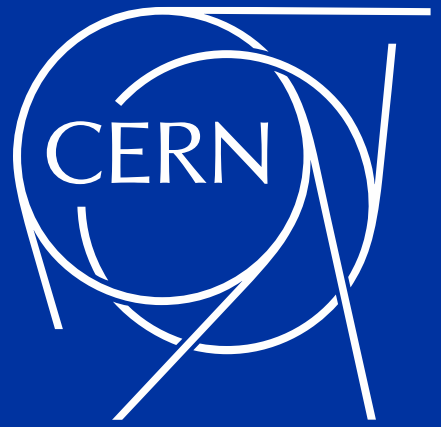

Radiation protection assessment of the AMBER Drell-Yan program

C. Ahdida, A. Devienne, V. Andrieux, D. Banerjee, J. Bernhard, S. Cholak, C. D. Da Rocha Azevedo, O. Denisov, A. Gerbershagen, S. Girod, F. Malacrida, P. M. Mendes Correia, F. Metzger, M. Quaresma, C. Quintans, M. Van Dijk, H. Vincke, P. Vojtyla

PAW’24, 18-20 March 2024

Overview

1. **RP principles**
   justification, limitation, optimization

2. **COMPASS Drell-Yan runs**
   past limitations

3. **AMBER design optimization**
   prompt and residual radiation, air activation, environmental impact

General Principles of Radiation Protection

ICRP recommends the international guidelines, which are transcribed into law on European and national level

Justification
Any exposure of persons to ionizing radiation has to be justified

Limitation
The personal doses have to be kept below the legal limits

Optimization
The personal doses and collective doses have to be kept as low as reasonably achievable (ALARA)

Limitation at CERN – *Safety Code F*

Occupationally exposed persons (Radiation Workers)

3.2.1 The effective dose received in any consecutive 12-month period by any occupationally exposed person must not exceed 20 mSv.

3.4.1 All occupationally exposed persons are classified in one of two categories:

a) Category A: persons who may be exposed in the exercise of their profession to more than 3/10 of the limit in terms of effective dose in 12 consecutive months.

b) Category B: persons who may be exposed in the exercise of their profession to less than 3/10 of the limit in terms of effective dose in 12 consecutive months.

Not occupationally exposed persons

3.2.3 The effective dose received in any consecutive 12-month period by persons not occupationally exposed must not exceed 1 mSv.

Environment (Public)

4.2.1 The effective dose resulting from CERN's activities received by any person living or working outside the site boundaries must not exceed 0.3 mSv per year. This limit includes both external and internal exposure, the latter resulting from the intake of radioactive releases.

Yearly limit

A: **20 mSv/12 months (*)**

B: **6 mSv/12 months (*)**

(*) Age 16-18: 6 mSv/12 months,
Pregnant women: 1 mSv during pregnancy

1 mSv/12 months

0.3 mSv/12 months

https://edms.cern.ch/ui/file/335729/LAST_RELEASED/F_E.PDF

General Principles of Radiation Protection

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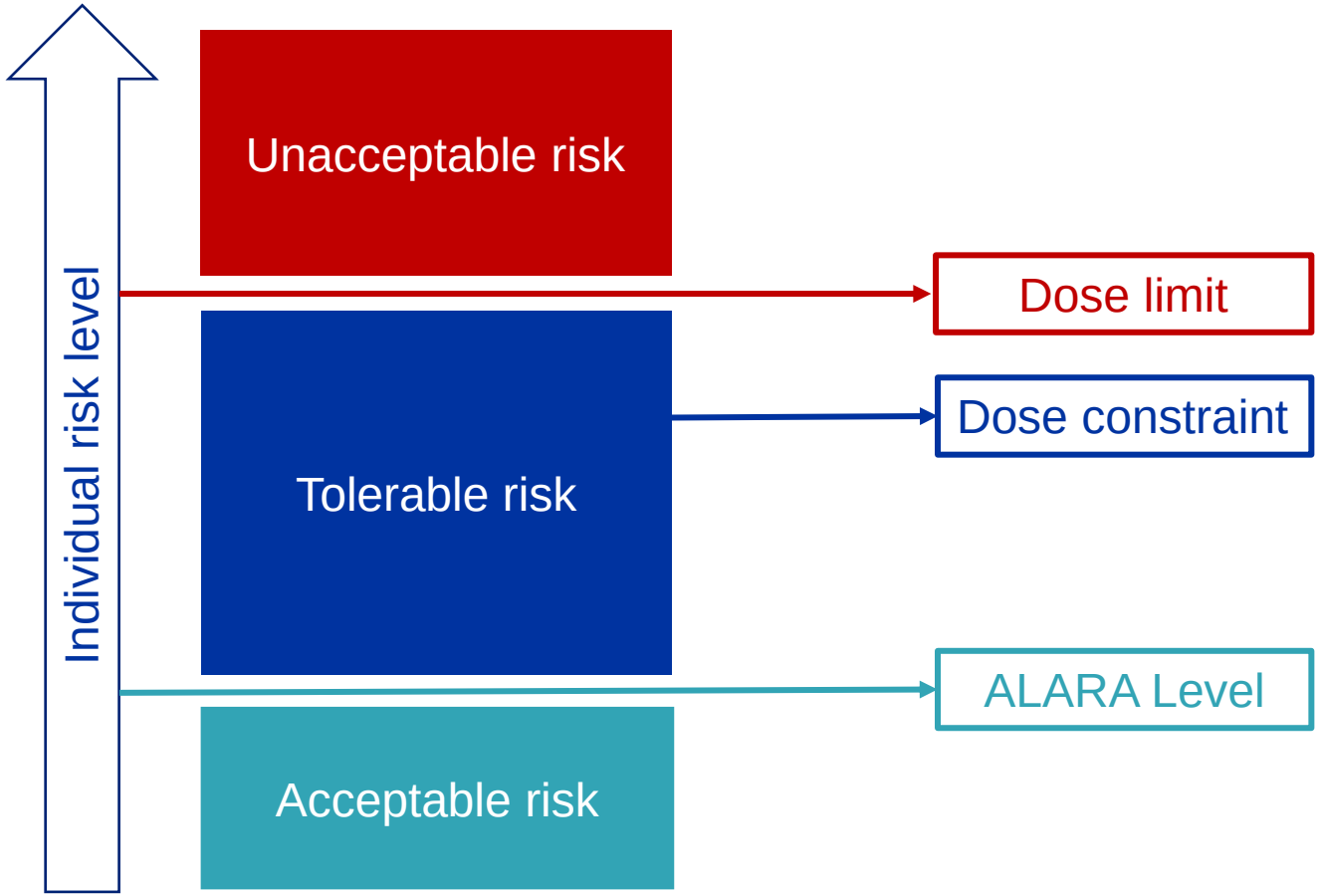
Dose Optimization at CERN



	CERN workers		Population
	Radiation Workers	Other Workers	
Dose limit	20 mSv/yr*	1 mSv/yr	300 µSv/yr
Dose constraint	3 mSv/yr	100 µSv/yr	10 µSv/yr
	Optimization process		
ALARA Level	100 µSv/yr	10 µSv/yr	10 µSv/yr

* Apprentices and students (age 16-18): 6 mSv/yr
Pregnant women: 1mSv/yr

AMBER at EHN2

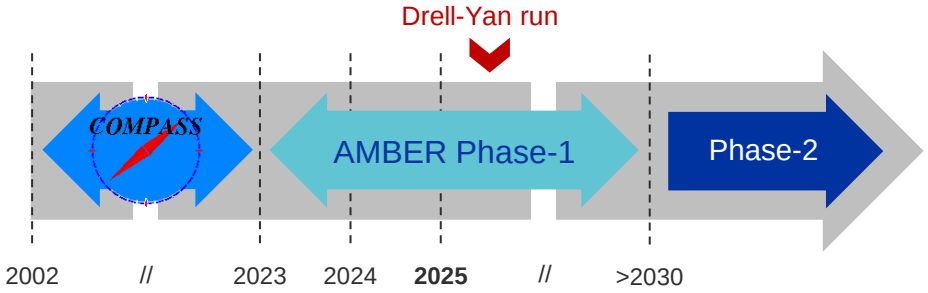
AMBER Phase-1 Program

- Antiproton production cross section measurement
- Proton radius measurement
- Pion-induced Drell-Yan measurements

