Activation of QA devices and phantom materials under clinical scanning proton beams – a gamma spectrometry study

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Introduction

- **Photon radiotherapy**
  - activation with energies above nuclear threshold
  - air activation (^{13}N ($t_{1/2}$ = 10 min), ^{15}O ($t_{1/2}$ = 2 min)) → forced ventilation mandatory (E > 10 MV)
  - collimation system activation
- **Proton radiotherapy**
  - a lot of reaction channels, neutrons

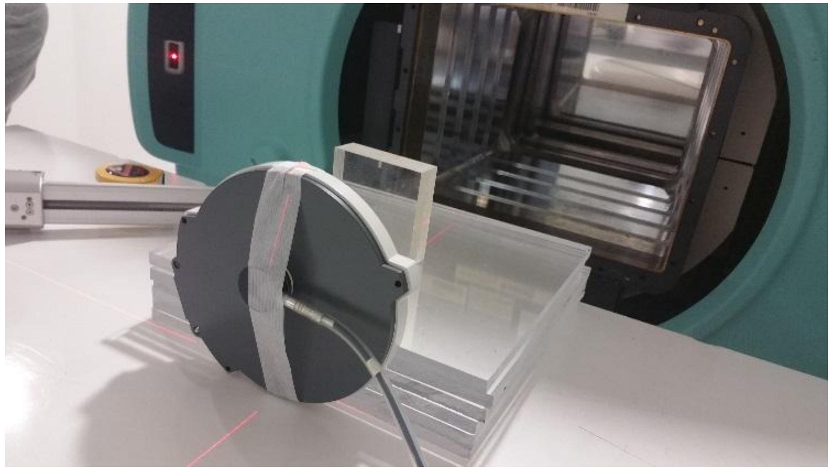
- **Literature review:**
  - shielding in treatment rooms
  - disposal of irradiated patient-specific compensators
  - activation of patient tissues
  - neutron spectra, neutron doses
  - excitation functions and activation cross sections of proton induced reactions

