Radiation protection challenges at CERN’s north experimental areas

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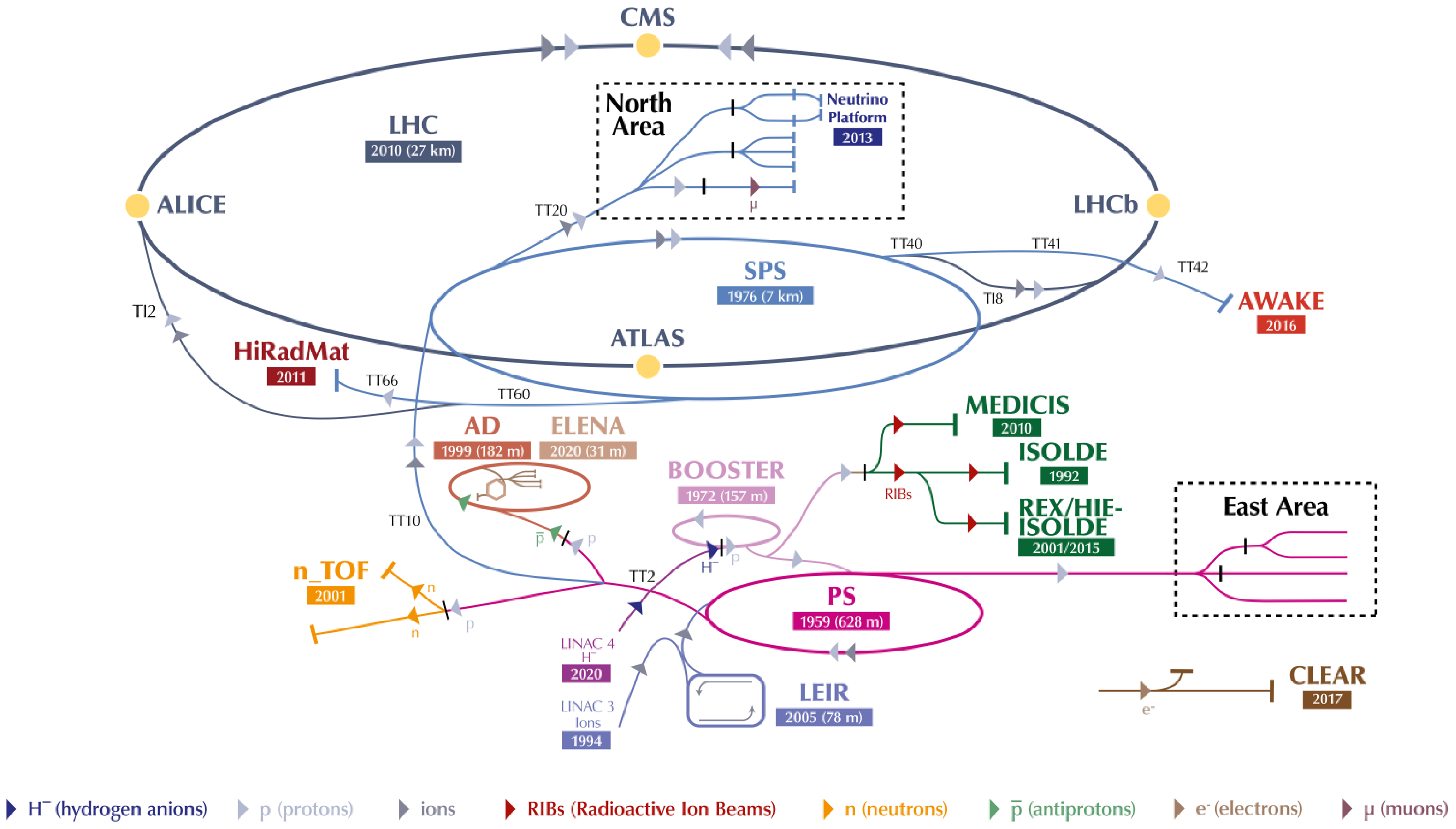
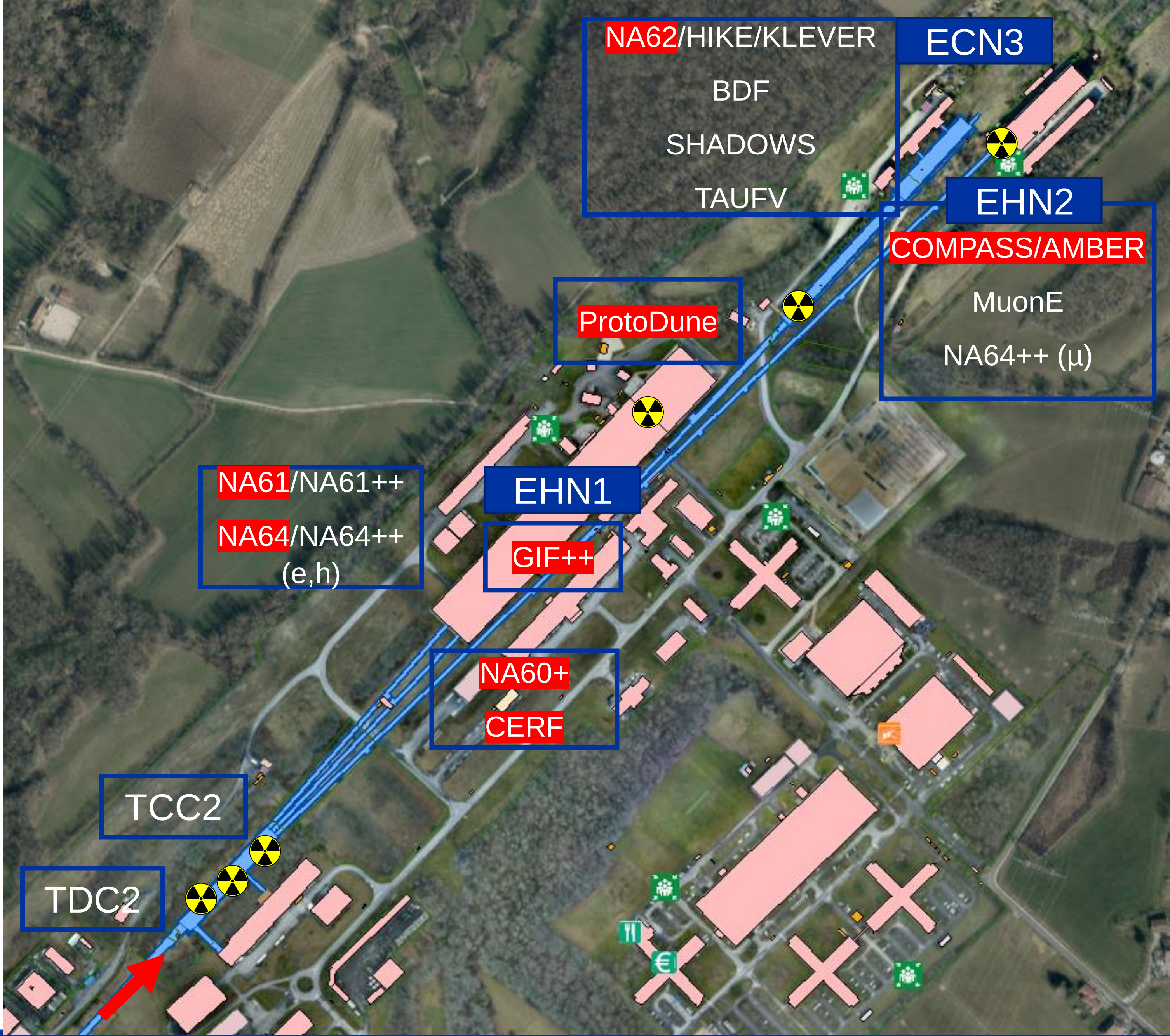

