Updates on an

Advanced Radiation Dose Estimation Tool for the Decommissioning of High Energy Physics Experiments

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EP-DT
Detector Technologies

The University Of Sheffield.

ATLAS EXPERIMENT

Overview

- **The need for a (better) Dose Estimation System**
  - Previous experience in preparing dose estimations for the DIMR
- **Concept of a novel Dose Estimation System**
  - Based on existing CERN standards & commercial solutions
- **First Experience with the Dose Estimation Tool**
  - Planning for ATLAS Inner Detector Decommissioning
- **Re-Implementation and Improvements** (v2)
  - Making the tool better maintainable and improve functionality
- **Outlook**
  - Adaptation for other use cases and
    considerations for higher radiation environments

Why we need a (better) Dose Estimation Tool ?

Work in Radiation Environment

- Any service work or de-installation of tracking detector components after their exposure to accelerator beams will have to be carried out in an radiation environment due to the possible activation of the components
- **Work dose planning needed for individual RP assessment according to CERN ALARA rule - long, complex and/or high dose rate interventions**
  [EDMS 1751123 Section 5.1, see backup slides]
  - DIMR included into the IMPACT declaration for your work
    (Dossier d'Intervention en Milieu Radioactif)
    - Description of the work, the duration, possible contamination due to cutting/grinding of activated components…
  - **Dose planning** needed for people involved in the work,
    both each **individual dose** and the **collective dose** for the whole project.
- **FLUKA simulations of radiation environment are provided by HSE-RP**
- **Position of people and duration of tasks need to be known !**
  - In case of a non-uniform radiation fields,
    this can be hard to determine correctly

ALARA Classification (CERN)

Individual dose equiv.	Level 1	100 μSv	Level 2	1 mSv	Level 3
Collective dose equiv.		500 μSv		5 mSv	

Ambient dose equivalent rate	Level 1	50 μSv/h	Level 2	2 mSv/h	Level 3
Airborne activity in CA		5 CA		200 CA	
Surface contamination in CS		10 CS		100 CS	

For Large LHC Experiments

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[8]	*Mandatory* Applicant[9]	*Mandatory* Applicant[8,9,10]
	provides dose rates	RPE and RP[11]	RP	RP
	DIMR level	RPE and RP[11]	RP and RPE[9]	RP and RSO
	Documented work optimization process	*Optional* RPE	*Mandatory* RP and RPE	*Mandatory* Applicant and RPE and RP and RSO
Inform PCR (if applicable)		on request	Yes	Yes
Approval		RPE[9] and RP	LEXGLIMOS and RP[12] and RSO	Complex manager (ALARA-c)
	Veto rights	RP Group leader	Leader of the HSE unit	Director General
Follow up	**Retour d'expérience**	*Optional* RPE[9]	*Mandatory* RP and RPE[9]	*Mandatory* RSO and RP and intervention supervisor
	Closure of WDP	*Optional*: RPE[9]	*Mandatory:* RP	*Mandatory:* RP
	Closure of intervention (DIMR)	RPE[13]	RSO	ALARA-committee responsible[14]
Controls		*Optional* *RPE[9]*	*Mandatory* RPE[15]	*Mandatory* RP and RSO

DIMR = **Dossier d'Intervention en Milieu Radioactif**
RSO = **Radio protection Safety Officer**
RPE = **Radio Protection Expert**

Work in the cavern :
No contamination expected
No airborne activity ->

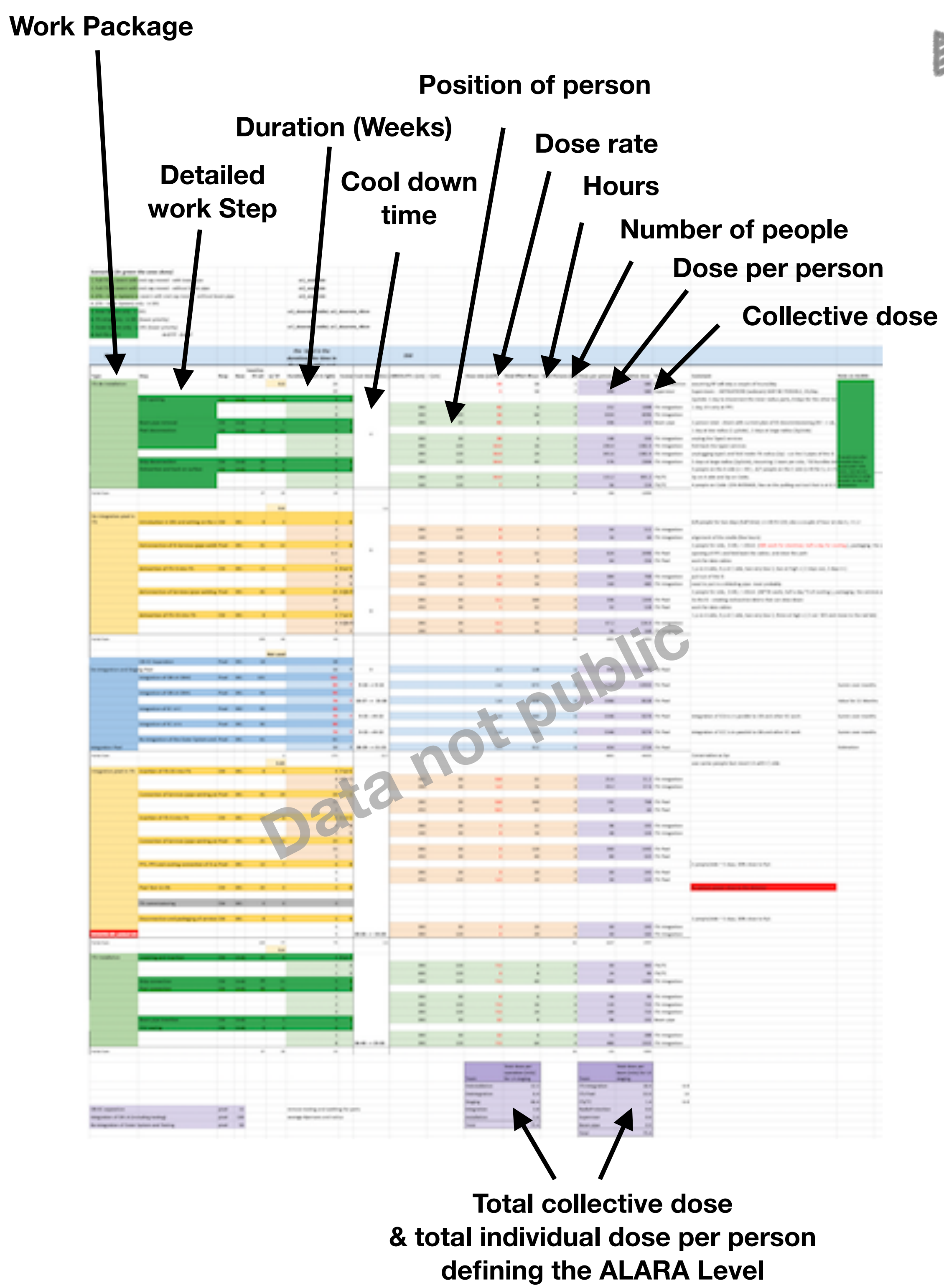
ALARA classification primarily based on ambient dose equivalent (individual and collective)

e.g. for ATLAS ID Decommissioning the ambient + individual dose equiv. would indicate ALARA Level 2, however the collective dose could require ALARA Level 3
(estimation based on experience from Pixel removal scaled with LS3 dose rate maps)

Need for a good and reliable dose estimation !

Good dose maps are not enough - we need to know where people really are during the intervention

Example of a recent dose planing

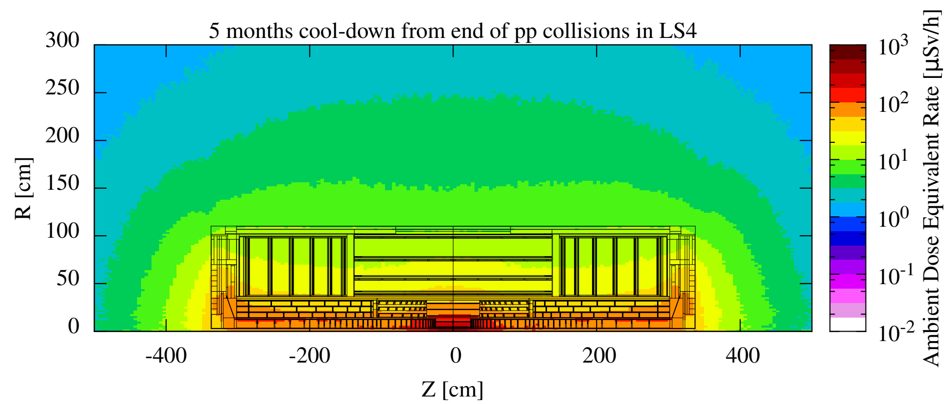


Feasibility study of staging the installation of a LHC experiment tracking detector

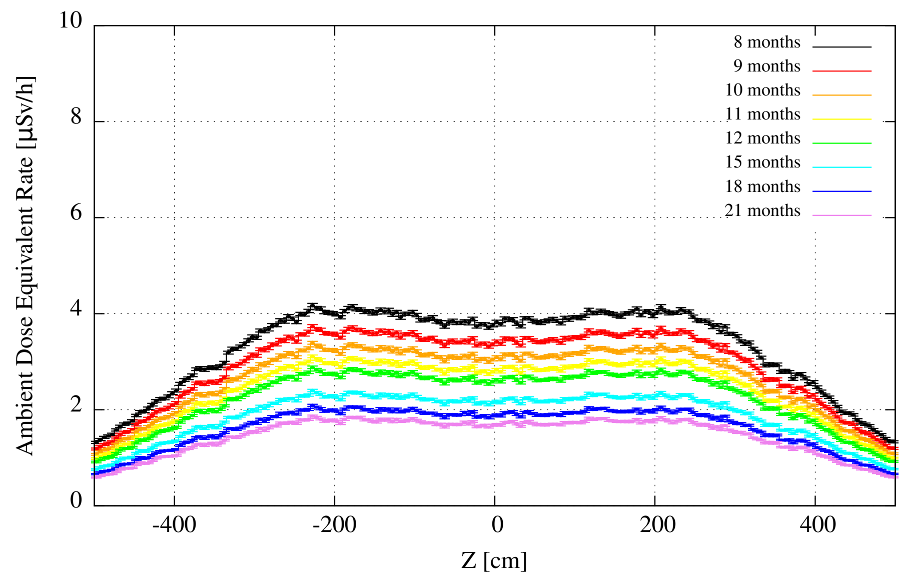
- Question : "Assuming that the detector is not fully finished before LS3 installation, is it feasible to de-install the detector in LS4 and finish it on the surface before re-installing it again ?"
- Different scenarios needed to be analysed for different staging option, leading to very different durations
- Position data (torsos) for each person is collected in the WDP tool inside IMPACT, based on best estimation from project engineer and system experts.
- As procedures get refined and work is optimised, duration and cool down times for **successive steps** keep changing
- Any shift in time needs a complete **- manual -** update of the table.
- Depending on the scenario, estimation were in the range of 30 to 100 mSv collective dose due to the long duration (majority of the work was in a ≤ 5μSv/h environment !)

Data provided by HSE-RP

Dose rate map by radius for a specific cool down time



Dose rate at 40cm for different cool down



Data Tables

R[cm]start	R[cm]end	1m	2m	3m	4m	5m	6m	7m	8m	9m	10m
0E+00	9.1869918699E+00	85.787	63.379	48.576	38.336	31.097	25.907	22.141	19.373	17.311	15.75
9.1869918699E+00	1.837398374E+01	72.31	51.825	38.578	29.611	23.419	19.086	16.018	13.816	12.211	11.02
1.837398374E+01	2.756097561E+01	54.688	40.878	32.545	26.894	22.86	19.897	17.678	15.987	14.675	13.639
2.756097561E+01	3.674796748E+01	51.819	40.036	32.791	27.787	24.152	21.435	19.363	17.753	16.48	15.452
3.674796748E+01	4.593495935E+01	51.488	40.272	33.382	28.597	25.09	22.442	20.401	18.798	17.516	16.472
4.593495935E+01	5.512195122E+01	43.533	34.568	29.095	25.28	22.471	20.338	18.681	17.368	16.306	15.43
5.512195122E+01	6.4308943089E+01	42.999	33.618	28.259	24.624	21.968	19.951	18.38	17.131	16.117	15.279
6.4308943089E+01	7.3495934959E+01	38.665	30.69	26.043	22.86	20.519	18.731	17.33	16.208	15.29	14.525
7.3495934959E+01	8.2682926829E+01	36.96	29.663	25.355	22.35	20.111	18.384	17.022	15.926	15.027	14.276
8.2682926829E+01	9.1869918699E+01	31.989	25.999	22.395	19.875	17.993	16.536	15.38	14.444	13.67	13.017
9.1869918699E+01	1.0105691057E+02	30.717	25.069	21.587	19.124	17.28	15.857	14.734	13.829	13.087	12.465
1.0105691057E+02	1.1024390244E+02	28.522	23.005	19.813	17.609	15.968	14.698	13.69	12.873	12.198	11.63
1.1024390244E+02	1.1943089431E+02	24.72	20.297	17.717	15.923	14.577	13.527	12.686	11.996	11.419	10.927
1.1943089431E+02	1.2861788618E+02	22.282	18.247	15.962	14.39	13.212	12.292	11.552	10.943	10.433	9.9955
1.2861788618E+02	1.3780487805E+02	21.539	17.385	15.156	13.662	12.555	11.692	10.997	10.425	9.9427	9.5291
1.3780487805E+02	1.4699186992E+02	18.552	15.165	13.273	11.977	11.009	10.252	9.6427	9.1404	8.7176	8.3545
1.4699186992E+02	1.5617886179E+02	16.657	13.843	12.224	11.103	10.258	9.5932	9.0535	8.605	8.2241	7.8942
1.5617886179E+02	1.6536585366E+02	15.883	13.147	11.594	10.522	9.7155	9.0824	8.5704	8.1465	7.7877	7.4781
1.6536585366E+02	1.7455284553E+02	14.492	12.112	10.733	9.7661	9.0335	8.4554	7.9863	7.5966	7.266	6.9799
1.7455284553E+02	1.837398374E+02	13.339	11.137	9.8816	9.0063	8.3412	7.8125	7.38	7.0178	6.7084	6.439
1.837398374E+02	1.9292682927E+02	12.51	10.325	9.1072	8.2703	7.6385	7.1381	6.7294	6.3875	6.0955	5.8414