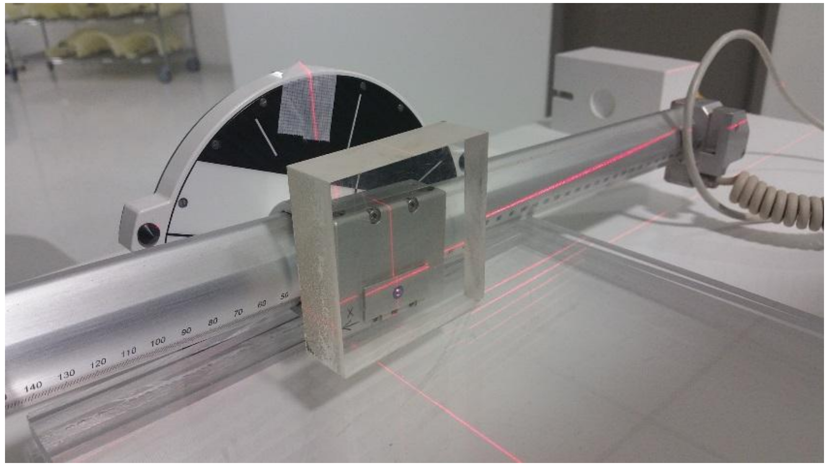
Methods

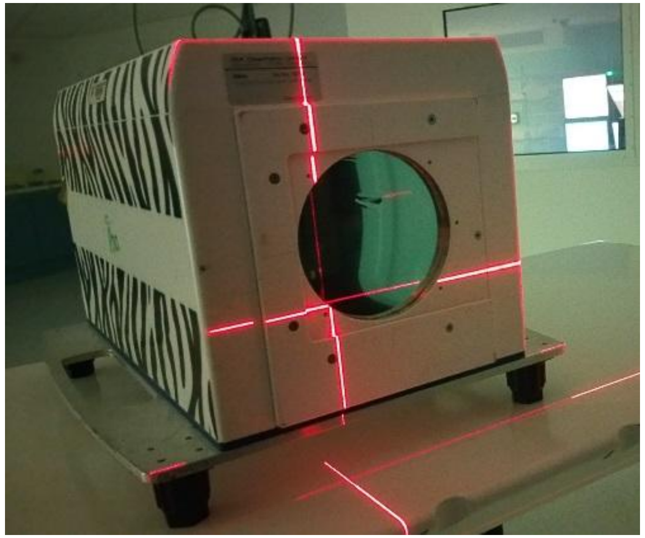
- Measured objects:
  - Zebra
  - Lynx
  - MatriXX PT
  - Stingray
  - PPC05 chamber
  - Blue phantom rail
  - four RW3 slabs
  - Carbon fibre
  - Cu disc
  - Ti plates
  - PMMA

Irradiation

- 3 irradiation sessions at PTC in Prague
- Highest energy 220 MeV
- High numbers of MU
- Selected geometry



