Induced radioactivity of metal samples in the radiation field by 9.6 GeV electrons at PAL-XFEL

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Overview

< Experiment Goal >

- To understand on **activation components** widely used for **electron accelerator**
- **Benchmarking study** of Monte Carlo code, **FLUKA**, for **electron accelerator** to identify safety margins

⇒ **Follow-up on previous experiments** performed by CERN & SLAC & PAL

- By PAL-XFEL, 10 GeV e- beams have been ready to used.
- Preliminary experiment using metal samples was conducted.

SLAC-CERN [1]
: 28.5 GeV e- on Cu for metals, water & soil

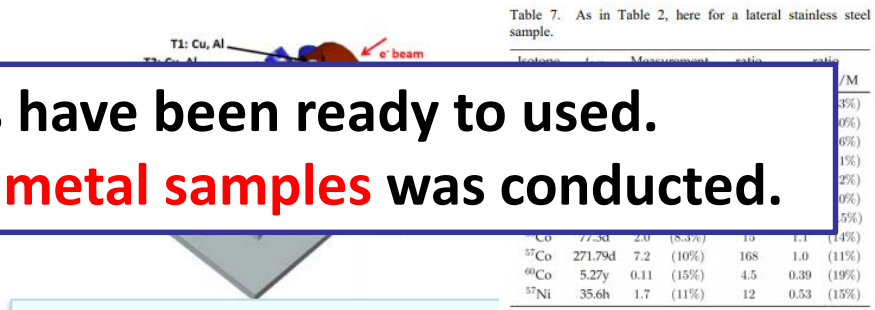
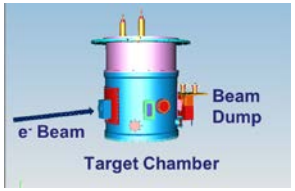
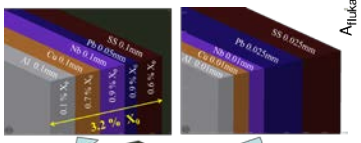


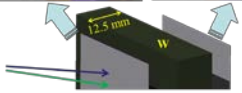
Table 7. As in Table 2, here for a lateral stainless steel sample.

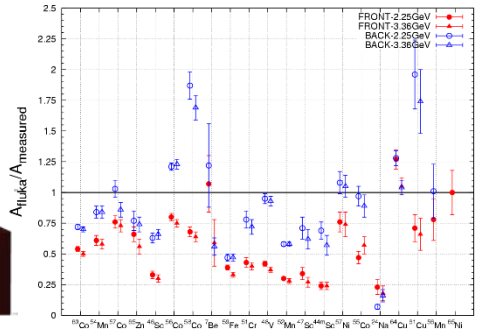
^{57}Co	271.79d	7.2	(10%)	168	1.0	(11%)
^{60}Co	5.27y	0.11	(15%)	4.5	0.39	(19%)
^{57}Ni	35.6h	1.7	(11%)	12	0.53	(15%)

CERN-PAL [2] : 2.5 GeV e- on Cu for metals









JLab [4] : 2.25 & 3.36 GeV e- on W for metals

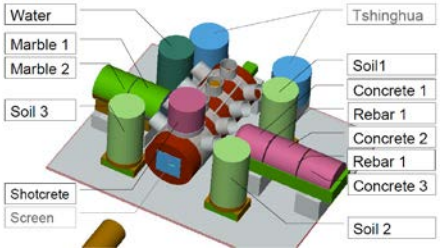


Table 2: *Measured* specific activities (t_c=118-123 days) in concrete and FLUKA to Measurement ratio (% error).

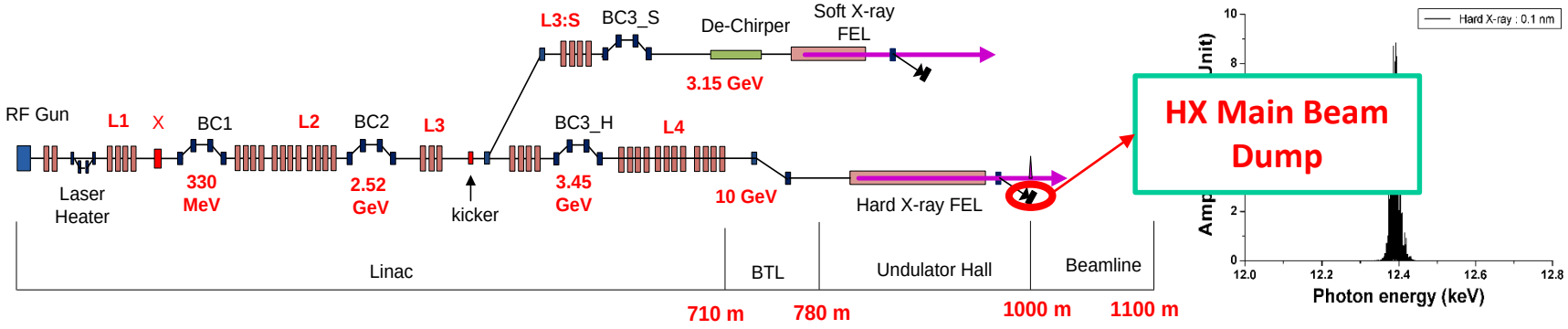
	② Next to dump		③ Intermediate		④ Exterior	
	M [Bq/g]	F/M	*M [Bq/g]*	F/M	*M [Bq/g]*	F/M
^{7}Be	*1.1E-1*	0.96 (2)	*4.4E-2*	0.79 (5)	*2.5E-2*	0.67 (16)
^{22}Na	*4.0E-2*	0.57 (1)	*1.7E-2*	0.41 (10)	*7.4E-3*	0.43 (22)
^{46}Sc	*9.2E-3*	0.60 (3)	*3.7E-3*	0.75 (8)	*7.3E-3*	0.29 (13)
^{51}Cr	*5.9E-3*	0.77 (17)	*3.0E-3*	0.50 (53)	*2.4E-3*	0.33 (99)
^{54}Mn	*6.5E-2*	0.43 (1)	*2.2E-2*	0.40 (3)	*1.1E-2*	0.35 (5)
^{56}Co	*6.3E-4*	0.43 (19)	NA		NA	
^{58}Co	*2.2E-3*	0.28 (9)	*4.7E-4*	0.39 (40)	*1.4E-4*	0.49 (51)
^{59}Fe	*7.3E-4*	0.72 (23)	*5.4E-4*	0.74 (23)	*6.3E-4*	0.60 (38)
^{60}Co	*3.1E-4*	0.80 (32)	NA		NA	
^{85}Sr	*7.1E-3*	0.26 (6)	*3.3E-3*	0.14 (28)	*1.9E-3*	0.13 (24)
^{86}Rb	*3.6E-3*	0.09 (31)	*3.1E-3*	0.003(36)	NA	
^{88}Y	*7.8E-4*	1.10 (15)	*4.7E-4*	0.49 (25)	*3.6E-4*	0.24 (24)
^{95}Nb	*5.0E-4*	0.65 (27)	NA		NA	

SLAC-PAL [3]
: 2.5 GeV e- on Cu for water, concrete & soil

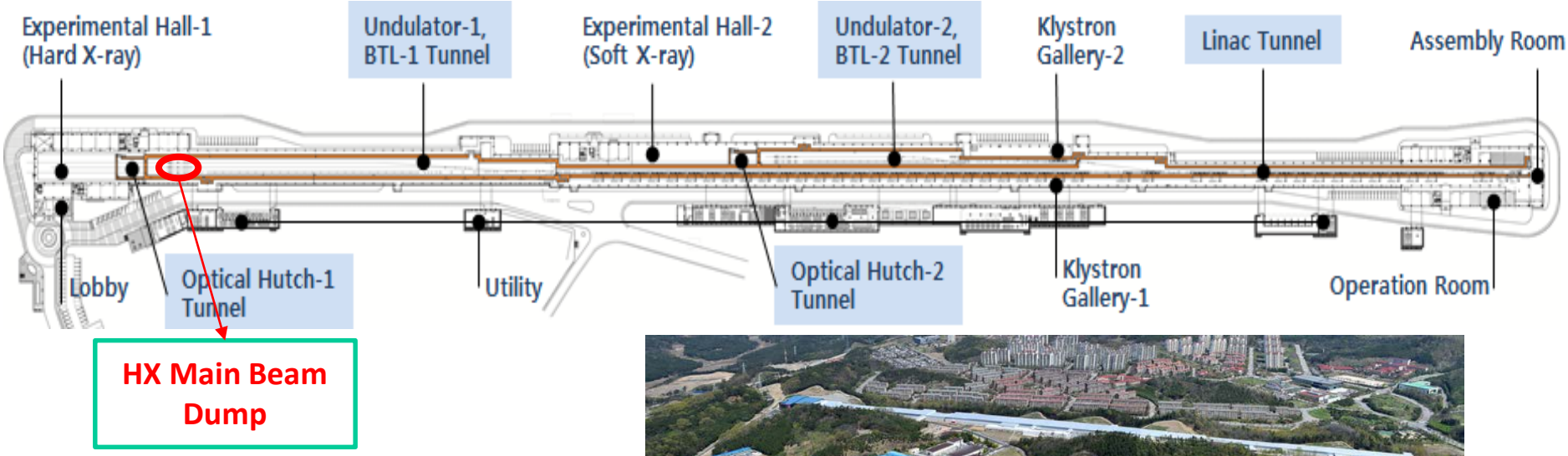
[1] J. Bauer et al., Proceedings of 1st ARIA workshop, PSI, Switzerland, Oct. 13-17 (2008)
[2] M. Brugger et al., Progress in Nuclear Science and Technology 4, 363 (2014)
[3] M. Santana Leiter et al., Proceeding of AccApp2013, Bruges, Belgium, Aug. 5-8 (2013)
[4] G. Kharashvili et al., Proceeding of SATIF14, FNAL, USA, Apr. 28-30 (2014)

PAL-XFEL

< Schematic Drawing of PAL-XFEL >



< Accelerator Building >

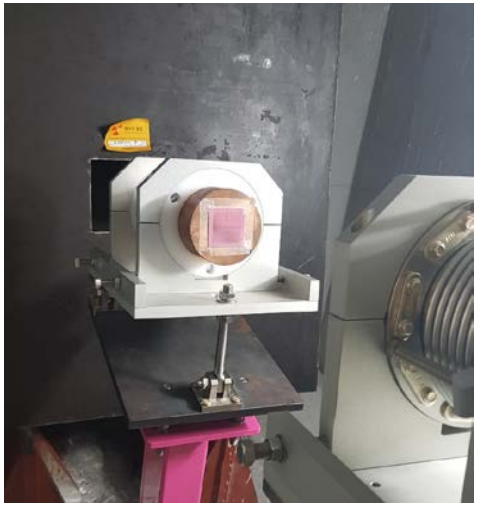


Target installation

< Experiment Location; HX Main Beam Dump Bunker of PAL-XFEL >

- In normal operation, electron beam is always dumped at Main Beam Dump.
- Max. permissible electron beam power : 264 W
  (11 GeV, 200 pC, 60 Hz, 2 bunches)

