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ESS Gamma Blockers Shielding Calculation

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1. SCOPE

The purpose of this document is to present the calculations and simulations prepared for the design of Gamma Blocker (GB) system for the ESS Dump Line (DmpL) and Accelerator to Target (A2T) sections.
The two independent gamma blocker systems, in A2T and in Dump sections, will be installed in ESS tunnel.
The gamma blockers will be used during equipment maintenance periods to reduce the gamma radiation from the activated target wheel and tuning dump.

2. CONTRIBUTORS

This report was authored by Karol Szymczyk, NCBJ.

3. ISSUING ORGANIZATION

This report is authored by the National Centre for Nuclear Research (NCBJ, Poland), as part of the European Spallation Source ERIC AIK 6.1, and subject to the controlled document approval workflow which will lead to its release as a ESS document.

4. METHODOLOGY

To properly design the gamma blocker systems, the dose equivalent rate levels inside the tunnel without and with different GB geometries were calculated. An optimal GB thickness was selected.
The FLUKA Simulation package [1] was used to calculate the dose equivalent rate (DOSE EQ) inside the A2T tunnel and DmpL section. During the radiation calculations, the gamma radiation inside the beam pipe coming from the target wheel and beam dump during the beam off period was observed. The input file delivered by ESS, with the gamma radiation spectrum, was analysed by FLUKA following the recommendations on [3] as instructed by the Accelerator Division. To speed up the simulation time, the Surface Splitting Biasing function in FLUKA was used.

5. ACCEPTANCE CRITERIA

With regard to the ESS Document "Hands on maintenance conditions for ESS accelerator" [2] the following assumption was taken into consideration:
“For gamma blocker in the line of target: 100 µSv/h on contact for 5 years of irradiation of target (max 2 GeV, 5 MW beam) and no cool-down.
For gamma blocker in the line of beam dump: 100 µSv/h on contact for 50 years of irradiation of beam dump (max 2 GeV, 12 kW beam) and no cool-down.”
With regard to the ESS Document "ESS Procedure for designing shielding for safety" [3], in all particle transport code calculations, the safety factor of 2 was applied, and all results (including dose rate maps) are multiplied by it, the acceptance criteria were not modified.

6. OPEN ITEMS

The GB design is completed and closed (pending the Critical Design Review result), however some modifications are possible in the future, in case they are needed for ESS upgrades.

7. ASSUMPTIONS

Two GB systems have been designed:

- One in the A2T section, before the Neutron Shield Wall (NSW)
- One in the Dump Line section, in front of the Tuning Dump

The requirements for the gamma blockers are specified at:

- A2T.ID and DMPL.ID L3 Requirements [6]
- A2T.ID L4 Requirements [7]
- DmpL.ID L4 Requirements [8]
- A2T.ID and DmpL.ID L4 interface requirements [9]

8. LIMITATIONS

The number of thickness variants of Gamma Blocker considered was our main limitation for this study. It was mitigated by approximate intermediate results.

9. COMPUTER HARDWARE AND SOFTWARE

The FLUKA version used was **FLUKA Flair 2.3-0 [R4cf6d2c]**.

Simulations were prepared on the NCBJ - CIŚ computer cluster using 700 threads on every calculation. The processors in the NCBJ-CIŚ computer cluster are **Intel® Xeon® Processor E5-2680 v2**, with the following characteristics:

- Number of Cores: 10
- Number of Threads: 20
- Processor Base Frequency: 2.80 GHz
- Max Turbo Frequency: 3.60 GHz
- Cache: 25 MB SmartCache
- Bus Speed: 8 GT/s QPI
- Number of QPI Links: 2
- TDP: 115 W
- VID Voltage Range: 0.65–1.30V

10.CALCULATION INPUTS

With regard to the ESS Document "ESS Procedure for designing shielding for safety" [3], the special flux to dose conversion factors for external radiation required for ESS, were implemented in every simulation, instead of the default FLUKA conversion factors used in some of the preliminary studies (for example in the Preliminary Design Review documentation).

10.1. GB design in the A2T section

With regard to the ESS Document "Hands on maintenance conditions for ESS accelerator" [2], residual dose rate maps for 0, 1 hour, 4 hours and 1 month of target cool-down times were prepared for the A2T section. The FLUKA code was used to simulate a residual dose rate after 5 years of exposure and cooling conditions inside the accelerator tunnel in A2T section. The implemented gamma energy spectrum on ESS target after 5 years of irradiation and various cool-down times is presented in Table 2, as provided by the Target Division.

Table 1: Gamma Energy Spectrum from the Target after 5 years of irradiation and various cool-down times.

		0s cooling time	**1h cooling time**	**4h cooling time**	**1m cooling time**
Emin (MeV)	**Emax (MeV)**	**photons/cm3/s**	**photons/cm3/s**	**photons/cm3/s**	**photons/cm3/s**
0,00E+00	1,00E-02	4,05E+11	1,05E+11	8,60E+10	3,34E+10
1,00E-02	3,00E-02	5,69E+10	5,04E+10	4,43E+10	3,43E+09
3,00E-02	6,00E-02	7,77E+11	2,87E+11	2,31E+11	7,49E+10
6,00E-02	1,00E-01	3,22E+11	1,70E+11	1,48E+11	1,86E+10
1,00E-01	2,00E-01	2,26E+11	9,93E+10	8,09E+10	8,09E+09
2,00E-01	3,00E-01	5,43E+10	3,56E+10	2,67E+10	2,97E+09
3,00E-01	5,00E-01	1,73E+11	1,42E+11	1,25E+11	7,86E+09
5,00E-01	5,25E-01	6,58E+10	2,59E+10	1,50E+10	3,96E+08
5,25E-01	7,50E-01	2,38E+11	2,17E+11	1,95E+11	3,28E+09
7,50E-01	1,00E+00	5,78E+10	4,38E+10	3,68E+10	3,07E+09
1,00E+00	1,33E+00	4,42E+10	3,12E+10	2,45E+10	6,82E+09
1,33E+00	1,66E+00	2,19E+10	1,31E+10	9,21E+09	4,97E+08
1,66E+00	2,00E+00	1,03E+10	6,84E+09	5,11E+09	2,34E+08
2,00E+00	2,50E+00	5,93E+09	3,96E+09	3,08E+09	5,63E+07
2,50E+00	3,00E+00	3,17E+09	2,38E+09	1,96E+09	4,17E+06
3,00E+00	4,00E+00	9,45E+08	4,54E+08	3,34E+08	3,01E+05
4,00E+00	5,00E+00	5,92E+07	1,37E+07	5,16E+06	4,22E+03
5,00E+00	6,00E+00	9,95E+06	1,04E+05	7,84E+01	6,43E+00
6,00E+00	7,00E+00	2,58E+06	1,57E+04	8,84E+00	0,00E+00
7,00E+00	8,00E+00	4,85E+05	5,51E+02	3,11E-01	0,00E+00
8,00E+00	9,00E+00	1,21E+05	2,07E+00	1,17E-03	0,00E+00
9,00E+00	1,00E+01	3,92E+04	9,96E-04	7,24E-18	0,00E+00
1,00E+01	1,20E+01	1,56E+04	3,59E-04	2,61E-18	0,00E+00
1,20E+01	1,70E+01	1,21E+03	8,91E-06	6,48E-20	0,00E+00
1,70E+01	3,00E+01	0,00E+00	0,00E+00	0,00E+00	0,00E+00