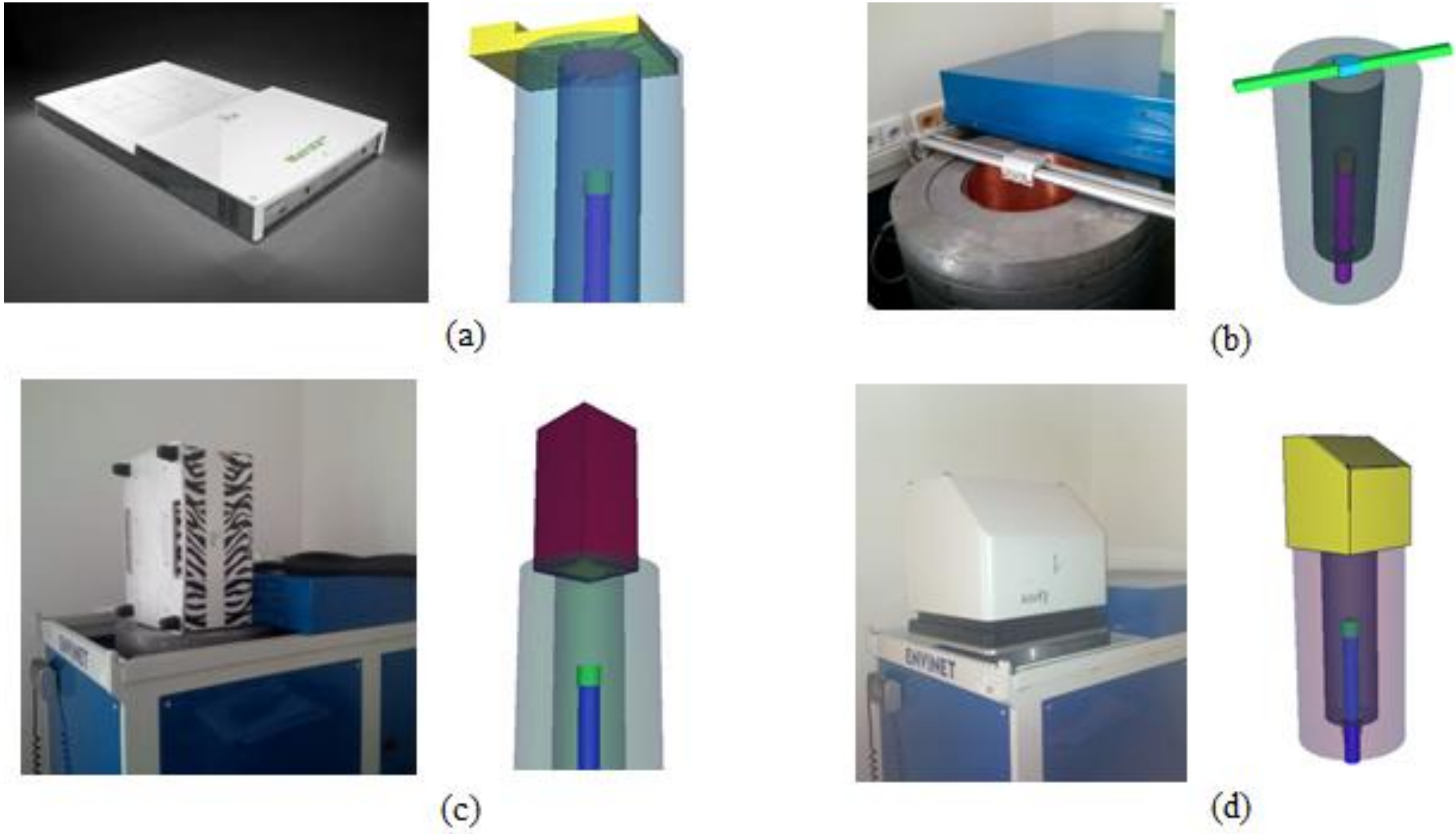




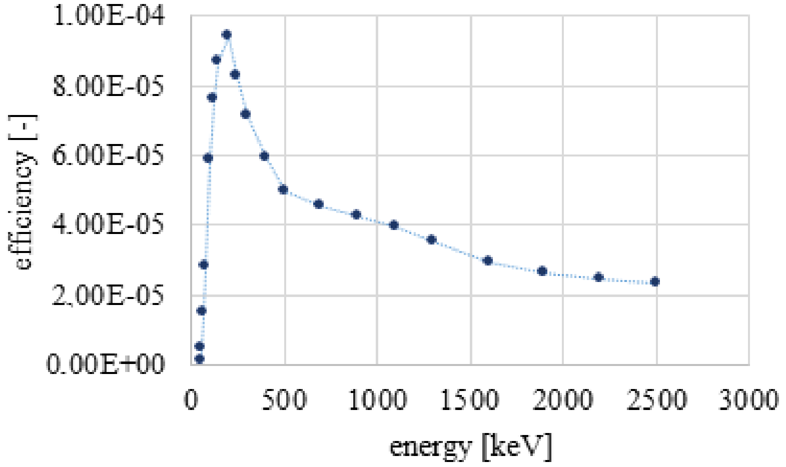
Gamma spectrometry

- HPGe coaxial detector with integrated preamplifier + multichannel analyser Multiport II + Software Genie 2000, version 3.1 (Canberra)
  - Energy region 50 - 3000 keV, resolution 1.89 keV at 1.33 MeV (^{60}CO), relative efficiency 32.3 % at 1.33 MeV
- Background measurements (radiation history)
- Post-irradiation measurements
  - 1st acquisition at least 2 days after irradiation (long lived radionuclides)
