HSE
Radiation Protection

Target and Target complex – Radiation Protection challenges

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HI-ECN3 BDF target & target complex initial review

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Content

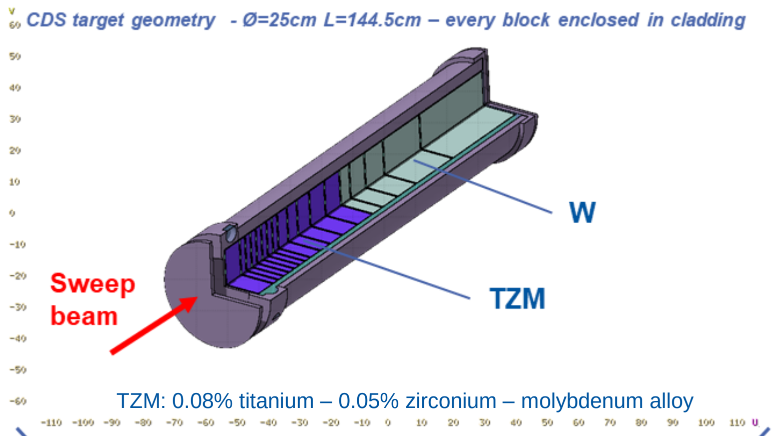
C. Ahdida *et al.*, *SPS Beam Dump Facility - Comprehensive Design Study*, **CERN-2020-002**
M. Casolino et al., *Radiological Assessment of the Beam Dump Facility at CERN*, **EDMS 2263868**

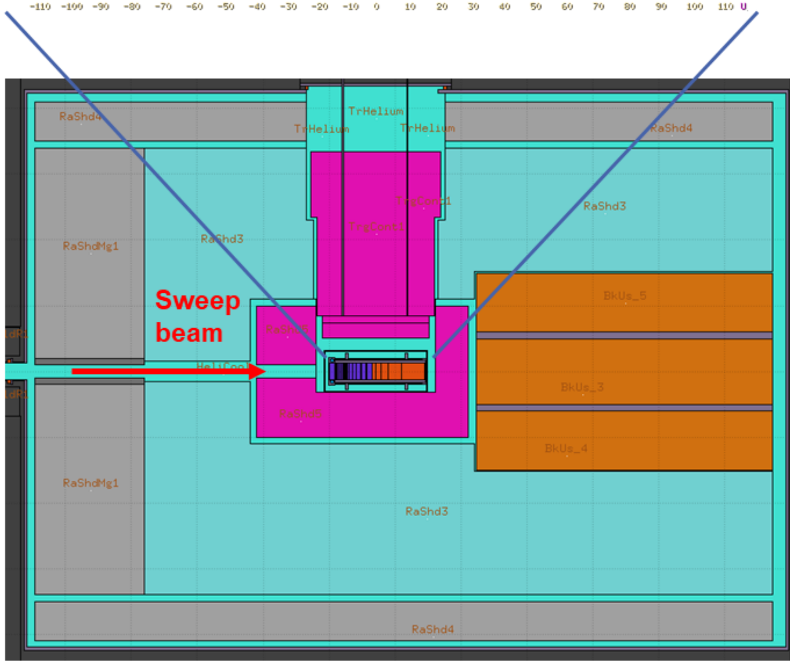
BDF Baseline Target

- Main RP studies for the BDF Baseline Target were performed during the BDF CDS phase
- **Target**:
  - 13 TZM blocks (Mo alloy)
  - 5 Tungsten blocks
  - Tantalum* cladding
- Target disks are water-cooled
- Maximum of 5 years of irradiation with a total of $4{\times}10^{19}$ PoT
- **RP studies**:
  - Residual radiation
  - Radionuclide inventory
  - Water activation
  - Alternative claddings (after CDS)
  - Prototype target tests

*Used pure Ta cladding not Ta2.5W for CDS RP studies

CDS BDF FLUKA model





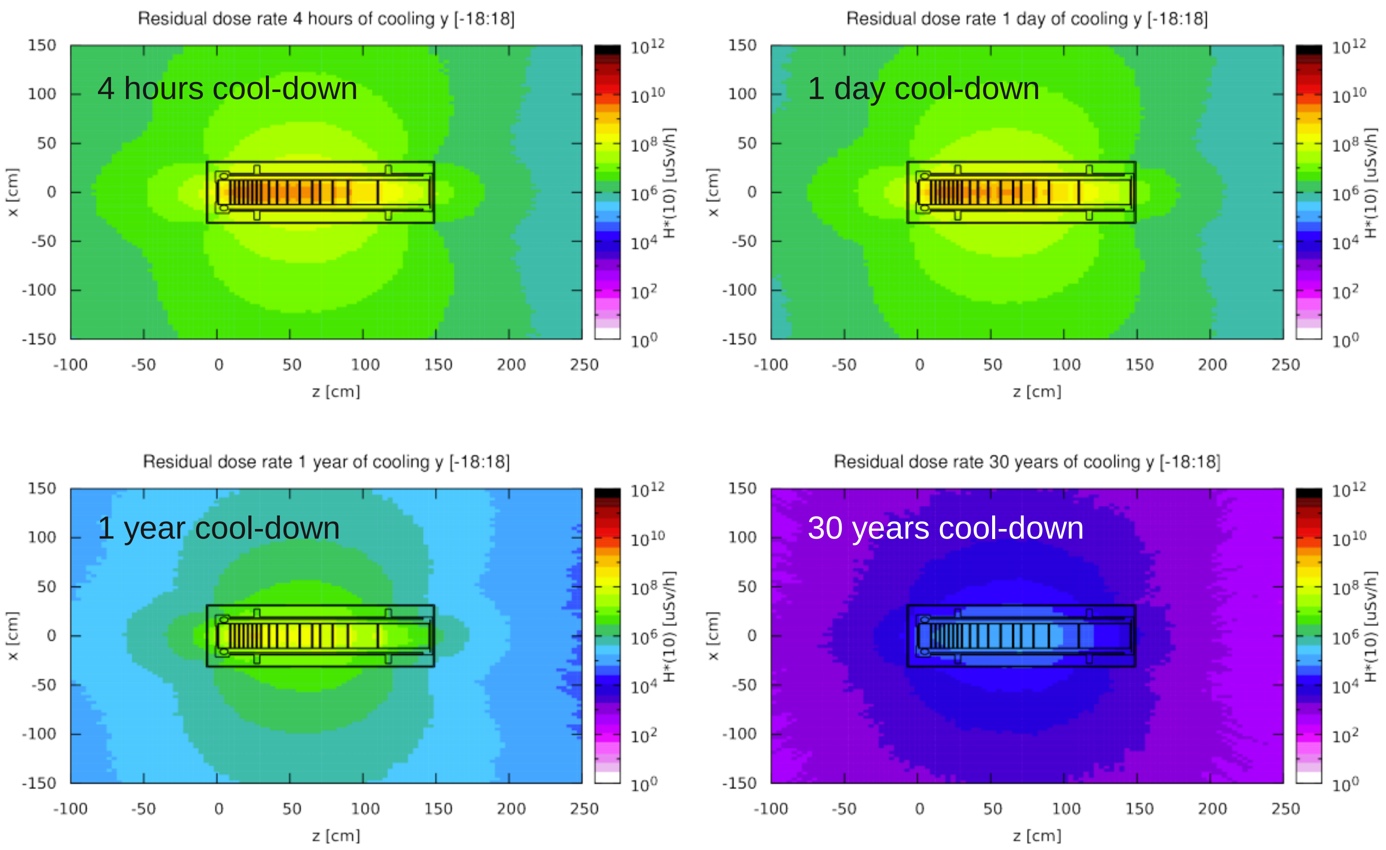
CDS target complex - target, shielding and hadron stopper – view from top