A special source routine was defined in FLUKA to include the energy spectrum. This isotropic on the surface source was designed for the geometry of the target wheel and beam dump. The gamma energy was always randomized from the field spectrum with the right probabilities, see Figure 1.

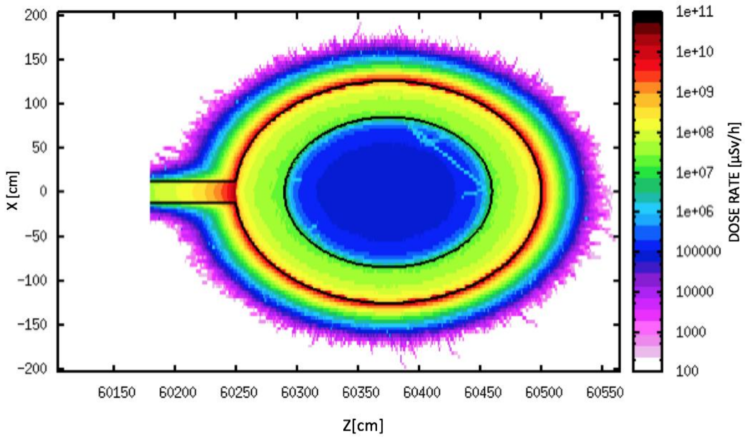


Figure 1: Implemented isotropic source on the external target wheel surface

To speed up the simulation time, only a part of target wheel in the neighborhood of the beam pipe was taken as an isotropic source of radiation. The final results are exactly the same (see Figure 2), and the simulation time, is several times shorter.

A) **B)**

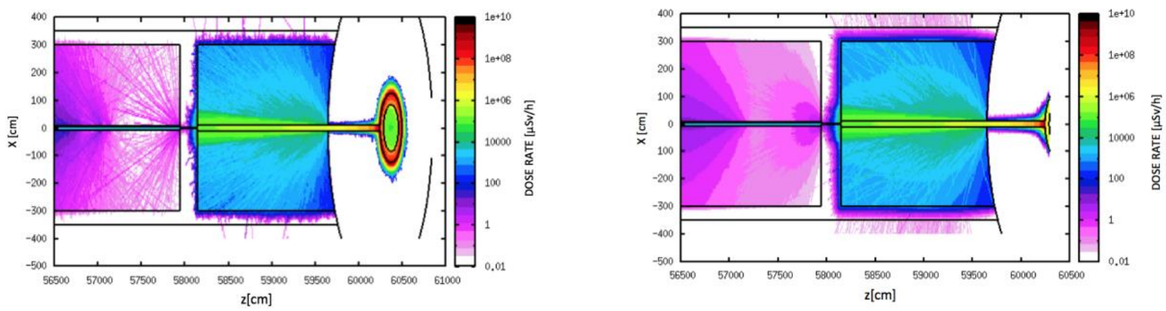


Figure 2: The residual dose rate in the last 40 m of A2T, with NSW and Target Wheel

A) Implemented isotropic source on the whole target wheel surface.
B) Implemented isotropic source only on the target wheel surface in the beam pipe line-of-sight

Recommendations on the design criteria for the radiation level upstream of the GB, presented in the document "Considerations for Gamma Blocker design related to radiation safety: ESS-0087526" [5], were taken into account during this study.

A dedicated FLUKA input file was prepared with complete definition of the geometry including target wheel, shielding and the tunnel. The A2T GB will be located 30cm upstream the NSW in the A2T section, i.e. as close as it is mechanically possible to the Neutron Shield Wall (NSW), see Figure 3.

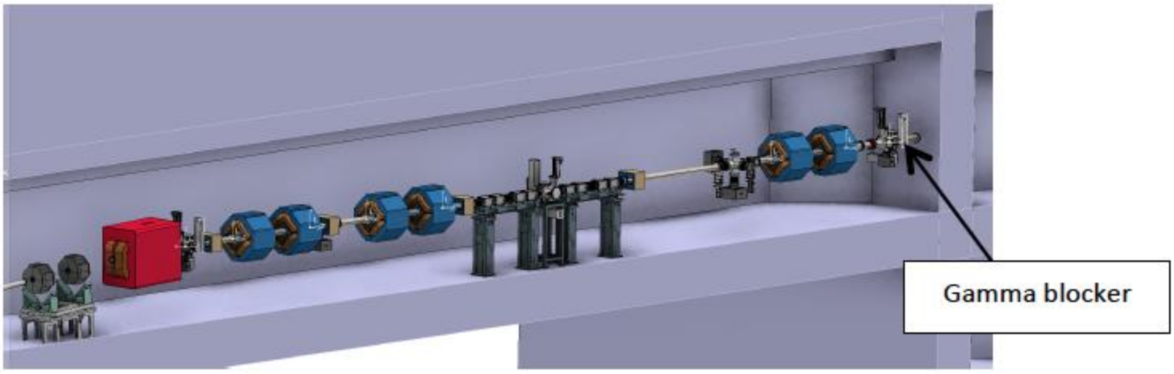


Figure 3: Location of a gamma blocker in A2T region

To simulate dose rate, an ESS A2T Geometry was prepared in FLUKA, as shown in Figure 4.

