HSE

Radiation Protection

Radiological Characterization for the Disposal of the LHC Beam Dumping System at CERN

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Outline

- Introduction: LHC Beam dump and Radioactive Waste Disposal pathways
- Materials and Methods
  - ✓Radiological Characterization methodology
  - ✓ETM estimation and Non-Destructive Assay technique
  - ✓Activity distribution estimation using Monte Carlo (FLUKA.CERN and FCC)
- Discussion
  - ✓ Results comparing uniform and actual activity distributions
- Conclusions and Take-home messages

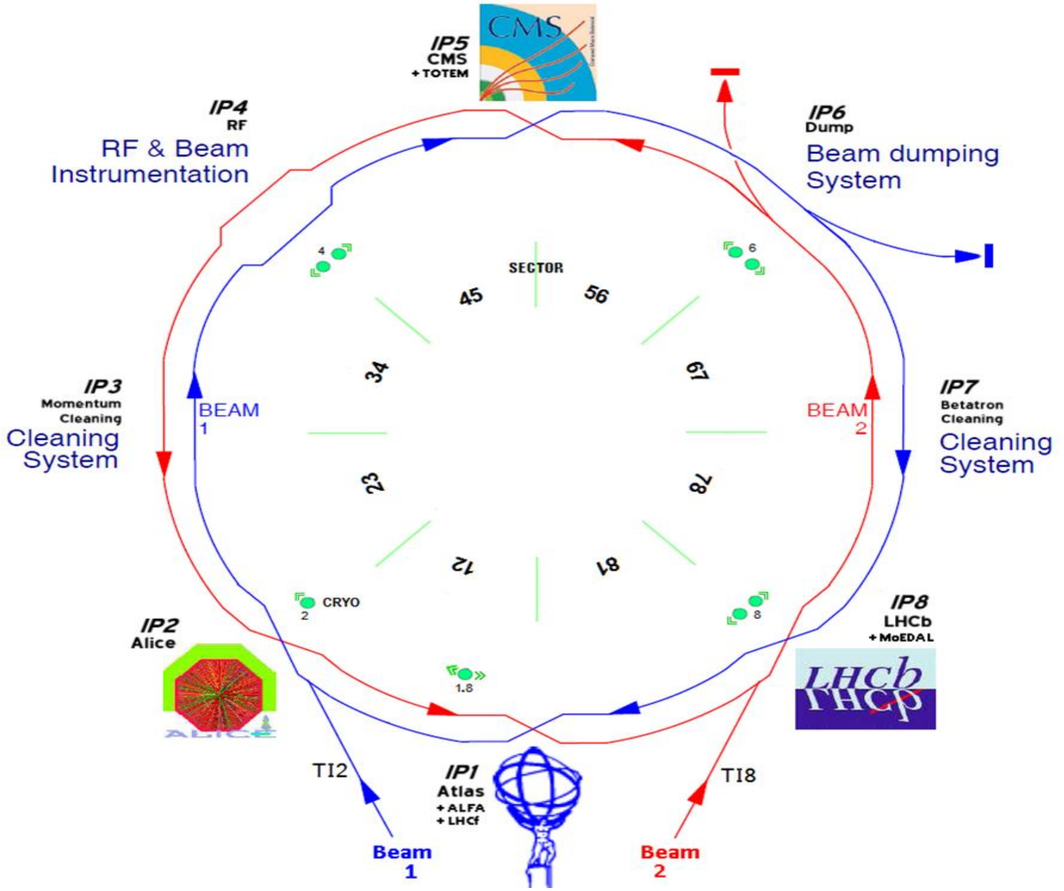
CERN Accelerator complex

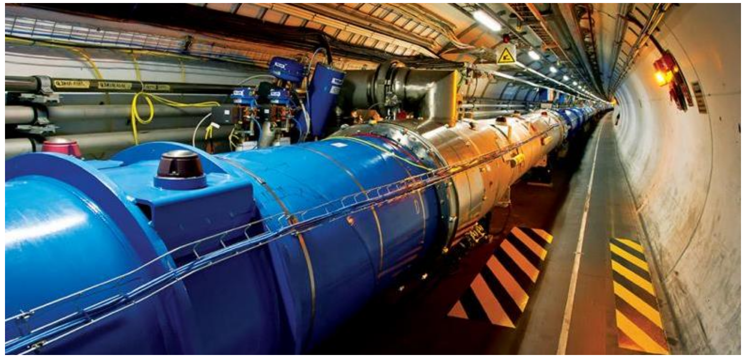
About **50 km of accelerator infrastructure and over 160 physics experiments**, all areas classified as Radiation Areas

The operation of CERN accelerator complex produces radioactive materials either **via activation or contamination mechanisms**

Radioactive materials with no future use are declared as radioactive waste

Radioactive Waste Treatment Centre and radioactive waste interim storage facility