Dose rate(*) calculations around the detector are provided by HSE-RP based on FLUKA simulations

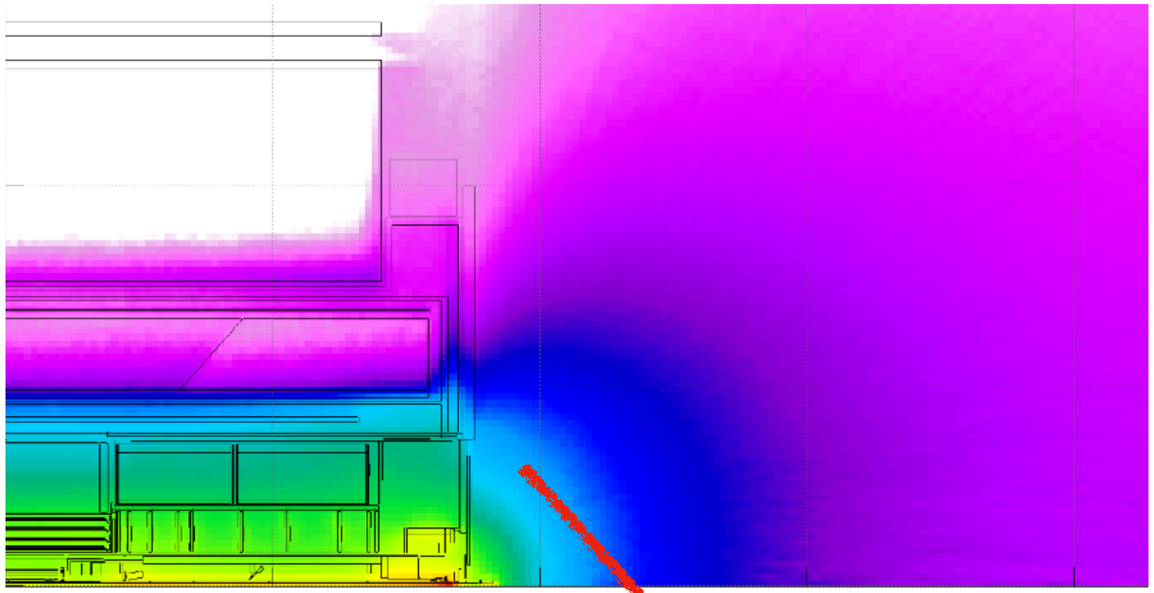
- Provided normally as radial symmetric colour contour plot, 40cm distance (working position) line plots, or raw data files.
- One contour plot for each cool down time, ranging from 1 month to full duration of long shutdown
- Granularity normally around 5-10 cm
- “Manual” lookup from plots, interpolating “by eye”…
- Position data and duration are by far the biggest uncertainty, while FLUKA simulations are now within 20% compared to reference measurements
- Experience from LS1 (ATLAS Pixel repair) show that this type of estimation can be quite off compared to real data collected with the operation dosimeters (DMC) during work (overestimation by a factor of 4 !)
- **We need to be more accurate for higher dose rates !** (especially for LS4 and beyond)

*) Ambient dose equivalent rate in [μSv/h]

Concept for a (novel) dose estimation system

A Dose Estimation System - Concept

FLUKA radiation maps (HSE-RP)



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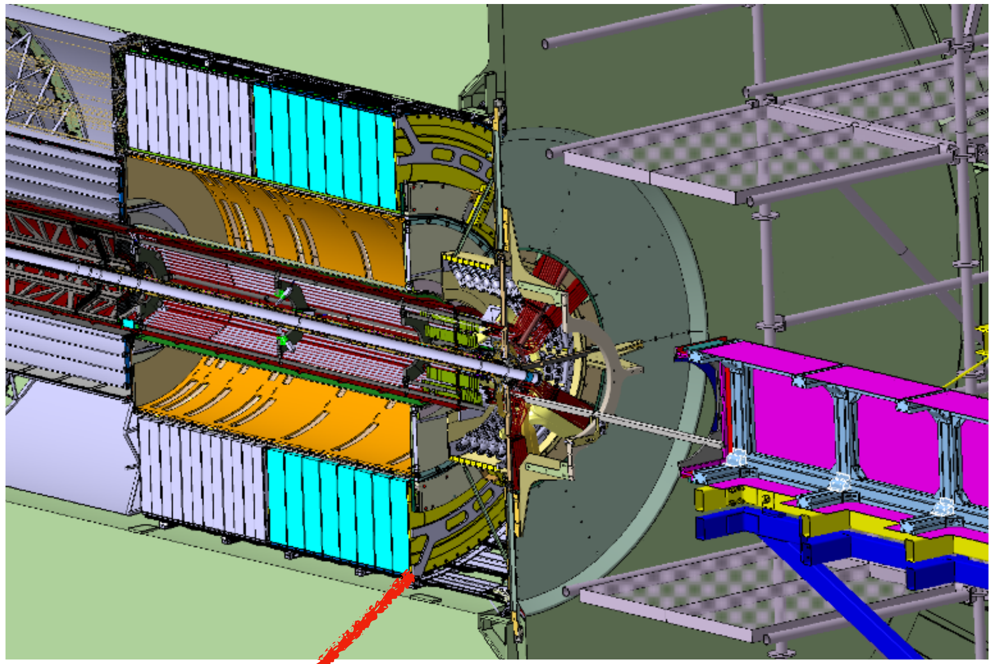
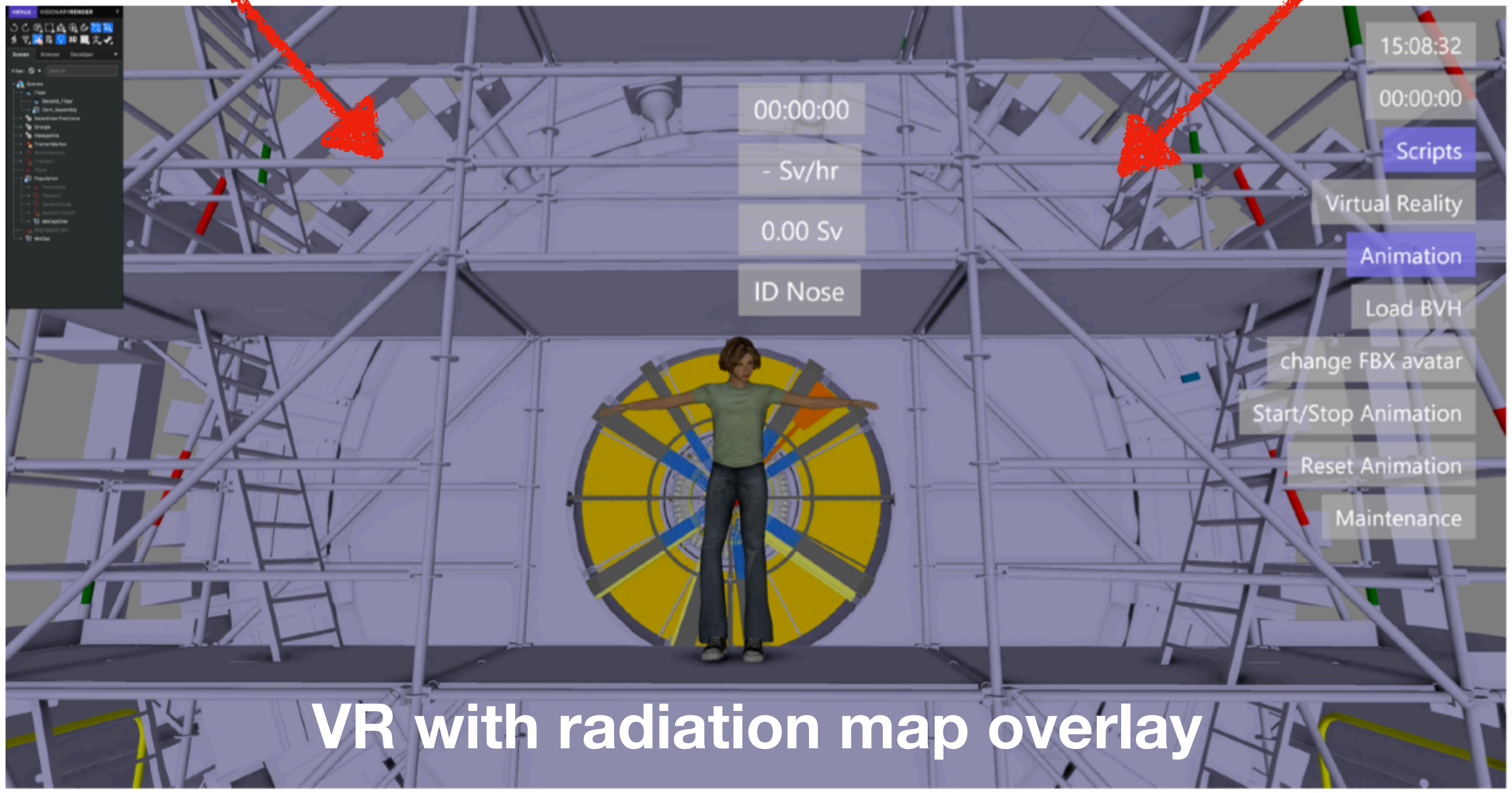
CATIA detailed drawings





Virtalis Visionary Render v2.1.0 / LuaJIT2.0.5 / CATIA exports (.step) / FLUKA export (.csv)

A Dose Estimation System - Concept

- **Converting the CATIA drawing into a Virtual Reality (VR) Suite ✓**
  - Often some cleanup after conversion needed
  - Some reduction in complexity advised (e.g. details of internal components)
- **Conversion from RP files into csv table ✓**
  - Provided by RP, normally no issue, check of correct granularity
- **Still left with the problem of getting correct data on position of persons and duration of tasks ✗**
  - No easy way to estimate the actual duration of any task in VR (removing of components, cutting cables, ….)
  - Exact position of person while working is difficult to get right
  - Moving around in a VR can give you a first estimation of the dose to be expected in environments where the dose doesn't vary significantly locally
- **So, we need another step….**

Need for Real World Mock-Ups !

Mock-Up ID endplate - detail

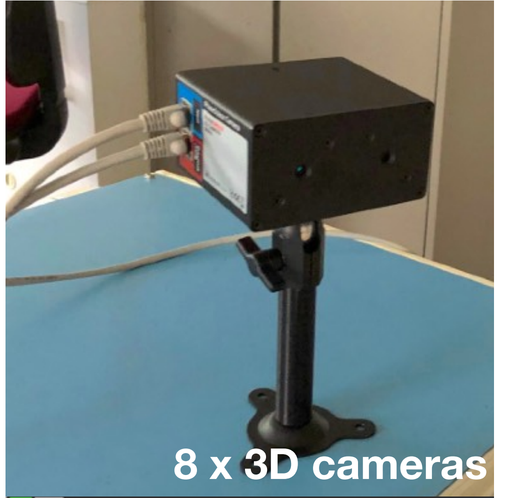
Mock-Up ID endplate

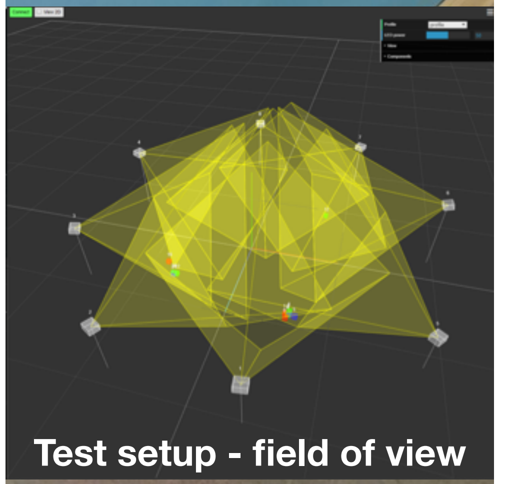
- **Direct training on a very elaborated representation** (here of the ATLAS ID endplate)
  - Created from spare components or components manufactured based on original design drawings
  - Technicians can train each deinstallation steps in safe (non radioactive) environment
  - Direct hands-on training, including alignment & installation of various extraction tools. Cutting cables and pipes in realistic conditions
  - **Actual tools** and transport containers that will be used for de-installation can be tested. Any missing tools or any adaptation needed can be identified
  - Various procedures can be tested for efficiency and de-installation can be optimised
  - **Realistic timing and positioning of people !**

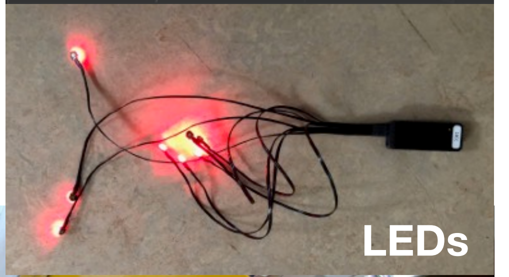
Mock-Up with PIXEL transport frame installed & aligned

