Radiation protection aspects for HL-LHC

A. Infantino & P. Dyrcz

On behalf of HSE-RP

With contributions from: HSE-RP management and colleagues, HL-LHC project management, PSO and WPs!

12th HL-LHC collaboration meeting – Plenary session 6 (Indico)

EDMS 2773490

Context and outline

- A number of studies delivered in the last years, covering LS3, HL-LHC operation, new HL-LHC galleries, specific components (e.g. TAXN, QXL, etc).
- RP studies disseminated in a number of *ad-hoc* presentations in WP meetings & HL-LHC TCC + dedicated HSE-RP Technical Notes → reference list in the backup slides.
- Key EDMS documents highlighted throughout the talk (released, in-work, to be done)

- Today's talk:

Recall on area classification and ALARA levels at CERN

RP assessment for specific equipment dismantle/upgrade (e.g. TAXN, QRL)

Radioactive wastes

Air activation in the new HL-LHC galleries and access constraints

Estimated residual radiation levels during LS3

RP constraints on the excavation of the HL-LHC cores

Projected radiation levels in the HL-LHC era

Cobalt content in steels

Radiation Areas classification

EDMS 810149

	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

Low-occupancy:
< 20% working time

- ✓ The CERN RP group has reviewed the signage used in radiation areas, by introducing a new colour code for better visualizing the radiological risk level
- ✓ The RP rules determining the area classification were not changed

ALARA Levels at CERN

EDMS 1751123

Group 1 Criteria:

'hard' limits used to determine the minimum ALARA Level

Individual dose equi.	Level I	100 µSv	Level II	1 mSv	Level III
Collective dose equi.		500 µSv		5 mSv	

Group 2 Criteria:

base of a radiological risk assessment

Ambient dose equivalent rate	Level I	50 µSv/hr	Level II	2 mSv/hr	Level III
Airborne activity in CA		5 CA		200 CA	
Surface contamination in CS		10 CS		100 CS	

Note: 1 mSv = 100 mrem

	Level	DIMR-1	DIMR-2	DIMR-3
Owner		Applicant (i.e. equipment owner, work coordinator, contract or activity responsible)		
Preparation (iterative)	WDP template	*Optional* Applicant[2]	*Mandatory* Applicant[2]	*Mandatory* Applicant[2,3]
	Provides dose rates	RP	RP	RP
	Sets DIMR level	RP and RSSO	RP and RSSO[3]	RP and RSO
	Documented work optimization process	*Optional* RSSO	*Mandatory* RP and RSSO	*Mandatory* Applicant and RSSO, RP and RSO
Inform PCR (if applicable)		on request	Yes	Yes
Approval		RSSO and RP	Dept. GL and RP[4] and RSO	Complex manager (ALARA-c)
	Veto rights	RP Group leader	Leader of the HSE unit	Director General
Follow up	**Retour d'expérience**	*Optional* RSSO	*Mandatory* RP and RSSO	*Mandatory* RSO and RP and intervention supervisor
	Closure of WDP	*Optional*: RSSO	*Mandatory:* RP	*Mandatory:* RP
	Closure of intervention (DIMR)	RSSO[5]	RSO	ALARA-committee responsible[6]
Controls		*Optional* RSSO	*Mandatory* RSSO[7]	*Mandatory* RP and RSO

- ALARA level → **Radiological risk assessment** based on different criteria
- **WDP/optimization** mandatory for ALARA II & III → early planning is crucial
- ALARA III approval by "**ALARA committee**" (complex manager, GL responsible for the equipment, RSO, RP GL, and more) → early planning is crucial

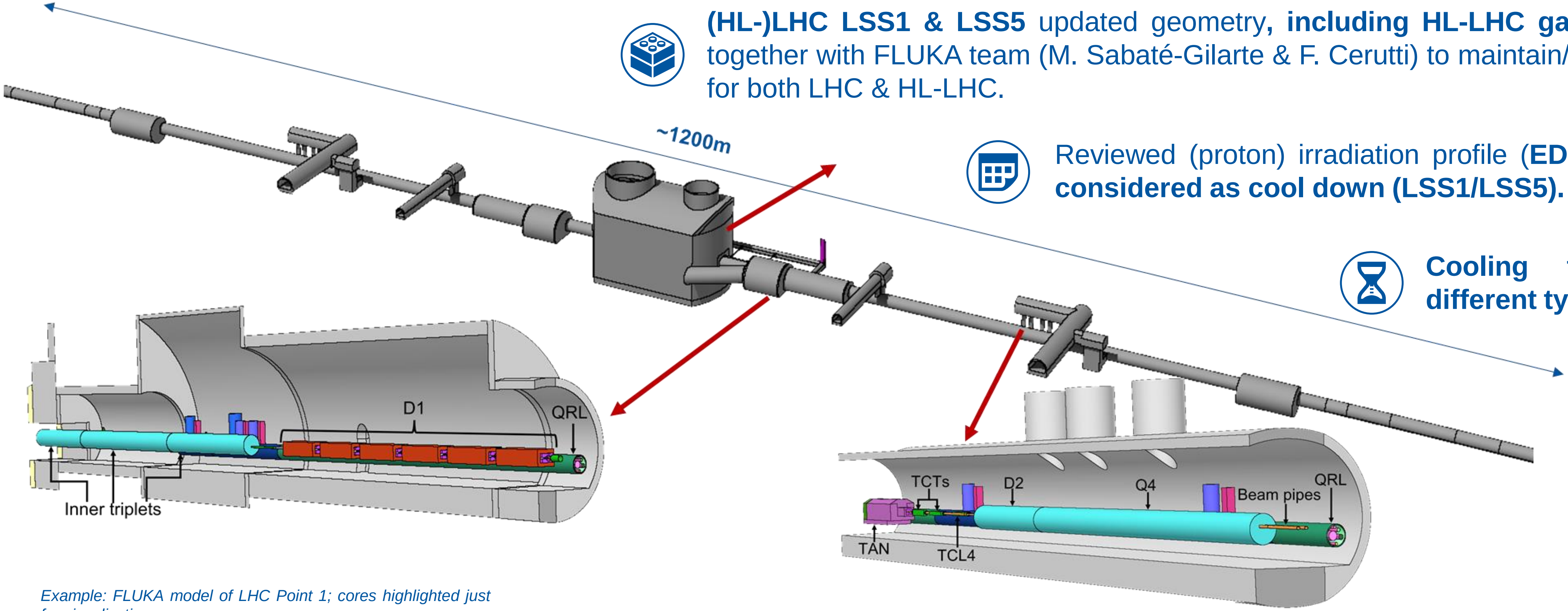
FLUKA modelling

HSE-RP preliminary LS3 estimates in **EDMS 2435122 (v1.0)** + *ad-hoc* studies within different HL-LHC WPs such as WP8, WP15, WP17. EDMS 2435122 v2.0 in-work following the extension of Run 3 up to 2025.

(HL-)LHC LSS1 & LSS5 updated geometry**, including HL-LHC galleries**. Common effort together with FLUKA team (M. Sabaté-Gilarte & F. Cerutti) to maintain/keep models up to date for both LHC & HL-LHC.

Reviewed (proton) irradiation profile (**EDMS 2641646**); **Ion run considered as cool down (LSS1/LSS5).**

Cooling times relevant for different types of interventions



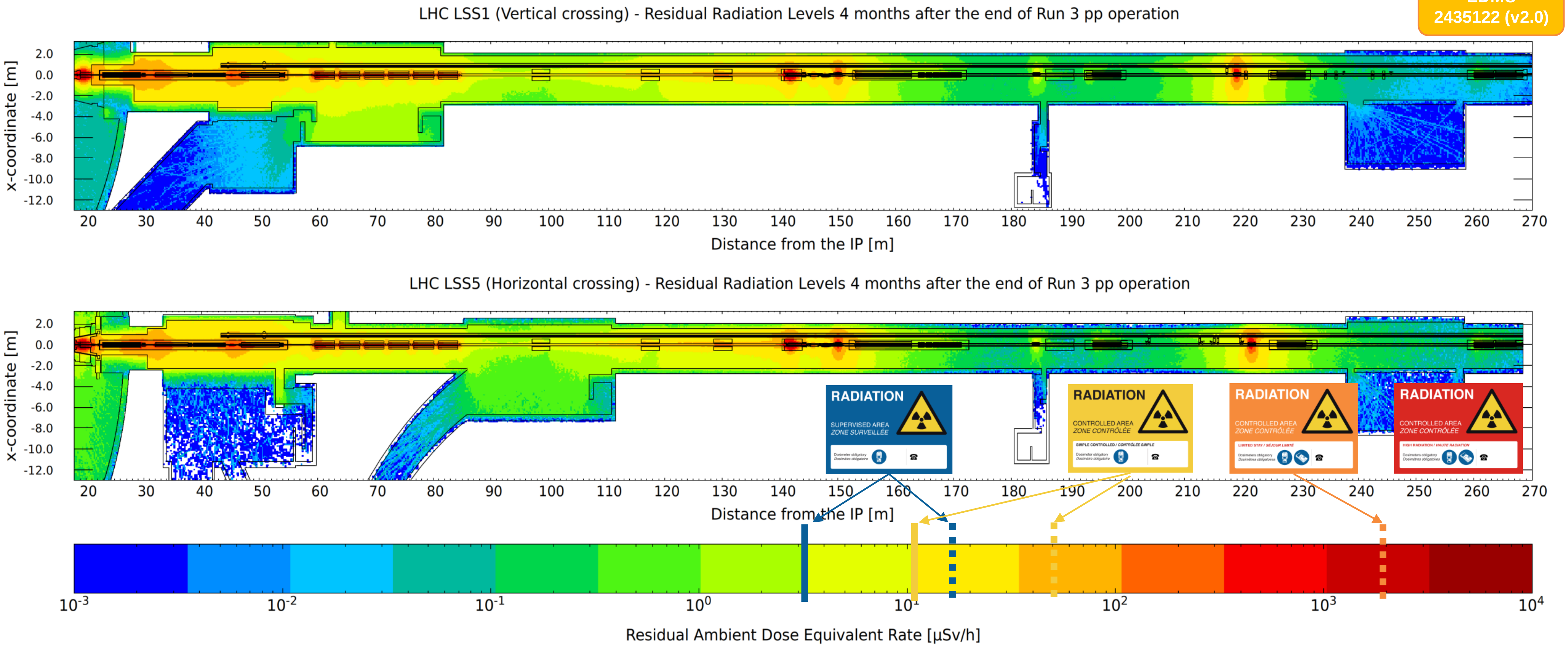
Example: FLUKA model of LHC Point 1; cores highlighted just for visualization purposes

EDMS 2435122 (v2.0)

LS3: Residual H*(10)

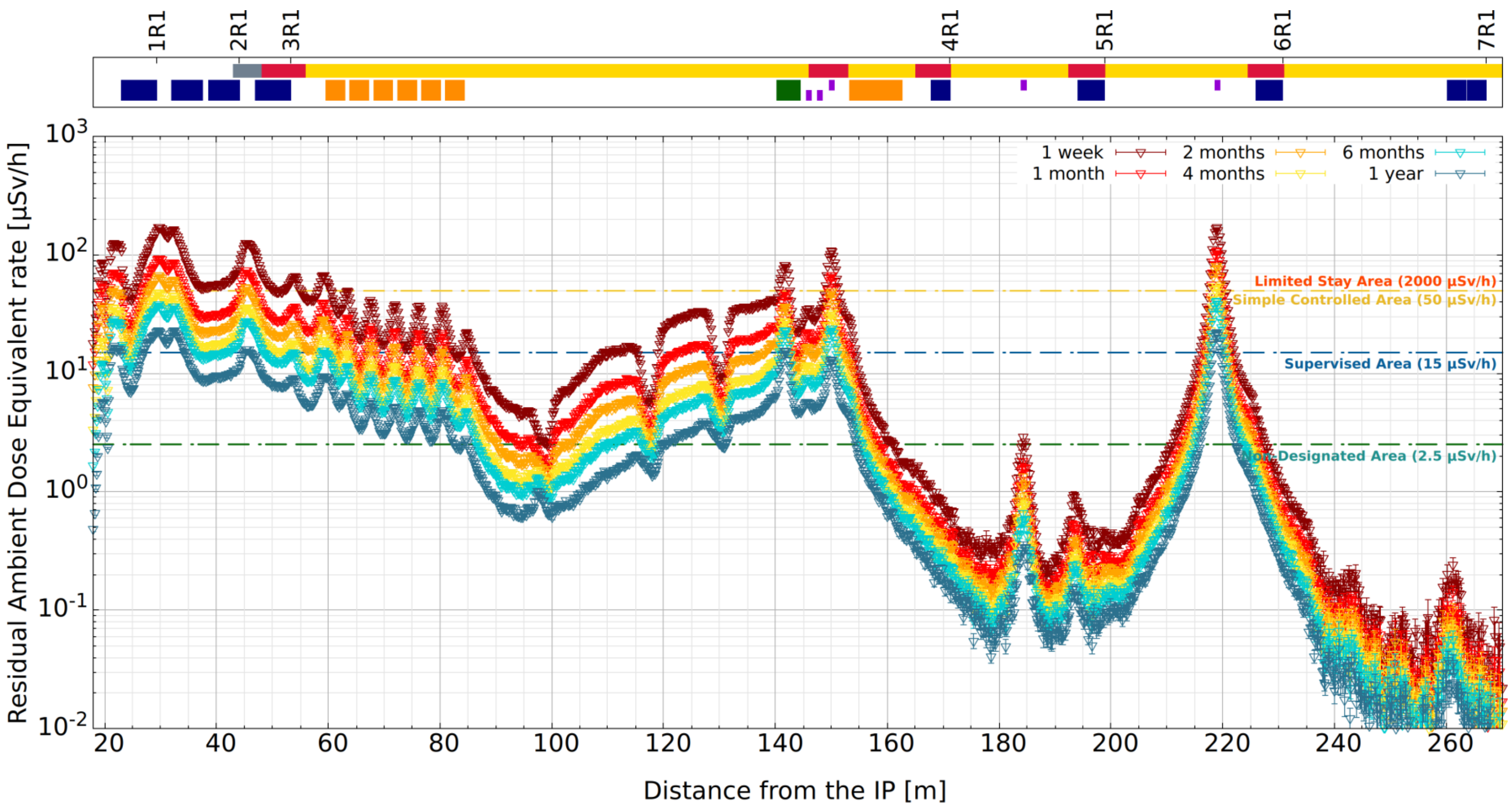
Permanent workplace
Low-occupancy area (<20 % of working time)

EDMS 2435122 (v2.0)



LS3: Residual H*(10) LSS1

*Projected radiation levels at the end of Run 3 proton-proton physics (**working distance**, ~40 cm) for **LSS1.***
Limits for low-occupancy area (<20 % of working time)

