HSE

Occupational Health & Safety
and Environmental Protection unit

Radiological Assessment of the Beam Dump Facility at CERN

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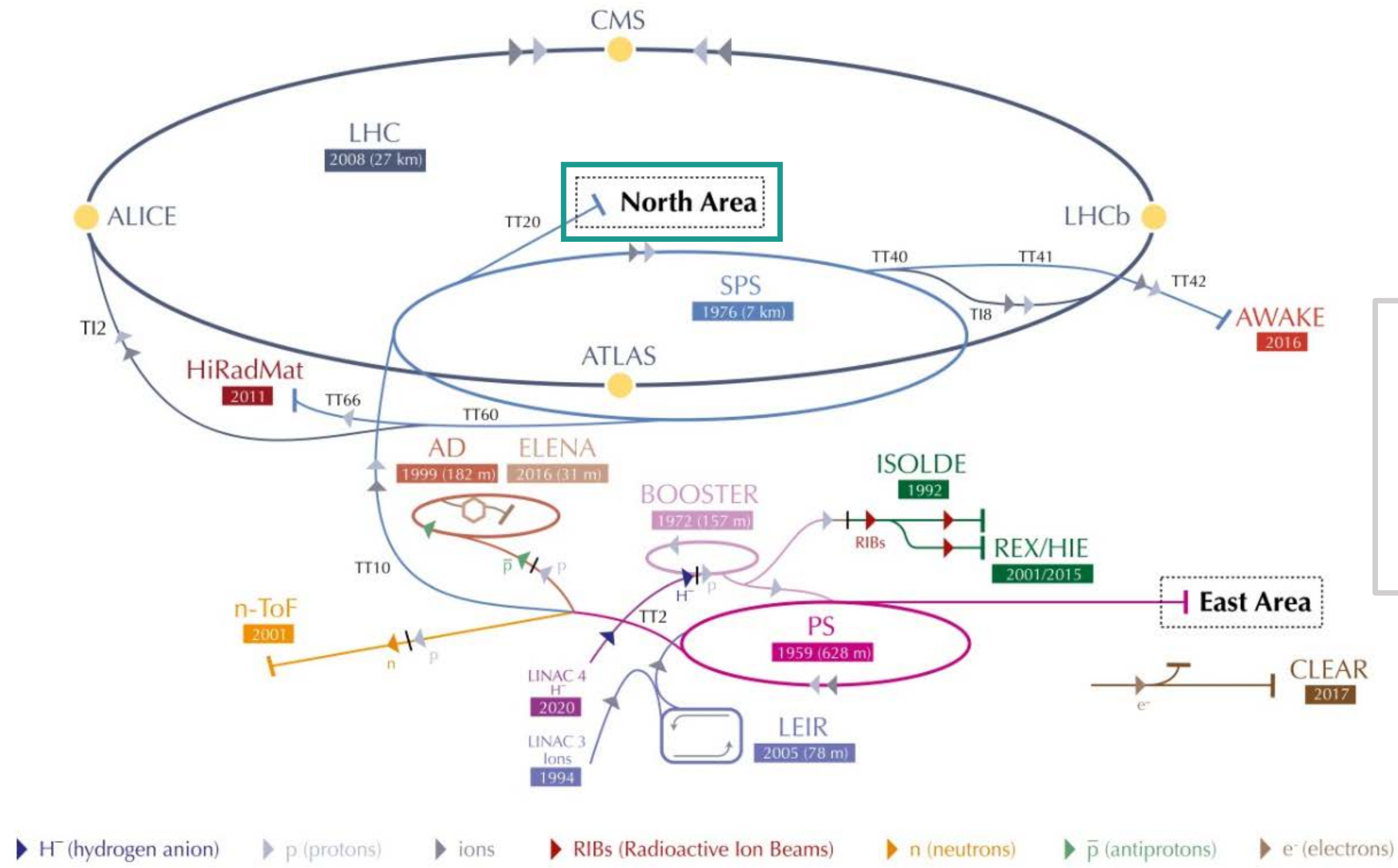
Outlook

- BDF concept and requirements
- General RP considerations
- RP evaluation
  - Prompt and residual radiation
  - Air and He activation
  - Water activation
  - Radioactive waste
- Summary

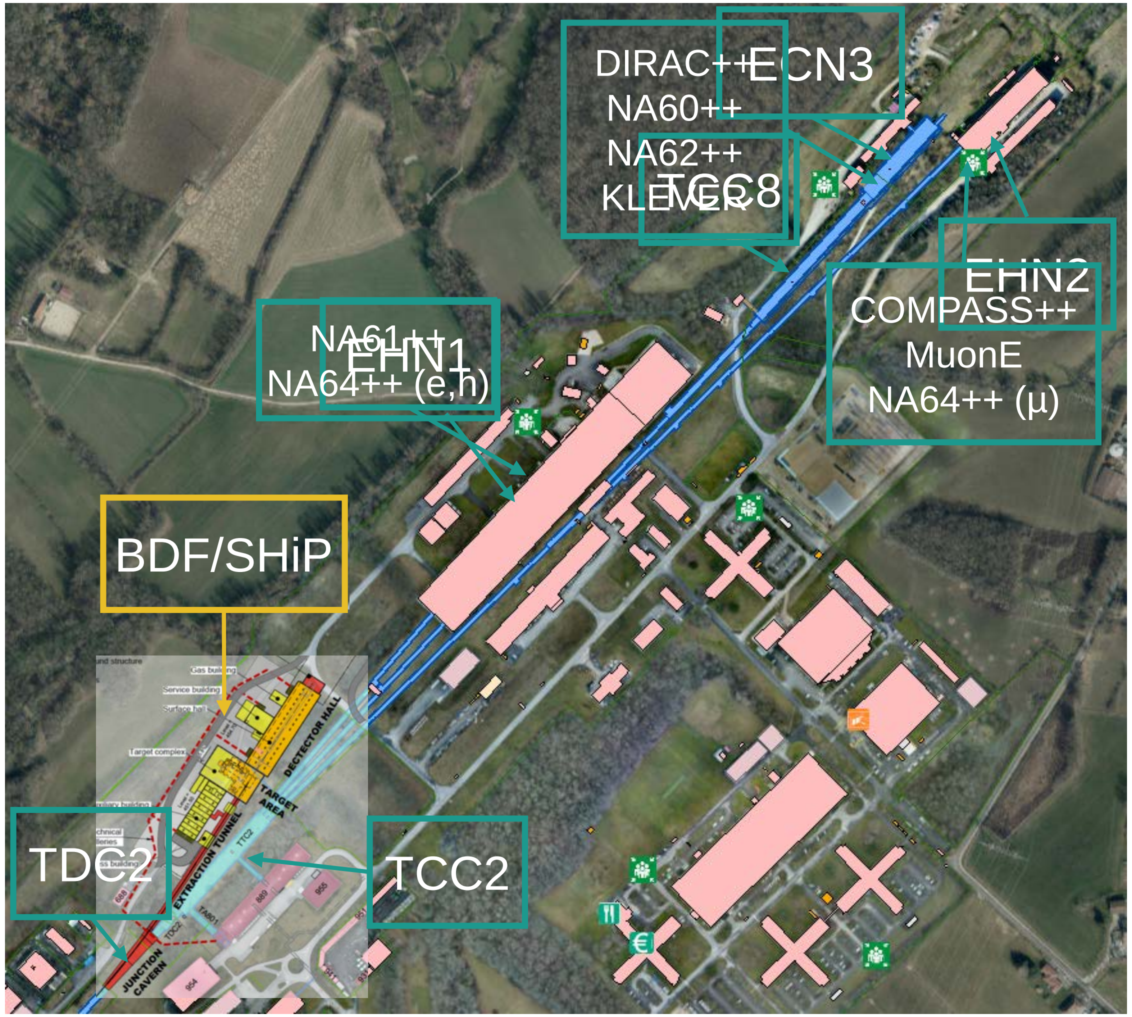
The CERN accelerator complex



Physics Beyond Colliders (PBC)

Study full scientific potential of the CERN's accelerator complex and scientific infrastructures through projects complementary to high-energy colliders

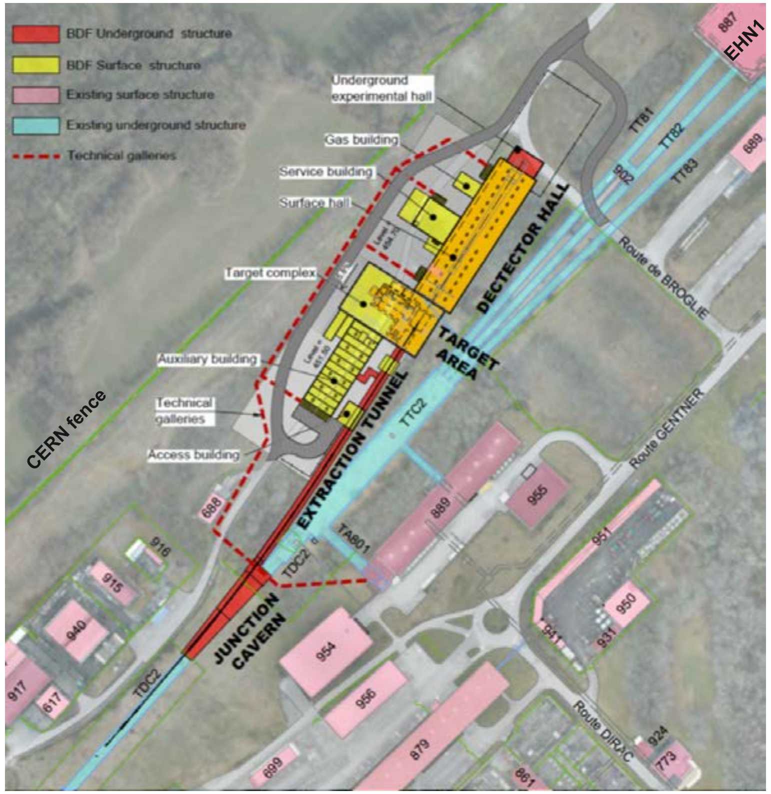
The SPS North Area

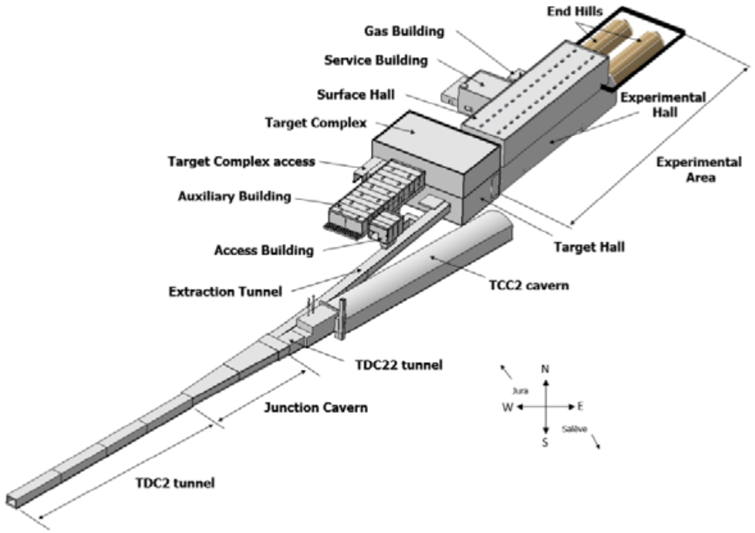


Various proposed projects in the framework of PBC!

