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Radiological assessment of the Collimator Materials tests at HiRadMat in 2012

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Abstract

A test for several collimator materials is planned to be performed in the HiRadMat facility of CERN/SPS. Before these samples can be brought to a surface laboratory for analysis after the irradiation, a certain cool-down period has to be respected in order to avoid unjustified exposure of personnel to residual radiation. In the present document, the results of Monte Carlo simulations performed for the radiological assessment of this experiment, are being presented.

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SHORT SUMMARY

Quantities calculated: - residual dose rate

- nuclide inventory

Simulation code: FLUKA version 2011.2

Conversion coefficients: Fluence-to-dose conversion coefficients by M. Pelliccioni
Radiat. Prot. Dosim. 88, pp. 279-297, (2000)

Assumed scenarios: 1.08 x 10^{13} protons delivered within one extraction of 1 second for the full samples and 1.5 x 10^{13} protons delivered within one extraction of 1 second for the sliced samples.

Beam momentum: 440 GeV/*c* protons

Transport thresholds: Neutrons followed down to thermal energies

100 keV for electrons & positrons, 10 keV for photons

Electromagnetic cascade: Switched on for residual dose rate calculation

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1.) Introduction

LHC Collimators, as well as other Beam Intercepting Devices (BID) are inherently exposed to the risk of extended damages induced by energetic particle beams hitting these components. This risk becomes even more severe with the expected increase in beam energies and intensities of the LHC and other future facilities.

Hence, predicting the consequences of such events by simulation, including material changes of the phase, shock wave propagation, explosions, material fragment projections etc., becomes a fundamental issue for machine protection: this can be done, to a certain extent, by making use of complex numerical tools such as Hydrocodes. In order for these simulations to be reliable, the constitutive models of the impacted materials must be accurate over their whole operational range. However, simulations cannot fully replace practical tests as their predictive power has some limitations, no matter how sophisticated the physics models are.

For the aforementioned reason, it is proposed to install in the HiRadMat facility of CERN/SPS [1] a multi-material sample holder [2] and test up to six different materials under intense particle beams in one test session.

Before these samples can be brought to a surface laboratory for analysis a certain cool-down period has to be respected after the irradiation in order to avoid unjustified exposure of personnel to residual radiation. In order to evaluate the expected dose rate as a function of the cooling time a dedicated FLUKA [3,4] study has been performed. In addition, the associated nuclide inventory has been determined in order to assess the classification of the workshop that is required to conduct destructive works on the samples.

2.) FLUKA studies

2.1) Residual dose rate

In order to study the residual dose rate as a function of the cooling period a model of the experimental sampler holder was used [5] (see Figure 1). More info on the material samples used can be found in Table 1.

Table 1: *The material samples placed on the sampler holder [2]*

Material	*Number of Samples*
Inermet®180	**3 full + 3 sliced**
Molybdenum	**5 full + 5 sliced**
Glidcop® Al-15 LOX (UNS C15715)	**6 full + 6 sliced**
Molybdenum-Diamond	**10 full + 10 sliced**
Copper-Diamond composite.	**10 full + 10 sliced**
Other Molybdenum matrix composite	**10 full + 10 sliced**

The composition of the materials, as well as their exact volume and density can be found in tables 2 & 3. The number of the samples for each material is reported in Table 1: the Full Cylinder samples have a diameter of 40 mm and a total length of 30 mm (Volume for one sample 37.699 cm3), while the Half Cylinder Samples are cylinders of diameter 40 mm and a total length of 30 mm cut at 2 mm from the centre (Volume one sample 22.246 cm3) [6]

Table 2: *The material samples placed on the sampler holder [6]*

Material	Rho (g/cm3)	Number of Samples per type	Weight full cylinder samples (g)	Weight half cylinder samples (g)	WEIGHT TOT (g)
Inermet® 180	18	3	2035.746	1201.284	3237.03
Molybdenum	10.22	5	1926.4189	1136.7706	3063.1895
Glidcop®	8.93	6	2019.91242	1191.94068	3211.8531
MoCuCD	6.7	10	2525.833	1490.482	4016.315
CuCD	5.34	10	2013.1266	1187.9364	3201.063
MoGR	5.4	10	2035.746	1201.284	3237.03
TOTAL			12556.78292	7409.69768	19966.4806

The chemical composition of the samples in % Weight and in Molar fraction can be found in Table 3.