  - 2nd acquisition 3 – 5 days after irradiation
  - 24 hours (depending on level of activation)

Monte Carlo models for efficiency calibration



Efficiency calibration curves

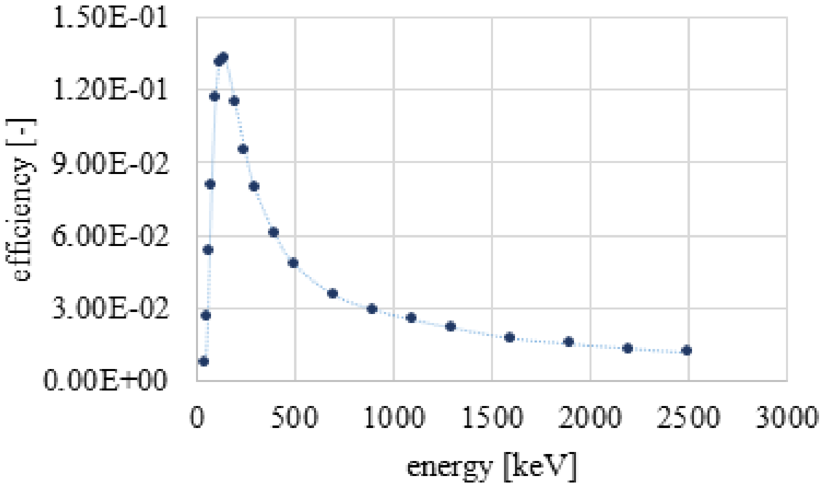


$$\log(\eta) = -1.136\times10^{-4}\cdot E - 4.401 + 1.091\times10^{2}\cdot \mathrm{E}^{-1} - 5.072\times10^{3}\cdot \mathrm{E}^{-2} - -5.997\times10^{5}\cdot \mathrm{E}^{-3} + 1.926\times10^{7}\cdot \mathrm{E}^{-4}$$