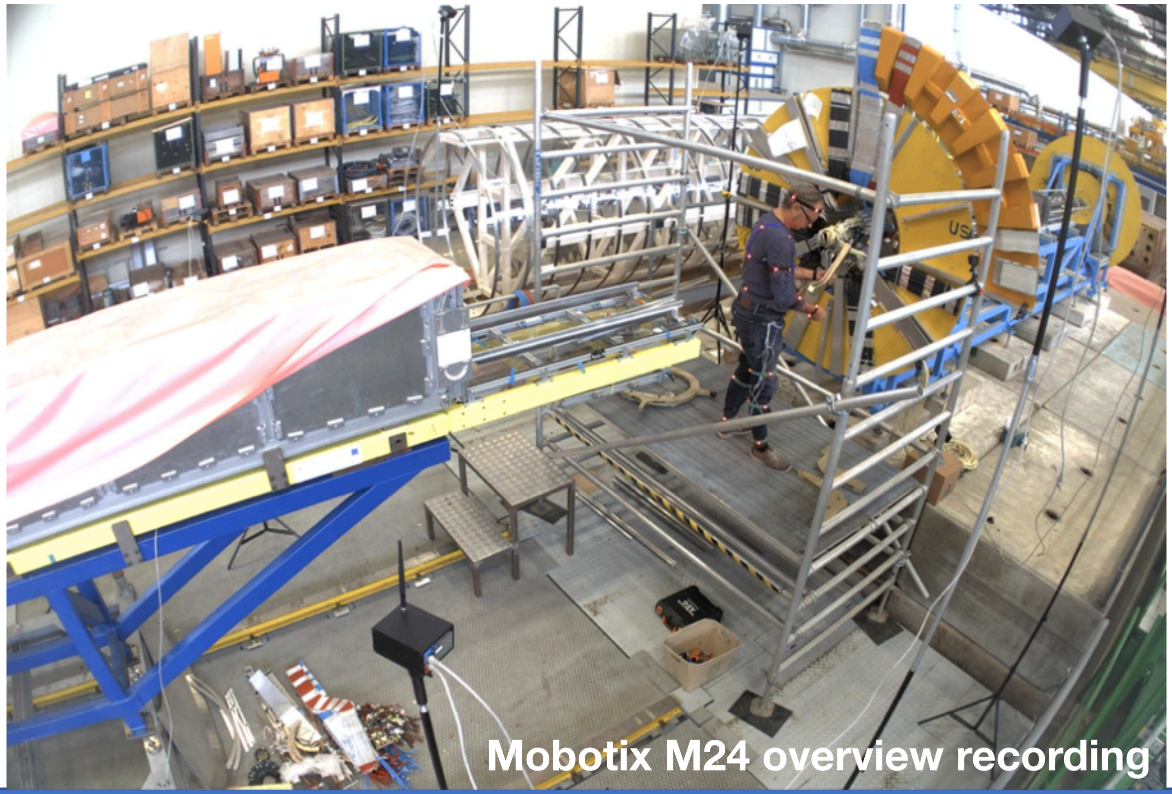
Motion Capture Solution

- **Commercial solution : <u>PhaseSpace</u>** (PhaseSpaceSDK_1_0_9)
  - Due to the challenging environment - where the area of interest is surrounded by reflective metal structure - an optical motion capture system was chosen
  - Based on individually coded LEDs and 3D cameras
  - High quality recording (refresh-rate 960 fps / accuracy ≤ cm)
  - Easily extendable (e.g. cameras and LEDs)
  - Originally rented for first tests, then bought by ATLAS TC
  - Available for use, currently by EP-DT-EO for blimp studies

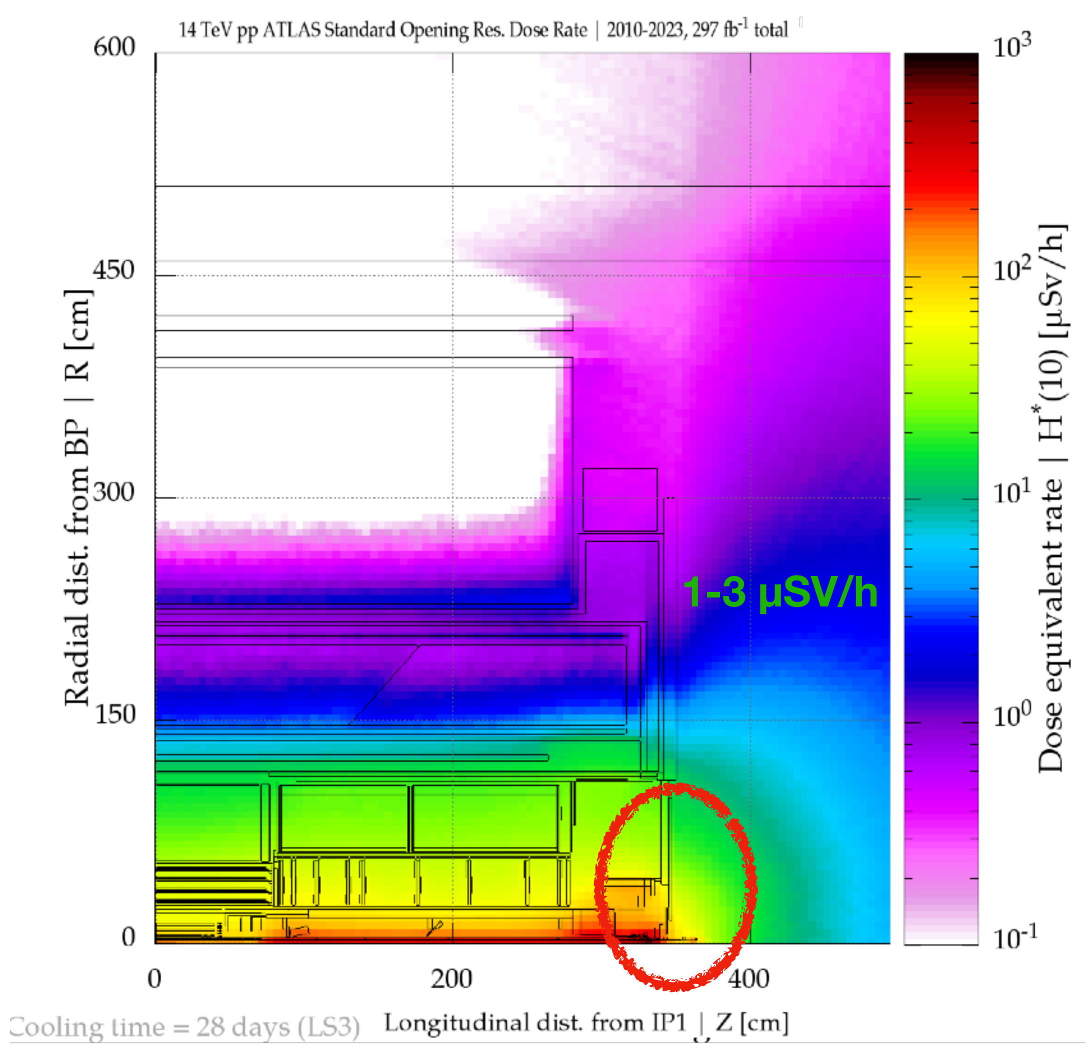




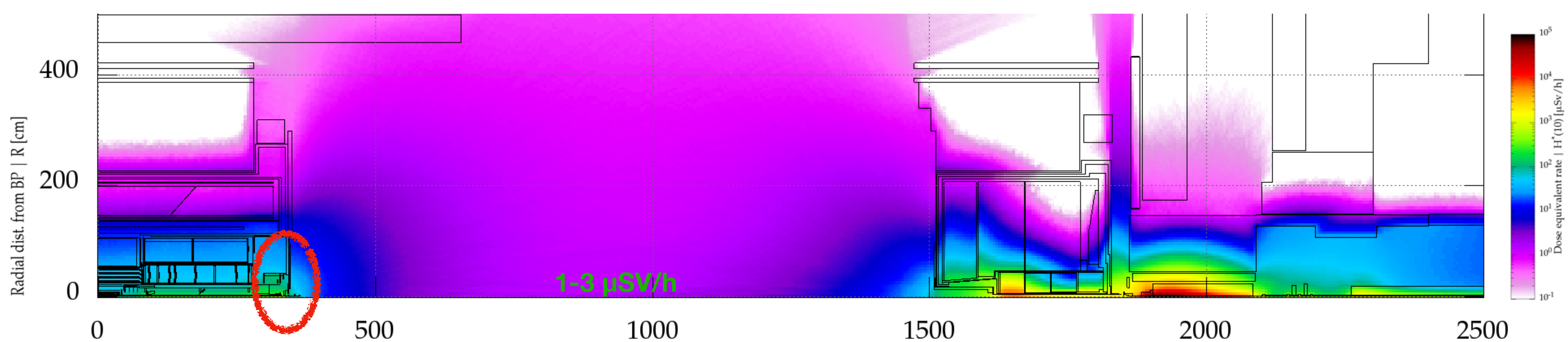




Area to cover with Motion Capture



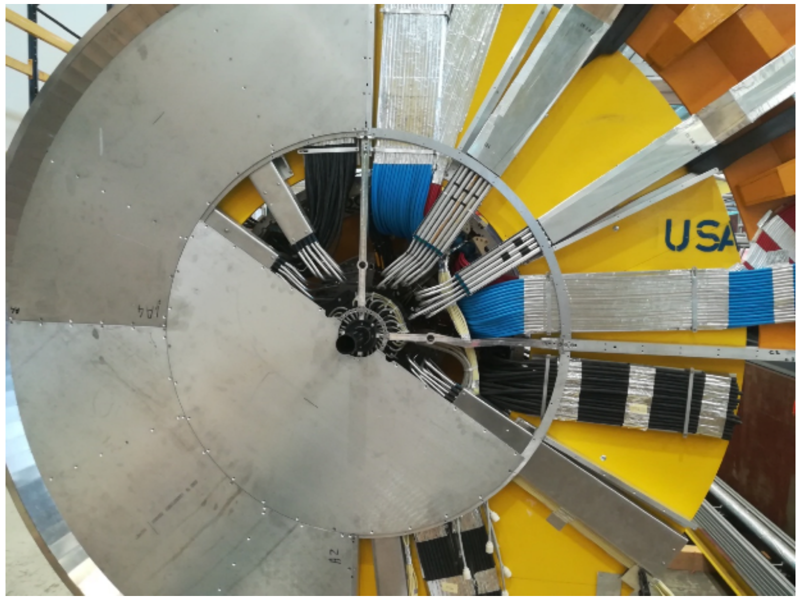
- **We need to cover the area where the dose is relevant for the calculation & where the dose rate is varying significantly within ≈ 1/2 meter**
  - near the beam pipe and inner most tracker, along the ID end plate
- The position in areas with either low dose or relative homogeneous radiation fields can then be added by other means
  - Outer calorimeter decabling
  - Work on the platform ("Mini-Vans")

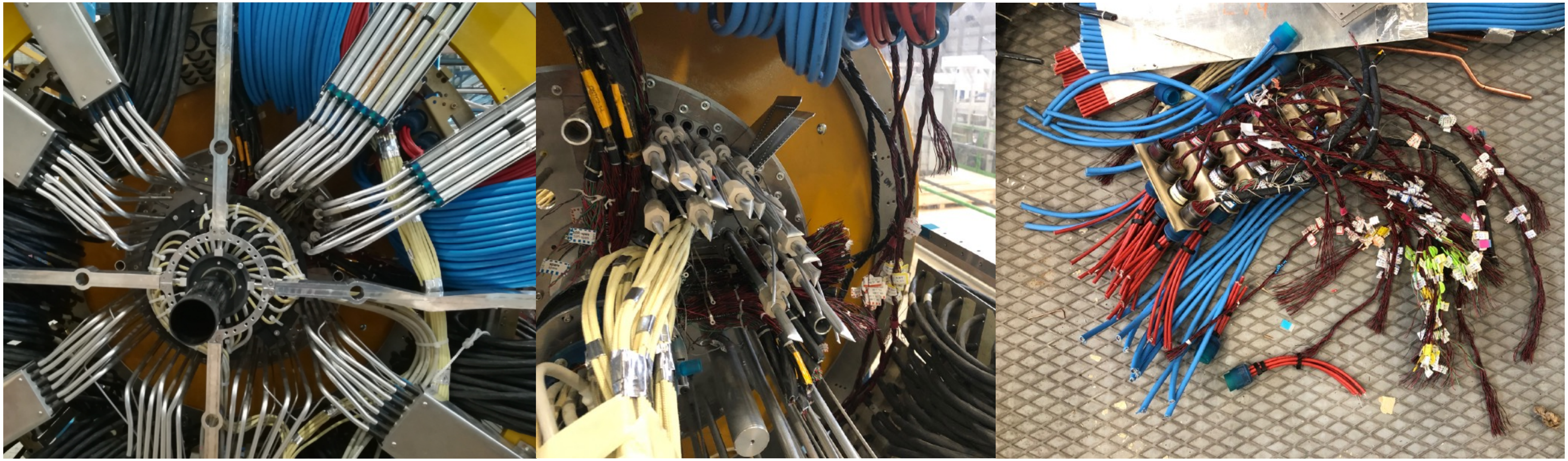


First Experience with the Dose Estimation Tool

Experience with the Dose Estimation Tool

- **Prepared existing mock-up to mimic specific higher dose steps during decommissioning – i.e. work near the beam-pipe**
  - ID End Plate removal (inner)
  - PIXEL electrical and cooling service removal
  - Connection of PIXEL extraction structures
  - Ready for PIXEL extraction
    (dose rate is significantly reduced after PIXEL removal)

