point °C	Half Life	Energy range*) MeV	Reaction channels (contributions in %)			
				Path 1	Path 2	Path 3	Path 4
^{93}Nb(n,x)^{88}Y	2477	106.7 d	27 – 55	**^{93}Nb(n,x)^{88}Y, 98.3** 99.0 (n,2na) 1.0 (n,3nh)	**^{93}Nb(n,x)^{88}Zr (b) → ^{88}Y, 1.7** 24.0 (n,5np) 7.0 (n,4nd) 68.9 (n,3nt)		
^{55}Mn(n,2n)^{54}Mn	1246	312.3 d	12 – 40	**^{55}Mn(n,x)^{54}Mn, 100** 99.8 (n,2n)			
^{nat}Ni(n,x)^{57}Co	1455	271.8 d	11 – 55	**^{58}Ni(n,x)^{57}Co, 79.7** 91.3 (n,np) 8.7 (n,d)	**^{58}Ni(n,x)^{57}Ni (b)→ ^{57}Co, 10.8** 100 (n,2n)	**^{60}Ni(n,x)^{57}Co, 9.1** 11.0 (n,2nd) 4.9 (n,nt) 84.1 (n,3np)	
^{nat}Ni(n,x)^{60}Co	1455	5.27 y	12 – 55	**^{60}Ni(n,x)^{60}Co, 54.0** 100.0 (n,p)	**^{61}Ni(n,x)^{60}Co, 10.4** 87.1 (n,np) 12.9 (n,d)	**^{62}Ni(n,x)^{60}Co, 34.5** 14.6 (n,nd) 83.3 (n,2np) 2.1 (n,t)	**^{64}Ni(n,x)^{60}Co, 0.6** 24.3 (n,2nt) 50.31 (n,4np) 25.3 (n,3nd)
^{nat}Ni(n,x)^{54}Mn	1455	312.3 d	17 – 55	**^{58}Ni(n,x)^{54}Mn, 93.2** 96.2 (n,n,pa) 3.7 (n,nph)	**^{60}Ni(n,x)^{54}Mn, 6.6** 2.0 (n,ta) 7.5 (n,nda) 90.4 (n,2npa)		
^{89}Y(n,2n)^{88}Y	1552	106.7 d	14 – 45	**^{89}Y(n,x)^{88}Y, 99.7** 100.0 (n,2n)			
^{nat}Fe(n,x)^{54}Mn	1538	312.3 d	3 – 55	**^{54}Fe(n,x)^{54}Mn, 35.2** 100.0 (n,p)	**^{56}Fe(n,x)^{54}Mn, 64.0** 9.9 (n,nd) 87.8 (n,2np) 2.2 (n,t)	**^{57}Fe(n,x)^{54}Mn, 0.7** 14.5 (n,2nd) 6.5 (n,nt) 79.0 (n,3np)	
^{59}Co(n,2na)^{54}Mn	1495	312.3 d	27 – 55	**^{59}Co(n,x)^{54}Mn, 100** 99.5 (n,2na) 0.5 (n,3nh)			
^{59}Co(n,3n)^{57}Co	1495	271.8 d	22 – 55	**^{54}Fe(n,x)^{54}Mn, 100** 100.0 (n,3n)			
^{197}Au(n,3n)^{195}Au	1064	186.1 d	16 – 40	**^{197}Au(n,x)^{195}Au, 100** 100.0 (n,3n)			
^{209}Bi(n,3n)^{207}Bi	271	31.2 y	17 – 50	**^{209}Bi(n,x)^{207}Bi, 100** 100.0 (n,3n)			

Selection from S. Simakov et.al., Development of activation foils method for the IFMIF neutron flux characterization, Fus.Eng.Des. 82 (2007), p.2510; additional reactions from present experimental test. Pathways calculated with FISPACT-II and EAF-2010 activation data assuming a neutron flux of 4.01·10^{14} cm^{-2}s^{-1} for 330 days.

*) Range defined by energies where the mainly contributing cross section approaches 10% of maximum

Test results

	Mass	Residual isotope	Half-life	Δ Half-life	Gamma line	Intensity	Δ Intensity	Net Peak	Δ Net Peak	Activity	Saturation Acivity	
	g		s	s	keV	%	%	Area	Area	Bq	σNΦ	ΔσNΦ/σNΦ
Ni	2.8186	Co-57	2.348E+07	4.3E+03	122.1	85.51	0.06	7.81E+06	2935.78	9.43E+03	1.09E+07	0.030
	2.8186	Co-57	2.348E+07	4.3E+03	136.5	10.71	0.15	9.41E+05	1077.42	9.50E+03	1.10E+07	0.033
	2.8186	Co-58	6.121E+06	2.6E+03	810.8	99.44	0.02	5.03E+06	2257.35	1.97E+04	9.11E+06	0.030
	2.8186	Co-60	1.663E+08	2.5E+04	1173.2	99.85	0.03	2.52E+04	215.12	1.31E+02	9.38E+05	0.031
	2.8186	Co-60	1.663E+08	2.5E+04	1332.5	99.98	0.00	1.76E+04	174.41	1.02E+02	7.29E+05	0.032
	2.8186	Mn-54	2.697E+07	2.6E+03	834.8	99.98	0.00	1.04E+05	382.74	4.14E+02	5.38E+05	0.030
Y	0.7	Y-88	9.213E+06	4.3E+03	898.0	93.70	0.30	8.13E3	91.89	6.29E+03	3.60E+06	0.032
	0.7	Y-88	9.213E+06	4.3E+03	1836.1	99.35	0.03	4.97E3	71.15	6.67E+03	3.82E+06	0.033
Co	2.7911	Co-57	2.348E+07	4.3E+03	122.1	85.51	0.06	3.24e4	217.75	3.16E+01	3.65E+04	0.031
	2.7911	Co-57	2.348E+07	4.3E+03	136.5	10.71	0.15	3.65e3	136.45	2.98E+01	3.44E+04	0.050
	2.7911	Co-58	6.121E+06	2.6E+03	810.8	99.44	0.02	1.35e5	369,00	4.27E+02	1.99E+05	0.030
	2.7911	Fe-59	3.844E+06	1.0E+03	1099.3	56.51	0.31	4.7e3	73.33	3.30E+01	1.37E+04	0.034
	2.7911	Fe-59	3.844E+06	1.0E+03	1291.6	43.23	0.33	3.22e3	58.08	3.38E+01	1.41E+04	0.036
	2.7911	Co-60	1.663E+08	2.5E+04	1173.2	99.85	0.03	1,37E+03	41.77	5.75E+00	4.12E+04	0.043
	2.7911	Co-60	1.663E+08	2.5E+04	1332.5	99.98	0.00	1,20E+03	36.82	5.60E+00	4.02E+04	0.043
	2.7911	Mn-54	2.697E+07	2.6E+03	834.8	99.98	0.00	6,32E+02	38.17	2.03E+00	2.65E+03	0.067
Fe	0.6402	Mn-54	2.697E+07	2.6E+03	834.8	99.98	0.00	6.0e3	31.03	3.45E+02	4.48E+05	0.030
Au	0.3047	Au-195	1.608E+07	2.7E+03	98.9	11.20	0.90	6.34e3	136.85	7.49E+02	6.34E+05	0.088

Half-lives, line intensities and corresponding uncertainties from JEFF-3.3; Net peak area and uncertainty obtained with Canberra Genie-2000 peak analysis. Saturation activity for further processing (see poster P1.069 P. Raj in this session).

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.