Table 3: *Chemical Composition of each material [6]*

Material Name	Element	Molar mass (g/mol)	Density (g/cm3)	%W	Molar fraction %
Inermet 180	W	183.85	19.3	95.00%	93.08%
	Cu	63.546	8.93	1.50%	1.9674%
	Ni	58.6934	8.9	3.50%	4.9534%
Molybdenum	Mo	95.94	10.22	100%	100.0000%
Glidcop AL-15	Cu	63.546	8.93	99.70%	99.8128%
	Al2O3	101.9633	3.96	0.30%	0.1872%
MoCuCD	Mo	95.94	10.22	49.59%	19.6900%
	Cu	63.546	8.93	30.95%	18.5600%
	CD	12.01	3.51	19.46%	61.7500%
CuCD	Cu	63.546	8.93	0.62057%	23.5903%
	B	10.811	2.34	0.00417%	0.9317%
	CD	12.01	3.51	0.375261%	75.4781%
MoGR	Mo	95.94	10.22	74.60%	27.2970%
	Pd	106.42	12.01	0.60%	0.1985%
	GR	12.01	2.25	24.80%	72.5045%

The irradiation profile planned to be used can be found in the following tables [2].

Calibration runs

Table 4: *The calibration runs irradiation profile [2]*

Target	Protons per bunch	Bunches per pulse	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses	Time between pulses [min]
Housing slit	1e10	1	0.25 x 0.25	3	20
Type 1 sample Molybdenum	5e10	1	0.25 x 0.25	2	20

Medium intensity tests (shot on the full samples – "Type 1")

Table 5: *The medium intensity runs irradiation profile [2]*

Target	Protons per bunch	Bunches per pulse	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses	Time between pulses [min]
Type 1 sample Tungsten	5e10	1	0.25 x 0.25	2	20
"	1.5e11	1	"	1	15
"	1.5e11	2	"	1	15
"	1.5e11	4	"	1	15
"	1.5e11	6	"	1	15
"	1.5e11	20	"	1	15
Type 1 sample Molybdenum	5e10	1	0.25 x 0.25	2	20
"	1.5e11	1	"	1	15
"	1.5e11	2	"	1	15
"	1.5e11	6	"	1	15
"	1.5e11	12	"	1	15
"	1.5e11	40	"	1	15
Type 1 sample Glidcop	5e10	1	0.25 x 0.25	2	20
"	1.5e11	1	"	1	15
"	1.5e11	2	"	1	15
"	1.5e11	6	"	1	15
"	1.5e11	12	"	1	15
"	1.5e11	40	"	1	15
Type 1 sample MoCD	5e10	1	0.25 x 0.25	2	20

“	1.5e11	1	“	1	15
“	1.5e11	2	“	1	15
“	1.5e11	8	“	1	15
“	1.5e11	16	“	1	15
“	1.5e11	72	“	1	15
Type 1 sample CuCD	5e10	1	0.25 x 0.25	2	20
“	1.5e11	1	“	1	15
“	1.5e11	2	“	1	15
“	1.5e11	8	“	1	15
“	1.5e11	16	“	1	15
“	1.5e11	72	“	1	15
Type 1 sample Mo comp.	5e10	1	0.25 x 0.25	2	20
“	1.5e11	1	“	1	15
“	1.5e11	2	“	1	15
“	1.5e11	8	“	1	15
“	1.5e11	16	“	1	15
“	1.5e11	72	“	1	15

High intensity tests (shot on the sliced samples – “Type 2”)

Table 6: *The high intensity runs irradiation profile [2]*

Target	Protons per bunch	Bunches per pulse	Beam size (σ_x x σ_y) [mm x mm]	Number of pulses	Time between pulses [min]
Type 2 sample Tungsten	5e10	1	0.25 x 0.25	2	20
Type 2 sample Tungsten	1.5e11	60	0.25 x 0.25	1	30
Type 2 sample Molybdenum	5e10	1	0.25 x 0.25	2	20
Type 2 sample Molybdenum	1.5e11	72	0.25 x 0.25	1	20
Type 2 sample Glidcop	5e10	1	0.25 x 0.25	2	20
Type 2 sample	1.5e11	72	0.25 x 0.25	1	30