The Beam Dump Facility (BDF)

BDF layout and surrounding facilities





Key beam parameters for SHiP

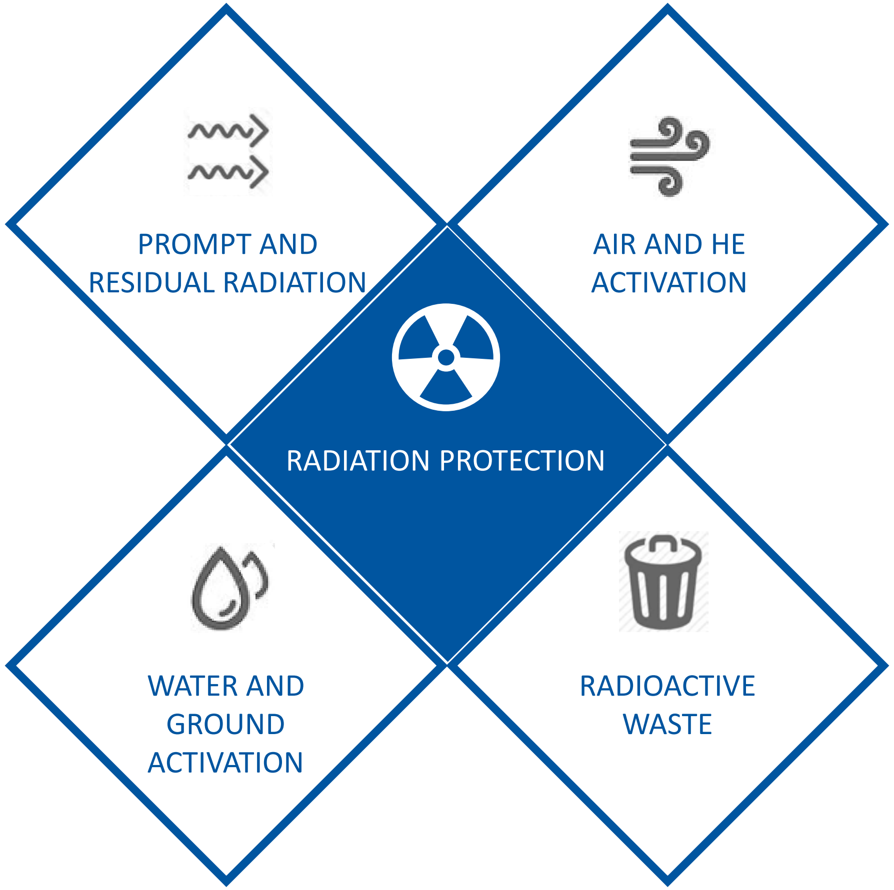
Momentum	400 GeV/c
Beam intensity on target	$4{\times}10^{13}$
Cycle length	7.2 s
Spill duration	1 s
Avg. beam power on target	355 kW
Protons on target (PoT)/year	$4{\times}10^{19}$
Total PoT in 5 years data taking	$2{\times}10^{20}$

- BDF is a proposed general purpose facility in the SPS North Area at CERN
- **Search for Hidden Particles** (SHiP) experiment first user of the facility
- A dense target/dump is located at the core of the facility, ~15 m underground
- Target/dump to absorb the vast majority of the particle cascade produced by the high intensity SPS proton beam
- RP challenges
  - High beam power
  - Proximity to surface, experimental and public areas
  - Keep flexibility for future installations
  - Construction of junction cavern and extraction tunnel

General RP considerations for BDF

- **High prompt dose** in the BDF target area calls for adequate shielding
- **Only** absolute **necessary equipment** is installed in the **target area**
- Due to high residual dose rate in the target area, **manual interventions** are **replaced** by **remote maintenance/repair**

- **Water cooling circuits** for the highly radioactive elements are **closed and separated** from others
- **Activation** and **contamination** of ground water and earth is **avoided** by considerable shielding and sumps

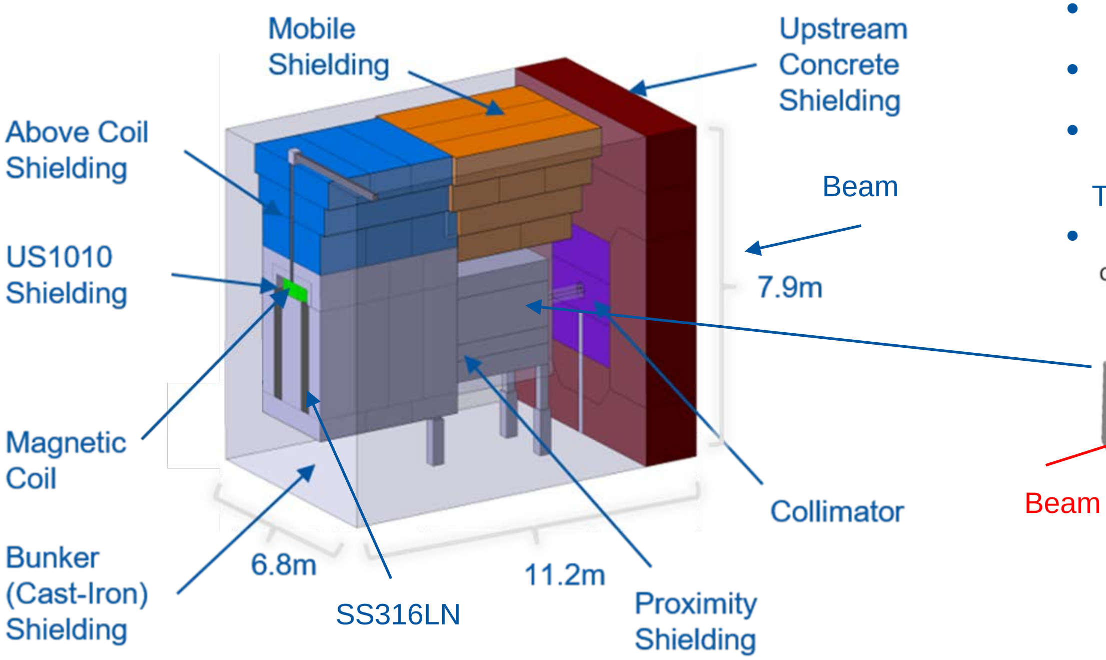


- **Air volumes** were **minimized** in the target area and in the most critical region **replaced by He**
- **Static confinement** of air by physical barriers to separate activated air from outside
- **Dynamic confinement** by a ventilation system guaranteeing a pressure cascade from low to high activated areas

- The design considers **minimization, decommissioning** and **dismantling** of radioactive waste

The BDF target complex

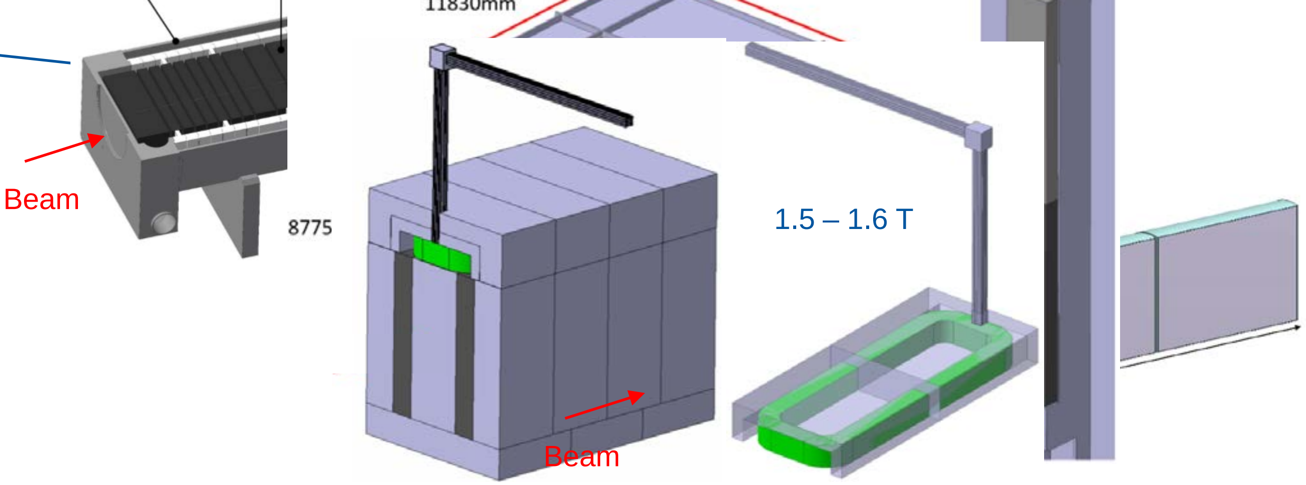
Target and hadron absorber



~ 3700 tonnes of cast iron and steel shielding

- The **target** (TZM[1], W) is surrounded by a **hadron absorber** (cast iron, steel)
- The target and the shielding immediately around it are **water cooled**
- A **He vessel** encloses the target and hadron absorber
- The beam will enter the surrounding He vessel through a removable beam window (0.3 cm thick Ti) and then pass through a collimator
- A magnetic coil and US1010 steel yoke are used to produce a magnetic field of 1.5-1.6 T downstream of the target to **sweep high energy muons**