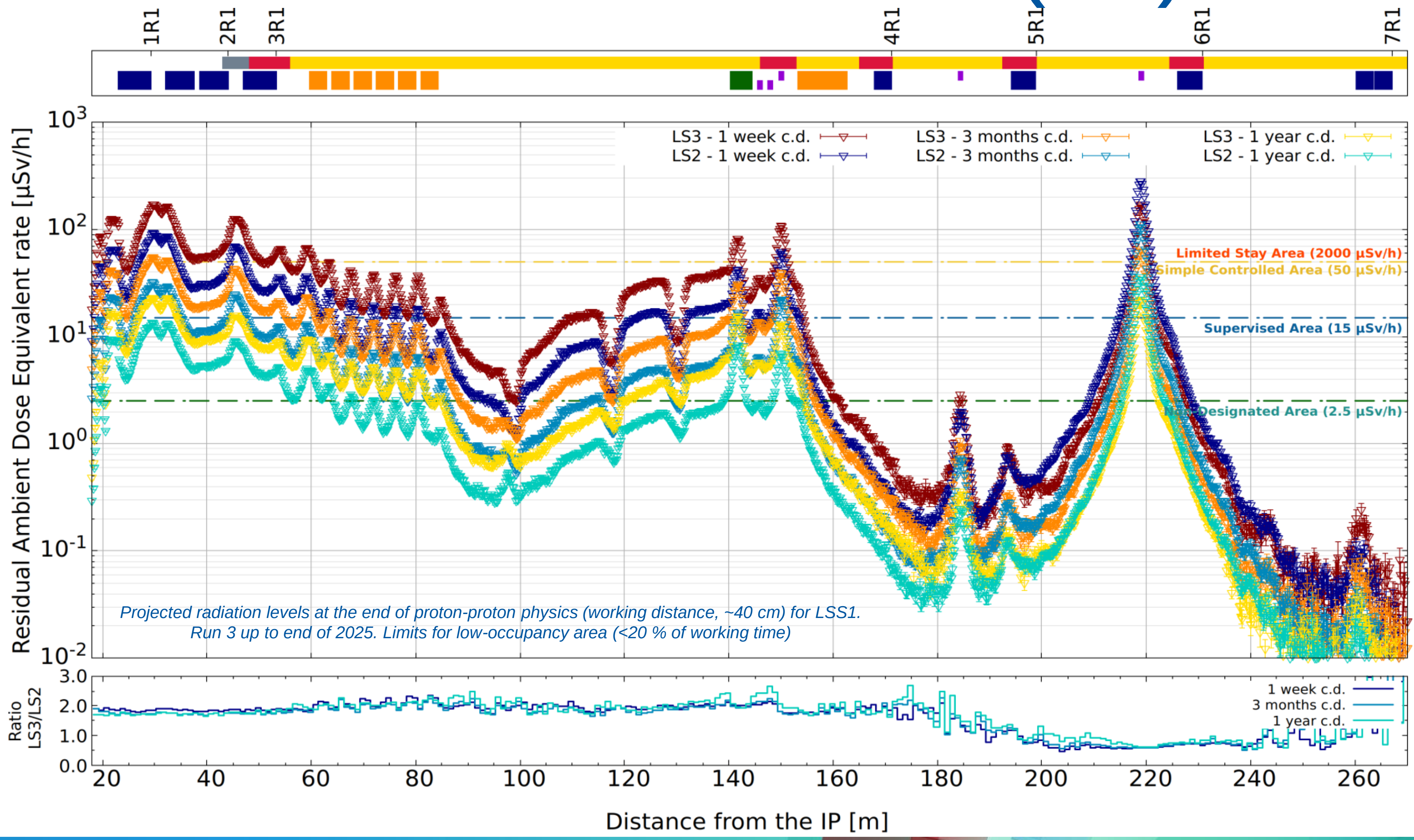


EDMS 2435122 (v2.0)

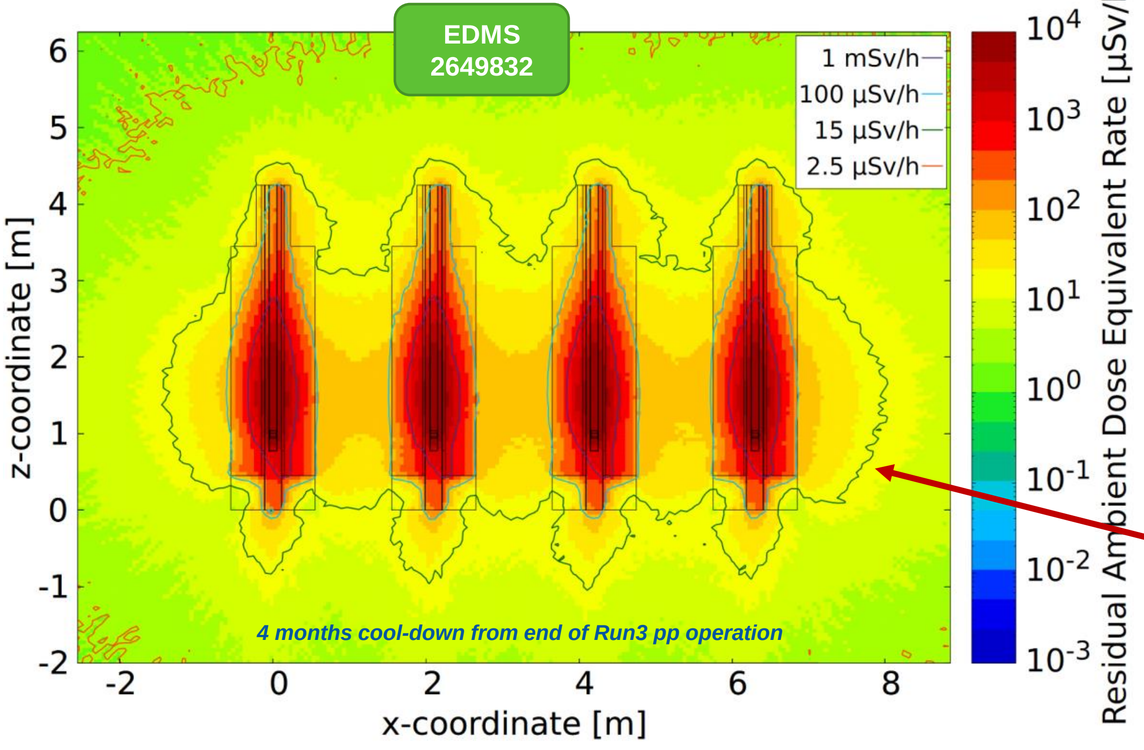
- ✓ **Hotspots** still present in the tunnel even after several months cool downs (e.g., inner triplet quadrupoles, absorbers, collimators) with expected dose rate up to few **mSv/h** at contact.
- ✓ Early begin of the dismantle activities currently scheduled after **4 months cool down** from the end of Run 3 proton-proton physics.
- ✓ Difference between LSS1 & LSS5 mainly due to the different crossing scheme → TCL4 (see backup)

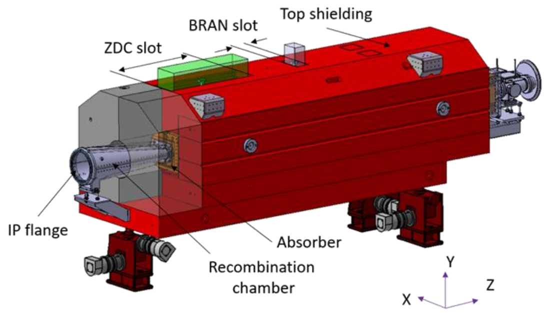
LS2 vs. LS3: Residual H*(10)

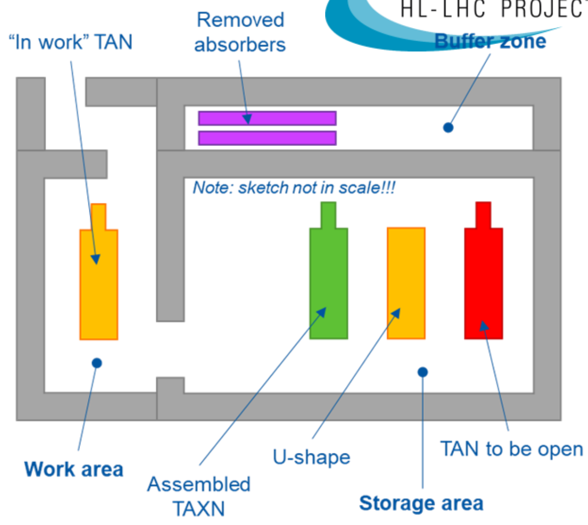
EDMS 2435122 (v2.0)



Upgrade of the LHC TAN







Upgrade activities

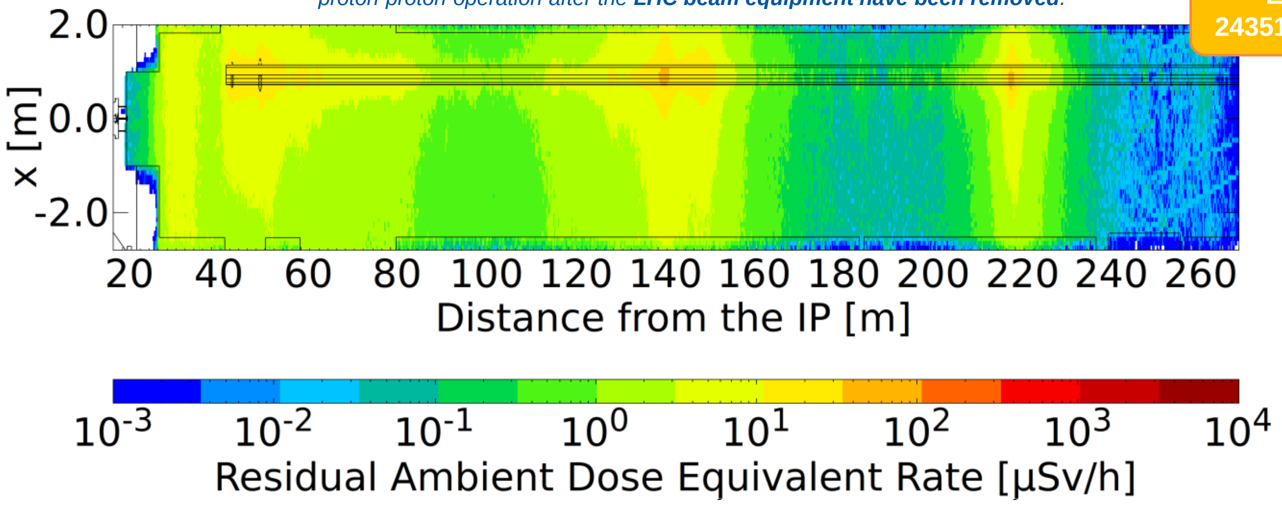
i. Extraction of the TAN from the LHC tunnel after 4 months;
ii. Storage of all four TAN in a dedicated area;
iii. Removal of non-reused parts and disposal as radioactive waste;
iv. Manipulation of the lateral/bottom shielding for the new TAXN;
v. Assembly of the new TAXN;
vi. Storage of the four upgraded TAXN;
vii. Installation of the TAXN in the HL-LHC tunnel.

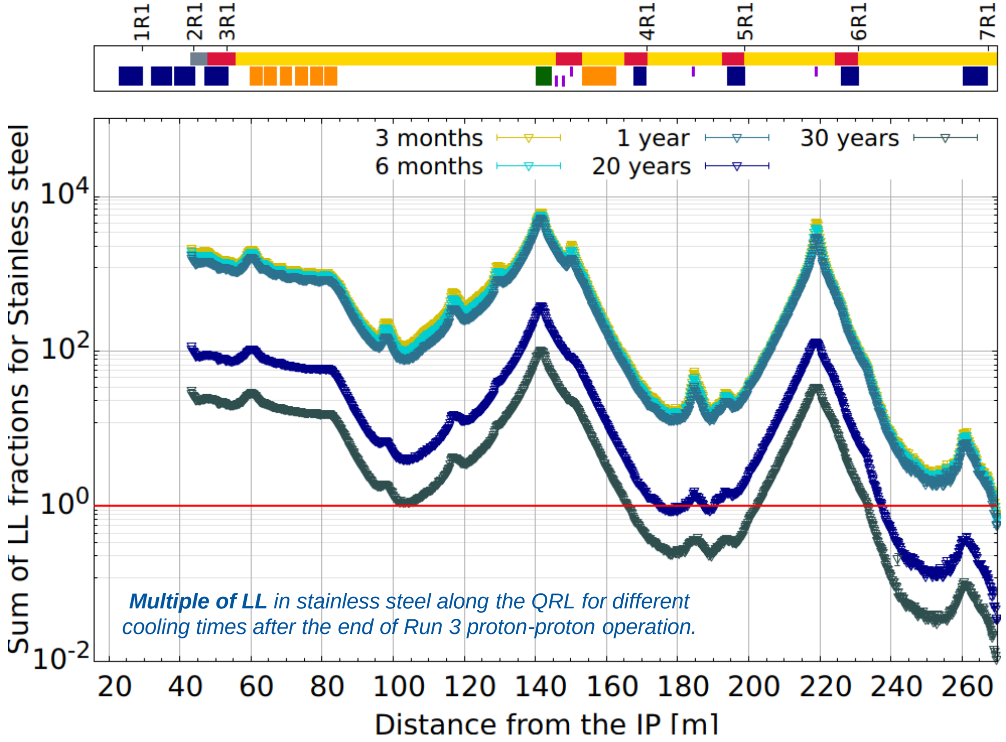
- **Complex manipulation** on highly activated equipment
- FLUKA (+ SESAME) simulations allow to estimate the **residual radiation environment at different stages of the upgrade activities and in different configuration/geometries** → "*2-steps*" method.
- Estimates used for: defying the **worksite** and its radiological **area classification**, producing **WDPs**, **optimizing** the intervention and minimizing of the radiological risk, **pre-characterizing radioactive waste**.

Upgrade of the LHC QRL

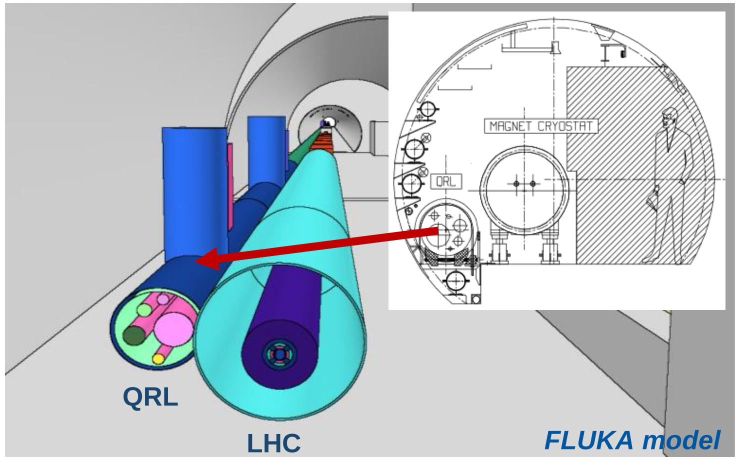
*Estimated residual radiation levels **4 months cool down** after the end of Run 3 proton-proton operation after the **LHC beam equipment have been removed**.*

EDMS 2435122 (v2.0)





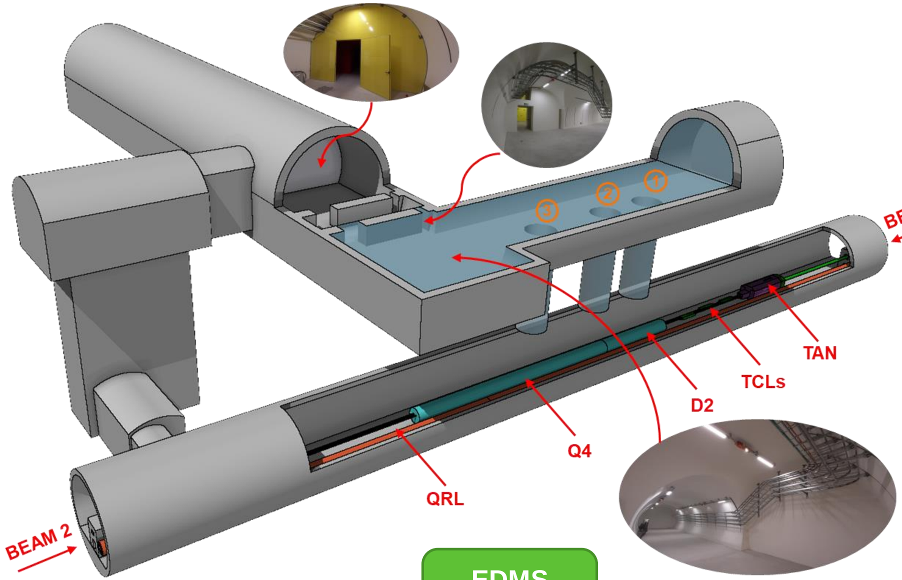
***Multiple of LL** in stainless steel along the QRL for different cooling times after the end of Run 3 proton-proton operation.*