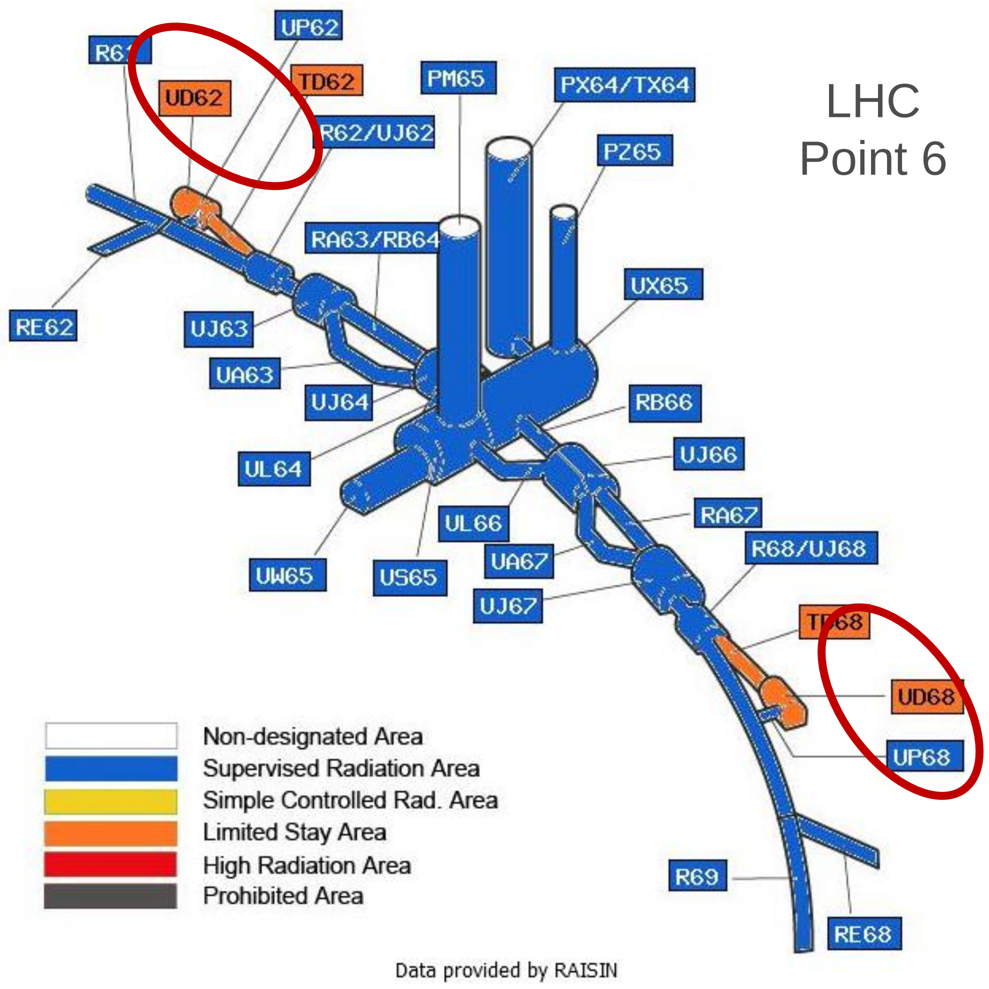




The Large Hadron Collider

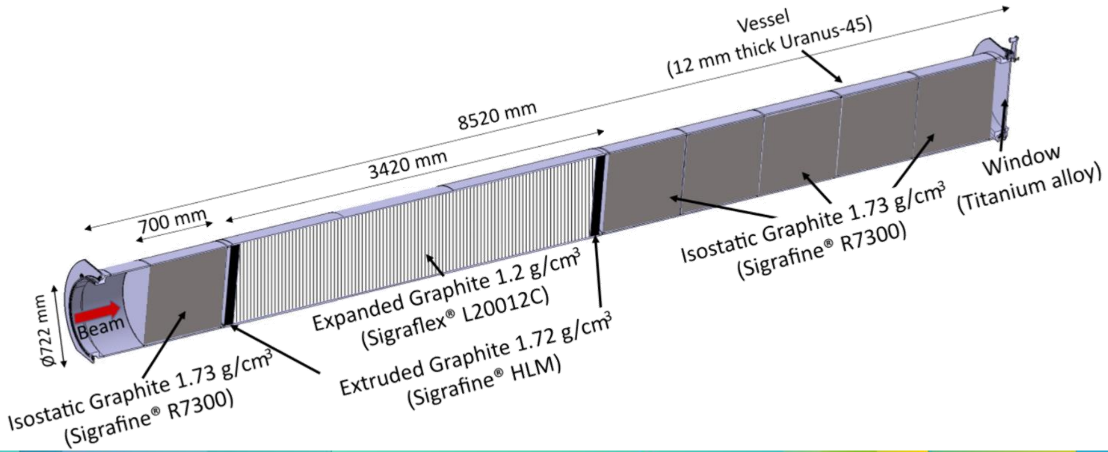
- **27 km** circumference, **~100** m underground
- 2x proton beams up to 7 TeV (**6.8 TeV in Run 3**)

The LHC beam dump



LHC
Point 6

- Target Dump External (TDE): absorb the energy of the two counter-rotating beams: ~ **350 MJ**
- Located at LHC Point 6, ~750 m downstream IP6.
- 2 x TDE, one for each beam, in UD62 and UD68 caverns.
- Each TDE is made of:
  - High and low density graphite (Sigrafine® ~1.7 and ~1.2 g/cm^3).
  - Stainless Steel 318 LN vessel



CERN RW disposal pathways

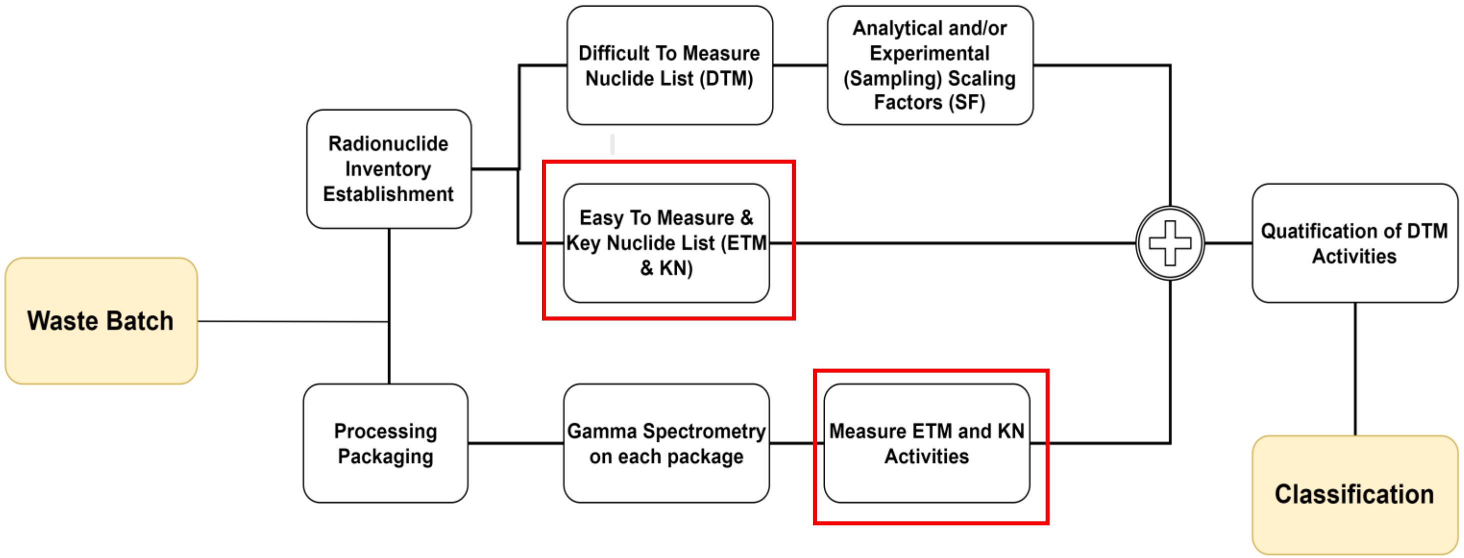
- ✓ Close collaboration with host states Switzerland and France in matters of Radiation Protection and Radiation Safety
- ✓ Since 2010, tripartite agreement between CERN and Host States, represented by Swiss Federal Office of Public Health (OFSP) and the French Nuclear Safety Authority (ASN) -> link
- ✓ "Fair Share" principle revised in March 2022, with three indicators: the **volume eliminated, radiotoxicity and costs**