(a)

Zebra – low efficiency

PPC05 chamber – high efficiency

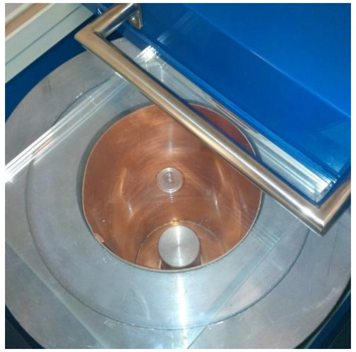


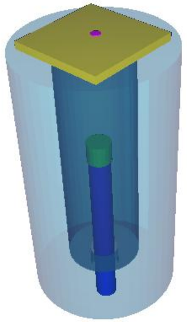
$$\log(\eta) = -1.591\times10^{-4}\cdot E - 1.643 + 2.515\times10^{2}\cdot \mathrm{E}^{-1} - 2.516\times10^{4}\cdot \mathrm{E}^{-2} + +8.911\times10^{5}\cdot \mathrm{E}^{-3} - 1.629\times10^{7}\cdot \mathrm{E}^{-4}$$

(b)

Verification of efficiency calibration method

Standard sources and PMMA slabs
Different geometries

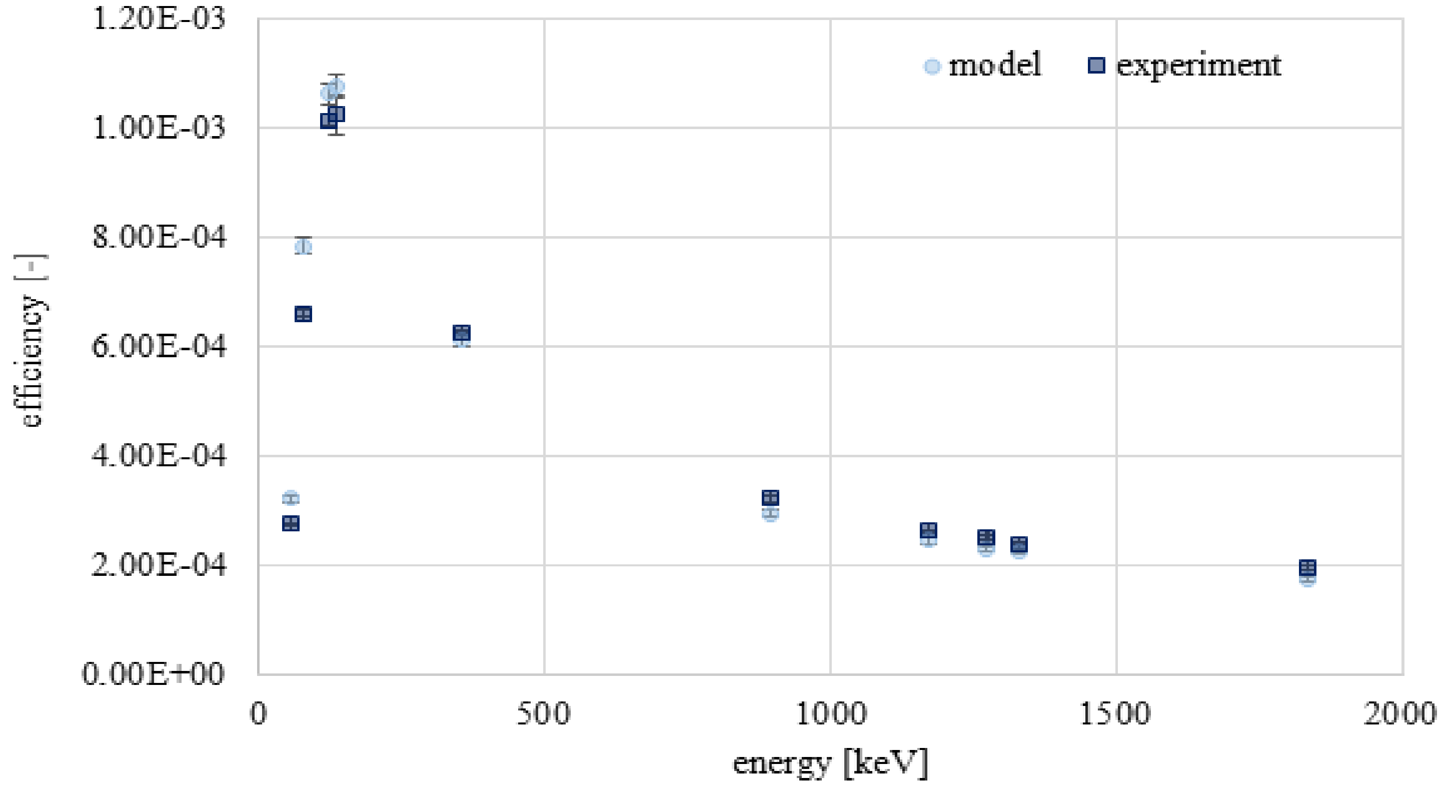


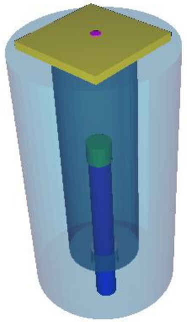


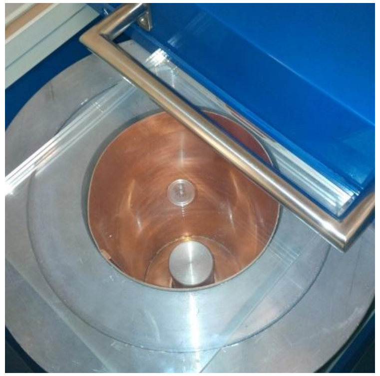
Radionuclide	Energy (keV)	Model (-)	Experiment (-)	Difference (%)
AM-241	59	3.20E-04	2.73E-04	17.1
BA-133	81	7.82E-04	6.59E-04	18.7
	356	6.09E-04	6.24E-04	2.4
CO-57	122	1.06E-03	1.01E-03	4.7
	136	1.07E-03	1.02E-03	5.1
Y-88	898	2.93E-04	3.19E-04	8.1
	1836	1.73E-04	1.94E-04	10.6
CO-60	1173	2.43E-04	2.60E-04	6.7
	1332	2.23E-04	2.38E-04	6.4
NA-22	1274	2.29E-04	2.48E-04	7.4