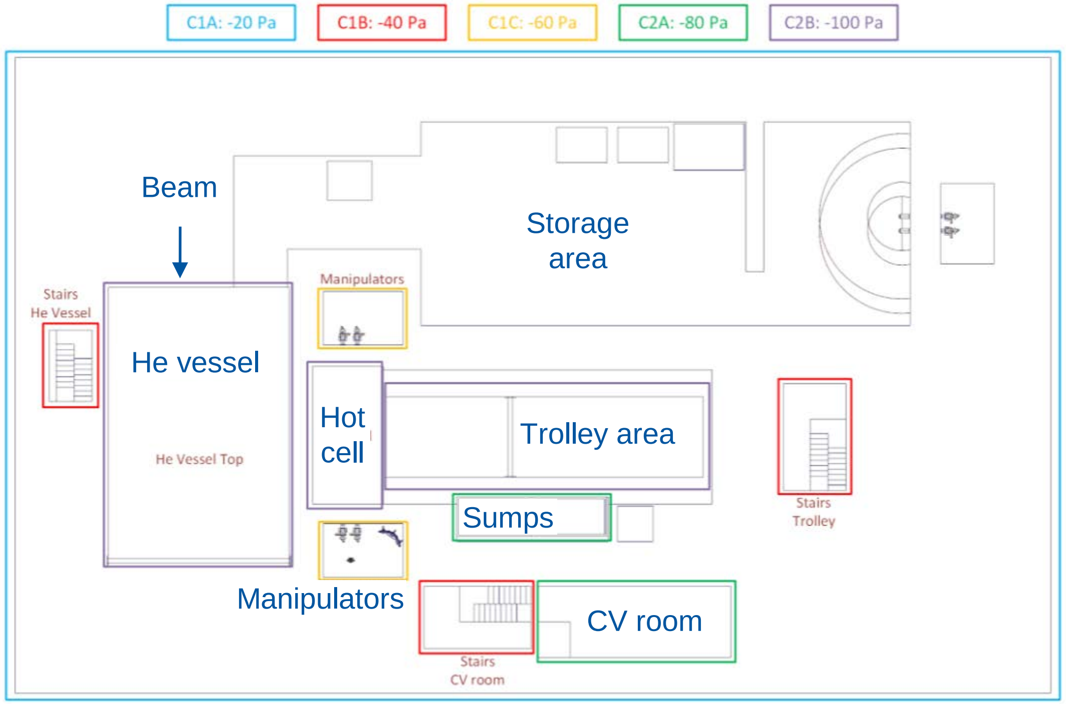
Target assembly in inner vessel



1. TZM: 0.08% titanium – 0.05% zirconium – molybdenum alloy

The BDF target complex

Layout of underground rooms



- The target complex houses the target, hadron absorber, He vessel, along with the cooling, ventilation and He purification services below ground level
- **Remote handling** and manipulation of the target and surrounding shielding will be mandatory due to the **high residual dose rates**
- Different handling concepts were developed: crane, trolley concepts, crane++
- A **cool-down area** below ground level with dedicated shielded pits for temporary storage of the highest dose rate equipment is foreseen
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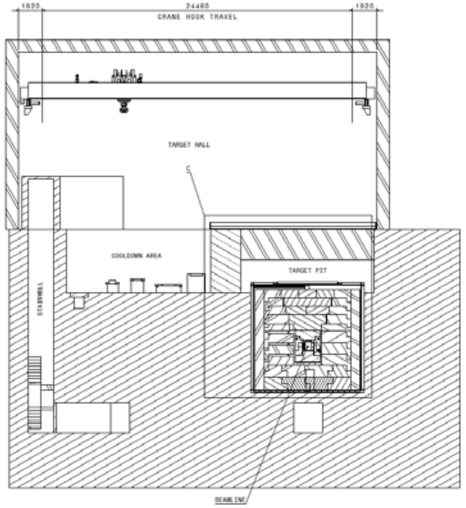
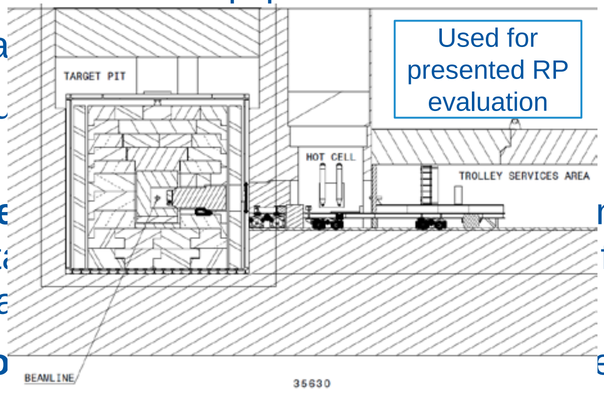
Crane concept overview



Trolley concept overview

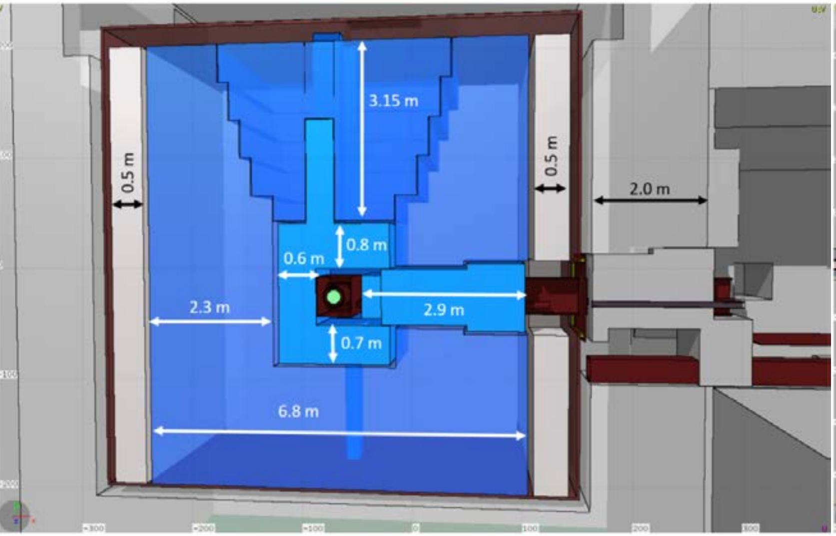


→ combination of advantages in crane++

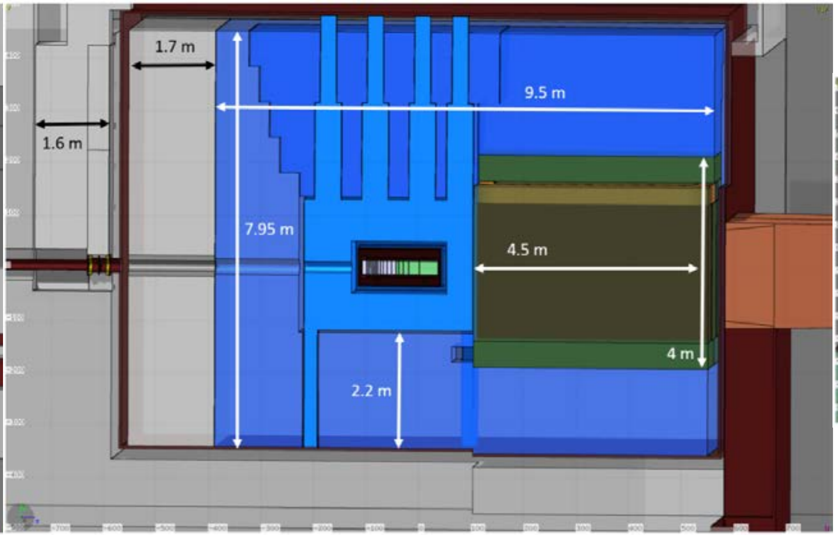
RP evaluation based on FLUKA simulations