Glidcop					
Type 2 sample MoCD	5e10	1	0.25 x 0.25	2	20
Type 2 sample MoCD	1.5e11	72	0.25 x 0.25	1	30
Type 2 sample CuCD	5e10	1	0.25 x 0.25	2	20
Type 2 sample CuCD	1.5e11	72	0.25 x 0.25	1	30
Type 1 sample Mo comp.	5e10	1	0.25 x 0.25	2	20
Type 1 sample Mo comp.	1.5e11	72	0.25 x 0.25	1	30

As the accurate number of particles is not yet fully confirmed at this time and as the micro-structure of the irradiation pattern will not be noticeable for the studied cooling periods, the irradiation pattern has been somewhat simplified as follows :

- One run, with the simulated beam impinging on the full samples, with a total intensity of 1.08 x 10^{13} protons during 1 second
- A second run, with the simulated beam impinging on the sliced samples, with a total intensity of 1.5 x 10^{13} protons during 1 second.

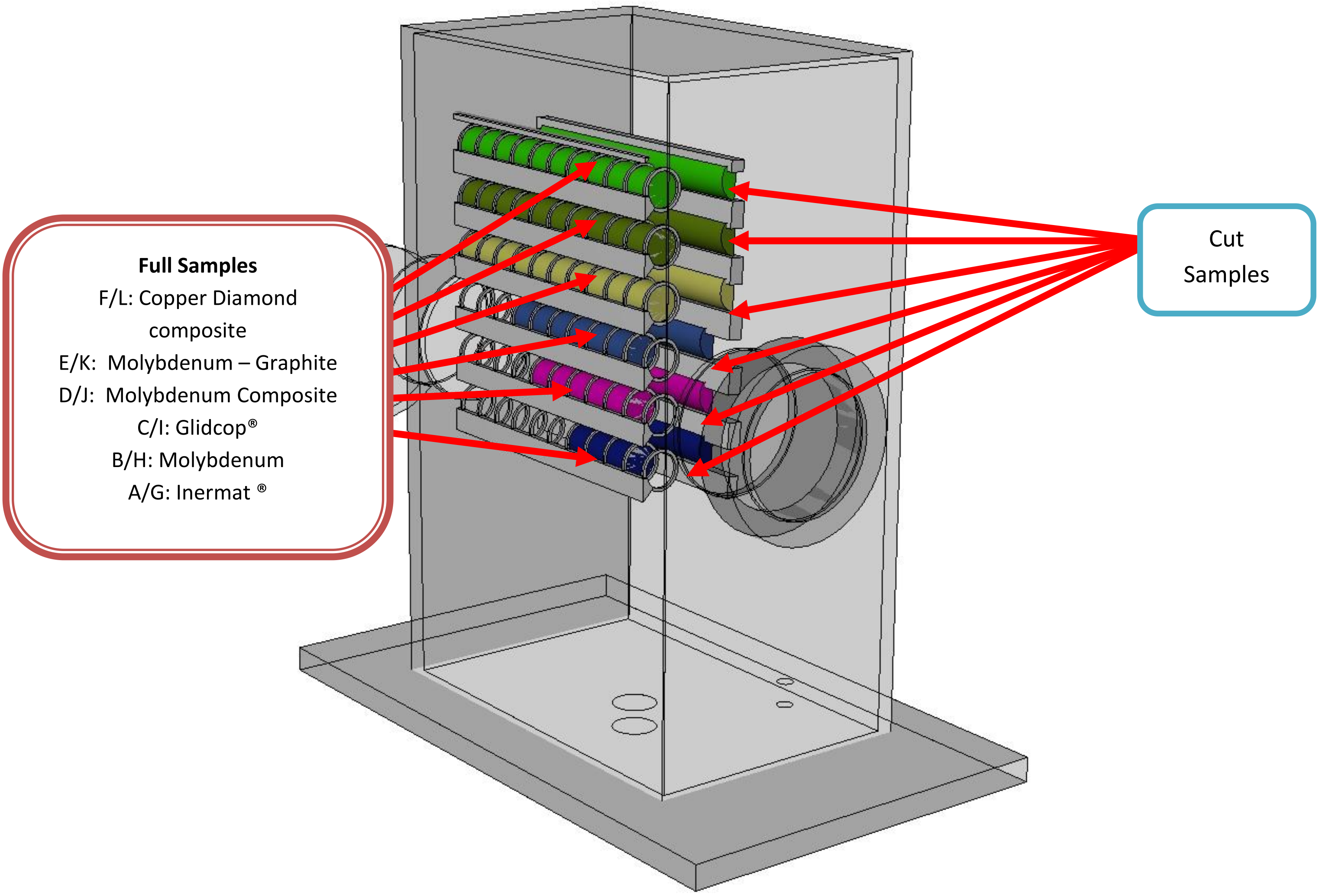

Figure 1: *FLUKA geometry of the sampler holder mode, using SimpleGeo [7].*