Verification of efficiency calibration method

Standard EG source and PMMA slabs

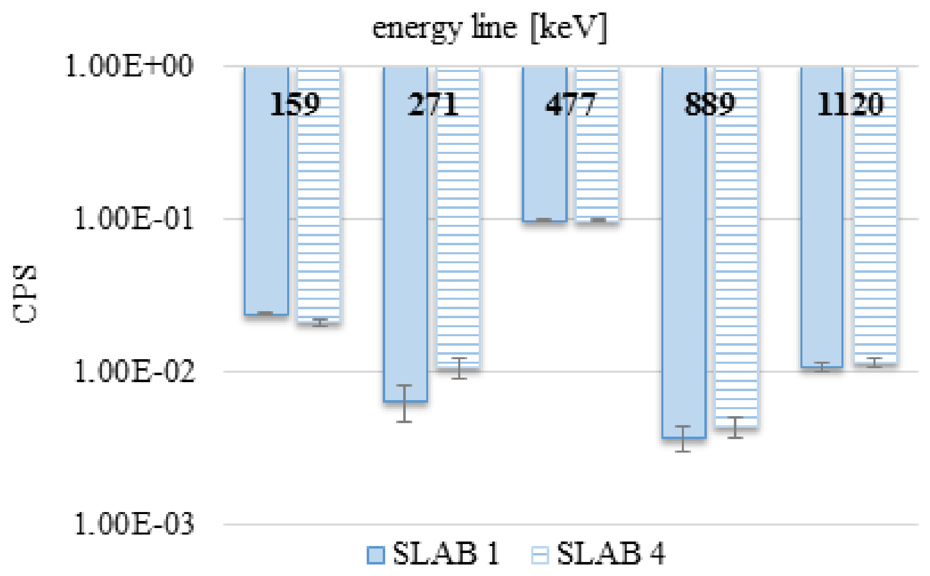






Homogeneity of activation

2 RW3 slabs at different depths in the beam path



Radionuclide	Energy (keV)	SLAB 1		SLAB 4	
		Area (CPS)	Uncertainity (CPS)	Area (CPS)	Uncertainity (CPS)
SC-47	159	2.37E-02	6.39E-04	2.10E-02	1.13E-03
SC-44m	271	6.44E-03	1.71E-03	1.07E-02	1.60E-03
Be-7	477	9.61E-02	1.68E-03	9.64E-02	1.51E-03
SC-46	889	3.64E-03	7.17E-04	4.30E-03	7.07E-04
	1120	1.08E-02	7.73E-04	1.15E-02	7.32E-04

Results – Activation products

IAEA Safety Standards Series No. RS-G-1.7: Application of the concepts of exclusion, exemption and clearance

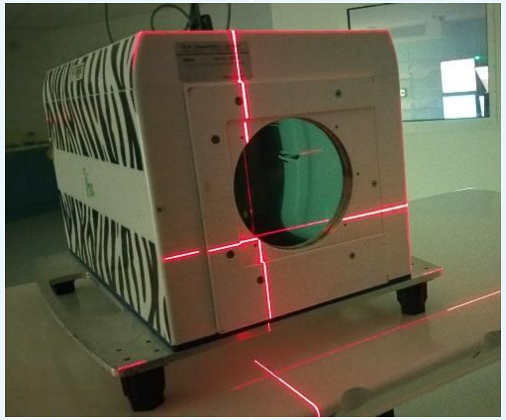
$$\sum_{i=1}^{n} \frac{C_i}{C_{Li}} \leq 1$$

PPC05 chamber

Radionuclide	Half life (days)	Measured activity 5 days after irradiation (Bq)	Uncertainty (Bq)	Calculated specific activity 5 days after irradiation (Bq/g)	IAEA activity concentration value 5 days after irradiation	MUs given
^{7}Be	53.12	126.07	1.38	4.67	1.846	133 547
^{24}Na	0.62	2.34	0.11	0.09		
^{44}Sc	0.16	151.31	15.13	5.60		
^{44m}Sc	2.44	1.20	0.04	0.04		
^{46}Sc	83.79	0.35	0.02	0.01		
^{47}Sc	3.35	1.63	0.16	0.06		
^{48}Sc	1.82	0.14	0.01	0.01		
^{48}V	15.97	1.28	0.13	0.05		
^{51}Cr	27.70	3.57	0.21	0.13		
^{52}Fe	0.34	1.28	0.14	0.05		
^{52}Mn	5.59	3.82	0.04	0.14		
^{54}Mn	312.05	0.43	0.04	0.02		
^{56}Co	77.24	1.21	0.12	0.04		
^{56}Ni	6.08	0.12	0.01	0.00		
^{57}Co	271.74	0.64	0.02	0.02		
^{57}Ni	1.48	1.28	0.06	0.05		
^{58}Co	70.86	4.24	0.06	0.16		
^{59}Fe	44.50	0.14	0.04	0.01		
^{65}Zn	243.93	0.45	0.03	0.02		
^{67}Cu	2.58	0.90	0.06	0.03		