Small modification to install the copper target for this experiment



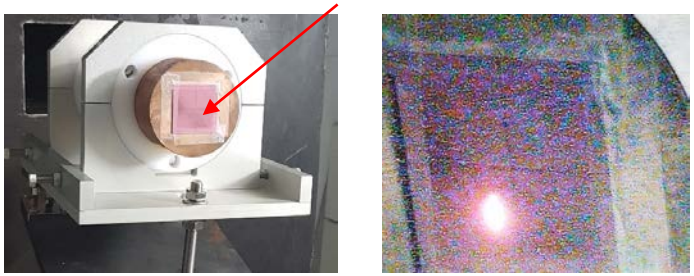
Methods

< Experiment Procedure >

Electron beam tuning

- Energy : **9.6 GeV**
- Position monitoring by **Al_2O_3 screen** in front of copper target surface
- Intensity monitoring by **Beam Current Monitor** (Turbo-ICT, Bergoz) upstream of Main Beam Dump

Al_2O_3 screen



Installation of samples

- **OFHC Cu, Steels, Al** (accelerator materials), Au, Co (for thermal neutron)
- Attaching samples to Cu target **laterally**

Irradiation

- About **3 days** irradiation, determined by pre-irradiation using 3 GeV electron beam

Taking out & Performing gamma-spectroscopy

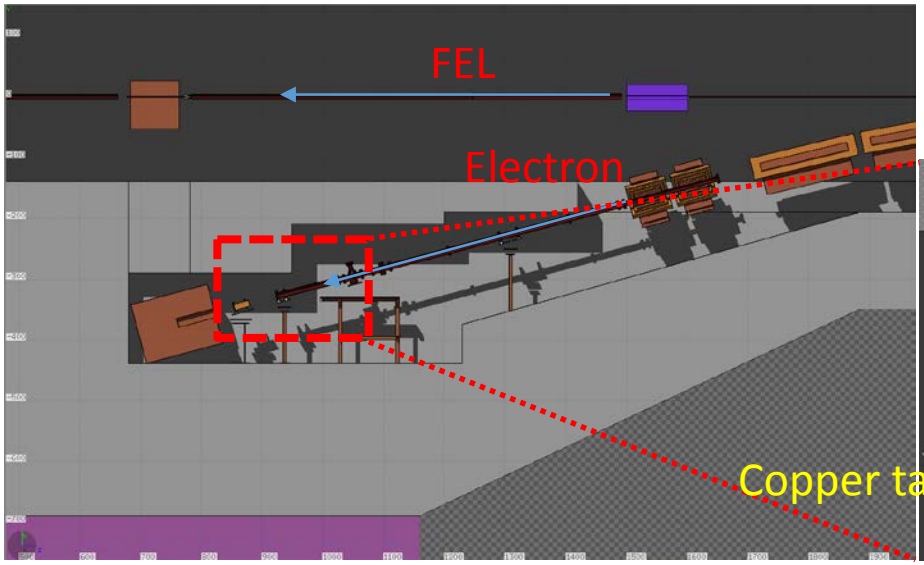
- By **HPGe detector** (relative efficiency : 20%)
- Measured several times for short & long-lived RIs
  ⇒ **Specific activities of RIs at the irradiation-end**

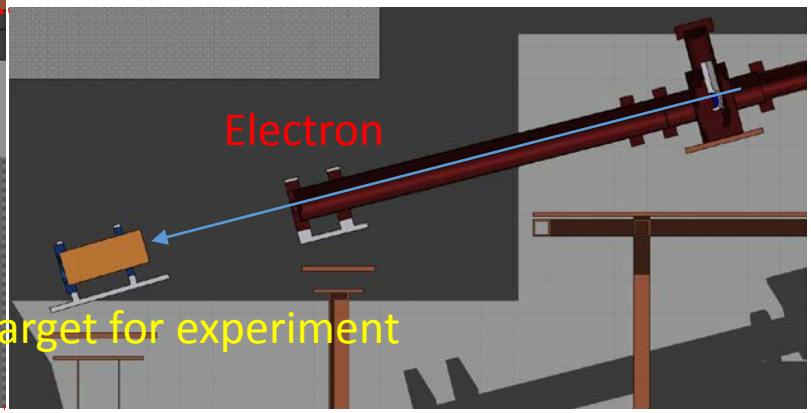
Methods

< Benchmarking >

By the **FLUKA 2011.2x** code (recent version of FLUKA)

- **Accurate description of input geometry** based on the real installation





- **Sensitivity check** of beam profile and beam shape by an iteration (several trials)
- Using **adequate model** and **biasing**
  - Threshold : 1 MeV for e+/e-, 1 MeV for photon, thermal for neutron
  - PEANUT nuclear model for all energies
  - Evaporation ON : New evap. with heavy frag.
  - Coalescence ON : ldpmqmd linked
  - LAM-biasing ON for Photonuclear reaction
  - Region importance biasing into samples : 1 to 3

Output of **RESNUCLEI card** (Decay time : 0)
⇒ Get specific activities of radionuclide at the irradiation-end
⇒ **Compare with measured specific activities!**

Used Samples

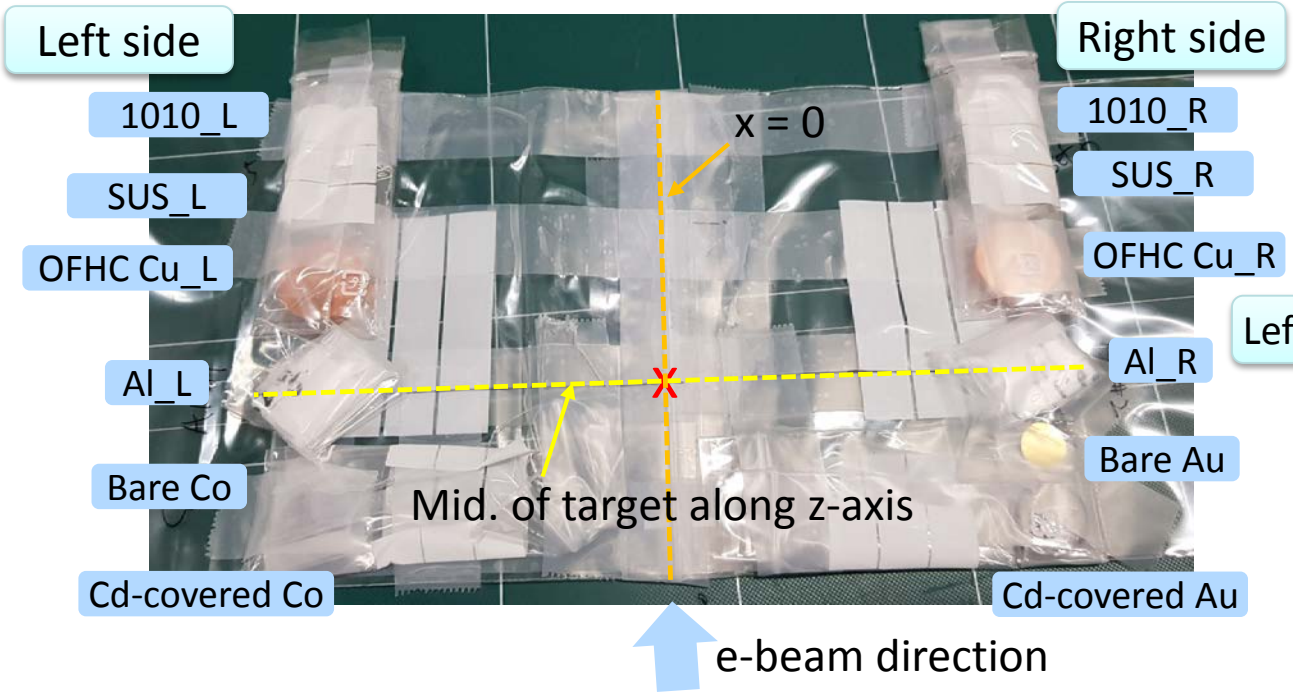
< Information of Installed Samples >

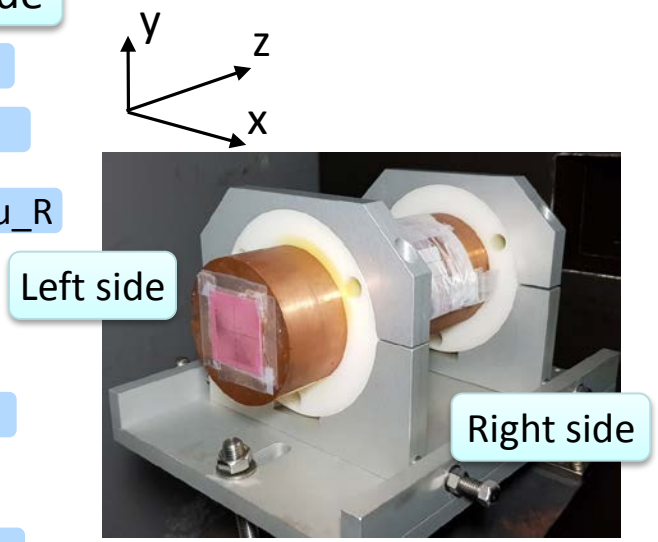
Type	Name	Size [mm]	*Pos.	Elements	**Purpose
Al	Al_L	Φ20 x 2	Left	**Al (99.99%)**	Understand about activated electron accelerator components
	Al_R	Φ20 x 2	Right		
SUS304	SUS_L	Φ20 x 5	Left	**Fe (68.027%)**, **Cr (19.2%)**, **Ni (9.6%)**, Co (0.190%), Mn (2.0%), Cu (0.55%), Mo (0.199%), Si (0.08%), C (0.05%) S (0.015%), P (0.01%), N (0.079%)	
	SUS_R	Φ20 x 5	Right		
AISI1010 (Carbon Steel)	1010_L	Φ20 x 5	Left	**Fe (99.2482%)**, Cr (0.058%), Ni (0.008%) Co (0.0018%), Mn (0.4 %), Cu (0.057%), Mo (0.012%), Si (0.035%), C (0.094%), S (0.015%), P (0.029%), Al (0.042%)	
	1010_R	Φ20 x 5	Right		
OFHC Cu	Cu_L	Φ20 x 5	Left	Cu (~ 99%)	
	Cu_R	Φ20 x 5	Right		
Co	Bare	Φ10 x 0.025	Left	Co (99.9%)	Measuring thermal neutron, ~~Fast neutron by (n,2n), (n,3n)~~
	Cd cov.	Φ10 x 0.025	Left		
Au	Bare	Φ10 x 0.025	Right	Au (99.99%)	Measuring thermal neutron
	Cd cov.	Φ10 x 0.025	Right		