CERN's Radioactive Waste Classification	
Clearance candidates – CL Very Very Low-Level waste (VVLLW) (*Candidats à la Liberation inconditionnelle*)	Release from regulatory control in **Switzerland** (Clearance <> "free-release")
Very Low-Level Waste - VLL (TFA) (*Très Faibles Activités*)	Surface disposal in **France.** As defined by the acceptance criteria of the ANDRA CIRES repository
Low & Intermediate Level waste (Short Lived) - SL-LILW (FMA-VC) (*Faibles et Moyennes Activités à Vies Courtes*)	Surface disposal in **France** (Short-Lived half-life $T_{1/2}$ < 30y) As defined by acceptance criteria in ANDRA CSA repository
Intermediate & Low-Level Waste - FA-MA (*Faibles Activités et Moyennes Activités*)	Disposal in **Switzerland**(1) When FMA-VC acceptance criteria (half-life, activity level) are not met

(1) In Switzerland, the PSI interim storage receives all FA-MA waste from research, industry and medical facilities, before its final disposal in a future deep geological repository

Strategy and Methodology for Radioactive Waste Characterization

- The requirements for each waste package include:
  - Criteria of activity distribution and of total activity (e.g. 50 GBq for H-3)
  - A list of radionuclides with activities higher than the Declaration Thresholds
  - Evidence that activity levels are lower than the maximum allowed values (LMA) at 2 standard deviations
- In this presentation, we focus on ETM estimation



ETM ⇒ Easy-to-Measure radionuclide (γ- and high-energy X-emitters)

DTM ⇒ Difficult-to-Measure radionuclide (Pure α- and β-emitters)

KN ⇒ Key Nuclide (Principal ETM radionuclide)

NDA ⇒ Non-destructive assay such as γ-spectrometry

References ⇒ *ISO 21238, ISO 16966 and IAEA-TECDOC-1537*

Simulation and computation codes

FLUKA

https://fluka.cern

- A general-purpose Monte Carlo code for calculations of particle transport and interactions with matter.
- Widely used and benchmarked in the RP domain.
- FLUKA can handle even very complex geometries, using an improved version of the well-known Combinatorial Geometry (CG) package.

Fluence Conversion Coefficient Tool (FCC)

- It is based on generating a set of coefficients for protons, charged pions, and neutrons and for a given radiological quantity.
- Visualisation of the radiological hazard factors (2D maps).
- Developed and maintained by CERN RP group.

ActiWiz 3

- It allows the computations of the radionuclide inventories and provides the estimations with respect to various radiological hazards.
- Input: pre-defined radiation environment or user-defined via particle fluence spectra
- Developed and maintained by CERN RP group.

Gamma spectrometry tools

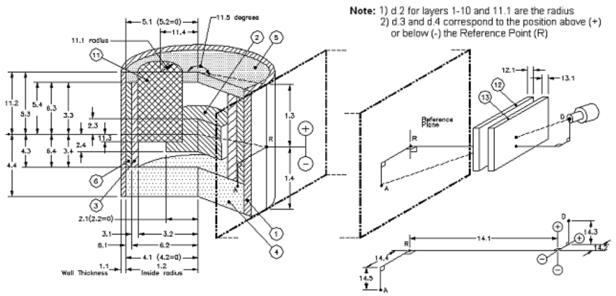
High-resolution HPGe gamma spectrometry (Mirion Technologies)

- The portable detector HPGe Falcon 5000 is frequently used in the radiological characterization process for the elimination of radioactive waste at CERN as well in the assessment of the radiological risk of material and equipment.
- BEGe Technology Germanium Detector included in HPGe Falcon 5000 enhances the efficiency and resolution at low energies, while preserving a good efficiency in high energy range

https://www.mirion.com/products/technologies/

ISOCS In-situ Object Counting System (Mirion Technologies)

- A calibration software tool (from Mirion Technologies) to calculate full peak efficiency values.
- The efficiency response is obtained using a factory-characterized detector model that is validated with NIST traceable radioactive sources.
- The Geometry input parameters are dimensions, material elemental composition, densities and relative activity concentration.



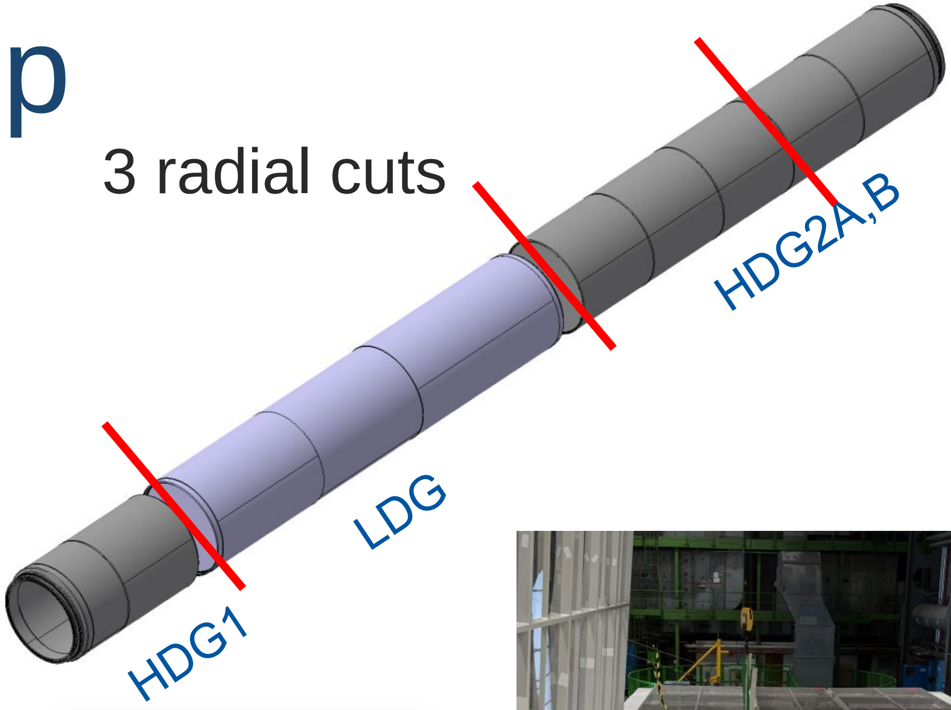
ISOCS drawing of the “Complex Pipe”

