HIKECN3

Radiation Protection Considerations for HI-ECN3

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WP6 - Radiation Protection & Safety

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Outline

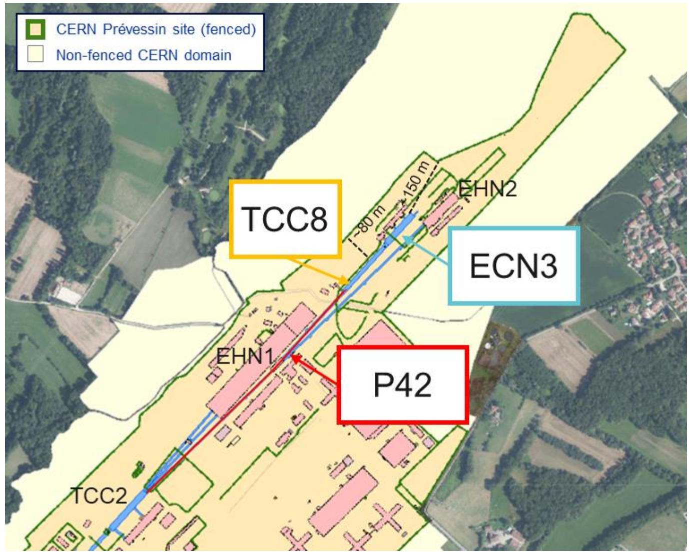
1. Overview of RP Challenges at HI-ECN3

2. Target Complex Design Optimization

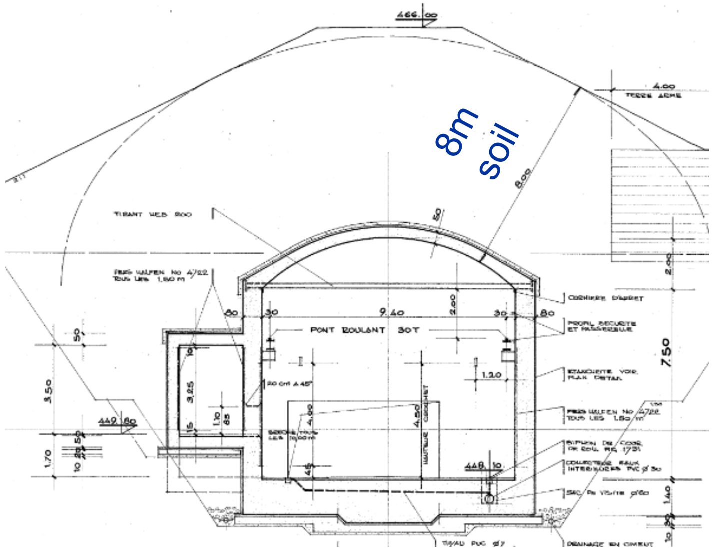
3. Target Studies

HI-ECN3 at ECN3

CERN's SPS North Area



TCC8 cross-section



Key beam parameters of BDF/SHiP

	BDF
Intensity (p/spill)	4×10^{13}
Spill duration (s)	≥1
Cycle length (s)	≥7.2
Avg. beam power (kW)	356
Average intensity (p/s)	$\leq5.6\times10^{12}$
Annual POT	4×10^{19}
Duration (years)	15
Total POT	6×10^{20}

- **High Intensity ECN3 (HI-ECN3) project** for a new state-of-the-art high intensity experimental facility in ECN3
  - exploiting the available high intensity SPS 400 GeV/c proton beam
  - benefiting from an existing cavern of comfortable size incl. its infrastructure
  - using the advantage of the shielding created by the soil

- **RP challenges**
  - High beam energy and intensity as well as high POT leading to high prompt radiation and activation levels
  - Proximity to surface, experimental and public areas
  - Losses during beam transfer (not covered here)

Target Complex Optimization

BDF/SHiP design optimization

- RP studies based on FLUKA MC simulations were performed for a design optimization of BDF/SHiP@HI-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**

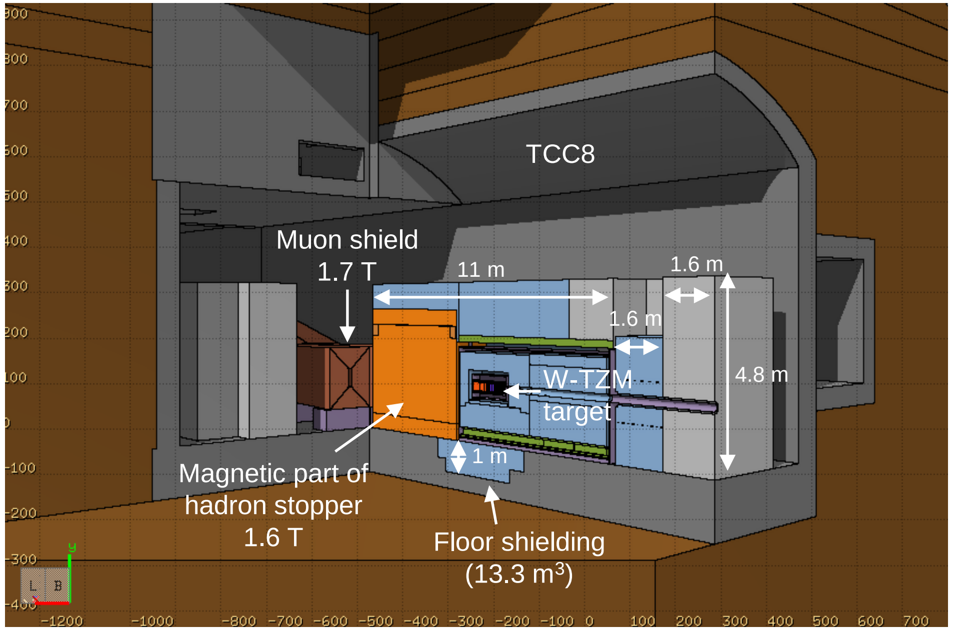
Radiation area classification

	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

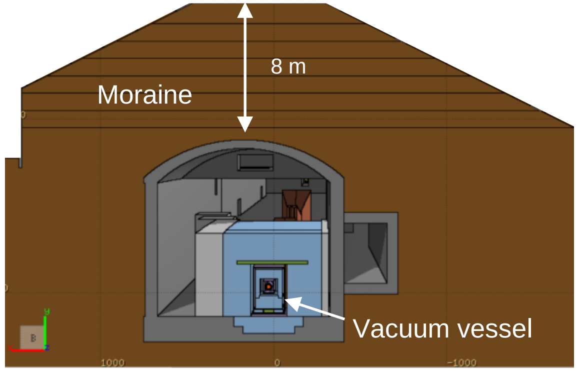
BDF/SHiP FLUKA model

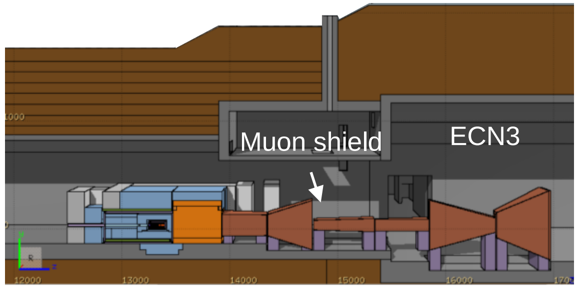
FLUKA hosted by CERN [1-3]

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



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





~180 m^3 of cast iron + US1010
~360 m^3 of concrete

- A detailed BDF/SHiP target complex together with the muon shield was implemented in FLUKA
- Optimized BDF dump with reduced shielding and re-use of existing, already activated TCC8/TT7 shielding blocks, while maintaining SHiP physics performance
- Shielding embedded in vacuum vessel
- FLUKA geometry includes 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

