HIKECN3

Radiation Protection Considerations for HI-ECN3

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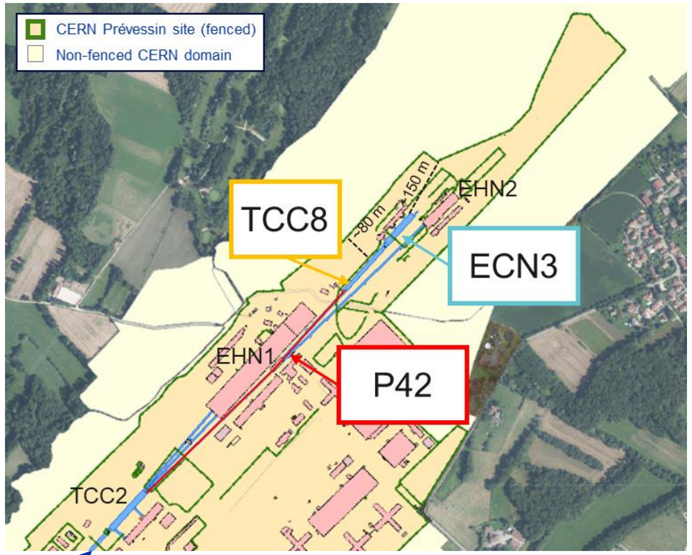
Outline

1. Overview of RP Challenges at HI-ECN3
2. Target Complex Design Optimization
3. Target Studies
4. Beam Transfer Studies
5. Dismantling studies

HI-ECN3 at ECN3

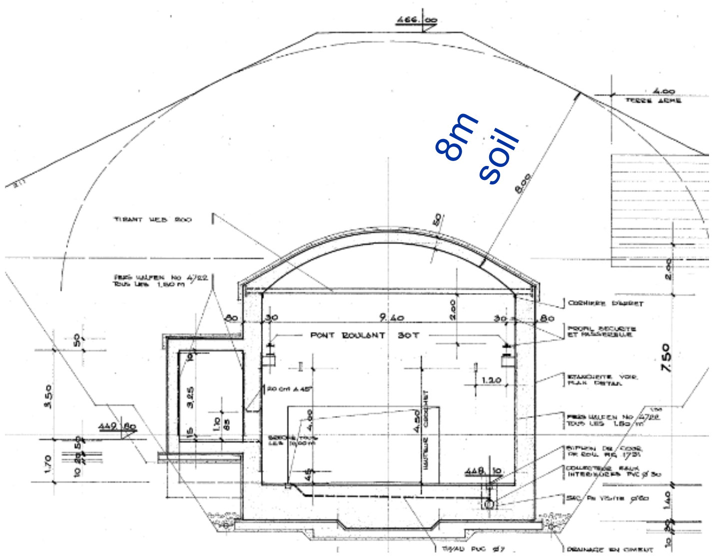
➢ See talks about the SHiP experiment by R. Jacobsson and the BDF target station design by J.L. Grenard

CERN's SPS North Area



400 GeV p+
from SPS

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 housing BDF/SHiP in ECN3
  - exploiting the available high intensity SPS 400 GeV/c p^+ 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
  - **High-intensity beam transfer**
  - **Dismantling** of **current TCC8/ECN3** equipment

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/y 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**

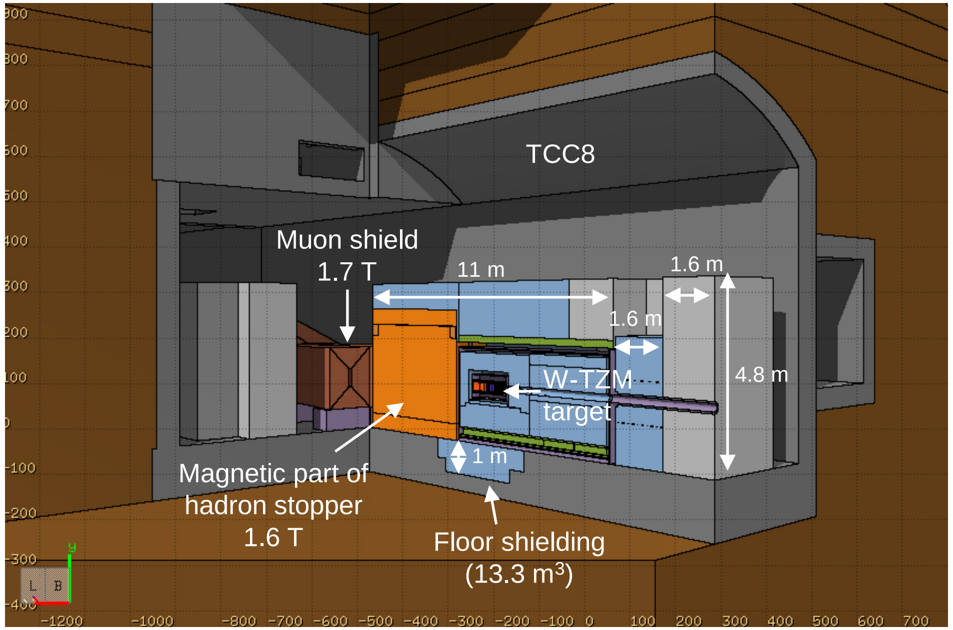
Radiation area classification

	Area	Annual dose limit (year)	Ambient dose equivalent rate		Airborne activity concentration	Surface contamination	
			permanent occupancy	low occupancy			
	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]