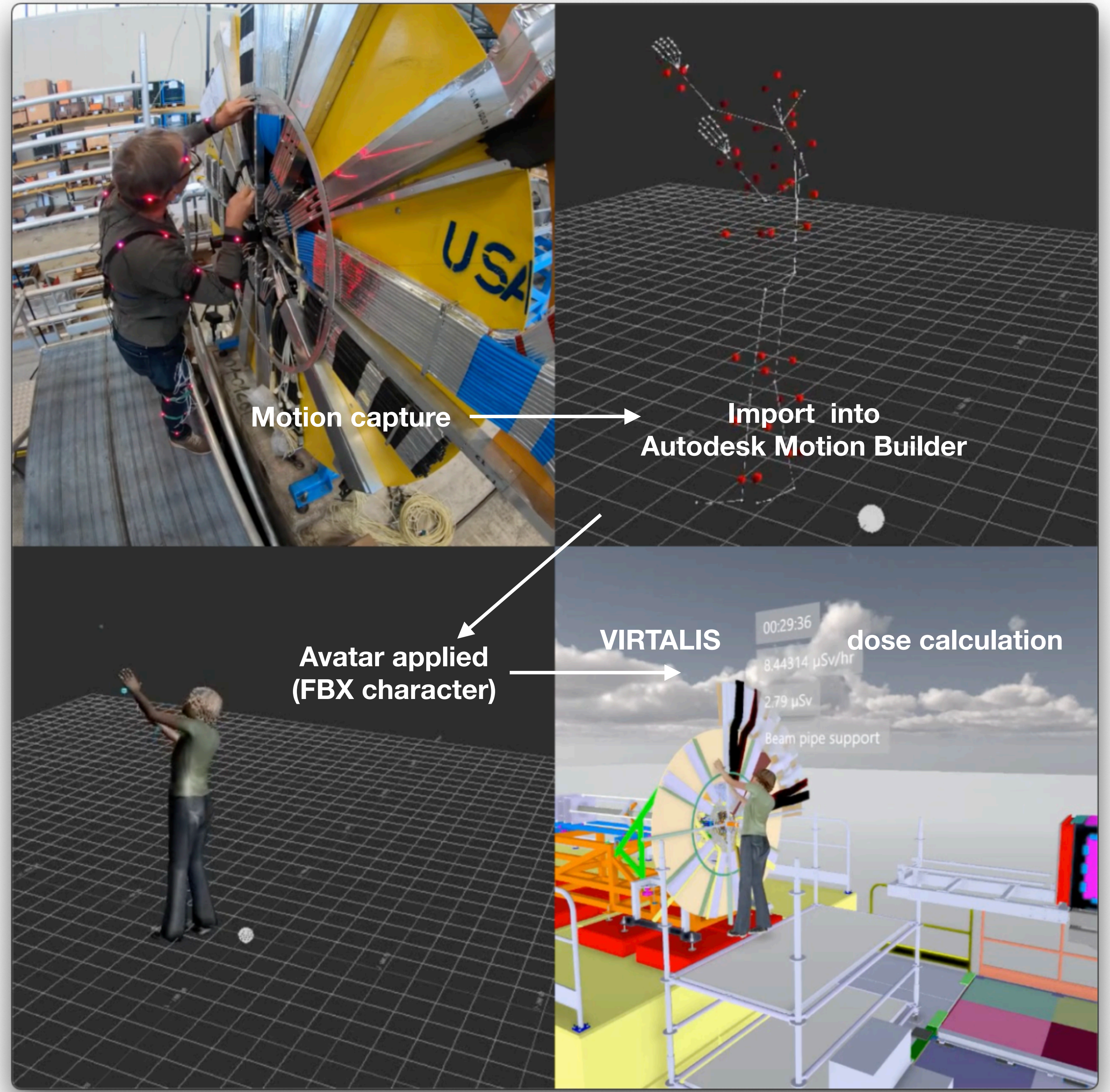




Experience with the Dose Estimation Tool

- **Technicians position during test sequences tracked using motion capture system**
  - Some difficulty with visual occlusions caused by mock-up or scaffolding
    ➔ minimised with multiple LED's per joint and position of cameras
  - No LED's were placed in some positions to reduce freedom, thus detail of hands and neck were not captured
- **Total dose at torso position calculated based on motion data**
  - Imported avatar tracked both instantaneous and accumulative dose
  - Some scaling factors of the avatar need to be introduced – affecting the torso position
- **Tracking of multiple people feasible**
  - Each LED has a unique identification and can be assigned to any position on the body
- **Limited flexibility with the VIRTALIS system resulted in the need for an inter-mediatory conversion of the position data**
  - Autodesk Motion Builder was used to convert the point data to an FBX character
  - The avatar is then imported to the VIRTALIS system

Experience with the Dose Estimation Tool

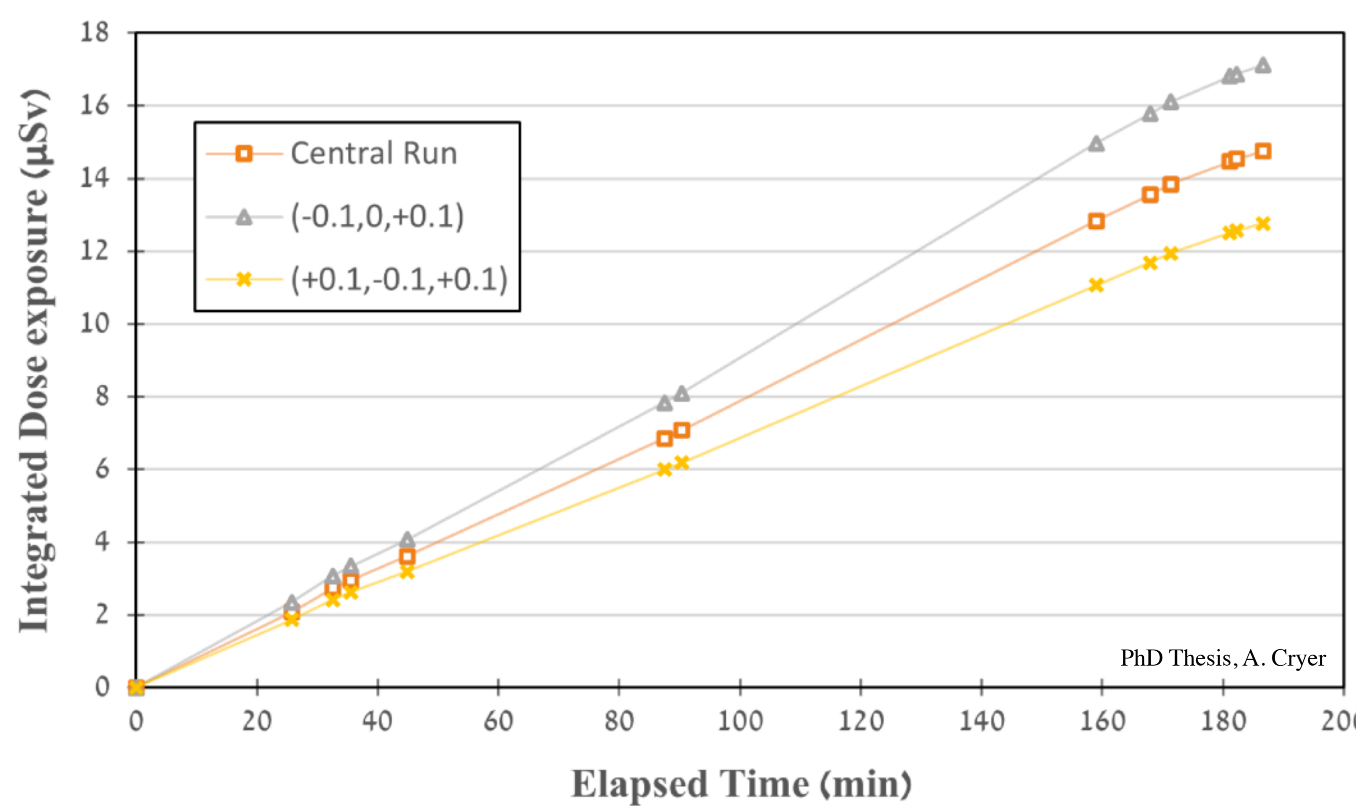


Experience with the Dose Estimation Tool

- **Initial Data collected gives a reasonable estimate for pixel removal based on the comparison data from the ID pixel exchange and scaled radiation fields**

Objective	Steps	Duration hh:mm:ss	Dose Estimate μSv
Remove IDEP	Remove inner IDEP Nose Remove outer IDEP Nose	25:44	[illegible]
Clear BeamPipe/IBL support structures	Remove rad monitor quarter circles, BP support beams, and BP sliding ring	6:49	[illegible]
	Remove outer quarter ring	3:02	[illegible]
Clear IBL and pixel services	Cut IBL services and Remove IBL service guide	9:18	[illegible]
	Remove heater trays and tubing	42:36	[illegible]
	Cut ER bundle	2:48	[illegible]
	Cutting internal Pixel services	1:08:40	[illegible]
Prepare Pixel for extraction	Remove PST seal plate	8:56	[illegible]
	Install PST rail interface	3:23	[illegible]
	Install pixel support ring	9:51	[illegible]
	Install internal transition rails	1:07	[illegible]
	Install intermediate rail and frogs	4:20	[illegible]
	Total	3:06:47	[illegible]

- **Possible to estimate the error in position of dosimeter location**
  - Varying the dosimeter position by ± 10 cm in all directions (x/y/z)
  - From the 27 combinations, we find the extrema for the highest and lowest dose to be within ≈ 15% of the initial position
  - **Reasonable accuracy** for radiation protection simulations



Re-Implementation and Improvements

Dose Estimation System 2.0

- Originally, the VR Suite used was VIRTALIS, for which the university of Sheffield has a licence. However, the project could not easily be transported to another computer or maintained by CERN (no license)
- Decision to re-write the whole project in UNITY (2020.3.30f1)
  - Cross-platform, already validated usage in Windows, Mac and Linux
  - Free for personal use or small companies.
    Eligible if revenue or funding is less than $100K in the last 12 months
  - Widely used in the game industry
  - Readily available documentation
  - Large number of assets and plugins (i.e. live motion capture)
  - **Used by the CERN robotics team** (BE-CEM-MRO)

Unity®

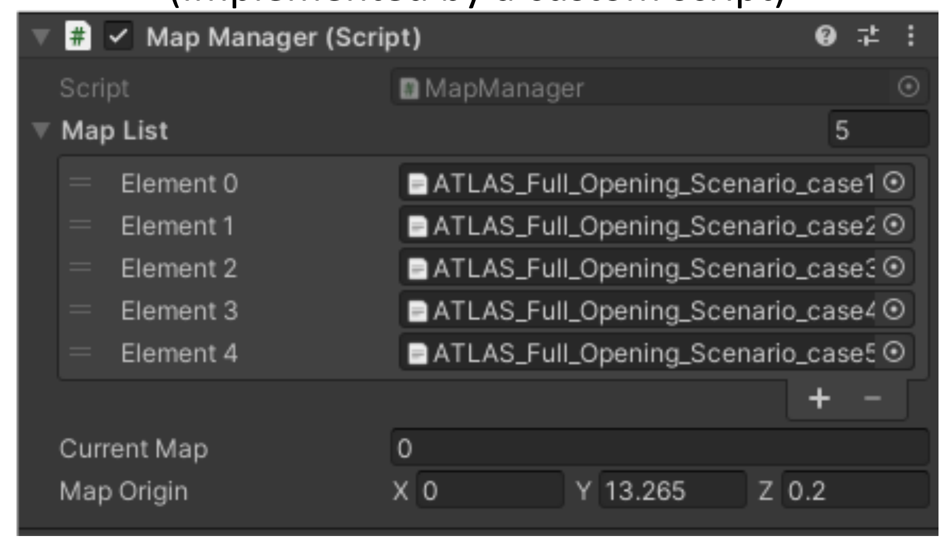
(https://unity.com/)

Dose Estimation System 2.0

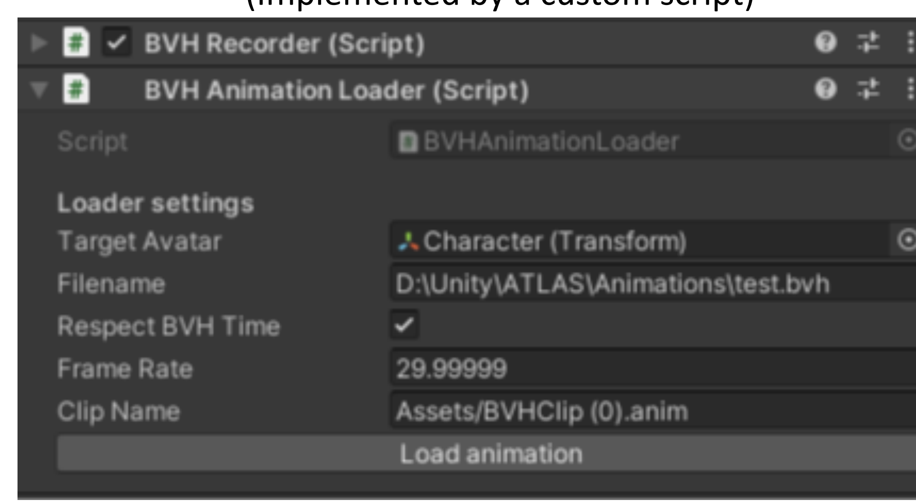
- Interaction with UNITY
  - Generally run with a graphical interface
  - Scripts allow customisation
  - Programming in C#
  - Multiple dose map files can be loaded, and selected according to the current scenario (e.g. beam pipe removed, PIXEL removed…)
  - Possible extension : different map types could be loaded, e.g **magnetic field data**
- Developments are backed up on CERN GitLab (facilitates long term support)
- Flexible system:
  - Save/load animations
  - Add more characters
  - Calculate dose without animation
- Reproduced the results of the previously existing implementation
- New scenarios are relatively straightforward to implement

Interaction with UNITY

Interface to import dose maps
(Implemented by a custom script)



Interface to import record and load animation files
(Implemented by a custom script)