CMS
LHC
2010 (27 km)
North Area
Neutrino Platform
2013
μ
ALICE
LHCb
TT20
TT40
TT41
TT42
AWAKE
2016
SPS
1976 (7 km)
TI8
TI2
ATLAS
HiRadMat
2011
TT66
TT60
AD
1999 (182 m)
ELENA
2020 (31 m)
MEDICIS
2010
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE-ISOLDE
2001/2015
East Area
TT10
p̄
p
H⁻
n_TOF
2001
n
TT2
PS
1959 (628 m)
LINAC 4
H⁻
2020
LINAC 3
Ions
1994
LEIR
2005 (78 m)
CLEAR
2017
e⁻
H⁻ (hydrogen anions)
p (protons)
ions
RIBs (Radioactive Ion Beams)
n (neutrons)
p̄ (antiprotons)
e⁻ (electrons)
μ (muons)

North Experimental Area

- Primary proton beam from SPS, **up to 450 GeV** energy
- Intensity **up to 4e13 p/spill**
- **3 primary targets – 6 beams** (H2,H4,H6,H8,M2,P42)
- Secondary targets and tertiary beams (lead ions, kaons, muons, mixed hadrons)

New experiments and upgrades of the existing ones require RP studies on:

- **Prompt and residual radiation** in the facility and within CERN fence
- **Environmental release aspects**: earth, air activation and stray radiation to the public areas
- Beam transfer lines: **accidental and continues beam losses** at the critical locations (e.g. for P42 beam line to ECN3: ECN1 ramp and bridge)



General Principles of Radiation Protection

1. Justification

Any exposure of persons to ionizing radiation has to be justified

2. Limitation

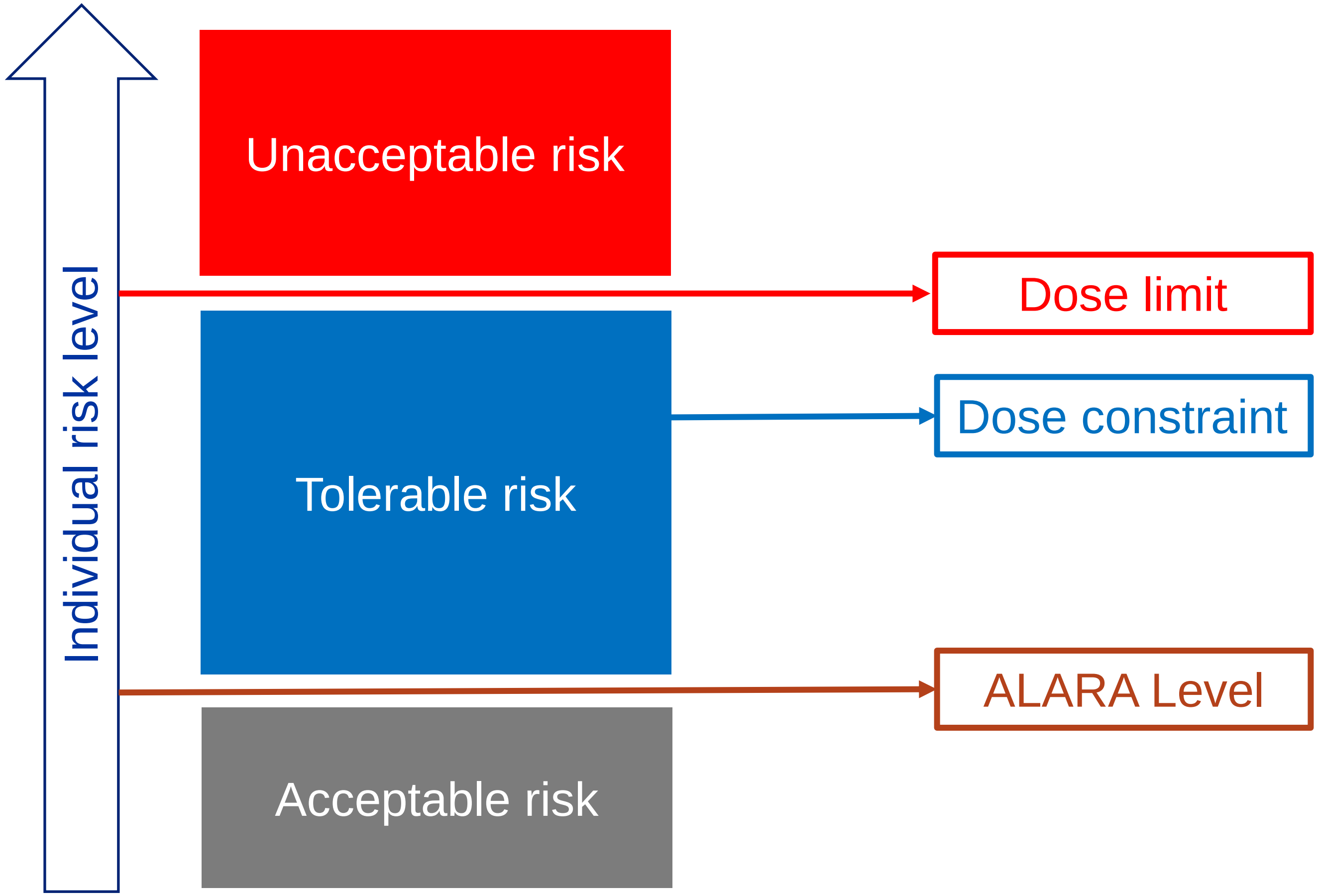
The personal doses have to be kept below the legal limits

Safety Code F [1]

3. Optimization

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

Dose limits and dose optimization at CERN



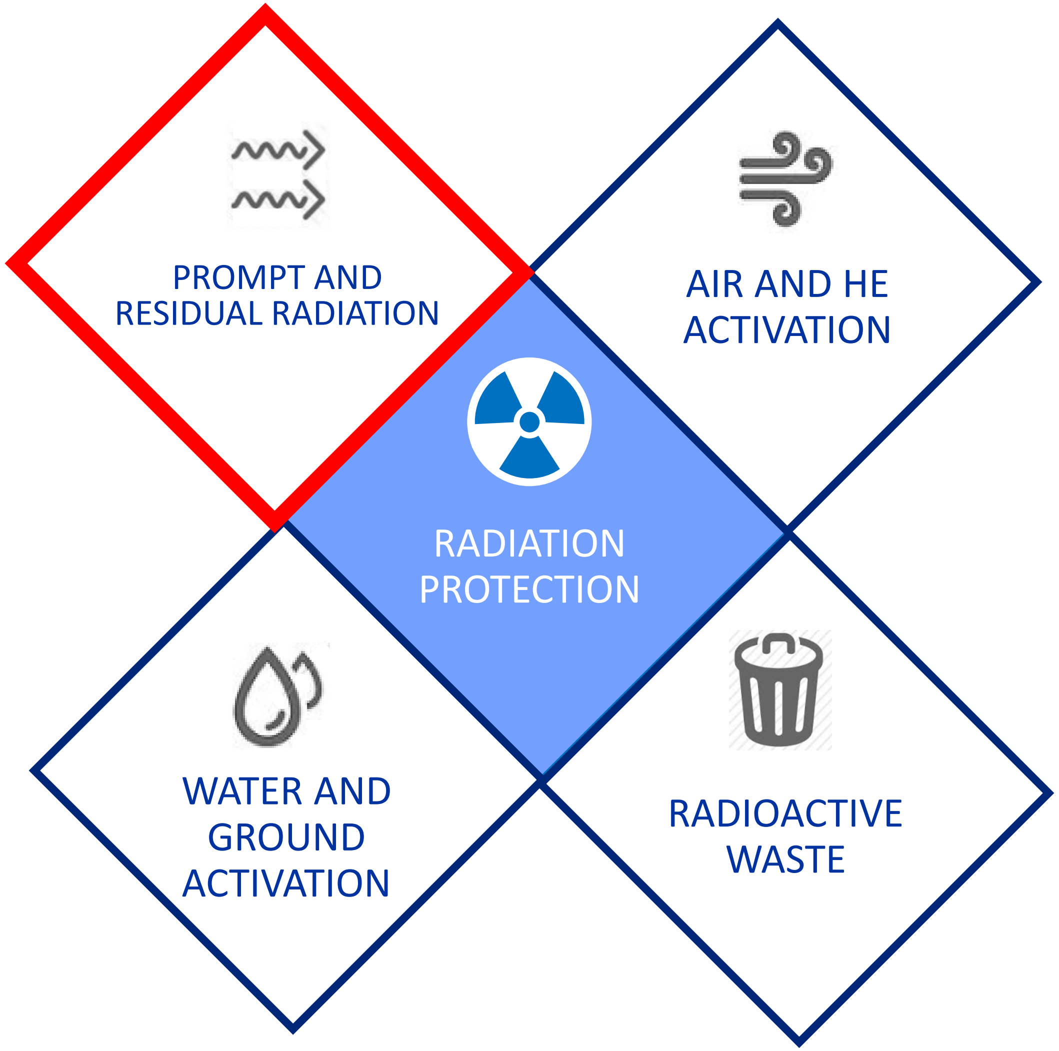
	CERN workers		Population
	Radiation Workers	Other Workers	
Dose limit	20 mSv/yr*	1 mSv/yr	300 µSv/yr
Dose constraint	3 mSv/yr	100 µSv/yr	10 µSv/yr
	Optimization process		
ALARA Level	100 µSv/yr	10 µSv/yr	10 µSv/yr