➢ From the RP point of view, the Drell-Yan measurement is the most critical in view of a high-intensity beam used

➢ Past COMPASS Drell-Yan runs (2015, 2018) reached a yearly maximum of 1.83×10^{14} POT (+68% for AMBER), while causing increased radiation levels

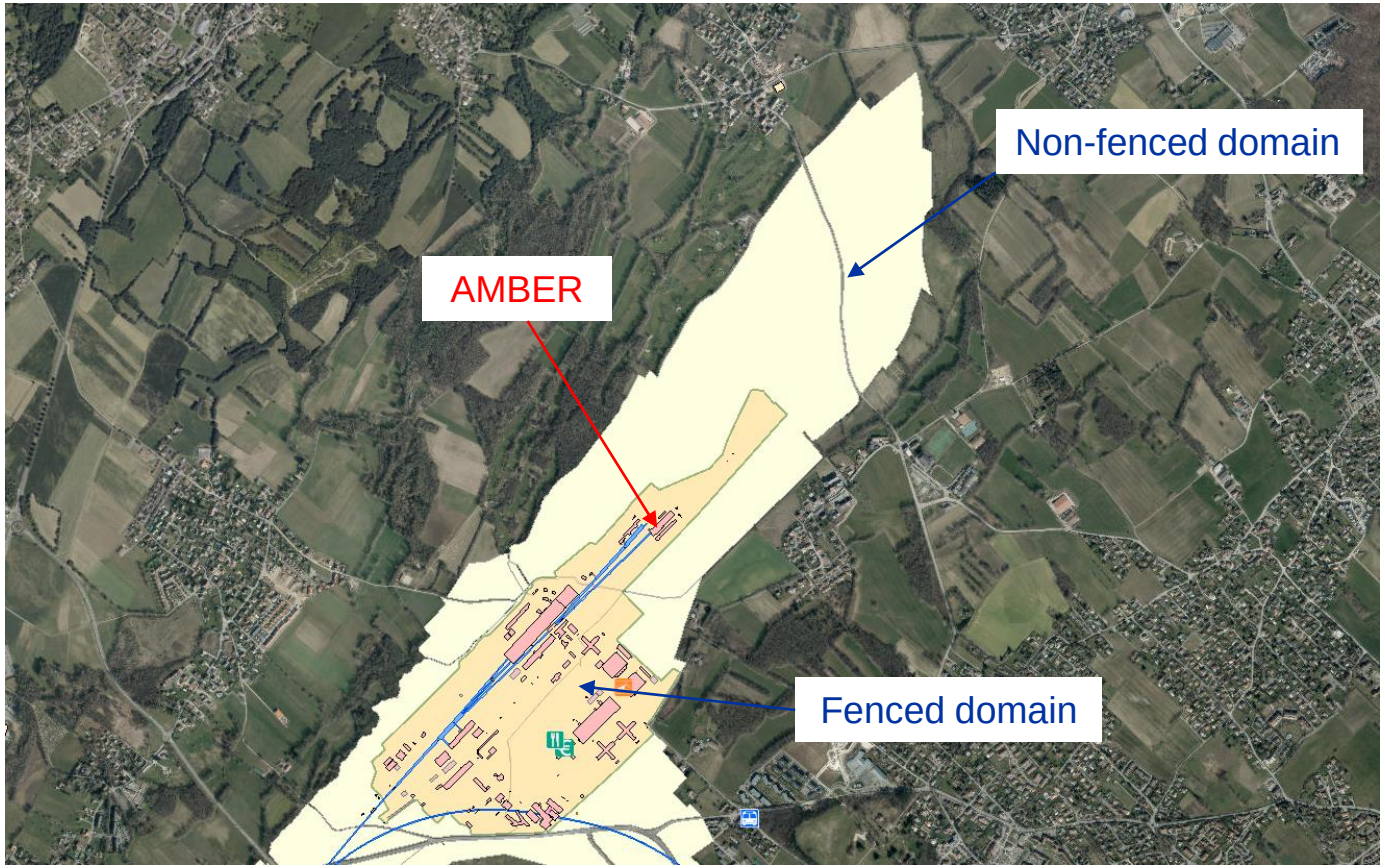
Timeline



Key beam parameters for AMBER Drell-Yan program

Momentum	190 GeV/c
Particle type	π^-
Beam intensity on target / spill	1×10^9
Spill duration	4.8 s
Cycle length	15 s
Yearly particles on target (POT)	3.07×10^{14}

CERN Prévessin site – EHN2

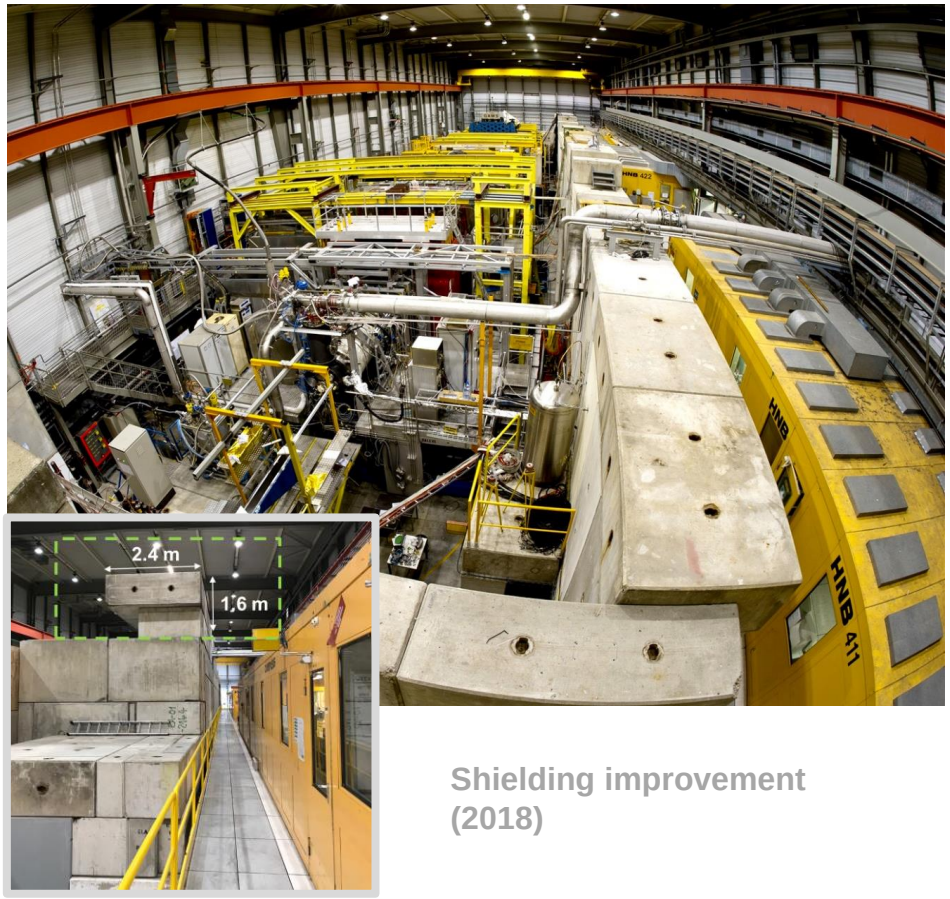


1 mSv/year ambient dose equivalent limit at the CERN fence

Effective dose to members of the public to remain below CERN's dose objective of 10 µSv/year