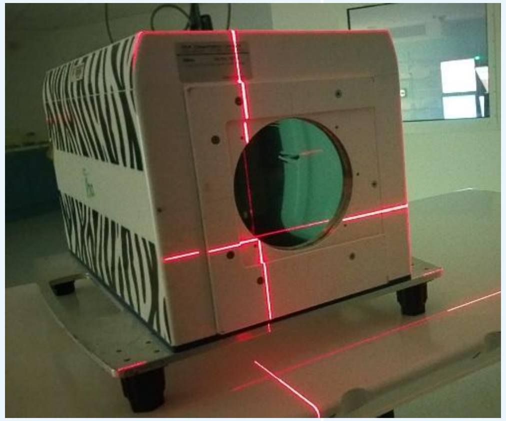
Zebra

Beam entrance end of Zebra facing the HPGe detector						
Radionuclide	Half life (days)	Measured activity 5 days after irradiation (Bq)	Uncertainty (Bq)	Calculated specific activity 5 days after irradiation (Bq/g)	IAEA activity concentration value 5 days after irradiation	MUs given
^{7}Be	53.12	37092	705	3.71	3.769	140 223
^{22}Na	949.37	97	10	0.01		
^{44}Sc	0.16	678331555	67833156	67833.16		
^{44m}Sc	2.44	2713	129	0.27		
^{46}Sc	83.79	398	18	0.04		
^{47}Ca	4.54	129	39	0.01		
^{47}Sc	3.35	6289	629	0.63		
^{48}V	15.97	3657	366	0.37		
^{51}Cr	27.70	20556	2056	2.06		
^{52}Mn	5.59	9941	91	0.99		
^{54}Mn	312.05	938	37	0.09		
^{56}Co	77.24	577	24	0.06		
^{56}Ni	6.08	1281	53	0.13		
^{57}Ni	1.48	1105	117	0.11		



Zebra

Bragg peak end of Zebra facing the HPGe detector						
Radionuclide	Half life (days)	Measured activity 5 days after irradiation (Bq)	Uncertainty (Bq)	Calculated specific activity 5 days after irradiation (Bq/g)	IAEA activity concentration value 5 days after irradiation	MUs given
^{7}Be	53.12	20728.76	2072.88	2.07	3.387	140 223
^{22}Na	949.37	679.96	41.14	0.07		
^{24}Na	0.62	2954.38	44.12	0.30		
^{43}K	0.93	91.44	10.67	0.01		
^{44}Sc	0.16	0.21	0.02	0.00		
^{44m}Sc	2.44	1007.03	34.69	0.10		
^{46}Sc	83.79	173.98	24.67	0.02		
^{47}Ca	4.54	212.44	41.25	0.02		
^{47}Sc	3.35	308.66	60.24	0.03		
^{48}Sc	1.82	54.73	5.47	0.01		
^{48}V	15.97	3407.52	340.75	0.34		
^{51}Cr	27.70	6131.85	440.43	0.61		
^{52}Mn	5.59	6850.67	63.72	0.69		
^{54}Mn	312.05	626.10	69.58	0.06		
^{55}Co	0.73	114.39	5.62	0.01		
^{56}Co	77.24	362.17	24.05	0.04		
^{56}Ni	6.08	372.14	35.72	0.04		
^{57}Ni	1.48	381.44	19.64	0.04		



Other objects – IAEA activity concentration value

	MatriXX PT	Lynx	Stingray	Four RW3 slabs	Ti plates	Carbon disc	Cu disc	Piece of Perspex	Blue phantom rail
MUs given	135 200	135 200	133 547	135 200	135 200	135 200	135 200	133 547	133 547
IAEA activity concentration value	0.134	0.137	0.328	0.287	**28.894**	**1.670**	**16.459**	**1.599**	**7.956**

Titanium, carbon fiber, copper, Perspex and Blue phantom rail – always part of a larger device → activity concentration would fall below the limit