*Category A – 20 mSv/y, Category B – 6 mSv/y
*Apprentices and students (age 16-18): 6 mSv/yr
*Pregnant women: 1mSv/yr

1 Sv = 100 rem

General RP considerations

- ✓ Both prompt and residual dose rates need to be optimized for commissioning, operation, maintenance and accidents
  - ✓ Studies for nominal, ultimate and accidental beam parameters
  - ✓ Study of accidental beam loss
- ✓ **Adequate shielding** needs to be designed and installed in view of operation and maintenance:
  - ✓ Prompt radiation: strongly depends on the access need over operation and RP area classification
  - ✓ Residual radiation: important for maintenance works, urgent reparations, etc. (cooling time plays role)
- ✓ Depending on residual dose and contamination levels manual interventions should be partially or completely replaced by remote maintenance/repair work
- ✓ Activation properties of materials must be optimized as may have direct impact on later handling and waste disposal (ActiWiz)



LAGUNA-LBNO (Long-Baseline Neutrino Beam Facility) CERN site

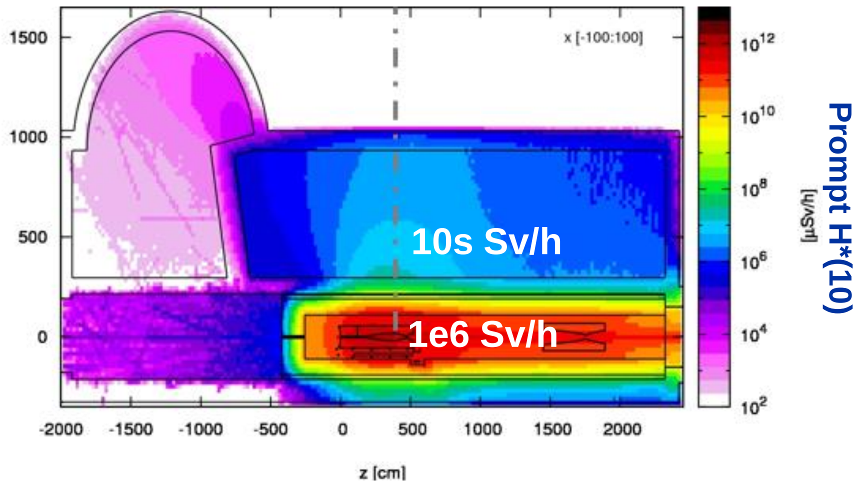
[2]

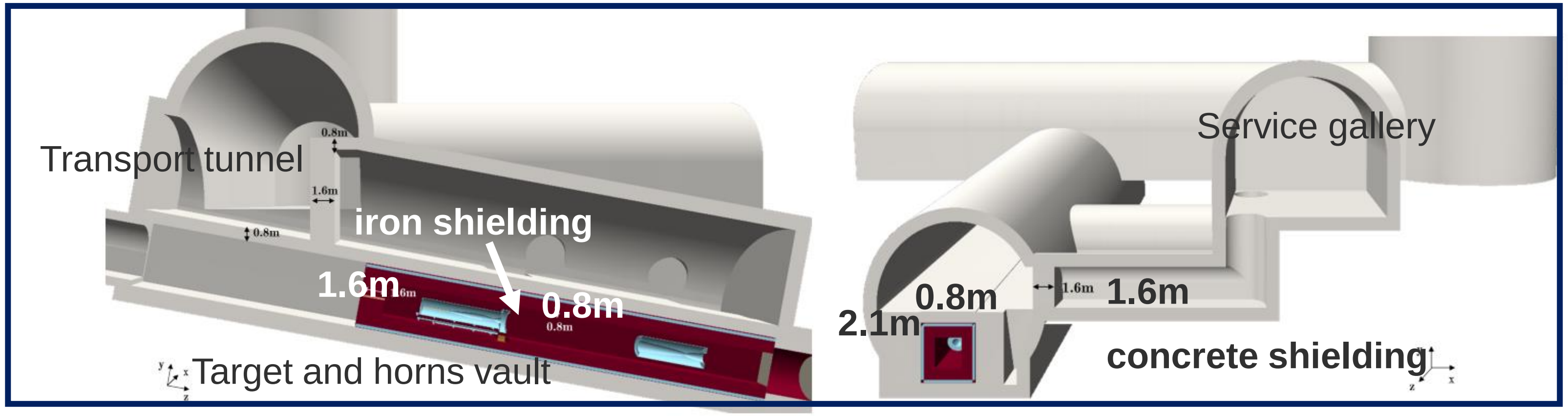
Fully underground target facility at CERN (2014), beam power up to 4 MW (50 GeV beam), 2.4e14 p/s or 750 kW (400 GeV beam) for 1.7e13p/s

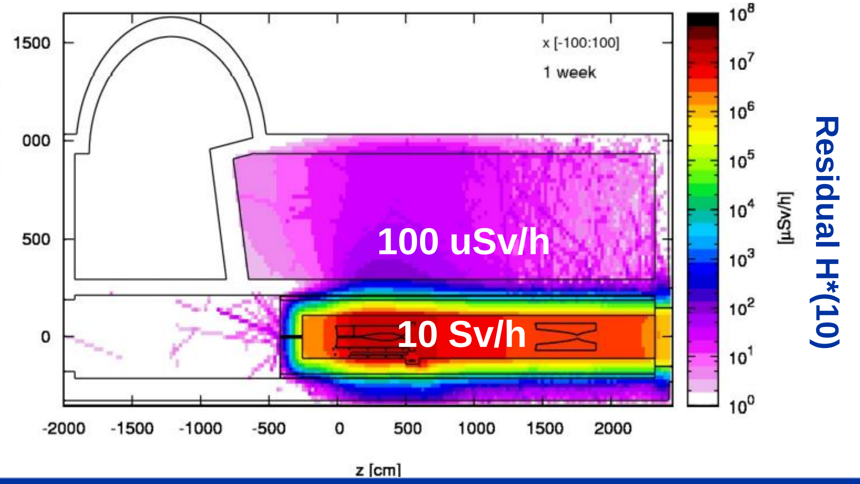
Deep underground location of 80-100m in impermeable molasse to avoid ground water activation/contamination and minimize prompt dose constraints

Challenges arising from highly elevated prompt and residual dose rates:

- <u>necessity of considerable shielding</u> to reduce prompt dose and as a result activation levels of the surrounding infrastructure and molasse (0.8m Fe on top/bottom plus concrete)
- radiation streaming to service gallery needed to be sufficiently reduced
- <u>necessity of remote handling</u> of the target area equipment (target, horn, reflector)
- a morgue room was foreseen for temporary storage and cool-down of hot equipment
- <u>risk of highly radioactive air,</u> replaced with He in the target chamber
- He vessel to reduce air activation and mitigate oxidation/corrosion