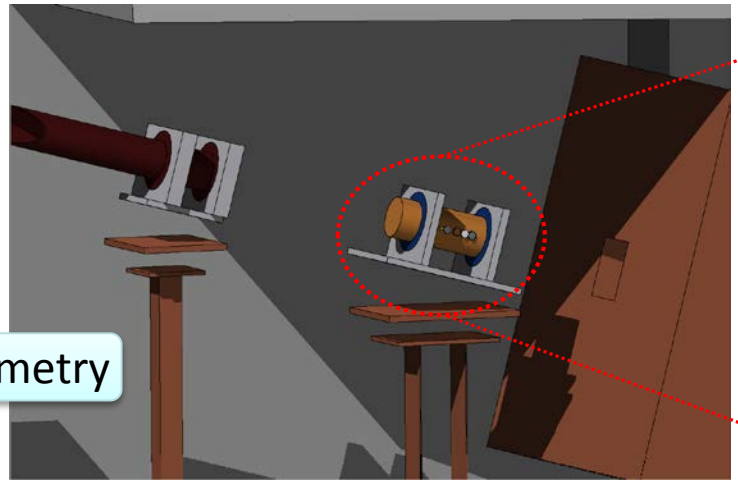
* Position when looking at the direction of e-beam travel

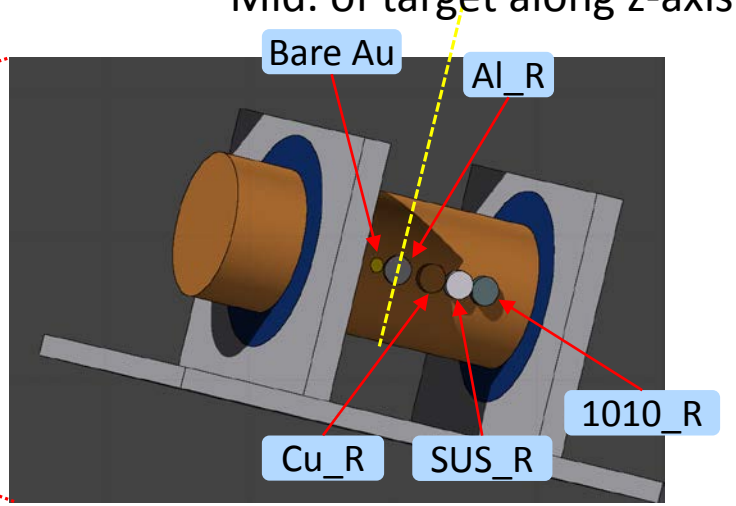
** Basically, including the FLUKA benchmarking

Used Samples

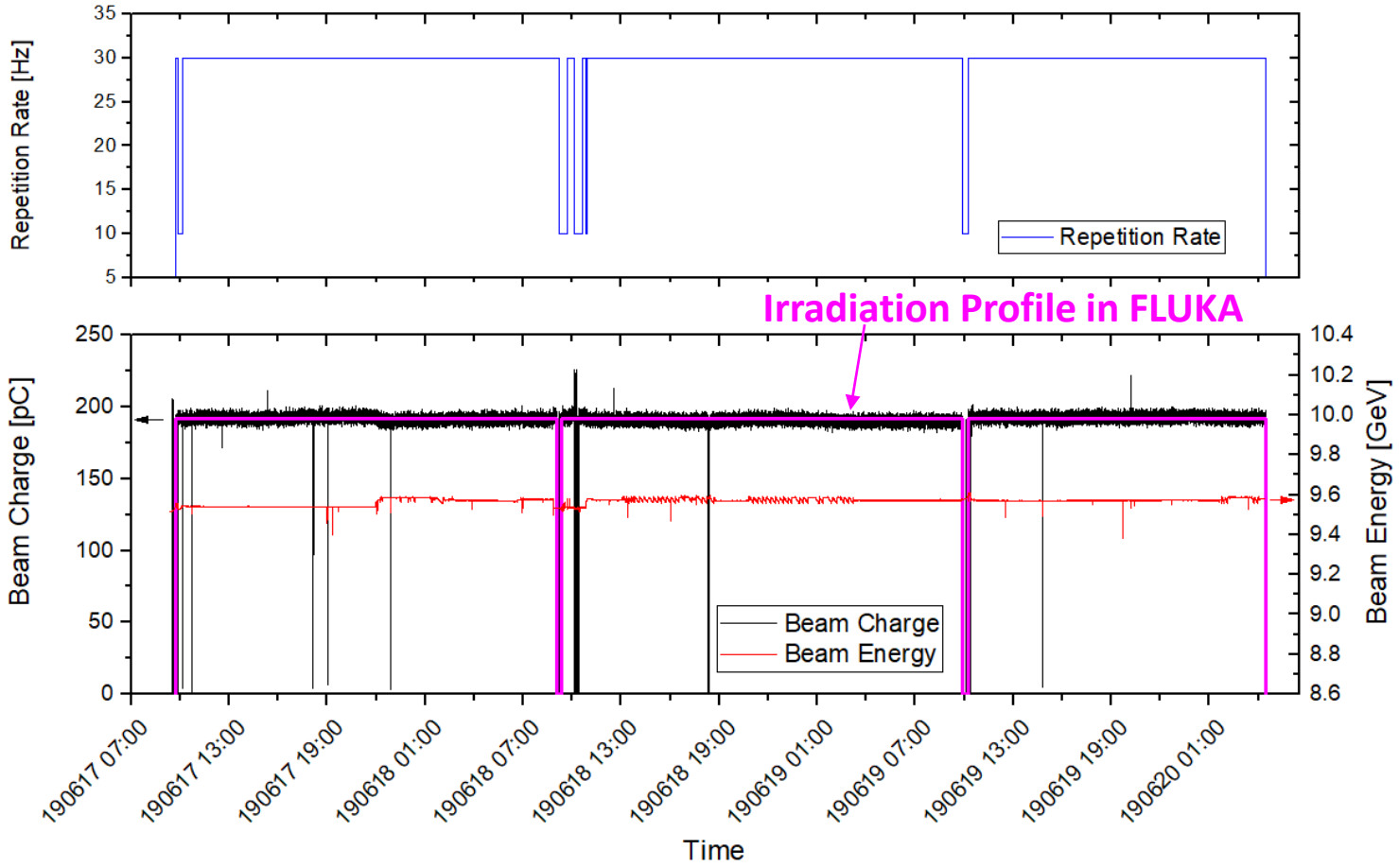








PAL-XFEL Operation

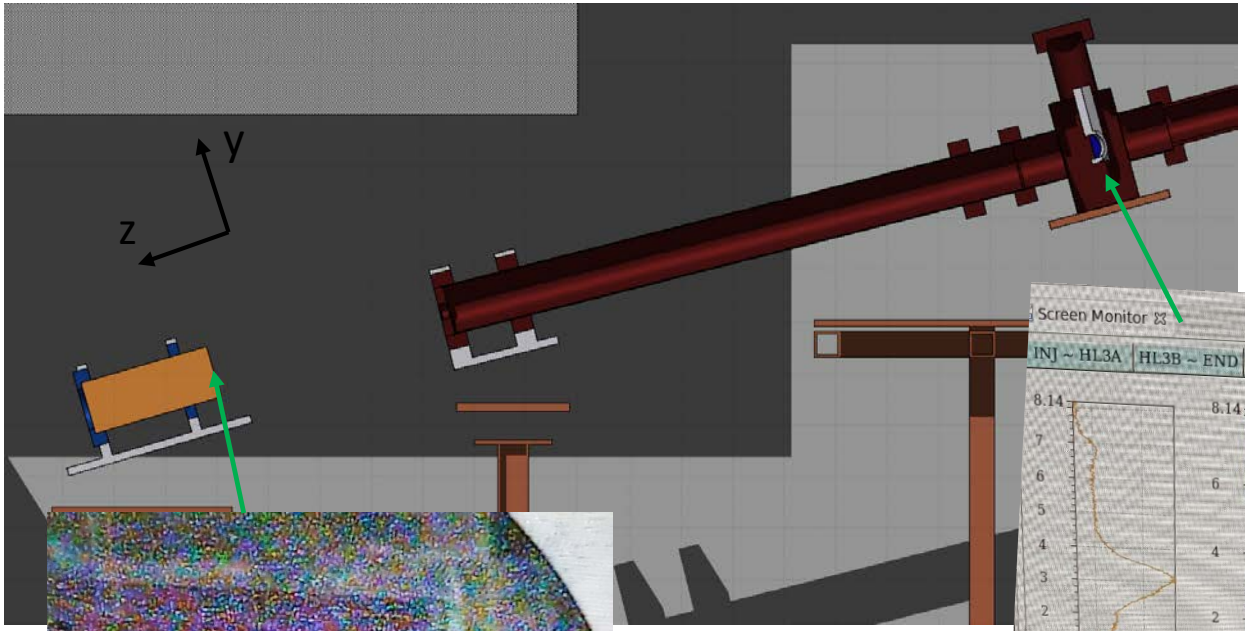


- Total irradiation time : 65 h 59 m 41 s (2.75 d)
- Mean beam charge : **191.8 pC**
- Mean beam energy : **9.6 GeV**
- Repetition Rate : **30 Hz**