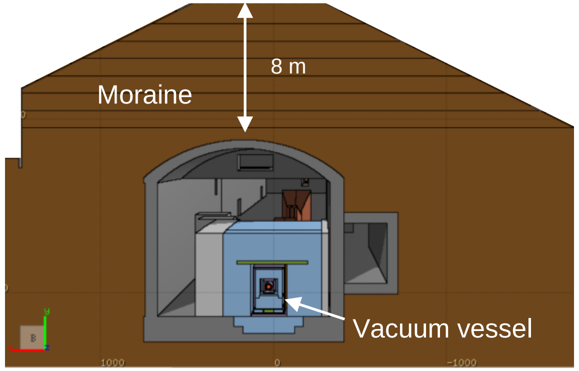
Stainless steel

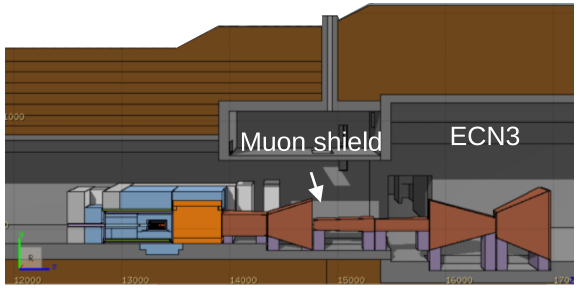
Concrete

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

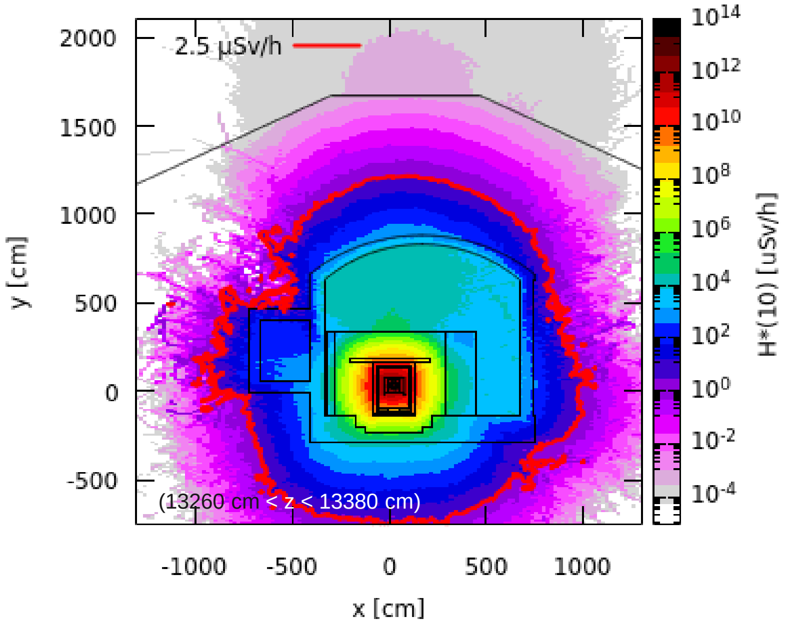
Prompt radiation in target area

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

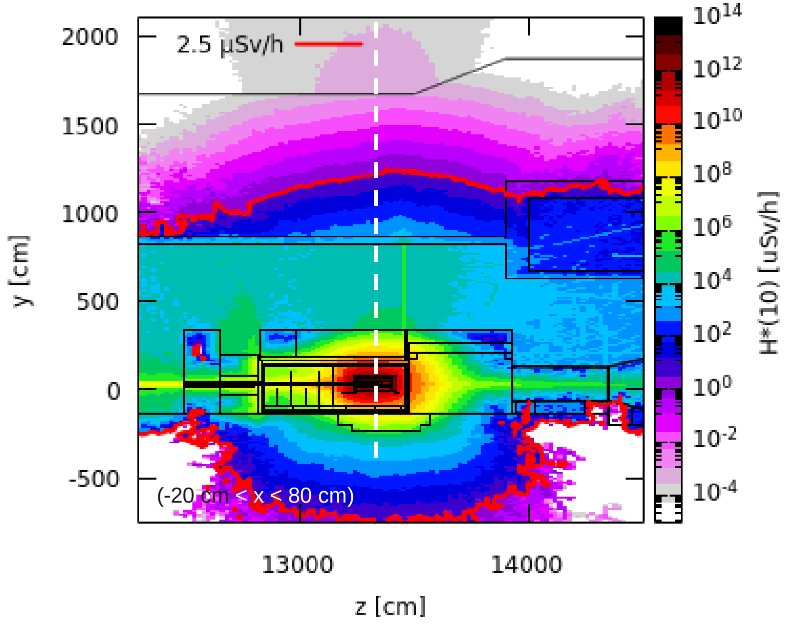
Radiation Area (Supervised to Prohibited); Controlled Area (Simple Controlled to Prohibited)

Avg. intensity of 5.6×10^{12} p/s

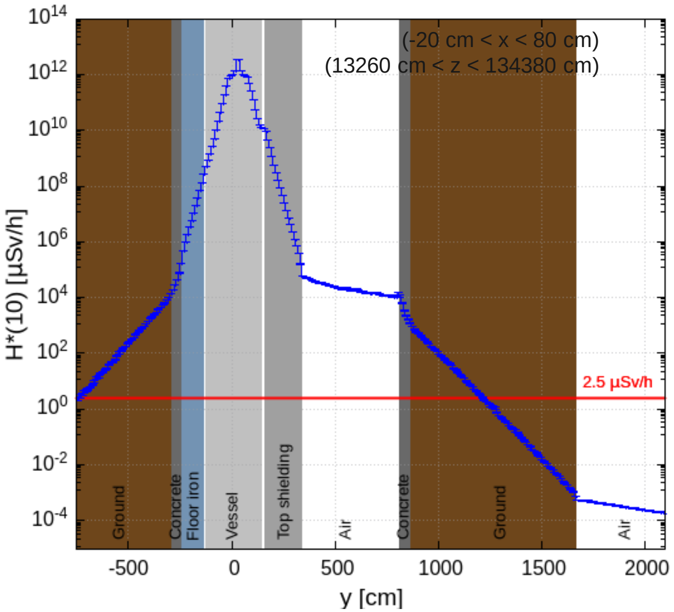
Cross-sectional view



Side view



Along y-axis



- ➢ Shielding design is well optimized for the prompt radiation
- ➢ Limit of Non-designated Area on CERN domain is by far met

100 rem = 1Sv

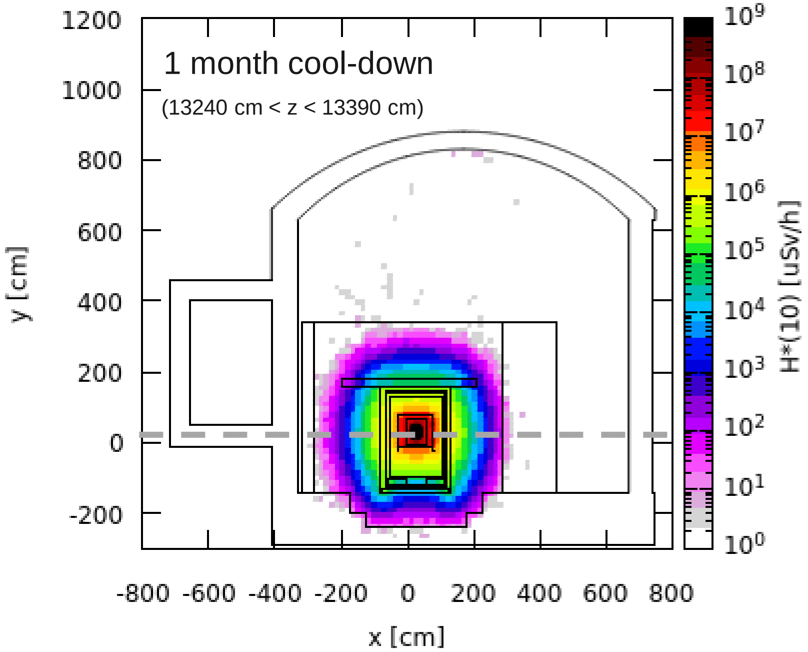
Residual radiation in target area

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	
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