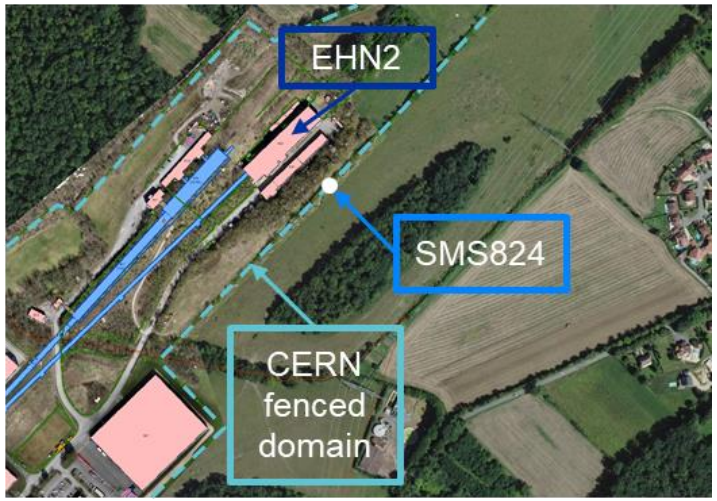
COMPASS Drell-Yan – Annual dose at CERN fence

COMPASS target area (2015)



Shielding improvement (2018)

Location of environmental monitoring station SMS824



- The environmental monitoring station SMS824 (n, γ) is located at the CERN fence close to EHN2
- Shielding improvement around the COMPASS target area was challenging due to polarized target infrastructure

	2015 run	2018 run
POT/year	1.67×10^{14}	1.83×10^{14}
Annual dose at fence	745 µSv	756 µSv

→ *10% increase for 2018*

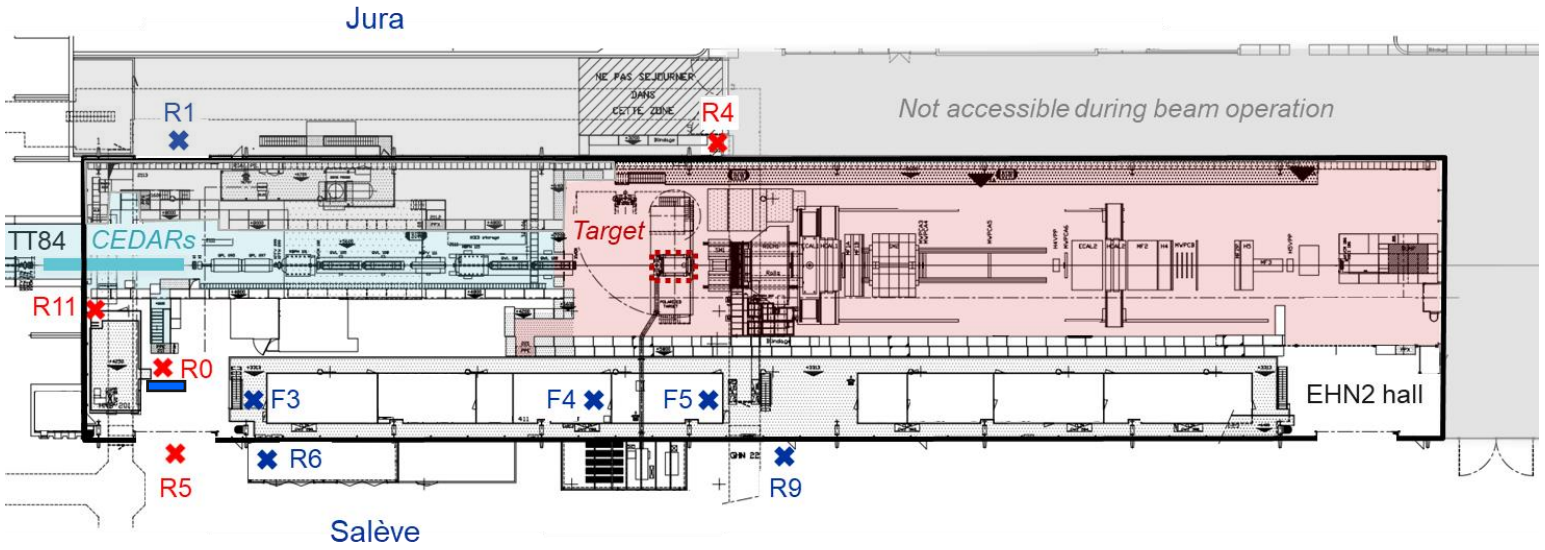
➢ *75% of the annual limit of 1 mSv at the CERN fence was reached*

COMPASS Drell-Yan – Dose rates at EHN2

- Radiation surveys inside/around EHN2 were performed during the 2018 Drell-Yan run [1,2]
- Elevated dose rates at several locations
- Dose rates on Jura side above the limit of a Supervised Radiation Area (15 µSv/h)
  → prevent access during beam operation
- Dose rates on Salève side inside and outside of EHN2 were exceeding or close to the area classification limits at several locations
  → increased dose rates at upstream part of EHN2 hinting to losses in the beamline
  → local shielding improvement with 80 cm concrete at position R0 only partially helped

➢ *Shielding improvement required particularly in the beamline region*

Measurement positions of 2018 radiation survey



Measured dose rates at critical positions

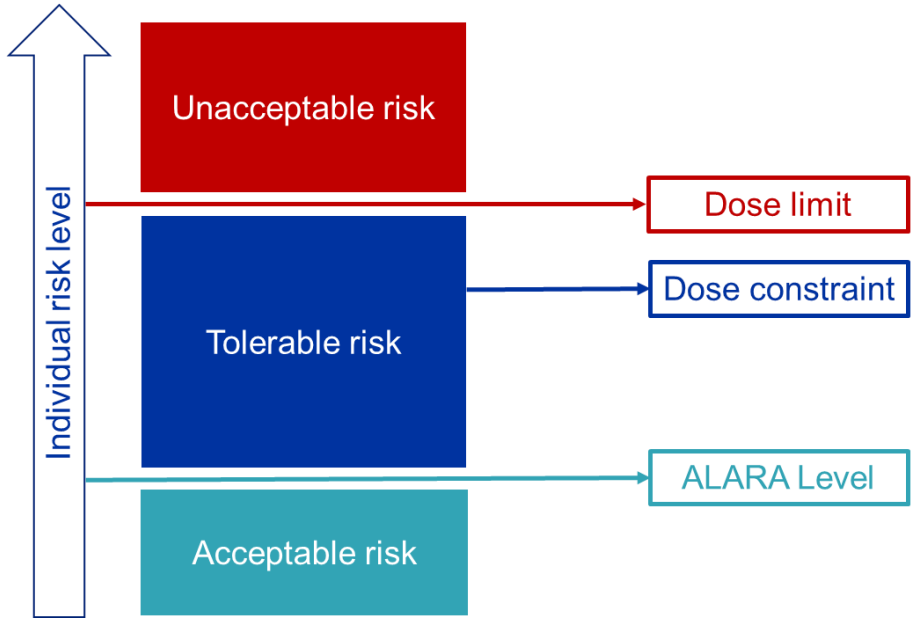
Position	R4	R0	R11	R5
Dose rate (µSv/h)	45	15	16	4 (3*)
Limit (µSv/h)	-	15	15	2.5

*w/ additional shielding

AMBER design optimization

- Shielding improvement at strategic EHN2 locations to cope with future high-intensity AMBER Drell-Yan runs
- **ALARA approach**
  Optimization required to ensure that exposure of personnel to radiation and radiological impact on environment are As Low As Reasonably Achievable

Dose optimization at CERN



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AMBER design optimization

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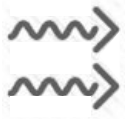