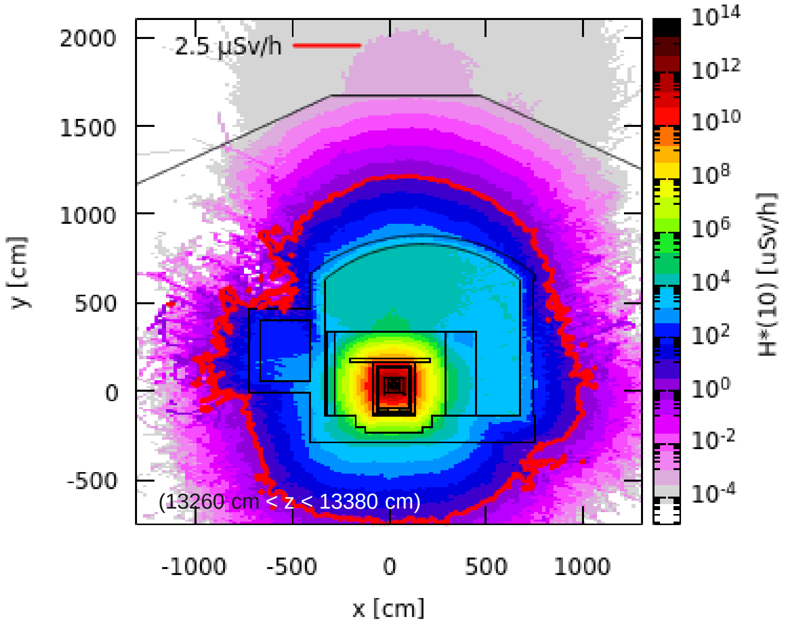
Prompt radiation in target area

Area	Annual dose limit (year)	Ambient dose equivalent rate permanent occupancy	Ambient dose equivalent rate low occupancy	Sign
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

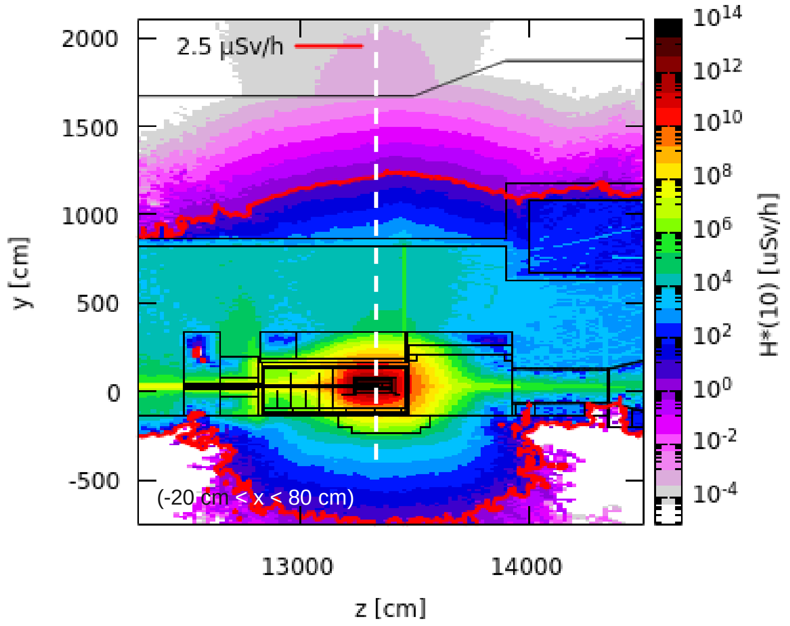
Radiation Area (Supervised to Prohibited); Controlled Area (Simple Controlled to Prohibited)

Avg. intensity of 5.6×10^{12} p/s

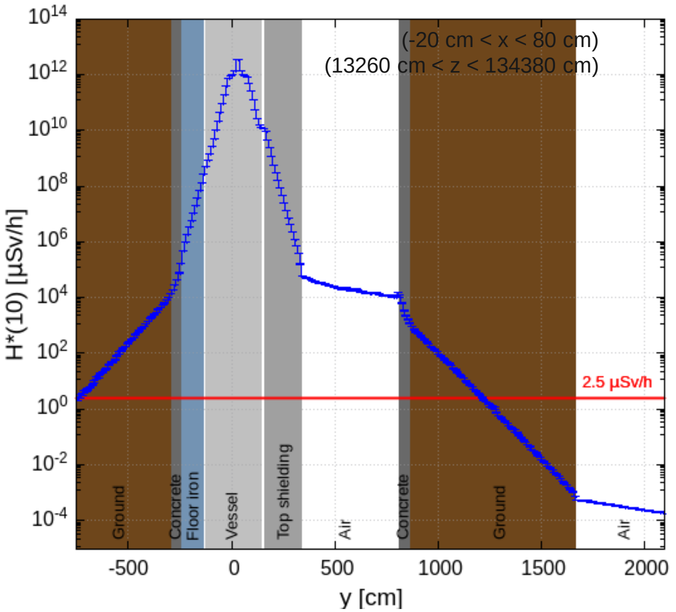
Cross-sectional view



Side view



Along y-axis



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

Residual radiation in target area

	Area	Annual dose limit (year)	Ambient dose equivalent rate: permanent occupancy	Ambient dose equivalent rate: low occupancy	Sign	
	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	
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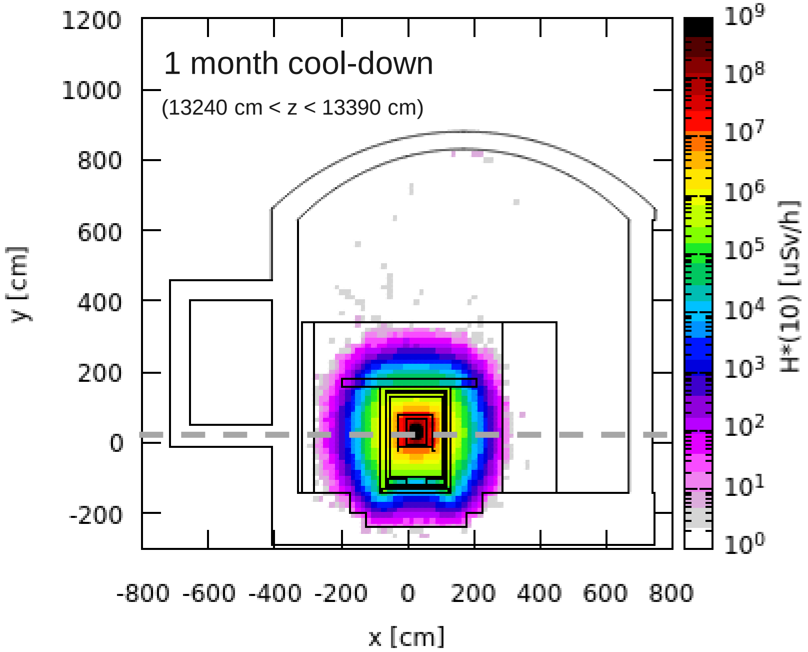
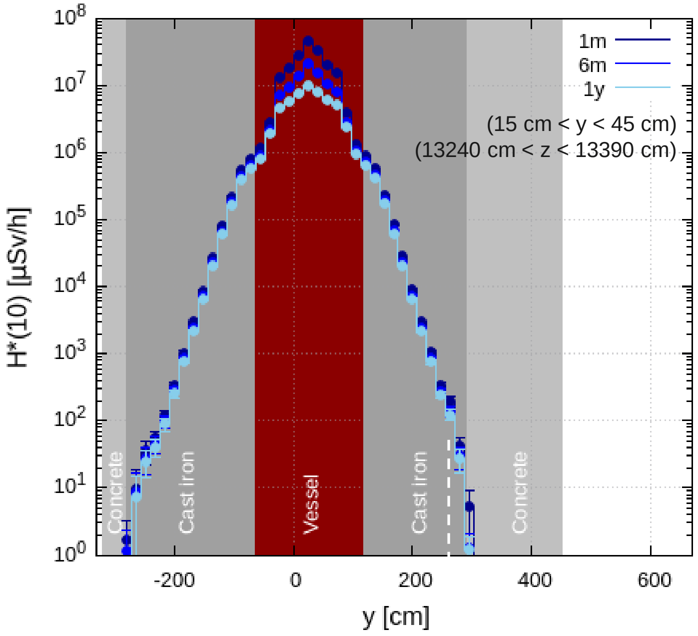
Radiation Area	Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY DÉFENSE D'ENTRER	Controlled Area