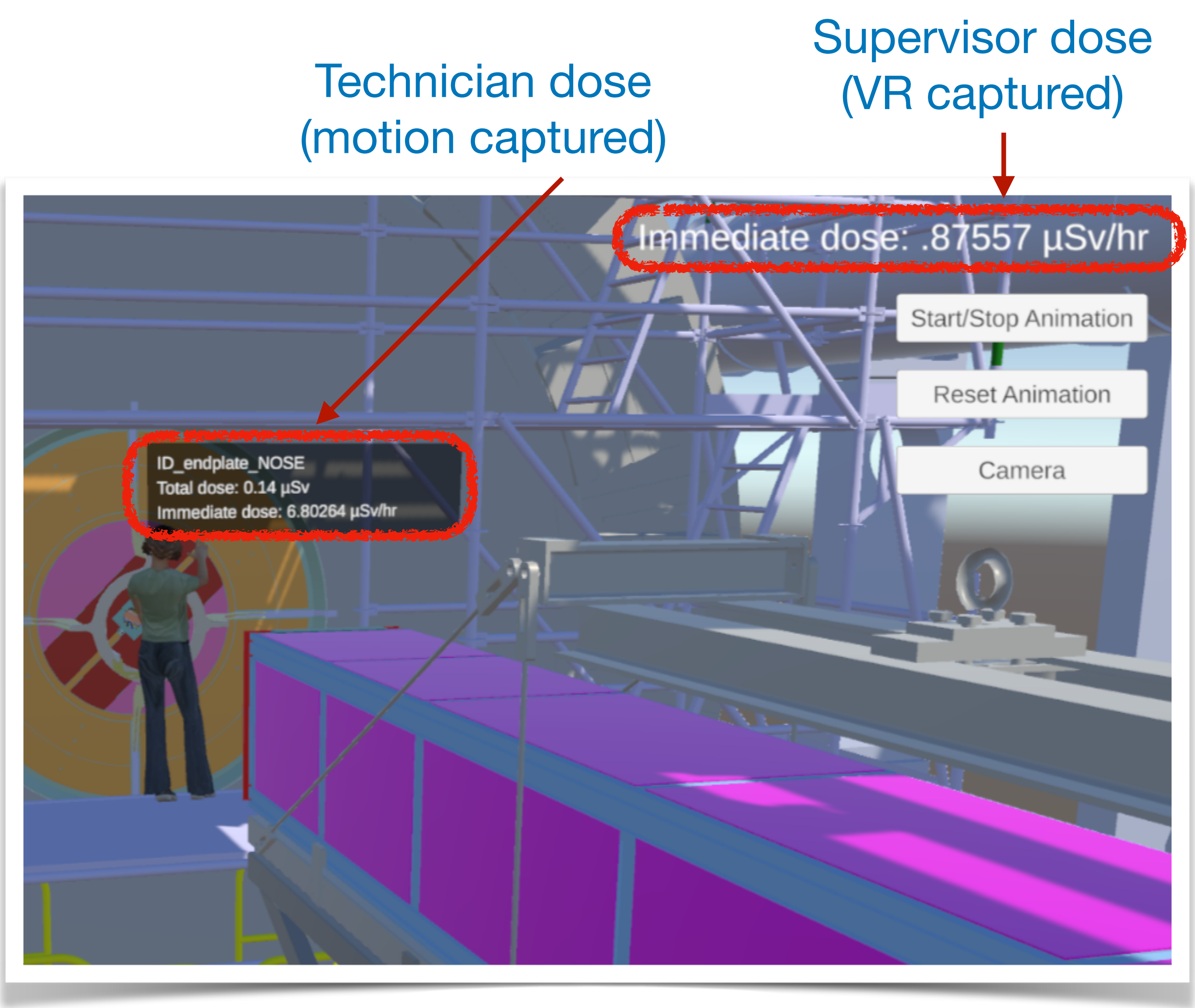


Dose Estimation System 2.0

- **Basic functionality and improvements :**
  - Motion capture system now integrated via a plug-in, possible to feed **live data** from PhaseSpace directly into UNITY
  - **Save and load bvh files** (ASCII file that contains motion capture data for 3D characters)
  - Re-Run with previously recorded data (e.g. with changed dose maps due to extended Run 3)

- **Supervisor / Inspector function added :**
  - Possible to move around VR (with/without animation) running by using VR headset
  - Ideal for inspections walks etc.
  - Collected dose of supervisor registered
  - Possibility to collect dose estimation for low dose / homogenous field areas
  - Dose collection for non-complex / low-interactive supervision/working scenarios

- **Improved training value :**
  - Possible to create a display showing the trainees the current dose while on the mockup, giving instant feedback on the body position & procedure



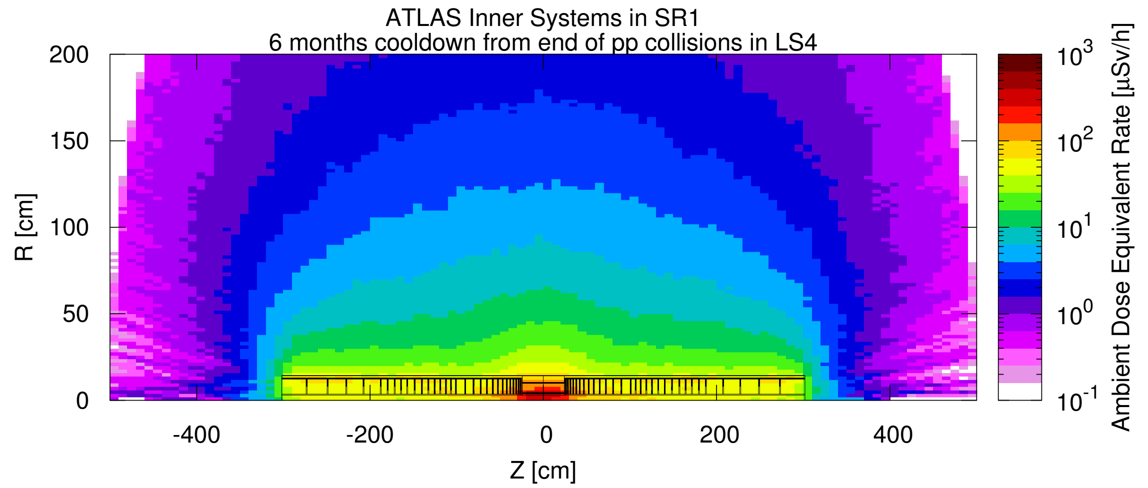
Dose Estimation System 2.0

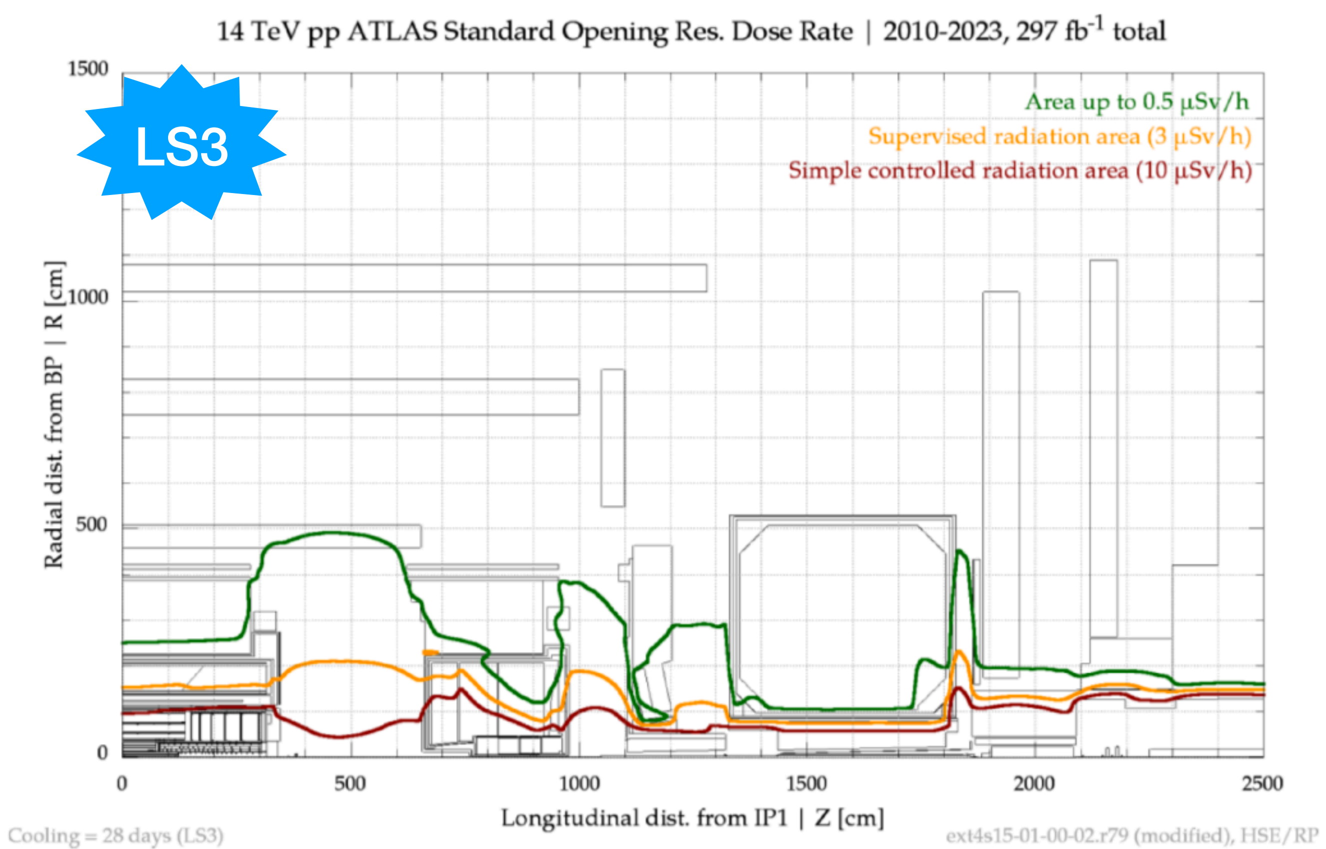
Video created from motion capture data and imported into UNITY

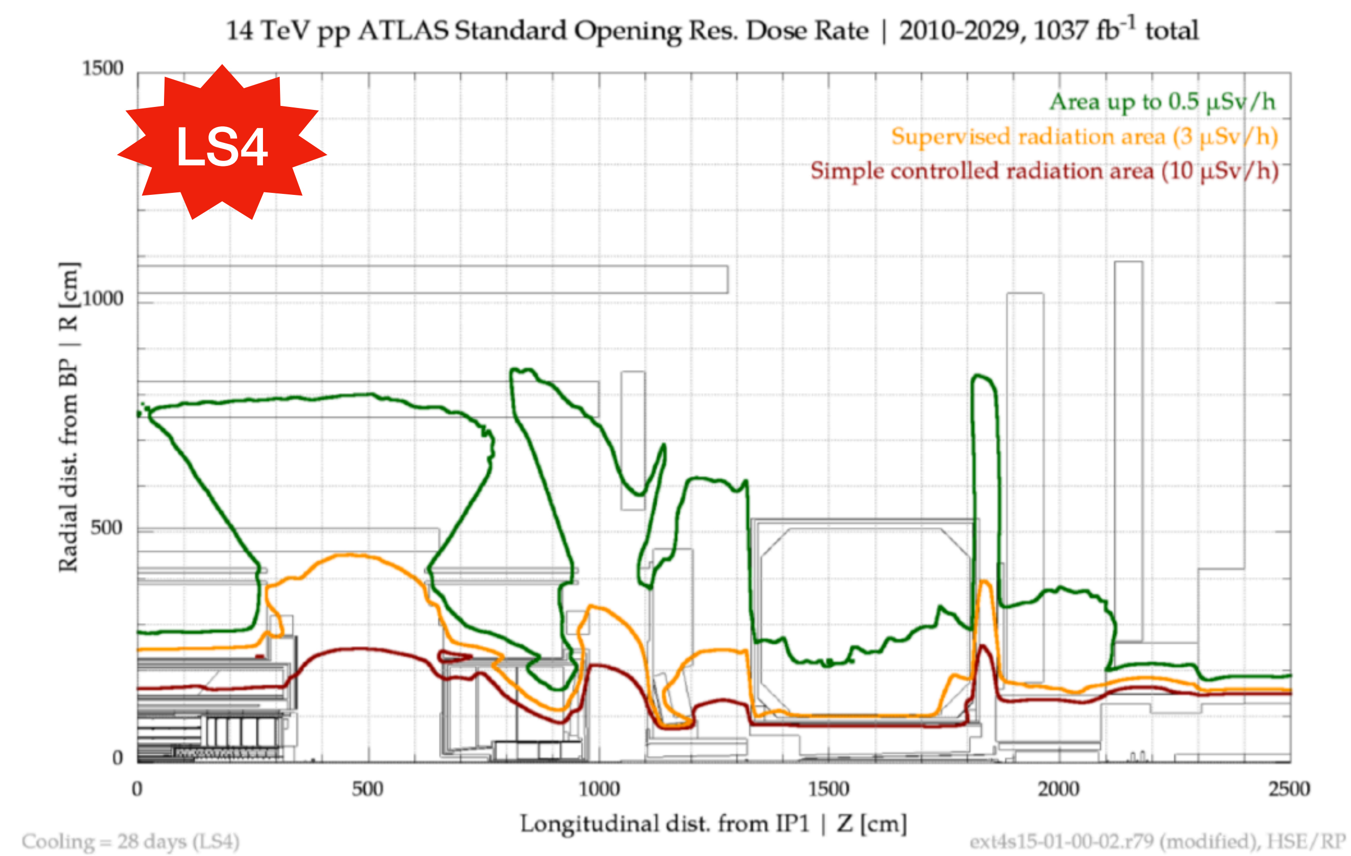
Outlook

Radiation Environment beyond LS3

- **For LS cool down times, radiation levels scale roughly with luminosity during the last year !**
  - Many of the isotopes produced have relatively short half life
  - Increases residual dose rates over the years for longer cool down times
  - LS3 will see a small increase ≈ 20% compared to LS2 (significantly higher then LS1!)
  - **LS4 and onwards will have significant higher radiation levels during interventions & repairs**
- **Requirement for good dose estimations for interventions will increase**
  - e.g. for ATLAS ITk Inner System replacement during LS4 or LS5







J. C. Armenteros, A. Cimmino, S. Roesler and H. Vincke : "13th international Topical Meeting on Nuclear Application of Accelerators , AccApp'17"