PROMPT RADIATION
Reduce prompt radiation to comply with **radiation area classification** inside/next to EHN2 as well as the **1 mSv limit** at the **CERN fence**

RESIDUAL RADIATION
Limit activation of experimental area and assess residual radiation in target area for defining adequate **area classification** and **access requirements**

AIR ACTIVATION
Reduce activation of air and ensure compliance with **airborne activity concentration** limits of given area classification

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

Radiation area classification

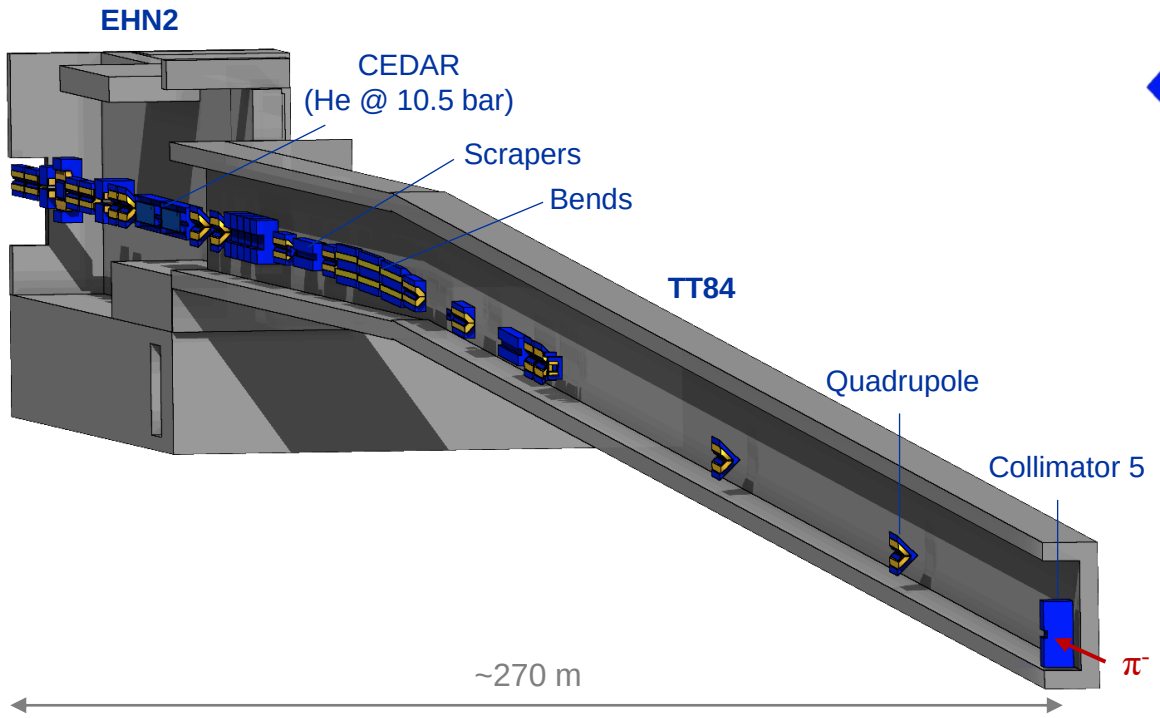
	Area	Annual dose limit (year)	Ambient dose equivalent rate		Airborne activity concentration	Surface contamination
			permanent occupancy	low occupancy		
	Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	0.05 CA	1 CS
Radiation Area	Supervised	6 mSv	3 µSv/h	15 µSv/h	0.1 CA	1 CS
	Simple Controlled	20 mSv	10 µSv/h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

FLUKA model of AMBER – Beamline

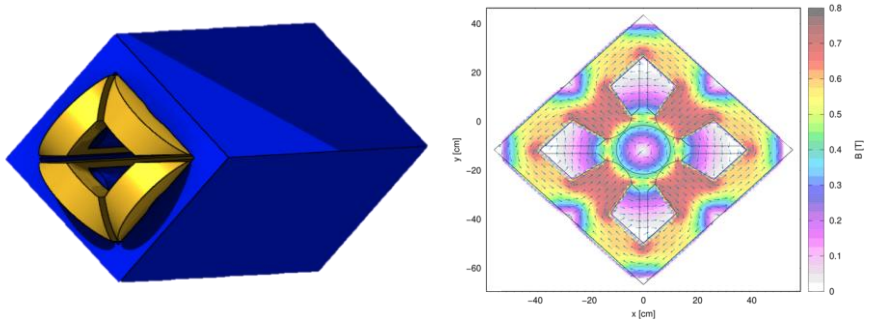
FLUKA hosted by CERN (FLUKA v4-2.2) [3-5]

FLUKA geometry

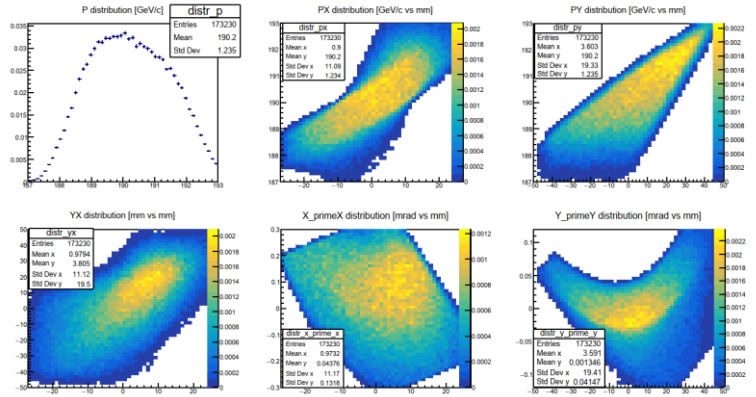
Created using FLAIR [6]



The full beamline starting from Collimator 5 with its magnets and respective magnetic fields were incorporated in the model



Geometry (left) and magnetic field map (right) of quadrupole magnet as implemented in FLUKA