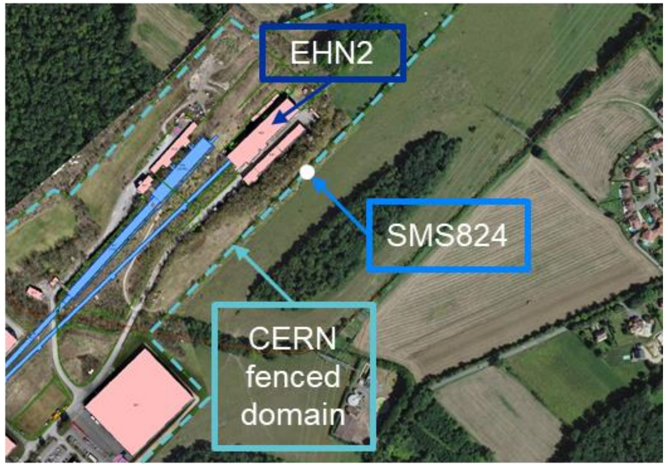






COMPASS/AMBER DRELL- YAN runs in EHN2

COMPASS in EHN2 hall, Pion- 4.2e8 p/spill @190 GeV, 1.83e14 POT/y (2018)



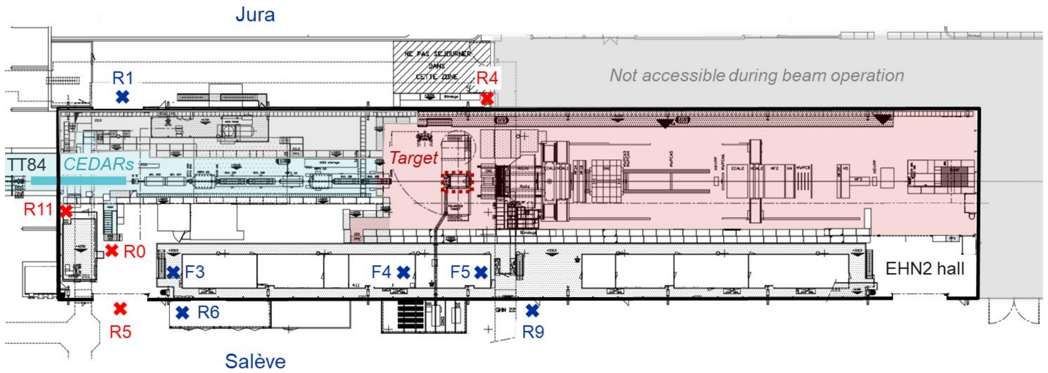
Challenges: elevated radiation in EHN2 accessible areas over operation, nearby public areas

2015 (1st DY run) 1.7e14 POT/y: environmental monitoring at CERN fence reached 75% of dose limit of 1 mSv

2017: additional shielding installed and counting rooms moved to different location, no target roof

2018 intensity increased by 23% and an RP survey was performed to verify dose levels in EHN2 and outside

→ elevated radiation (close to/above area classification limits) found in several locations which triggered detailed studies on the required shielding and origin of the beam loss



Shielding improvement required

particularly in the beamline region

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

[3,4]

Pressent open target

Additional shielding installation

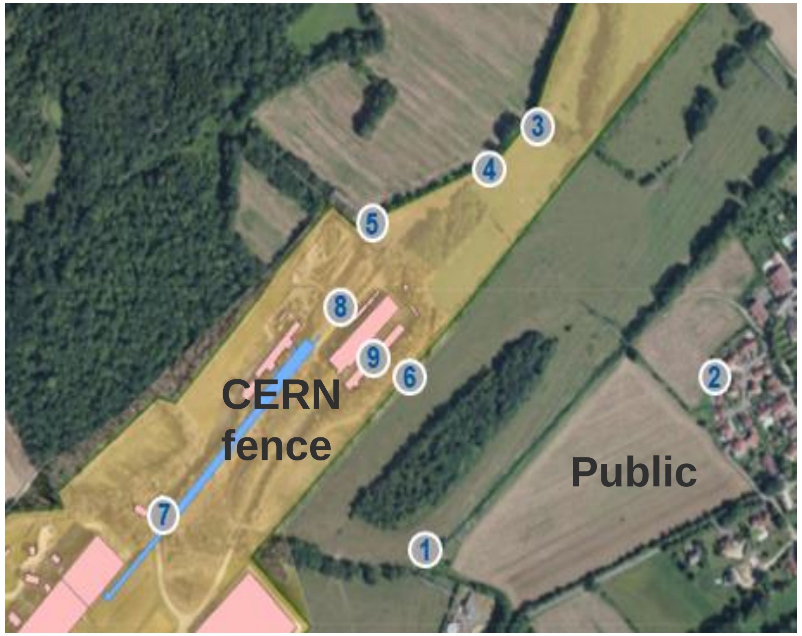
AMBER DRELL- YAN runs in EHN2

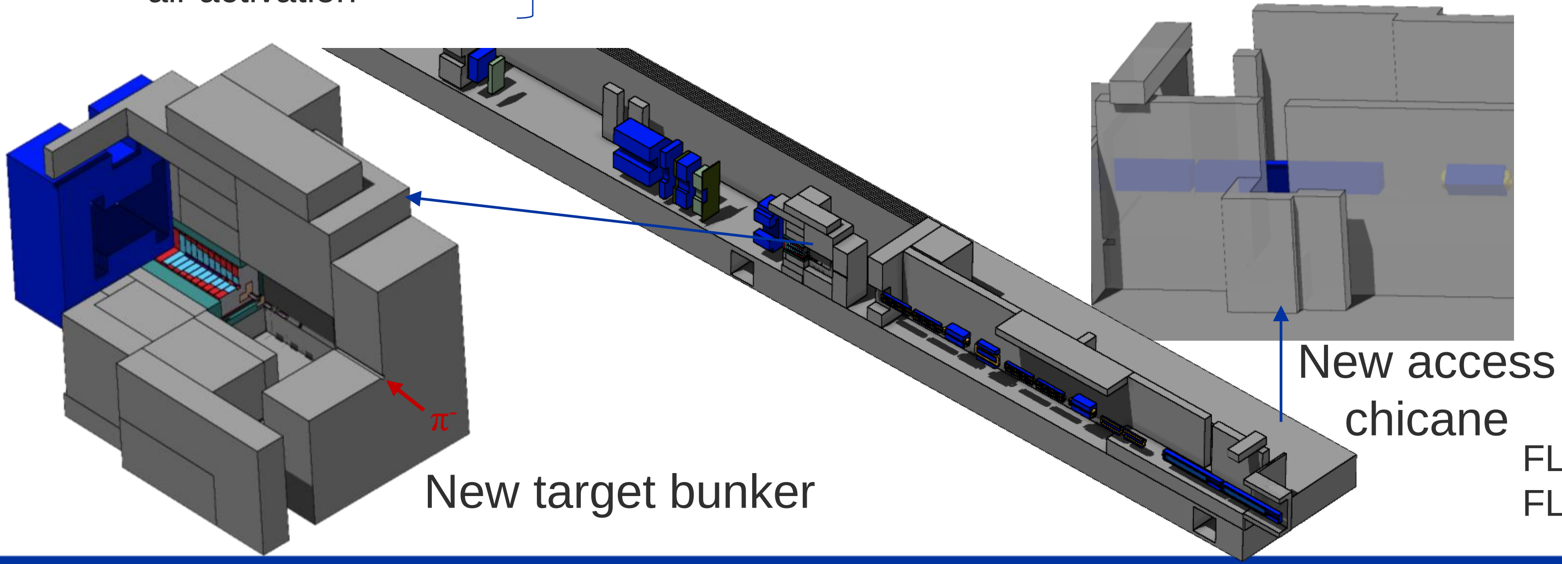
AMBER (as of 2023) : 1e9 pi-/spill, 3.07e14 POT (68% higher wrt COMPASS 2018 run)

Complex MC FLUKA studies have been triggered after the survey in 2018 and in view of future intensity upgrade

- Additional shielding at strategic EHN2 locations to comply with radiation area classification and **1 mSv limit at CERN fence**
- Design new shielding bunker for AMBER Drell-Yan to cope with higher intensity runs
- Assess environmental impact outside of CERN fence to respect dose objective for the public:
  - stray radiation
  - skyshine optimization
  - air activation