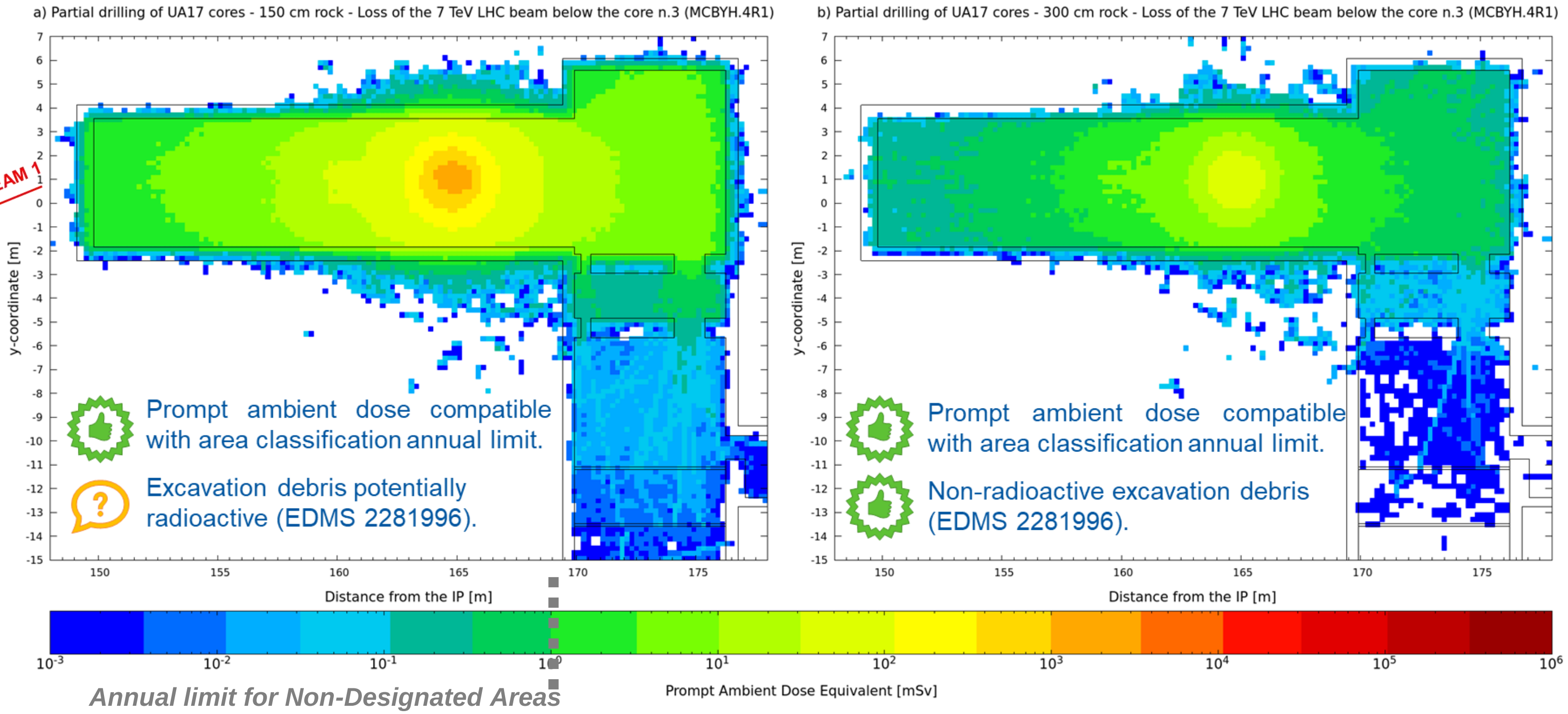
FLUKA model

- Dismantling of **800+ m** of QRL → **activity scheduled over several weeks**.
- **FLUKA** simulations of the radiological environment relevant for the QRL dismantle.
- Significant reduction of the background radiation after the removal of LHC beam line equipment: **on average <10 μSv/h in contact** with hotspots close to jumpers, heat exchangers, collimators → **integrated dose to be estimated (WDP)**
- QRL still **radioactive** after several years cool down → relevant for waste disposal/storage of spares.

Core excavation: EYETS vs LS3



EDMS 2683459

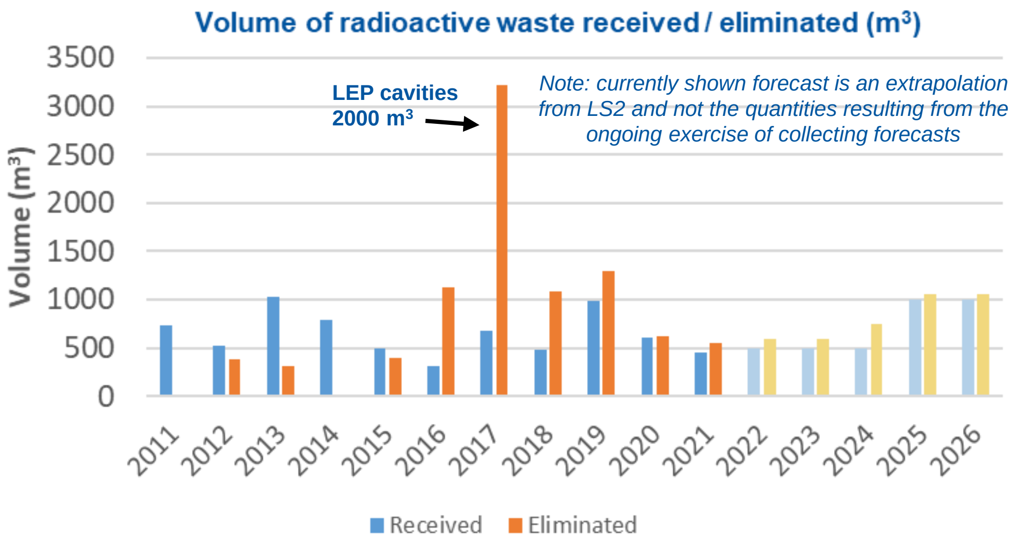


- Different (pre-)excavation options under discussion → detailed study presented in Chamonix 2022
- FLUKA simulation to check **potential RP constrains in UAs** (and ULs) if cores pre-excavated during the EYETS 24/25
- **Beam loss in the LHC machine** (MBRC.4R1 or MCBYH.4R1), **Run 3** operational conditions and different soil thickness in the cores
- Expected integrated dose due to the accidental scenario **<1 mSv**; Expected prompt ambient dose rate in Run 3 operation condition **<<1 μSv/h at the sector door location** (transmission factor ~10^{-8}, EDMS 2212147)

HL-LHC/LS3 RW forecast

- RW waste at CERN: From 2010, **tripartite agreement** between CERN and Host States; "**Fair Share**" principle revised in March 2022.
- **LS3: Dedicated meetings** (as from May 2021) coordinated by WP15 and devoted to collect data regarding RW and gathering contact persons & RP.
- **WPs with significant RW quantities identified**.
- HSE-RP-AS (A. Infantino/P. Dycrz) **support to WPs** to identify RW wastes + HSE-RP-RWM (C. Celce) **collecting and registering the estimates**.
- Missing WPs are encouraged to provide data as soon as possible to **keep forecasts up-to-date**.

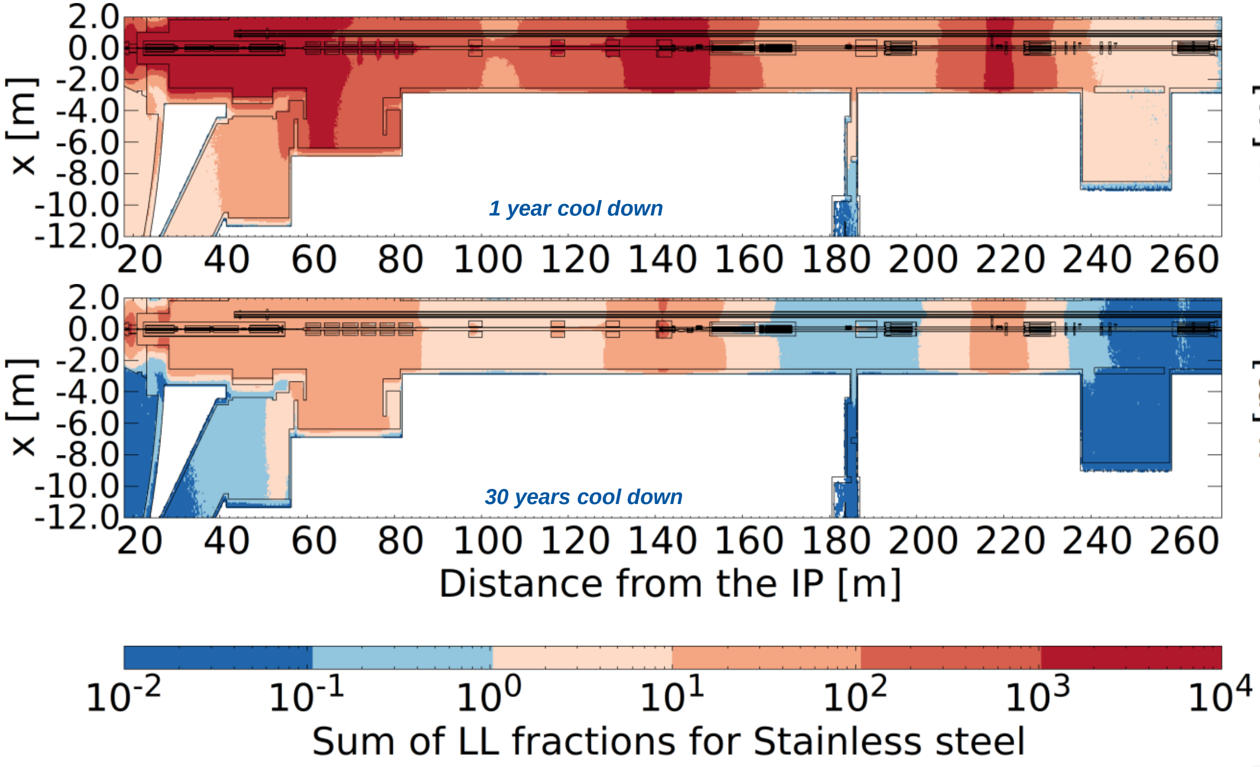
Rad. Waste description	Dep-Grp	Contact person
HL-LHC - WP3 Magnets	TE-MSC	Ezio Todesco
HL-LHC - WP5 Collimation	TE-ABT	Stefano Redaelli
HL-LHC - WP7: Machine protection	TE-MPE	Daniel Wollmann
HL-LHC - WP8: LHC-Experiment interface	BE-EA	Francisco Sanchez Galan
HL-LHC - WP9: Cryogenics	TE-CRG	Serge Claudet
HL-LHC - WP12: Vacuum & beam screen	TE-VSC	Vincent Baglin
HL-LHC - WP14 TDE LHC	SY-STI	Marco Calviani
HL-LHC - WP15 De-cabling LSS1/5	EN-EL	Georgi Minchev Georgiev
HL-LHC - WP15 cable fibre and duct	EN-EL	Jeremy Blanc

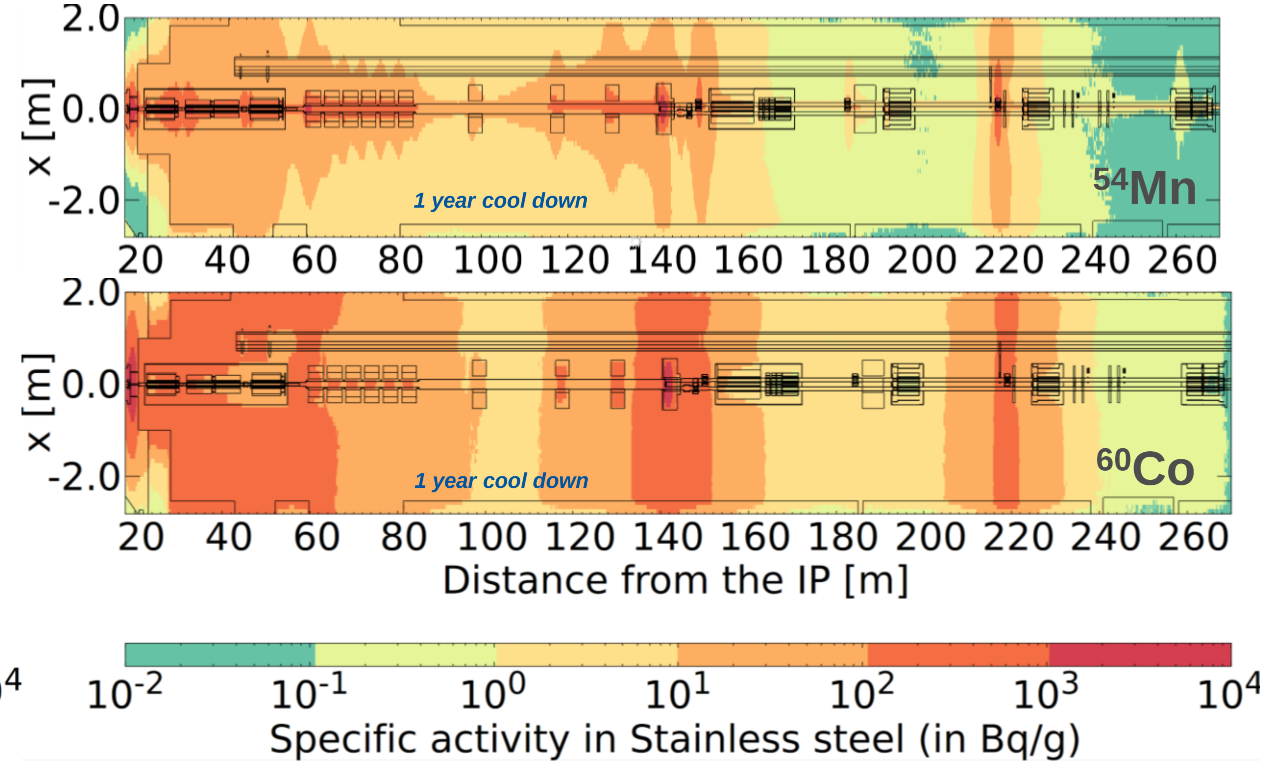


Radioactive material/waste

EDMS 2435122 (v2.0)

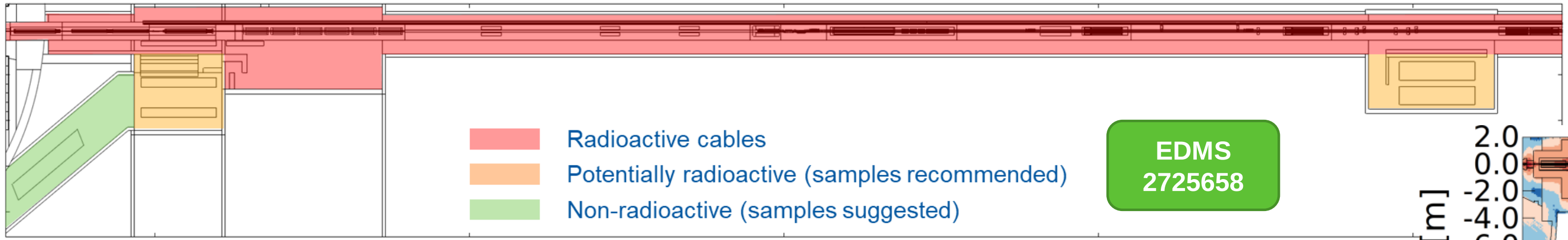
- **FLUKA simulations** allow to estimate the activation levels of LHC equipment by targeting quantities such as multiple of Swiss clearance limits (LL) and/or specific key-radionuclides.
- **Detailed radiological characterization** for radioactive waste pre-characterization and for determining the most suitable elimination path.