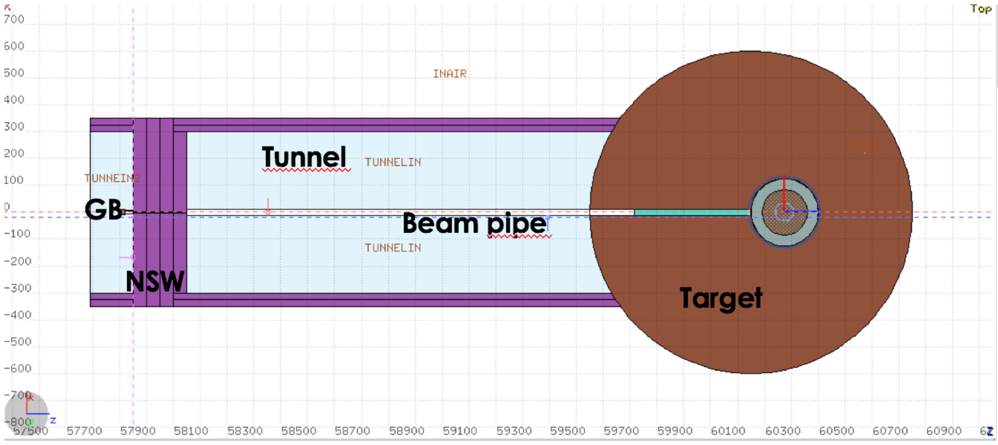


Figure 4 : Target Geometry in FLUKA

During the simulations, the NSW was nominally 2 m thick but its final thickness will be determined after the detailed calculations. The shielding walls are made of concrete with a density of 2.35g/cm^3. Results were typically obtained by simulating 10 million source protons in 700 separated jobs, the results of which were combined. During the simulations, special attention was given to the thickness, shape, and arrangement of the Gamma Blocker.

10.2. GB design in the Dump Line section

A gamma blocker will be used during equipment maintenance periods to reduce the gamma radiation from the activated tuning dump. The gamma spectrum was calculated for a 2 GeV, 12.5 kW beam operation on beam dump for a continuous 99360000 seconds. This corresponds to 50 years of 552 hours/year operation time. The decay effect during beam-off was not taken into account.

Homogenous distribution of gamma source in the outer 1 cm layer of the whole beam dump surface is presented below in Table 2, as provided by the Target Division.

Table 2: Gamma Spectrum from the Beam dump

E (MeV)	0s cooling time photons/cm3/s
5,00E-03	7,33E-01
1,50E-02	2,85E+04
3,50E-02	9,82E+02
7,50E-02	2,63E+05
1,50E-01	2,63E+05
2,50E-01	1,36E+05
3,50E-01	4,02E+04
5,00E-01	2,73E+04
7,00E-01	1,16E+05
9,00E-01	9,65E+05
1,10E+00	4,11E+06
1,30E+00	1,47E+06
1,55E+00	7,05E+04
1,85E+00	6,17E+04
2,25E+00	3,43E+04
2,75E+00	1,59E+04
3,50E+00	1,72E+04
4,50E+00	7,37E+02
5,75E+00	1,68E+01
7,25E+00	3,56E-03
9,00E+00	1,59E-05
1,10E+01	3,15E-08
1,30E+01	0,00E+00
1,70E+01	0,00E+00

The DmpL GB will be located 30cm upstream the concrete shielding in the Dump Line section, i.e. as close as it is mechanically possible, see Figure 5. To simulate the dose rate, the ESS Dump section geometry was prepared. All simulations were prepared for GBs made of steel.

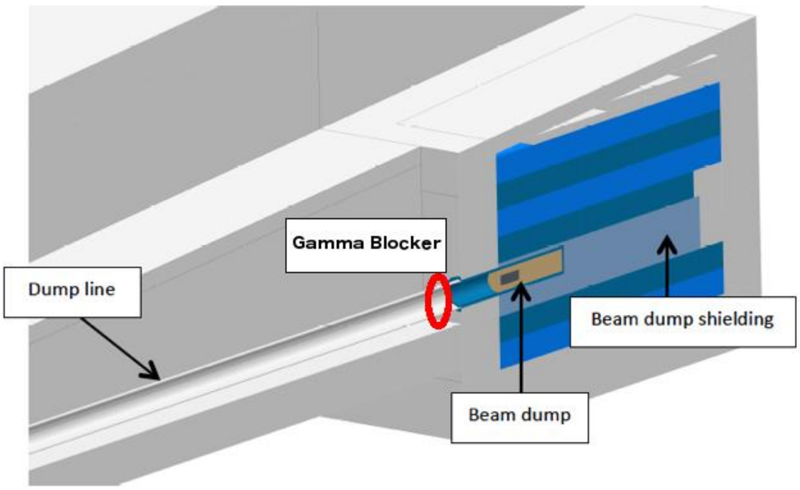


Figure 5 : Location of gamma blocker in dump line region

11.CALCULATIONS

11.1. GB design in the A2T section

The first simulation was run in FLUKA without any gamma blocker, to find the gamma radiation level inside the A2T ESS region. The residual dose rate after 5 years of exposure inside the accelerator tunnel in the last part of the A2T section was calculated and is shown in Figure 6.