Residual Radiation

- The residual dose rates of the target were studied for 5 years of operation (now we have a max. of 15 years) and different cool-down times
- The highest dose rates are in the order of 100 Sv/h after 4 hours of cooling and a few Sv/h after 1 year
- Even after 30 years, dose rates at 40 cm still of the order of a few mSv/h → dedicated storage place in facility for irradiated target
- For radioactive transport the max. dose rate level at any point on the external surface of a package shall not exceed 2 mSv/h
- Thick iron cask (~30 cm thick) for transportation and storage as well as during handling

Total PoT 2×10^{20} (5 yrs)

Longitudinal cut along the target



Radionuclide inventories

Total PoT 2×10^20 (5 yrs)

Tungsten – Total Activity (Bq)

Radionuclide	Half-life	Activity [Bq]			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
H-3	12.33y	6.2E+12	5.9E+12	3.6E+12	1.2E+12
Pm-145	17.70y	6.6E+10	8.1E+10	7.0E+10	3.2E+10
Gd-148	74.60y	3.0E+10	3.0E+10	2.7E+10	2.3E+10
Tb-157	99.00y	2.8E+10	2.8E+10	2.6E+10	2.3E+10
Lu-172m	3.7min	4.9E+12	3.5E+12	1.2E+11	7.5E+07
Lu-172	6.7d	5.0E+12	3.5E+12	1.2E+11	7.6E+07
Hf-172	1.87y	4.9E+12	3.5E+12	1.2E+11	7.5E+07
Lu-173	1.34y	6.9E+12	4.3E+12	4.0E+10	1.3E+06
Hf-175	70.0d	1.9E+13	6.7E+11	5.0E-03	2.0E-34
Ta-178	9.3min	2.9E+13	6.3E+08	1.0E-37	1.9E-139
W-178	21.6d	2.9E+13	6.3E+08	1.0E-37	1.9E-139
Ta-179	1.61y	2.8E+13	1.9E+13	3.9E+11	7.2E+07
W-181	121.0d	1.0E+14	1.5E+13	1.0E+05	6.8E-14
Ta-182	114.7d	6.7E+12	8.8E+11	3.5E+04	3.3E+04
W-185	75.1d	6.5E+14	2.9E+13	2.0E+00	1.1E-29
Sum of all		9.2E+14	8.8E+13	4.6E+12	1.3E+12

Pure alpha/beta emitters are shown in bold
Dominant radionuclide is shown in red
Main contributors (>1%), sum for all radionuclides

Tungsten – Multiple of LL

Radionuclide	Half-life	Multiple of LL value			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
H-3	12.33y	9.0E+04	8.5E+04	5.1E+04	1.7E+04
Co-60	5.27y	1.3E+05	1.2E+05	3.6E+04	2.6E+03
Ba-133	10.54y	8.8E+05	8.3E+05	4.6E+05	1.2E+05
Pm-145	17.70y	9.6E+03	1.2E+04	1.0E+04	4.6E+03
Eu-146	4.6d	1.9E+06	1.6E+04	5.1E-17	1.5E-62
Gd-146	48.3d	1.7E+06	1.4E+04	4.6E-17	1.4E-62
Gd-148	74.60y	4.3E+04	4.3E+04	4.0E+04	3.3E+04
Eu-150	36.36y	3.4E+03	3.4E+03	2.8E+03	1.9E+03
Lu-172	6.7d	7.1E+06	5.0E+06	1.8E+05	1.1E+02
Hf-172	1.87y	7.0E+05	5.0E+05	1.8E+04	1.1E+01
Lu-173	1.34y	9.9E+06	6.2E+06	5.8E+04	1.8E+00
Lu-174	3.56y	1.4E+05	1.3E+05	2.4E+04	4.9E+02
Hf-175	70.0d	2.7E+07	9.7E+05	7.2E-09	2.9E-40
Ta-178	9.3min	4.2E+06	9.1E+01	1.5E-44	2.7E-146
W-178	21.6d	4.2E+06	9.1E+01	1.5E-44	2.7E-146
Ta-179	1.61y	4.0E+06	2.7E+06	5.7E+04	1.0E+01
W-181	121.0d	1.5E+07	2.1E+06	1.4E-02	9.8E-21
Ta-182	114.7d	9.6E+07	1.3E+07	5.0E-01	4.7E-01
Re-184m	168.0d	3.2E+06	8.0E+05	1.0E+00	8.6E-14
Sum of all		1.9E+08	3.4E+07	9.6E+05	1.9E+05