Total PoT 6×10^{20}

Cross-sectional view, target level

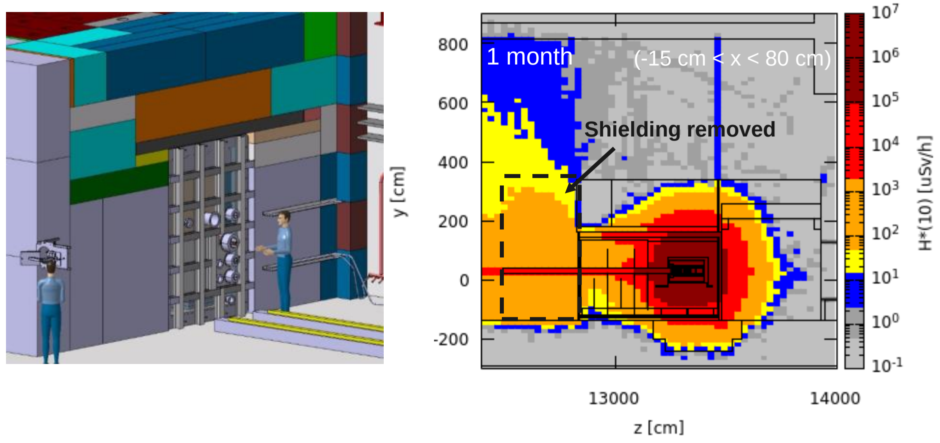


Along x-axis, working height



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 of several 100 µSv/h are expected
- Supervised Radiation Area on the sides
- Further optimization by movable shielding

- 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

Air and soil activation

Area	Annual dose limit (year)	Ambient dose equivalent rate: permanent occupancy	Ambient dose equivalent rate: low occupancy	Sign
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
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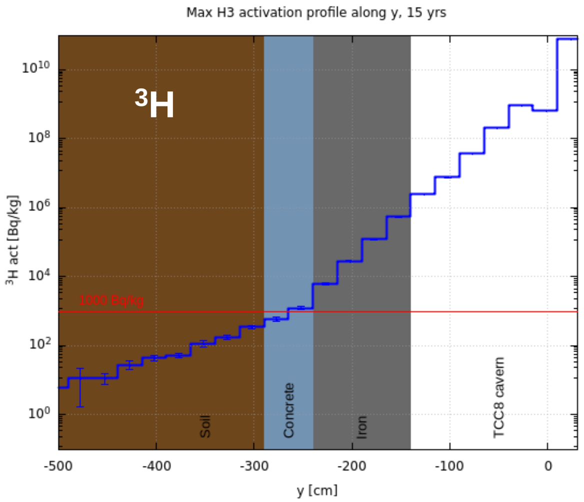
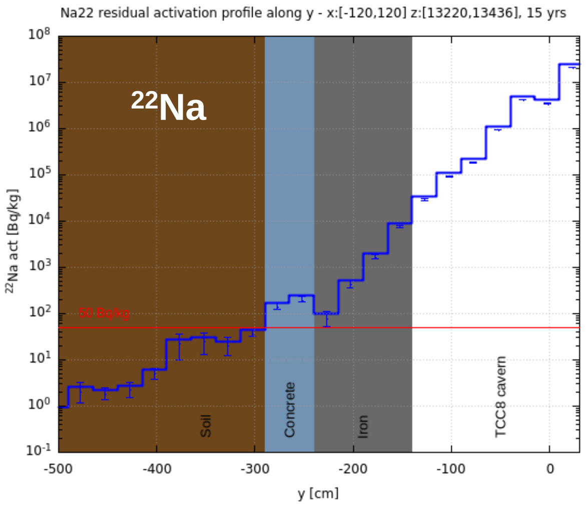
Radiation Area (Supervised to Prohibited); Controlled Area (Simple Controlled to Prohibited). Sign header: RADIATION

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]

		CASE 1			CASE 2
Region	Volume [m^3]	Total A [Bq]	As [Bq/m^3]	CA [μSv/h][1]	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
- Exposure of members of the public due to air releases is negligible

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

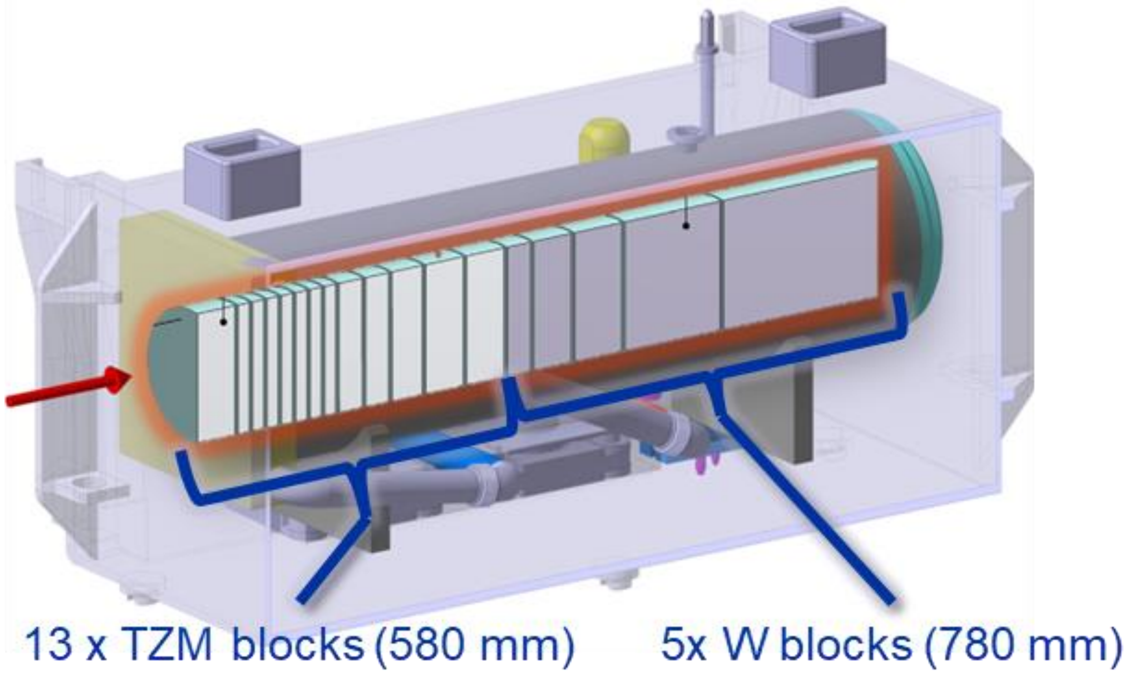
BDF Target Studies

BDF Target baseline design

Baseline Design (CDS) – Water cooled, W + TZM cladded w/ Ta2.5W

- Pursued during the comprehensive design phase → C. Ahdida et al., *SPS Beam Dump Facility - Comprehensive Design Study*, CERN-2020-002