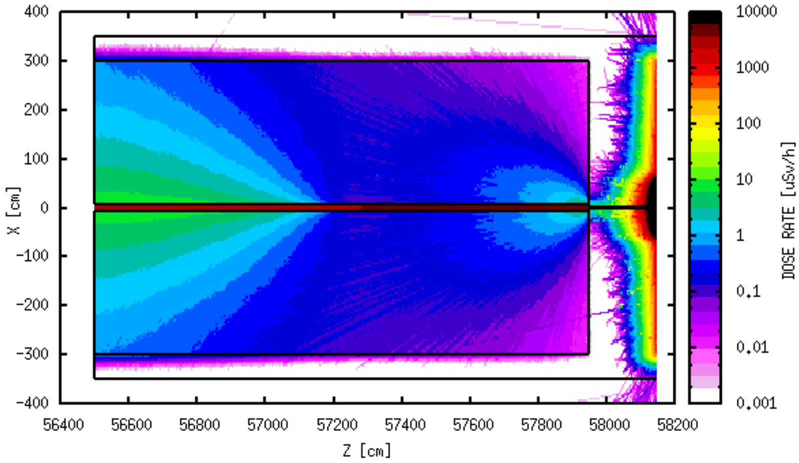


Figure 6 : Residual dose rate after 5 years of exposure and no cooling times

The level of residual dose rate inside was calculated on a cross section of the A2T tunnel. Figure 7 presents the residual dose rate after 5 years of exposure and various cooling down times inside the tunnel on the NSW contact plane, transversal to the accelerator tunnel. It can be seen that the radiation dose level inside the accelerator tunnel after the neutron shield wall is the sum of two components:

- Scattered gamma radiation coming from the shielding tunnel and NWS
- Central Gamma radiation beam transmitted through the beam-pipe

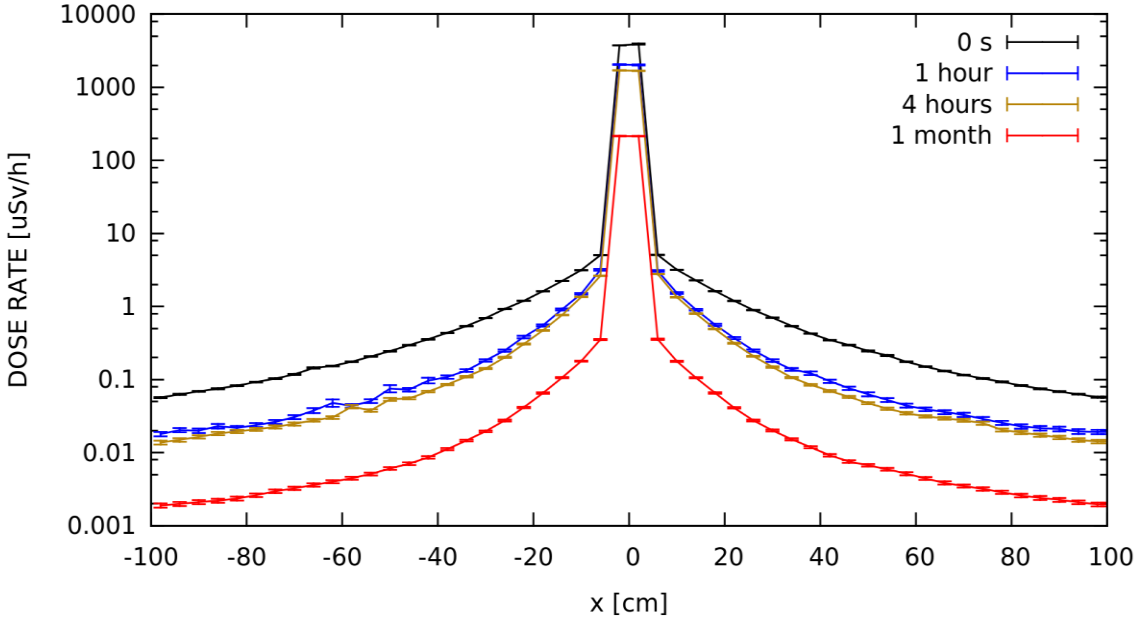


Figure 7 : Gamma radiation dose rate vs. distance from the beam pipe. Projection on X-axis. Cooling times: 0s, 1hour, 4 hours,1 month (black). Z=57950cm

To remove the central, very intense gamma radiation peak emitted from the target a special element (the gamma blocker, GB), was designed. All simulations were prepared for GBs made of steel. The residual dose rates after 5 years of exposure and 0s cooling times, for different GB thicknesses, in the last part of A2T section, were simulated and are presented bellow in Figure 8.

Considered GB thicknesses:

- 0cm
- 5cm
- 10cm
- 15cm
- 20cm
- 40cm

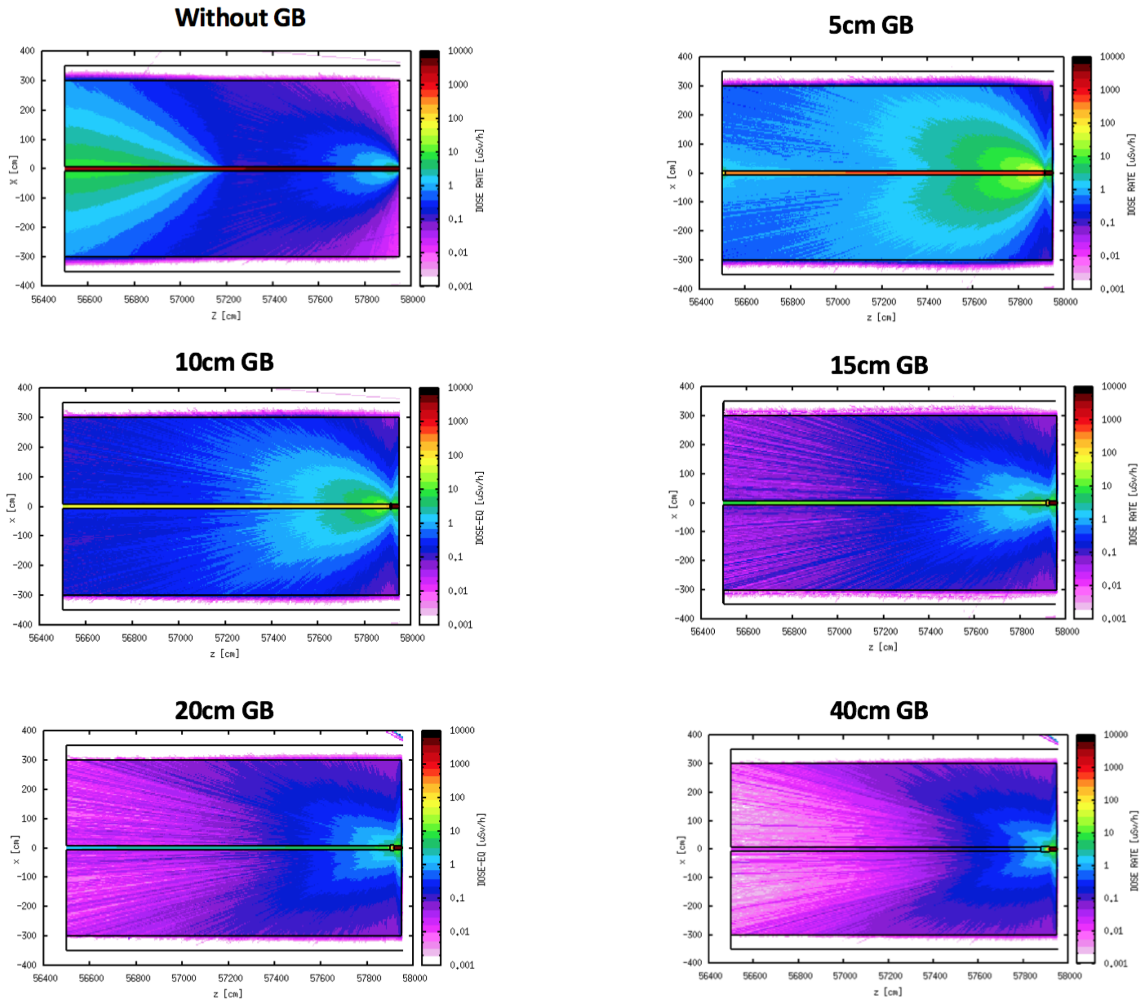


Figure 8 : Dose rate after 5 years of exposure, no cooling time for different steel GB thicknesses

The level of the dose rate was calculated on two cross sections of the A2T tunnel. The locations of this measurements are on contact to the face of the GB away from the Target, and 14,5m upstream the NSW (z=56500cm), results are presented in Figure 9 and Figure 10 respectively.

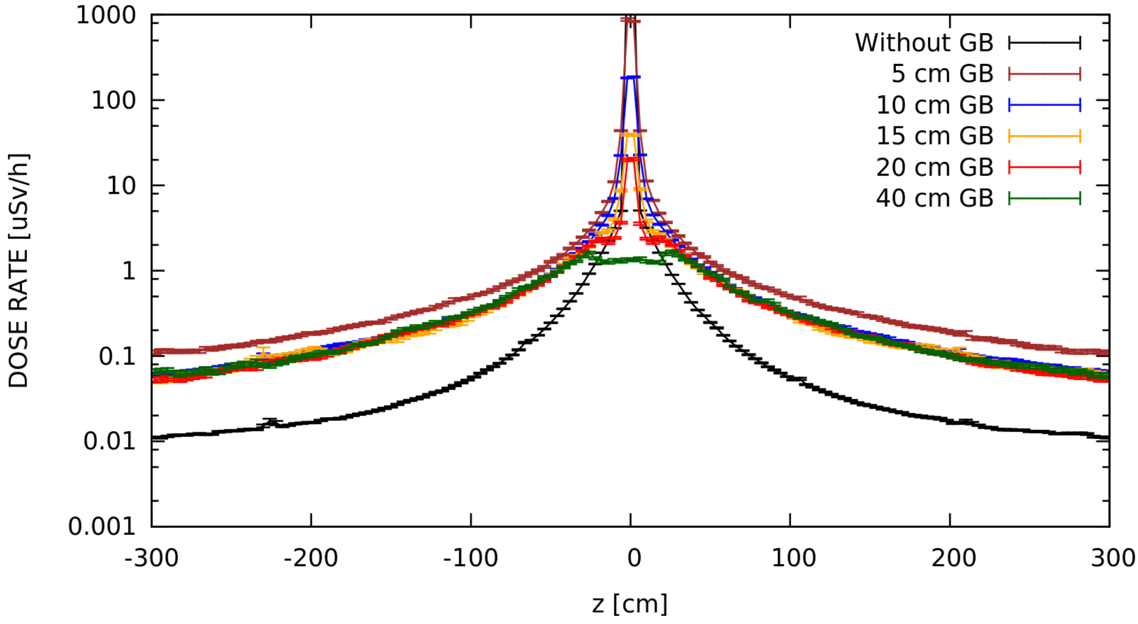


Figure 9 : Residual dose rate vs. distance from the beam pipe. Projection on X-axis. Z = on GB contact (on the NSW contact in situation without GB). 5 years of exposure, cooling time 0s, GB thickness: 0cm, 5cm, 10cm, 15cm, 20cm, 40cm

The GB presence inside the beam pipe stops gamma radiation and increases the transverse radiation field. The GB removes the central intense peak inside the beam pipe but, on the other hand, also generally increases the levels at larger transverse distances in the GB neighbourhood, e.g. Figure 9 where the effect is very clear. This is due to the fact that the gamma radiation from the target undergoes Compton Scattering on the GB core.