Mean beam power : 55 W

Electron Beam Position

< Electron Beam Position in Screens >



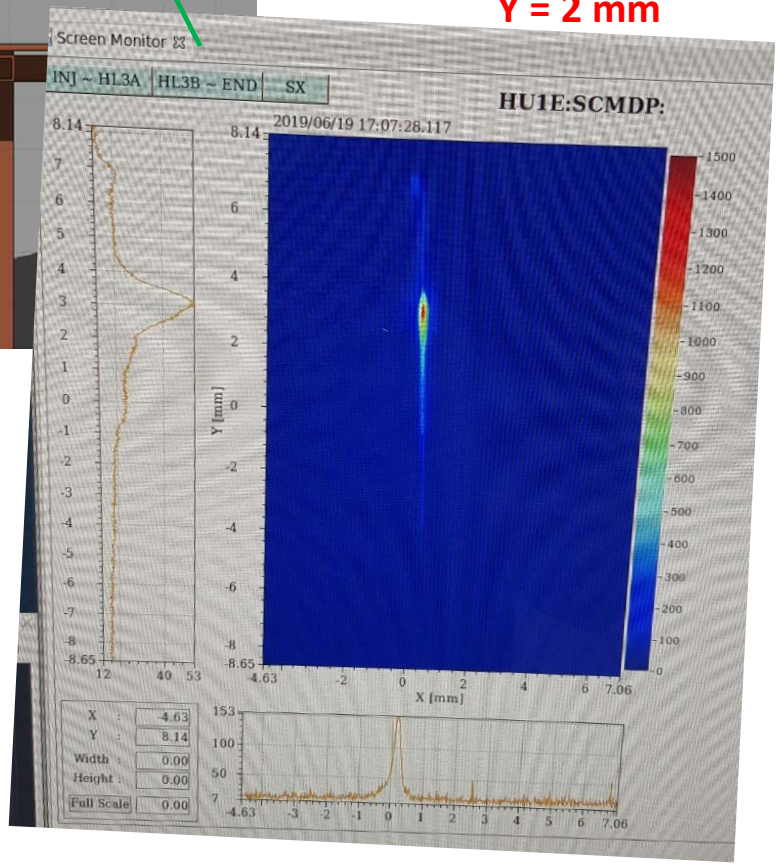
Screen dimension : 50 x 50 mm

y
x

Hotspot
X = - 5 mm
Y = - 10 mm
FWHM
X = ~ 3 mm
Y = ~ 8 mm

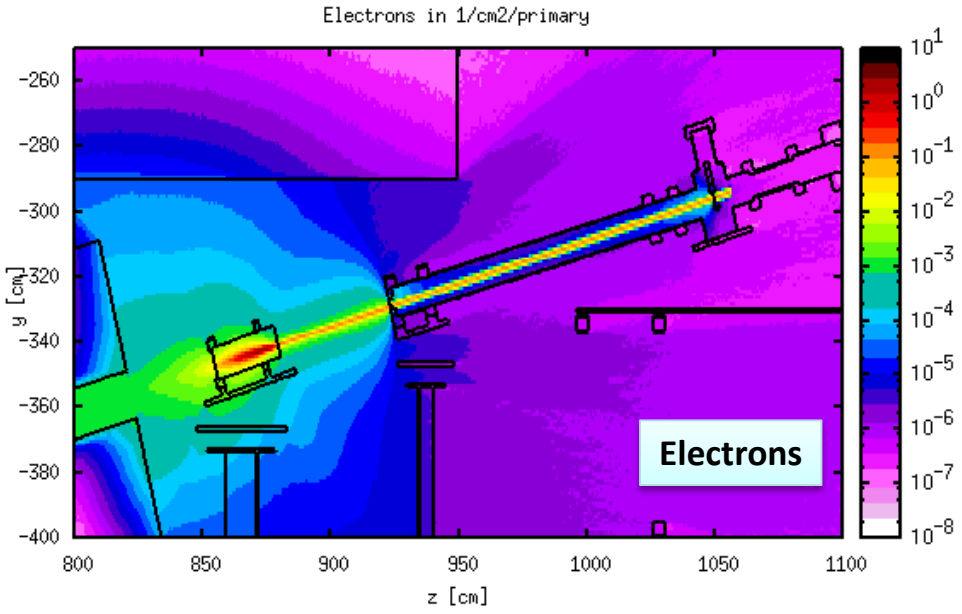
YAG(Ce) Screen monitor

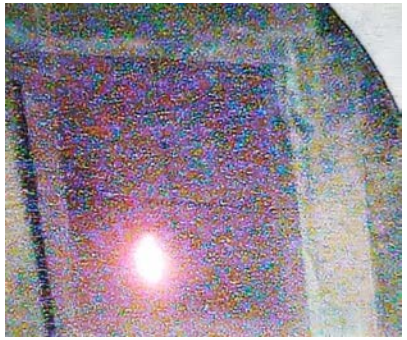
Hotspot
X = + 0.25 mm
Y = + 3 mm
FWHM
X = 0.25 mm
Y = 2 mm



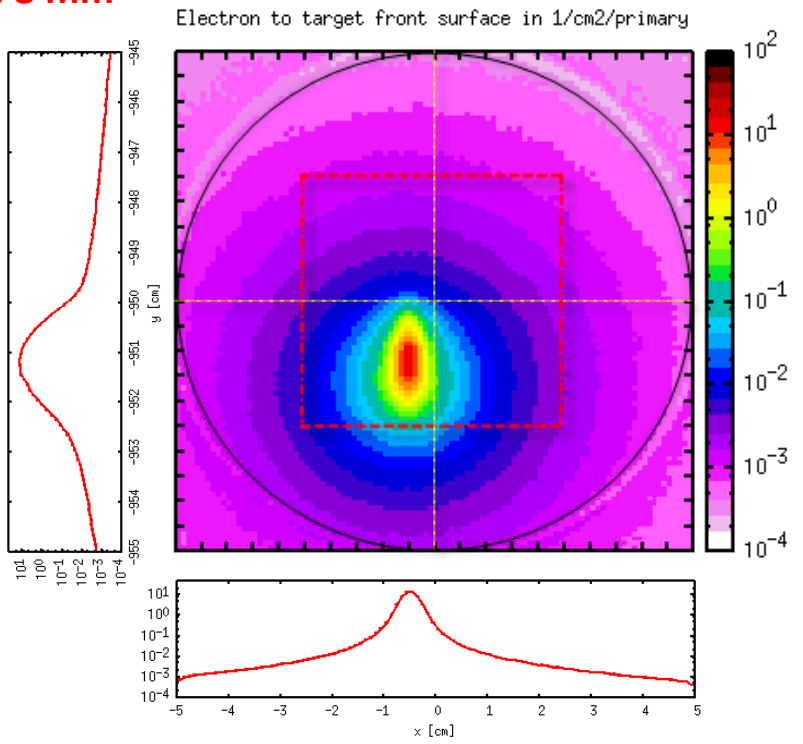
Electron Beam Position

< Electron Beam on Copper Target in FLUKA Calculation >





Hotspot_Y : - 12 mm
FWHM_Y : 8 mm



- Starting point : screen monitor upstream
  (Screen monitor was inserted during experiment period.)

- Used Gaussian beam profile
  FWHM_X : 3 mm FWHM_Y : 8 mm

Electrons on Cu target

Hotspot_X : - 5 mm
FWHM_X : 3 mm

Electron Beam Position

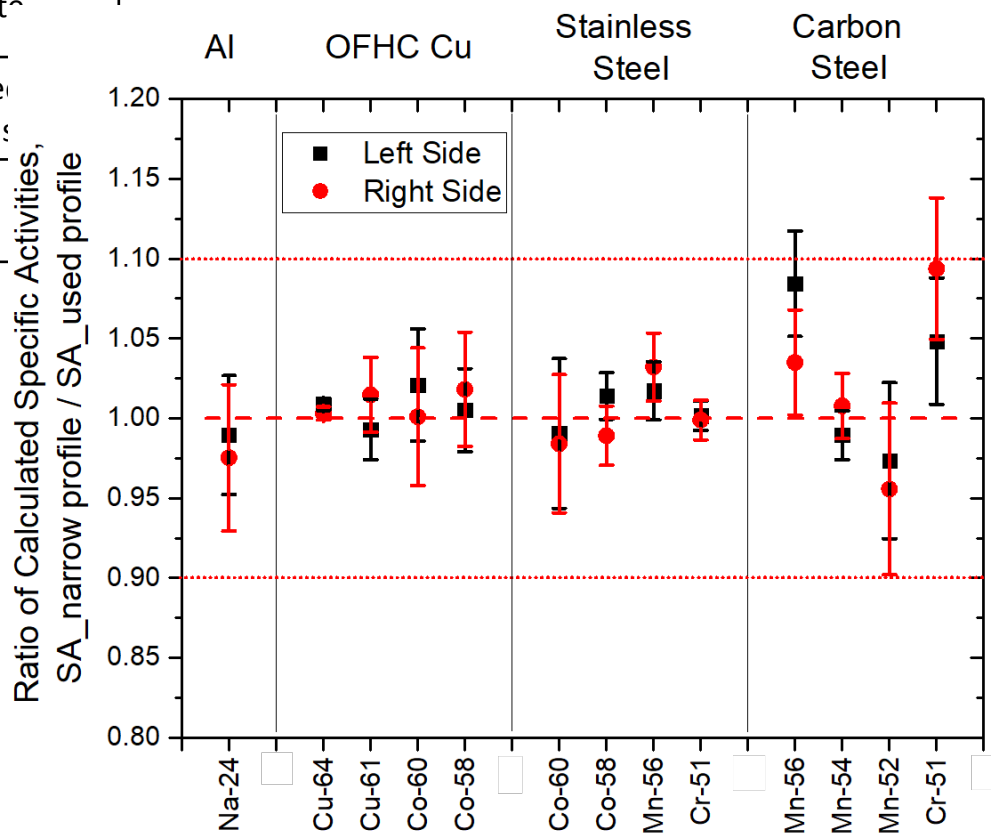
< Electron Beam on Copper Target in FLUKA Calculation >

- **Sensitivity of beam profile**

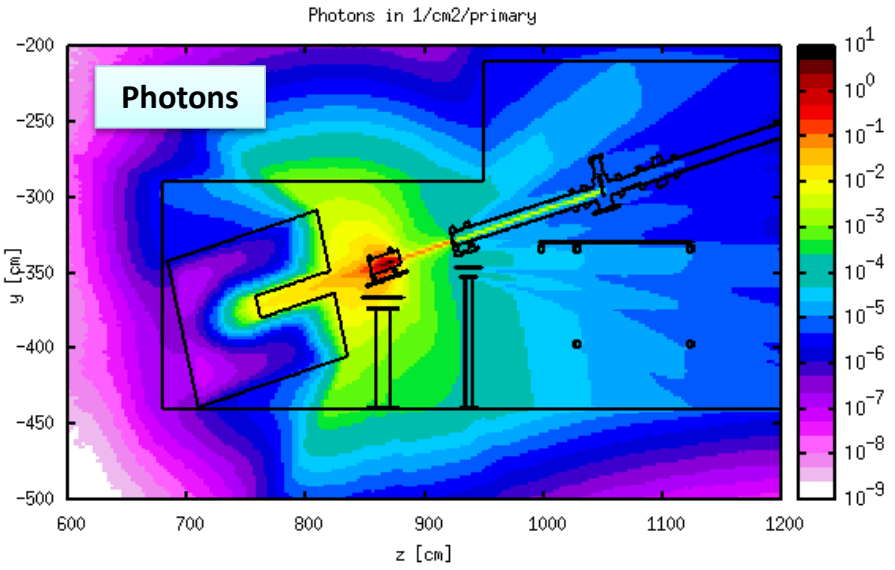
$\frac{SA_{Narrow\ profile}}{SA_{Used\ Profile}}$: Ratio of calculated specific activities of major radionuclides* between 'Narrow profile' & 'Used profile'