- Prototype + test with beam + Post irradiation examination

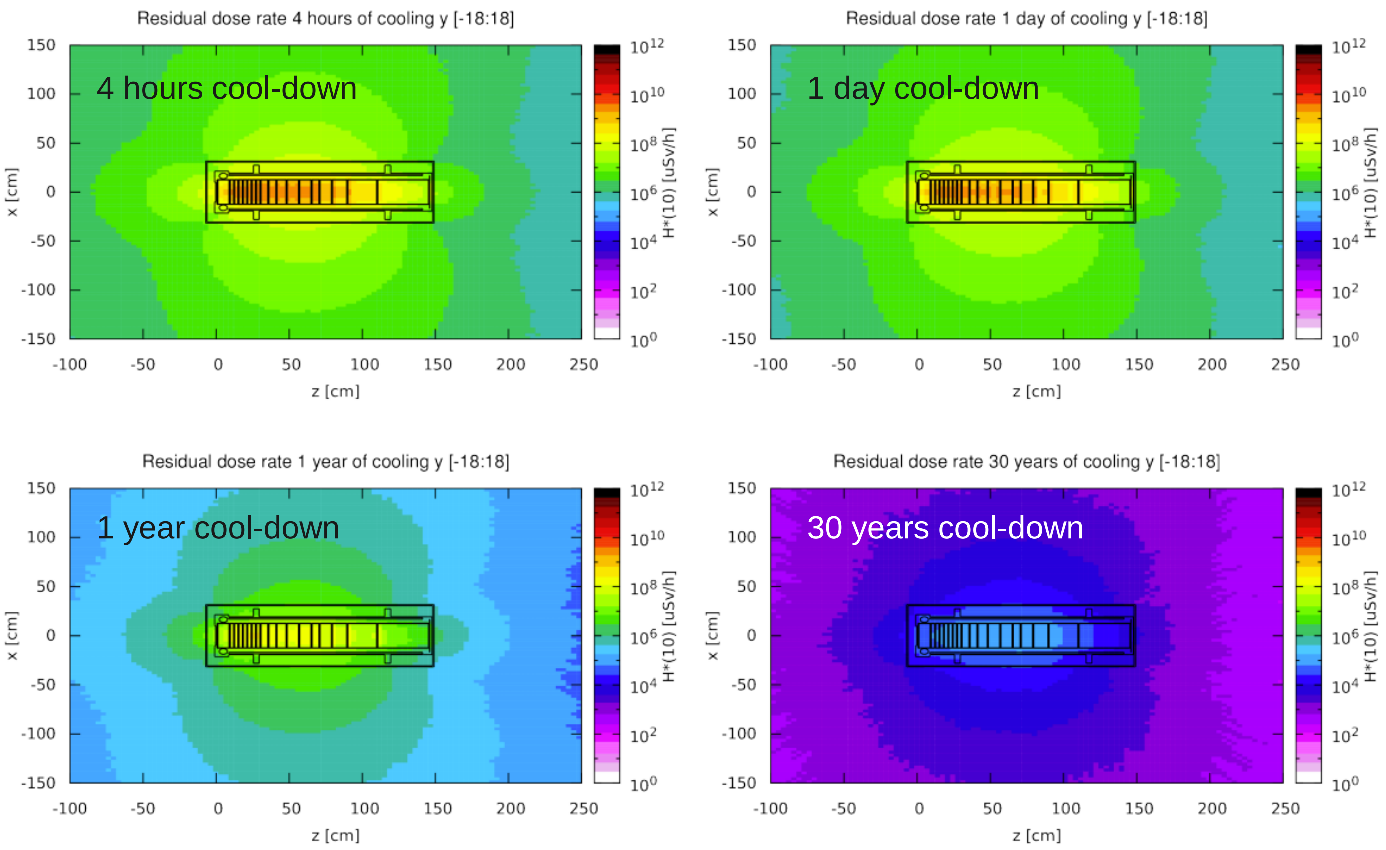


Residual Radiation – baseline CDS target

Total PoT 4×10^{19} (5 yrs)

Longitudinal cut along the target

- The residual dose rates of the target were studied for 5 years of operation (now 15 yrs) 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



CDS target radionuclide inventories

Total PoT 2×10^{20} (5 yrs)

LA multiples of BDF target materials

Main contributors (>1%), sum for all radionuclides

W

Radionuclide	Half-life	Multiple of LA value			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
Gd-148	74.60y	1.5E+08	1.5E+08	1.4E+08	1.1E+08
Yb-169	32.0d	3.2E+06	2.3E+03	2.9E-28	6.8E-97
Hf-172	1.87y	4.9E+07	3.5E+07	1.2E+06	7.5E+02
Hf-175	70.0d	3.1E+06	1.1E+05	8.4E-10	3.4E-41
Ta-182	114.7d	9.5E+06	1.3E+06	5.0E-02	4.7E-02
W-185	75.1d	3.2E+07	1.5E+06	1.0E-07	5.5E-37
Sum of all		2.6E+08	1.9E+08	1.4E+08	1.1E+08

Ta

Radionuclide	Half-life	Multiple of LA value			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
Gd-148	74.60y	1.9E+07	1.9E+07	1.7E+07	1.4E+07
Hf-172	1.87y	6.4E+06	4.6E+06	1.6E+05	9.9E+01
m-Hf-178	4s	8.6E+05	8.4E+05	6.9E+05	4.4E+05
Ta-182	114.7d	6.6E+08	8.8E+07	2.1E-01	1.5E-20
Sum of all		6.9E+08	1.1E+08	1.8E+07	1.5E+07

Pure alpha/beta emitters are shown in bold

Dominant radionuclide is shown in red

TZM

Radionuclide	Half-life	Multiple of LA value			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
H-3	12.33y	8.2E+04	7.8E+04	4.7E+04	1.5E+04
Si-32	132.00y	7.0E+03	7.0E+03	6.6E+03	6.0E+03
Ti-44	60.00y	2.4E+04	2.4E+04	2.2E+04	1.7E+04
Co-60	5.27y	6.8E+05	6.0E+05	1.8E+05	1.3E+04
Zn-65	244.2d	3.9E+05	1.5E+05	1.4E+01	1.3E-08
Ge-68	271.0d	1.2E+06	5.2E+05	1.2E+02	9.0E-07
Se-75	119.6d	8.5E+05	1.2E+05	6.6E-04	2.8E-22
Sr-82	25.6d	8.8E+06	1.0E+03	2.0E-36	1.9E-122
Rb-83	86.2d	1.6E+06	1.1E+05	3.7E-07	1.2E-32
Sr-85	64.8d	1.4E+06	3.8E+04	2.2E-11	2.8E-45
Zr-88	83.0d	2.2E+07	1.3E+06	1.6E-06	5.4E-33
Y-88	106.6d	9.4E+06	3.1E+06	2.9E-03	7.1E-24
Sr-90	28.79y	4.7E+04	4.6E+04	3.7E+04	2.3E+04
m-Nb-91	60.9d	1.3E+07	2.8E+05	1.6E-11	1.3E-47
Nb-91	680.00y	1.6E+05	1.7E+05	1.7E+05	1.6E+05
m-Nb-93	16.13y	1.6E+05	1.6E+05	1.1E+05	4.9E+04
Mo-93	3999.92y	1.1E+04	1.1E+04	1.1E+04	1.0E+04
Nb-94	19989.57y	7.2E+03	7.2E+03	7.2E+03	7.2E+03
Zr-95	64.0d	1.3E+07	3.5E+05	1.3E-10	6.0E-45
Nb-95	35.0d	7.2E+06	1.9E+05	6.9E-11	3.3E-45
Sum of all		8.4E+07	7.5E+06	5.9E+05	3.1E+05

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

Target	Material	Mass [kg]	Multiple LL	Multiple LA	A [Bq]
CDS	W	695	1.9E+08	2.6E+08	9.2E+14
	TZM	271	1.1E+09	8.4E+07	1.8E+14
	Ta	28	1.7E+11*	6.9E+08	9.8E+14

*Dominated (99.9%) by Ta-182 (115 d half-life)

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
- 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
- Both samples showed the presence of high-Z spallation products some of them could have been produced in the target materials
- Water-cooling filter with debris was analysed via EDX
  - No peaks were found for Ta, W, Mo or Ti
  - Metallic particle (Al, Ca, Fe, Cl, Fe, Cr)

Benchmark of residual dose rates (mSv/h)

Position	Ambient dose rate [mSv/h]		Ratio
	Predicted (FLUKA)	Measured	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