Dose Estimation Tool - Outlook

- Although developed for the ATLAS Inner Detector decommissioning in LS3, the tool is now **based on CERN standards** and **commercial available solutions**
- Easy to apply for a multitude of **new scenarios** for other (CERN) experiments
  - Long duration (≈ 4-6 months) of deinstallation and decommissioning of tracking detectors can lead to significant dose even in low radiation environment
  - Changes in radiation fields (changed schedule, cool down times, luminosity,…) only require to run the program with updated field maps
- Life motion capture allows the direct comparison between simulated dose and actual collected dose (with DMC)
- Especially useful for high radiation scenarios where position and duration are critical
  - Intervention on beam line elements, dumps etc.   (recent SPS related intervention at ≈ 20mSv/h)
  - Interventions on forward detectors located near beam pipe (LUCID, AFP,….)
- Integration into other CERN projects (e.g. Robotics) should be straight forward

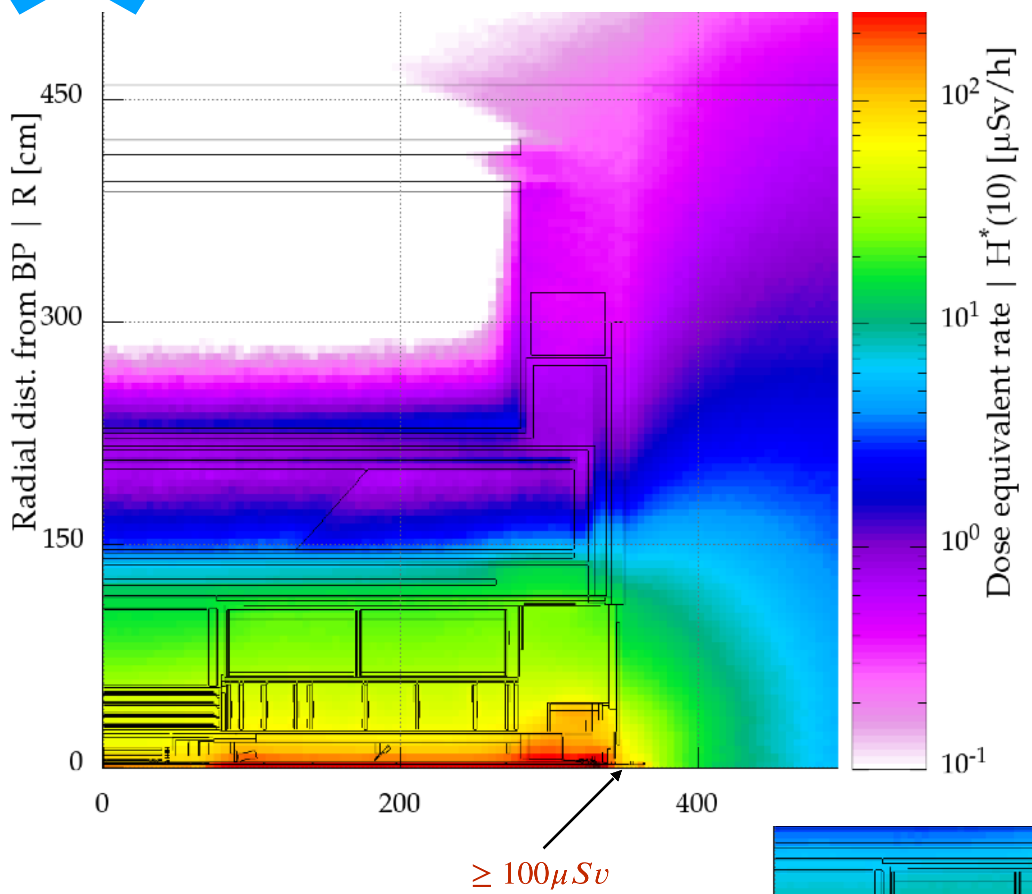
Some Publications :

- 18.06.2019 - *An Advanced Radiation Dose Estimation Tool for the Decommissioning of High Energy Physics Experiments*
  [M.R.Jäkel, A. Cryer, R. French, N. Hartman, G. Kapellmann, H.Marin-Reyes, K.L. Veale] Forum on Tracking Detector Mechanics 2019, Cornell University, NY
- 06.02.2020 - *An Advanced Radiation Dose Estimation Tool for Decommissioning of HEP Experiments*
  [M.Jäkel] - Presentation to HSE and TC (Indico, restricted)
- 12.02.2021 - Integrating motion capture in a virtual reality intervention planning platform to study radiation protection measures for the ATLAS inner detector decommissioning
  [A. Cryer, G. Kapellmann-Zafra, H. Marin-Reyes, K. Lohwasser, A. Steel, K. Veale and M. Jaekel], 2021 JINST 16 P03020
- 10.2021 - *Using emerging technologies to reduce occupational radiation exposure in the ATLAS ID Decommissioning, and other high-radiation environments*.
  [A.Cryer]; PhD Thesis, University of Sheffield , UK

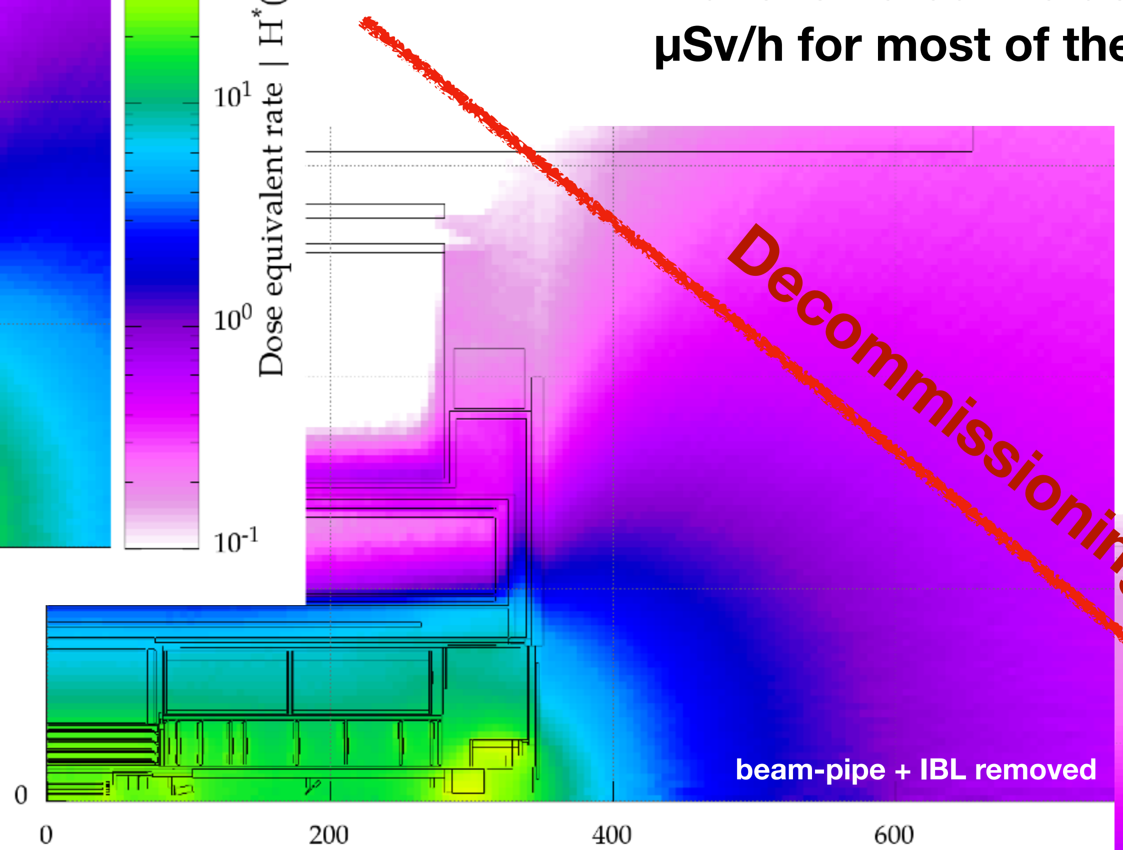
Backup Slides

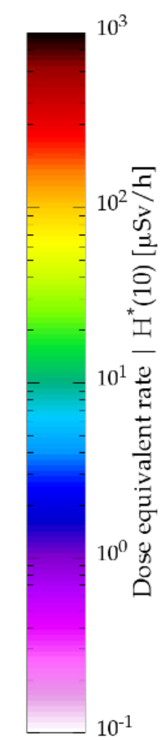
See also 2019 talk

Radiation Environment during Decommissioning

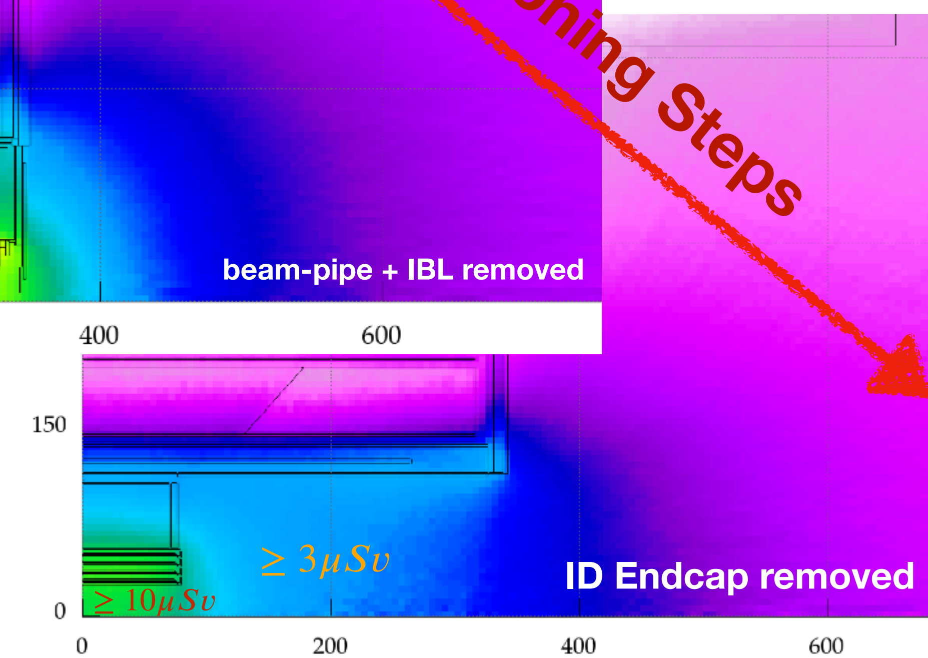


With beam-pipe and IBL removed, we have lowered the dose equiv. to ≤ 10 μSv/h for most of the accessible area.

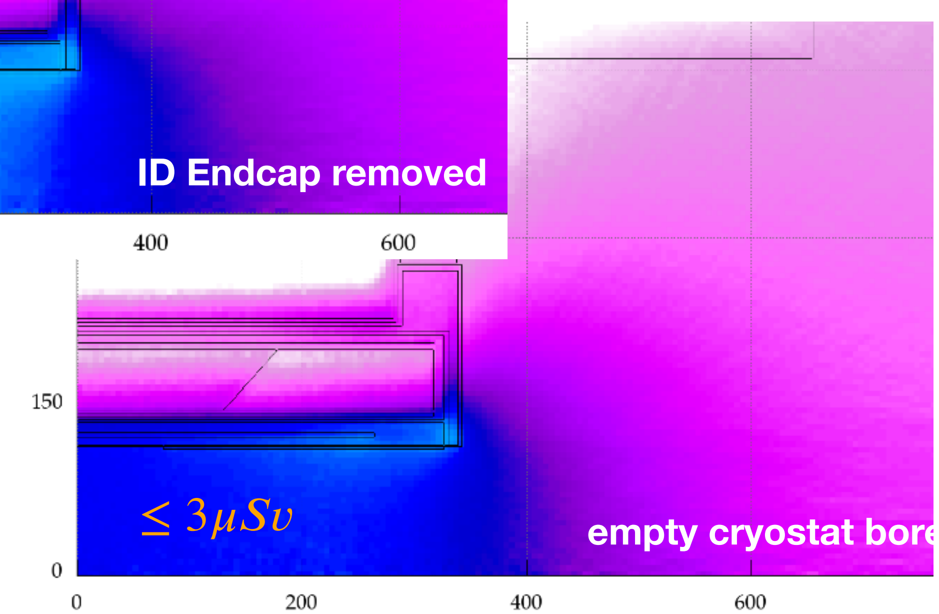




Radiation maps for each major decommissioning step available



During the final removal of services inside the cryostat bore, we are below 3 μSv/h except for small local areas.



ALARA rule applied to interventions at CERN

EDMS 1751123 Rev 1.2

- **5.1. INDIVIDUAL RP RISK ASSESSMENT**

An individual RP risk assessment is performed if one of the following conditions applies:

- The intervention is performed in a Limited Stay or High Radiation Area.
- The estimated intervention duration in a Controlled Radiation Area is longer than 100 hours or 500 man hours, i.e., there is a risk to exceed the ALARA Level 1 criteria (100 µSv or 500 man µSv, respectively) already at low dose rates.
- The intervention carries contamination risks (e.g., destructive work).
- The intervention is performed in an area classified as Work Sector (e.g., radioactive workshops).
- It is a radiography.