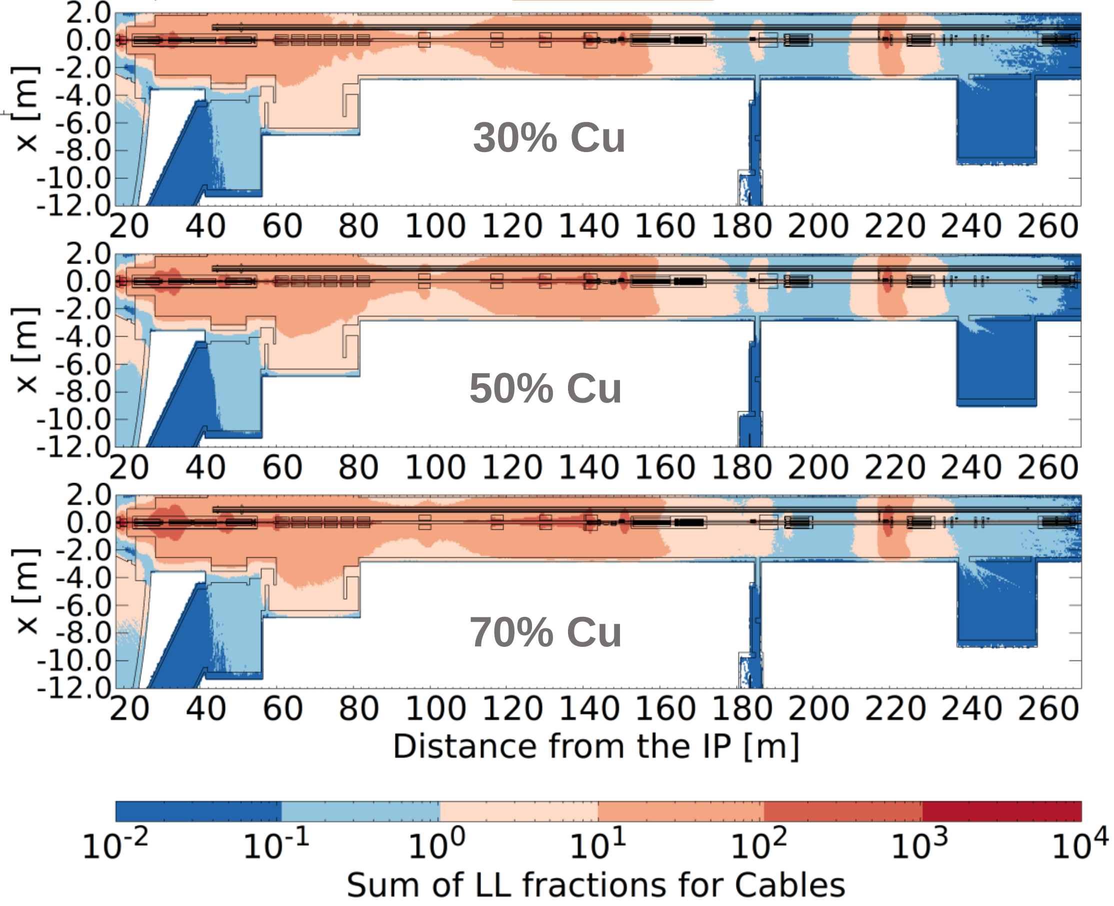


Note: considered max 0.3 wt% Co in steel

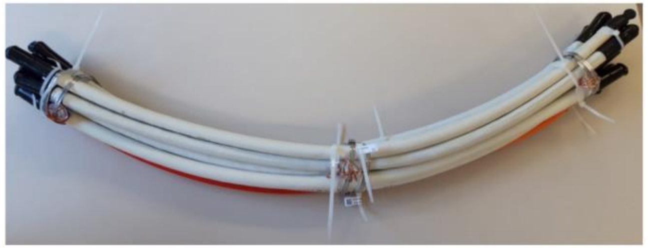
De-cabling



Note: similar zoning for LSS5

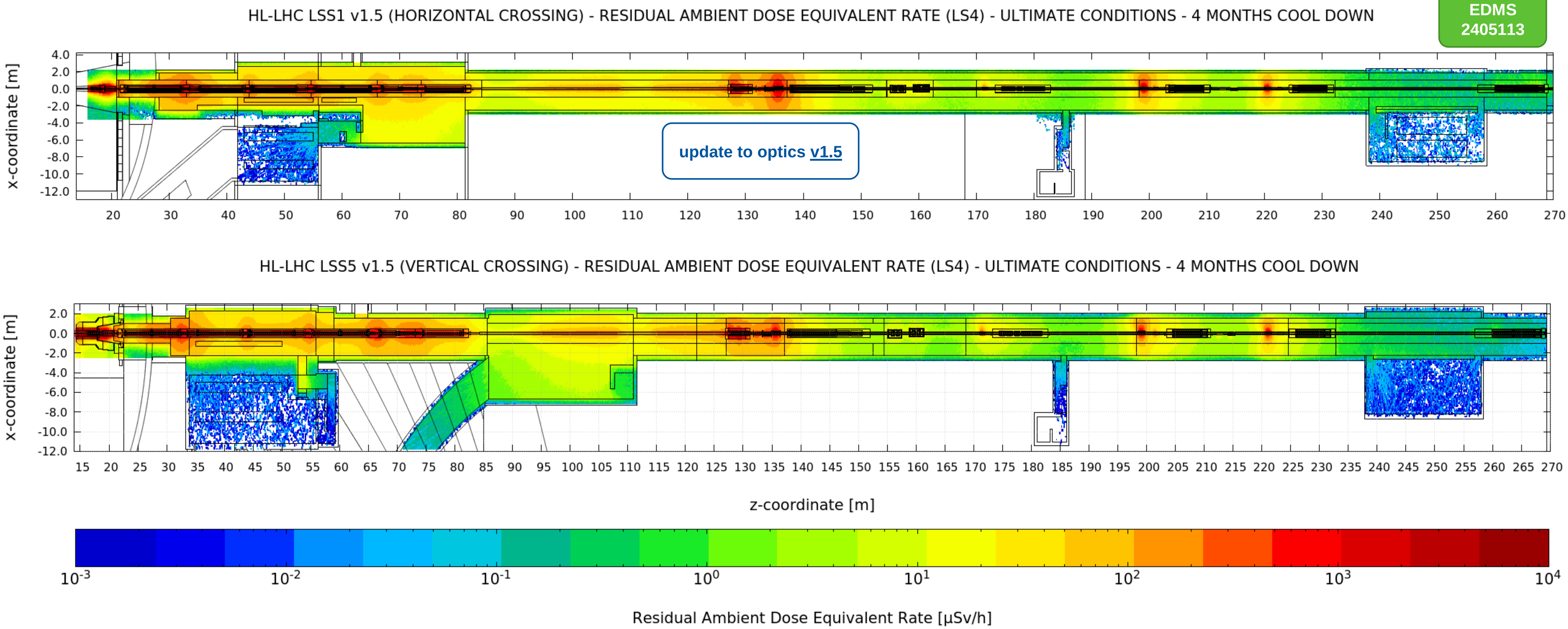


- Ongoing ad-hoc discussions within WP15 Friday meetings.
- New FLUKA simulations of multiple of the Swiss clearance levels in cables, assuming different ratio between conductor (Cu) and insulator.
- Tentative zoning for the de-cabling campaign at LHC Point 1; similar approach for LHC Point 5.
- Samples strategy: shared with CARE project (sample deployment to be discussed).

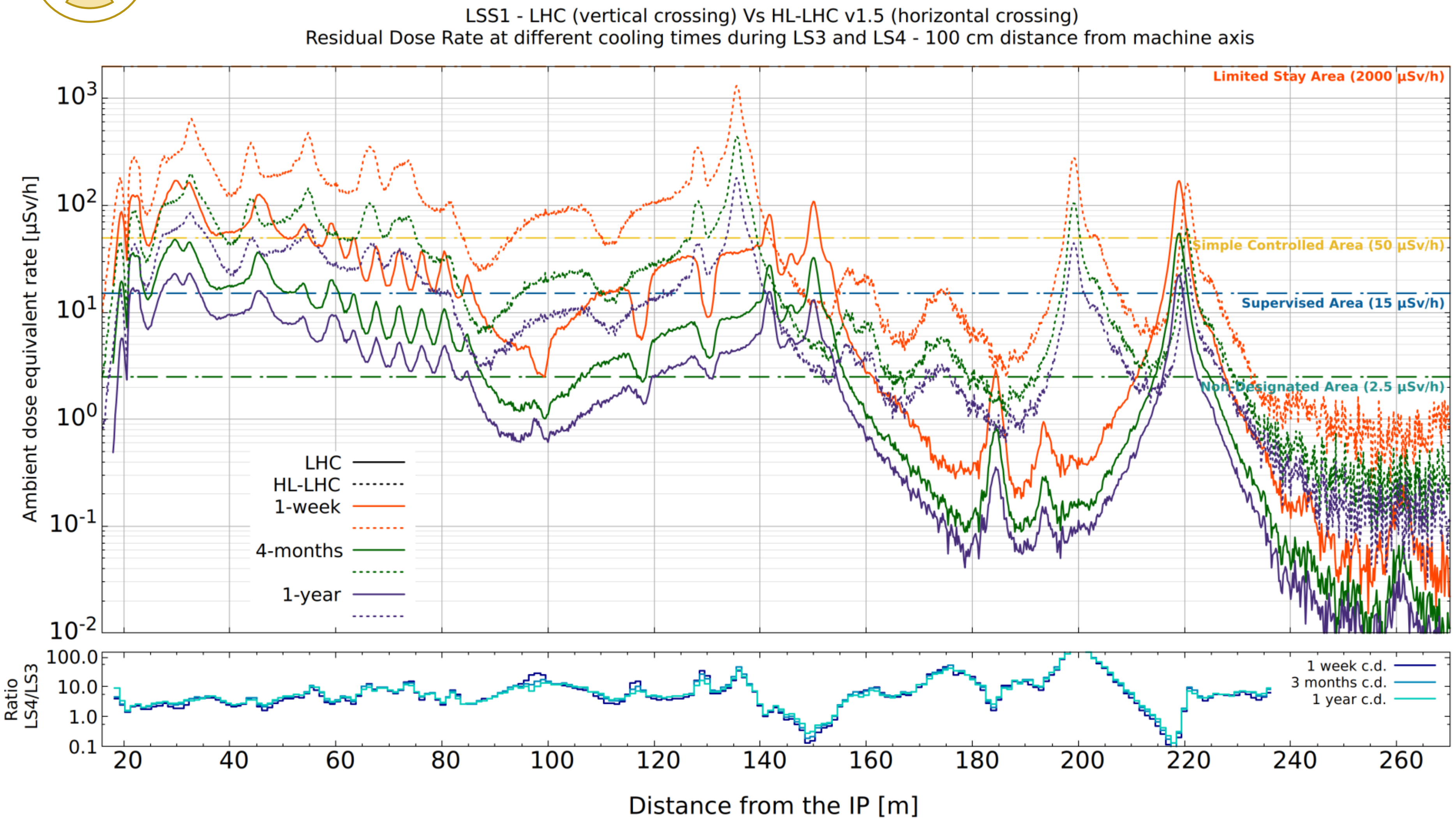


HL-LHC LSS1& LSS5 – RDR LS4

EDMS 2405113



HL-LHC LSS1& LSS5 – RDR LS4



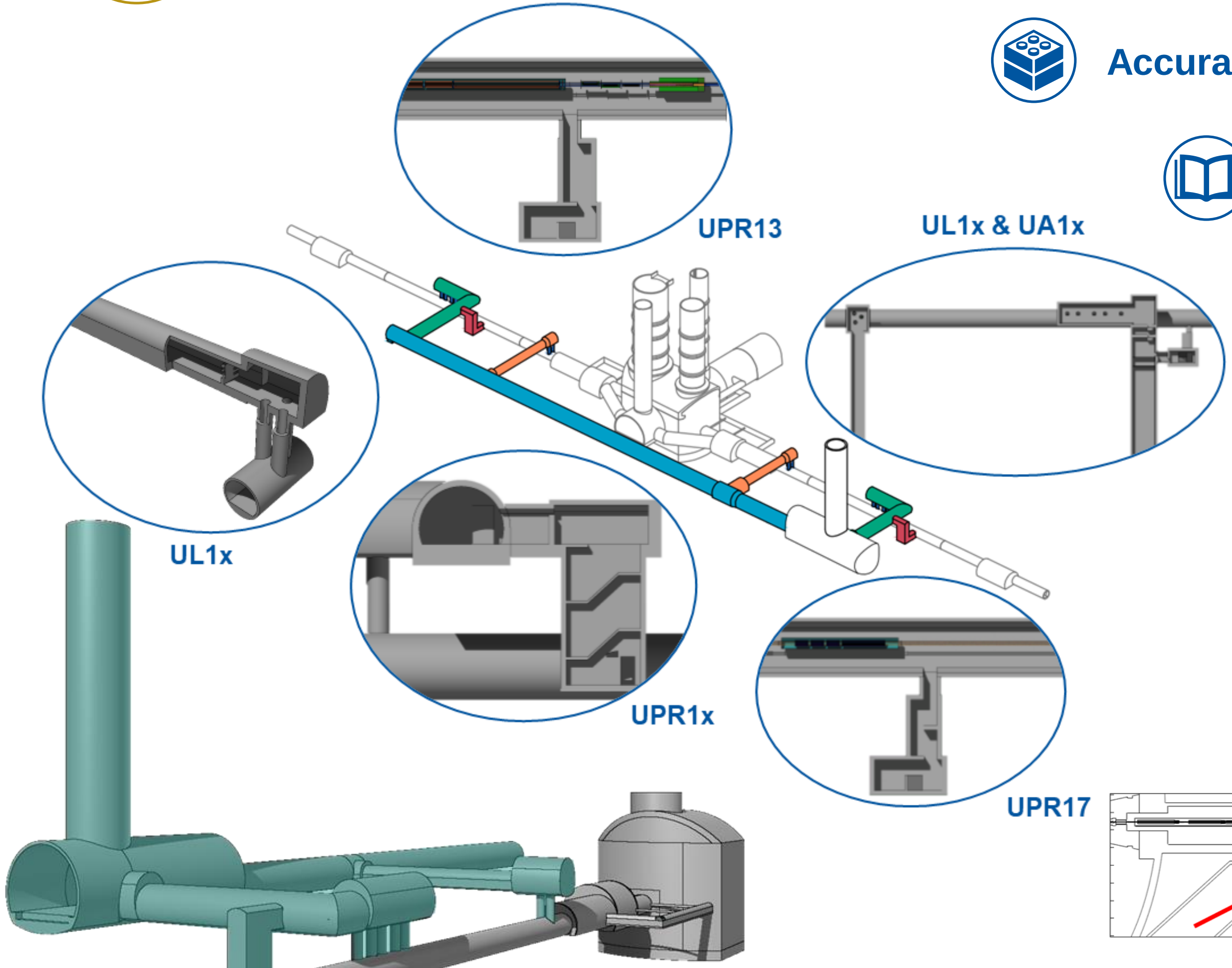
EDMS 2405113

- ✓ **Crossing scheme** LHC/HL-LHC is swapped: HL-LHC Pt.1 horizontal, Pt.5 vertical.
- ✓ Peaks in different position due to the **different optics & crossing scheme**.
- ✓ Significant increase of radiation levels due to **luminosity boost**
- ✓ More **challenging access conditions** → impact on interventions.