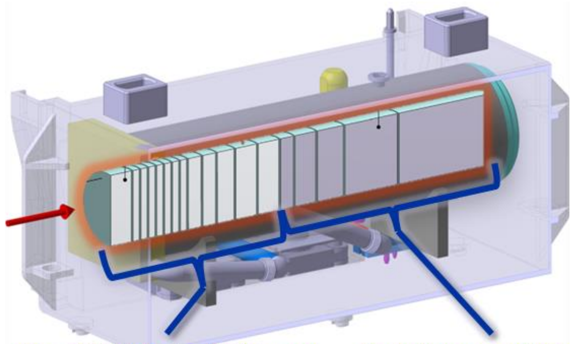
Radionuclide	Activity [Bq/l]	
	Sample 1	Sample 2
H-3	$1.96 \times 10^5 \pm 4.0\%$	$4.8 \times 10^5 \pm 4.0\%$
Be-7	$7.7 \times 10^3 \pm 6.6\%$	$2.37 \times 10^3 \pm 6.8\%$
Sc¡Sc44m	$2.49 \times 10^1 \pm 6.9\%$	$4.85 \times 10^1 \pm 5.7\%$
Sc-46	$1.51 \times 10^1 \pm 7.8\%$	$6.88 \times 10^1 \pm 6.8\%$
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

Alternative BDF target design studies

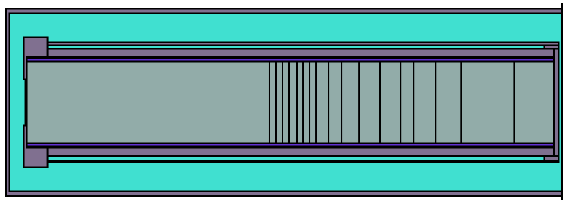
Baseline Design (CDS) – Water cooled, W + TZM cladded w/ Ta2.5W

- Investigation of alternative claddings (Nb, Nb-1Zr, Nb-10Hf-1Ti)



Alternative designs currently being studied in the TDR

W Helium cooled Target

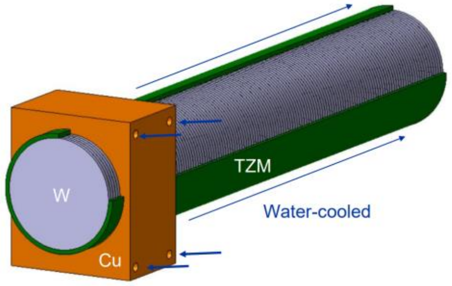


D = 33 cm, L = 201 cm

- Investigation of radionuclide inventories

Enclosed compact Cu + W Target

- Expected to be less critical from a radiological point of view



This is just a conceptual design. It is not optimized

Alternative Claddings

Cladding materials:

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

Total PoT 2×10^{20} (5 yrs)

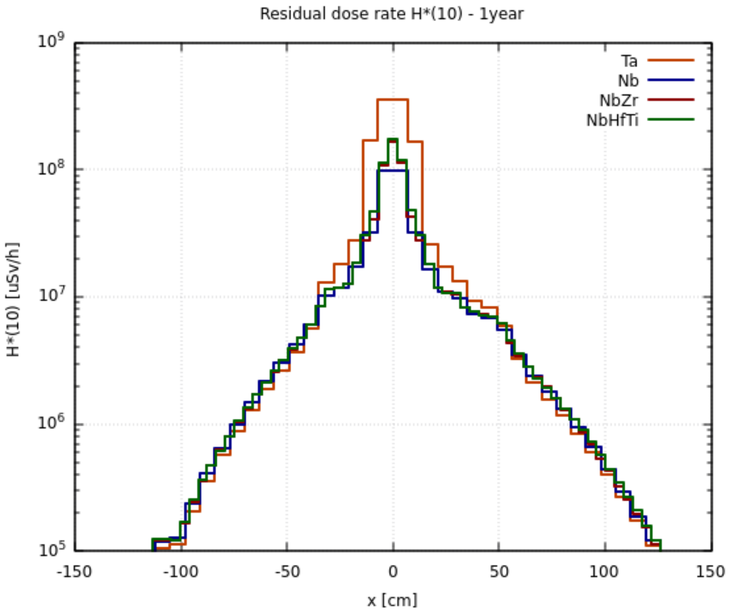
Material	Activity/LL - 5y	Activity/LL - 300y	Max. LMA fraction	RN exceeding LMA	RW Class.
Ta	1.30E+07	7.72E+03	7.58E+01	H-3 (75), Gd-148 (1.65)	FA-MA (CH)
Nb	1.62E+07	7.36E+06	6.19E+03	Nb-94 (6190), H-3 (65)	FA-MA (CH)
Nb-1Zr	1.60E+07	7.28E+06	5.23E+03	Nb-94 (5230), H-3 (66)	FA-MA (CH)
Nb-10Hf-1Ti	1.55E+07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

Nb-94 half-life of 20300 yrs

- Waste classification as FA-MA waste to be disposed of in Switzerland (no open pathway so far for such activation of Ta/Nb)

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

Residual dose rates (uSv/h)



Includes residual dose rates from surrounding material

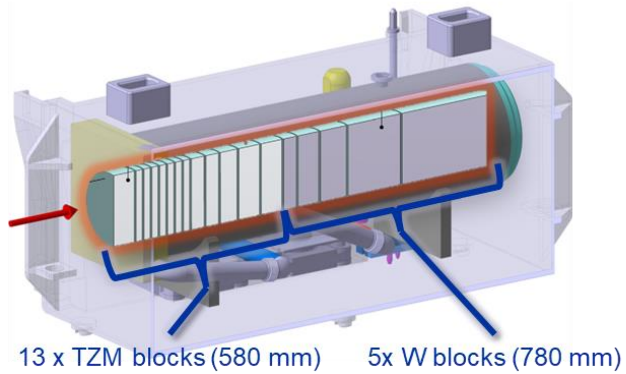
- No difference in the residual dose rates for the various Nb claddings

* LMA: Acceptance Activity Limits, if activity levels < LMA candidate for elimination in France

Alternative BDF target design studies

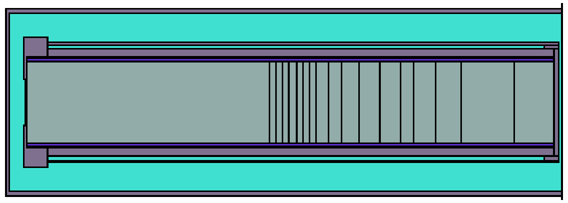
Baseline Design (CDS) – Water cooled, W + TZM cladded w/ Ta2.5W

- Investigation of alternative claddings (Nb, Nb-1Zr, Nb-10Hf-1Ti)



Alternative designs currently being studied in the TDR

W Helium cooled Target

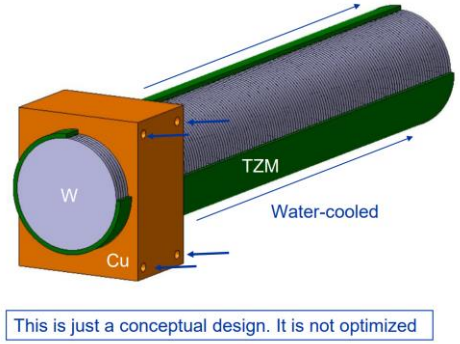


D = 33 cm, L = 201 cm

- Investigation of radionuclide inventories

Enclosed compact Cu + W Target

- Expected to be less critical from a radiological point of view



Radionuclide inventories comparison

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

Target	Material	Mass [kg]	Multiple LL	Multiple LA	A [Bq]
Large W	W	3178	1.3E+08	8.2E+08	3.7E+15
	TZM[1]	219	4.0E+07	1.8E+06	5.0E+12
CDS	W	695	1.9E+08	2.6E+08	9.2E+14
	TZM	271	1.1E+09	8.4E+07	1.8E+14
	Ta	28	1.7E+11*	6.9E+08	9.8E+14

*Dominated (99.9%) by Ta-182 (115 d half-life)

[1]TZM cladding layer

- See backup slides for list of radionuclides
- When comparing the W parts of the two targets, the multiple of LA and total A are a factor 3-4 higher (mainly due to the higher mass) for the large W target than the CDS target
- There are only few percent differences between the TZM quantities
- The Ta cladding of the CDS target exhibits mostly the highest values

LA for short-cool-down times:

- For 1h (4h), **Hf-178m** (4s half-life) produced via Ta-178m (2.36h half-life) is dominant (48%)
- For 1d, **Gd-148** (74y half-life) becomes most important (38%) (as for 1 month)

Possible radioactive volatile chemicals
H_2
H_2O
H_2O_2
NH_3
HNO_3
Re_2O_7
WO_3

Also Iodine can make volatile molecules with Cobalt, Hafnium and Tantalum

Summary & Questions

- Main radiological aspects regarding an implementation of BDF/SHiP in ECN3 were investigated
- First shielding design for an optimization of exposure of personnel to radiation and radiological impact on environment

➢ Further detailed studies and optimization in the Technical Design Phase until end of 2025 to achieve first beam on target in 2030

- Questions
  - What potential release of radionuclides from the target to the He loop do you expect? How do you plan to mitigate the contamination?
  - How do you account for H-3 out-diffusion?
  - What are your plans for radioactive waste management (characterization, conditioning, waste packaging, shielding, elimination)
  - Do you foresee any destructive works on the activated target/surrounding elements?