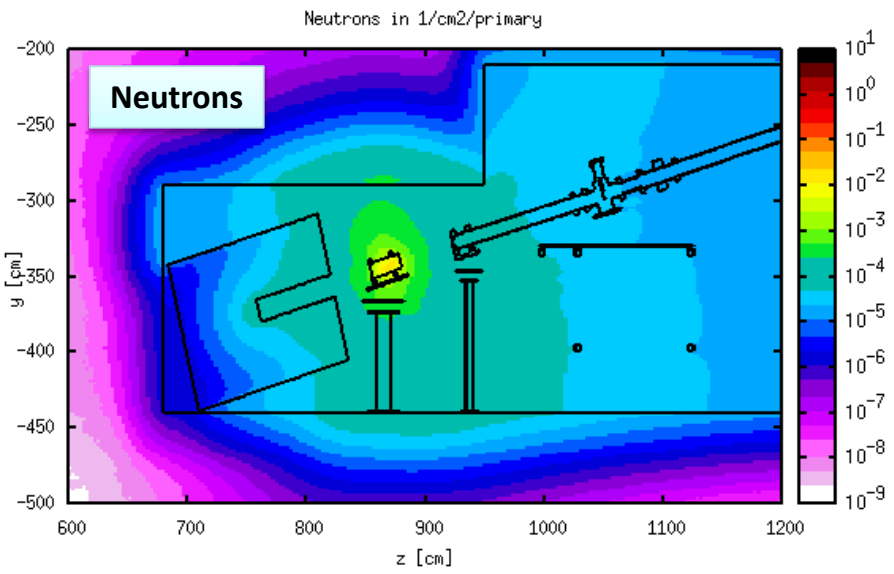
* Statistical error of both calculation < 5%

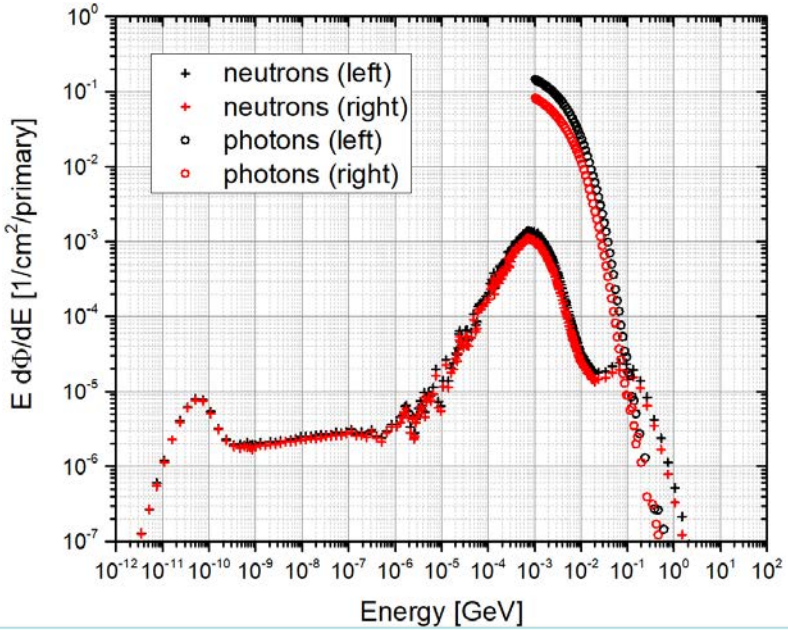
Case	FWHM_X (mm)	FWHM_Y (mm)	Not
Narrow Profile	0.25	2	Measure YAG(Ce)
Used Profile	3	8	



Stray Radiation Fields







Energy fluence spectra of neutrons & photons at lateral samples

Type	Energy	Φ_Left [1/cm²/e-]	Φ_Right [1/cm²/e-]	Φ_Left / Φ_Right
Photons	E > 5 MeV	4.2E-2	2.0E-2	2.1
Neutrons	Thermal	1.7E-5	1.6E-5	**1.1**
	E > 10 MeV	7.0E-5	5.6E-5	1.3

Measured specific activity ratio bet. left & right is expected to represent the value greater than 1.3 except (n,γ) reaction.

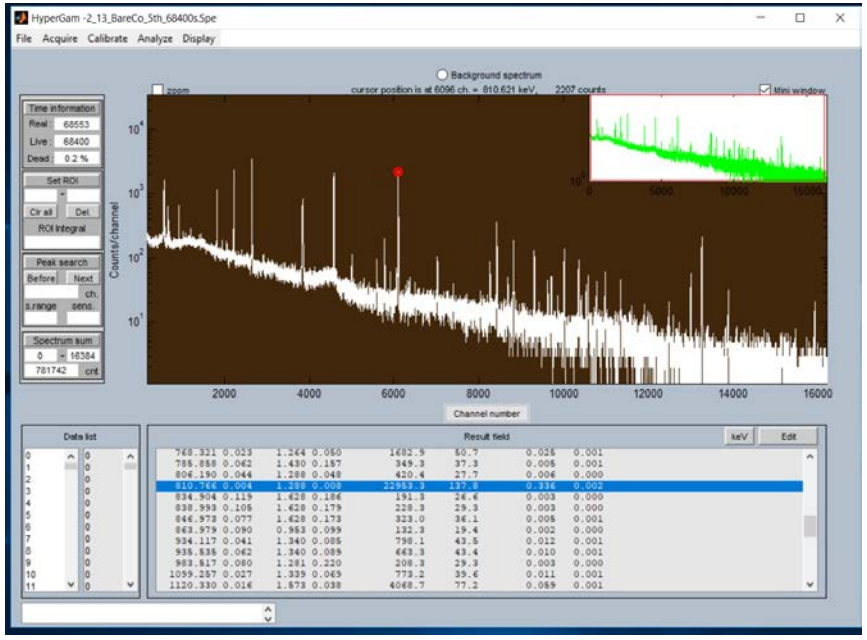
Gamma Spectroscopy

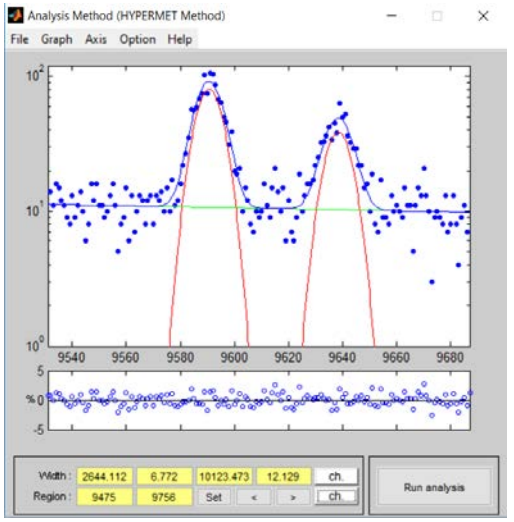
< Gamma Spectroscopy System >

- ORTEC **p-type HPGe detector (rel. eff. : 20%)** and DSPEC-50 (digital processing)
- ORTEC X-cooler-II for detector cooling
- Detector head in the lab-made lead-copper shield to reduce background gamma-rays
- ORTEC MAESTRO program to control the DSPEC-50

< Determination of Full Energy Absorption Peak Area >

- Using **HyperGam 3.0** developed at Dept. of Nucl. Eng. of Seoul Nat'l Univ. (**HYPERMET** algorithm)