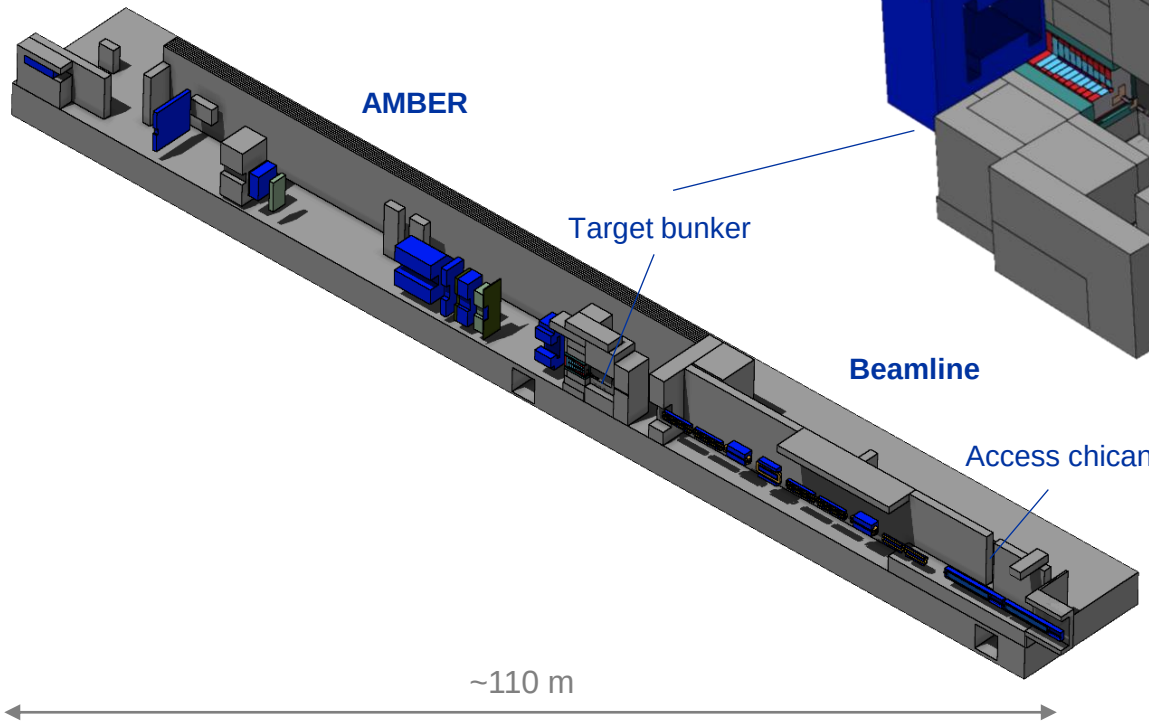


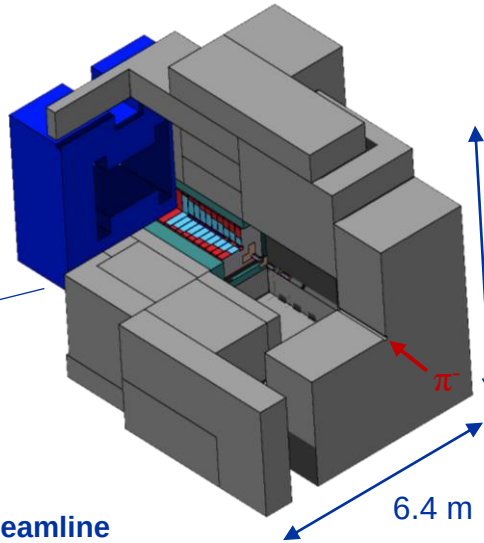
π^- beam starting upstream of Collimator 5 simulated according to beam distributions as resulting from HALO [7]

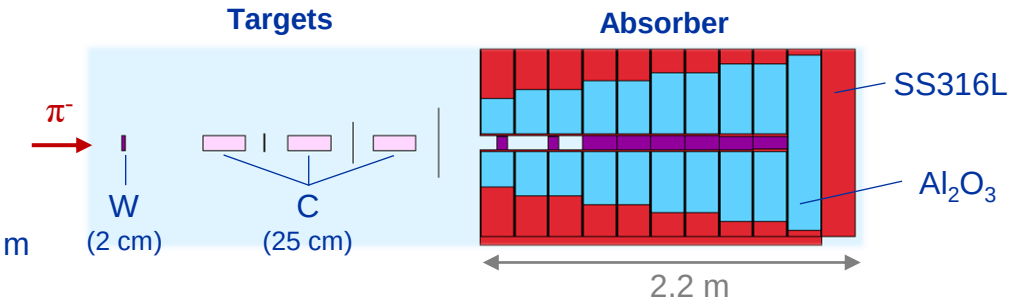
FLUKA model of AMBER – EHN2

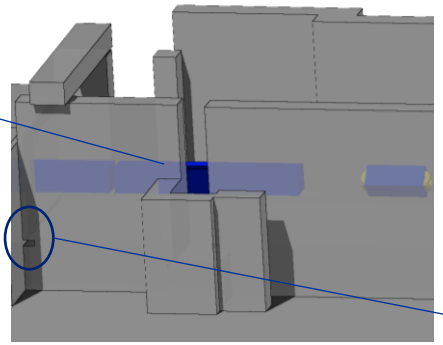
FLUKA hosted by CERN (FLUKA v4-2.2) [3-5]

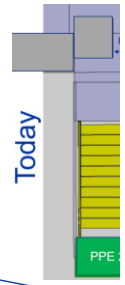
FLUKA geometry
Created using FLAIR [6]

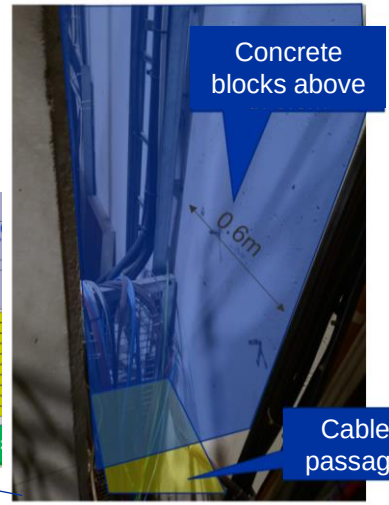


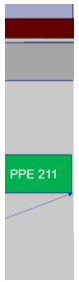








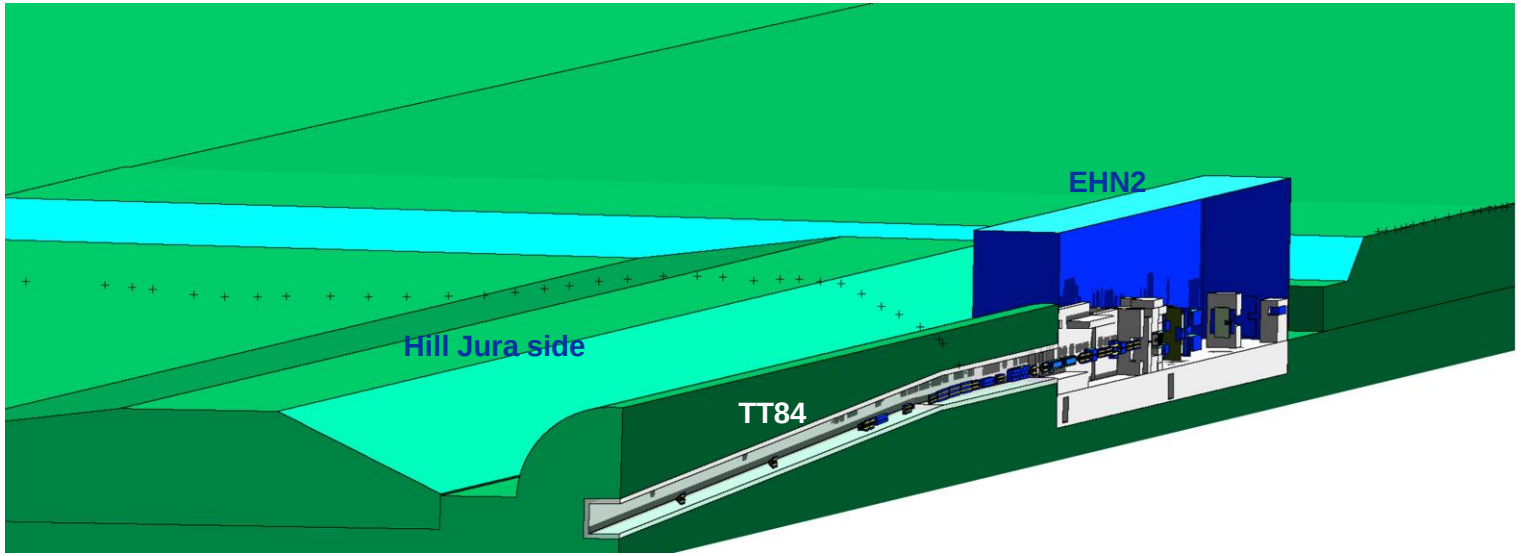


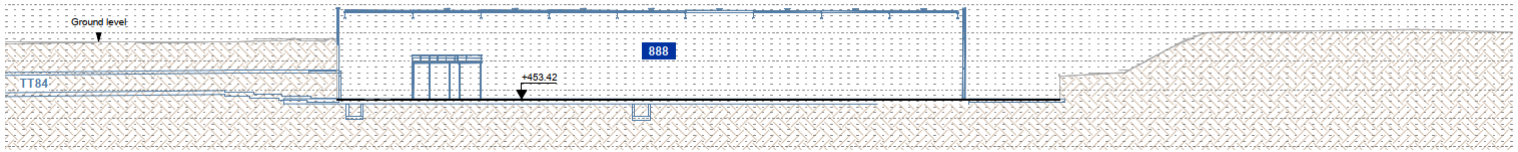


FLUKA model of AMBER – Surroundings

FLUKA hosted by CERN (FLUKA v4-2.2) [3-5]