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Activities multiples – CDS target

Total PoT 2×10^{20} (5 yrs)

Activities of BDF target materials

W

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

Ta

Radionuclide	Half-life	Activity [Bq]			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
H-3	12.33y	7.8E+11	7.4E+11	4.4E+11	1.4E+11
Pm-145	17.70y	8.6E+09	1.0E+10	9.0E+09	4.1E+09
Gd-148	74.60y	3.8E+09	3.8E+09	3.5E+09	2.9E+09
Tb-157	99.00y	3.7E+09	3.7E+09	3.5E+09	3.0E+09
Lu-172	6.7d	6.7E+11	4.6E+11	1.6E+10	1.0E+07
m-Lu-172	3.7min	6.4E+11	4.6E+11	1.6E+10	9.9E+06
Hf-172	1.87y	6.4E+11	4.6E+11	1.6E+10	9.9E+06
Lu-174	3.56y	4.1E+10	3.8E+10	6.9E+09	1.4E+08
m-Hf-178	4s	1.7E+10	1.7E+10	1.4E+10	8.8E+09
n-Hf-178	31.00y	1.7E+10	1.7E+10	1.4E+10	8.8E+09
Ta-179	1.61y	3.5E+12	2.4E+12	4.9E+10	9.0E+06
Ta-182	114.7d	4.6E+14	6.1E+13	1.5E+05	1.0E-14
Sum of all		4.8E+14	6.7E+13	6.1E+11	1.7E+11

TZM

Radionuclide	Half-life	Activity [Bq]			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
H-3	12.33y	8.2E+12	7.8E+12	4.7E+12	1.5E+12
Fe-55	2.73y	2.7E+11	2.1E+11	2.2E+10	1.4E+08
Zn-65	244.2d	7.8E+11	3.0E+11	2.7E+07	2.7E-02
Ga-68	1.1h	7.3E+11	3.1E+11	6.9E+07	5.4E-01
Ge-68	271.0d	7.3E+11	3.1E+11	6.9E+07	5.4E-01
m-Ge-73	0.5s	2.0E+12	1.1E+11	5.5E-02	2.4E-29
As-73	80.3d	2.0E+12	1.1E+11	5.5E-02	2.4E-29
Se-75	119.6d	2.5E+12	3.7E+11	2.0E+03	8.5E-16
Rb-82	1.3min	5.3E+12	6.0E+08	1.2E-30	1.2E-116
Sr-82	25.6d	5.3E+12	6.0E+08	1.2E-30	1.2E-116
Rb-83	86.2d	8.1E+12	5.5E+11	1.8E+00	5.9E-26
m-Kr-83	1.8h	6.1E+12	4.1E+11	1.4E+00	4.4E-26
Mo-93	3999.92y	4.2E+10	4.2E+10	4.2E+10	4.2E+10
Sr-85	64.8d	1.1E+13	3.1E+11	1.7E-04	2.2E-38
Zr-88	83.0d	2.2E+13	1.3E+12	1.6E+00	5.4E-27
Y-88	106.6d	1.9E+13	6.1E+12	5.7E+03	1.4E-17
m-Nb-91	60.9d	2.5E+13	5.5E+11	3.2E-05	2.6E-41
Nb-91	680.00y	1.6E+11	1.7E+11	1.7E+11	1.6E+11
m-Nb-92	10.2d	4.2E+12	4.9E+02	1.8E-95	-
m-Nb-93	16.13y	9.7E+11	9.3E+11	6.4E+11	2.9E+11
Nb-95	35.0d	2.9E+13	7.7E+11	2.8E-04	1.3E-38
Zr-95	64.0d	1.3E+13	3.5E+11	1.3E-04	6.0E-39
Sum of all		1.8E+14	2.2E+13	5.6E+12	2.1E+12

Pure alpha/beta emitters are shown in bold

Dominant radionuclide is shown in red

Main contributors (>1%), sum for all radionuclides

Multiples of Swiss Clearance Limits (LL)

CDS Target

Total PoT 2×10^{20} (5 yrs)

LL multiples of BDF target materials

W

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

Ta

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

Pure alpha/beta emitters are shown in bold

Dominant radionuclide is shown in red

Main contributors (>1%), sum for all radionuclides

TZM

Radionuclide	Half-life	Multiple of LL value			
		T_c = 1m	T_c = 1y	T_c = 10y	T_c = 30y
H-3	12.33y	3.0E+05	2.9E+05	1.7E+05	5.7E+04
Na-22	2.60y	7.5E+05	5.9E+05	5.3E+04	2.6E+02
Ti-44	60.00y	6.3E+04	6.2E+04	5.6E+04	4.4E+04
Sc-46	83.8d	2.2E+07	1.4E+06	2.1E-06	1.3E-32
Mn-54	312.1d	1.4E+07	6.5E+06	4.4E+03	4.0E-04
Co-60	5.27y	2.2E+06	2.0E+06	6.1E+05	4.4E+04
Zn-65	244.2d	2.9E+07	1.1E+07	1.0E+03	1.0E-06
Rb-83	86.2d	3.0E+07	2.0E+06	6.8E-06	2.2E-31
Sr-85	64.8d	4.1E+07	1.1E+06	6.4E-10	8.3E-44
Y-88	106.6d	6.9E+08	2.3E+08	2.1E-01	5.2E-22
Zr-88	83.0d	8.0E+07	4.9E+06	6.0E-06	2.0E-32
Sr-90	28.79y	1.0E+04	1.0E+04	8.1E+03	5.0E+03
Nb-91	680.00y	6.0E+03	6.2E+03	6.1E+03	6.0E+03
Nb-93m	16.13y	3.6E+05	3.4E+05	2.4E+05	1.1E+05
Mo-93	3999.92y	1.6E+04	1.6E+04	1.6E+04	1.5E+04
Nb-94	19989.57y	5.3E+04	5.3E+04	5.3E+04	5.3E+04
Nb-95	35.0d	1.1E+08	2.8E+06	1.0E-09	4.9E-44
Zr-95	64.0d	4.8E+07	1.3E+06	4.6E-10	2.2E-44
Tc-99	213995.36y	6.2E+03	6.2E+03	6.2E+03	6.2E+03
Sum of all		1.1E+09	2.6E+08	1.2E+06	3.4E+05

Water activation – CDS

- 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 cladding materials

Material:		Niobium (ASTM R04210 Type 2)	Nb-1Zr (ASTM R04261 Type 4)	Nb-10Hf-1Ti "C103" (ASTM R04295)
Density (g/cm3):		8.6	8.6	8.86
Composition:	C	0.01	0.01	0.015
Max Weight %	N	0.01	0.01	0.01
	O	0.025	0.025	0.025
	H	0.0015	0.0015	0.0015
	Zr	0.02	0.8-12	0.7
	Ta	0.3	0.5	0.5
	Fe	0.01	0.01	-
	Si	0.005	0.005	-
	W	0.05	0.05	0.5
	Ni	0.005	0.005	by difference
	Mo	0.02	0.05	-
	Hf	0.02	0.02	9-11"
	Ti	0.03	0.03	0.7-1.3"
Reference:		[1]	[2]	[3]