BDF/SHiP as implemented in FLUKA

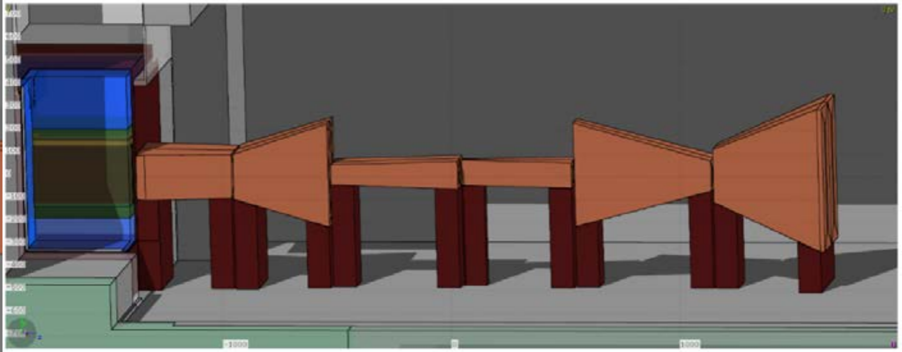
Side view – target area



Side view – target area

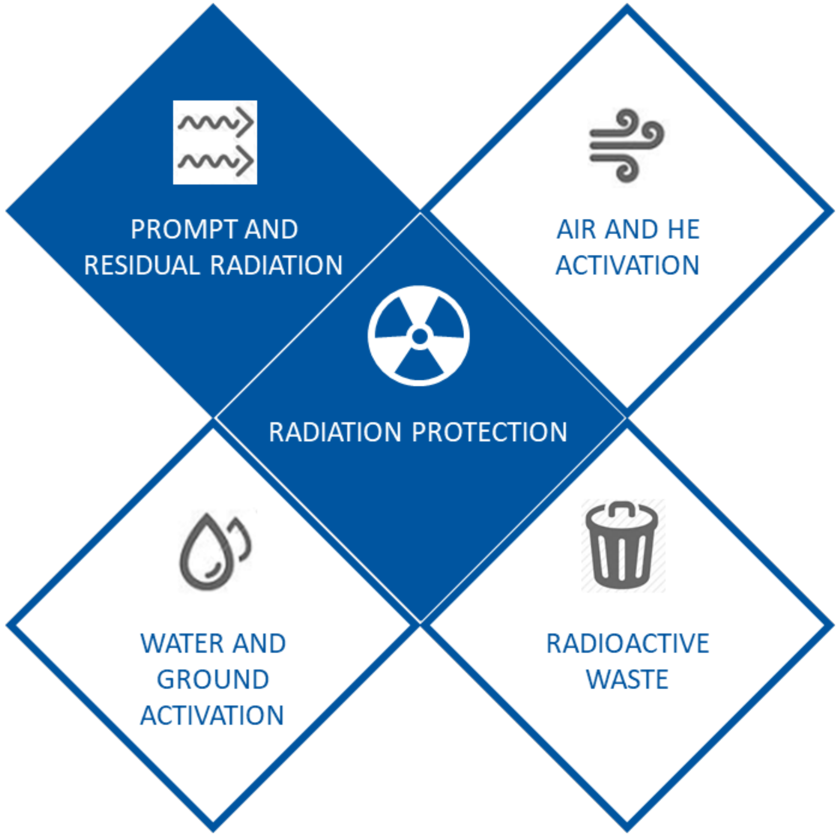


Side view – muon shield



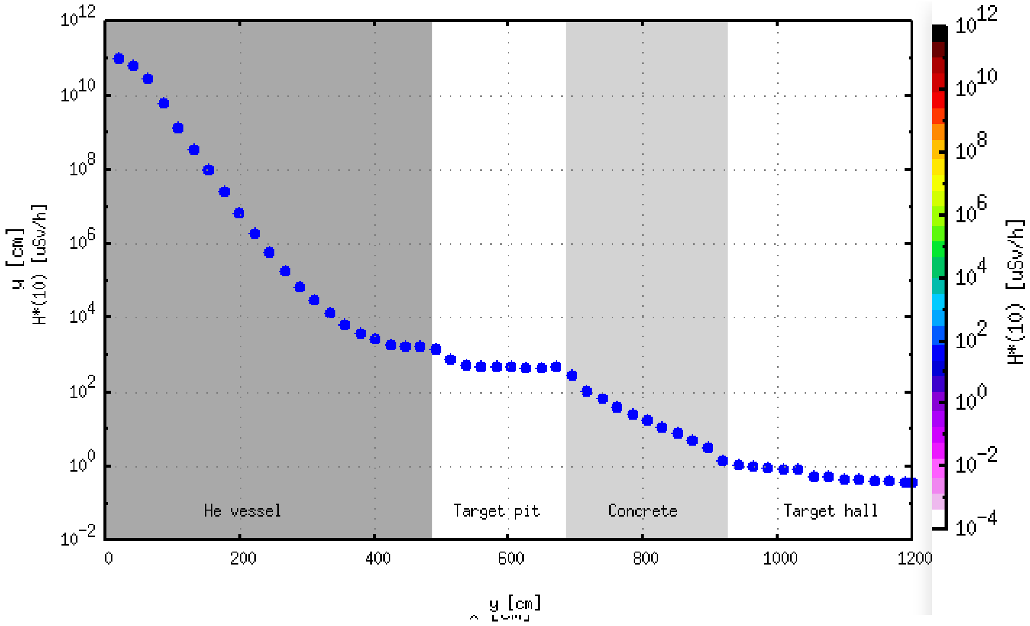
- **No access during operation** to the underground infrastructure during beam operation
- **Massive shielding** to keep prompt/residual dose rate and airborne **radioactivity as low as possible**
- Active muon shield with magnets (1.8 T) from the SHiP experiment was included

Prompt and residual radiation



Prompt dose rates in the target area

Target area – Front view / Along the height



CERN area classification / Target area – Side view

Area	Dose limit [year]	Ambient dose equivalent rate: permanent	Ambient dose equivalent rate: low occupancy	Sign
Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	
Supervised (Radiation Area)	6 mSv	3 µSv/h	15 µSv/h	Dosimeter obligatory / Dosimètre obligatoire
Simple (Radiation Area, Controlled Area)	20 mSv	10 µSv/h	50 µSv/h	Dosimeter obligatory / Dosimètre obligatoire
Limited Stay (Radiation Area, Controlled Area)	20 mSv		2 mSv/h	LIMITED STAY / SÉJOUR LIMITÉ – Dosimeters obligatory / Dosimètres obligatoires
High Radiation (Radiation Area, Controlled Area)	20 mSv		100 mSv/h	HIGH RADIATION / HAUTE RADIATION – Dosimeters obligatory / Dosimètres obligatoires
Prohibited (Radiation Area, Controlled Area)	20 mSv		> 100 mSv/h	PROHIBITED AREA / ZONE INTERDITE – No Entry / Défense d'entrer

Prompt dose rates reach a **few mSv/h** above He-vessel and drop further down in the concrete shielding towards the target hall

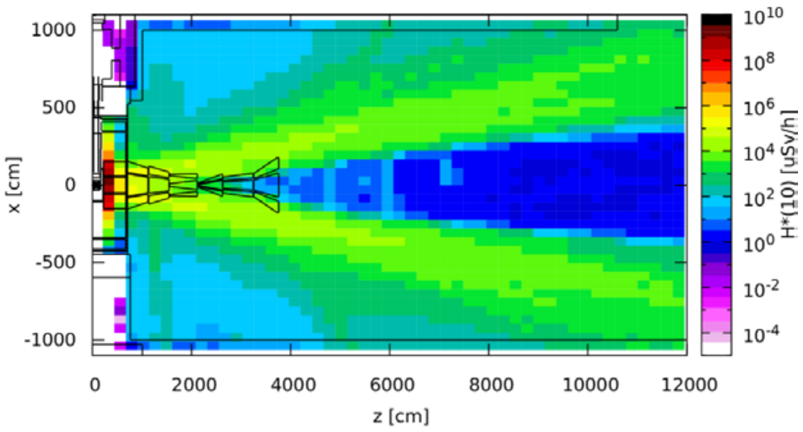
→ Expected classification: **Supervised Radiation Area** in the target hall

100 rem = 1Sv

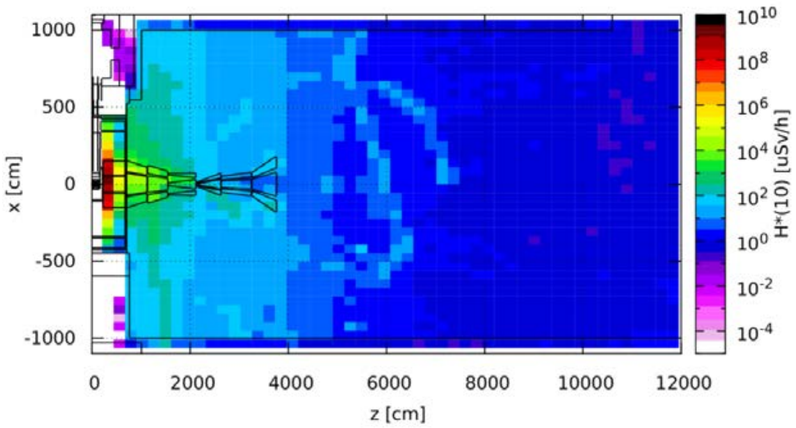
Prompt dose rates in the experimental area

Experimental area – Top view

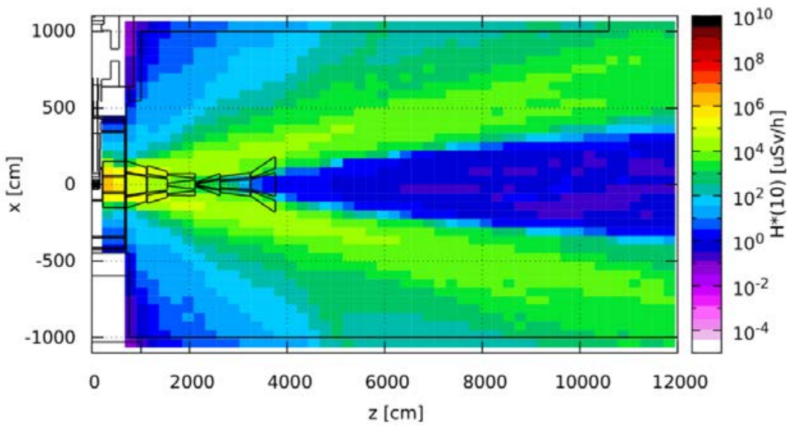
All particles



Neutrons



Muons



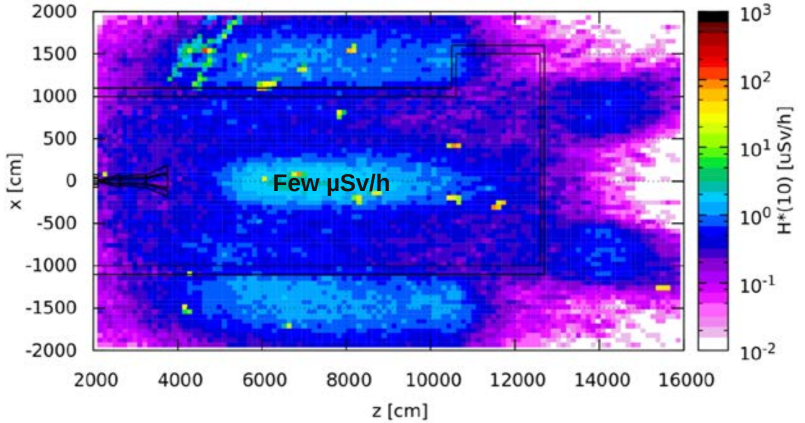
Prompt dose rates reach **a few mSv/h** at the magnet mainly due to muons and drop down to below ~1 mSv/h in the surrounding soil

→ **No access during beam operation** will be permitted to the underground experimental hall