Tantalum – Multiple of LL

Radionuclide	Half-life	Multiple of LL value			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
H-3	12.33y	2.8E+05	2.7E+05	1.6E+05	5.2E+04
Co-60	5.27y	4.8E+05	4.3E+05	1.3E+05	9.4E+03
Ba-133	10.54y	3.0E+06	2.8E+06	1.5E+06	4.1E+05
Pm-145	17.70y	3.1E+04	3.8E+04	3.3E+04	1.5E+04
Gd-148	74.60y	1.4E+05	1.4E+05	1.3E+05	1.0E+05
Eu-150	36.36y	1.2E+04	1.2E+04	1.0E+04	6.9E+03
Lu-172	6.7d	2.4E+07	1.7E+07	5.9E+05	3.6E+02
Hf-172	1.87y	2.3E+06	1.7E+06	5.9E+04	3.6E+01
Lu-173	1.34y	3.7E+07	2.3E+07	2.2E+05	6.8E+00
Lu-174	3.56y	1.5E+06	1.4E+06	2.5E+05	5.1E+03
m-Hf-178	4s	6.2E+04	6.1E+04	5.0E+04	3.2E+04
Ta-179	1.61y	1.3E+07	8.6E+06	1.8E+05	3.3E+01
Ta-182	114.7d	1.7E+11	2.2E+10	5.3E+01	3.7E-18
Sum of all		1.7E+11	2.2E+10	3.4E+06	6.5E+05

LL: CERN clearance limit (see backup slides)

- Total of ~18 TBq of H-3 during 5 yrs operation

Water activation

- Activation of water from cooling circuits was estimated
- Shielding estimate around demineralization cartridges was performed assuming Be-7 to be stopped, but no target debris

  → 50 cm cylindrical concrete shielding was foreseen and for the roof of the area 165 cm concrete
- Remaining water in circuit mostly contains H-3 with a concentration of around 0.5 GBq/l per year of operation
- Due to the high H-3 production in the target (~18 TBq during 5 yrs operation), a significant contribution to the H-3 concentration in the water can come from H-3 out-diffusion from the target disks and subsequent trapping in the cooling water
- In case of 1% of out-diffusion every 2 months (best guess, no data available) and 100% trapping, the H-3 concentration from out-diffusion amounts to ~60 MBq/l every 2 months
- The exchange of cooling water (1 m^3) in one year would result in ~220 GBq of H-3 activity

PoT 1×10^{19} (1 yr)

Total Activity (Bq) for H-3 and Be-7

Radioisotope	Target	Proximity shielding	Magnetic coil
Be-7	1.3×10^{12}	2.6×10^{9}	6.2×10^{6}
H-3	7.4×10^{10}	1.8×10^{8}	4.1×10^{5}

Results above do not take out-diffusion from target into account

Alternative Claddings

Cladding materials (EDMS 2838723):

1. Tantalum – rho = 16.6 g/cm3
2. Nb (ASTM R04210 – Type 2) – rho = 8.6 g/cm3
3. Nb-1Zr (ASTM R04261 – Type 4) – rho = 8.6 g/cm3
4. Nb-10Hf-1Ti (ASTM R04295) – rho = 8.86 g/cm3

Total PoT 2×10^{20} (5 yrs)

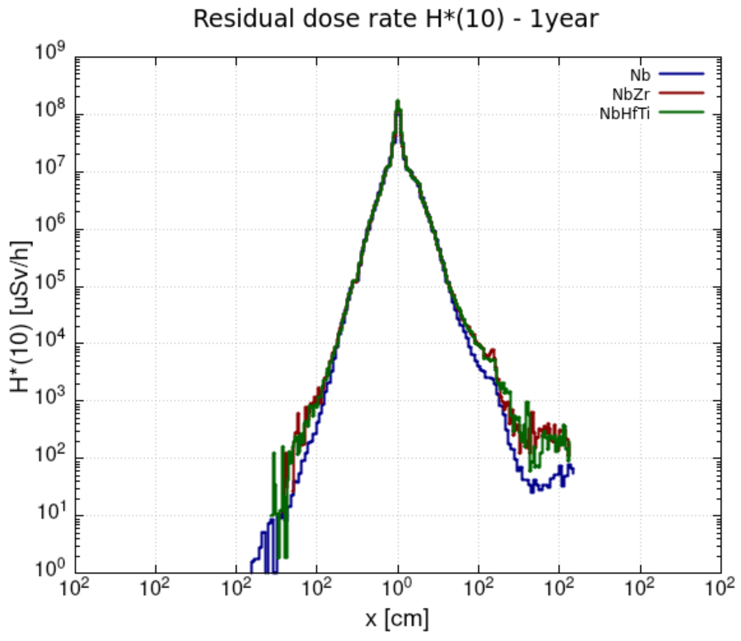
Material	Activity/LL - 5y	Activity/LL - 300y	Max. LMA fraction	RN exceeding LMA	RW Class.
Ta	1.30E+07	7.72E+03	7.58E+01	H-3 (75), Gd-148 (1.65)	FA-MA (CH)
Nb	1.62E+07	7.36E+06	6.19E+03	Nb-94 (6190), H-3 (65)	FA-MA (CH)
Nb-1Zr	1.60E+07	7.28E+06	5.23E+03	Nb-94 (5230), H-3 (66)	FA-MA (CH)
Nb-10Hf-1Ti	1.55E+07	6.22E+06	6.12E+03	Nb-94 (6120), H-3 (65)	FA-MA (CH)