As can be seen in the irradiation profile tables, prior to the actual irradiation, several low intensity pilot beam extractions ("calibration shots") will be used to correctly set up the beam line and the experiment. These calibration shots only contribute to a percentage of 1% of the total number of protons, so they were neglected in the simulation scenario. In the simulation the respective medium and high-intensity scenarios had to be calculated separately as different irradiation patterns had to be used. However, the results from the two calculations were combined with the use of a special routine [8], and the respective values for the cooling times of 1 hour, 1 day, 1 week, 1 month and 2 months can be found in Figures 2 – 6. This superposition of the individually carried out simulations allows for studying the residual dose rate of the whole sample holder as it will be experienced in practice.

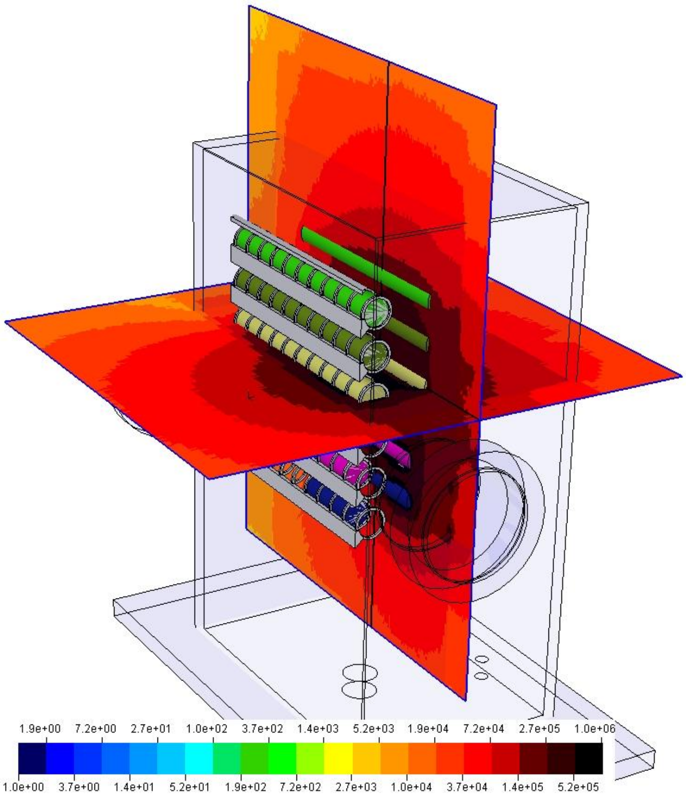

Figure 2: *Residual dose rate of the sampler holder after 1 hour of cool-down. The results are given in terms of [μSv/h].*