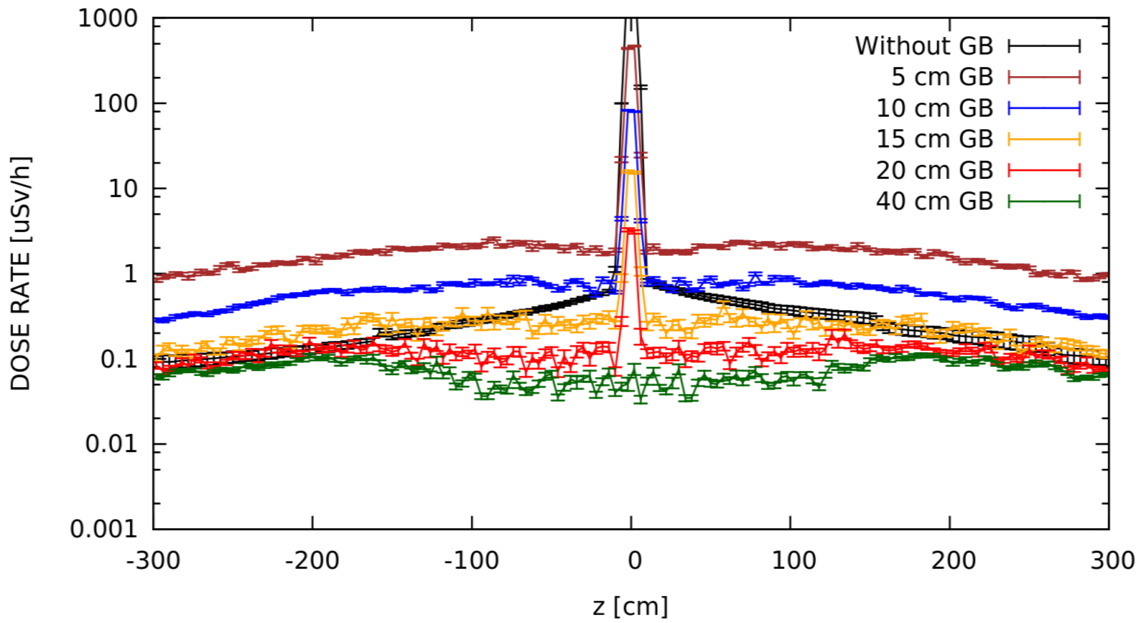


Figure 10: Residual dose rate vs. distance from the beam pipe. Projection on X-axis. Z=57400cm. 5 years of exposure, cooling time 0s, GB thickness: 0cm, 5cm 10cm,15cm 20cm 40cm GB

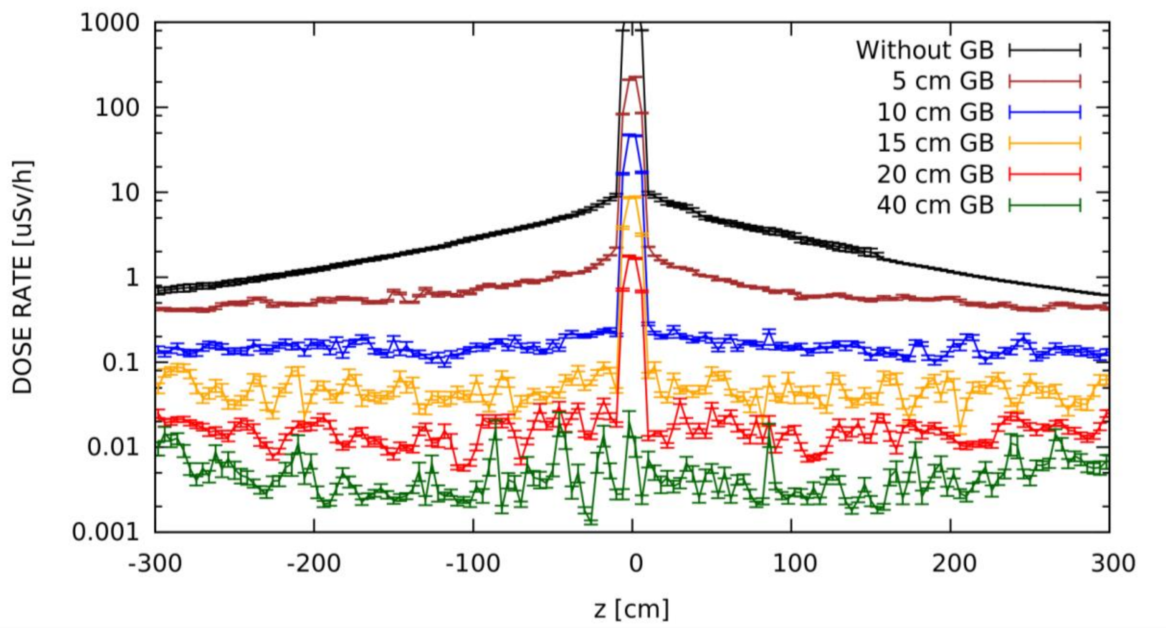


Figure 11 : Residual dose rate vs. distance from the beam pipe. Projection on X-axis. Z=56500cm. 5 years of exposure, cooling time 0s, GB thickness: 0cm, 5cm 10cm,15cm 20cm 40cm GB

At 14,5 m upstream of the NSW, the GB presence reduces the radiation level inside not only the beam pipe, but also its surroundings. Figure 11 shows that the GB is required to reduce the level of radiation inside the A2T tunnel.
To find the optimal thickness of the GB, the dose rate in the line of target on the contact behind the GB as a function of the GB thickness for 5 years of irradiation of target (max 2 GeV, 5 MW beam) for a number of different cooling times was calculated and is presented in Table 3 and Figure 12 respectively, in logarithmic and linear scale.

Table 3: Dose rate after 5 years of exposure and various cooling times inside the 'beam pipe' for a different GB thickness

	Dose rate after 5 years of exposure at various cooling times inside the 'beam pipe' [uSv/h]			
GB thickness [cm]	**0s Cooling**	**1h Cooling**	**4h Cooling**	**1m**
0	3800	2060	1700	230
5	850	460	370	58
10	180	92	72	9
15	40	21	18	2,2
20	14	6	5	0,8
40	1,15	0,85	0,54	0,2