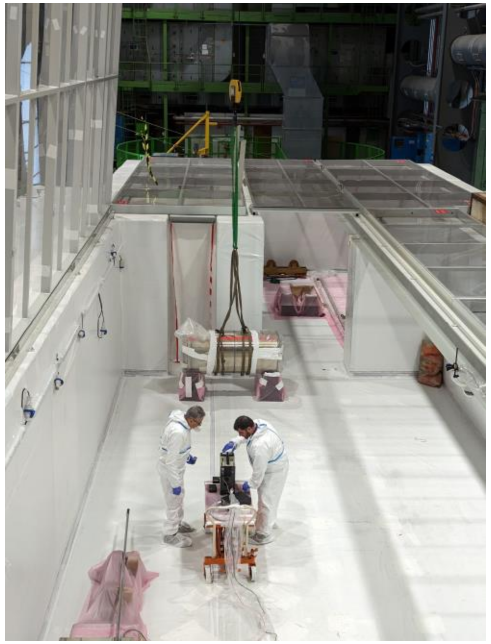
		Dimensions (mm)								
No.	Description	d.1	d.2	d.3	d.4	d.5	d.6	Material	Density	Rel. Conc.
1	Pipe	2	361.3	1050	-1050			dryair	0.0013	
2	Source 1	38.8	38.8	1050	-1050			carbon	1.8	0.06
3	Source 2	38.8	77.6	1050	-1050			carbon	1.8	0.06
4	Source 3	38.8	116.4	1050	-1050			carbon	1.8	0.05
5	Source 4	38.8	155.2	1050	-1050			carbon	1.8	0.05
6	Source 5	38.8	194	1050	-1050			carbon	1.8	0.04
7	Source 6	12	349.3	1050	-1050			ss	7.8	0.61
8	Source 7	38.8	232.8	1050	-1050			carbon	1.8	0.03
9	Source 8	38.8	271.6	1050	-1050			carbon	1.8	0.03
10	Source 9	38.8	310.4	1050	-1050			carbon	1.8	0.02
11	Source 10	38.8	1050	-1050	0	360		carbon	1.8	0.06
12	Absorber1							none		
13	Absorber2							none		
14	Source-Detector	1000	0	0	0	0				