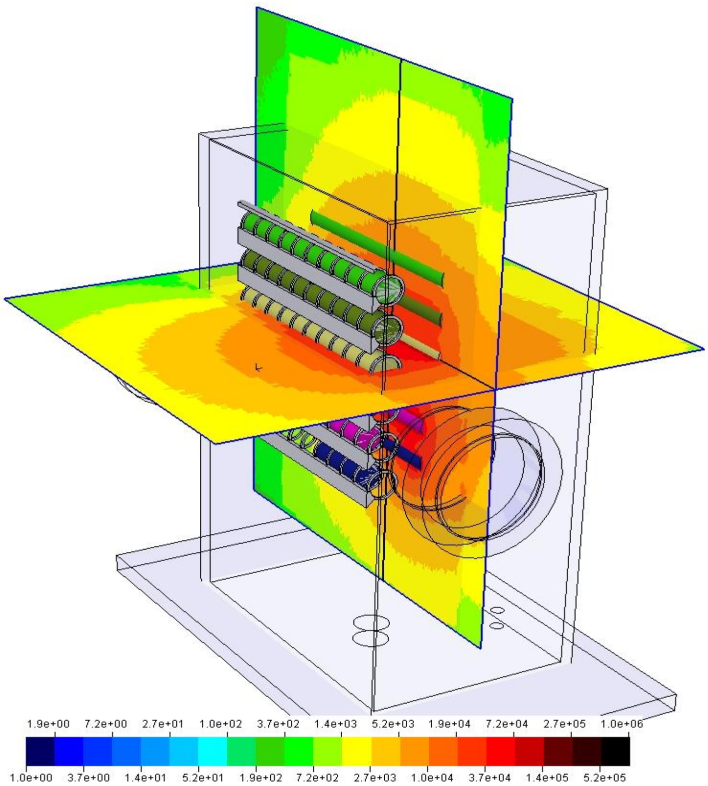

Figure 3: *Residual dose rate of the sampler holder after 1 day of cool-down. The results are given in terms of [μSv/h].*

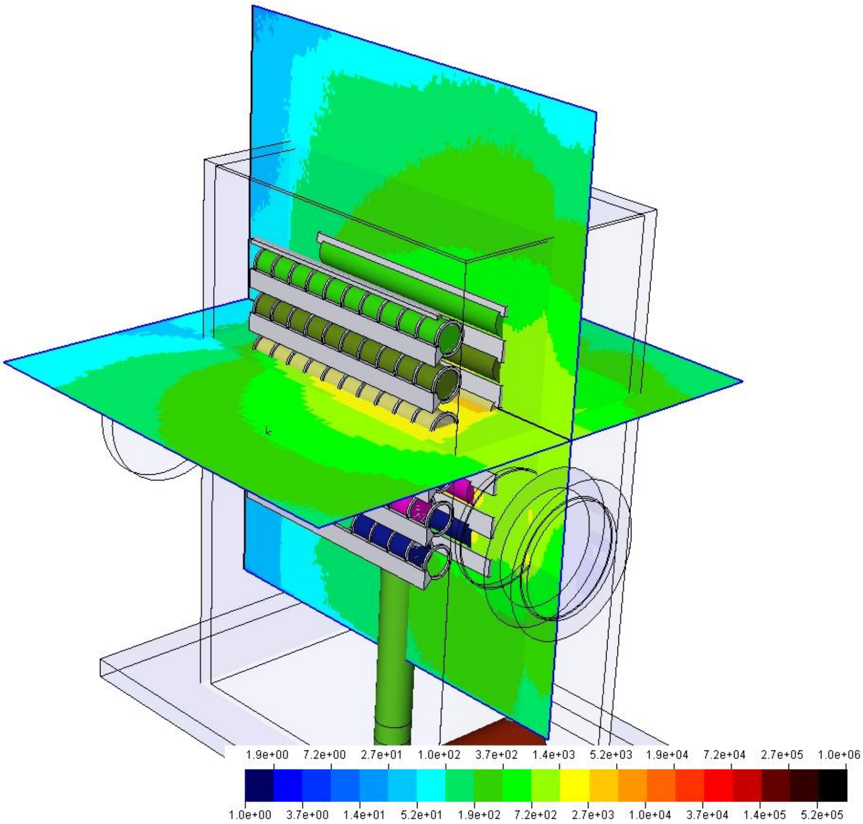

Figure 4: *Residual dose rate of the sampler holder after 1 week of cool-down. The results are given in terms of [μSv/h].*