FLUKA geometry
Created using FLAIR [6]



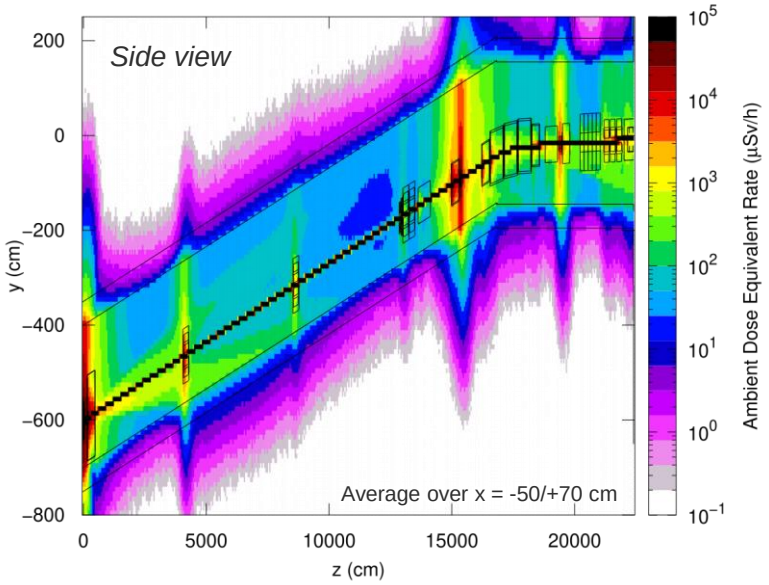


Ground profile data from CERN's Geographic Information System and technical drawings were used to model the surrounding ground

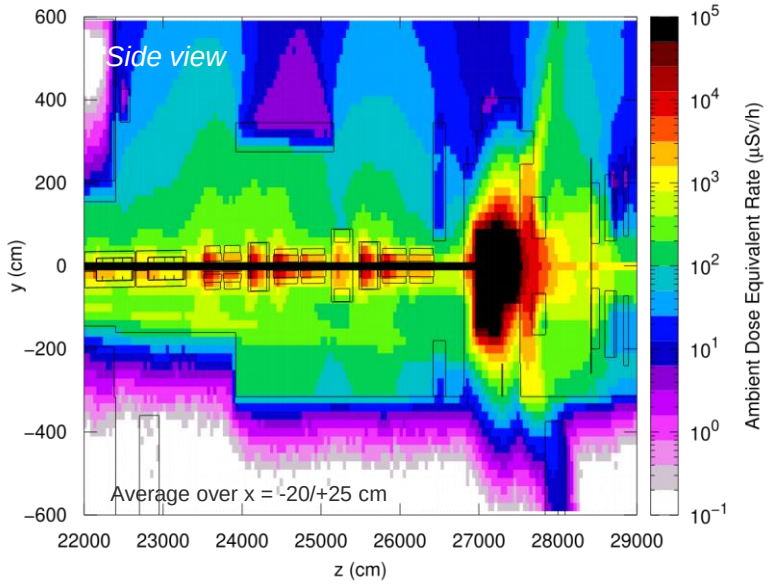
The above-ground air volume reaches up to 5 km in height

Results – Prompt radiation in beamline

Transfer Tunnel TT84
From Collimator 5 to CEDAR



Beamline in EHN2
From CEDAR to target bunker

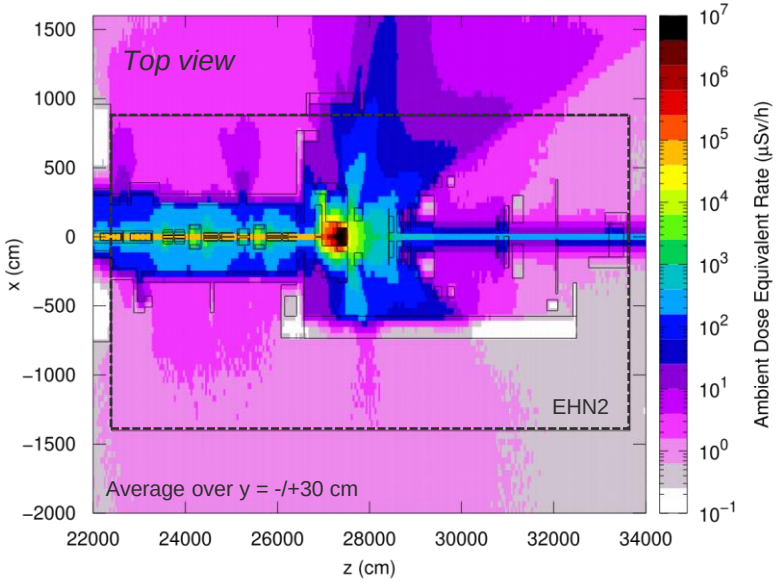


- Prompt ambient dose equivalent rates in the beamline were evaluated with an intensity of 1×10^{9} π^{-}/spill and 240 spills/h on target
- Main streaming towards the top from downstream region of target bunker but also from beamline region
- Beam losses from Collimator 5 up to the target amount to 11.8%
- Less than 1% beam losses from CEDAR up to target

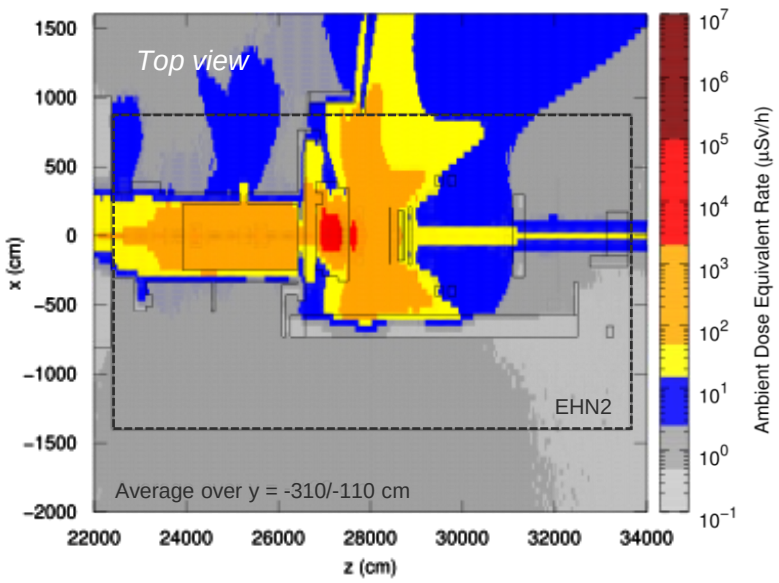
➢ *Beam losses upstream of the target taken into account in normalization for pions on target*

Results – Prompt radiation at EHN2

Prompt dose rate inside and next to EHN2
$1 * 10^9$ π^-/spill and 240 spills/h on target



Color scale according to area classification

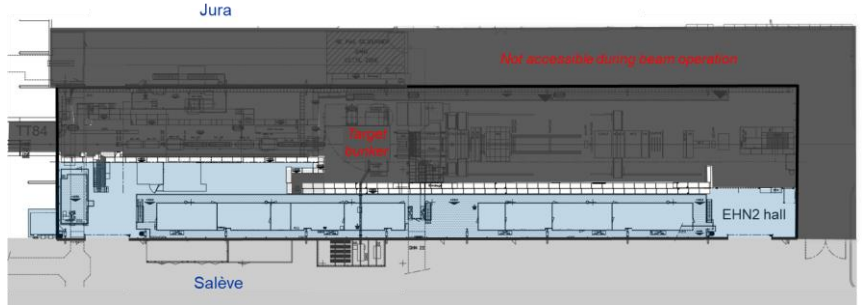


Radiation area classification

	Area	Annual dose limit (year)	Ambient dose equivalent rate	
			permanent occupancy	low occupancy
	Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h
Radiation Area	Supervised	6 mSv	3 μSv/h	15 μSv/h
	Simple Controlled	20 mSv	10 μSv/h	50 μSv/h
	Limited Stay	20 mSv	-	2 mSv/h
	High Radiation	20 mSv	-	100 mSv/h
	Prohibited	20 mSv	-	> 100 mSv/h