ISOCS “Complex Pipe” geometry parameters

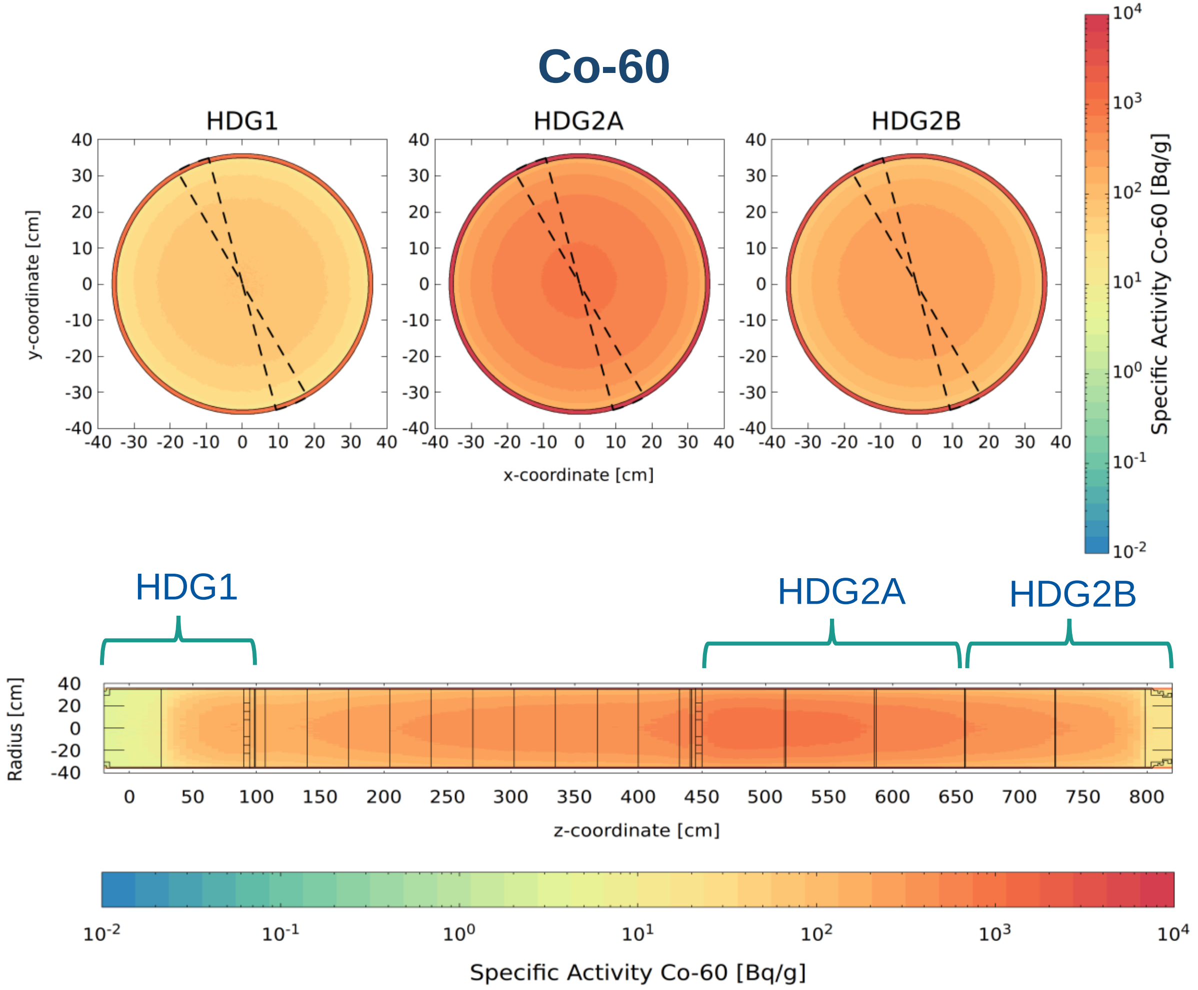
Gamma spectrometry setup

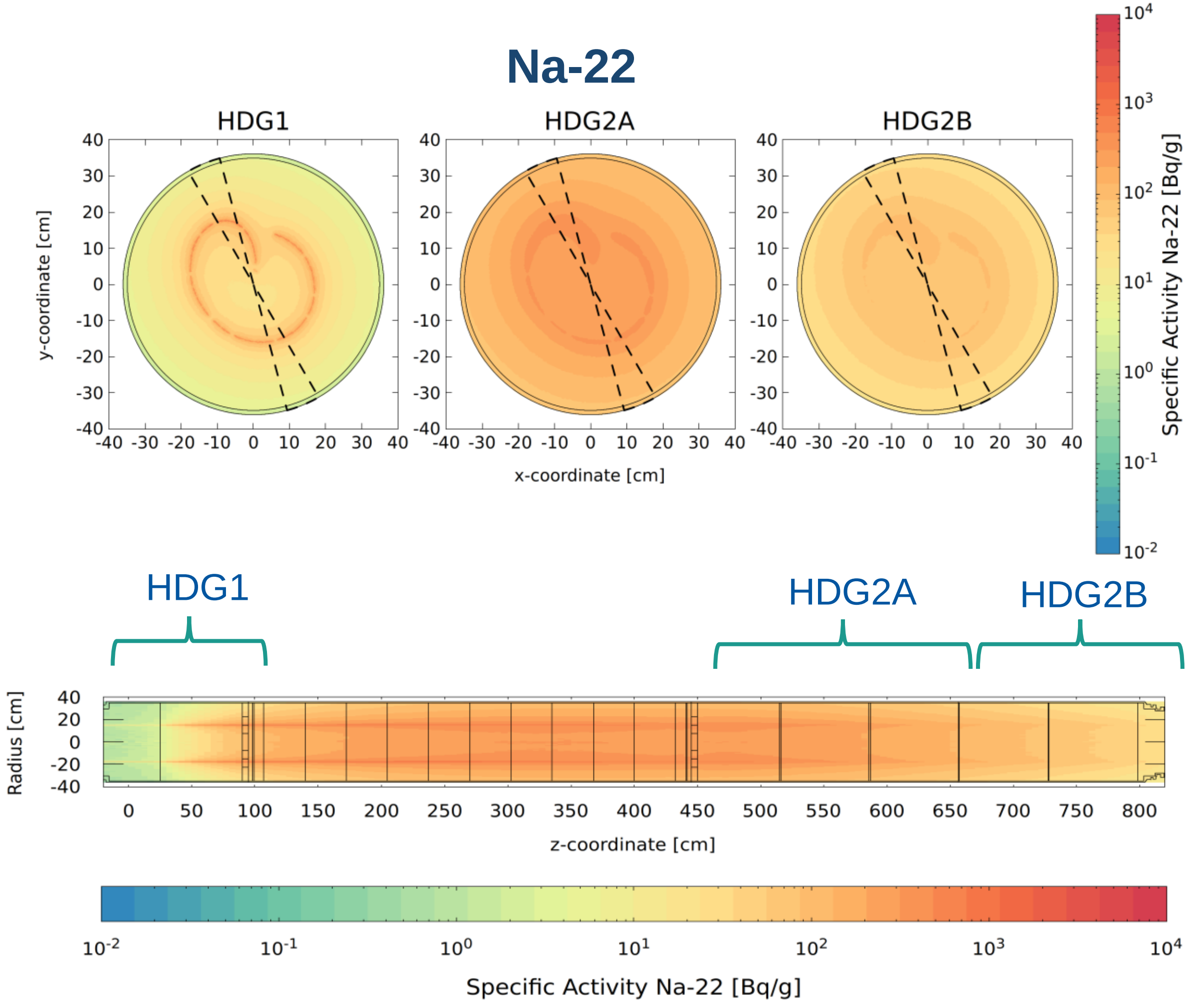
- The 2 beam dumps were cut for packaging
- Measured individual pieces (items) HDG1, HDG2A, and HGD2B
- Massive items: ~800 kg – 1800 kg
- Dose rate reaching 2 mSv/h after ~ 3 years of cooling time
- Deadtime up to ~15%
- Item-To-Detector distance up to ~9m
- Uncertain geometry modelling parameters: activity concentration distribution





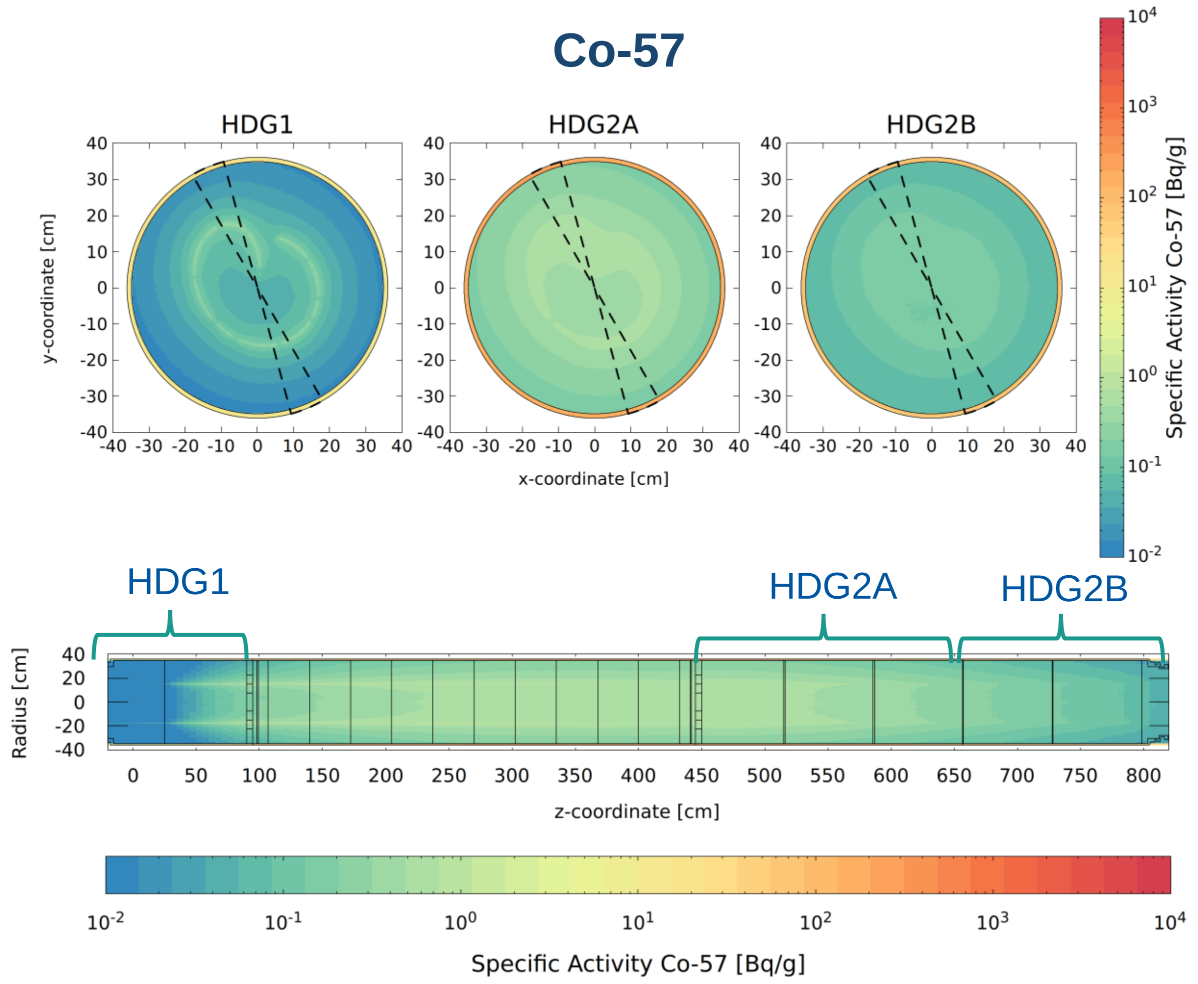
Activity distributions given by FLUKA and FCC method (1)