New HL-LHC galleries

Accurate FLUKA geometry of the "as-built" HL-LHC galleries at Pt.1 and Pt. 5.

A number of studies developed for the new HL-LHC galleries at Pt. 1 & 5 such as **air activation**, **shielding requirements**, **dose during an emergency** evacuation via the LHC tunnel, and more → List in backup.

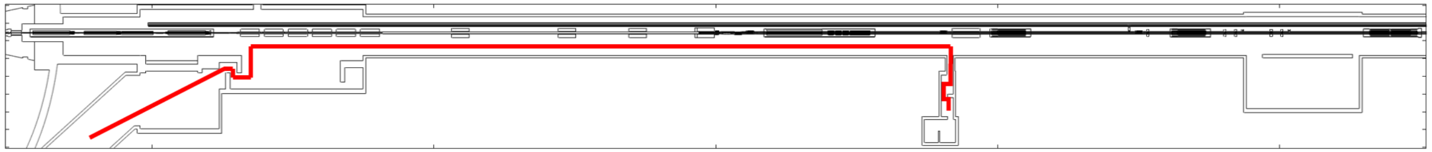


FLUKA model of HL-LHC infrastructure at Pt. 1 (right)
__Highlighted__: new HL-LHC underground infrastructure, as built during LS2.

Cumulated effective dose E (µSv) for different cooling times and walking speeds. Run 3 operation, rounded numbers.

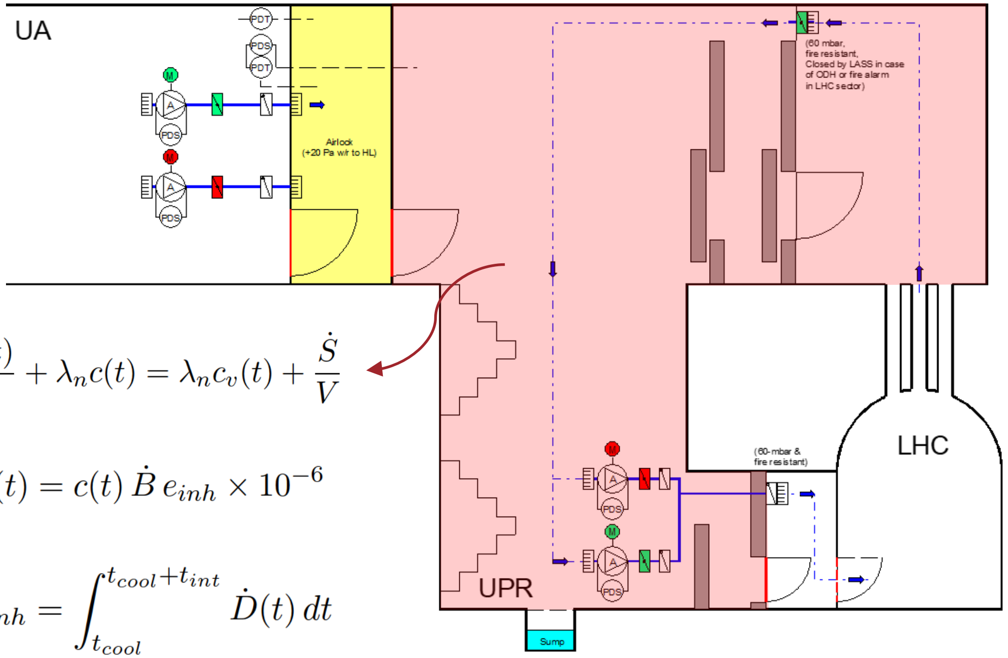
		Walking speed [m/s]					
		0.25	0.5	0.8	1.0	1.5	3.0
Cooling time	1 min	49	24	15	12	8	4
	2 min	45	22	14	11	7	4
	5 min	38	19	12	9	6	3
	10 min	33	17	10	8	6	3
	15 min	31	16	10	8	5	3
	30 min	28	14	9	7	5	2
	60 min	23	11	7	6	4	2

EDMS 2719989



Sketch of the escape path in right LSS1 (UPR17 via PM15) as implemented in Flair's WDP planner.

Air activation in the HL-LHC galleries



$$\frac{dc(t)}{dt} + \lambda_n c(t) = \lambda_n c_v(t) + \frac{\dot{S}}{V}$$

$$\dot{D}(t) = c(t)\,\dot{B}\,e_{inh} \times 10^{-6}$$

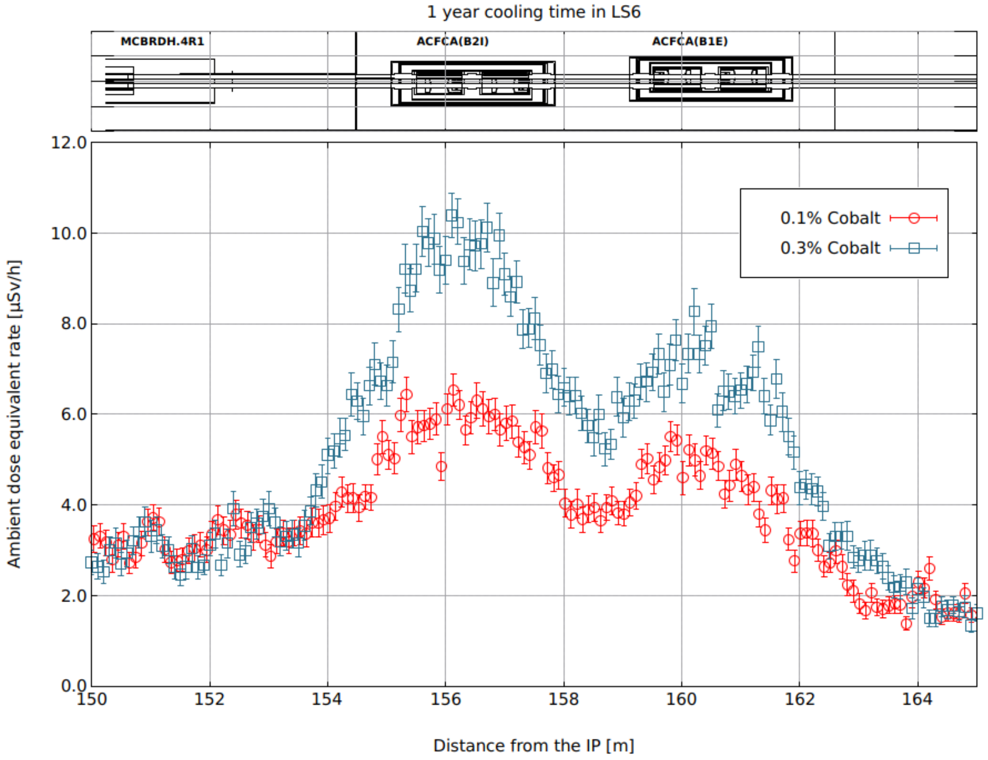
$$D_{inh} = \int_{t_{cool}}^{t_{cool}+t_{int}} \dot{D}(t)\,dt$$

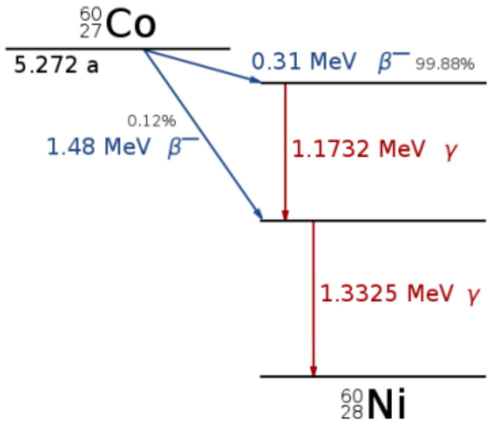
$$D_{inh_{tot}} = \sum_{j=1}^{R} (D_{inh})_j$$

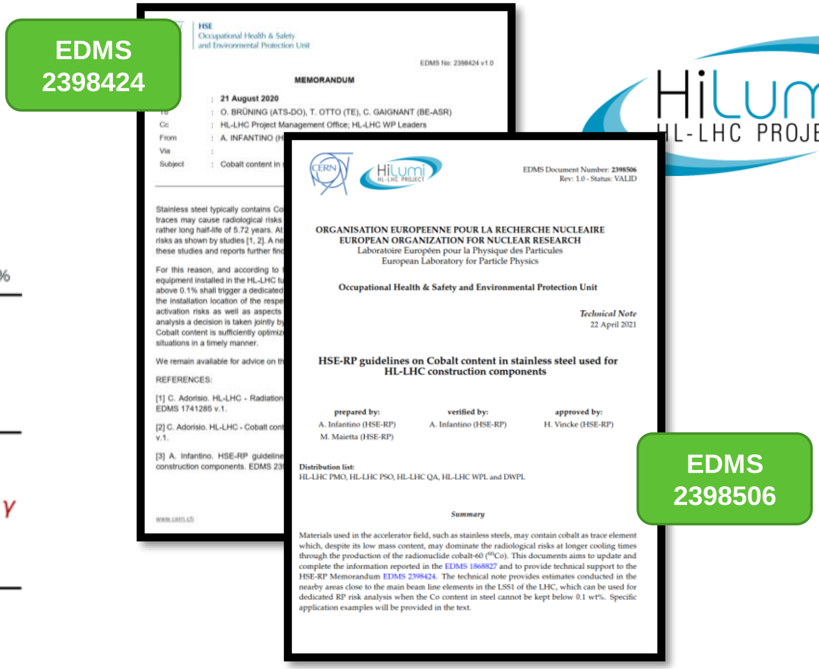
EDMS 2489958

- Final ventilation configuration (HL-LHC): complex ventilation model (**loop**) with radioactive air injected in a activation-free area (EDMS 2416918).
- **Optimization criteria**: 1 μSv inhalation dose per 1 hour intervention.
- **Access requirements** to be revised → solution of the ventilation model (considering **effective decay constant**, i.e. ventilation + physical decay) in the UA/UPR volume.
- Assuming HL-LHC ultimate conditions, 1-week of operation, t_{int}=60 min and t_{cool}=30 min → **D_{inh}~1.3 μSv**.
- Waiting time before access from 30 min → 60 min to match the optimization criteria.

^{60}Co HL-LHC: Co content







0.3% Cobalt				
Cooling time	**H*(10) @ 1m [μSv/h]**	**Co-60 contribution to H*(10) [%]**	$\sum_n^{i=1} \frac{a_i}{LL_i}$	**Co-60 contribution to LL [%]**
1 week	6.27E+00	33	1.52E+03	37
1 month	4.65E+00	44	1.41E+03	40
6 months	2.85E+00	68	1.04E+03	51
1 year	2.27E+00	80	8.08E+02	62

- Cobalt content in steel is a **critical parameter** in the design of future accelerators due to the production of ^{60}Co which **can dominate the radiation field** at long cooling times (e.g. > 1y).
- **CERN approach**: guideline value **max. 0.1 wt% Co in steels** based on market survey and radiological study.
- Purchased steel quantity and retrieval through international collaborators are **limiting factors**. In addition Co content typically **not indicated** in the product specifications (minor impurity for the industry).
- HSE-RP conducts **dedicated risk analyses** in case Co > 0.1 wt%.
- Final decision taken together with hilumi management, evaluating **cost-benefit aspects (ALARA)**.

Take home message

Number of studies deployed by HSE-RP in the context of **LS3 preparation and HL-LHC operation**.

LS3 will be **challenging** from RP point of view: working in a **high residual dose rate** environment, **multiple co-activities** to be carried out in the LHC tunnel, **radioactive waste** estimate/sorting.

LS3 **ALARA** optimization:

- Ensuring **adequate cool down**, considering the general LS3 planning/coordination & ion operation;
- **Preparation and optimization** of high-dose activities (WDP);
- **ALARA Level 3** interventions (such as triplet exchange, etc.) need approval from the ALARA committee. Approval has to be received (well) in advance of the start of the work (as for LS2);
- **Remote handling** when possible;
- Integration of **radioactive waste** aspects into shutdown planning is essential → ad-hoc WP15 integration meetings including link persons and RP (AS and RWM) ongoing.
- **Waste treatment** should be considered at the source (e.g. TDE autopsy) for reducing dose to personnel and minimize costs for CERN.

HL-LHC operation will further challenge RP aspects

- Expected **higher radiation levels**
- **New underground galleries** (partially) accessible during operation
- LHC tunnel possibly used as **emergency/escape path**
- **Ventilation** between HL-galleries and LHC tunnel
- Other ongoing studies on TDE, collimators, etc

HSE
Occupational Health & Safety
and Environmental Protection unit

ANGELO INFANTINO

CERN HSE-RP-AS
@ angelo.infantino@cern.ch

BACKUP SLIDES

Reference list (Technical Notes)

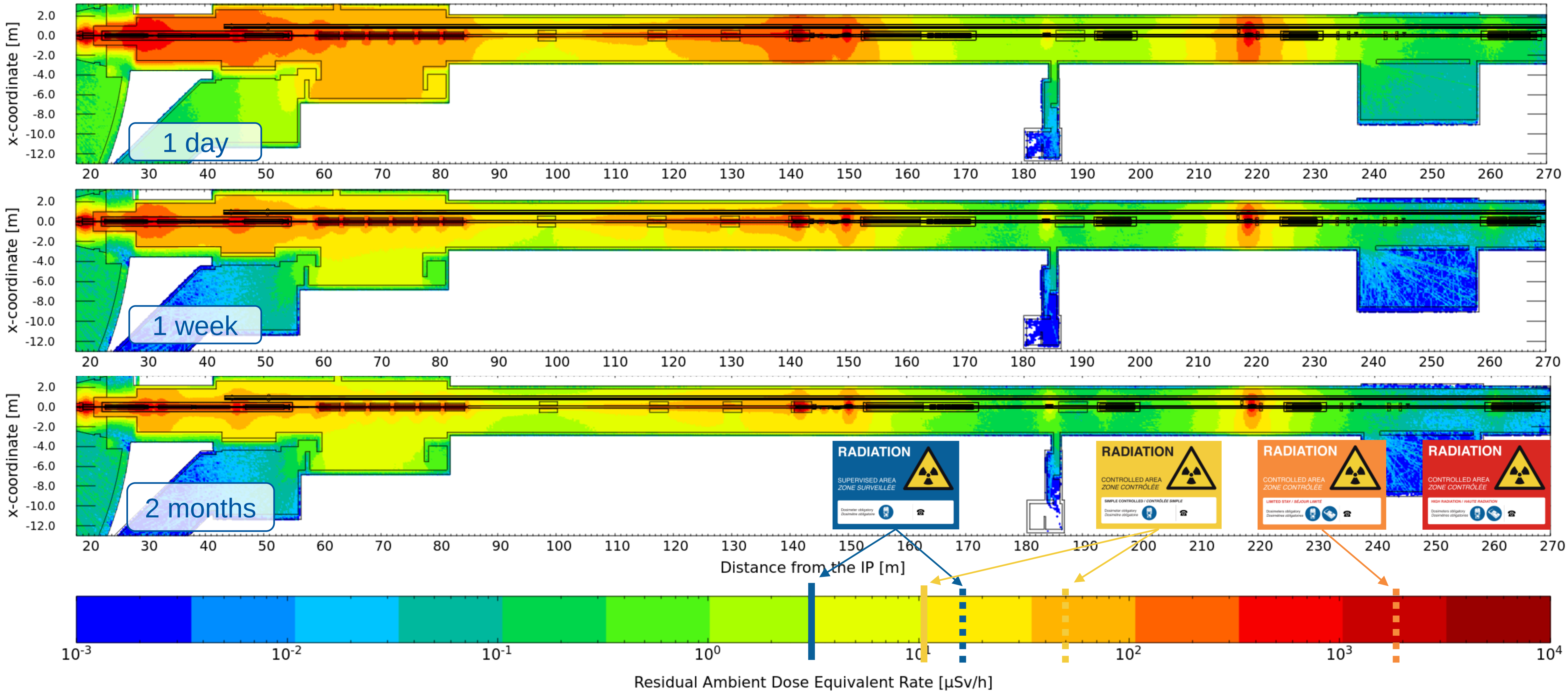
EDMS Id	HSE-RP Technical Notes relevant for HL-LHC
2159991	HL-LHC TDIS: Evaluation of the residual dose rates in accidental scenarios
2212147	HL-LHC UPR underground galleries: review of the ambient dose equivalent rate during operation
2212244	HL-LHC TAXN: shielding requirements verification
2339490	List of RP-related HL-LHC Technical Notes (in-work)
2489958	Ventilation model for the LHC and HL-LHC operation
2719989	Estimate of the individual effective dose during the evacuation from the HL-LHC underground galleries via the UPR and LHC tunnel
2435122	Radiation Protection estimates for LS3 activities in LHC LSS1 and LSS5
2649832	Radiation protection studies relevant for the LS3 TAN upgrade: usage of the existing shielding and preliminary considerations on the worksite
2398506	HSE-RP guidelines on Cobalt content in stainless steel used for HL-LHC construction components
2405113	Radiation levels in HL-LHC LSS1 and LSS5: update to optics v1.5
2641646	LHC and HL-LHC luminosity and irradiation profiles for Radiation Protection studies
2773825	Radiation Protection assessment of the activated collimators in the LHC Upgrade (in-work)