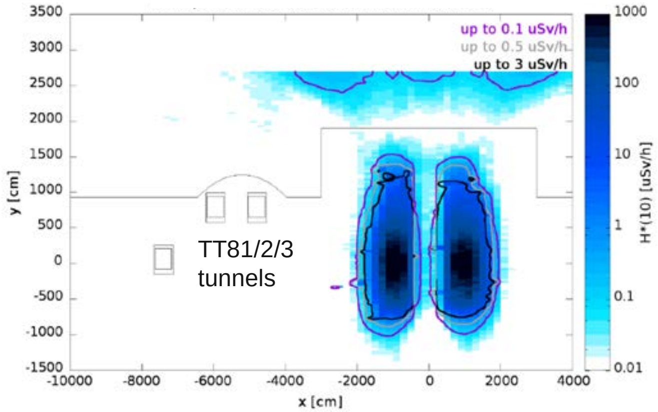
100 rem = 1Sv

Prompt muon dose rates in the surrounding areas

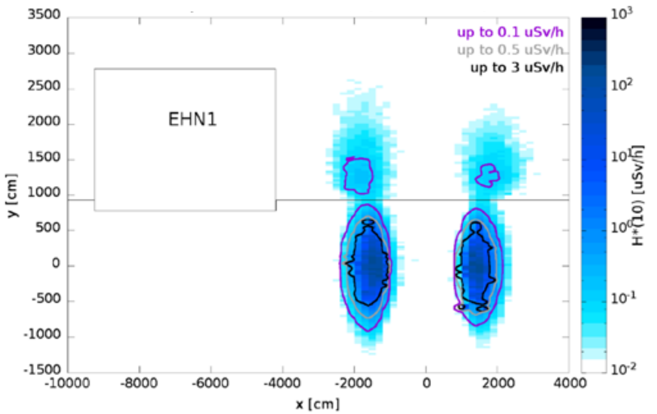
In the surface hall



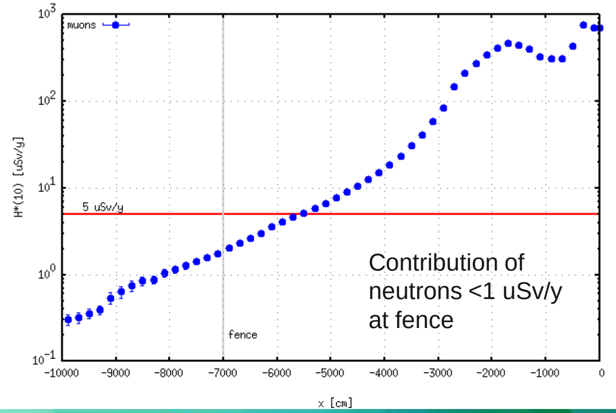
At existing transfer lines



At EHN1



At CERN fence [µSv/y]



Only a **few µSv/h** are reached in the surface hall

→ **No personnel access** to the surface hall is **required** during **beam operation**

→ The area around experimental hall will be fenced

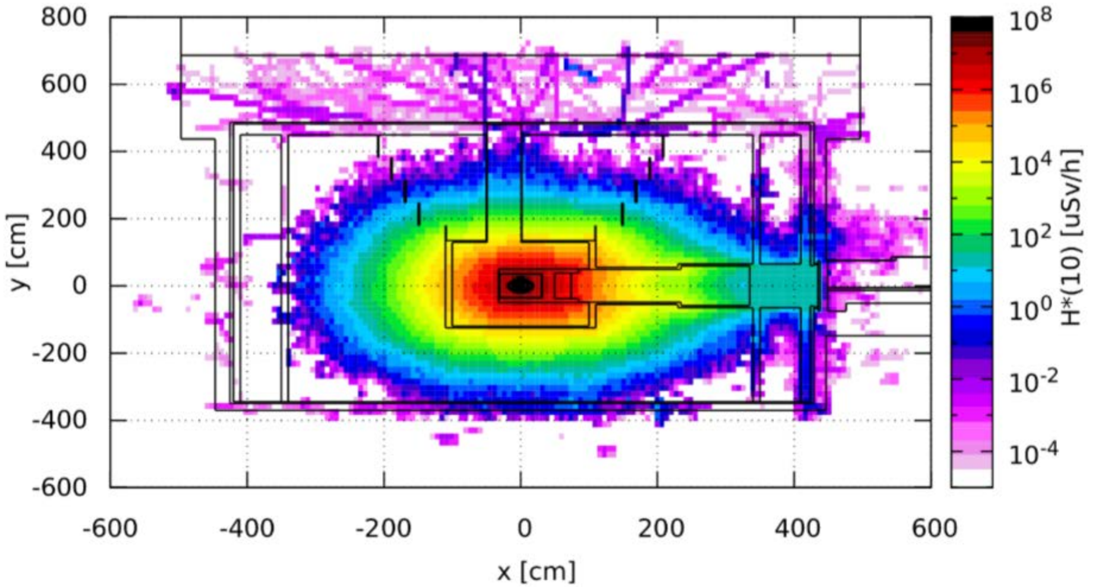
The prompt muon dose around the existing facilities are **below** a **Non-designated Area** level (<0.5 µSv/h)

The prompt radiation outside of the fenced CERN site, thus the **publicly accessible area**, is **below** the envisaged **5 µSv/y**

100 rem = 1Sv

Residual dose rates in the target area and experimental hall

5 years operation - 1 month cooling

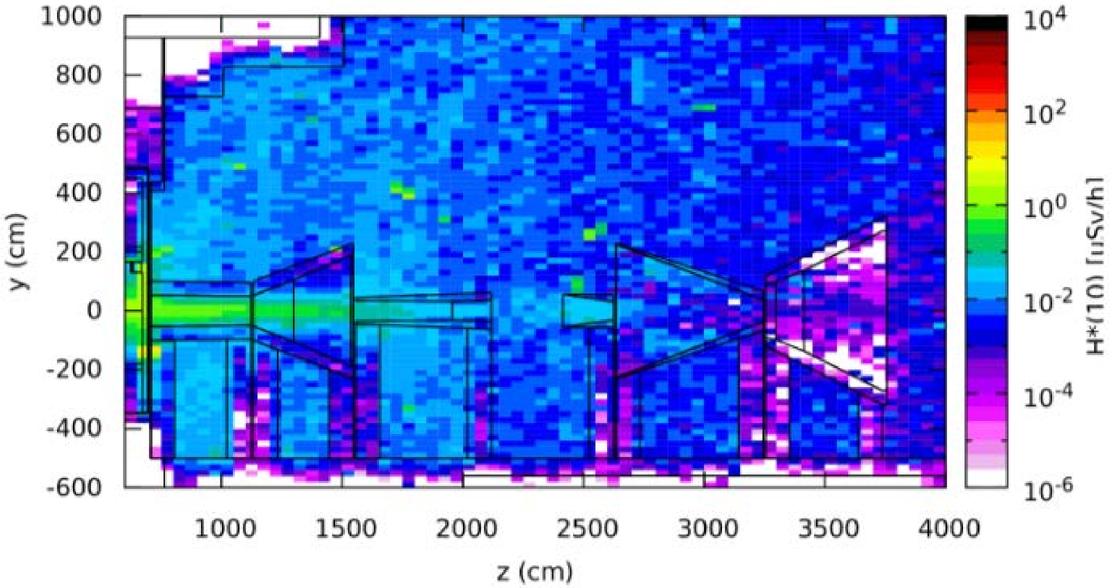


The dose rates reach a **few 10^8 µSv/h** after **1 month** of cooling and at an **accessible point** (next to He vessel) a **few µSv/h after 1 week of cooling**

→ **Facility design** such that all the **interventions** in the target area will be executed **remotely**

100 rem = 1Sv

5 years operation - 4 hours cooling

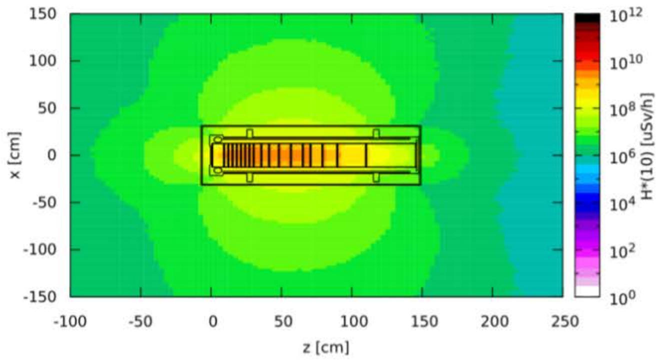


The dose rates close to the upstream part of the muon shield reach a **few µSv/h** after **4 hours** of cooling

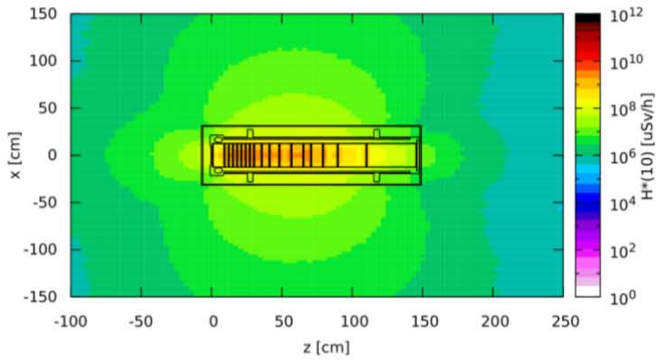
→ **Simple Controlled Radiation Area (<50 µSv/h)** with low occupancy in upstream part, while the rest will be a **Supervised Radiation Area** with permanent stay **(3 µSv/h)**