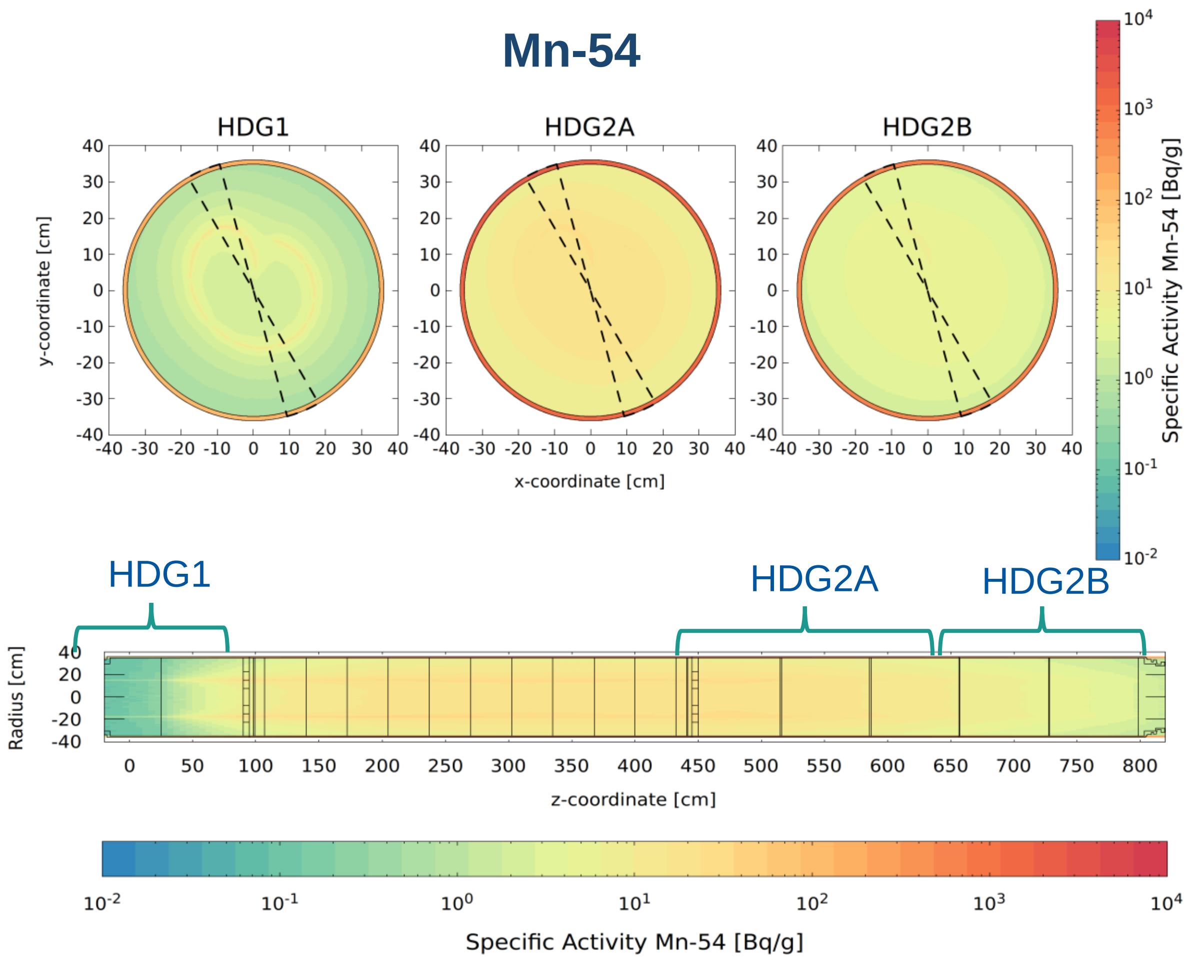




Circular crowns (dashed lines) highlight the areas used to produce the longitudinal plot.
Average over105° ≤ φ ≤ 120° and 285° ≤ φ ≤ 300° from positive x-axis

Activity distributions given by FLUKA and FCC method (2)





Circular crowns (dashed lines) highlight the areas used to produce the longitudinal plot.
Average over105° ≤ φ ≤ 120° and 285° ≤ φ ≤ 300° from positive x-axis

ISOCS efficiency calibration calculations

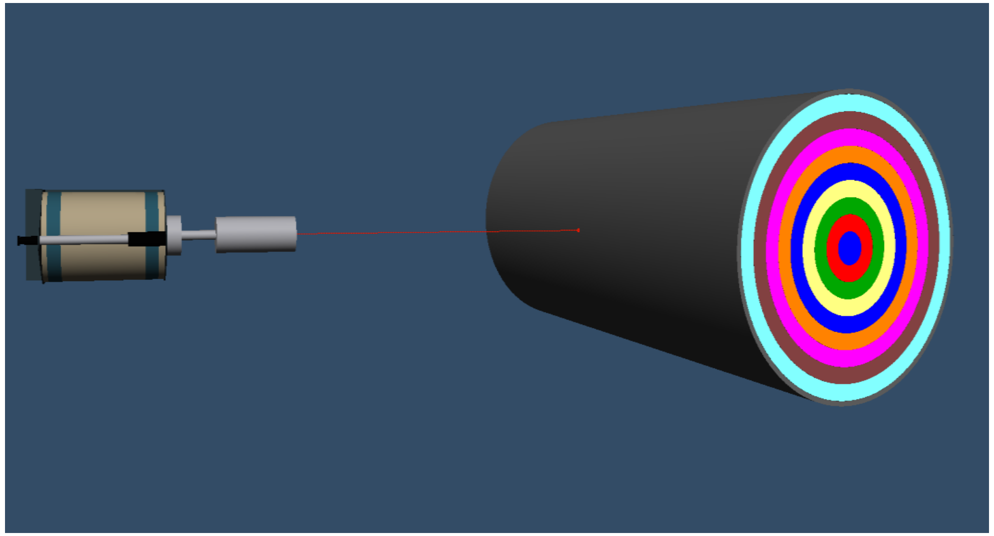
- Re-calculate the efficiency calibration values for each radionuclide of interest: Co-60, Co-57, Na-22, and Mn-54.
- Apply the relative activity concertation obtained from dedicated FLUKA simulations with the associated FCC method.