- ➢ Waste classification as FA-MA waste to be disposed of in Switzerland

* LMA: *Limite Maximale d'Admissibilité,* no summation rule for the LMA

Total PoT 2×10^{20} (5 yrs), 1y cool-down

Residual dose rates (uSv/h)



Includes residual dose rates from surrounding material

- ➢ No difference in the residual dose rates for the various Nb claddings

Prototype Target Tests

- BDF target prototype w/ in total 14 h irradiation in TCC2, leading to 2.4E16 PoT
- Target activation was measured and compared to FLUKA simulations showing excellent agreement (uncertainty mainly from measurement position)
- Cooling water activation was estimated w/ FLUKA
- Estimated residual dose rate after 1h of cooling at 40 cm from the cartridge is 18.7 mSv/h, while the PMI monitor measured 16.9 mSv/h
  → 10% discrepancy may be due to the fact that not all ions are captured by the cartridge
- Both samples showed the presence of high-Z spallation products some of them could have been produced in the target materials

Benchmark of residual dose rates (mSv/h)

Position	Ambient dose rate [mSv/h]		Ratio
	Predicted (FLUKA)	Simulated	Predicted/Measured
contact	25.15 ± 0.01	26 ± 1	0.97 ± 0.04
40 cm	4.42 ± 0.01	5 ± 1	0.9 ± 0.2

Radionuclides in water samples

Radionuclide	Activity [Bq/l]	
	Sample 1	Sample 2
H-3	$1.96 \times 10^5 \pm 4.0\%$	$4.8 \times 10^5 \pm 4.0\%$
Be-7	$7.7 \times 10^3 \pm 6.6\%$	$2.37 \times 10^3 \pm 6.8\%$
Sc¡Sc44m	$2.49 \times 10^1 \pm 6.9\%$	$4.85 \times 10^1 \pm 5.7\%$
Sc-46	$1.51 \times 10^1 \pm 7.8\%$	$6.88 \times 10^1 \pm 6.8\%$
Sc-47	-	$1.17 \times 10^2 \pm 9.2\%$
Y-87	$1.45 \times 10^1 \pm 8.4\%$	$4.85 \times 10^1 \pm 6.2\%$
Ru-97	-	$1.27 \times 10^1 \pm 9.3\%$
Ag-106m	$1.41 \times 10^1 \pm 9.6\%$	-
In-111	-	$1.13 \times 10^1 \pm 8.5\%$
Eu¡Gd146	-	$1.19 \times 10^1 \pm 8.3\%$
Gd-149	-	$3.79 \times 10^1 \pm 8.1\%$
Tb-155	-	$4.57 \times 10^1 \pm 7.0\%$
Tm-166	-	$7.05 \pm 7.7\%$
Tm-167	-	$7.14 \times 10^1 \pm 8.9\%$
Yb-169	-	$3.13 \times 10^1 \pm 7.8\%$
Lu-171	-	$8.51 \times 10^1 \pm 6.8\%$

Water samples were analysed by liquid scintillation and gamma spectrometry

EDX of debris in water was inconclusive of material. No peaks were found for Ta, W, Mo or Ti. Metallic particle (Al, Ca, Fe, Cl, Fe, Cr) (EDMS 2364297)

TDR Studies for the Target

WP6.2 Radiation Protection

- Execute the required RP studies for latest target design option(s) and full 15-years lifecycle of facility
  - Residual dose rates
  - Radionuclide inventories
  - Shielding requirements
  - Water activation
- Execute the required RP studies for beam tests with prototype targets

WP6.3 Radioactive Transport and Waste Management

  - Study the radioactive transport and waste aspects for the prototype target tests
  - Provide guidance and support related to radioactive transport and waste for the BDF target design(s)

Content

HI ECN3 facility design optimization

- RP studies based on FLUKA MC simulations were performed for a design optimization of BDF/SHiP@ECN3
- ALARA approach
  Optimization required to ensure that exposure of personnel to radiation and radiological impact on environment are As Low As Reasonably Achievable

PROMPT RADIATION
Reduce prompt radiation to comply with **radiation area classification** in the surrounding accessible areas as well as the **1 mSv limit** at the **CERN fence**

RESIDUAL RADIATION
Limit activation of target and experimental area to reduce residual dose rates to be compatible with an adequate **area classification**

AIR AND SOIL ACTIVATION
Reduce activation of air and its releases into the environmental. Limit soil activation (^{3}H<1000 Bq/kg, ^{22}Na<50 Bq/kg) and transfer to groundwater

ENVIRONMENTAL IMPACT
Reduce environmental impact from prompt radiation and releases of activated air to fulfill CERN's **dose objective** for the **public** of <**10 uSv/year**