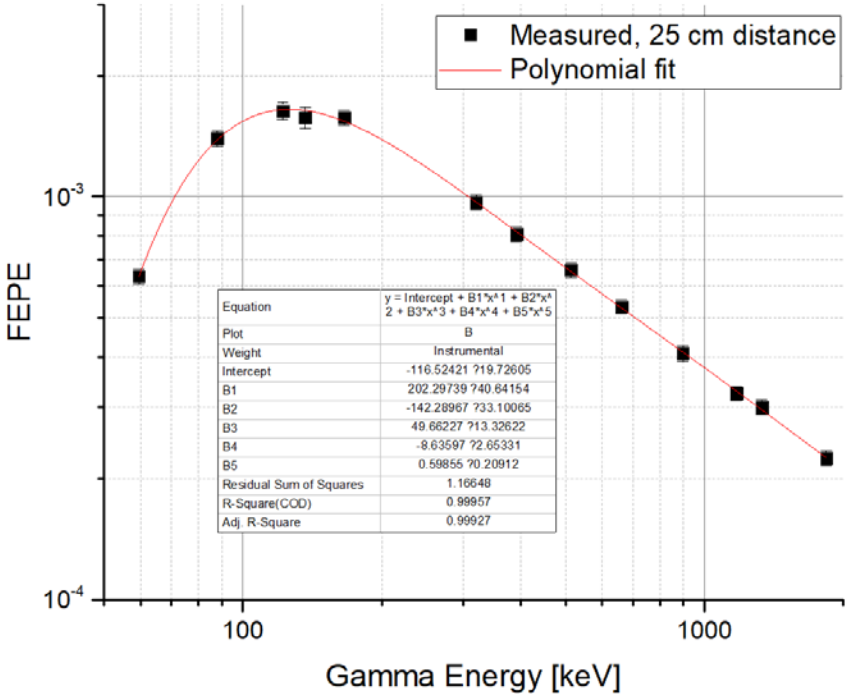


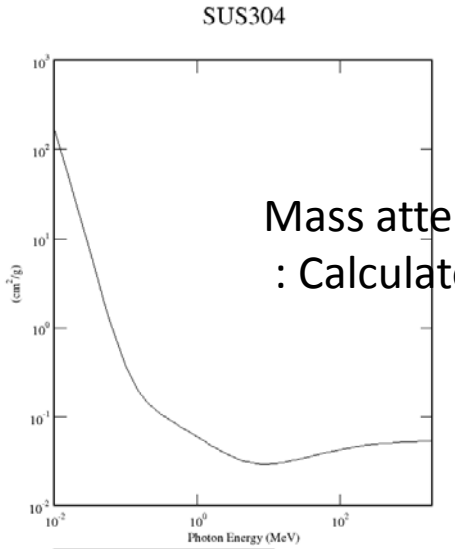


Gamma Spectroscopy

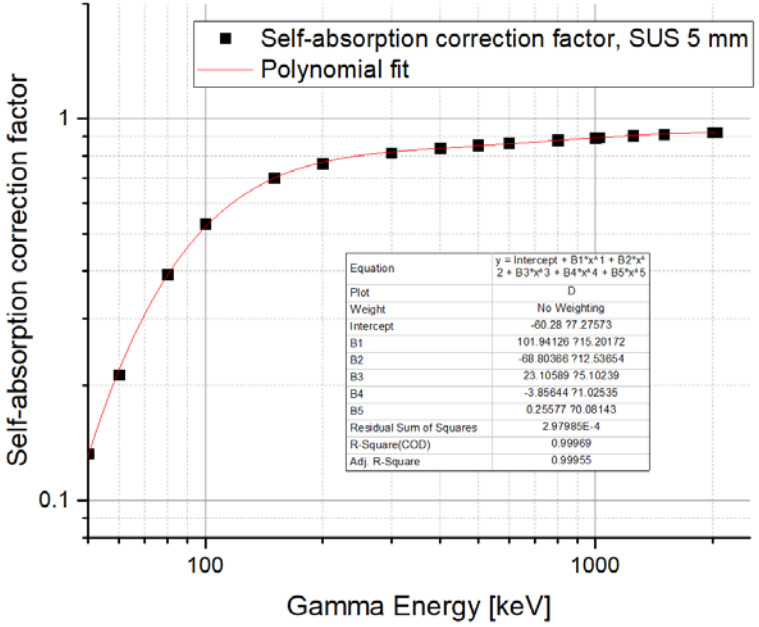
< Full Energy Peak Efficiency >

Using corrected measuring FEP efficiency
- Φ47 mm paper KRISS CRM (purchased in 2019)
- Solid angle correction by Tsoulfanidis' Eq.
  : Far enough distance, 25 cm (or 5 cm)
- Self-absorption correction in case of thick samples, i.e. OFHC Cu, SUS304 and AISI1010





Mass attenuation coeff.
: Calculated using XCOM



Results of Carbon Steel

< Lateral carbon steel, AISI 1010 >

- Elements : Fe (99.2482%)

- Measured radioisotope

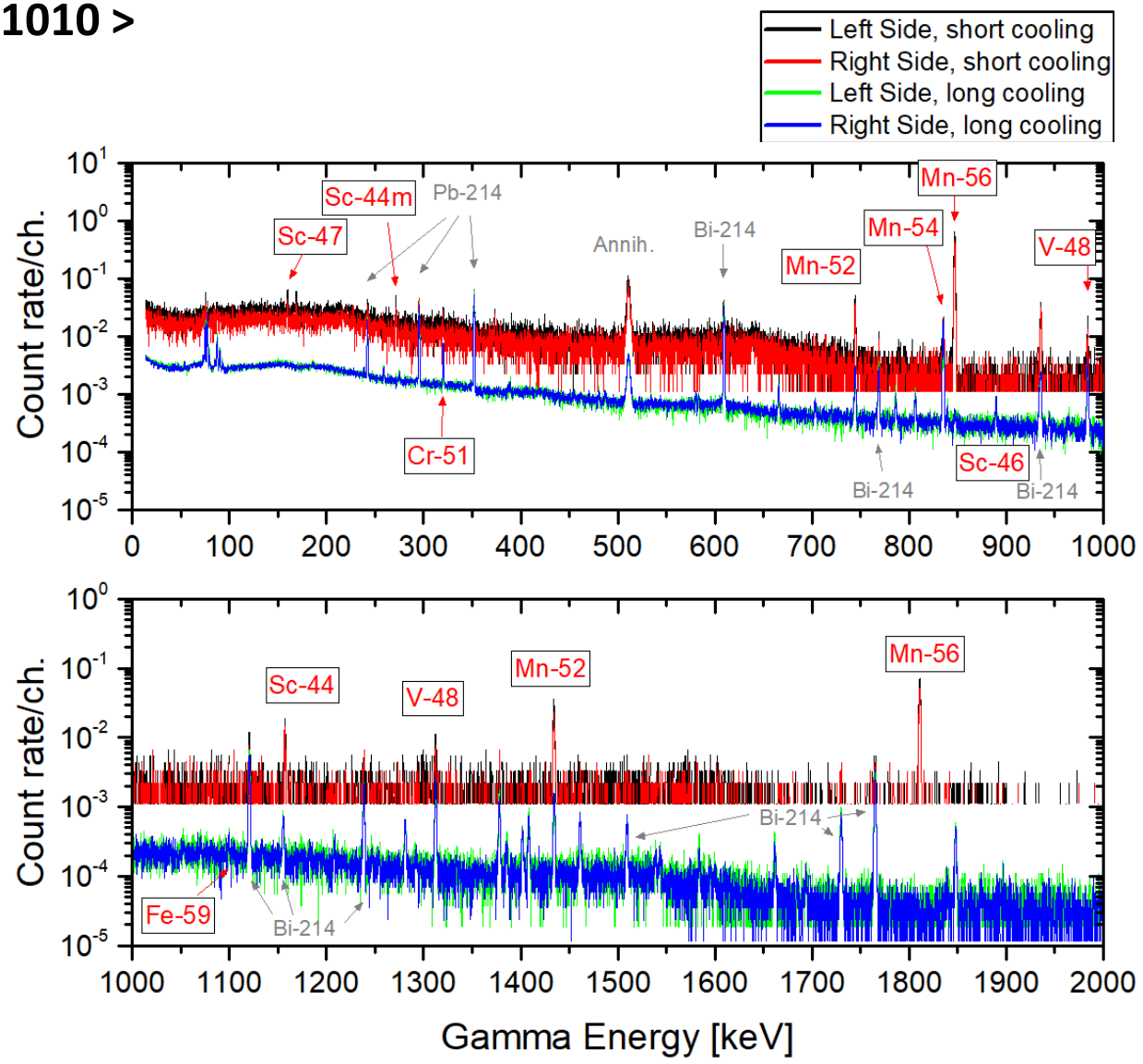
RI	Half-life	Production
Fe-59	44.5d	Fe-58(n,γ)
Mn-56	2.57h	Fe-57(γ,p)
Mn-54	312.2d	Fe-56(γ,pn)
Mn-52	5.59d	Fe-54(γ,pn)

+

Spallation product

: Sc-44, Sc-44m, Sc-46,

Sc-47, V-48, Cr-51



Results of Carbon Steel

< Lateral carbon steel, AISI 1010 >

Radio-isotope	Half-life	Measurement [Bq/g] @ irradiation end		Ratio, M_Left / M_Right
		Left	Right	
Sc-44	3.9h	57.5 (15%)	44.4 (15%)	1.3
Sc-44m	58.6h	21.6 (11%)	14.9 (13%)	1.4
Sc-46	83.8d	1.82 (5%)	1.27 (11%)	1.4
Sc-47	3.3d	18.1 (5%)	13.4 (8%)	1.3
V-48	16.0d	22.7 (2%)	17.8 (2%)	1.3
Cr-51	27.7d	82.3 (2%)	60.3 (4%)	1.4
Mn-52	5.6d	90.0 (1%)	71.3 (2%)	1.3
Mn-54	312.2d	42.5 (1%)	26.6 (1%)	1.6
Mn-56	2.6h	3029. (1%)	2195. (1%)	1.4
Fe-59	44.5d	**0.94 (21%)**	**0.98 (25%)**	**1.0**

⇒ **Fe-58(n,γ) reaction**

Benchmarking Results: Carbon Steel

< Lateral carbon steel, AISI 1010 >

Radio-isotope	Half-life	Measurement [Bq/g] @ irradiation end		FLUKA [Bq/g] @ irradiation end		Ratio, FLUKA/M		Ratio, FLUKA/M @ CERN-PAL
		Left	Right	Left	Right	Left	Right	
Sc-44	3.9h	57.5 (15%)	44.4 (15%)	**53.7 (9%)**	**40.5 (10%)**	**0.9**	**0.9**	**1.1**
Sc-44m	58.6h	21.6 (11%)	14.9 (13%)	**19.3 (9%)**	**14.6 (10%)**	**0.9**	**1.0**	**0.62**
Sc-46	83.8d	1.82 (5%)	1.27 (11%)	1.40 (9%)	1.18 (10%)	**0.8**	**0.9**	**0.84**
Sc-47	3.3d	18.1 (5%)	13.4 (8%)	12.5(13%)	7.6 (15%)	0.8	0.7	NA
V-48	16.0d	22.7 (2%)	17.8 (2%)	27.8 (5%)	20.5 (5%)	**1.2**	**1.2**	**1.2**
Cr-51	27.7d	82.3 (2%)	60.3 (4%)	75.4 (2%)	54.8 (3%)	**0.9**	**0.9**	**1.1**
Mn-52	5.6d	90.0 (1%)	71.3 (2%)	97.6 (3%)	69.9 (3%)	**1.1**	**1.0**	**1.1**
Mn-54	312.2d	42.5 (1%)	26.6 (1%)	27.6 (0.8%)	17.9 (1%)	**0.7**	**0.7**	**0.61**
Mn-56	2.6h	3029. (1%)	2195. (1%)	1161. (2%)	998. (2%)	0.4	0.5	NA
Fe-59	44.5d	**0.94 (21%)**	**0.98 (25%)**	**1.24 (5%)**	**1.10 (5%)**	**1.3**	**1.1**	NA

* From Table 7 (for **lateral stainless steel sample**) in M. Brugger et al., Progress in Nuclear Science and Technology 4, 363 (2014)

$\frac{^{44m}Sc}{^{44}Sc}$ FLUKA 2011.2.4 (Released in Mar. 2011) for CERN-PAL study : **~ 1**