Table 1: Calculated relative activity concentration for TDE HDG 1 piece.

Region	Material	Na-22	Mn-54	Co-57	Co-60
1	HDG	0.09	0.01	0.003	0.05
2	HDG	0.10	0.01	0.004	0.05
3	HDG	0.12	0.02	0.004	0.05
4	HDG	0.20	0.02	0.006	0.05
5	HDG	0.27	0.03	0.008	0.04
6	HDG	0.11	0.01	0.004	0.04
7	HDG	0.05	0.01	0.002	0.03
8	HDG	0.03	0.01	0.001	0.02
9	HDG	0.02	0.004	0.001	0.02
10	SS 318L	0.01	0.88	0.966	0.65

Table 2: Calculated relative activity concentration for TDE HDG 2A piece.

Region	Material	Na-22	Mn-54	Co-57	Co-60
1	HDG	0.12	0.01	0.003	0.06
2	HDG	0.13	0.01	0.003	0.06
3	HDG	0.13	0.01	0.003	0.06
4	HDG	0.15	0.01	0.003	0.05
5	HDG	0.15	0.01	0.003	0.05
6	HDG	0.11	0.01	0.002	0.04
7	HDG	0.08	0.01	0.002	0.03
8	HDG	0.06	0.01	0.001	0.03
9	HDG	0.05	0.004	0.001	0.02
10	SS 318L	0.04	0.92	0.98	0.61



ISOCS “Complex Pipe” 3D rendering of TDE beam dump piece

Table 3: Calculated relative activity concentration for TDE HDG 2B piece.

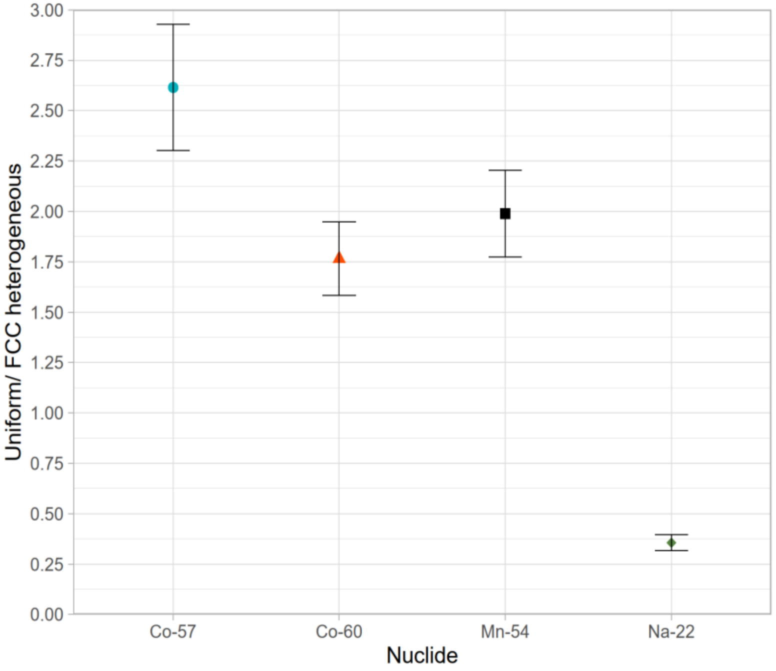
Region	Material	Na-22	Mn-54	Co-57	Co-60
1	HDG	0.12	0.01	0.002	0.06
2	HDG	0.13	0.01	0.002	0.06
3	HDG	0.13	0.01	0.002	0.05
4	HDG	0.14	0.01	0.002	0.05
5	HDG	0.13	0.01	0.002	0.05
6	HDG	0.11	0.01	0.002	0.04
7	HDG	0.08	0.01	0.001	0.03
8	HDG	0.07	0.005	0.001	0.02
9	HDG	0.05	0.004	0.001	0.02
10	SS 318L	0.04	0.94	0.98	0.63

Dimensions (mm)

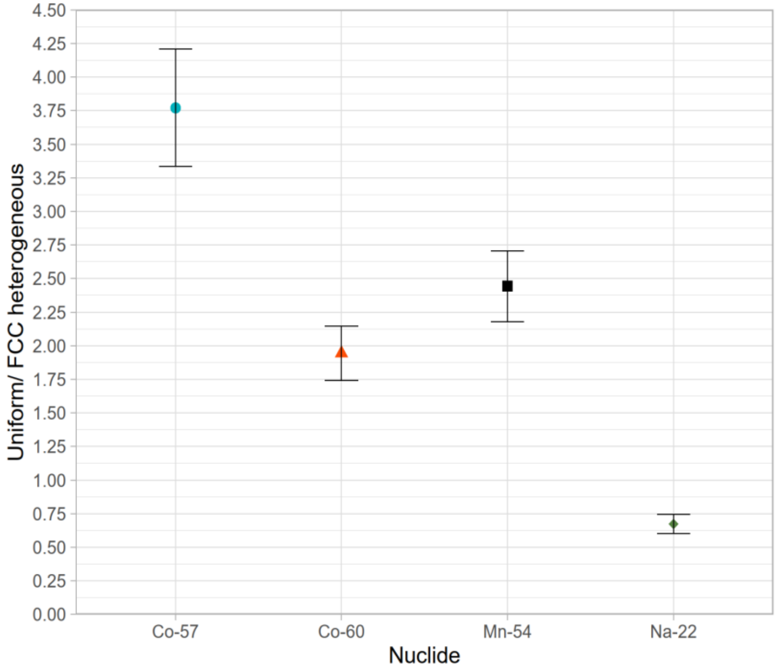
No.	Description	d.1	d.2	d.3	d.4	d.5	d.6	Material	Density	Rel. Conc.
1	Pipe	2	361.3	1050	-1050			dryair	0.0013	
2	Source 1	38.8	38.8	1050	-1050			carbon	1.8	0.06
3	Source 2	38.8	77.6	1050	-1050			carbon	1.8	0.06
4	Source 3	38.8	116.4	1050	-1050			carbon	1.8	0.05
5	Source 4	38.8	155.2	1050	-1050			carbon	1.8	0.05
6	Source 5	38.8	194	1050	-1050			carbon	1.8	0.04
7	Source 6	12	349.3	1050	-1050			ss	7.8	0.61
8	Source 7	38.8	232.8	1050	-1050			carbon	1.8	0.03
9	Source 8	38.8	271.6	1050	-1050			carbon	1.8	0.03
10	Source 9	38.8	310.4	1050	-1050			carbon	1.8	0.02
11	Source 10	38.8	1050	-1050	0	360		carbon	1.8	0.06
12	Absorber1							none		
13	Absorber2							none		
14	Source-Detector	1000	0	0	0	0				