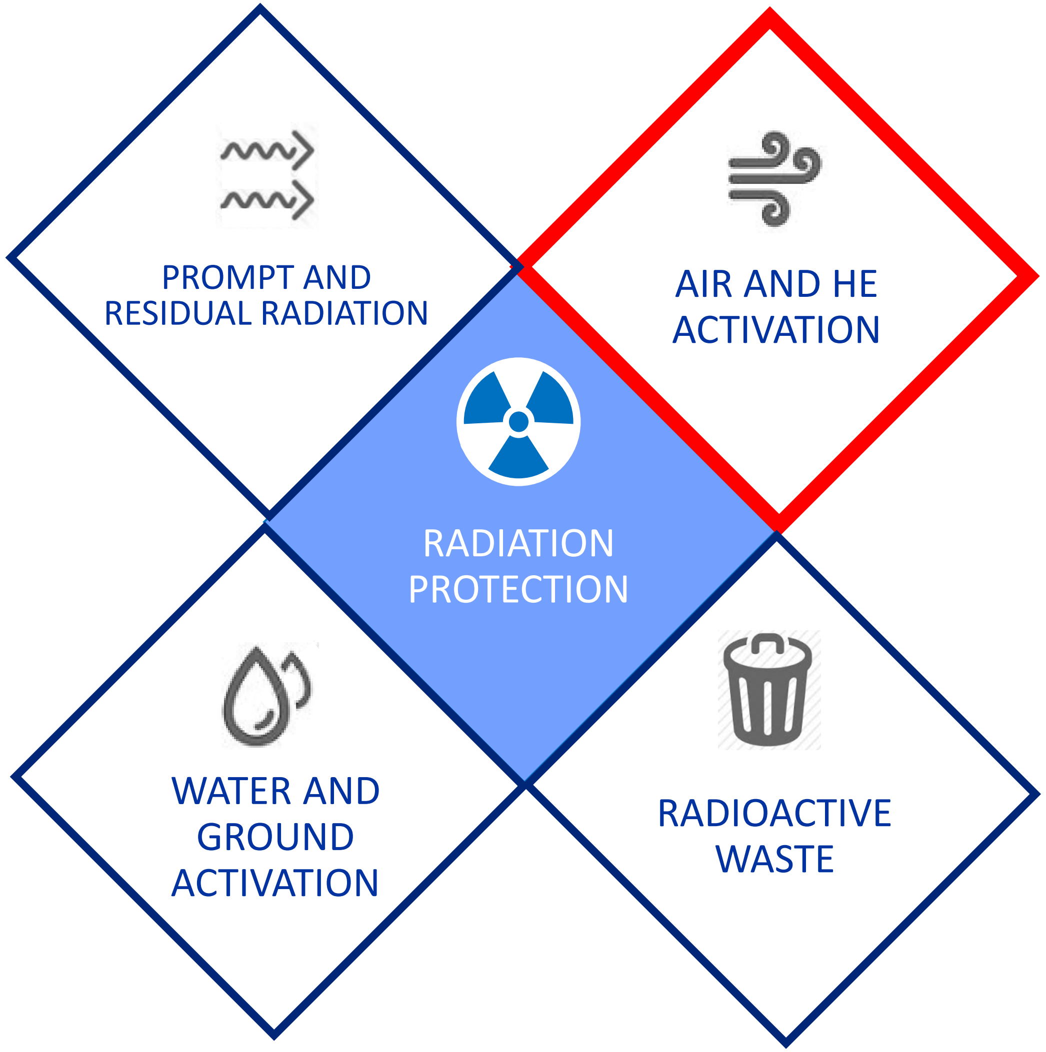
Effective dose to **the members of the public** in nearby areas to respect the dose objective of **10 μSv/year** from all facilities at CERN





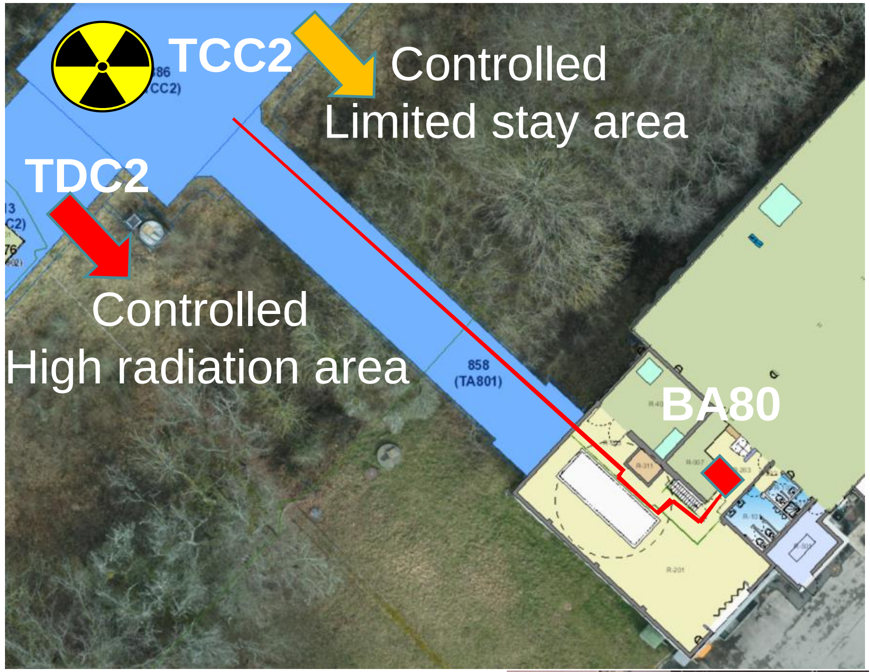
FLUKA hosted by CERN (FLUKA v4-2.2) *[5-7]*
FLUKA geometry created using FLAIR *[8]*

- ✓ Air volumes should be **minimized** in hot areas or **replaced by vacuum or helium environment**
- ✓ **Static confinement** - air areas should be separated by physical barriers from adjacent areas and the outside
- ✓ **Dynamic confinement** by a ventilation system guaranteeing a pressure cascade from low to high contaminated areas
- ✓ **Air extraction** systems should be equipped with HEPA (High Efficiency Particle and Aerosols) filters on exhaust and **air monitoring systems** (in North Area: target areas, high intensity ECN3 cavern and new facilities)
- ✓ Access to an area can only be given if the committed effective dose per hour of stay originating from the activated air is < 1 µSv



BA80 (surface of TCC2 area)

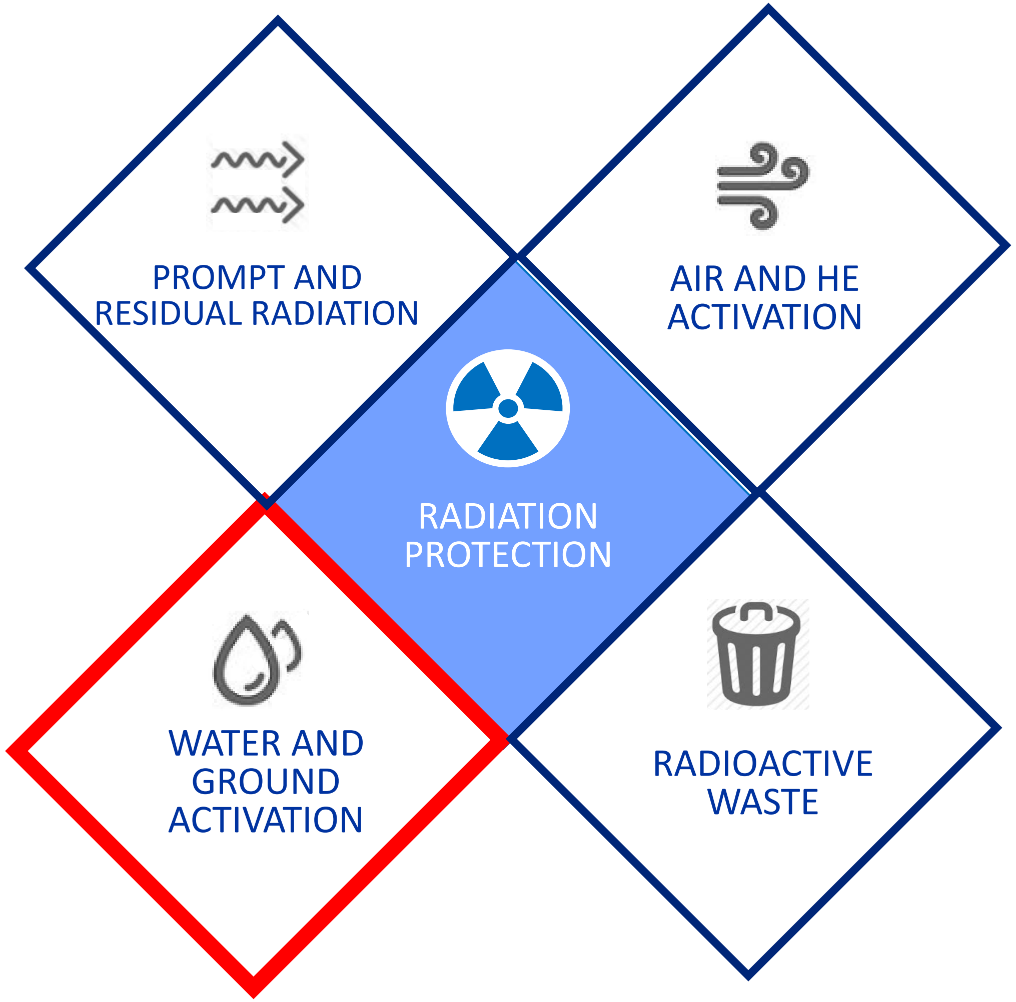
- Gases can't be retained by filters thus the only way to reduce their activity is by a delayed release or by a long duct (long transport time) for short lived ones
  - Short lived gases: C-11, N-13, O-15 (half-life minutes scale) (in the form of CO, CO2, N2, O2, NOx), Ar-41(1.83h)
  - Issues with long lived ones e.g. H-3(12.3y) (HT, HTO), C-14(5700y), Ar-37(35d), Ar-39(269y), Cl-36(5e5y)
- Radionuclides attaching to aerosols: Be-7, P-32, P-33, S-35 and Na-22 can be retained by high efficiency particles and aerosols HEPA filters. In addition, dust, corrosion, erosion particles containing Mn-54, Co-60.