FLUKA 2011.2x for this study : **0.36**

Results of Stainless Steel

< Lateral stainless steel, 304 >

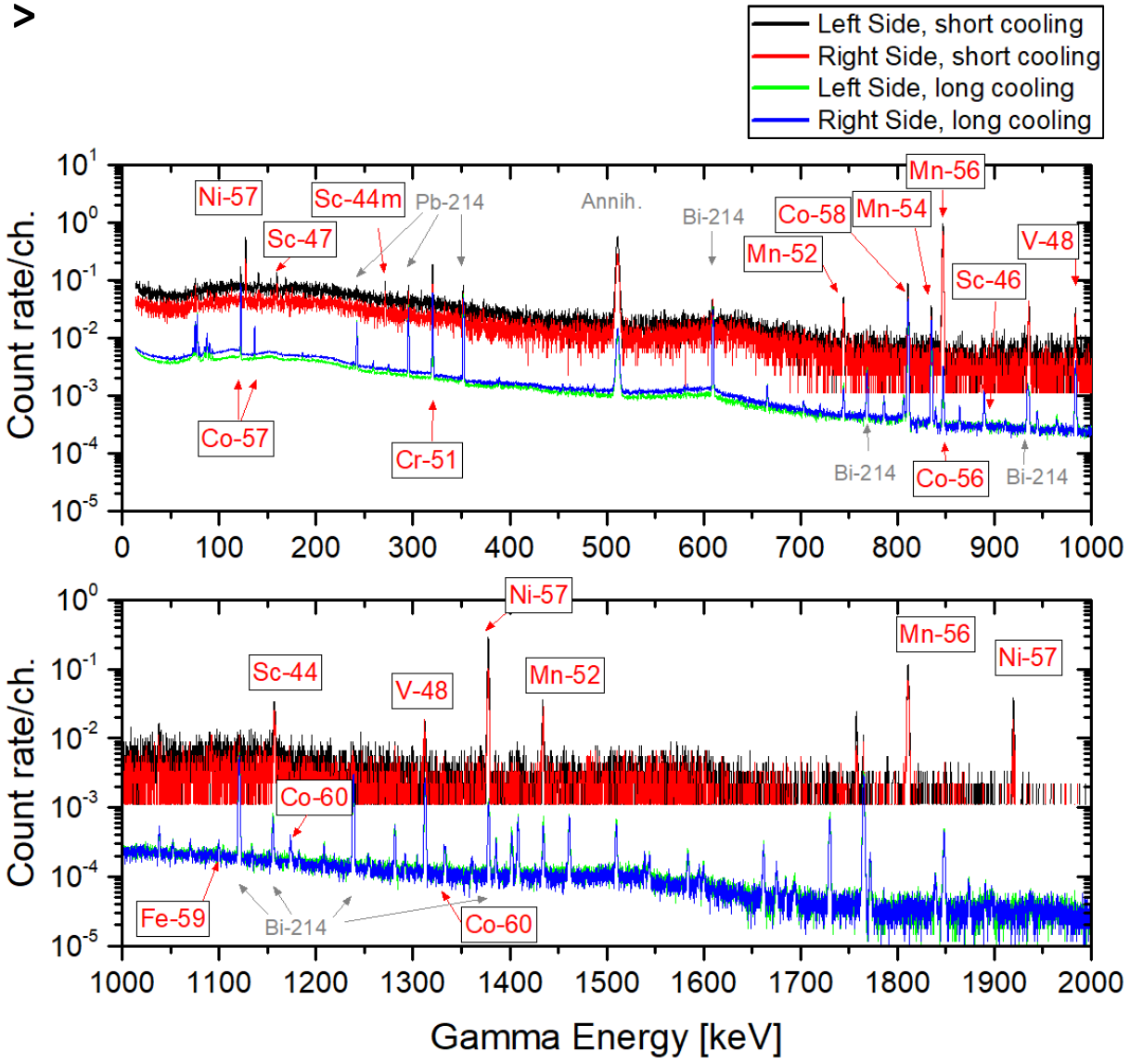
- Elements : Fe (68.027%),
  Cr (19.2%),
  Ni (9.6%),
  Co (0.190%)

- Measured radioisotope

Isotopes of carbon steel

+

RI	Half-life	Production
Co-56	77.2d	Ni-58(γ,pn)
Co-57	271.7d	Ni-58(γ,p), Co-59(γ,2n), Daughter of Ni-57
Co-58	70.9d	Ni-60(γ,pn), Co-59(γ,n)
Co-60	5.27a	Ni-61(γ,p) Co-59(n,γ)
Ni-57	35.6h	Ni-58(γ,n)



Results of Stainless Steel

< Lateral stainless steel, 304 >

Radio-isotope	Half-life	Measurement [Bq/g] @ irradiation end		Ratio, M_Left / M_Right
		Left	Right	
Sc-44	3.9h	116.4 (10%)	86.9 (11%)	1.3
Sc-44m	58.6h	33.9 (10%)	23.7 (13%)	1.4
Sc-46	83.8d	3.45 (2%)	2.59 (3%)	1.3
Sc-47	3.3d	36.7 (13%)	26.8 (11%)	1.4
V-48	16.0d	39.2 (1%)	29.0 (1%)	1.3
Cr-51	27.7d	955. (1%)	449. (1%)	2.1
Mn-52	5.6d	95.2 (1%)	74.0 (2%)	1.3
Mn-54	312.2d	48.2 (1%)	29.0 (1%)	1.7
Mn-56	2.6h	3821. (1%)	2951. (1%)	1.3
Fe-59	44.5d	**1.02 (8%)**	**0.88 (9%)**	**1.2**
Co-56	77.2d	8.62 (1%)	4.67 (2%)	1.8
Co-57	271.7d	46.7 (1%)	20.4 (1%)	2.3
Co-58	70.9d	138. (1%)	94.6 (1%)	1.5
Co-60	5.27a	**0.74 (5%)**	**0.62 (6%)**	**1.2**
Ni-57	35.6h	1317. (3%)	549. (4%)	2.4

⇒ **Fe-58(n,γ) reaction**

Benchmarking Results: Stainless Steel

< Lateral stainless steel, 304 >

Radio-isotope	Half-life	Measurement [Bq/g] @ irradiation end		FLUKA [Bq/g] @ irradiation end		Ratio, FLUKA/M		Ratio, FLUKA/M @ CERN-PAL*
		Left	Right	Left	Right	Left	Right	
Sc-44	3.9h	116.4 (10%)	86.9 (11%)	**82.2 (7%)**	**76.4 (7%)**	**0.7**	**0.9**	**1.1**
Sc-44m	58.6h	33.9 (10%)	23.7 (13%)	**29.6 (7%)**	**27.5 (7%)**	**0.9**	**1.2**	**0.62**
Sc-46	83.8d	3.45 (2%)	2.59 (3%)	2.51 (7%)	1.85 (8%)	**0.7**	**0.7**	**0.84**
Sc-47	3.3d	36.7 (13%)	26.8 (11%)	30.3 (8%)	17.3 (12%)	0.8	0.6	NA
V-48	16.0d	39.2 (1%)	29.0 (1%)	50.5 (3%)	36.3 (4%)	**1.3**	**1.3**	**1.2**
Cr-51	27.7d	955. (1%)	449. (1%)	1266. (0.6%)	614. (0.8%)	**1.3**	**1.4**	**1.1**
Mn-52	5.6d	95.2 (1%)	74.0 (2%)	85.6 (3%)	59.4 (3%)	**0.9**	**0.8**	**1.1**
Mn-54	312.2d	48.2 (1%)	29.0 (1%)	32.9 (1%)	20.0 (1%)	**0.7**	**0.7**	**0.61**
Mn-56	2.6h	3821. (1%)	2951. (1%)	2391. (1%)	2112. (1%)	0.6	0.7	NA
Fe-59	44.5d	**1.02 (8%)**	**0.88 (9%)**	**1.10 (6%)**	**1.03 (7%)**	**1.1**	**1.2**	NA
Co-56	77.2d	8.62 (1%)	4.67 (2%)	8.61 (4%)	5.33 (5%)	**1.0**	**1.1**	**1.1**
Co-57	271.7d	46.7 (1%)	20.4 (1%)	46.8 (1%)	22.8 (1%)	**1.0**	**1.1**	**1.0**
Co-58	70.9d	138. (1%)	94.6 (1%)	68.0 (1%)	48.3 (1%)	0.5	0.5	NA
Co-60	5.27a	**0.74 (5%)**	**0.62 (6%)**	**0.50 (2%)**	**0.48 (2%)**	**0.7**	**0.8**	**0.39**
Ni-57	35.6h	1317. (3%)	549. (4%)	629. (2%)	309. (3%)	**0.5**	**0.6**	**0.53**

Gamma Spectrum - Cu

< Lateral OFHC Cu >

- Elements : Cu (~ 99%)

- Measured radioisotope

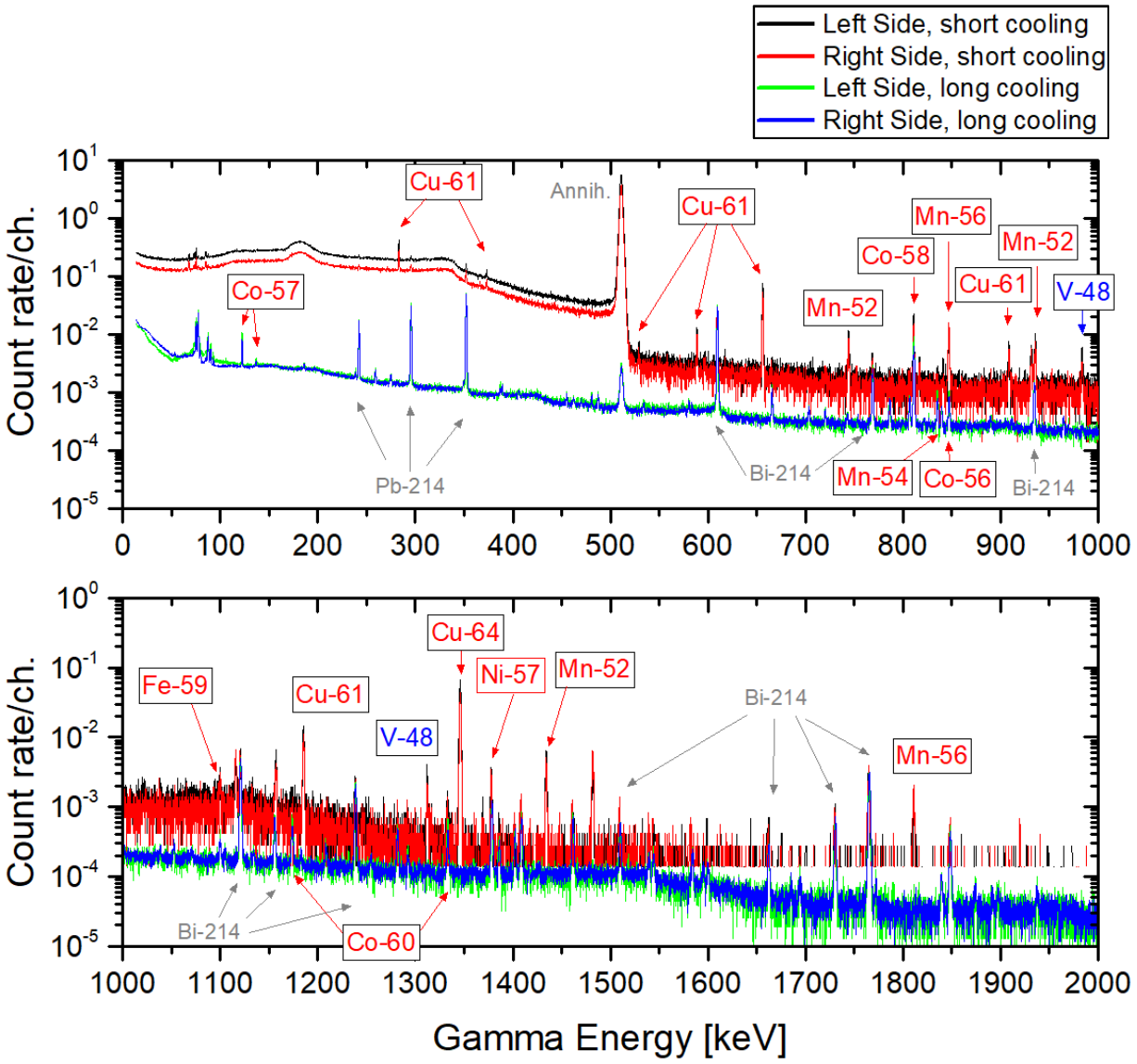
RI	Half-life	Production
Cu-64	12.7h	Cu-65(γ,n) Cu-63(n,γ)
Cu-61	3.32h	Cu-63(γ,2n)
Co-60	5.27a	Cu-63(γ,2pn)