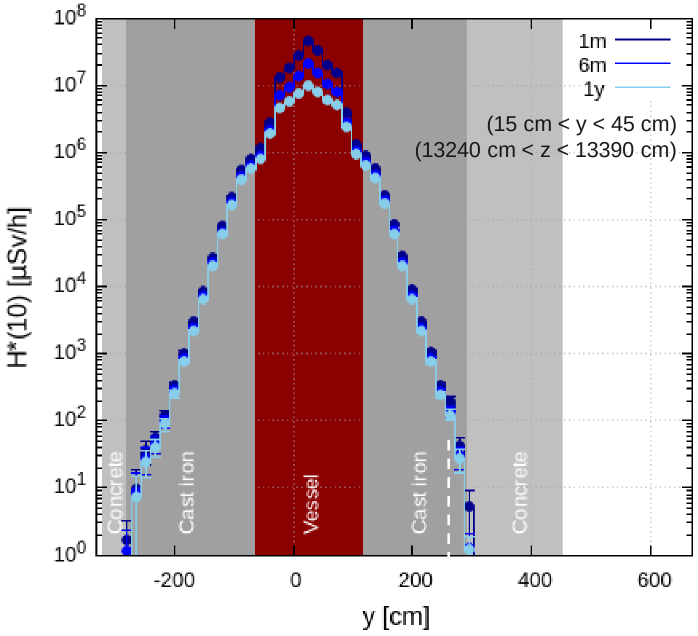
Radiation Area (Supervised to Prohibited); Controlled Area (Simple Controlled to Prohibited)

Total PoT 6×10^{20}

Cross-sectional view, target level

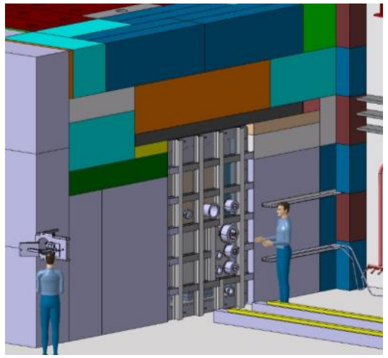


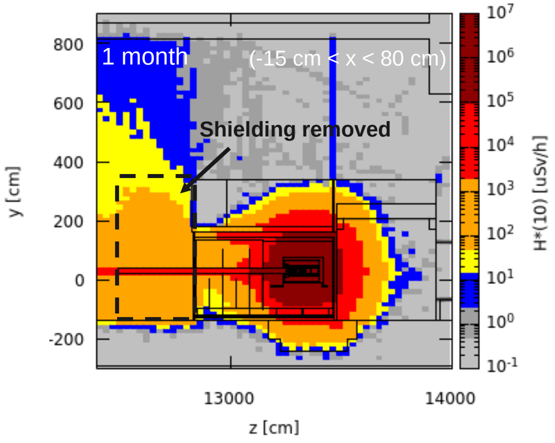
Along x-axis, working height



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

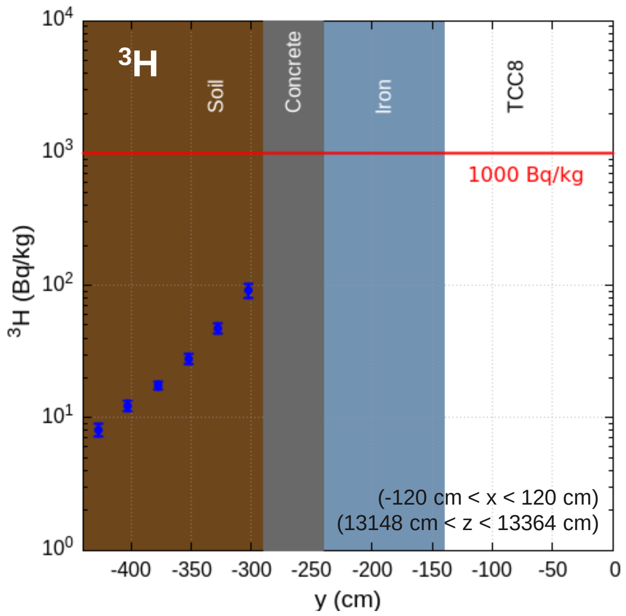
- The shielding design contains well the high residual dose rates reaching in the central target region several 10 Sv/h after 1 month of cool-down
- The residual dose rates outside the shielding are < 1 µSv/h

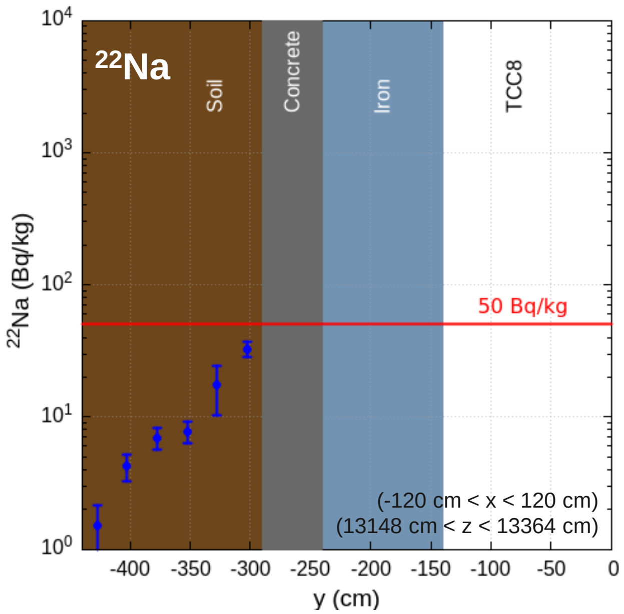
100 rem = 1Sv

Soil activation

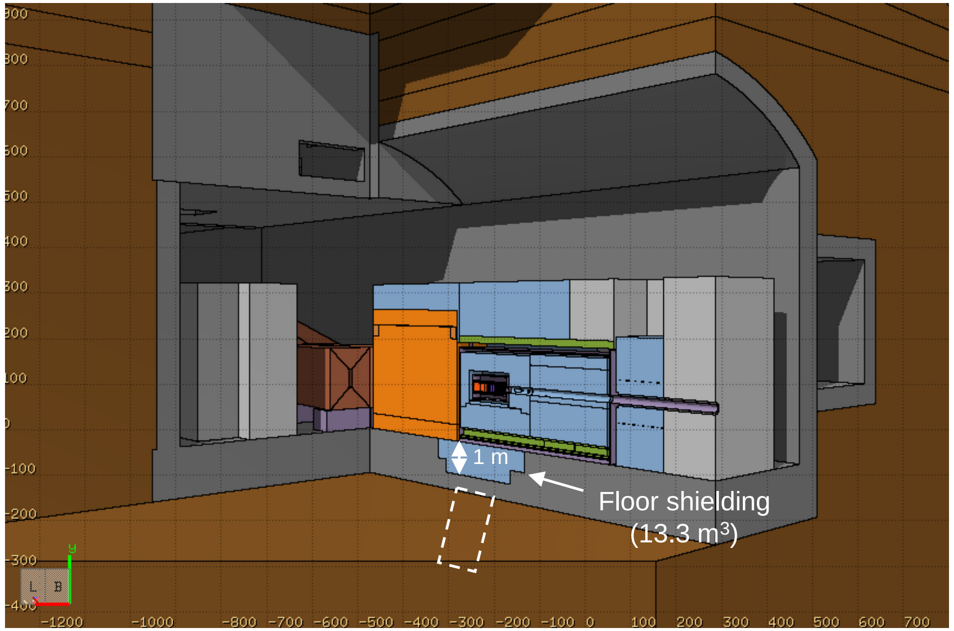
Total PoT 6×10^{20}

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





Most critical area for soil activation



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

100 rem = 1Sv

Air activation

Area	Annual dose limit (year)	Ambient dose equivalent rate		Airborne activity concentration	Surface contamination
		permanent occupancy	low occupancy		
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