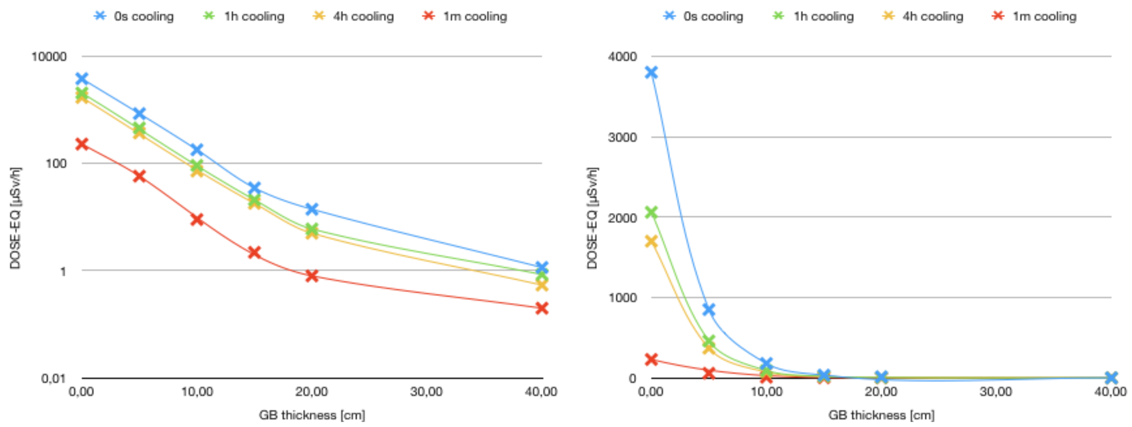


Figure 12 : Residual dose rate after 5 years of exposure at various cooling times inside the 'beam pipe' as a function of GB thickness

11.2. GB design in the Dump Line section

For the Dump Line section, the residual dose rate after 50 years of exposure and no cooling down, for different GB thicknesses was simulated and is presented in Figure 14.

Considered GB thickness in Dump section:

- 0cm
- 5cm
- 10cm
- 20cm

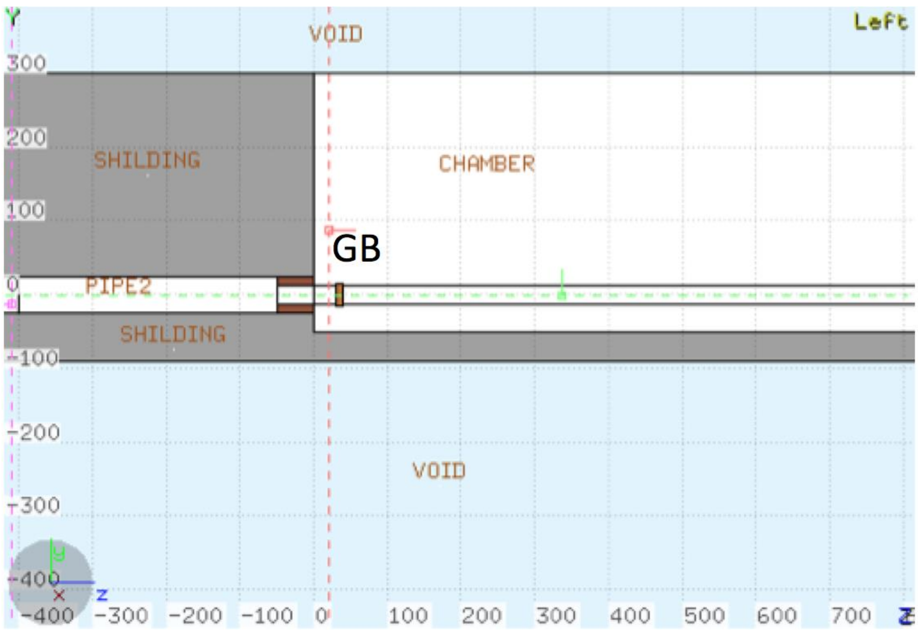


Figure: 12 Beam Dump section geometry in FLUKA

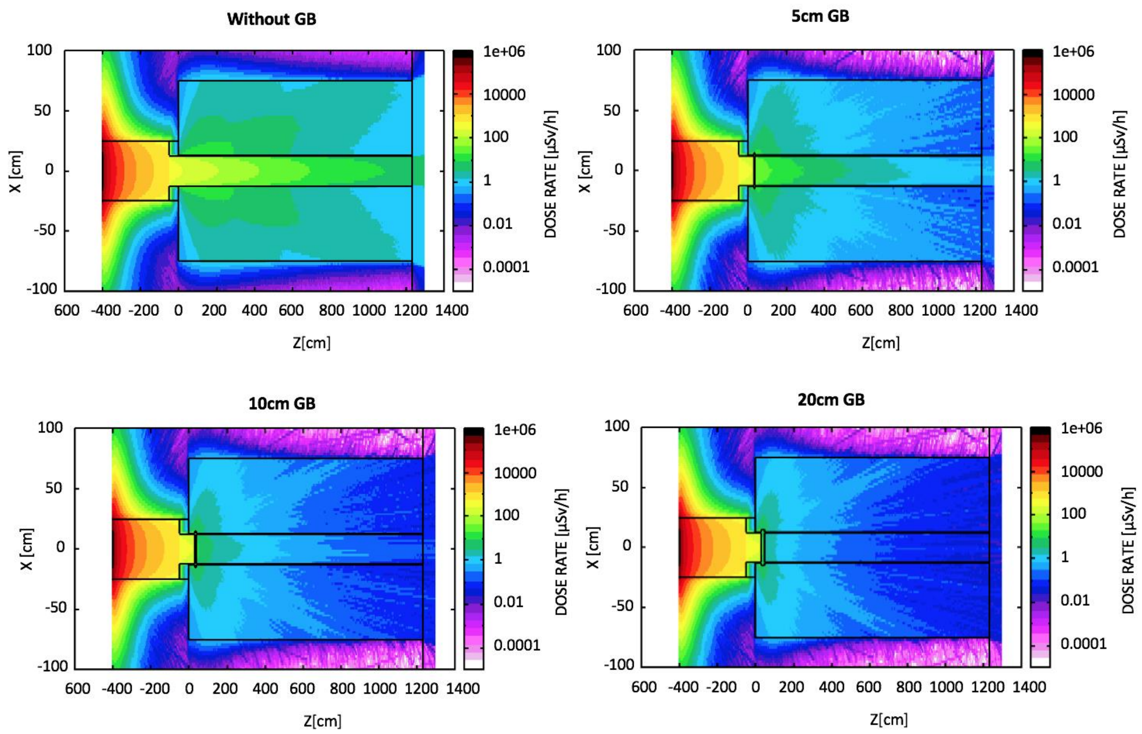
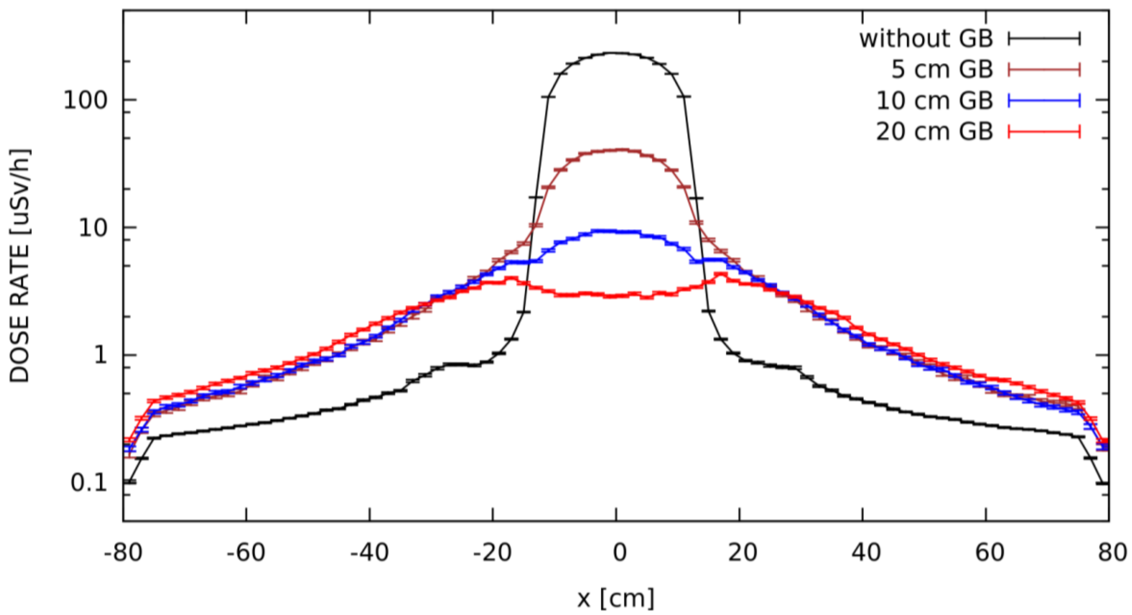