Other objects – important radionuclides

Radionuclides with activity higher than 100 Bq 5 days after irradiation and/or half life longer than 10 days

Tested item	Important radionuclides
MatriXX PT	^{7}Be, ^{22}Na, ^{46}Sc, ^{48}V, ^{54}Mn, ^{56}Co, ^{57}Co
Lynx	^{7}Be, ^{48}V, ^{54}Mn, , ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co
Stingray	^{7}Be, ^{46}Sc, ^{48}V, ^{51}Cr, ^{54}Mn, ^{56}Co
RW3 slabs	^{7}Be, ^{44m}Sc, ^{46}Sc, ^{47}Sc
Ti plates	^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}V
Carbon disc	^{7}Be
Cu disc	^{7}Be, ^{46}Sc, ^{48}V, ^{51}Cr, ^{54}Mn, ^{56}Co, ^{57}Co, ^{58}Co, ^{59}Fe, ^{60}Co, , ^{65}Zn
Piece of Perspex	^{7}Be
Blue phantom rail	^{7}Be, ^{22}Na, ^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}V, ^{51}Cr, ^{52}Mn, ^{54}Mn, ^{56}Co, ^{57}Ni, ^{58}Co

Activity of Zebra after one year of clinical use

Proton Therapy Center Czech, s.r.o.

- Daily checks
  - 3 beam energies
  - 100 MU with each energy
  - performed only in 1 treatment room per day
- Monthly QA tests
  - 12 x 100 MU with different energies
  - in all 4 treatment rooms - usually one test per week

- 5 working days/week, 52 weeks/year

→ decay law and periodical irradiation

Activity of Zebra after one year of clinical use

Radionuclide	Half life (days)	Beam entrance end of Zebra facing the HPGe detector		Bragg peak end of Zebra facing the HPGe detector	
		Specific activity after 1 year of use (Bq/g)	IAEA activity concentration value	Specific activity after 1 year of use (Bq/g)	IAEA activity concentration value
^{7}Be	53.12	0.8439	1.221	0.4716	2.156
^{22}Na	949.37	0.0086		0.0602	
^{24}Na	0.62	low		0.8324	
^{43}K	0.93	low		0.0042	
^{46}Sc	83.79	0.0133		0.0058	
^{47}Ca	4.54	0.0006		0.0010	
^{47}Sc	3.35	0.0328		0.0016	
^{48}Sc	1.82	low		0.0005	
^{48}V	15.97	0.0308		0.0287	
^{51}Cr	27.70	0.2660		0.0793	
^{52}Mn	5.59	0.0498		0.0343	
^{54}Mn	312.05	0.0654		0.0437	
^{55}Co	0.73	low		0.0143	
^{56}Co	77.24	0.0180		0.0113	
MUs given over a year			140 400		

Activity of Lynx after one year of clinical use

Radionuclide	Half-life (days)	Specific activity after 1 year of use (Bq/g)	IAEA activity concentration value
^{7}Be	53.12	0.1888	1.120
^{47}Ca	4.54	0.0012	
^{47}Sc	3.35	0.0036	
^{48}V	15.97	0.0027	
^{52}Mn	5.59	0.0055	
^{54}Mn	312.05	0.0802	
^{56}Co	77.24	0.0075	
^{57}Co	271.74	0.0201	
^{58}Co	70.86	0.0147	
^{60}Co	2087.80	0.0181	
	MUs given over a year		1 859 540

Supposing use of the same device for all tests – not true in reality

Conclusions

- Most identified radionuclides are in accordance with previous expectations (NCRP 2003)
- Activities comparable to IAEA levels of activity concentration for exemption and clearance (= Czech legislation since January 2017)
- Some devices proved to cumulate activity in time
- Care should be taken during commissioning of proton beams (high number of MUs)
- Paper provides useful data to determine nuclide inventories (required by legal authorities in some countries)
- Knowledge of radionuclides is important when choosing instruments for routine contamination monitoring

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