PoT 4×10^{19} per year

- Activation of air in target complex area was studied
- Production of radionuclides evaluated with FLUKA in combination with ActiWiz [5] ➢ See talk by H. Vincke
- Two cases were investigated:

CASE 1: build-up of radionuclides during yearly operation without 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)

➢ Even without any cooldown time, the air activity concentration in the target complex would be compatible with access (< 0.1 CA[1])

➢ Flush of target complex with fresh air before any access

Air activation

		CASE 1			CASE 2
Region	Volume [m^3]	Total A [Bq]	As [Bq/m^3]	Multiple of CA[1]	Total A [Bq]
Air	2127	3.69×10^{6}	1.73×10^{3}	3.34×10^{-2}	1.18×10^{11}

Activities of main radionuclides with % contribution to total activity

CASE 1 - *Air*			
Radionuclide	**Half life**	**A [Bq]**	**%**
Ar-41	110 min	2.44×10^{6}	66.31
Be-7	53.3 d	4.55×10^{5}	12.35
C-11	20.4 min	2.54×10^{5}	6.878
N-13	10 min	2.31×10^{5}	6.259
Ar-37	35 d	9.19×10^{4}	2.493
C-14	5700 y	7.71×10^{4}	2.091
H-3	12.32 y	7.49×10^{4}	2.032
Cl-39	55.6 min	2.44×10^{4}	0.661
S-35	87.37 d	1.15×10^{4}	0.312
Cl-38	37.24 min	7.56×10^{3}	0.205
Sum		3.68×10^{6}	99.59

CASE 2 - *Air*			
Radionuclide	**Half life**	**A [Bq]**	**%**
O-15	2 min	7.12×10^{10}	60.04
N-13	10 min	3.11×10^{10}	26.25
C-11	20.4 min	5.75×10^{9}	4.866
Ar-41	110 min	4.49×10^{9}	3.792
O-14	1.2 min	4.17×10^{9}	3.521
Cl-40	84 s	9.76×10^{8}	0.824
P-35	47 s	2.33×10^{8}	0.196
S-37	5 min	1.98×10^{8}	0.167
Sum		1.18×10^{11}	99.63

In red main contriubtors to CA (>4%)

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

Environmental impact

	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	
Radiation Area	Supervised	6 mSv	3 µSv/h	15 µSv/h	Dosimeter obligatory / Dosimètre obligatoire
Radiation Area / Controlled Area	Simple Controlled	20 mSv	10 µSv/h	50 µSv/h	SIMPLE CONTROLLED / CONTRÔLÉE SIMPLE — Dosimeter obligatory / Dosimètre obligatoire
Radiation Area / Controlled Area	Limited Stay	20 mSv	-	2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ — Dosimeters obligatory / Dosimètres obligatoires
Radiation Area / Controlled Area	High Radiation	20 mSv	-	100 mSv/h	HIGH RADIATION / HAUTE RADIATION — Dosimeters obligatory / Dosimètres obligatoires
Radiation Area / Controlled Area	Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY / DÉFENSE D'ENTRER

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}

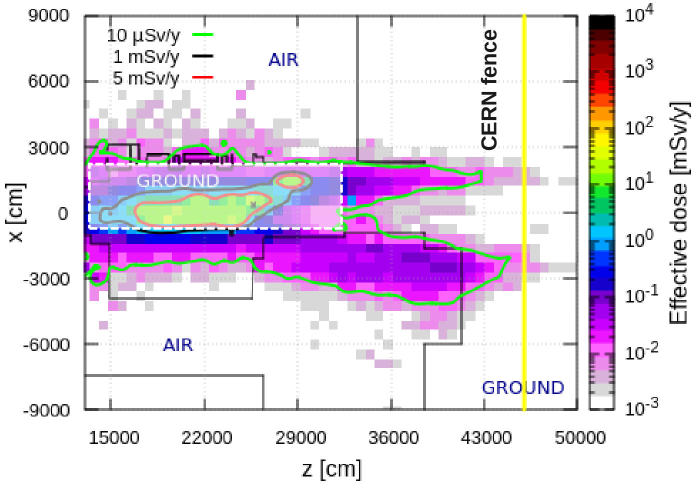
H-3 release due to air activation of ~80 kBq

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

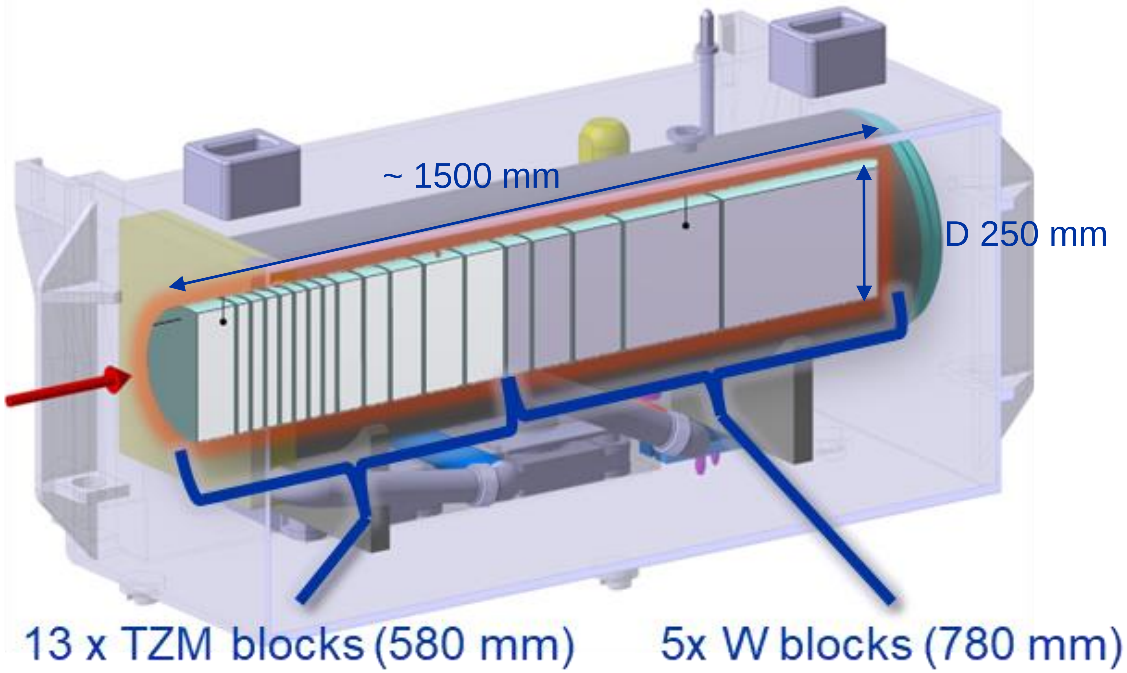
100 rem = 1Sv

BDF Target Studies

BDF target baseline design

Baseline Design (CDS)

- Water-cooled target: TZM (0.08% titanium – 0.05% zirconium – molybdenum alloy) and W blocks cladded with 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 in 2018 + Post irradiation examination