Solutions for TCC2/TDC2:

- Access to TDC2/TCC2 can be given after 2 hours of waiting + 2 hours of flush after beam operation
- Air activation monitor installed in BA80 and operational since mid-2018 allows to sample air from TCC2 target (via CV) region before access and is connected to REMUS (global RP monitoring system)
- Recent ventilation system (in surface building) issue provoked air drawing in from TCC2 towards the surface building/access point) → RP monitoring alarm of the air activation monitor was triggered

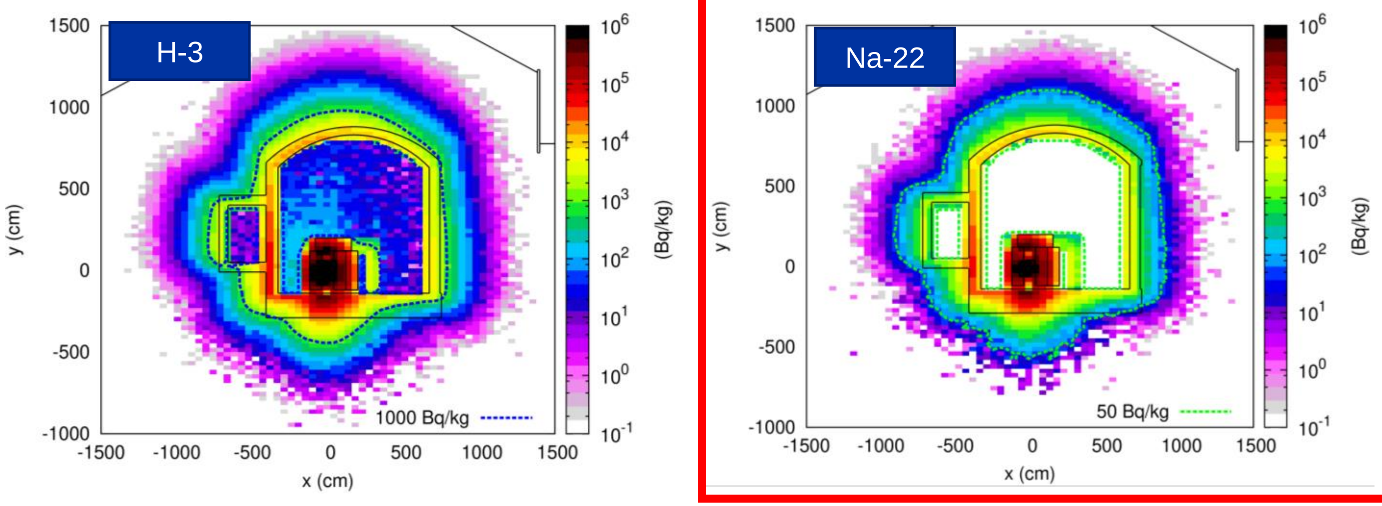
- ✓ **Minimize the risk of earth activation** by using appropriate shielding
- ✓ **Minimize ground water contamination** – depending on the hydrogeological properties of the facility surroundings:
  - ✓ Deep impermeable molasse with no contact with shallower aquifers in moraine above and not suitable for drinking water exploitation
  - ✓ Less deep locations in semi/permeable moraine require complex studies:
    - ✓ For a new facility: hydrogeological studies, geo-membrane may be a solution, soil composition should be evaluated
    - ✓ **Na-22 and H-3** with high affinity to water passing aquifers (leaching from rock) are the most concerning ones
    - ✓ Limits of **2 Bq/kg for Na-22** and **10 Bq/kg for H-3** must be respected (proposed in 2014 for CENF Neutrino Facility [9]) unless further information (e.g. dedicated hydrogeological study) exists allowing to reduce the risks
- ✓ **Water cooling circuits** for highly radioactive elements (such as targets, dumps) should be **closed** and separated from others (retention tanks) to avoid environmental leak (ideally to be avoided)



Earth activation and water contamination ECN3 study case

- ECN3 located 19 m underground (8 m of moraine above)
- 400 GeV, 2e13 p/spill, 1e19 POT/year for future HIKE experiment (NA62 intensity increase 3.5 times)
- Assuming 4 years of operation (180 days/year) moraine gets activated to extensive levels in terms of Na-22 (T1/2=2.6y) and H-3 (T1/2=12y)
- Conservative limits for Na-22: 2 Bq/kg and H-3: 10 Bq/kg established for CENF exceeded by more than 1000 times in target and TAX region (Na-22 of particular concern) (here non-diluted water intake assumed, 100% leaching)
- New limits proposed (based on Swiss RP Ordinance/Annex7/ Immission limits for water and other factors taken into account) Na-22: 50 Bq/kg and H-3: 1000 Bq/kg – but still exceeded in the target/TAX region (geological studies done in the past and no deep aquifer found, moraine of low permeability) [10]

Na-22 and H-3 specific activity (Bq/kg) at the target area



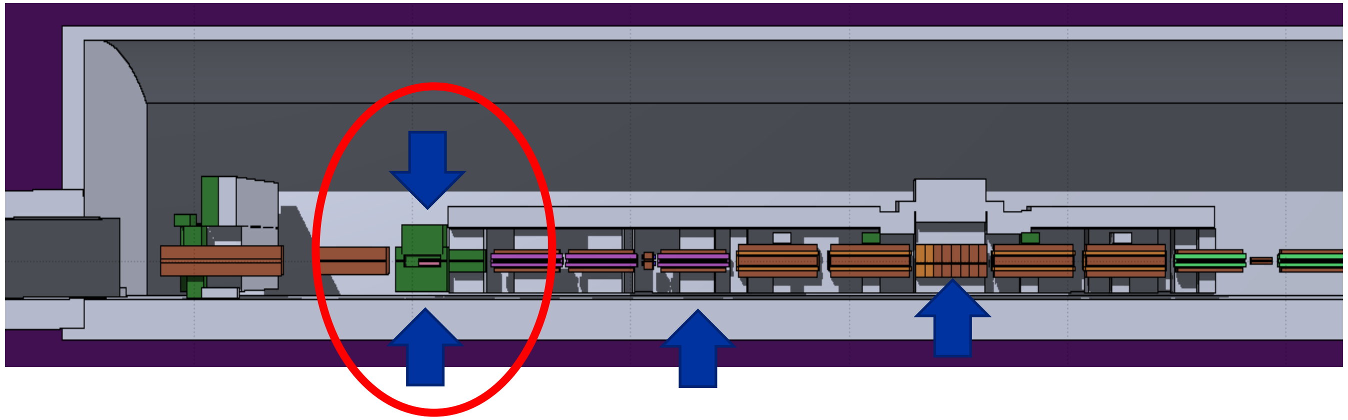
Still 2.2 m on top and 2.8 m bottom layer exceeds the limit with max up to 3700 Bq/kg (bottom)