Controlled Area

EHN2 area classification



- *Additional shielding allowed significant improvement of the dose rates in the accessible areas inside/next to EHN2 well within the respective area classification limits*

Results – Residual radiation

Irradiation profile
6-month irradiation with overall 3.07×10^{14} POT/year

Decay times
2 min, 10 min, 30 min, 1h, 3h, 6h, 1d, 3d, 1w, 1month, 6 months and 1 year

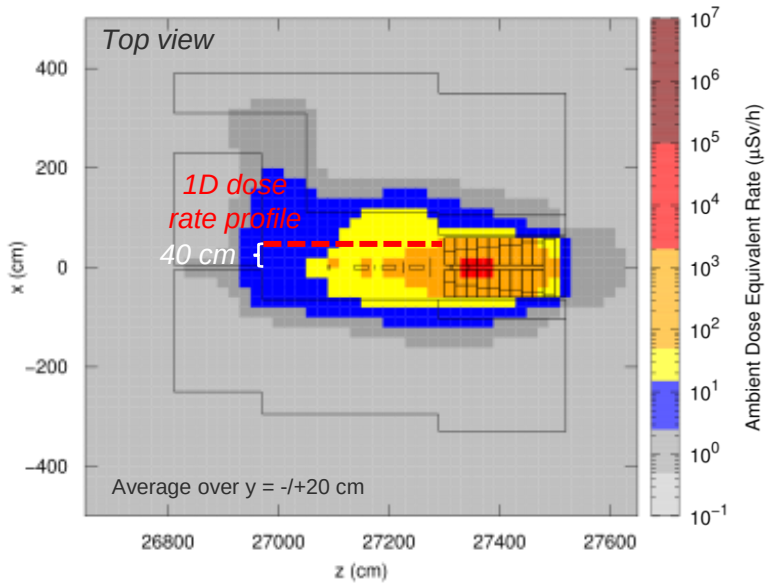
Radiation area classification

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

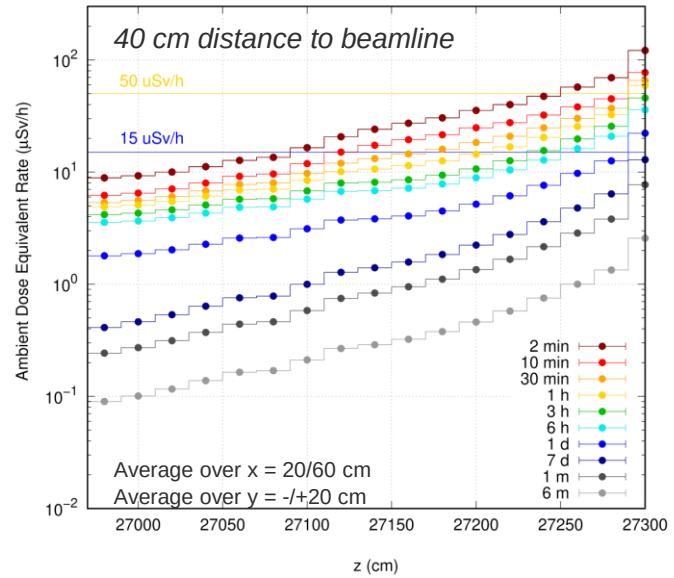
- *Dose rates above Supervised Radiation Area limit for <1 day decay and Simple Controlled Area limit for < 10 min decay*
- *Access mostly during commissioning time with low intensity*

➢ Installation of a PMI to monitor residual dose rate inside the bunker before access

Residual dose rate in target bunker
2 minutes cooling *(min. time from access system)*

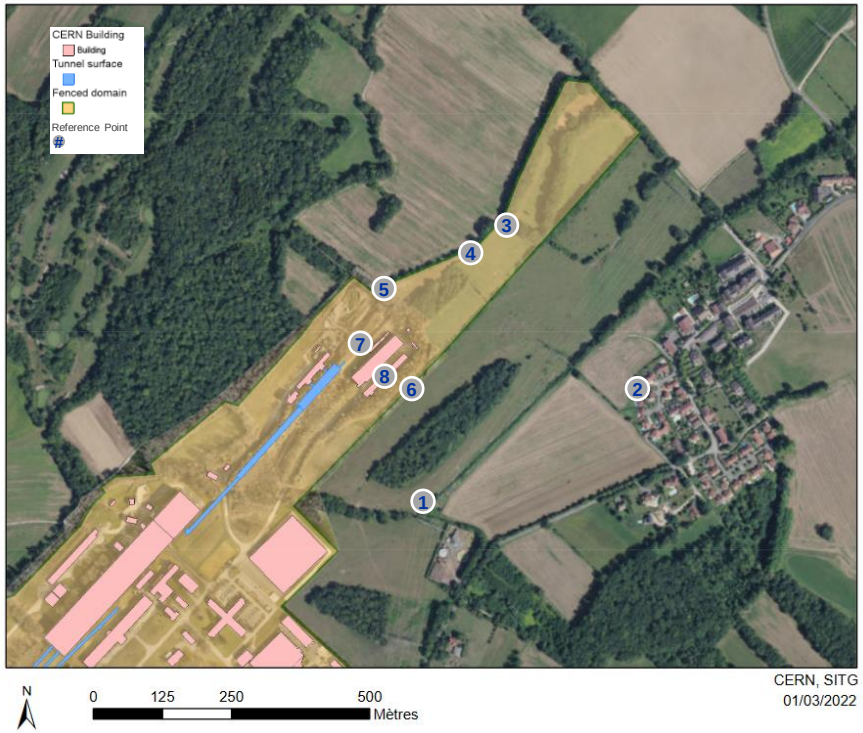


Different cooling times



Results – Skyshine radiation

Aerial view of CERN domain and surroundings



Selected reference points

1. Garden
2. Residential area

Locations outside CERN fenced area

3. PMS823
4. PMS822
5. PMS821
6. PMS824

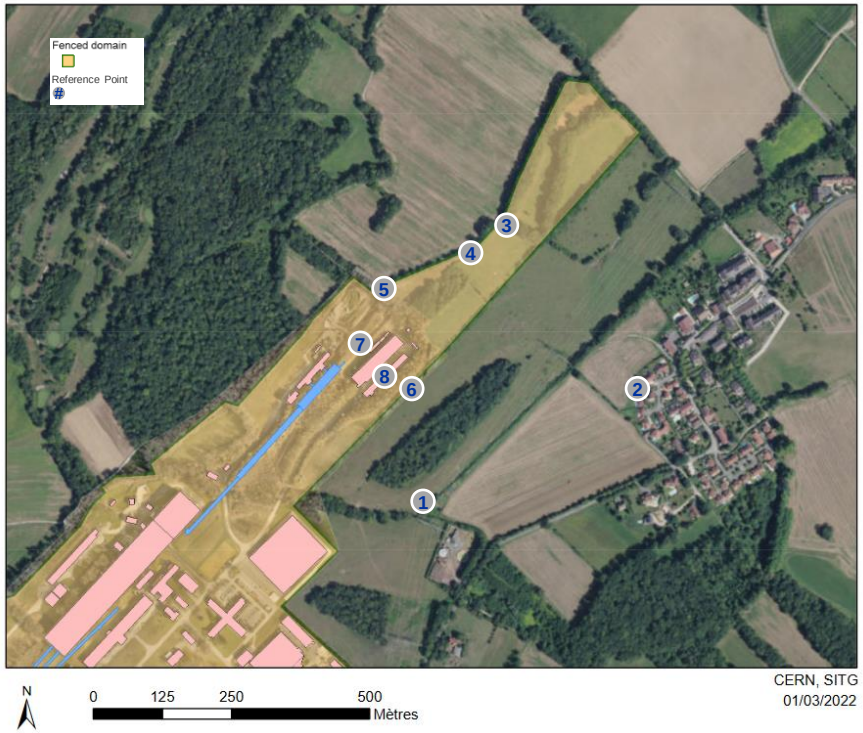
Monitoring stations at CERN fence

7. Jura Side Top Hill
8. Road Salève

Non-designated area (low occupancy) inside CERN fenced area

Results – Skyshine radiation

Aerial view of CERN domain and surroundings



Annual dose for 3.07×10^{14} π^-/year on target (µSv/year)
Statistical uncertainty < 10%