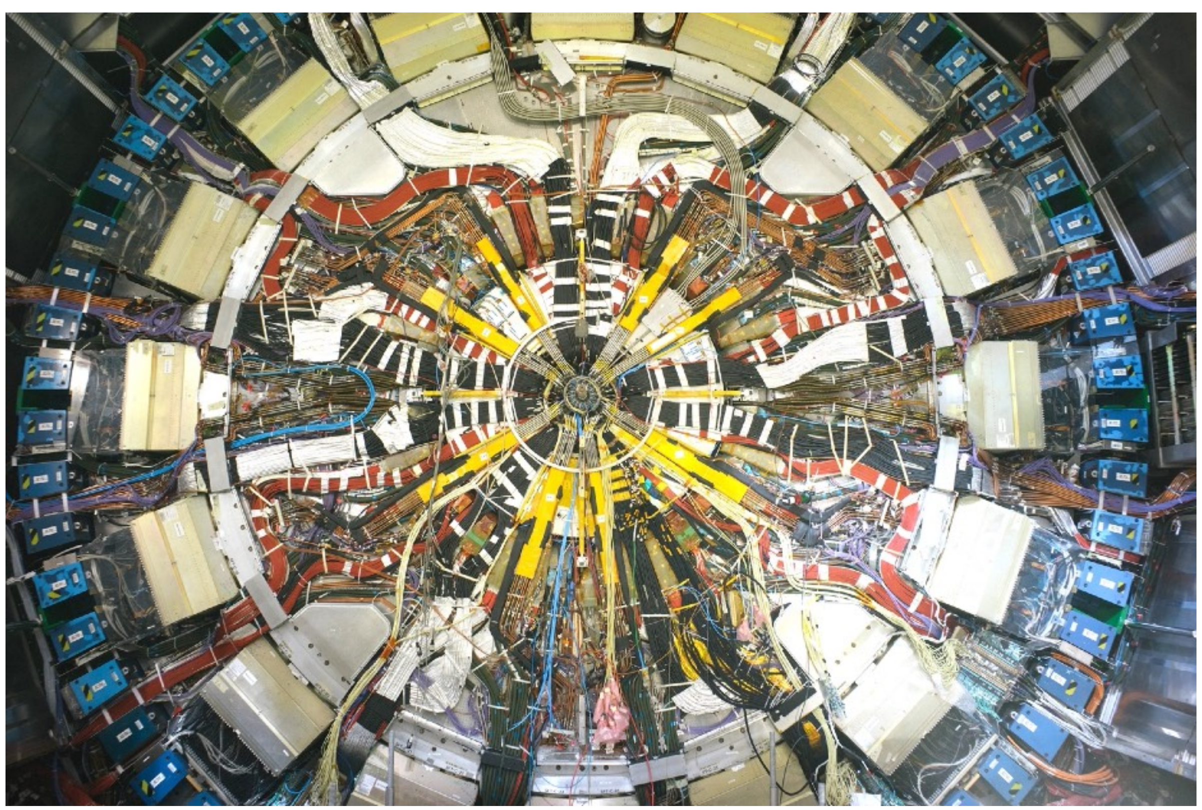
If none of the above conditions apply, the RP group has nevertheless the right to request an individual RP risk assessment (e.g., for long interventions in Supervised Radiation Areas).

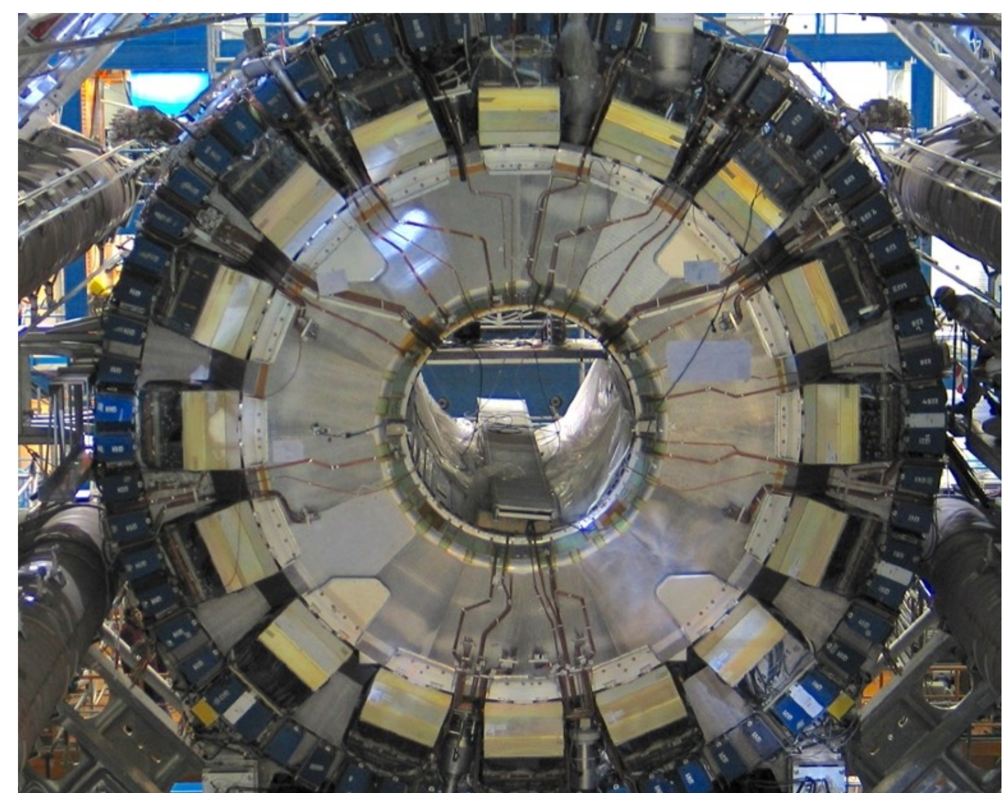
For each intervention leading to individual or collective doses exceeding 50% of the ALARA Level 1 criteria (i.e., 50 µSv or 250 man µSv, respectively) a DIMR is established. It follows the workflow including its approval as detailed further below.

[See also 2019 talk]

Scope of the ID Decommissioning

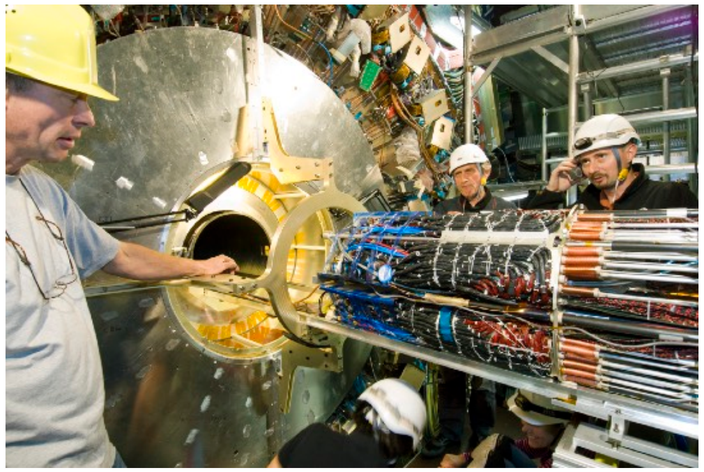
- **Complete removal of the ATLAS tracking detector (PIXEL/SCT/TRT), which will be replaced by the ITk during the Long Shutdown 3 (LS3, 2024)**
- **Removal of all services up to (and including) the Patch Panels (PP2) inside the Muon spectrometer**
- **Cleaning of the cryostat bore** (as much as feasible)
- **Work scheduled for ~~6~~ 4 months, starting approx. 250 days after end of Run 3** (current schedule v7.1, assuming one month ion run in Dec. ~~2024~~ 2025)