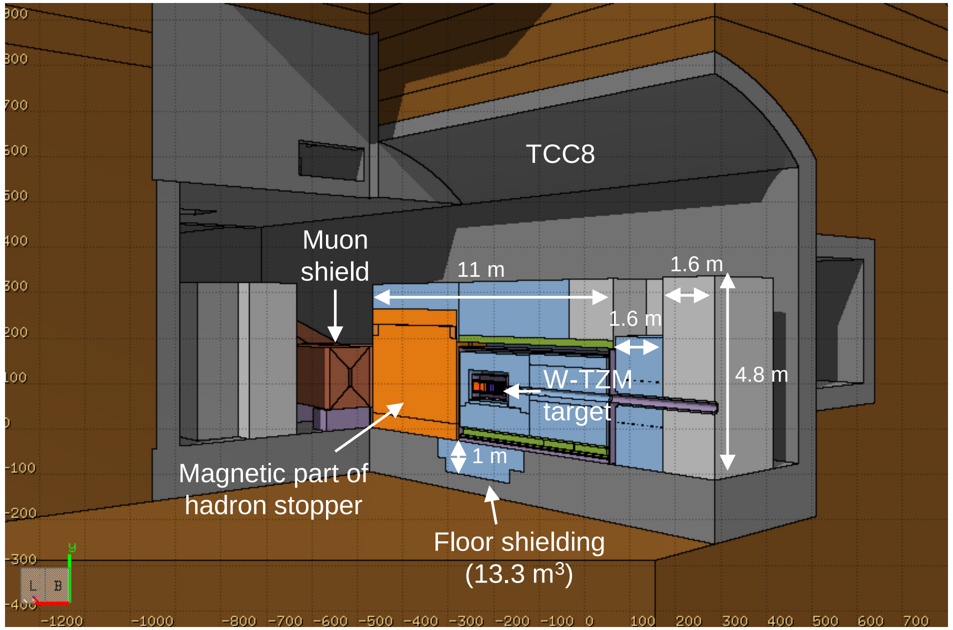
Radiation area classification

	Area	Annual dose limit (year)	Ambient dose equivalent rate: permanent occupancy	Ambient dose equivalent rate: low occupancy	Airborne activity concentration	Surface contamination	
	Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	0.05 CA	1 CS	
Radiation Area	Supervised	6 mSv	3 µSv/h	15 µSv/h	0.1 CA	1 CS	
Radiation Area	Simple Controlled	20 mSv	10 µSv/h	50 µSv/h	0.1 CA	1 CS	Controlled Area
Radiation Area	Limited Stay	20 mSv	-	2 mSv/h	100 CA	4000 CS	Controlled Area
Radiation Area	High Radiation	20 mSv	-	100 mSv/h	1000 CA	40000 CS	Controlled Area
Radiation Area	Prohibited	20 mSv	-	> 100 mSv/h	> 1000 CA	> 40000 CS	Controlled Area

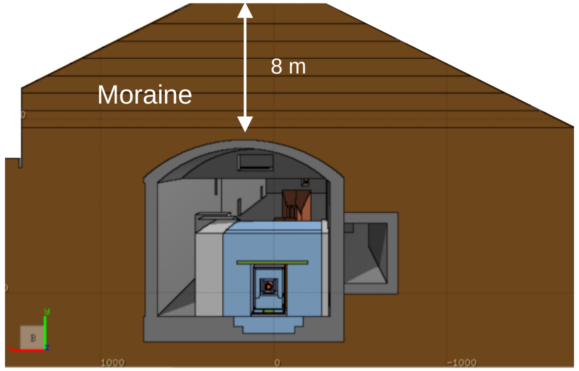
BDF/SHiP FLUKA model

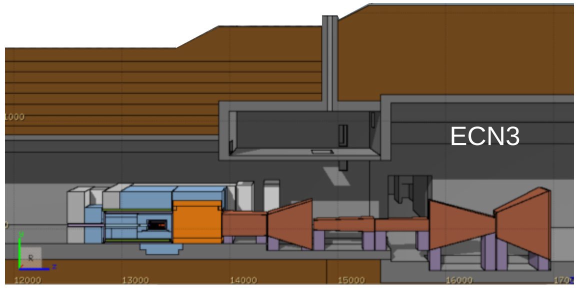
FLUKA hosted by CERN (FLUKA v4-3.0) [1-3]

Target complex & muon shield, Created using FLAIR [4]



- Stainless steel
- Concrete
- Cast iron
- US1010
- Moraine





- A detailed BDF/SHiP target complex together with the muon shield was implemented in FLUKA
- It was integrated in a FLUKA geometry including the full underground TCC8/ECN3 cavern and surrounding galleries, tunnels, rooms, etc.
- Ground profile data from CERN's Geographic Information System and technical drawings were used to model the surrounding ground

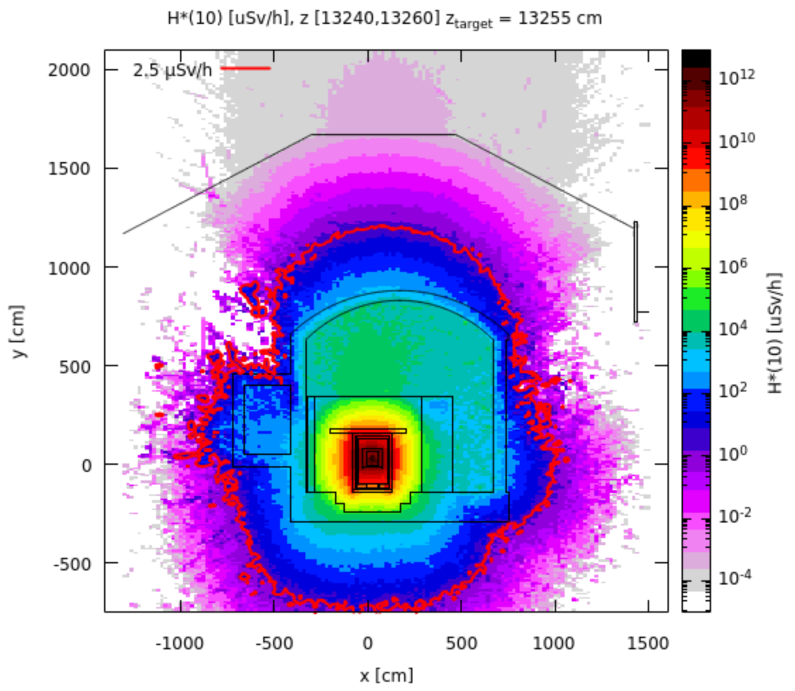
Prompt radiation in target area

Area	Annual dose limit (year)	Ambient dose equivalent rate		Sign
		permanent occupancy	low occupancy	RADIATION
Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h	
Supervised	6 mSv	3 μSv/h	15 μSv/h	Dosimeter obligatory / Dosimètre obligatoire
Simple Controlled	20 mSv	10 μSv/h	50 μSv/h	SIMPLE CONTROLLED / CONTRÔLÉE SIMPLE. Dosimeter obligatory / Dosimètre obligatoire
Limited Stay	20 mSv	-	2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ. Dosimeters obligatory / Dosimètres obligatoires
High Radiation	20 mSv	-	100 mSv/h	HIGH RADIATION / HAUTE RADIATION. Dosimeters obligatory / Dosimètres obligatoires
Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY / DÉFENSE D'ENTRER