Residual dose rates and activation of the target

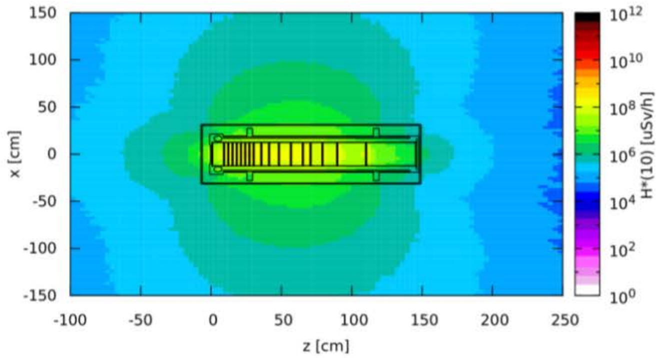
5 years irradiation – 4 hours



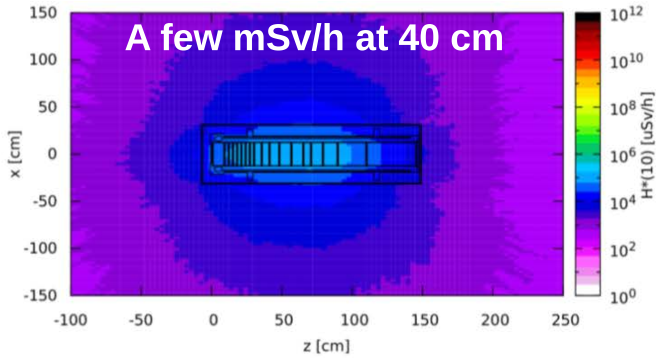
1 day



1 year



30 years



100 rem = 1Sv

Activation of W for 5 years irradiation

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
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		9.1E+14	8.4E+13	4.4E+12	1.3E+12

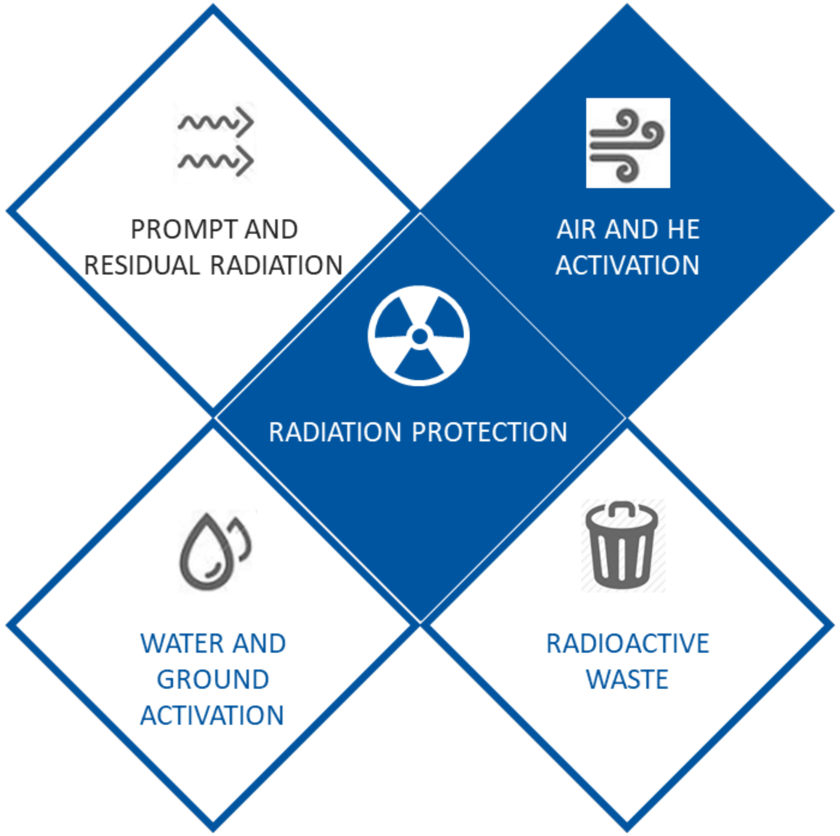
s

was defined to decrease dose rates to below 2 mSv/h

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

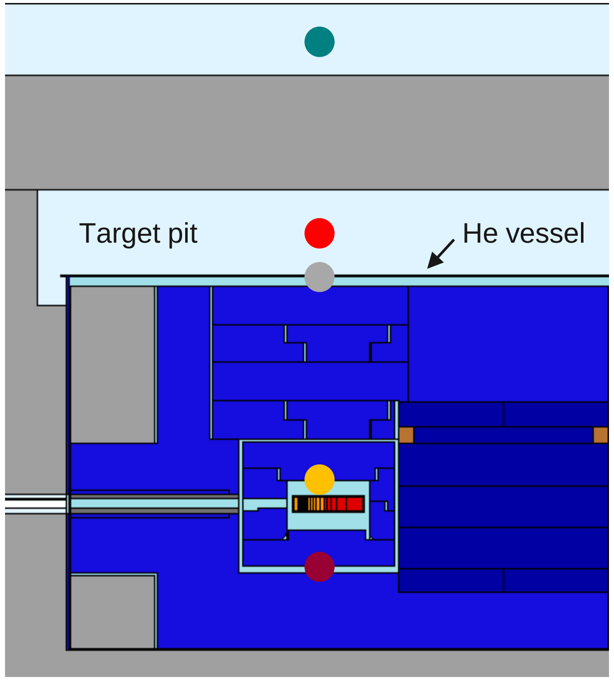
LA = Swiss Authorization Limit

Air and He Activation



Air and helium activation

Air and He regions in the target complex



A helium purification system provides a purity of at least **99.9% He** (<0.1% air contamination)

5 years operation – 60 s of cooling

Volume	Activity [Bq]		Multiple of CA	
	Air	He	Air	He
Middle He	7.8×10^5	4.1×10^7	1.3×10^3	8.7×10^{-4}
Inner He	5.6×10^7	2.8×10^9	7.5×10^5	4.2×10^{-1}
External He	1.5×10^2	9.0×10^3	2.0×10^{-2}	1.5×10^{-8}
Lower air	1.7×10^7	–	7.0×10^{-1}	–
Upper air	8.3×10^4	–	6.7×10^{-3}	–

No H-3 out-diffusion was taken into account due to the deficient availability of diffusion constants

→ Out-diffusion experiment were performed (see talk by M. Casolino)

Accident case: He vessel breakdown

→ 2.7 CA and 8 µSv for 1 hour from inhalation

39 isotopes were considered, including the radiologically most relevant short-lived (^{11}C, ^{13}N, ^{14}O, ^{15}O and ^{41}Ar) and long-lived (^{3}H, ^{7}Be, ^{14}C, ^{32}P, ^{35}S) isotopes

Ventilation system:

- ISO 17873:2004[2] was taken as guideline for classification of BDF ventilation system
- Classification of type C2 with pressure differences between compartments

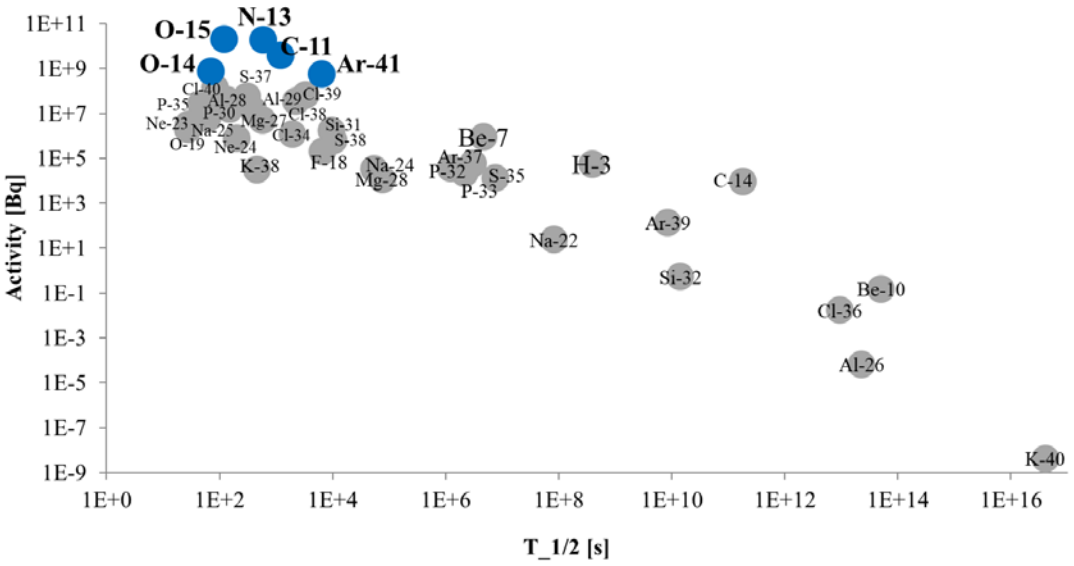
[1] Person working 40h/w, 50w/y with standard breathing rate (1.2 m^3/h) in activated air with CA = 1 receives 20 mSv

2. ISO 17873:2004: Criteria for the design/operation of ventilation systems for nuclear installations other than nuclear reactors

Air and helium releases

Annual releases from target pit

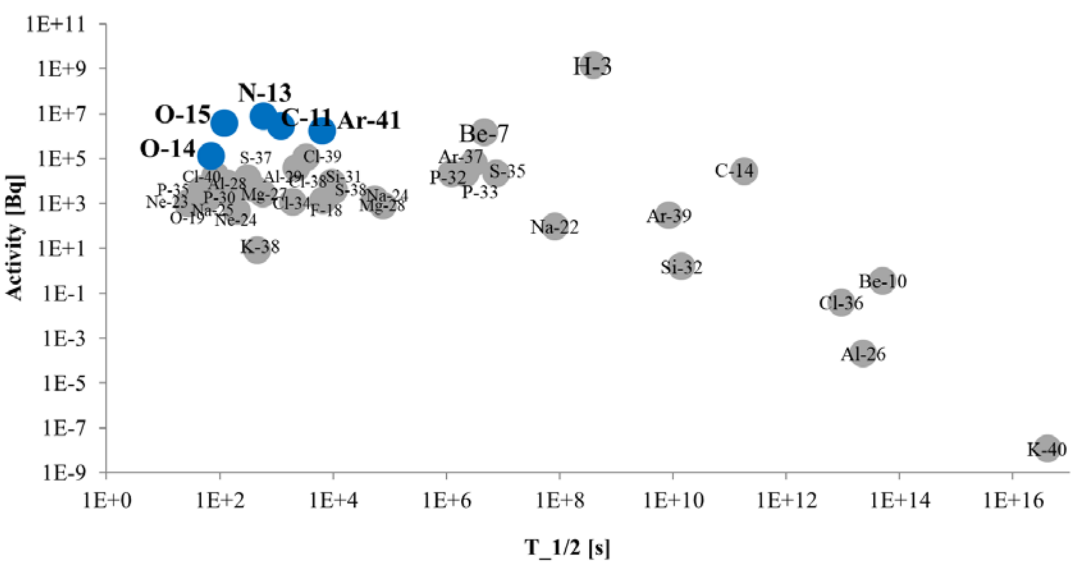
Assuming continuous air releases without any delays or filters