Reference list (Presentations)

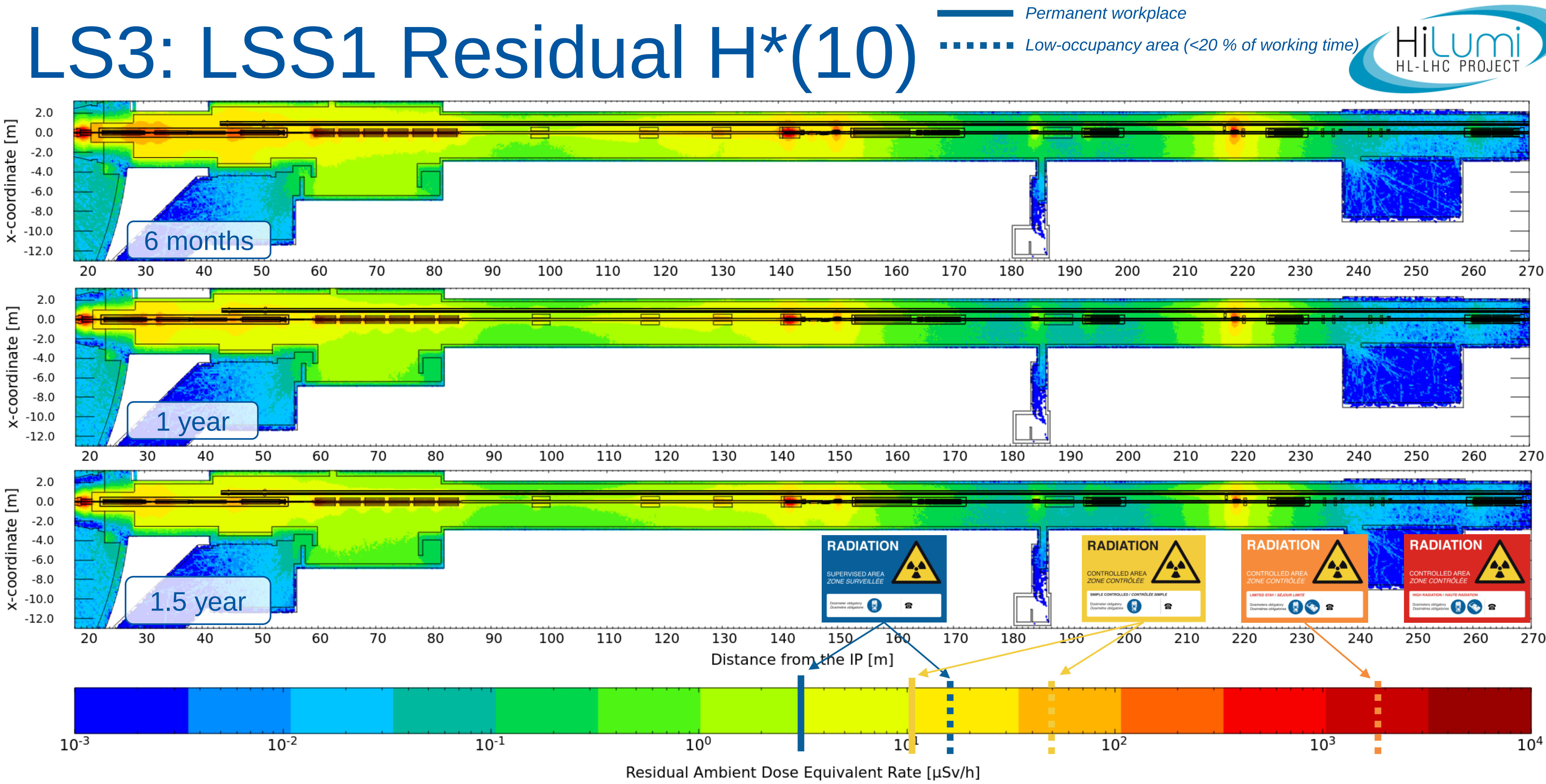
EDMS Id	HSE-RP Presentations relevant for HL-LHC
2195180	HL-LHC TDIS: Residual Dose Rate Estimation
2216246	HL-LHC UPR underground galleries: review of the ambient dose equivalent rate during operation
2220425	HL-LHC alignment: preliminary RP considerations
2248866	Overview of the radiation levels (RP and R2E) in the HL-LHC UPRs/UAs underground galleries
2256546	HL-LHC TAXN: RP considerations on shielding requirements
2331769	RP-recap of the residual dose rates in the HL-LHC LSS 1 and 5
2339827	List of RP-related HL-LHC presentations
2403936	New TAXN shielding design for ZDC operation: radiation levels and preliminary considerations
2467997	Radiation protection studies on the HL-LHC TAXN design and optimization
2683459	HL-LHC LS3 Radiation protection aspects in IP1 and IP5
2748377	Expected residual dose rates in LSS1/LSS5 during HL-LHC
2749148	Radiation levels relevant for the HL-LHC TCLM in LSS1 and LSS5
2725658	RP considerations on the LS3 decabling: activities and samples to be taken during RUN3
2411858	Preliminary RP considerations for LS3 activities
2367047	Overview of radiation levels in the LHC dump area (UD6x) during LS2, RUN3 and LS3
2574668	Preliminary RP considerations on the QRL dismantling during LS3
2435416	Update on Radiation Protection estimates for the HL-LHC project
2513434	Preliminary considerations on collimators dismantling during LS3
2596841	Preliminary RP considerations on the TAN dismantle, storing and upgrade during LS3
2744737	Radiation protection challenges for the Large Hadron Collider upgrade
2513055	RP risk analysis on the Co content for the Crab Cavities cryostat
2416918	Air activation in the new HL-LHC galleries
2773490	Presentation HSE-RP 12th HL-LHC collaboration meeting
2355222	RP considerations on the air activation in the LHC experiments and IT region
2406245	Radiation Levels in HL-LHC UPRs & UAs due to industrial radiographies
2780135	Updated RP studies on the HL-LHC UL shielding requirements

LS3: LSS1 Residual H*(10)

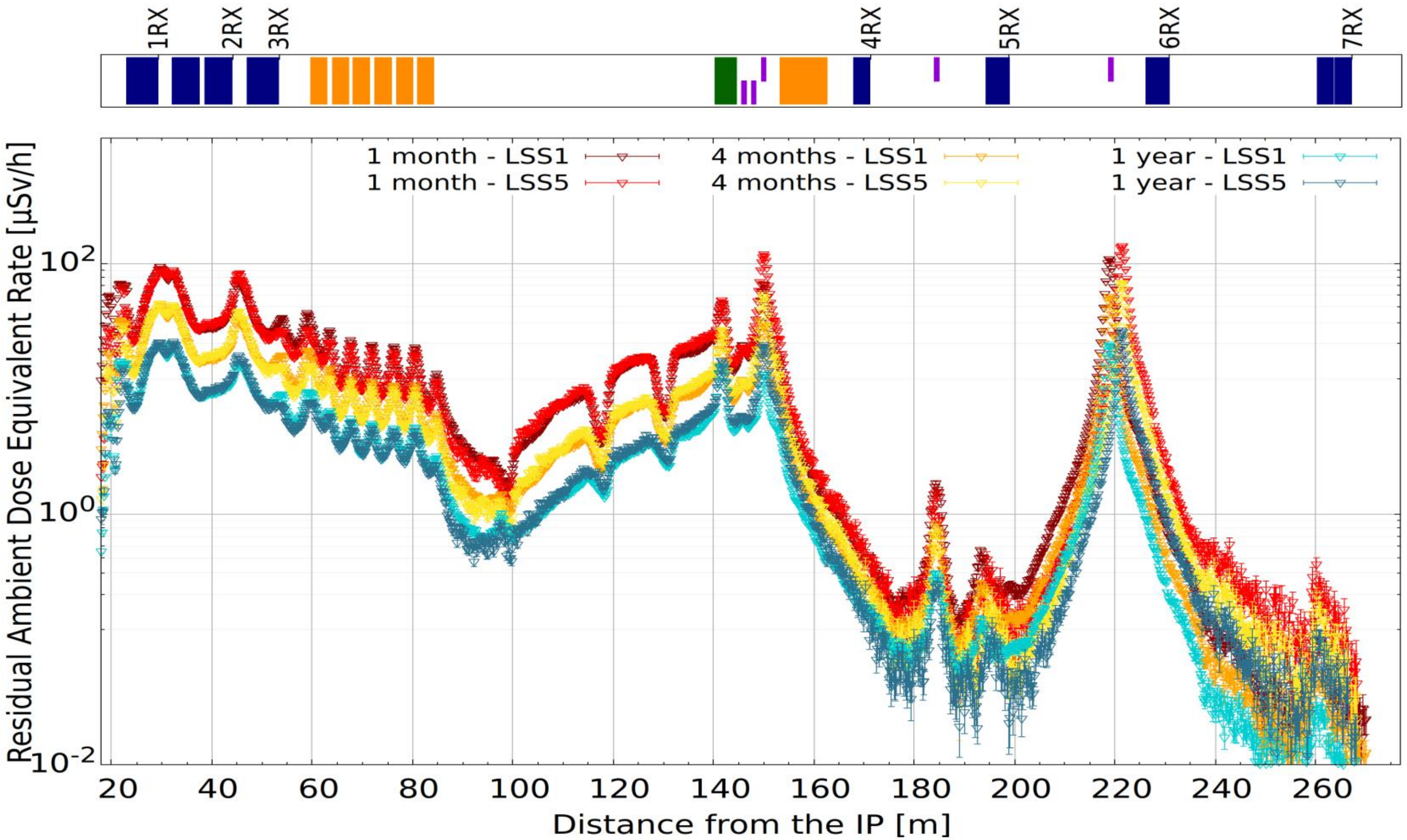
Permanent workplace
Low-occupancy area (<20 % of working time)



LS3: LSS1 Residual H*(10)



LS3: Residual H*(10) LSS1 vs. LSS5

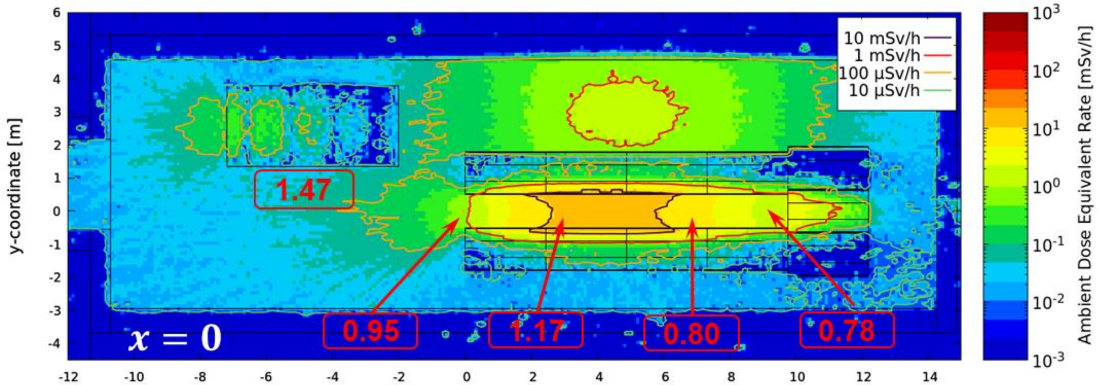


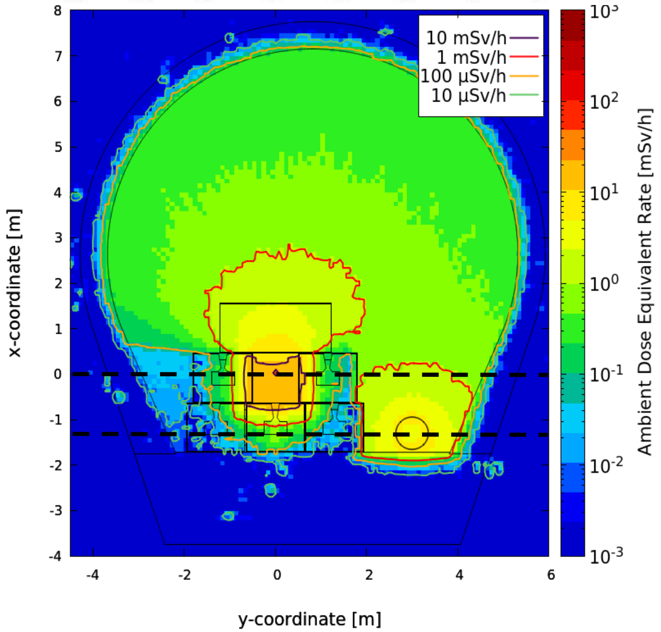
Projected radiation levels at the end of Run 3 proton-proton physics (**working distance**, ~40 cm) for **LSS1 and LSS5**

- Comparison of LSS1 and LSS5
- **Slight difference** due to the different crossing scheme
- **Similar results** in terms of residual radiation levels