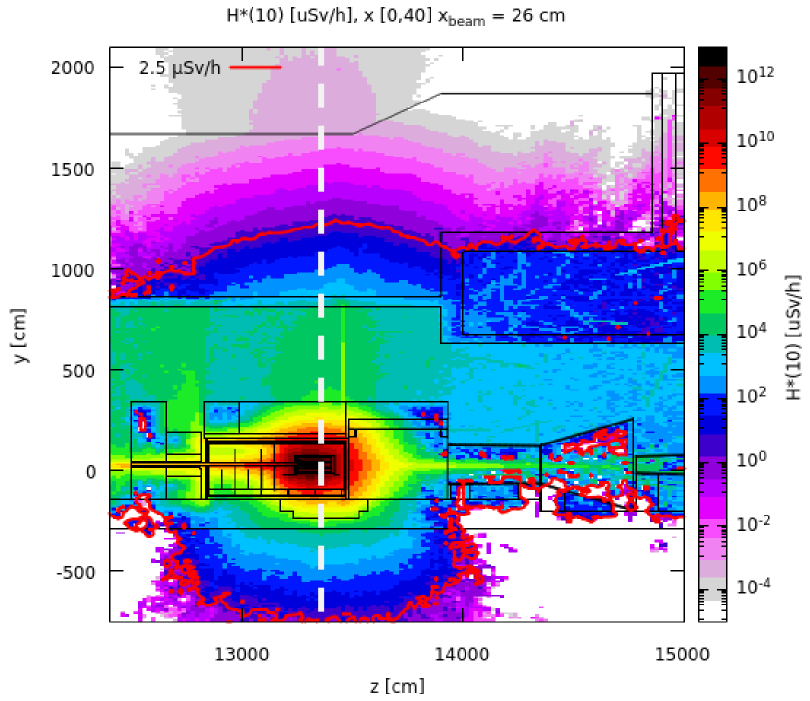
Radiation Area (Supervised to Prohibited); Controlled Area (Simple Controlled to Prohibited)

Avg. intensity of 5.6×10^{12} p/s

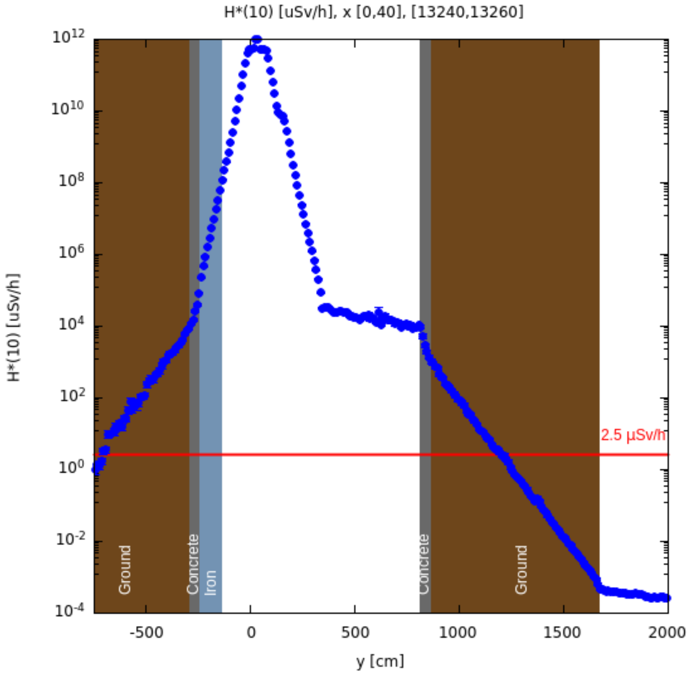
Cross-sectional view



Side view



Along y-axis



- Shielding design is optimized for the prompt radiation
- Thanks to shielding reinforcements towards the bottom, no increase of soil activation expected