Figure 13 : Dose rate after 50 years of exposure, no cooling time, without GB for different steel GB thicknesses



The level of the dose rate was calculated on a cross section of the dump tunnel. The location of this measurement is on the GB contact plane behind the GB, see Figure 15.

Figure 14 : Dose rate vs. distance from the beam pipe. Projection on X-axis. Z=on GB contact (on the NSW contact in situation without GB). 50 years of exposure, no cooling time, GB thickness: 0cm, 5cm, 10cm, 20cm

To find the optimal thickness of the GB, the dose rate in the line of beam dump on the GB contact as a function of GB thickness for 50 years of irradiation 0s cooling times was calculated and is presented in Figure 16 respectively, in linear and logarithmic scale.

Table 5: Dose rate after 50 years of exposure and cooling times inside the 'beam pipe' for a different GB thickness

GB thickness	Dose rate after 5 years of exposure and 0 s cooling times inside the 'beam pipe' [μSv/h]
0,00	210
5,00	42
10,00	9,5
20,00	3

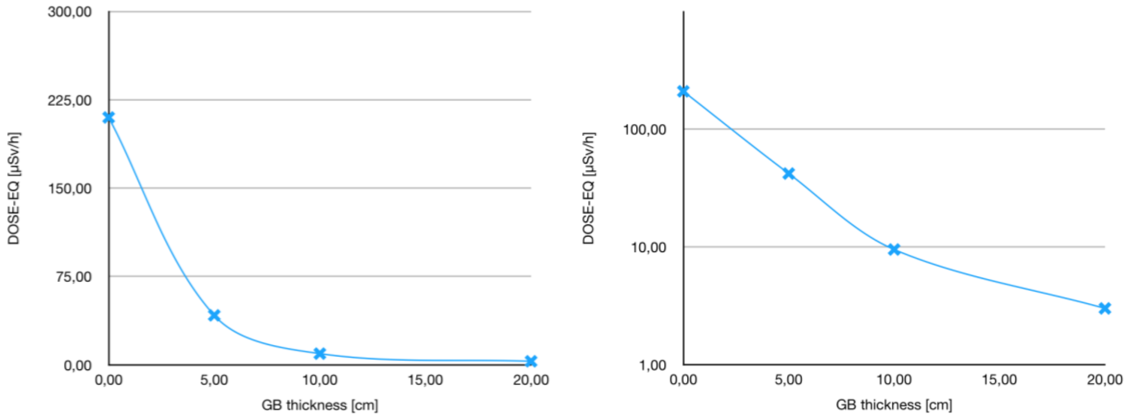


Figure 15 : Residual dose rate after 5 years of exposure at various cooling times inside the 'beam pipe' as a function of GB thickness

12. CONCLUSIONS AND RECOMMENDATIONS

Based on the presented simulations and calculations in Chapter 11, the Gamma blocker thickness in the A2T section must not be less than 10 cm. Minimum GB thickness in Beam Dump section is 5 cm.

13. GLOSARY

Term	Definition
A2T	Accelerator to Target section of the linac
DmpL	Dump Line section of the linac
ES&H	Environment, Safety and Health Division
GB	Gamma Blocker
NCBJ	National Centre for Nuclear Research (Poland)

14.REFERENCES

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Editor: C.H. CLEMENT Authors on behalf of ICRP N. Petoussi-Henss, W.E. Bolch, K.F. Eckerman, A. Endo, N. Hertel, J. Hunt, M. Pelliccioni, H. Schlattl, M. Zankl

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[9] A2T.ID and DmpL.ID L4 interface requirements, ESS-0126539

DOCUMENT REVISION HISTORY

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0	First draft issue	Karol Szymczyk	2017-07-17
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