→ $4.5 \cdot 10^{10}$ Bq total activity, of which 99% are due to short-lived radionuclides

Annual releases from He vessel

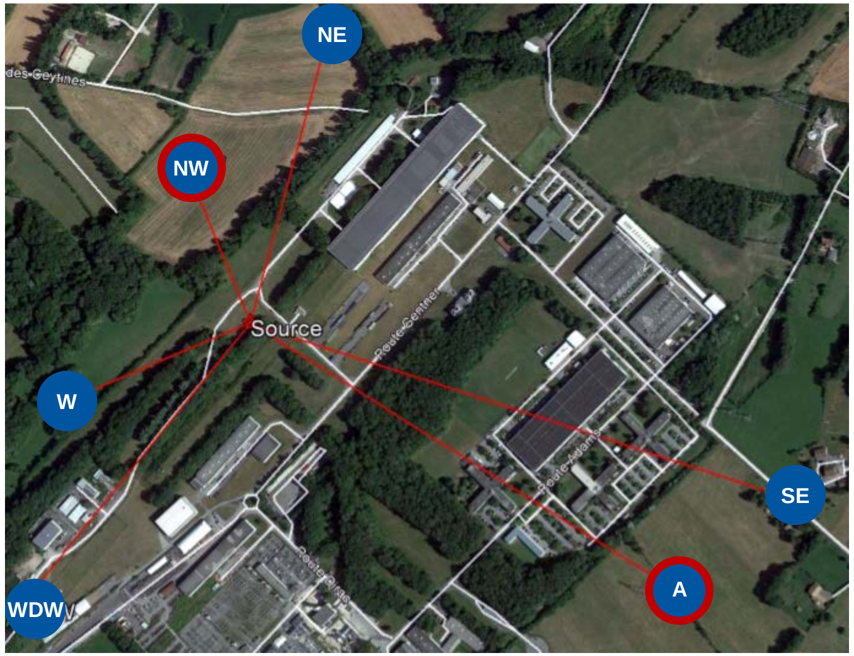
Assuming 1 release per year without any delays or filters



→ $1.5 \cdot 10^{10}$ Bq total activity, of which 1% are due to short-lived radionuclides and 99% due to H-3

Radiological impact of air and helium releases

Positions of reference groups



- Identified 6 reference groups around BDF facility

  → used max. dose coefficients from the different age groups

- Parameters of the ventilation stack not yet defined

  → assumed a ground release

Effective dose (main radioisotopes)

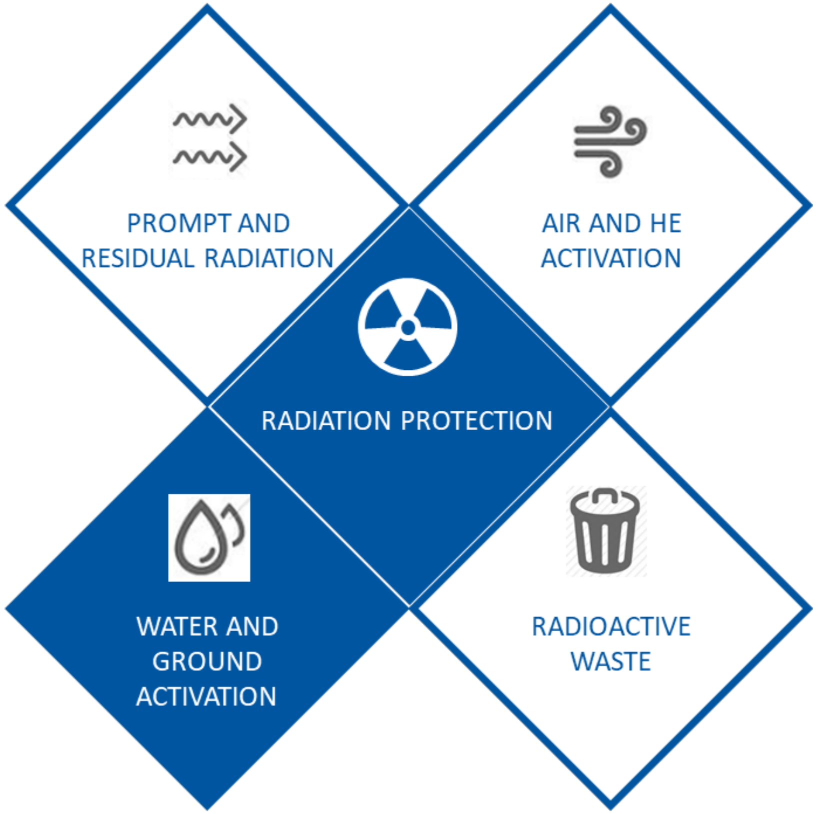
Radioisotope	NW [Sv/y]
H-3	4.7×10^{-9}
N-13	1.8×10^{-9}
Be-7	1.6×10^{-9}
C-11	6.1×10^{-10}
O-15	4.5×10^{-10}
Ar-41	1.4×10^{-10}
Cl-39	1.1×10^{-10}
P-32	6.5×10^{-11}
Cl-38	4.5×10^{-11}
Na-22	4.4×10^{-11}
Al-28	3.2×10^{-11}
Sum of all 39	9.8×10^{-9}

Radioisotope	A [Sv/y]
H-3	2.4×10^{-9}
P-32	2.3×10^{-9}
P-33	2.8×10^{-10}
Sum of all 39	5.3×10^{-9}

→ HEPA filters will further reduce effective dose

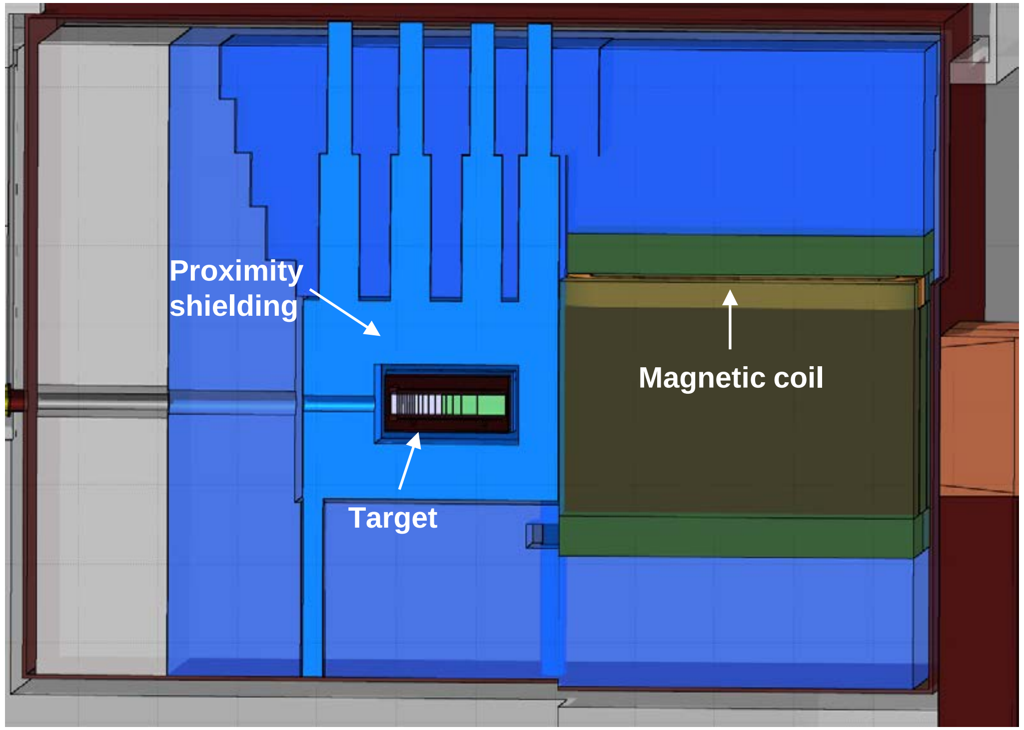
→ Doses sufficiently below 10 µSv/year from all facilities at CERN, which is the dose objective for public

Water activation



Water activation

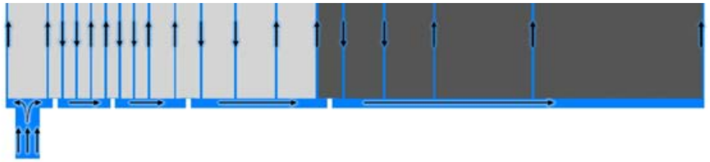
BDF water cooling circuits



- The He vessel includes three demineralized water cooling circuits for the target, the proximity shielding and the magnetic coil
- The water activation was evaluated for all circuits

Activity [Bq] – 1 operational year, 4 hours cooling

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}



- Deminer ing water will main
- Due to the high H-3 production in the target and surrounding shielding, out-diffusion could contribute significantly

→ Out-diffusion experiment were performed (see talk by M. Casolino)