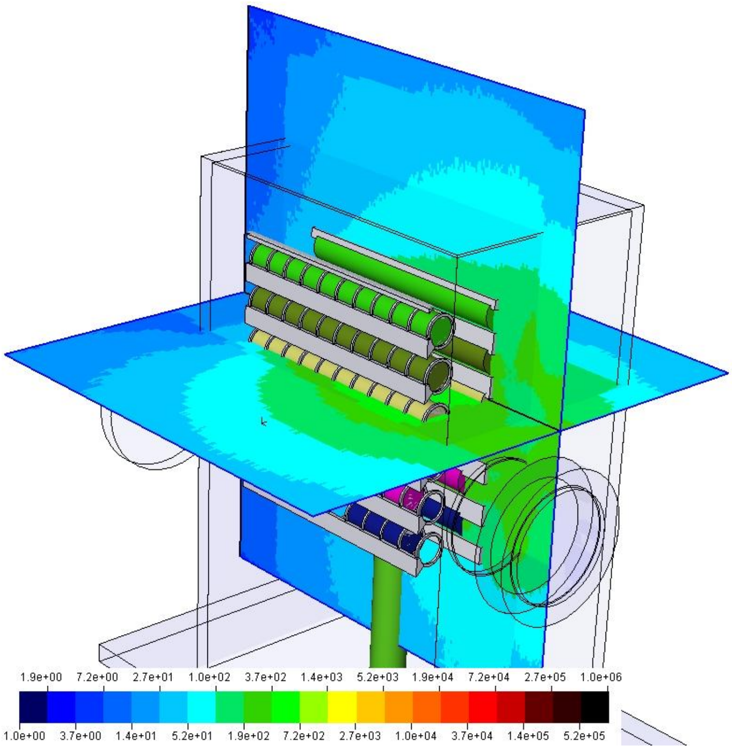

Figure 5: *Residual dose rate of the sampler holder after 1 month of cool-down. The results are given in terms of [μSv/h].*

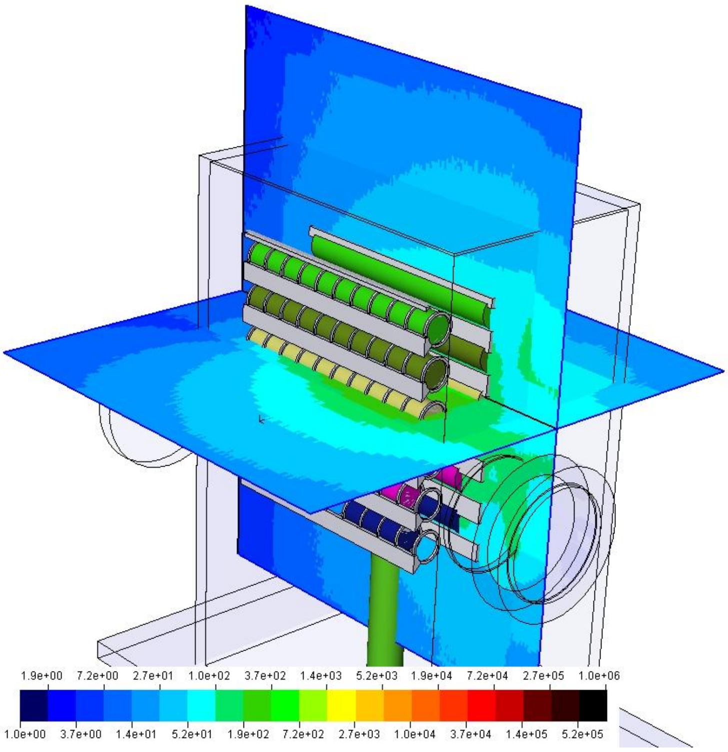

Figure 6: *Residual dose rate of the sampler holder after 2 months of cool-down. The results are given in terms of [µSv/h].*

The maximum residual dose rates at contact outside of the surrounding hull (made of Stainless Steel and with a total width of 10mm) enclosing the samples are listed in Table 7.

Table 7: *Maximum residual dose rates at contact outside of the steel tank enclosing the sample holder. The statistical fluctuations are generally below 10%.*

Cooling period	Residual dose rate [uSv/h]	Cooling period	Residual dose rate [uSv/h]
1 hour	5.2×10^5	1 day	7.2×10^4
1 week	2700	1 month	370
2 months	190	4 months	100

The maximum residual dose rates found within the container are given in Table 6. It should be noted that they are found within the object and are in principle not accessible from the outside unless the surrounding hull of the sample holder is opened.

Table 8: *Maximum residual dose rates within the samples. It should be noted that these dose rates occur within the sampler holder tank and are not accessible from the outside unless the container is opened. The statistical fluctuations are generally below 10%.*

Cooling period	Residual dose rate [uSv/h]	Cooling period	Residual dose rate [uSv/h]
1 hour	7.4×10^6 (Sample A)	1 day	3.11×10^5 (Sample B)
1 week	1.92×10^4 (Sample G)	1 month	2.52×10^3 (Sample B)
2 months	1.5×10^3 (Sample B)	4 months	1.02×10^3 (Sample B)