Cooling time of 1 s

Earth activation and water contamination ECN3 study case

CHALLANGE: Necessity of an adequate shielding to reduce prompt dose and in consequence bring down soil activation to the limits

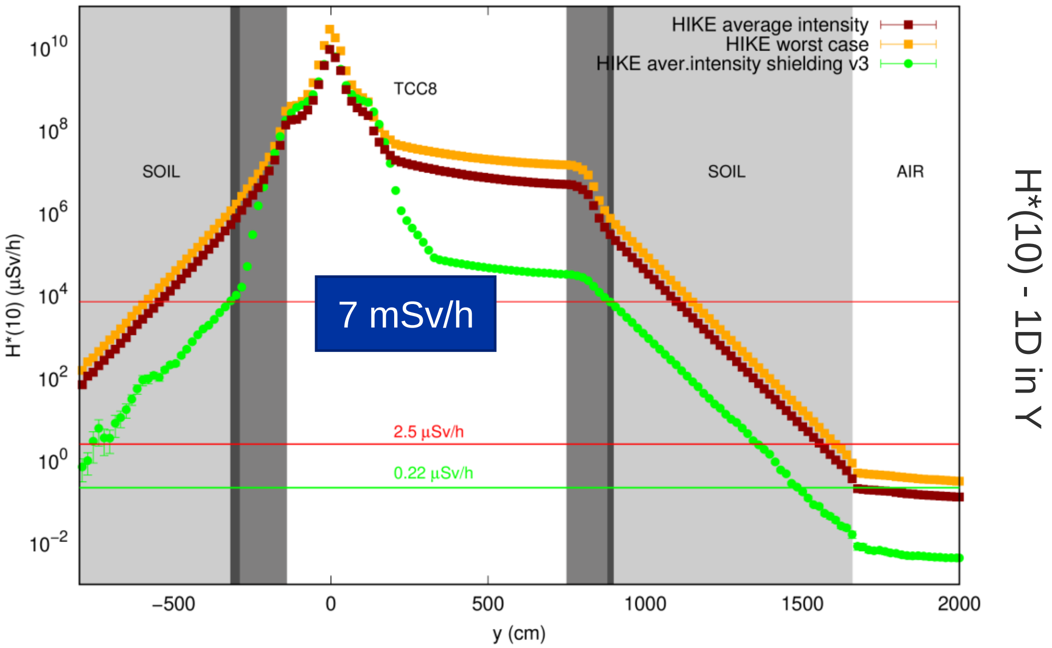
Present ECN3: NA62 MC FLUKA model
Shielding (side view)



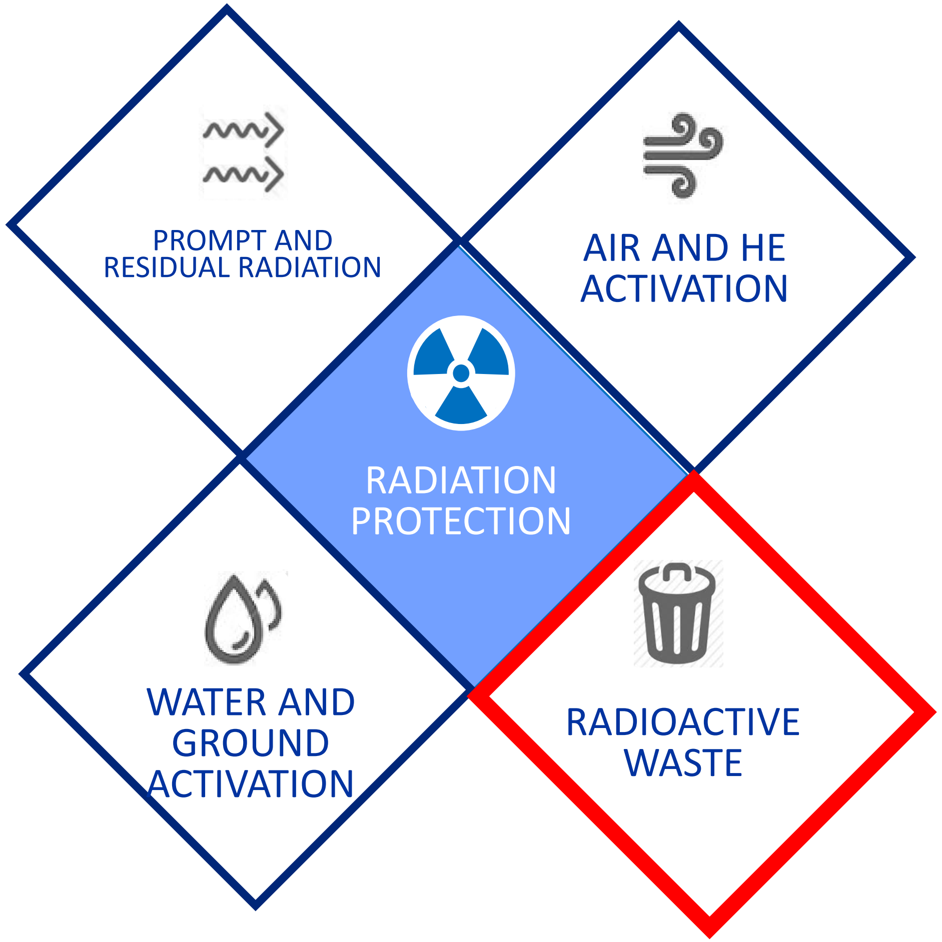
Shielding optimization is ongoing :
Semi-Optimized shielding design assumes:
0.8 m – 1 m of Fe floor shielding for the target and TAX region
0.4 m Fe and 1.4 m of concrete on the target top
Target to TAX – floor shielding 0.4- 0.6 m of iron

Correlation of the limits of soil activation with the H*(10) prompt dose at the critical location (target: bottom soil and top soil):

Na-22 (50 Bq/kg) – 7 mSv/h
H-3 (1000 Bq/kg) – 50 mSv/h



- A new facility design must consider **minimalization**, decommissioning and dismantling process of radioactive waste
  - Cost of materials used vs cost of waste disposal
  - Lessons learned from previous dismantling: (CV should be preserved to avoid degradation and corrosion - WANF)
- **Material minimalization** – usage of materials of low activation level, as may have a direct impact on later handling and waste disposal
  - particle field dependent
  - high purity, low critical impurities as cobalt
  - ActiWiz tool to compare operational aspects and radioactive waste produced at different location with different materials used – General Hazard Factors [11]
  - E.g. modular equipment and shielding, easily separated parts
- **Good practice** to avoid unnecessary equipment activation: only absolutely necessary equipment should be installed in areas of high radiation levels.



$\sum_i^n \frac{A_i}{LL_i} > 1$ or H*(10)@10cm distance > 0.1 µSv/h or $\sum_i^n \frac{c_i}{CS_i} > 1$

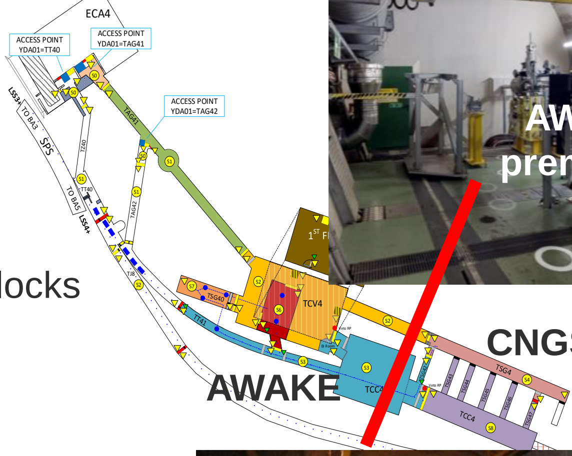
LL – swiss clearance limit for a radioisotope i (Bq/g)
Ai – specific activity of a radioisotope i