+

Sc-46, Sc-47, Cr-51, Mn-52,

Mn-54, Mn-56, Co-56, Co-57,

Ni-57, Co-58, Fe-59



Results of Cu

< Lateral OFHC Cu >

Radio-isotope	Half-life	Measurement [Bq/g] @ irradiation end		Ratio, M_Left / M_Right
		Left	Right	
Sc-46	83.8d	0.63 (22%)	0.42 (28%)	1.5
Sc-47	3.3d	7.01 (8%)	4.09 (12%)	1.7
Cr-51	27.7d	10.3 (13%)	7.98 (12%)	1.3
Mn-52	5.6d	21.2 (1%)	14.2 (2%)	1.5
Mn-54	312.2d	1.96 (3%)	1.35 (4%)	1.5
Mn-56	2.6h	114. (5%)	82.5 (4%)	1.4
Fe-59	44.5d	4.36 (5%)	2.54 (11%)	1.7
Co-56	77.2d	3.91 (4%)	2.99 (3%)	1.3
Co-57	271.7d	5.40 (2%)	3.86 (2%)	1.4
Co-58	70.9d	41.3 (1%)	29.1 (1%)	1.4
Co-60	5.27a	1.85 (3%)	1.29 (3%)	1.4
Ni-57	35.6h	13.7 (6%)	12.4 (7%)	1.1
Cu-61	3.32h	3922. (2%)	1831. (2%)	2.1
Cu-64	12.7h	65802. (1%)	38030. (2%)	1.7

Benchmarking Results - Cu

< Lateral OFHC Cu >

Radio-isotope	Half-life	Measurement [Bq/g] @ irradiation end		FLUKA [Bq/g] @ irradiation end		Ratio, FLUKA/M		Ratio, FLUKA/M @ CERN-PAL*
		Left	Right	Left	Right	Left	Right	
Sc-46	83.8d	0.63 (22%)	0.42 (28%)	0.55 (14%)	0.46 (15%)	**0.87**	**1.09**	**0.77-0.93**
Sc-47	3.3d	7.01 (8%)	4.09 (12%)	4.45 (20%)	2.70 (25%)	0.66	0.66	0.8
Cr-51	27.7d	10.3 (13%)	7.98 (12%)	11.5 (5%)	7.1 (6%)	1.12	**0.89**	**0.69-0.93**
Mn-52	5.6d	21.2 (1%)	14.2 (2%)	15.0 (7%)	8.6 (9%)	**0.74**	**0.62**	**0.61-0.79**
Mn-54	312.2d	1.96 (3%)	1.35 (4%)	1.67 (4%)	1.38 (4%)	**0.85**	1.03	**0.62-0.89**
Mn-56	2.6h	114. (5%)	82.5 (4%)	84.4 (7%)	55.1 (8%)	0.74	0.67	NA
Fe-59	44.5d	4.36 (5%)	2.54 (11%)	1.89 (10%)	1.10 (12%)	**0.43**	**0.43**	**0.32-0.45**
Co-56	77.2d	3.91 (4%)	2.99 (3%)	4.91 (5%)	3.47 (5%)	**1.26**	**1.16**	**1.1-1.5**
Co-57	271.7d	5.40 (2%)	3.86 (2%)	5.77 (2%)	4.05 (3%)	**1.07**	**1.05**	**0.72-1.1**
Co-58	70.9d	41.3 (1%)	29.1 (1%)	44.3 (1%)	27.1 (2%)	**1.07**	**0.93**	**0.69-1.3**
Co-60	5.27a	1.85 (3%)	1.29 (3%)	0.76 (2%)	0.58 (2%)	**0.41**	**0.45**	**0.38-0.45**
Ni-57	35.6h	13.7 (6%)	12.4 (7%)	14.1 (15%)	13.4 (16%)	1.03	1.08	NA
Cu-61	3.32h	3922. (2%)	1831. (2%)	5230. (1%)	2476. (1%)	1.33	1.35	NA
Cu-64	12.7h	65802. (1%)	38030. (2%)	68113.(0.2%)	43319.(0.3%)	1.04	1.14	NA

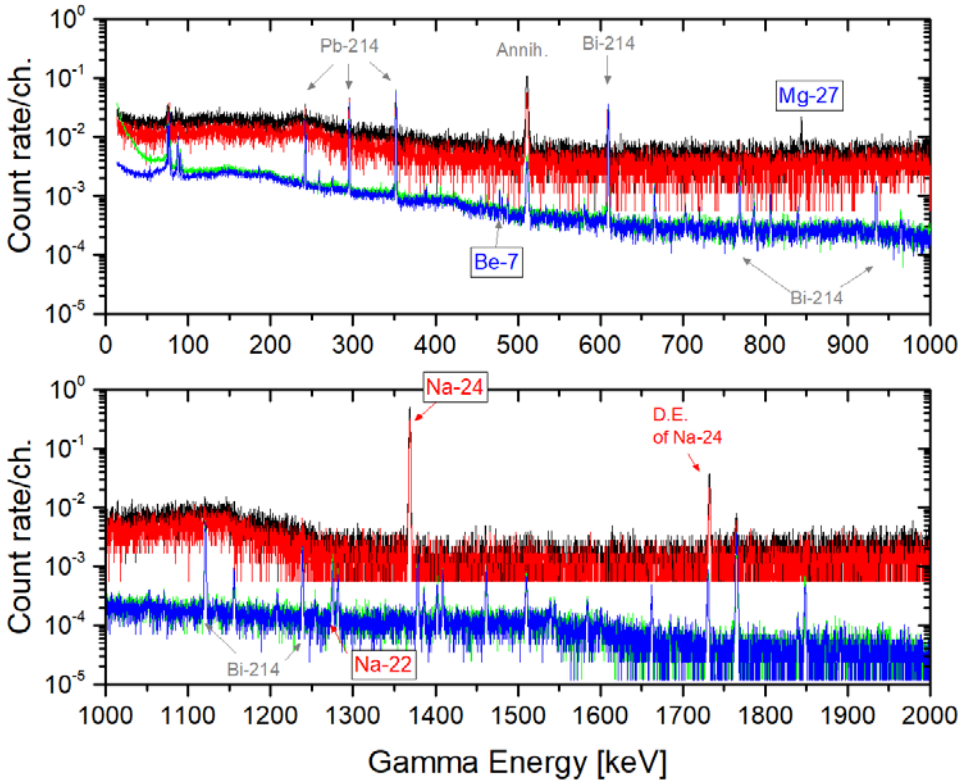
* From Table 6 (for **Cu samples in lateral side and top pos.**) in M. Brugger et al., Progress in Nuclear Science and Technology 4, 363 (2014)

Benchmarking Results - Al

< Aluminum, Pure >

- **Elements : Al (99.99%)**
- **Measured radioisotope**

RI	Half-life	Production
Na-22	2.602 a	Al-27(γ,3n2p)
Na-24	14.99 h	Al-27(γ,1n2p) Al-27(n,α)



Ratio, M_Left /M_Right : 1.5 for Na-22 & Na-24

Radio-isotope	Half-life	Measurement [Bq/g] @ irradiation end		FLUKA [Bq/g] @ irradiation end		Ratio, FLUKA/M		Ratio, FLUKA/M @CERN-PAL*
		Left	Right	Left	Right	Left	Right	
Na-22	2.602a	2.91 (3%)	1.91 (4%)	2.03 (6%)	1.43 (7%)	**0.70**	**0.75**	**0.62-0.81**
Na-24	14.99h	14073. (1%)	9328. (1%)	4555. (2%)	3231. (2%)	0.33	0.35	NA

* From Table 5 (for **Al samples in lateral side and top pos.**) in M. Brugger et al., Progress in Nuclear Science and Technology 4, 363 (2014)

Conclusions

- Radioisotopes produced in **Steels, OFHC Cu and Al** samples in the stray radiation field generated by **9.6 GeV electron** beam of PAL-XFEL were measured. **Specific activities of well-known radioisotopes** were determined well by the **gamma-spectroscopy**.
- The setup of experiment was simulated in detail using **Monte Carlo code, FLUKA**. The measured data was compared with simulated results to **benchmark** the FLUKA code, and the **benchmark results showed good agreement** for many radioisotopes.
- Even though the electron beam energy is 9.6 GeV, the **ratio** between the FLUKA simulation and measurement was **very similar** with **previous ratio** by **2.5 GeV electron** beam of PLS-II.
- Additional activation studies have been planned such as **adding downstream samples** and **other metal or environmental samples**.
- These results will be used to determine the 'Proxy' radioisotope instead of the 'Hard-to-Measure' radioisotope such as H-3, Fe-55 which emits only low-energy X-rays or beta rays for the **clearance of used metal properties of PAL**.

Thank you for your attention !!

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