FLUKA simulations: operational RP

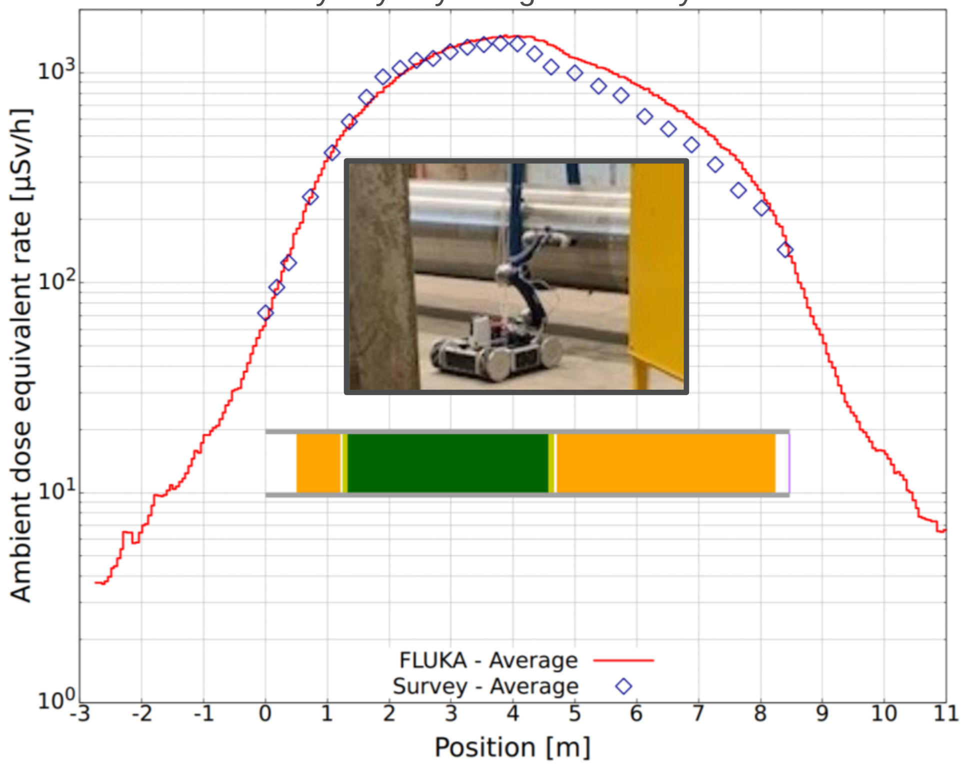
EDMS 2744734





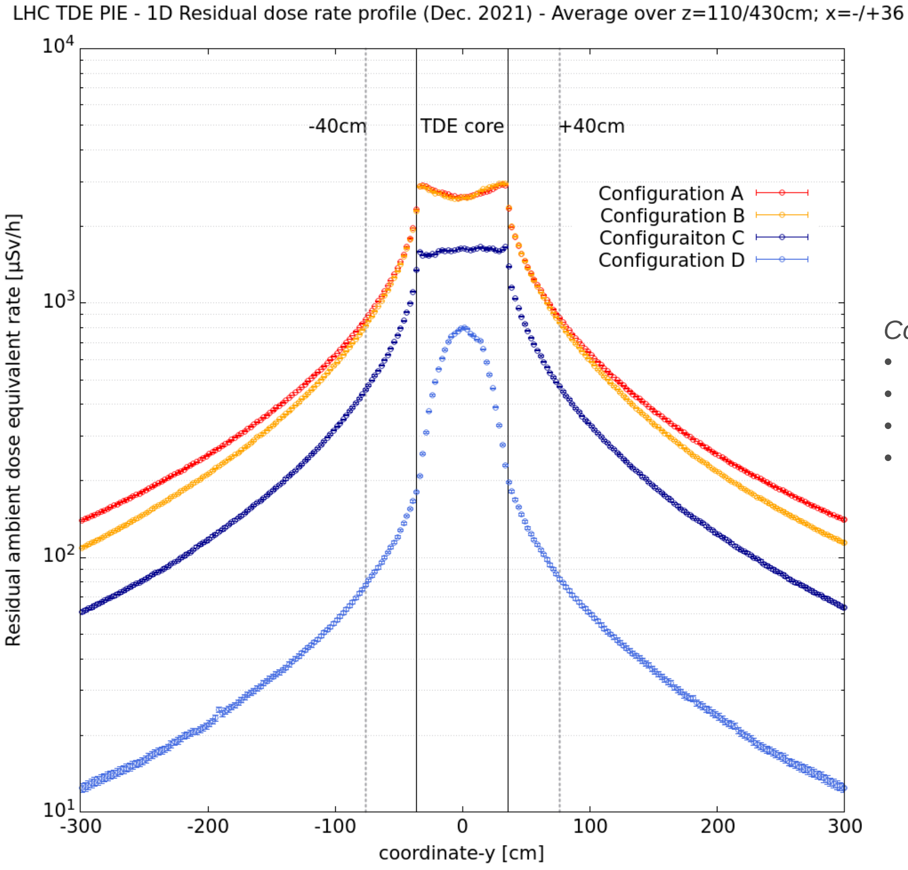
February 2020 – opening of the TDE shielding and RP surveys.

June 2021 –RP syrveys by using a remotely controlled robot

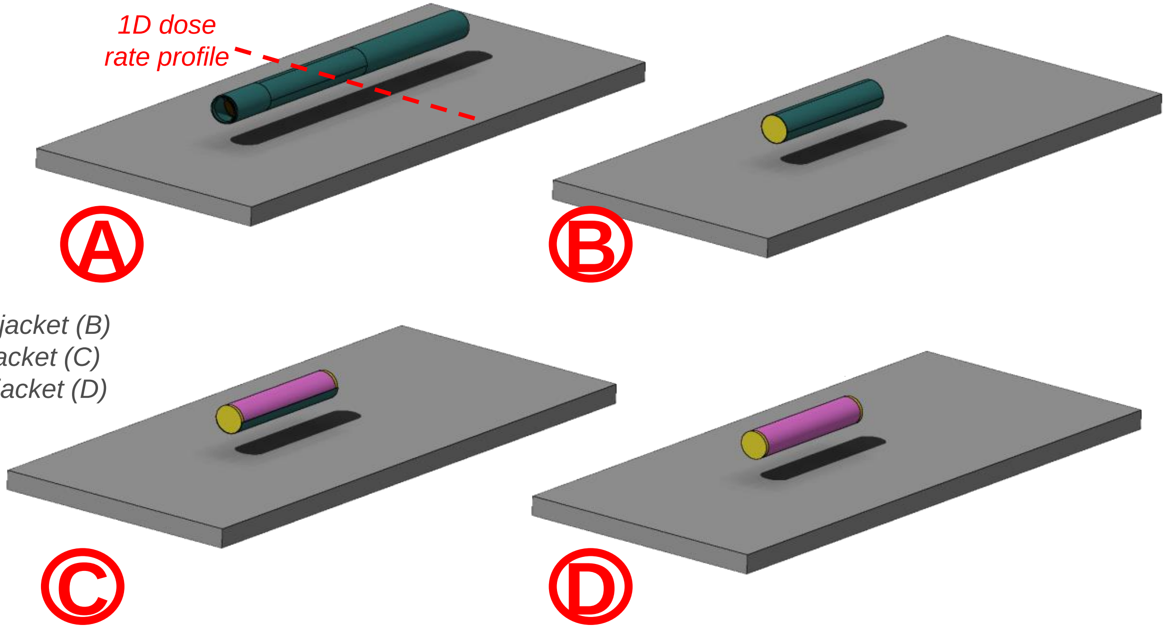


- Combination of **FLUKA-SESAME**, **FLUKA-FCC** simulations to extend built-in FLUKA capabilities and to study residual dose field and activation in complex geometries.
- Cross-validation with measurements within **± 20%** (average).

FLUKA simulations: TDE autopsy sequence



EDMS 2744734



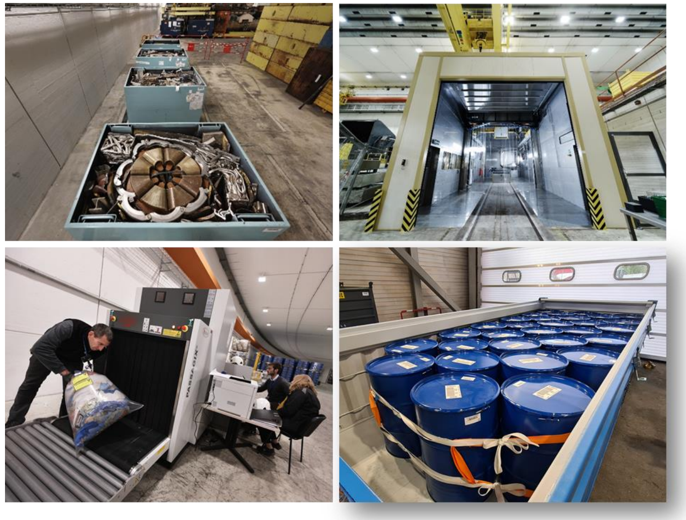
Configurations evaluated:

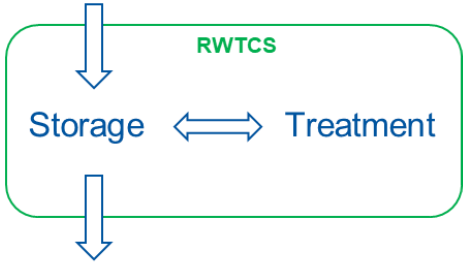
- *Entire TDE core (A)*
- *LDG section + full steel jacket (B)*
- *LDG section + ½ steel jacket (C)*
- *LDG section + no steel jacket (D)*

- **FLUKA-SESAME** simulations allowed to optimize (**ALARA**) the cutting sequence (**full 3D simulations of different steps**).
- **Work-Dose Plan** based on cross-validated FLUKA simulations.
- WDP: initial estimate 4.8 mSv.man collective dose; 550 µSv max individual dose -> after intervention **4884 µSv.person & 508 µSv (final 2920 µSv.person; 255 µSv)**.

Radioactive Waste Management

- The Radioactive Waste (RW) management at CERN is led by the **Radioactive Waste Management (RWM)** section within the Radiation Protection (RP) group.
- CERN operates a **Radioactive Waste Treatment Centre (RWTCS)** inside the former accelerator tunnel of ISR which is also used as interim-Storage for Radioactive Waste pending disposal.
- **Waste pre-conditioning** (sorting, etc) is needed → e.g. LHC TDE
- Radioactive Waste produced from CERN activities are sent to the RWTCS to get processed, packed, characterized and finally disposed.





Stored waste (31.12.21)	Volume (m3)
Clearance candidates	1604
TFA	3881
FMA	340
Total	5824
Percentage of storage space	60%

CERN Radioactive Waste disposal pathways

- ✓ From 2010, **tripartite agreement** between CERN and Host States, represented by **Swiss Federal Office of Public Health** (OFSP) and the **French Nuclear Safety Authority** (ASN) -> link
- ✓ "**Fair Share**" principle revised in March 2022, with three indicators: the volume eliminated, radiotoxicity and elimination costs.
- ✓ With these indicators, it will now be possible to better compare and measure the share between the two Host States

CERN RW classification	Disposal pathway
Clearance candidates – **CL** (Candidats à la Liberation Inconditionelle)	Release from regulatory control in **Switzerland** (clearance ↔ "free release")
Very Low-Level Waste – **TFA** (Très Faibles Activités)	Surface disposal in **France**, as defined by the acceptance criteria of the ANDRA CIRES repository.
Intermediate & Low-Level Waste – **FMA-VC** (Faibles et Moyennes Activités a Vies Courtes)	Short-lived intermediate and low level waste, half-life <30 years. Surface disposal in **France** as defined by acceptance criteria in ANDRA CSA repository.
Intermediate & Low-Level Waste – **FA-MA** (Faibles Activites et Moyennes Activités)	Intermediate and low-level waste which does not fulfil the FMA-VC criteria and disposal in Switzerland (PSI).

Context and FLUKA modelling

Several RP studies in the past considering HL-LHC conditions and different cores layout → 2x80 cm shielded doors.
RP memo EDMS 2281996 on activated excavation spoils.

Aim: verify RP constraints if the **cores are partially excavated during Run 3** (e.g. EYETS).

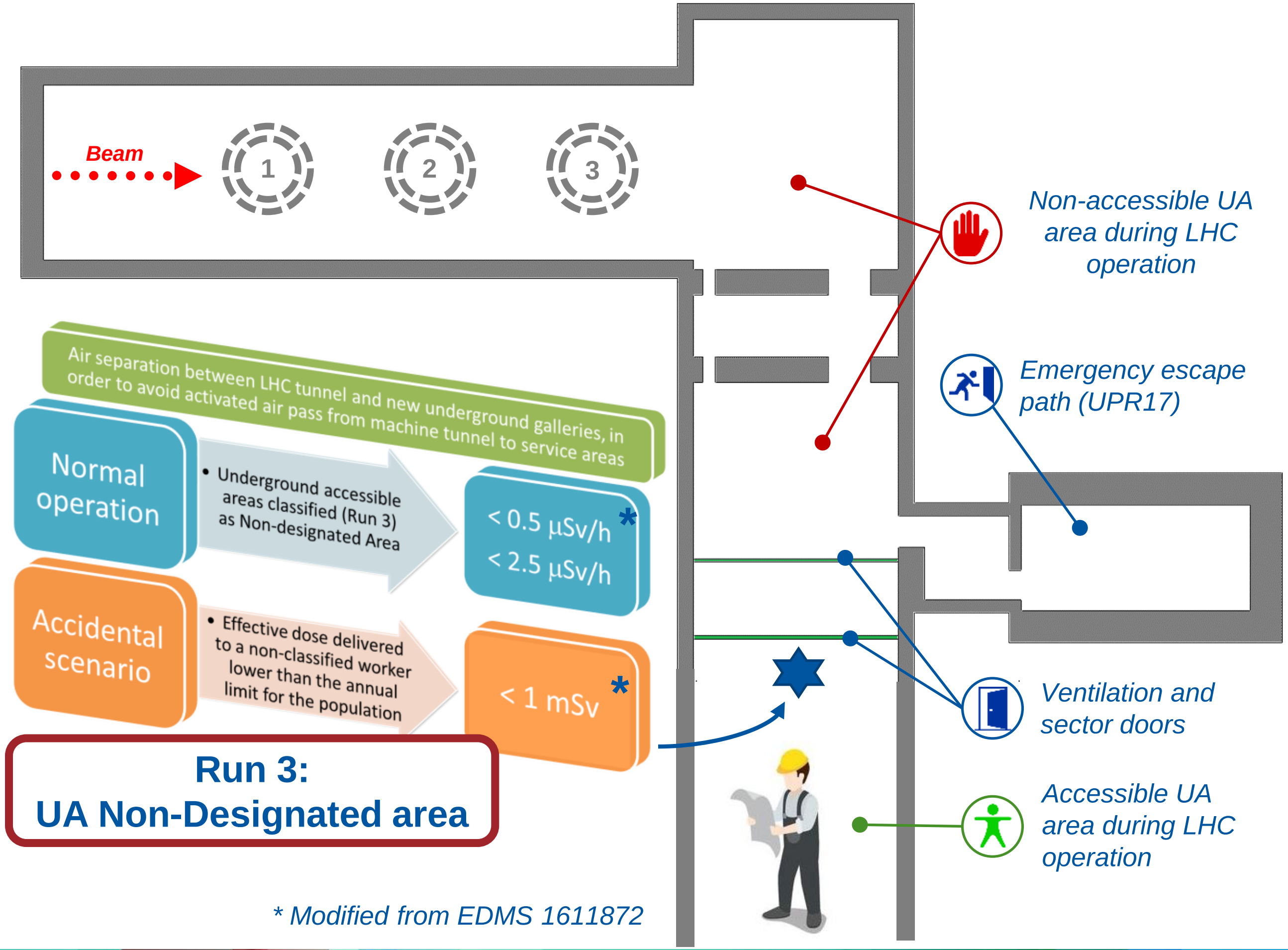
LHC Point 1 geometry: **UA17 + LHC tunnel** from 130m to 190m from IP1. Main outcome applicable to all UAs.