TDR phase for CDS design improvement

- Alternatives with pure W and He cooling under investigation

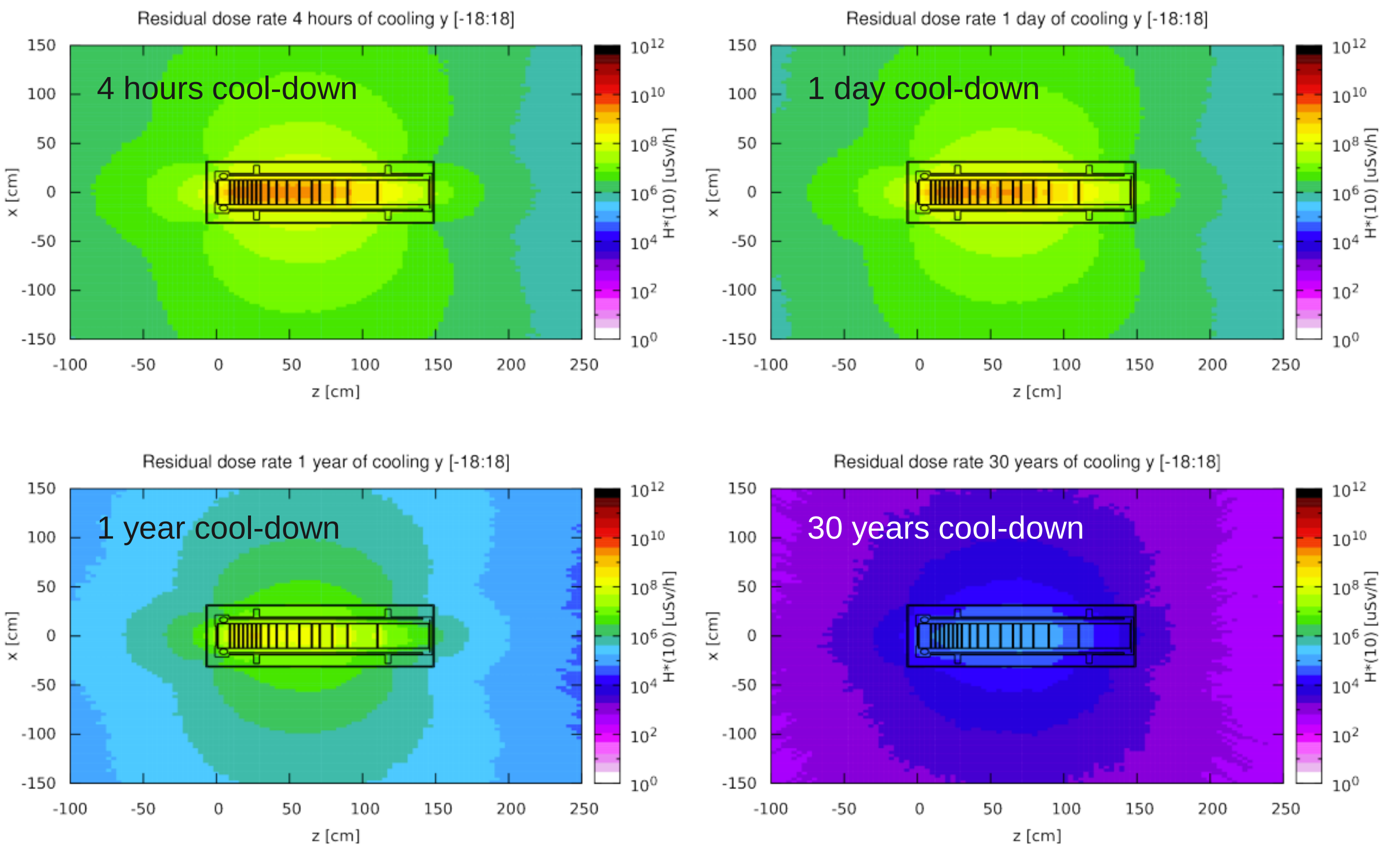
➢ See talk "Design considerations for the BDF/SHiP production target" by R. Ximenes on Wednesday

Residual radiation of CDS target

- The residual dose rates of the target were studied for 5 years of operation 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
- Dedicated casks for transportation and storage as well as during handling will be designed

Total PoT 4×10^{19} (5 yrs)

Longitudinal cut along the target



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

- **Radionuclide inventory of target materials** evaluated with FLUKA in combination with ActiWiz → important for radioactive transport and waste considerations (characterization, processing, disposal)
- Comparison to **Authorization Limits (LA)** and **Swiss Clearance Limits (LL)**

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

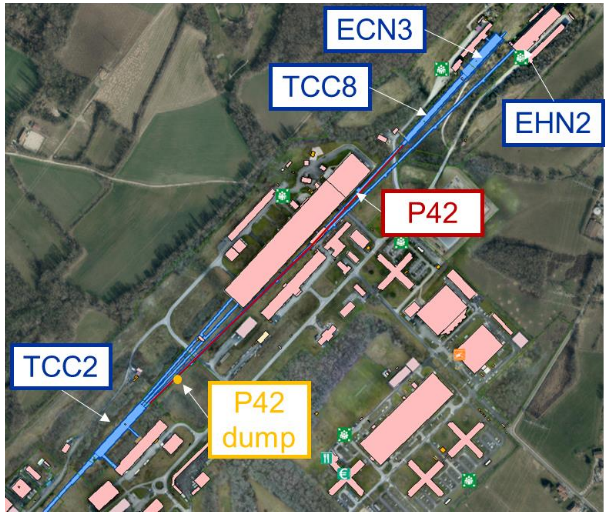
Radionuclide	Activity [Bq/l]	
	Sample 1	Sample 2
H-3	$1.96 \times 10^5 \pm 4.0\%$	$4.8 \times 10^5 \pm 4.0\%$
Be-7	$7.7 \times 10^3 \pm 6.6\%$	$2.37 \times 10^3 \pm 6.8\%$
Sc¡Sc44m	$2.49 \times 10^1 \pm 6.9\%$	$4.85 \times 10^1 \pm 5.7\%$
Sc-46	$1.51 \times 10^1 \pm 7.8\%$	$6.88 \times 10^1 \pm 6.8\%$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

Beam Transfer Studies

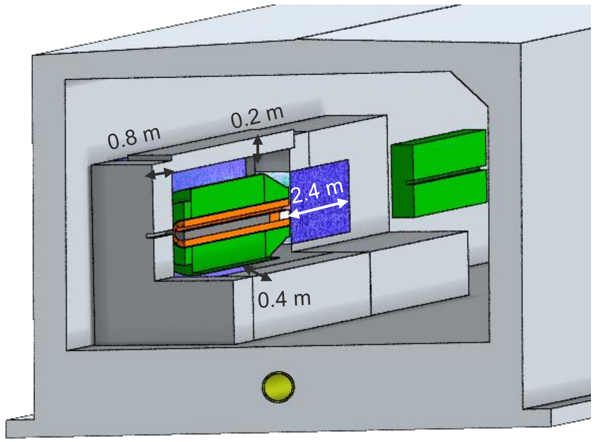
- See talk on HI-ECN3 by M. Fraser on Wednesday