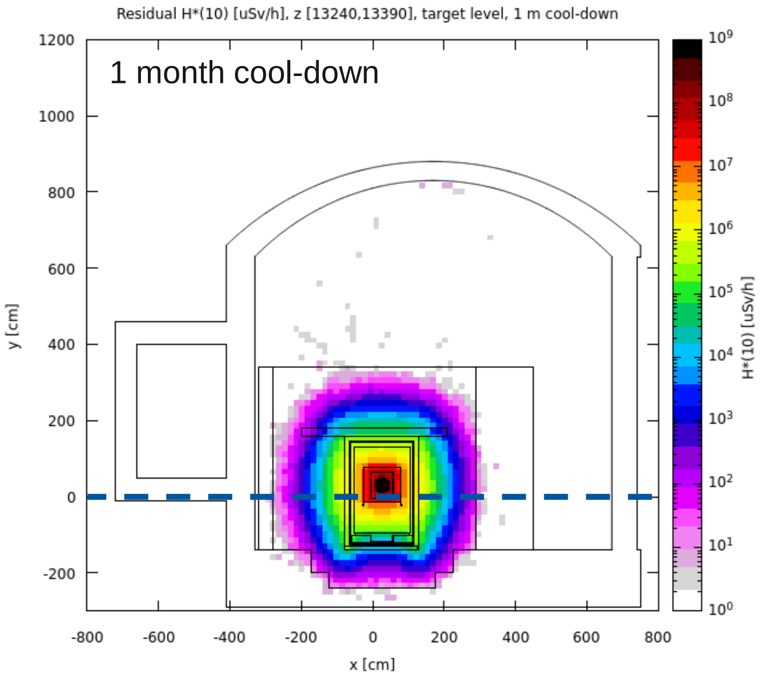
100 rem = 1Sv

Residual radiation in target area

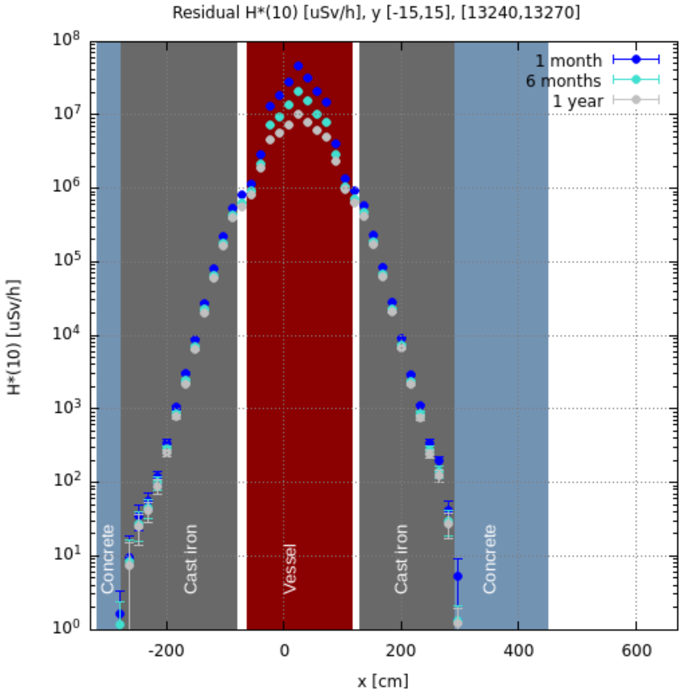
Area		Annual dose limit (year)	Ambient dose equivalent rate		Sign	
			permanent occupancy	low occupancy		
	Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h		
Radiation Area	Supervised	6 mSv	3 μSv/h	15 μSv/h	Dosimeter obligatory / Dosimètre obligatoire	
Radiation Area	Simple Controlled	20 mSv	10 μSv/h	50 μSv/h	SIMPLE CONTROLLED / CONTRÔLÉE SIMPLE, Dosimeter obligatory / Dosimètre obligatoire	Controlled Area
Radiation Area	Limited Stay	20 mSv	-	2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ, Dosimeters obligatory / Dosimètres obligatoires	Controlled Area
Radiation Area	High Radiation	20 mSv	-	100 mSv/h	HIGH RADIATION / HAUTE RADIATION, Dosimeters obligatory / Dosimètres obligatoires	Controlled Area
Radiation Area	Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY / DÉFENSE D'ENTRER	Controlled Area

Total PoT 6×10^{20}

Cross-sectional view, target level



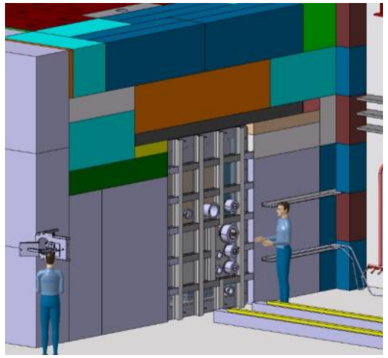
Along x-axis, working height

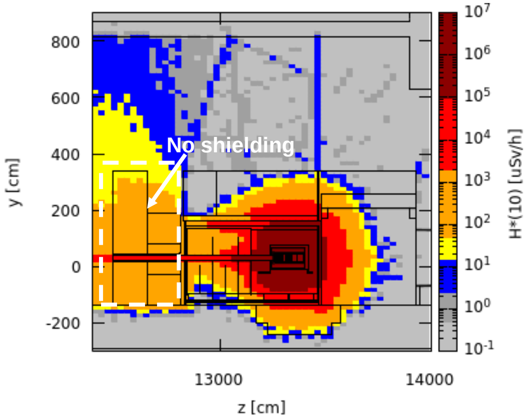


- The shielding design contains well the high residual dose rates reaching in the central target region several 10 Sv/h after 1 month of cool-down
- The residual dose rates outside the shielding are < 1 μSv/h

Upstream of vessel w/o upstream shielding

Preliminary worst case manual intervention scenario





- After removal of the shielding upstream of the vessel, residual dose rates are within a Limited Stay Controlled Radiation Area
- Supervised Radiation Area on the sides
- Further optimization by movable shielding

100 rem = 1Sv

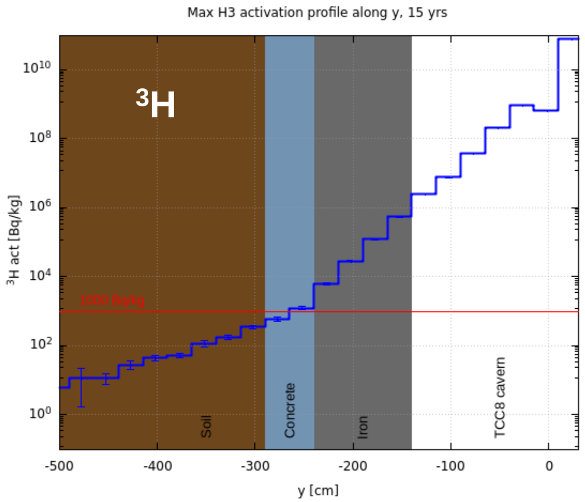
Air and soil activation

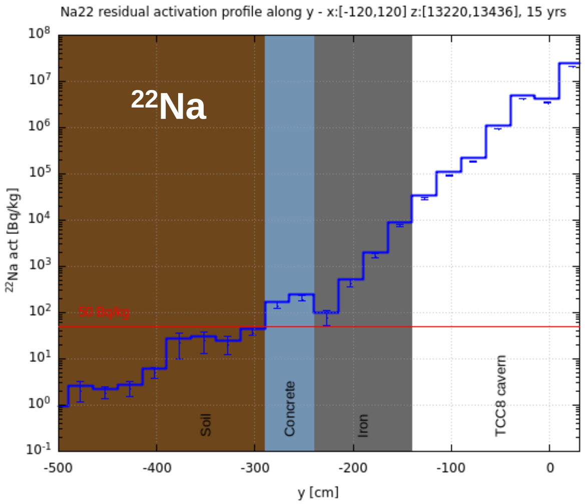
Area	Annual dose limit (year)	Ambient dose equivalent rate: permanent occupancy	Ambient dose equivalent rate: low occupancy	Airborne activity concentration	Surface contamination
Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h	0.05 CA	1 CS
Supervised	6 mSv	3 μSv/h	15 μSv/h	0.1 CA	1 CS
Simple Controlled	20 mSv	10 μSv/h	50 μSv/h	0.1 CA	1 CS
Limited Stay	20 mSv	-	2 mSv/h	100 CA	4000 CS
High Radiation	20 mSv	-	100 mSv/h	1000 CA	40000 CS
Prohibited	20 mSv	-	> 100 mSv/h	> 1000 CA	> 40000 CS