Run3 beam conditions: Beam 1, E_{beam} = 7 TeV protons, 2748 bunches, 1.8E11 ppb.

Excavation scenarios: average rock thickness from the LHC vault of 150/300 cm → preliminary assumptions.

Accidental scenario: **loss of the LHC beam** below the 2nd or the 3rd core (i.e. on the MBRC.4R1 or MCBYH.4R1).

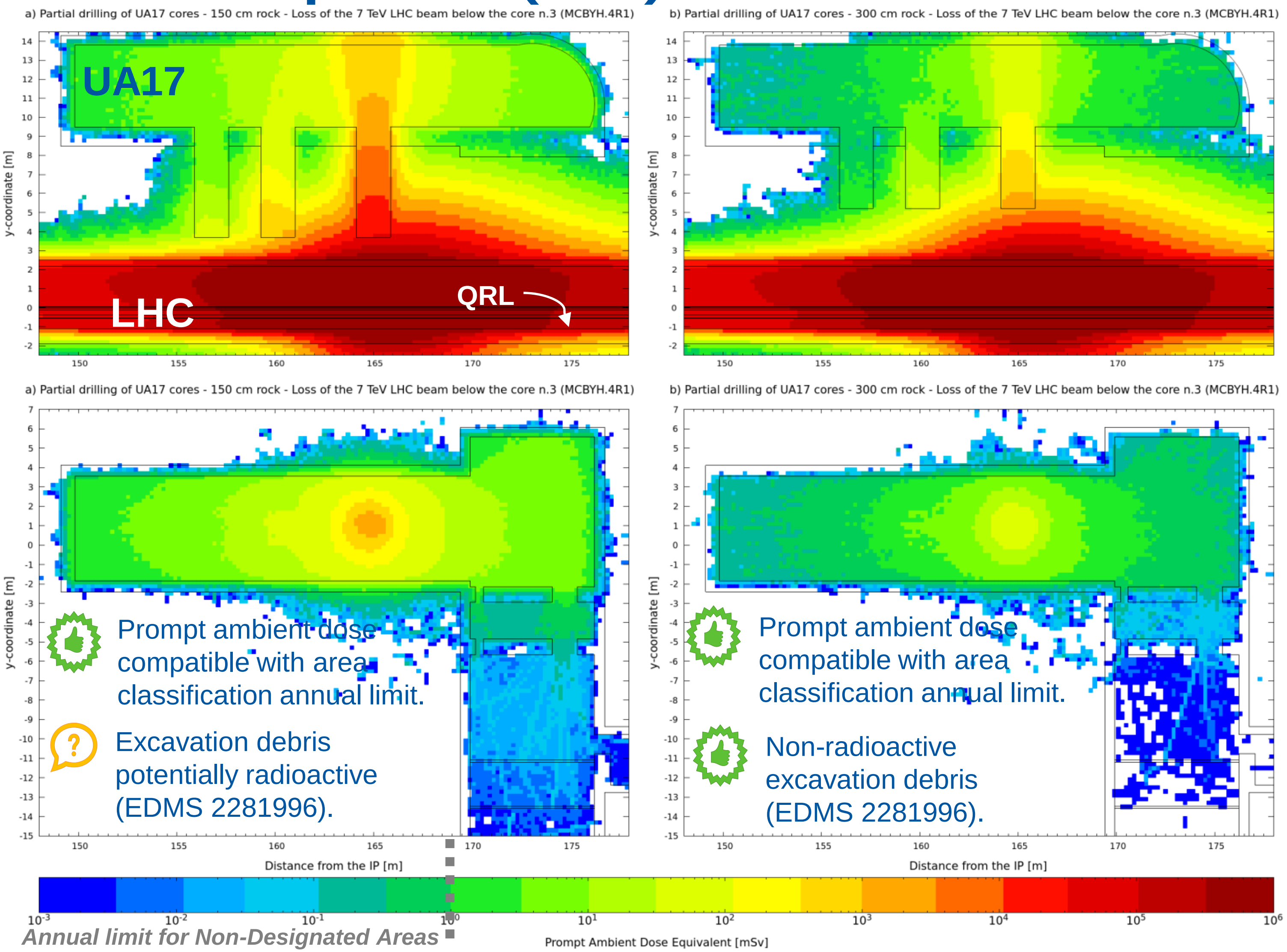
No shielded doors in the UA → The presence of the shielded doors ensure the respect of the dose limits when the cores are fully excavated (see **EDMS 1611872**).



* Modified from EDMS 1611872

Prompt H*(10)

Excavation scenarios: average rock thickness from the LHC vault of 150/300 cm.

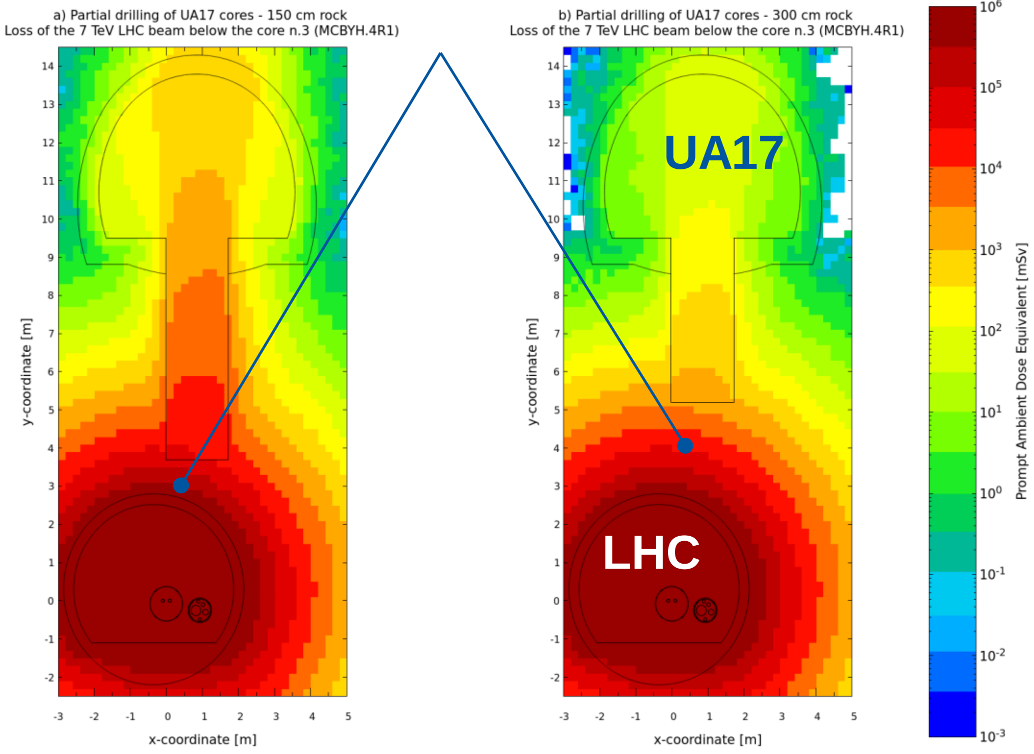


Prompt ambient dose compatible with area classification annual limit.

Excavation debris potentially radioactive (EDMS 2281996).

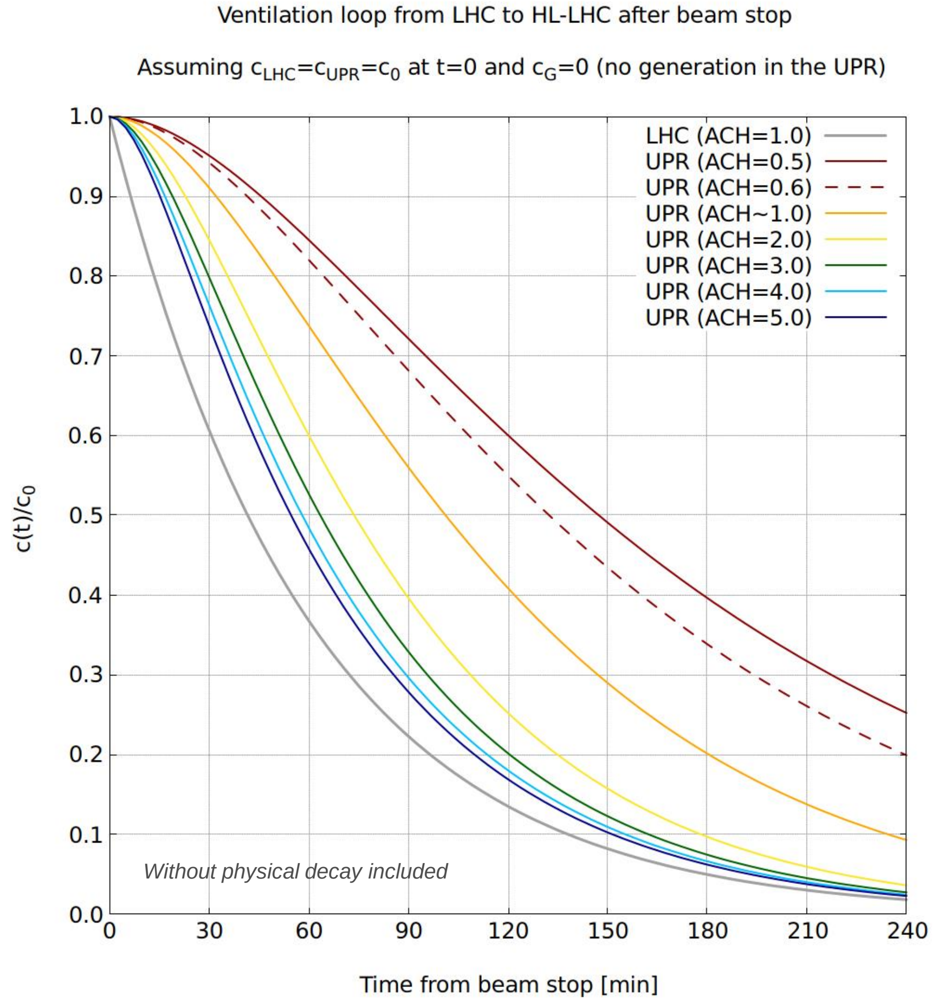
Prompt ambient dose compatible with area classification annual limit.

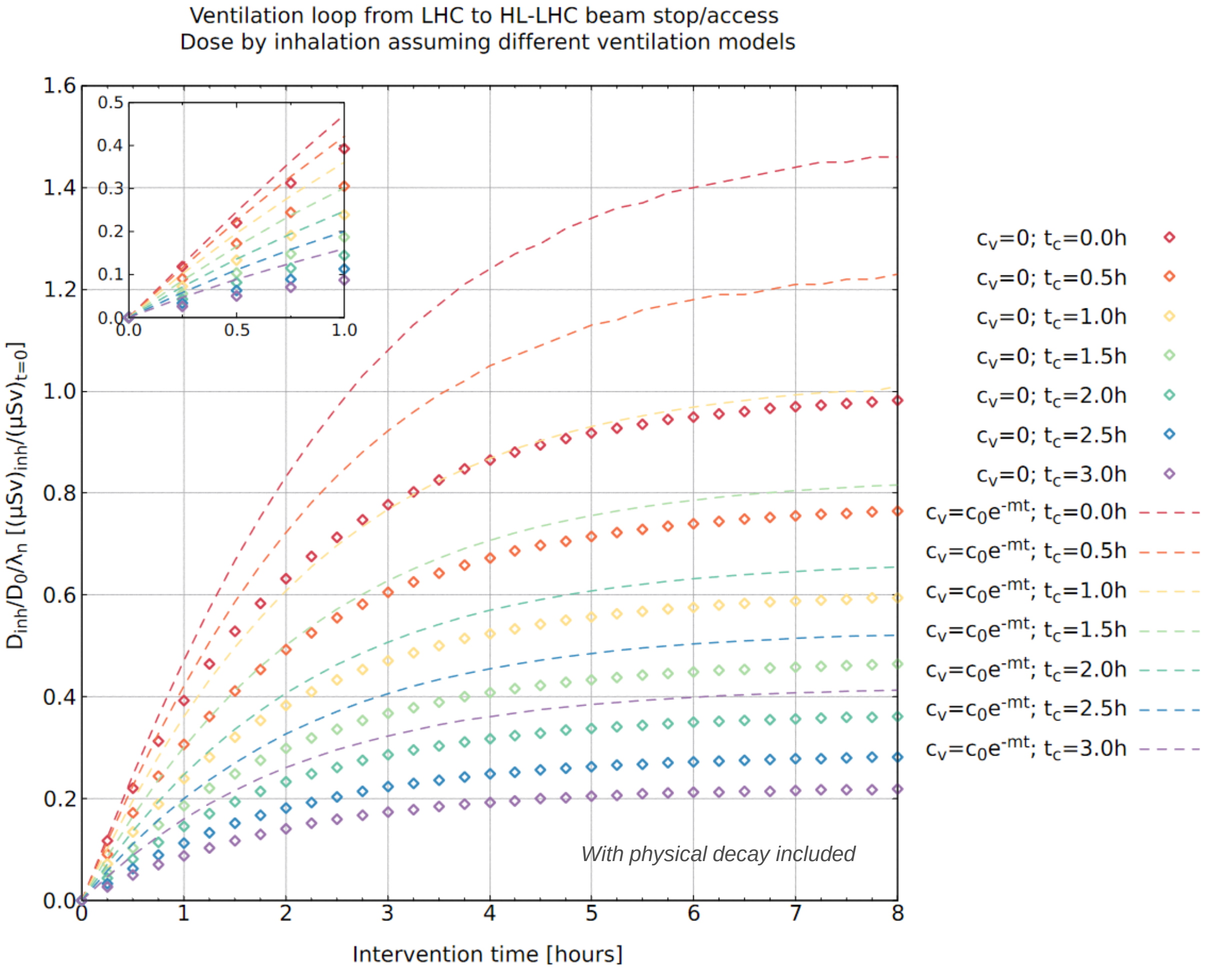
Non-radioactive excavation debris (EDMS 2281996).



Note:
- Expected prompt ambient dose rate **<<1 µSv/h** at the sector door location (transmission factor ~10^{-8})
- **Similar considerations** can be made for the **ULs** (based on UL shielding simulations not presented here)

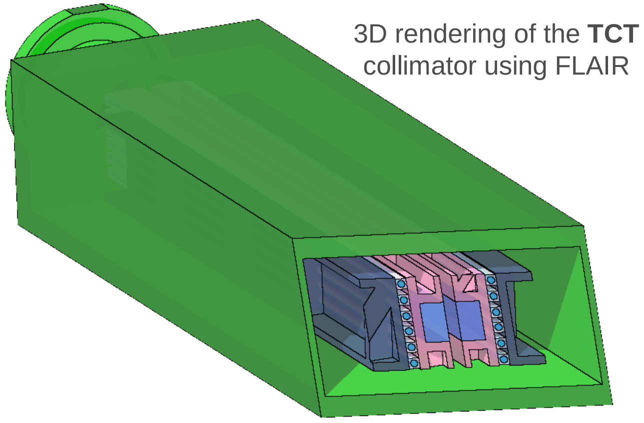
Air activation in the HL-LHC galleries





HL-LHC collimators:

- Update of EDMS 2280338
- FLUKA-RP simulations to compare different materials for collimators, considering a generic loss term → impact of a 7 TeV proton beam
  - tungsten alloy (Inermet180),
  - copper–diamond (CuCD),
  - molybdenum alloy containing Ti and Zr (TZM),
  - molybdenum carbide – graphite (MoGr).
- Work ongoing



3D rendering of the **TCT** collimator using FLAIR