P42 beam dump



- A new beam dump will be installed in the P42 beamline
- It shall allow commissioning the most critical part of the dedicated beam transfer (SPS → P42 beamline), while works in TCC8/ ECN3 are ongoing
- The former, already activated SPS beam dump is to be reused
- Additional shielding is placed around the dump to allow complying with the RP constraints related to prompt radiation, residual radiation, soil and air activation

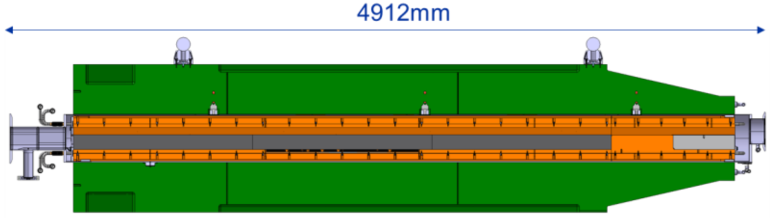
FLUKA model of P42 dump



Key beam parameters of P42 dump

Intensity (p/spill)	2.2×10^{12}
Cycle length (s)	7.2
Average intensity (p/s)	2.8×10^{11}
Operational hours/year	100
Duration (years)	3
Total POT	1.8×10^{17}

Former SPS beam dump



Max. contact dose rate in Apr. 24 amounted to 0.5 mSv/h

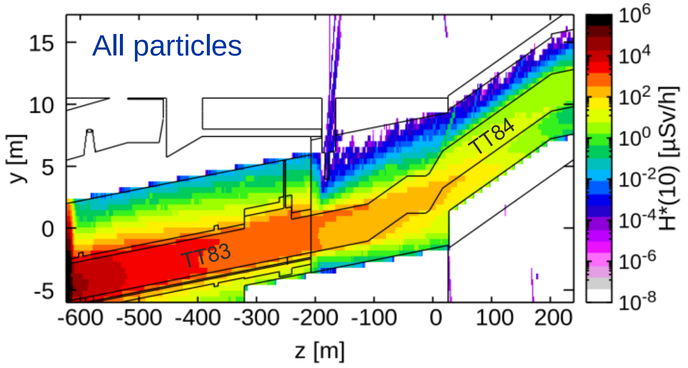
P42 beam dump

Area	Annual dose limit (year)	Ambient dose equivalent rate		Airborne activity concentration	Surface contamination
		permanent occupancy	low occupancy		
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 (Supervised to Prohibited); Controlled Area (Simple Controlled to Prohibited)

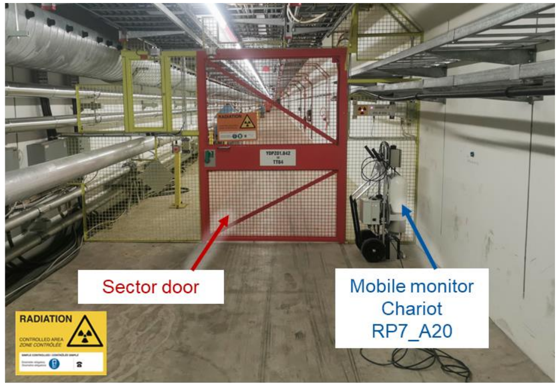
Prompt dose rates

Side view, 2.8×10^{11} p/s



- Prompt dose rates (<30 uSv/h w/ safety factor 3) in the accessible downstream part of TT84 would be compatible with a Simple Controlled Radiation Area (50 uSv/h)
- A radiation monitor is in the accessible part of TT84 to monitor the dose rates during access conditions
- An additional benchmark of the dose rates measured in TT84 during a deliberate full beam loss on a collimator showed very good agreement with dedicated FLUKA simulations

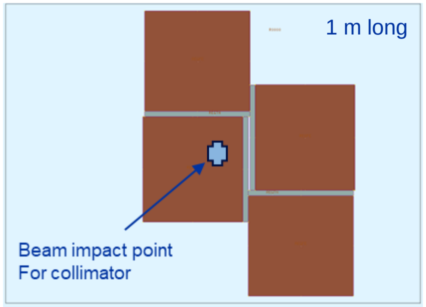
Collimator benchmark



Measured dose rate: 27.8 µSv/h

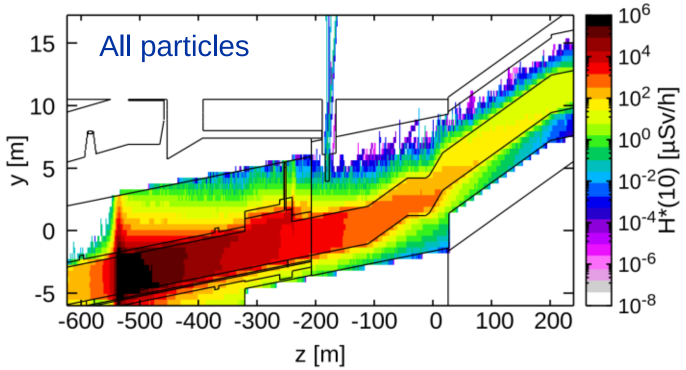
FLUKA model of collimator

Cross-sectional view



Prompt dose rates

Side view, 1.25×10^{10} p/s



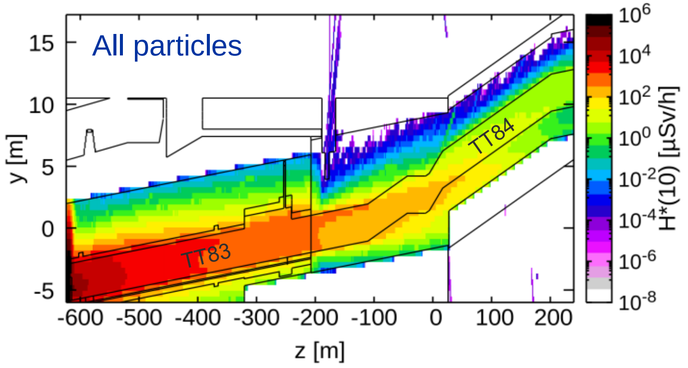
Simulated dose rate: 22.7 uSv/h

P42 beam dump

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

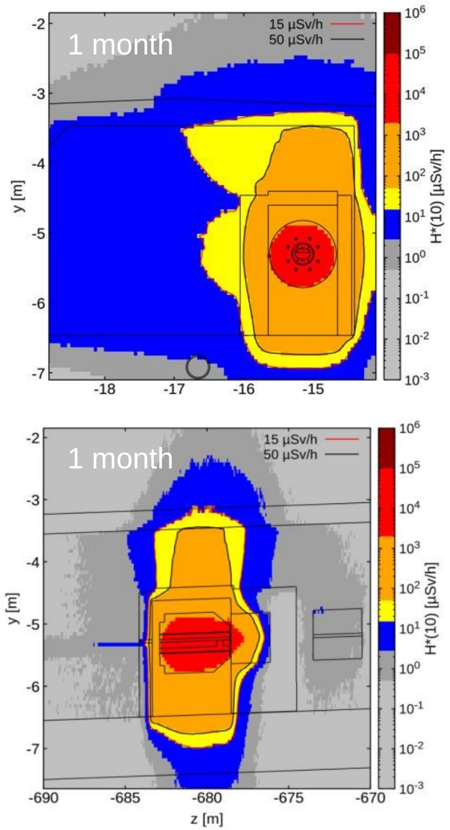
Radiation Area / Controlled Area

Prompt dose rates
Side view, 2.8×10^{11} p/s



- Prompt dose rates (<30 uSv/h w/ safety factor 3) in the accessible downstream part of TT84 would be compatible with a Simple Controlled Radiation Area (50 uSv/h)
- A radiation monitor is in the accessible part of TT84 to monitor the dose rates during access conditions
- An additional benchmark of the dose rates measured in TT84 during a deliberate full beam loss on a collimator showed very good agreement with dedicated FLUKA simulations