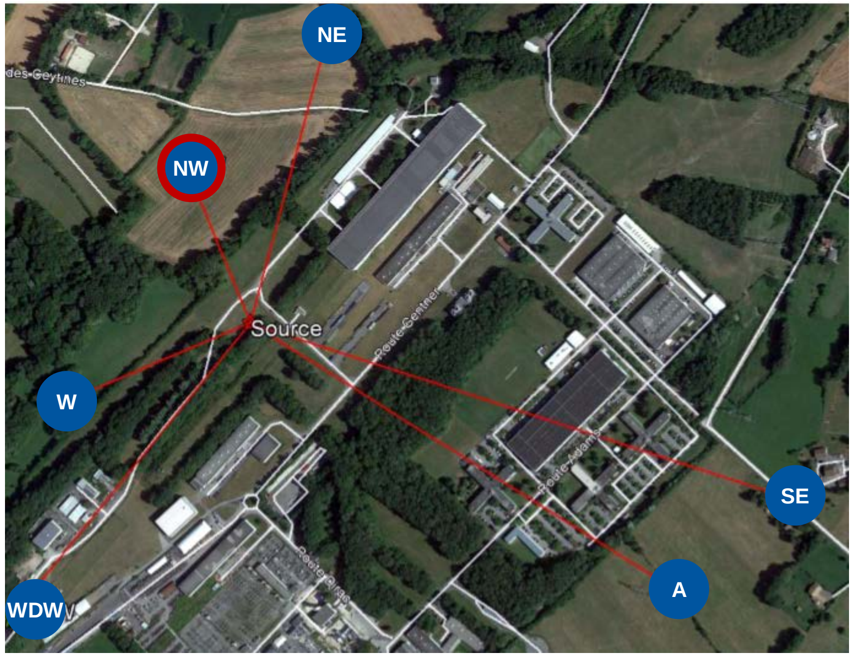
Radiological impact of water releases

Target water releases

- Assuming one purge of the target cooling water per year:
  - 74 GBq from direct production
  - 180 GBq assuming 3% out-diffusion from the target

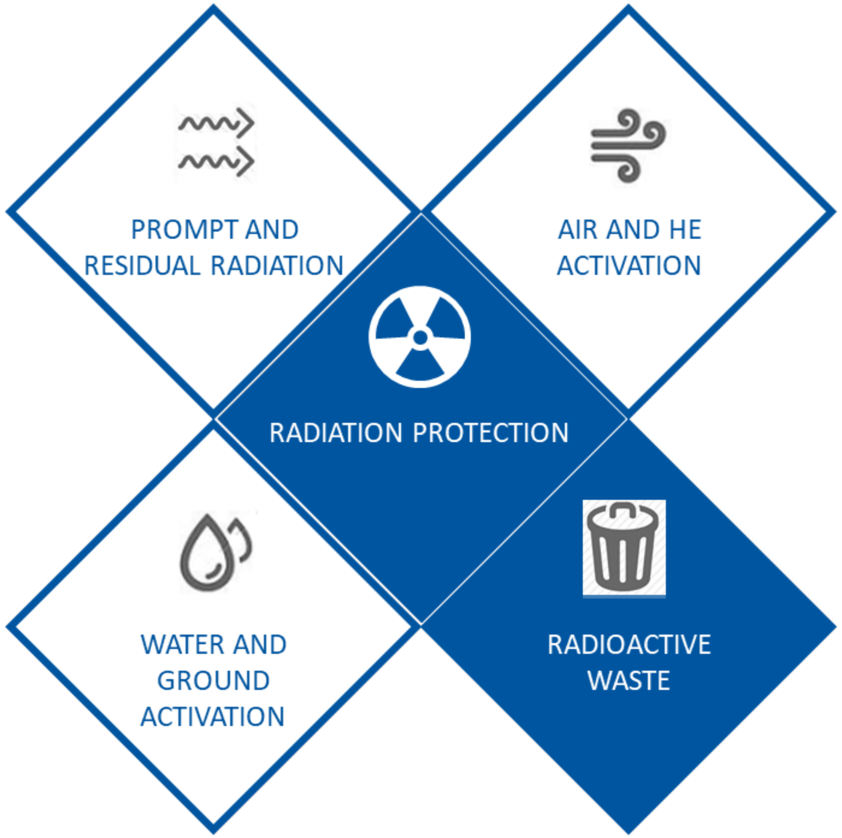
  → results in a total H-3 activity of 254 GBq and a concentration of 0.25 GBq/l
- A new evaporator was included in the BDF facility design to slowly evaporate the water into the atmosphere
- Again, several hypothetical population groups were examined (NW most critical)
- A maximum effective dose of 42 nSv/y was obtained

Positions of reference groups



→ Doses sufficiently below 10 µSv/year from all facilities at CERN, which is the dose objective for public

Radioactive waste



Radioactive waste production

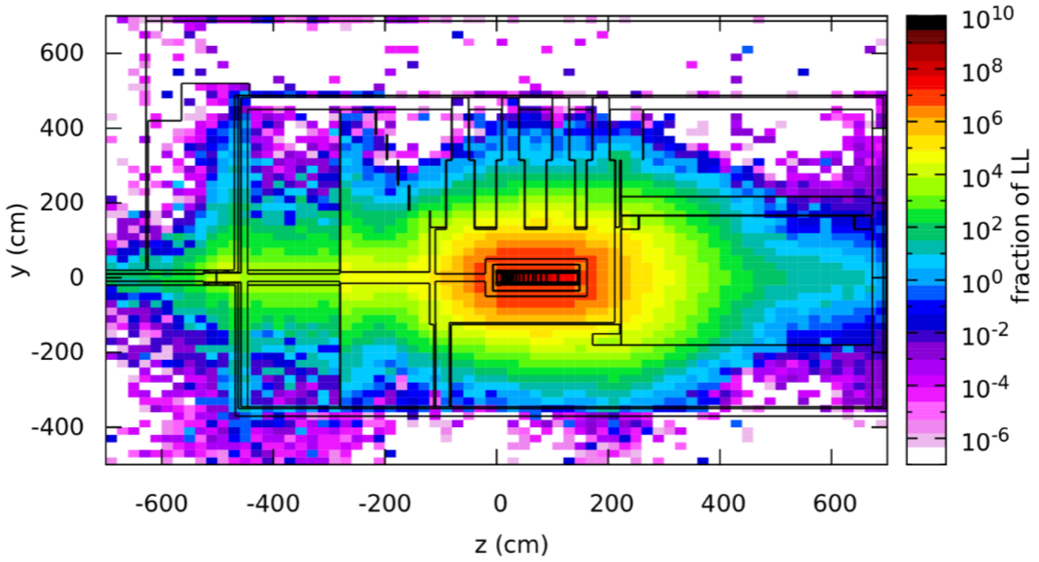
- To distinguish areas of radioactive waste from conventional ones the Swiss clearance limits (LL) were used
- The following sum rule was applied for material containing a mixture of radionuclides

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

a_i - specific activity (Bq/kg) or total activity (Bq) of the i^{th} radionuclide
LL_i - respective Swiss clearance limit for the radionuclide i
n - number of radionuclides present

- The most activated parts are the target and the iron shielding elements (also for 30 years of cooling)
- The minimisation of radioactive waste was taken into account in the shielding design by having a modular shielding such that activated parts can easily be separated from non-radioactive parts

1 year of cooling



Summary and conclusions

- The proposed BDF would be a **new facility** in the CERN SPS North Area with unprecedented average beam power

- An in-depth radiological assessment of the proposed BDF/SHiP at CERN has been conducted
  - High prompt and residual dose rates → massive shielding and remote interventions
  - **Target area particularly critical** → embedded in a Helium vessel
  - **Environmental impact** of air, helium and water releases lies **well below CERN's dose objective**
  - Understanding **tritium out-diffusion** will be **crucial** for the environmental impact → see talk by M. Casolino

- The BDF project team has written a **Comprehensive Design Study** report as input for the next update of the European Strategy for Particle Physics (ESPP):

  C. Ahdida et al., SPS Beam Dump Facility: Comprehensive Design Study, CERN-PBC-REPORT-2018-001

Publications (non-exhaustive)

BDF

- C. Hessler et al., Beam Optics Studies for BDF and for Tests of a Prototype Target, IPAC 2018, ISBN: 978-3-95450-184-7
- K. Kershaw et al., Design Development for the Beam Dump Facility Target Complex at CERN, 2018, JINST 13 P10011
- E. Lopez Sola et al., Design of a high power production target for the Beam Dump Facility at CERN, 2019, arXiv:1904.03074
- E. Lopez Sola et al., Beam impact tests of a prototype target for the Beam Dump Facility at CERN: experimental setup and preliminary analysis of the online results, 2019, arXiv:1909.07094

SHiP

- C. Ahdida et al., The experimental facility for the Search for Hidden Particles at the CERN SPS, 2019, JINST 14 P03025
- W. Bonivento et al., Proposal to Search for Heavy Neutral Leptons at the SPS, arXiv:1310.1762
- S. Alekhin et al., A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case, Rept. Prog. Phys. 79 (2016), no. 12 124201, arXiv:1504.04855
- SHiP Collaboration, M. Anelli et al., A facility to Search for Hidden Particles (SHiP) at the CERN SPS, Technical Proposal, arXiv:1504.04956
- SHiP Collaboration, C. Ahdida et al., SHiP Experiment - progress report, CERN-SPSC-2019-010 / SPSC-SR-248, 25/01/2019

Backup slides

BDF Roadmap

Indicative BDF project execution time-line

Indicative dates	Years	Activity
2023 - 2024	2.0	**CE pre-construction**
		Environmental impact study
		Building permit submission/approval
		Tender and CE detailed design
2023 - 2025	3.0	**Component production**
		Beamline systems and components
		Tender technical services production
		Target assembly
		Target complex handling systems etc.
2025-2027	3.0	**Underground CE**
	1.25	Junction Cavern/Beamline-part-1
	1.25	Beamline-part-2/Access building
	1.5	Target complex
	1.75	Experimental hall
2026 - 2028	2.5	**Surface CE**
	0.75	Access and auxiliary buildings
	1.0	Service building/Target Hall
	1.0	Experimental hall
2026 - 2028	2.5	**Installation**
	0.5	Junction Cavern/Beamline-part-1
	0.5	Beamline-part-2
	1.25	Access and auxiliary buildings
	2.5	Service building/Target Hall
	2.0	Experimental Hall

Possible TDR time-line

2020	Continued design studies and prototyping
End 2020	Approval to go ahead with TDR
2021 - 2022	Engineering design studies towards TDR Detailed integration studies Specification towards production Begin CE pre-construction activities: environmental impact study; detailed CE design and pre-tender process.
2022	TDR delivery
2023	Seek approval
2023+	Tender, component production, CE contracts

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