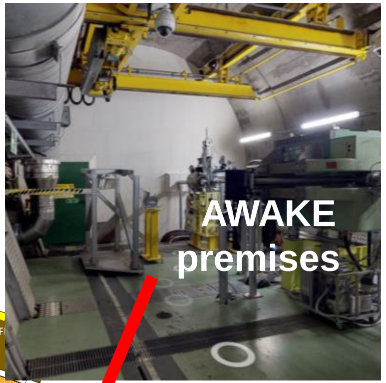
Ci – limit for surface contamination for a radioisotope i (Bq/cm2)
Csi – surface contamination of a radioisotope i (Bq/cm2)

Cern Neutrino to Gran Sasso experiment dismantling

[12]

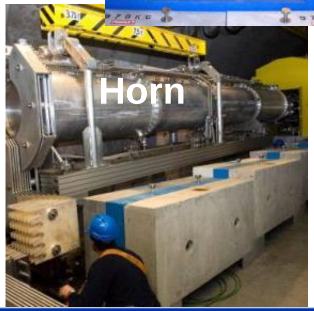
- CNGS in operation from 2008-2012, 2.25e20 POT, 160 kW (500 kW), 60 m underground
- 100 m beam line equipment in TCC4 cavern still radioactive despite 9.5 y of cooling
- To be dismantled and disposed: target, horns (7m), beam monitor, helium vessel (70m), shielding blocks
- High contact dose rates: up to 50 mSv/h at the target tube





Challenges

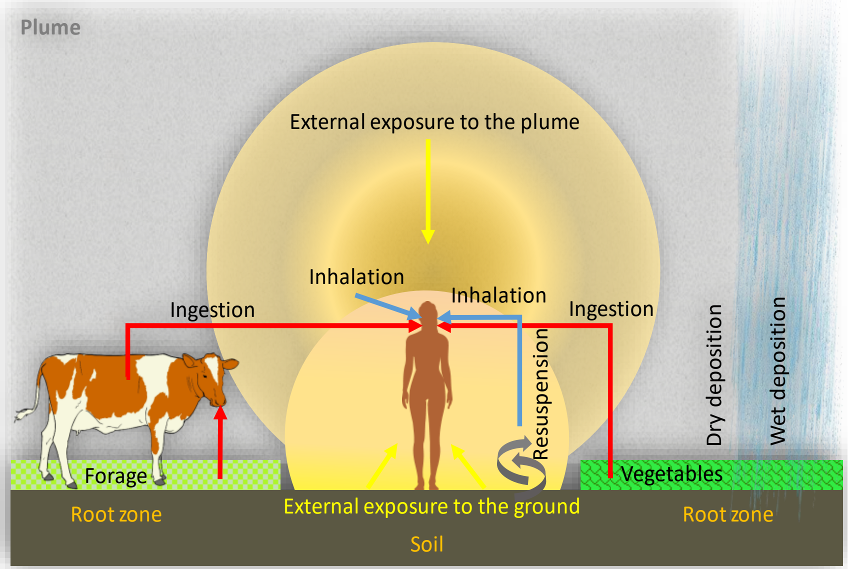
- No direct access to the beam line and any possibility to measure dose rates close to the beam - MC FLUKA and ACTIWIZ calculations essential!
- Requires preparation on waste classification and management strategy work → classification based on radionuclide inventories and residual dose rates to establish elimination pathways (huge computational work)
- CERN site: RWTC Radioactive Waste Treatment Center at CERN has limited space (temporary storage only) a new storage building in proximity required
- Each step of dismantling: decontamination, transport, storage, processing, volume reduction and final disposal each action respecting the ALARA principle (risk due to contamination and irradiation)
- Particular concern for highly activated items – target, horn, beam monitor but also huge items to be processed and further disposed – detailed procedures
- High cost of radioactive waste disposal in general but reuse of concrete blocks in other CERN's experiments/upgrades allows to save ~4MCHF!



Environmental impact assessments – accidents involving fire in CERN’s accelerator facilities

FIRIA (Fire Integrated Radiological Impact Assessment) multidisciplinary project (2018-2025)

- Fire safety and radiological impact of radioactive substances discharged to the environment
- Fire engineers, CFD modelers, RP physicists, fire intervention planners
- Exposure of: a bystander (inhalation of smoke) and a resident member of the public (ingestion of a locally produced food)
- Aim: Mitigation and protective measures
- https://hse.cern/content/firia



Pilot case ISOLDE:

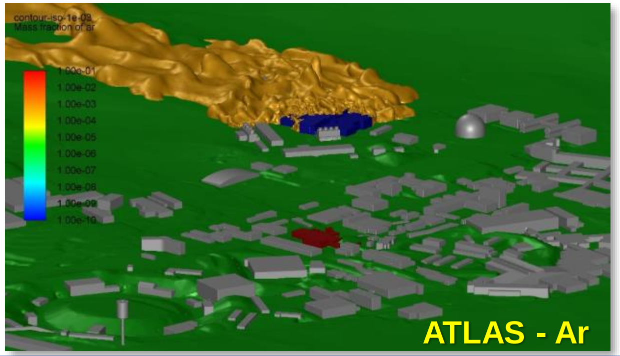
- Fire of contaminated oil in target vacuum pumps
- Water/air leak to a UC_4, (La, Th) targets with loss of target integrity
- Cable fire: Insulation + RNs outgassed from activated wires

Pilot case ATLAS:

- Fire of the ITk detector
- Rupture of the LAr Calorimeter with discharge of all activated Ar gas and other Ar activation products to the environment

CMS currently under study

<u>**North area’s TCC2/TDC2 will be the next!**</u>



Conclusions

- Each new facility requires complex RP studies and **limitation and optimization significantly affect the design: target area, shielding, auxiliary infrastructure**
- For each upgrade of the existing facility (as shown for high beam power cavern ECN3) or surface EHN2: RP limitation and optimization need to be fulfilled:
    - area classification revision
    - effective dose **limit 1 mSv per year at the CERN fence**
    - environmental releases: radioactive **air** and stray radiation → **objective of 10 µSv/y to the public**
    - **Earth/ground water activation** should stay below the CERN defined limits for Na-22 and H-3
- **Air induced radioactivity** pose problems for zones of high dose levels/target areas: air compartments should be kept at lower pressure than adjacent compartments and connected CV circuits – **air activation monitoring essential**
- **Dismantling** of the radioactive facilities must be well planned and follow the ALARA principle
    - Pre-studies are important for radioactive waste classification, transport, storage and disposal

References

[1] CERN Radiation Protection Safety Code F

[2] The CERN Neutrino Beam to Pyhasalmi – CN2PY : Conceptual Design report

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

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

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

[6] 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)

[7] 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)

[8] V. Vlachoudis, ***F****LAIR: 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)

[9] P. Vojtyla, C. Strabel, H. Vincke, *CENF radiological environmental considerations* – CERN Internal Report (2015)

[10] Swiss Radiation Protection Ordinance (2017)

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

[12] E. Nowak, C. Ahdida, H. Vincke, C. Saury, *Characterization o the radiological CNGS environment*, CERN Internal Note (2021)

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Limitation – *Area Classification (external exposure)*

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

Limitation – *Area Classification (internal exposure)*

CS, CA: Nuclide-specific Guidance values from Swiss legislation

Specific airborne radioactivity
1 CA = effective committed dose of 20 mSv for a stay of 2000 hours/year

Specific surface contamination
1 CS = 1/10th of dose limit to skin and/or 0.5 mSv/year for daily ingestion of contamination on 10 cm^2

"No contamination"
- < 1 CS for identified isotopes
- < 1 Bq/cm^2 for non-identified gamma and beta emitters
- < 0.1 Bq/cm^2 for non-identified alpha emitters

	Area	Annual dose limit (year)	Specific airborne radioactivity	Specific surface contamination	
	Non-designated	1 mSv	0.05 CA	1 CS	
Radiation Area	Supervised	6 mSv	0.1 CA	1 CS	
Radiation Area	Simple Controlled	20 mSv	0.1 CA	1 CS	Controlled Area
Radiation Area	Limited Stay	20 mSv	100 CA	4000 CS	Controlled Area
Radiation Area	High Radiation	20 mSv	1000 CA	40000 CS	Controlled Area
Radiation Area	Prohibited	20 mSv	> 1000 CA	> 40000 CS	Controlled Area