Radiation Area; Controlled Area

Total PoT 6×10^{20}

Specific activity of ^{3}H and ^{22}Na in the soil below TCC8
(most critical area)





- Thanks to floor iron shielding, ^{3}H and ^{22}Na activity concentrations in the soil are below respective design limits
- A hydro-geological study is underway, which will allow to refine the design limits and possibly allow to reduce the required shielding

PoT 4×10^{19} per year

Air activation

- Activation of air in target complex area were studied
- Production of radionuclides evaluated with FLUKA in combination with ActiWiz [5]

Region	Volume [m^3]	CASE 1: Total A [Bq]	CASE 1: As [Bq/m^3]	CASE 1: CA [$\mu Sv/h$]	CASE 2: Total A [Bq]
Air	2127	3.69×10^{6}	1.73×10^{3}	3.34×10^{-1}	1.19×10^{11}

CASE 1: build-up of radionuclides during operation w/o air extraction and 30 min cooldown time before air release
CASE 2: constant immediate release of air (worst-case for upper limit of environmental impact)

- Flush of target complex with fresh air before any access to reduce specific airborne radioactivity to be compatible with 0.1 CA

[1] Person working 40h/w, 50w/y with standard breathing rate in activated air with CA = 1 receives 20 mSv

Environmental impact

Dose from air releases

- Used max. dose coefficients from different age groups [6]

Effective dose estimates

Air	Total A [Bq]	Effective Dose [μSv/y]
CASE 1	3.69×10^{6}	1×10^{-5}
CASE 2	1.19×10^{11}	3×10^{-3}

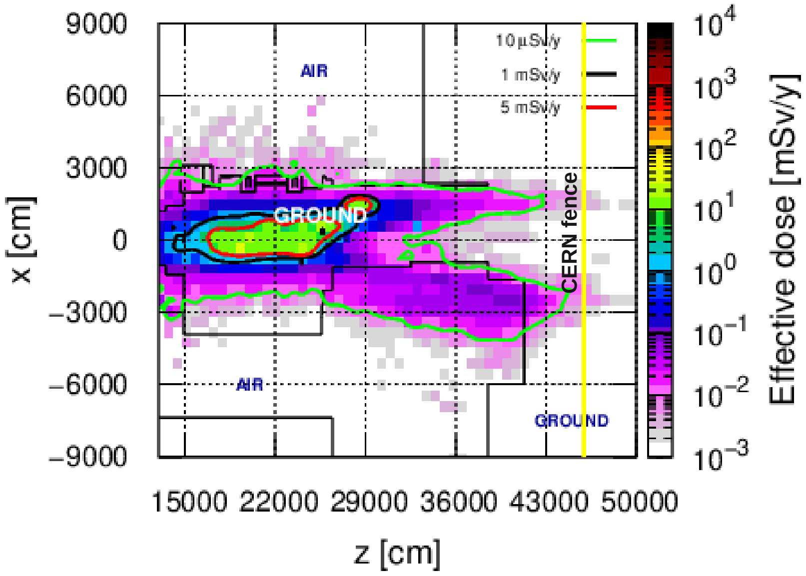
H-3 release due to air activation of ~80 kBq

Positions of nearby population groups

- ➢ Worst-case immediate air release (CASE 2) yields 3 nSv/year and is thus well below the annual dose objective of CERN
- ➢ Exposure of members of the public due to air releases is negligible

100 rem = 1Sv

Dose from stray radiation



Muon prompt radiation aboveground downstream ECN3

- ➢ Annual limit of Non-designated Area on CERN domain (5 mSv/y) and at CERN fence (1 mSv/y) as well as dose objective for members of the public (10 uSv/y) by far met

TDR Studies for the Target Complex

WP6.2 Radiation Protection

- Re-evaluate the target complex shielding requirements depending on the outcome of the hydrogeological study and possibly relaxed soil activation limits
- Execute the required RP studies for the design optimization/integration of the target complex including handling considerations
- Perform the residual dose rate studies for maintenance scenarios (e.g. target exchange) w/ different irradiation and cool-down scenarios
- Perform the required RP studies (e.g. residual dose rates, radionuclide inventories, shielding requirements) for target sub-systems for transport, waste disposal and FIRIA
- Evaluate RP requirements (e.g. shielding, ventilation, cooling station) for the service building
- Evaluate RP requirements for irradiation stations at the Target Complex

WP6.3 Radioactive Transport and Waste Management

- Provide guidance and support related to radioactive transport and waste for the BDF complex design

Thank you for your attention!

Radioactive Material

When is a material radioactive?

Specific and total activity exceed clearance limits (LL values)
as given in the Annex of EDMS 942170 (adopted from Swiss legislation)

Examples: 0.1 Bq/g for ^{22}Na, ^{54}Mn, ^{60}Co
1000 Bq/g for ^{55}Fe

OR

Sum rule for mixture of radionuclides:

$$\sum_{i=1}^{n} \frac{a_i}{LL_i} < 1$$

Net ambient dose equivalent rate > 0.1 µSv/h in 10 cm distance

OR

Surface contamination exceeds limits
as given in the Annex of EDMS 942170 (> 1 CS)

Sum rule for mixture of radionuclides:

$$\sum_{i=1}^{n} \frac{c_i}{CS_i} < 1$$

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942170	8.0	RELEASED

RÉFÉRENCE

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Operational Radiation Protection Rule

Clearance Limits for
Radioactive Material at CERN

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