[1] - https://www.navstarsteel.com/niobium-sheet.html
[2] https://www.tantalum-niobium.com/niobium/nb-1zr-wire-rod.html
[3] Ximenes Franqueira R., Internal communication, (2021)

Radionuclide inventory of large W target

Tungsten part

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

Tungsten – Total Activity (Bq)

Radionuclide	Half-life	Activity [Bq] $T_c = 1$m
H-3	12.33y	2.0E+13
Pm-145	17.70y	1.9E+11
Gd-148	74.60y	8.6E+10
Tb-157	99.00y	8.1E+10
Lu-172	6.7d	1.5E+13
Hf-172	1.87y	1.5E+13
Lu-173	1.34y	2.1E+13
Hf-175	70.0d	5.8E+13
Ta-178	9.3min	9.7E+13
W-178	21.6d	9.7E+13
Ta-179	1.61y	9.4E+13
W-181	121.0d	3.8E+14
Ta-182	114.7d	2.2E+13
W-185	75.1d	2.8E+15
Sum of all		3.7E+15

Tungsten – Multiple of LL

Radionuclide	Half-life	Multiple of LL value $T_c = 1$m
H-3	12.33y	6.3E+04
Co-60	5.27y	9.3E+04
Ba-133	10.54y	5.6E+05
Pm-145	17.70y	6.0E+03
Eu-146	4.6d	1.2E+06
Gd-148	74.60y	2.7E+04
Eu-150	36.36y	2.2E+03
Lu-172	6.7d	4.8E+06
Hf-172	1.87y	4.7E+05
Lu-173	1.34y	6.6E+06
Lu-174	3.56y	9.4E+04
Hf-175	70.0d	1.8E+07
Ta-178	9.3min	3.1E+06
W-178	21.6d	3.1E+06
Ta-179	1.61y	2.9E+06
W-181	121.0d	1.2E+07
Ta-182	114.7d	6.9E+07
Re-184m	168.0d	2.1E+06
Sum of all		1.3E+08

Tungsten – Multiple of LA

Radionuclide	Half-life	Multiple of LA value $T_c = 1$m
Gd-148	74.60y	4.3E+08
Yb-169	32.0d	9.5E+06
Hf-172	1.87y	1.5E+08
Hf-175	70.0d	9.7E+06
Ta-182	114.7d	3.1E+07
W-185	75.1d	1.4E+08
Sum of all		8.2E+08

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

Large W target – LA for short cool-down

Tungsten part

Total PoT 2×10^{20} (5 yrs)

Tungsten – Multiple of LA

1 hour

Radionuclide	Halflife	1h
Hf-178m	4s	1.2E+09
Gd-148	74.60y	4.3E+08
W-187	23.9h	3.2E+08
W-185	75.1d	1.9E+08
Hf-172	1.87y	1.5E+08
Ta-182	114.7d	3.8E+07
Sum of all		**2.52E+09**

1 day

Radionuclide	Halflife	1d
Gd-148	74.60y	**4.3E+08**
W-185	75.1d	1.9E+08
W-187	23.9h	3.2E+08
Hf-172	1.87y	1.5E+08
Ta-182	114.7d	3.8E+07
Yb-169	32.0d	1.7E+07
Ta-183	5.1d	1.7E+07
Hf-175	70.0d	1.3E+07
Sum of all		**1.13E+09**

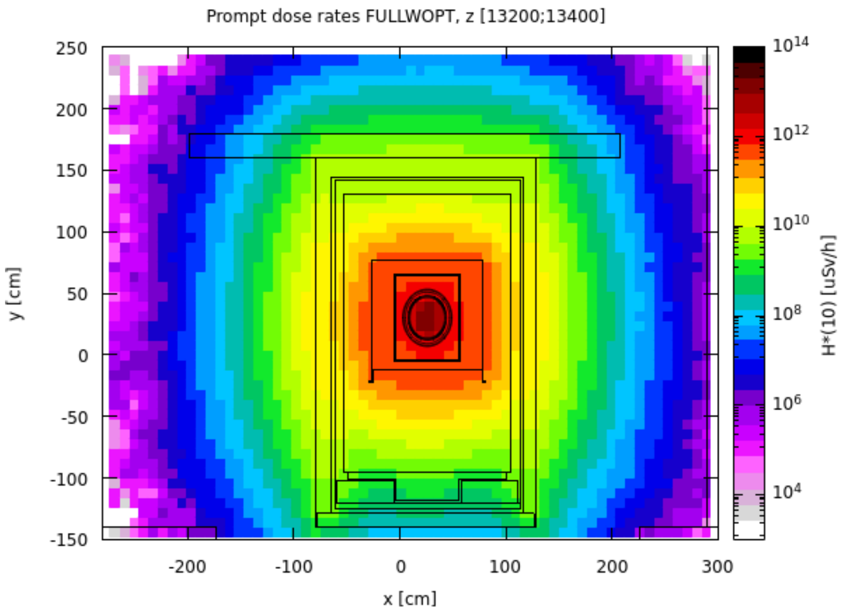
Pure alpha/beta emitters are shown in bold
Dominant radionuclide is shown in red
Main contributors (>1%), sum for all radionuclides

- For 1 h of cool-down, Hf-178m is dominant (48%) and wrt. to 1 month of cool-down also W-187 and W185 are relevant (Hf-178m comes from the decay of Ta-178m (2.36h half-life)
- For 4 hours of cool-down, the important radionuclides are as for 1 hour
- For 1 day of cool-down, Gd-148 becomes most important (38%)