Reference point	Name	Annual dose (µSv/year)⁺		Occupancy factor	*Dose objective* / limit
		Full Source	Only Target		
1	Garden	**1**	0.7	0.06	*<10 uSv/y*
2	Residential Area	**2**	1	1	
3	PMS823 (Down)	**7**	4	-	1 mSv/y
4	PMS822 (Mid)	**17**	10		
5	PMS821 (Jura)	**105**	70		
6	PMS824 (Salève)	**258**	165		
7	Jura Side Hill	**29**	24	0.05*	1 mSv/y
8	Road Salève	**53**	48		

⁺ Including occupancy factor
*Low occupancy workplace (20% of permanent workplace occupancy factor of 0.23)

➢ *Annual dose well within the respective limits and dose objective for the public*

Results – Air activation

Air activation assessment

- Air activation was evaluated for **AMBER target bunker area** and the rest of the **EHN2 hall**
- 6-month irradiation with overall 3.07×10^{14} POT/year
- Production of radionuclides evaluated with FLUKA in combination with ActiWiz [8]
- Neither decay time nor air extraction were conservatively assumed

➢ *Airborne activity well within limit (< 0.1 CA[1]) for the target bunker and EHN2 hall*

Environmental impact assessment

- Conservative assumption of immediate release on the EHN2 roof
- Used max. dose coefficients from different age groups [9]

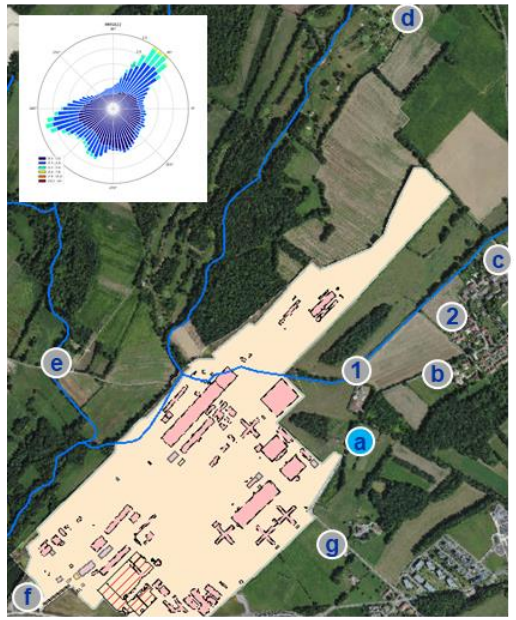
➢ *Exposure of members of the public due to air releases below 1 nSv/y (negligible)*

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

Air activation per air region

Air region	Total activity concentration	Multiple of CA[1]	Inhaled dose for 1 hour of stay
Target bunker	1 kBq/m³	2E-02	0.02 µSv
EHN2 hall	2 Bq/m³	3E-05	<< 1 µSv

Positions of the examined population groups



Total activity for immediate release

Total activity
8.2 GBq

Effective dose – worst case – group a
Main radionuclides (>98% contribution)

Radionuclide	Dose [Sv/y] (contribution to total)
N-13	1.00E-10 (48%)
C-11	4.51E-11 (22%)
Ar-41	2.60E-11 (12%)
O-15	2.42E-11 (12%)
Cl-39	3.79E-12 (2%)
O-14	3.51E-12 (2%)
Sum of all 39	2.09E-10

Summary

Radiation Protection challenges for AMBER

- High-intensity Drell-Yan program
- Aboveground experimental hall EHN2 with limited shielding located close to the CERN fence
- Previous COMPASS Drell-Yan runs of lower intensity revealed shielding weaknesses

AMBER design optimization

- Shielding improvement to optimize prompt and residual radiation, air activation and environmental impact

Main takeaway points

- ➢ Additional shielding not only in the target region but also the beamline is essential for lowering dose rates inside and next to the EHN2 hall
- ➢ Contributions from losses in the beamline are non-negligible
- ➢ Environmental impact is dominated by skyshine, while exposure of members of the public due to air releases is negligible
- ➢ Effective dose to members of the public well below the dose objective of <10 µSv/year

References

[1] C. Ahdida, M. Casolino, H. Morimoto, ***COMPASS - 2018 Radiation Protection Survey***, CERN internal Survey Note (2019)

[2] C. Ahdida, H. Morimoto, ***COMPASS - 2018 Radiation Protection Survey 2***, CERN internal Survey Note (2021)

[3] Website: https://fluka.cern

[4] C. Ahdida, D. Bozzato, D. Calzolari, F. Cerutti, N. Charitonidis, A. Cimmino, A. Coronetti, G. L. D'Alessandro, A. Donadon Servelle, L. S. Esposito, R. Froeschl, R. García Alía, A. Gerbershagen, S. Gilardoni, D. Horváth, G. Hugo, A. Infantino, V. Kouskoura, A. Lechner, B. Lefebvre, G. Lerner, M. Magistris, A. Manousos, G. Moryc, F. Ogallar Ruiz, F. Pozzi, D. Prelipcean, S. Roesler, R. Rossi, M. Sabaté Gilarte, F. Salvat Pujol, P. Schoofs, V. Stránský, C. Theis, A. Tsinganis, R. Versaci, V. Vlachoudis, A. Waets, M. Widorski, ***New Capabilities of the FLUKA Multi-Purpose Code***, Frontiers in Physics 9, 788253 (2022)

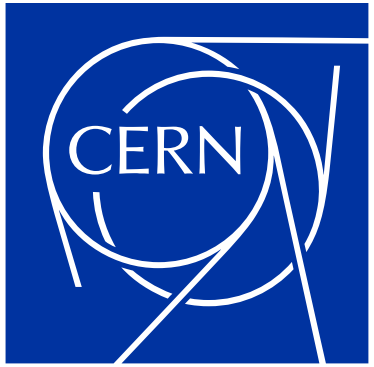
[5] G. Battistoni, T. Boehlen, F. Cerutti, P.W. Chin, L.S. Esposito, A. Fassò, A. Ferrari, A. Lechner, A. Empl, A. Mairani, A. Mereghetti, P. Garcia Ortega, J. Ranft, S. Roesler, P.R. Sala, V. Vlachoudis, G. Smirnov, ***Overview of the FLUKA code***, Annals of Nuclear Energy 82, 10-18 (2015)

[6] V. Vlachoudis, ***FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA***, in Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York (2009)

[7] C. Iselin, ***HALO: a computer program to calculate muon halo***, CERN report, 10.5170/CERN-1974-017(1974)

[8] H. Vincke, C. Theis, ***ActiWiz – optimizing your nuclide inventory at proton accelerators with a computer code***, Progress in Nuclear Science and Technology (2014)

[9] P. Vojtyla, ***Models for assessing the dosimetric impact of releases of radioactive substances from CERN facilities to the environment – Air***, CERN Internal report (2021)



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