2.2) Nuclide inventory

After the irradiation of the samples, an examination of the irradiated samples has to be performed. As a consequence a workshop has to be found which is appropriately classified and equipped for this kind of radioactive materials. Due to the envisaged cutting of the samples and the associated risk of internal exposure to potentially released radionuclides this assessment has to be made based on the external residual dose rate as well as the nuclide inventory with respect to the so called licensing limits ("LA limits") taken from the Swiss legislation [9]. In compliance with section 5, articles 69 of Ref. [8] workplaces for handling unsealed radioactive sources are classified as follows:

- Type C: An activity from 1 – 100 times the licensing limits
- Type B: An activity from 1 – 10000 times the licensing limits
- Type A: An activity from 1 – to an upper limit to be defined by the legal authorities during a specific licensing process

The processing of the simulation files was performed with the help of a custom made program which automated the process of calculating the radionuclides and comparing them with the LA limits. The results for each one of the 12 samples can be found in Table 9. A notation of capital letters has been attributed to the samples, for reasons of simplicity, which can be found at Figure 8.

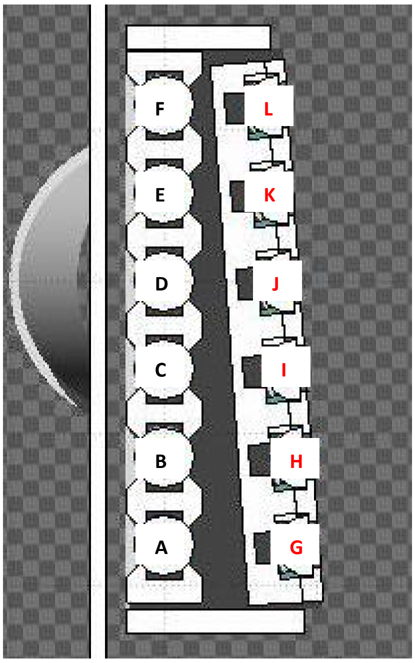

Figure 8: *A notation of the samples contained in the sampler holder, used in Table 9.*

Table 9: *Ratio of the respective total activity with respect to the licensing limits [9] after 2 months of cooling. The statistical uncertainty of this ratio is well below 1% for all cases. The total sum of the ratios relates to 14, which would allow for the handling the whole setup at once in a class C lab.*

FULL SAMPLES RATIO						CUT SAMPLES RATIO					
A	B	C	D	E	F	G	H	I	J	K	L
2.2	2.0	0.9	1.7	1.4	0.5	1.3	1.1	0.6	0.9	0.8	0.3

As can be seen from Table 9 after 2 months of cool-down a workshop of Type C is sufficient to conduct destructive work on the irradiated samples individually or even all at once as the total sum equals 14.

3.) Summary & conclusions

In order to evaluate the performance of several materials under the beam impact, a test is foreseen to be carried out at HiRadMat facility of CERN/SPS. Moreover, a possible “post-mortem” analysis of the irradiated samples may be necessary, therefore an appropriate cool-down period needs to be respected to avoid unjustified exposure of personnel to residual radiation. FLUKA studies have been carried out to evaluate the residual dose rates as well as study the nuclide inventory, which in turn determines the type of workshop required to conduct destructive tests.

After 2 months of cooling the maximum residual dose rate at contact outside the sample holder’s enclosure was found to be around 190 uSv/h. A period of 4 months after the experiment reduces the maximum dose rate at about 100 uSv/h.

The convolution of the nuclide inventory with the respective licensing limits results in ratios well below the value of 100. . Nevertheless, before any handling of the sample holder, measurements will be performed in order to confirm the simulations results and confirm the assessments done. Consequently, a workshop of type C might be sufficient to conduct destructive studies with a potential risk of internal exposure. Given the fact that destructive tests are foreseen and that after 4 months of cooling the maximum dose rate within sample B (Molybdenum) is still ~1 mSv/h, it is favourable to wait at least 4 months, preferably longer. Due to the significant activation any handling and destructive work requires a specific assessment with work and dose planning by RP before it can be conducted.

References

[1] The HiRadMat facility of CERN/SPS – *http://www.cern.ch/hiradmat*

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[8] A. Mereghetti, *Private Communication*, (2012).

[9] Bundesamt fuer Gesundheit, Strahlenschutzverordnung (StSV) 814.501 vom 22. Juni 1994 – Stand am 1. Januar 2012, Appendix 3, Column 10, (2012).