Residual dose rates
1.8×10^{17} POT, 1 week cool-down



- After 1 week, the residual dose rates close to the dump require a Controlled Radiation Area
- After 1 month, most of the accessible area is compatible with a Supervised Radiation Area
- Even for unlikely unforeseen accesses to TT83 with 2h cool-down only, the dose for walking past the dump would be acceptable

Soil activation

- Soil activation was evaluated for 3 years of operation (1.8×10^{17} POT) and found to be acceptable

Air activation

- Considering 3 years of operation and 10 min of cool-down the air activation in the tunnel is compatible with a 0.1 CA even without considering additional fresh air injection into the tunnel
- The total activity for 5 min of cool-down amounts to 0.2 MBq (N-13, O-15, C-11)
- Environmental impact of released air activation is negligible

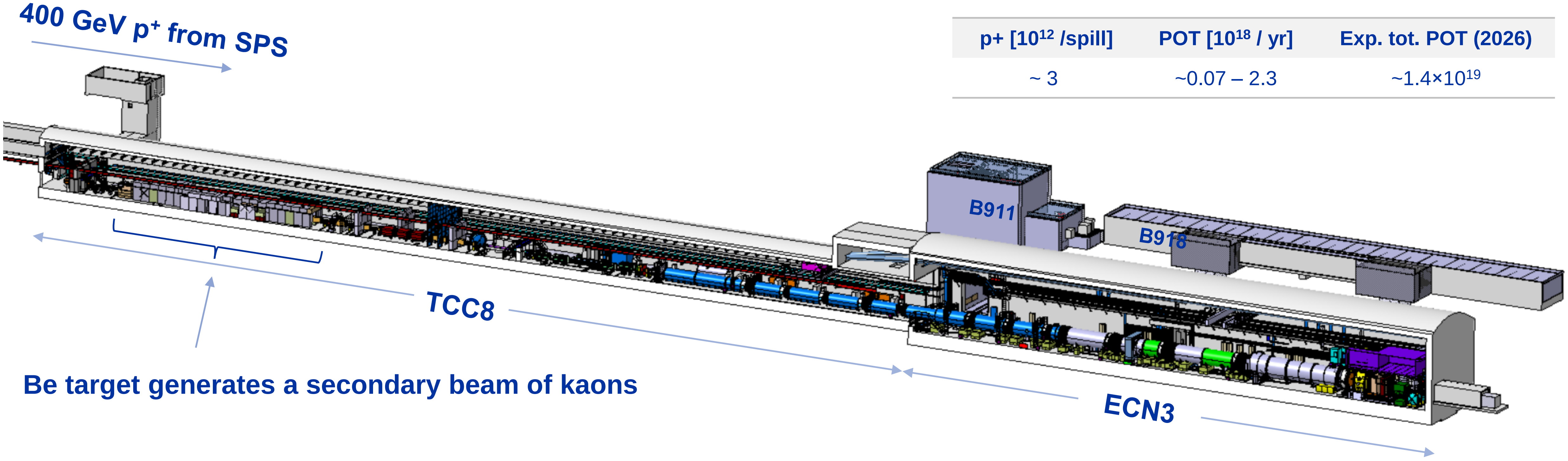
Dismantling Studies

TCC8/ECN3 today

- **NA62 experiment** is currently located in ECN3, while its target area is situated upstream in TCC8
- It is in operation since 2009 searching for rare kaon decay modes

NA62 beam parameters

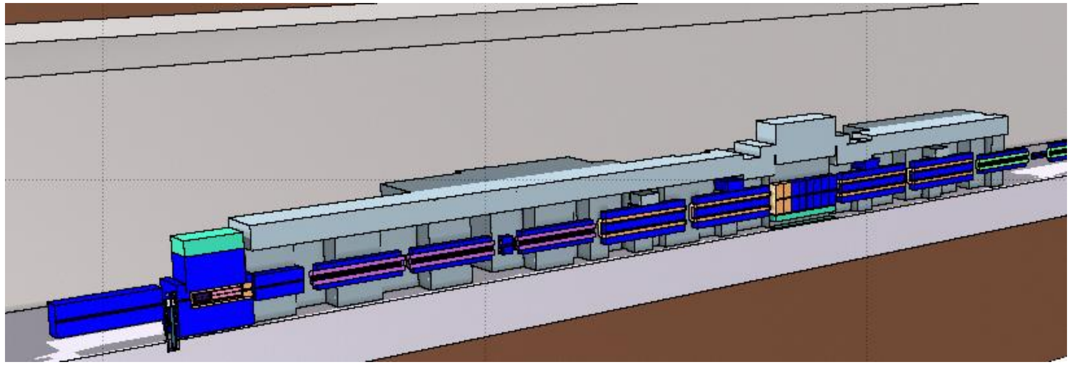
p+ [10^{12} /spill]	POT [10^{18} / yr]	Exp. tot. POT (2026)
~ 3	~0.07 – 2.3	~1.4×10^{19}



TCC8 dismantling

	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	
Radiation Area	Supervised	6 mSv	3 µSv/h	15 µSv/h	Dosimeter obligatory / Dosimètre obligatoire
Radiation Area / Controlled Area	Simple Controlled	20 mSv	10 µSv/h	50 µSv/h	SIMPLE CONTROLLED / CONTRÔLÉE SIMPLE; Dosimeter obligatory / Dosimètre obligatoire
Radiation Area / Controlled Area	Limited Stay	20 mSv	-	2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ; Dosimeters obligatory / Dosimètres obligatoires
Radiation Area / Controlled Area	High Radiation	20 mSv	-	100 mSv/h	HIGH RADIATION / HAUTE RADIATION; Dosimeters obligatory / Dosimètres obligatoires
Radiation Area / Controlled Area	Prohibited	20 mSv	-	> 100 mSv/h	NO ENTRY / DÉFENSE D'ENTRER