Activity results comparison: TDE from UD62

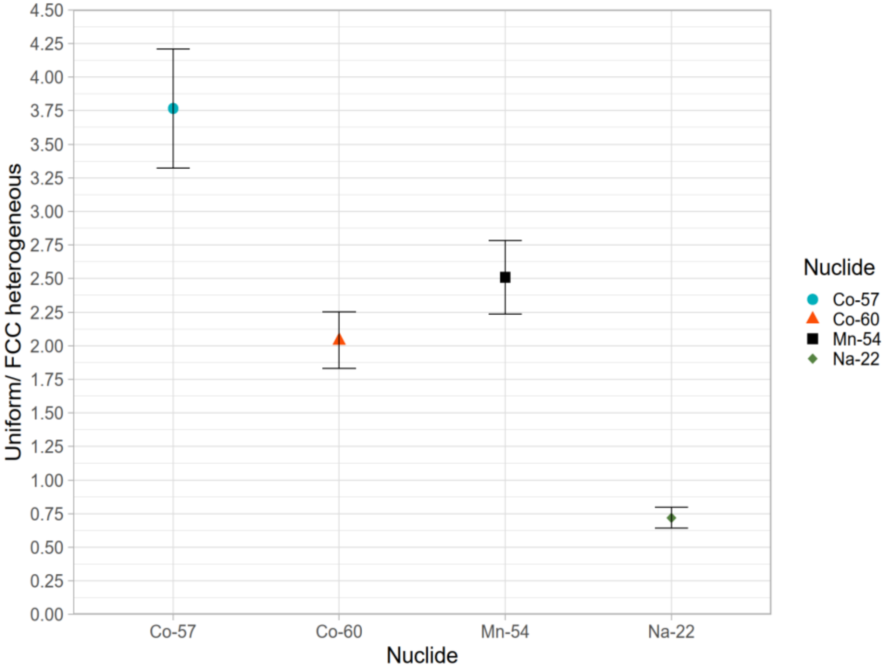
HDG 1



HDG 2A



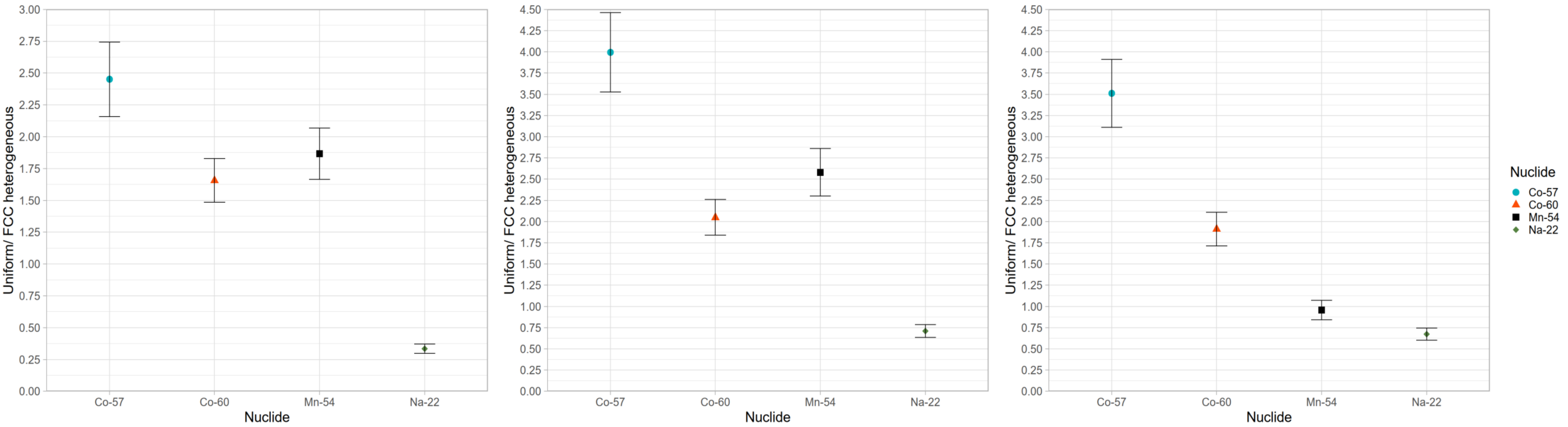
HDG 2B



Compared to actual activity distribution, assuming uniform geometry model leads to:
Na-22 activity **lower** by a factor of 1.4 to 2.8.
Co-60 activity **higher** by a factor of 1.8 to 2.0.

Activity results comparison: TDE from UD68

HDG 1 **HDG 2A** **HDG 2B**



Compared to actual activity distribution, assuming uniform geometry model leads to:
Na-22 activity **lower** by a factor of 1.4 to 3.0.
Co-60 activity **higher** by a factor of 1.7 to 2.0.

Take-Home messages

- Developed a **NDA technique** that addresses various challenges: High dose rates, massive items and heterogenous activity distributions
- Used state of the art tools **FLUKA**, **ISOCS**, ActiWiz, FCC to predict the activity distributions
- **Accurate** geometry modeling needed to improve the accuracy of the activity results
- Confirmed the equivalence and symmetry of TDE UD62 and UD68
- Compared to actual activity distributions, the uniform geometry models lead to:
    - Na-22 activities lower by a factor of **1.4 to 3.0**.
    - Co-60 activities higher by a factor of **1.7 to 2.0**.
- The developed methodologies followed can guide addressing similar challenges in other accelerator and nuclear facilities.

Publications

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