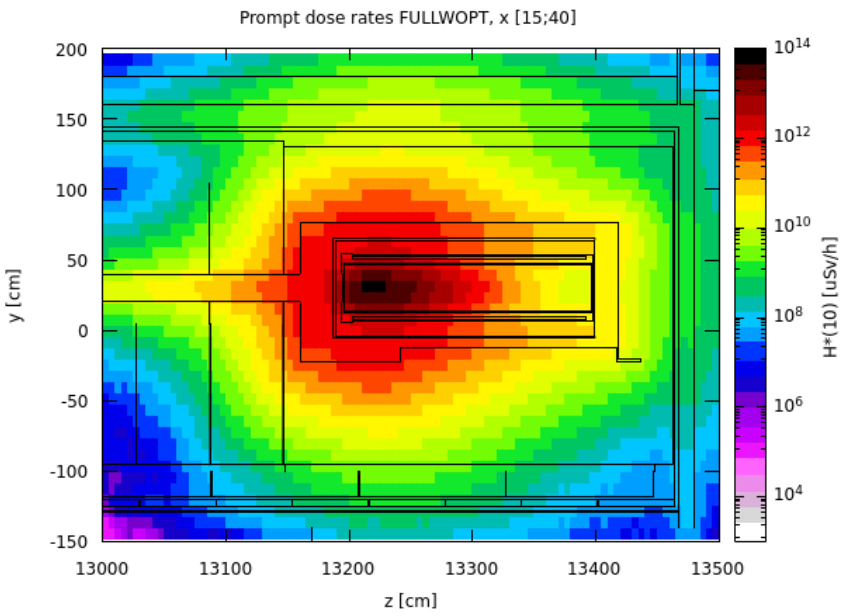
Prompt radiation for large W target

$4{\times}10^{13}$ p / 7.2 s

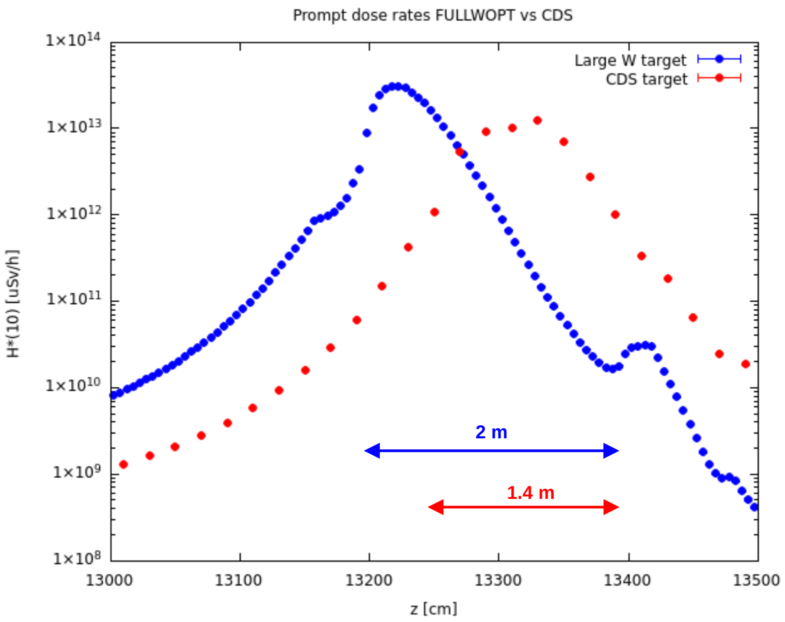
Cross-sectional cut at the target



Longitudinal cut at the target



Along z – Large W target vs. CDS target

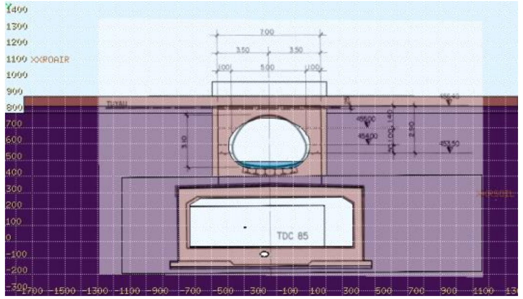


- The highest dose rate are observed in the upstream part of the large W target with a sharp decrease towards its downstream end, which will lead to a significantly higher activation in the upstream than the downstream part of the target
- The max. dose rate reached in the large W target is with ~3.2e13 uSv/h about a factor 2.6 higher than what is reached at maximum in the CDS target

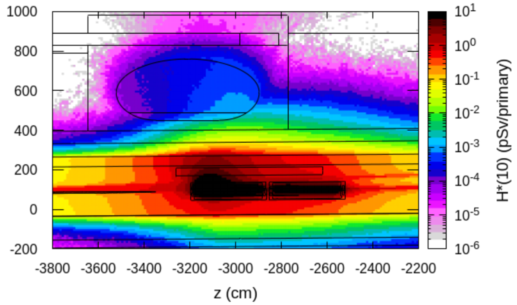
Some additional studies

Beam transfer

- Several RP studies for the high intensity SPS-ECN3 beam transfer were performed
- This includes studies for a bridge above the TDC85 transfer tunnel near ECN3



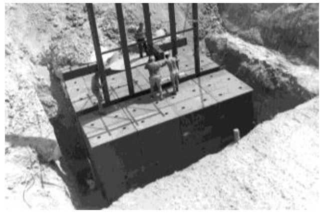
Prompt H*(10)



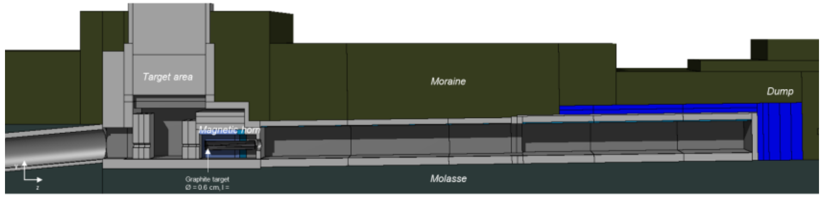
Various beamline and shielding configurations were investigated

TT7 shielding recovery

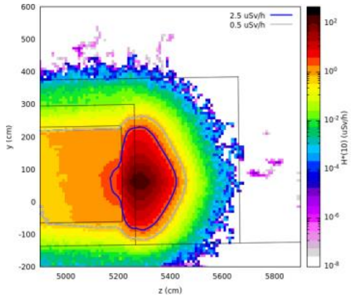
- Shielding recovery from discontinued CERN PS Neutrino Facility (PSNF)



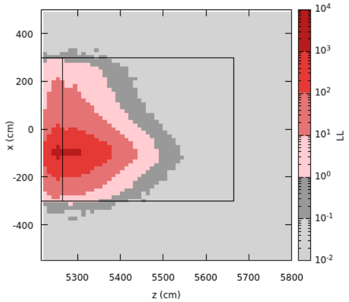
- ~100 m^3 std. cast iron blocks
- ~50 m^3 non-std cast iron blocks
- ➢ ~3 MCHF, investment <1/3



Residual H*(10)

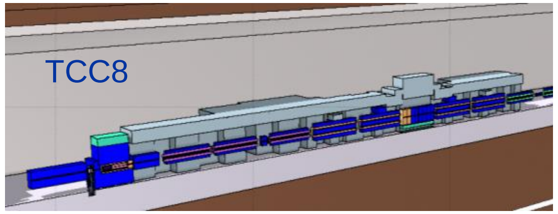


Radioactive waste zoning

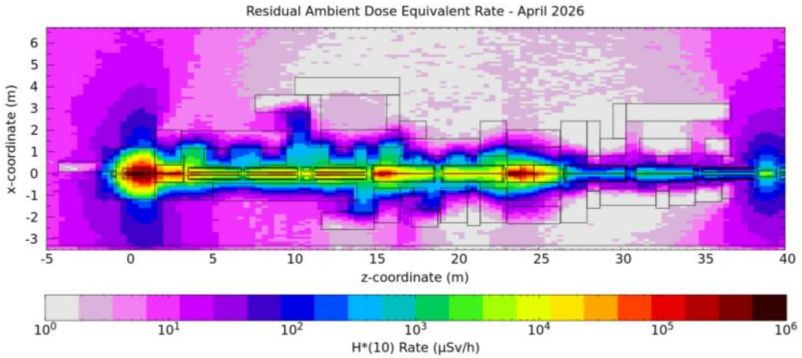


TCC8 dismantling

- Dismantling of the highly radioactive TCC8 target area in 2026
- Evaluation of residual dose rates and radio-nuclide inventories for operational RP as well as radioactive transport and waste studies



Residual H*(10)



Environmental impact

PoT 4×10^{19} per year

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}

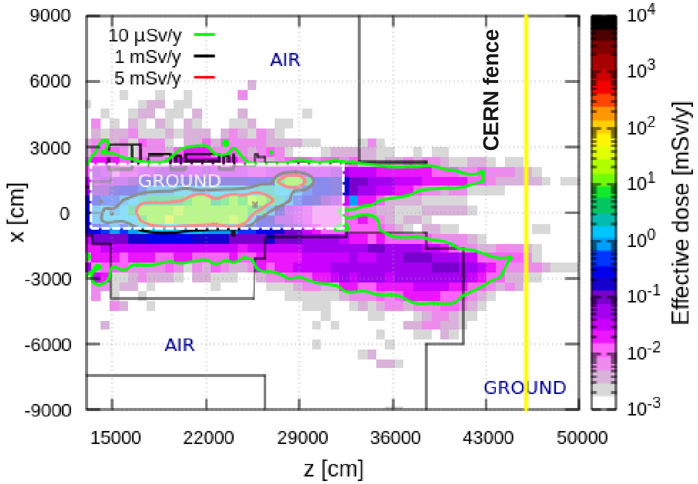
H-3 release due to air activation of ~80 kBq

Positions of nearby population groups

- ➢ Worst-case immediate air release (CASE 2) yields 3 nSv/year (main contributors: N-13, Ar-41, C-11, O-15) and is thus well below the annual dose objective of CERN
- ➢ Exposure of members of the public due to air releases is negligible

Dose from stray radiation

Annual effective dose from muons



Muon prompt radiation aboveground downstream ECN3

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