TCC8 FLUKA model



Concrete composition studies

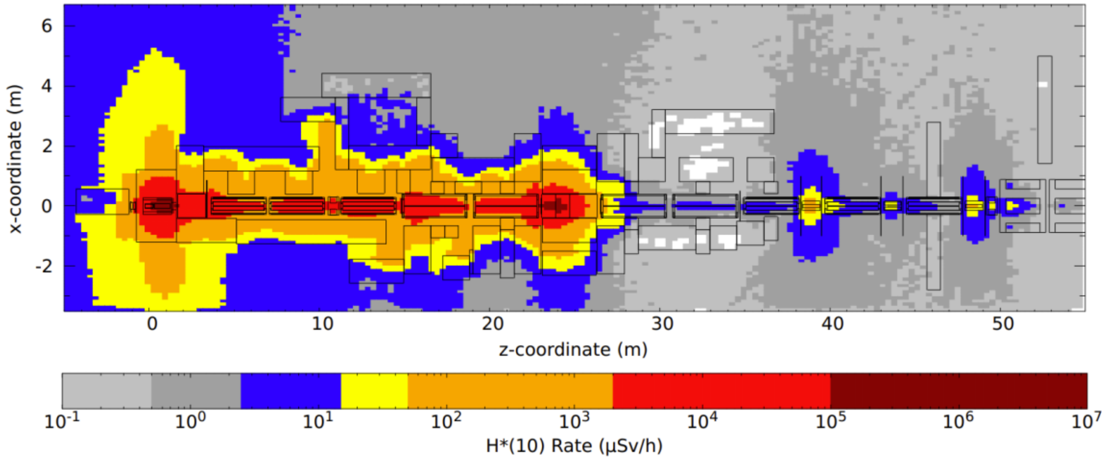
- Concrete samples were taken and analyzed via gamma spec and XRF measurements
- Particle fluences were scored at the given locations via FLUKA, which were then used for subsequent ActiWiz studies to match the measured radionuclide production

➢ Evaluation of refined elemental concrete composition

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) – Sep 2027



Summary

- 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
- Additional studies for the beam transfer and the TCC8 dismantling were conducted

➢ Further detailed studies and optimization in the Technical Design Phase until 2026 to achieve first beam on target in 2031 home.cern

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Activities – 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

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

Pure alpha/beta emitters are shown in bold

Dominant radionuclide is shown in red

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

CDS target radionuclide inventories

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**

- Ta cladding dominates for 1 month of cool-down due to Ta-182 ($\tau_{½}$ - 115 d)

30 years cool-down

Target	Material	Mass [kg]	Multiple LL	Multiple LA	A [Bq]
CDS	W	695	1.9E+05	**1.1E+08**	1.3E+12
	TZM	271	3.4E+05	3.1E+05	**2.1E+12**
	Ta	28	**6.5E+05**	1.5E+07	1.7E+11

- For 30 years of cool-down, the LL for Ta and W is dominated by Ba-133 ($\tau_{½}$ - 10.5 y), while the LA by Gd-148 ($\tau_{½}$ - 74.6 y)
- For all materials, the total activity is dominated by H-3 (1.5E12 Bq for TZM, $\tau_{½}$ - 12.3 y)

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 (guess, currently 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

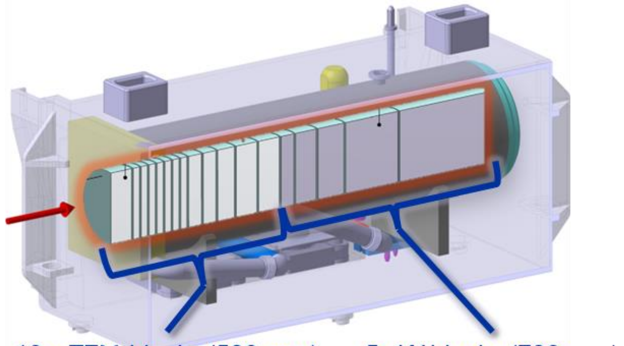
Radioisotope	Target	Proximity shielding	Magnetic coil
Be-7	1.3×10^{12}	2.6×10^{9}	6.2×10^{6}
H-3	7.4×10^{10}	1.8×10^{8}	4.1×10^{5}

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

Alternative BDF target design studies

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

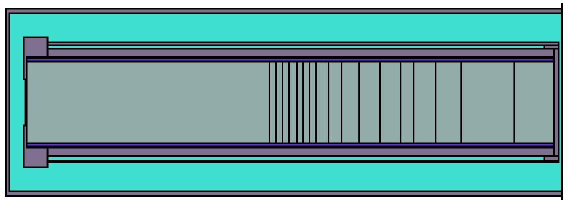
- Investigation of alternative claddings (Nb, Nb-1Zr, Nb-10Hf-1Ti) → Nb-94 (half-life of 20k yrs) w/ higher waste disposal challenges



➢ See talk "Design considerations for the BDF/SHiP production target" by R. Ximenes

Alternative designs currently being studied in the TDR

W Helium cooled Target

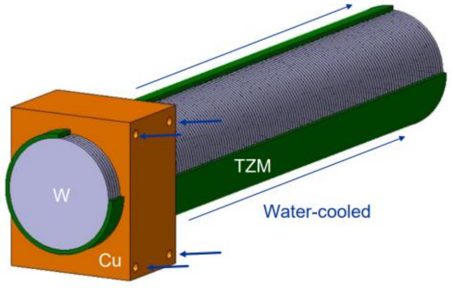


D = 33 cm, L = 201 cm

- Investigation of radionuclide inventories

Enclosed compact Cu + W Target

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



Radionuclide 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%)

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)

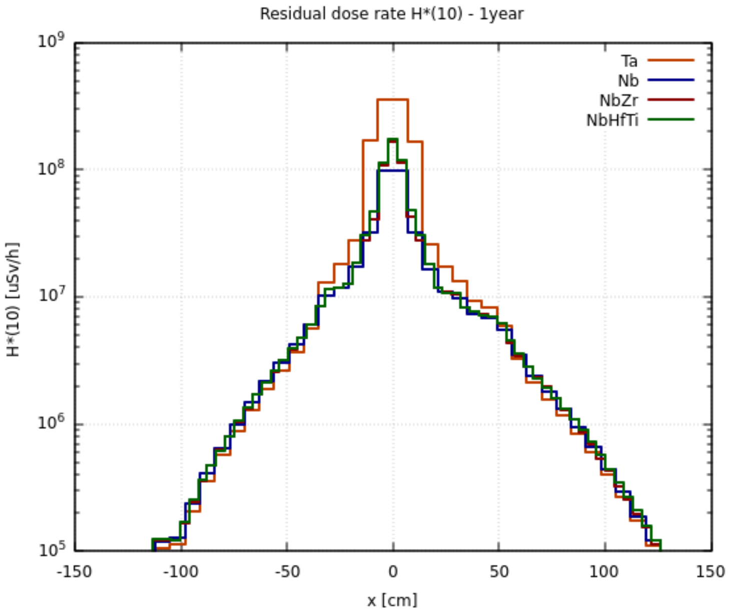
Material	Activity/LL - 5y	Activity/LL - 300y	Max. LMA fraction	RN exceeding LMA	RW Class.
Ta	1.30E+07	7.72E+03	7.58E+01	H-3 (75), Gd-148 (1.65)	FA-MA (CH)
Nb	1.62E+07	7.36E+06	6.19E+03	Nb-94 (6190), H-3 (65)	FA-MA (CH)
Nb-1Zr	1.60E+07	7.28E+06	5.23E+03	Nb-94 (5230), H-3 (66)	FA-MA (CH)
Nb-10Hf-1Ti	1.55E+07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