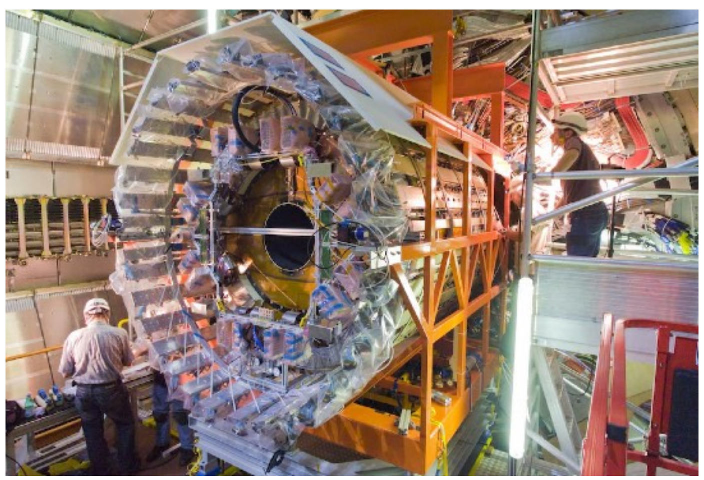


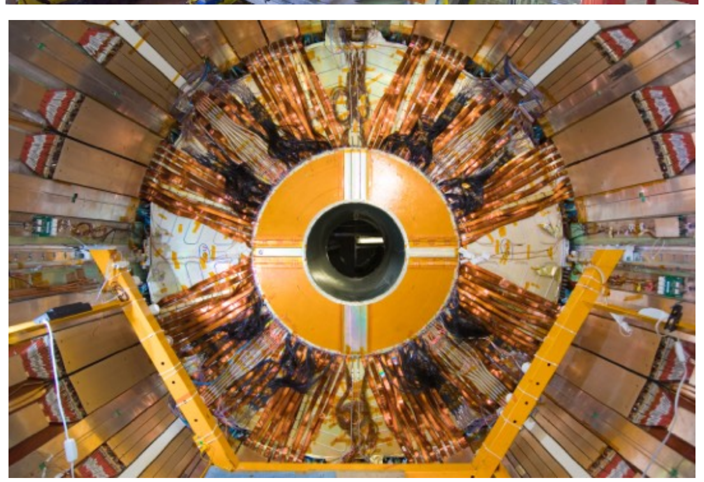


See also 2019 talk

De-Installation Process



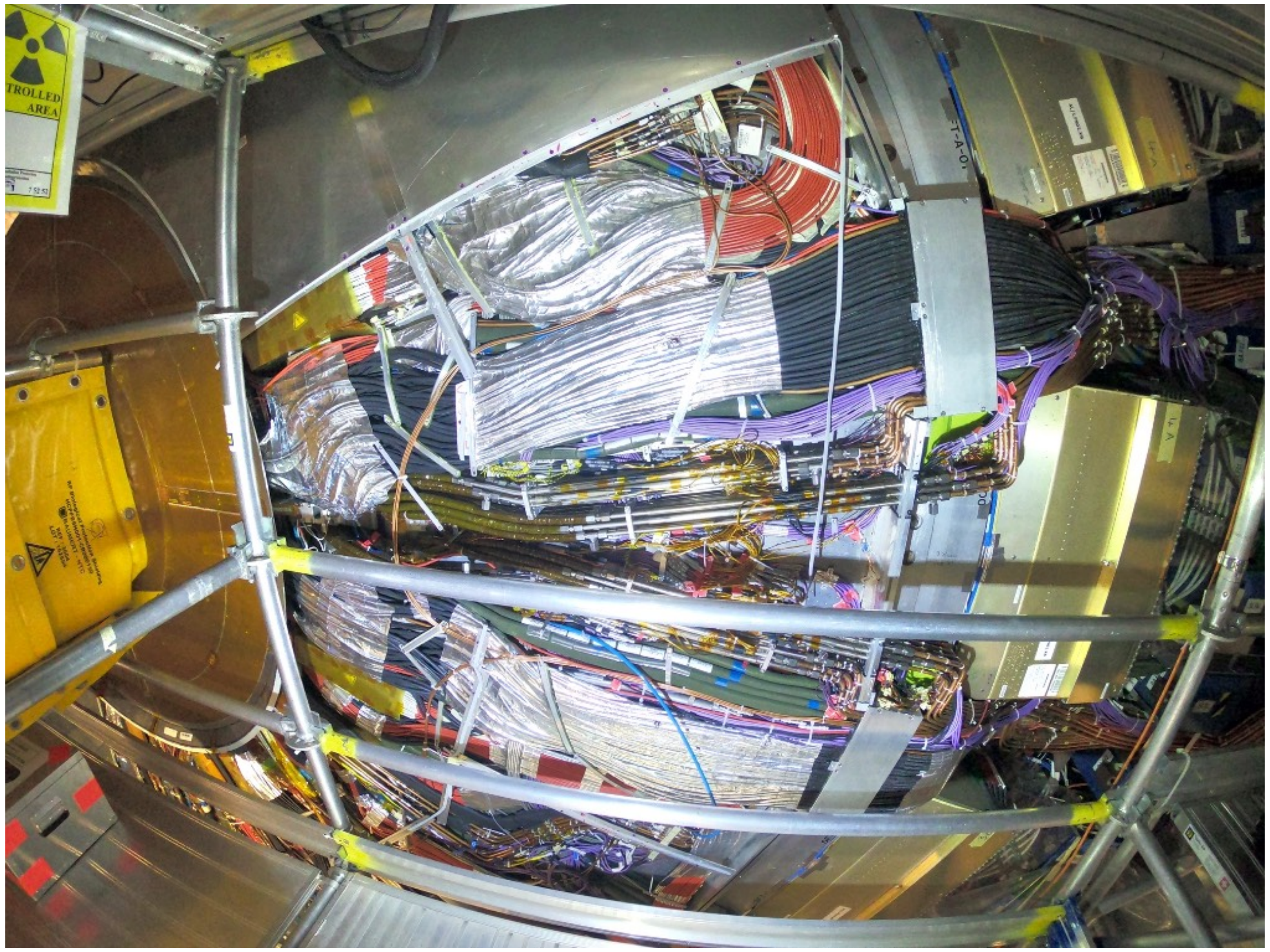


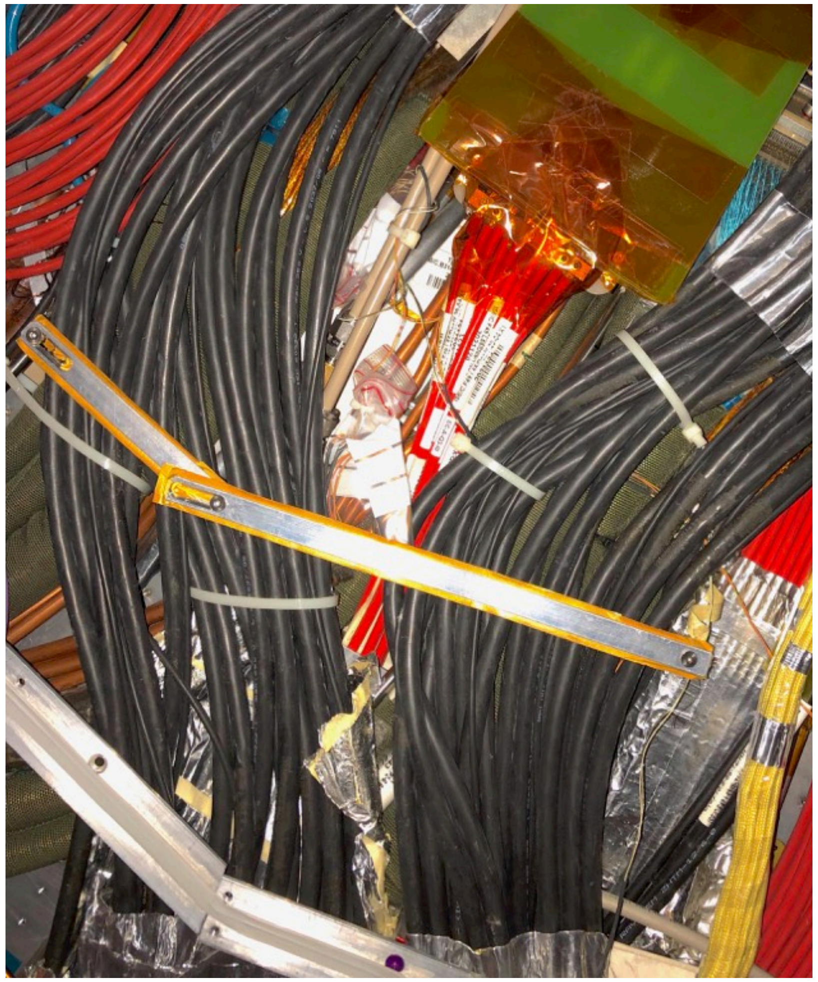


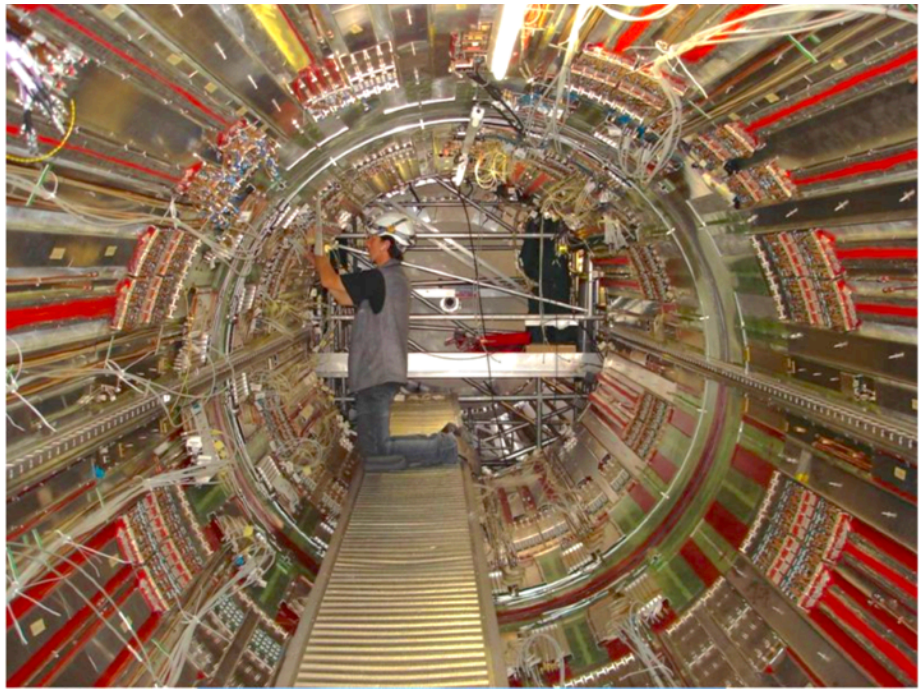
- **Removal inner beam pipe (VI) (Side C)**
  - Cut\disconnect any services on both the A and C Sides
  - Align frames and transport tools
  - Use traction tool to extract BP into BP container
- **Remove IBL (Side C)**
  - Cut and removes IBL services at PP1
  - Pull IBL into MPC
- **Remove PIXEL package (Side C)**
  - Cut and remove Pixel services at PP1
  - Align fames and transport tools
- **Remove IDEP nose and supports (both sides)**
- **Remove services from cryostat flange (both sides)**
  - Disconnect Service boxes from ID chamfer for clearance (PP1F)
  - Cut/remove services from flange
  - Remove SCT\TRT cooling services which inhibit EndCap extraction
- **Remove ID endcap (Side C)**
  - Lower and align ID EndCap trolley
  - Install interface rails
  - Extract EndCap
- **Remove ID Endcap (Side A)**
  - Side C to Standard Opening
  - Side A to Large Opening
  - Remove ID EndCap as for Side C
- **Disconnect barrel services (both sides)**
  - Cut\disconnect PP1B services
  - Ensure clearance between services and Barrel envelope
- **Remove ID barrel (Side A)**
  - Replace EndCap V-Rails with barrel flat-rails
  - Lower and align Barrel trolley
- **Remove services and trays from cryostat bore**
- **Remove all services from cryostat face**

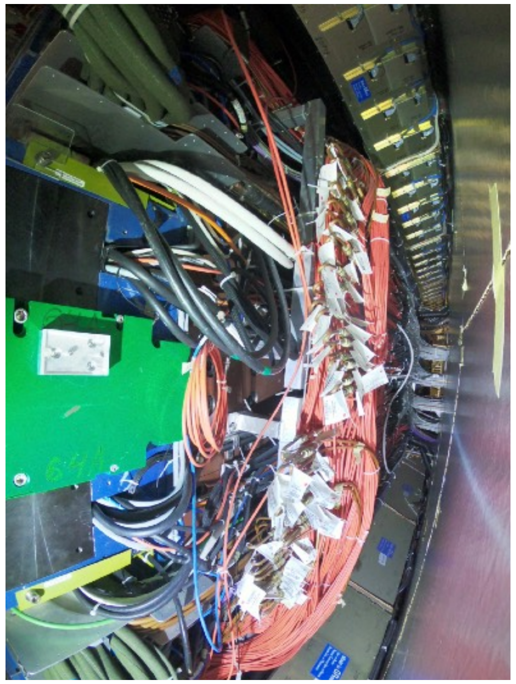
See also 2019 talk

Removal of Services

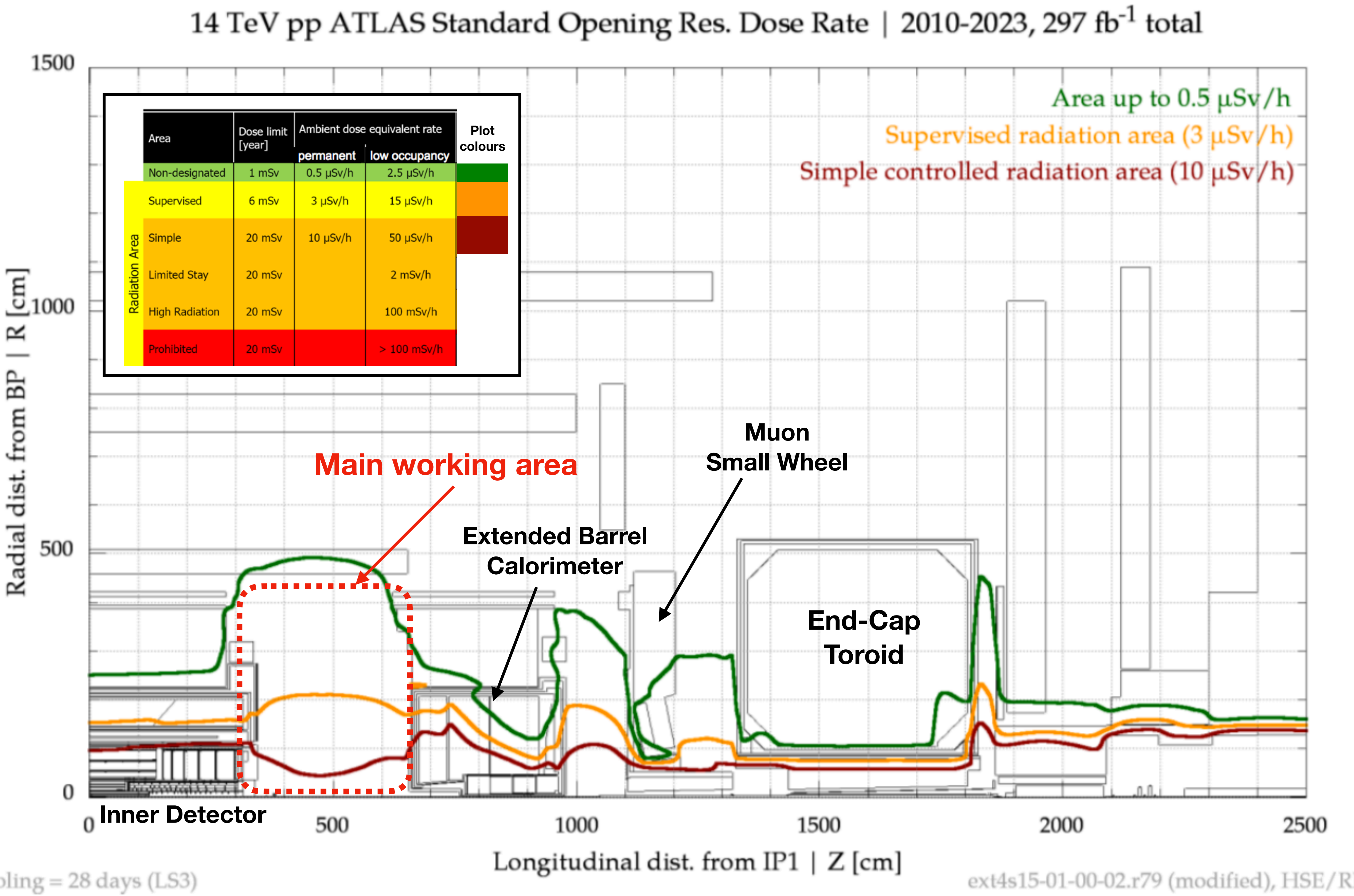




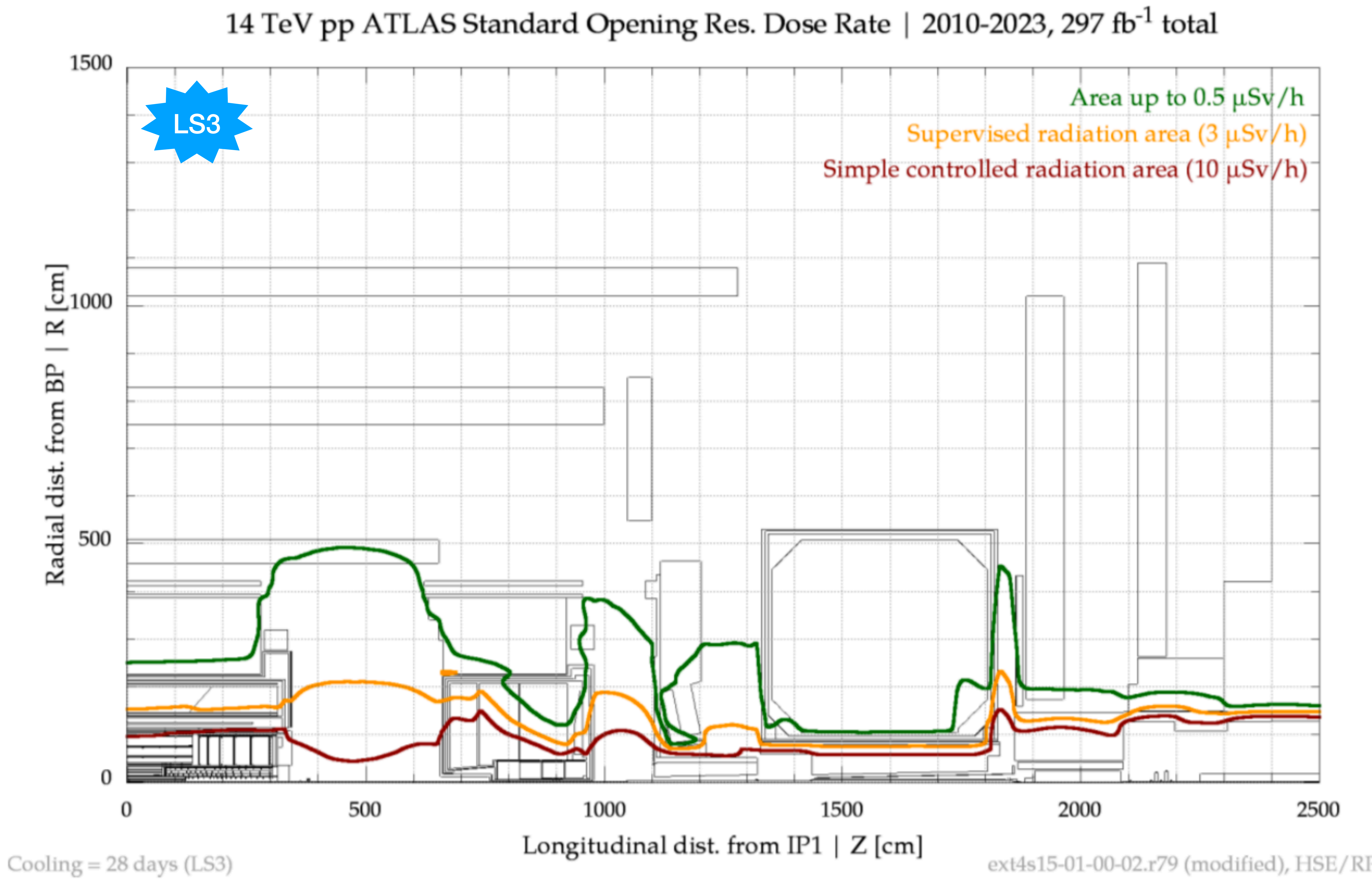


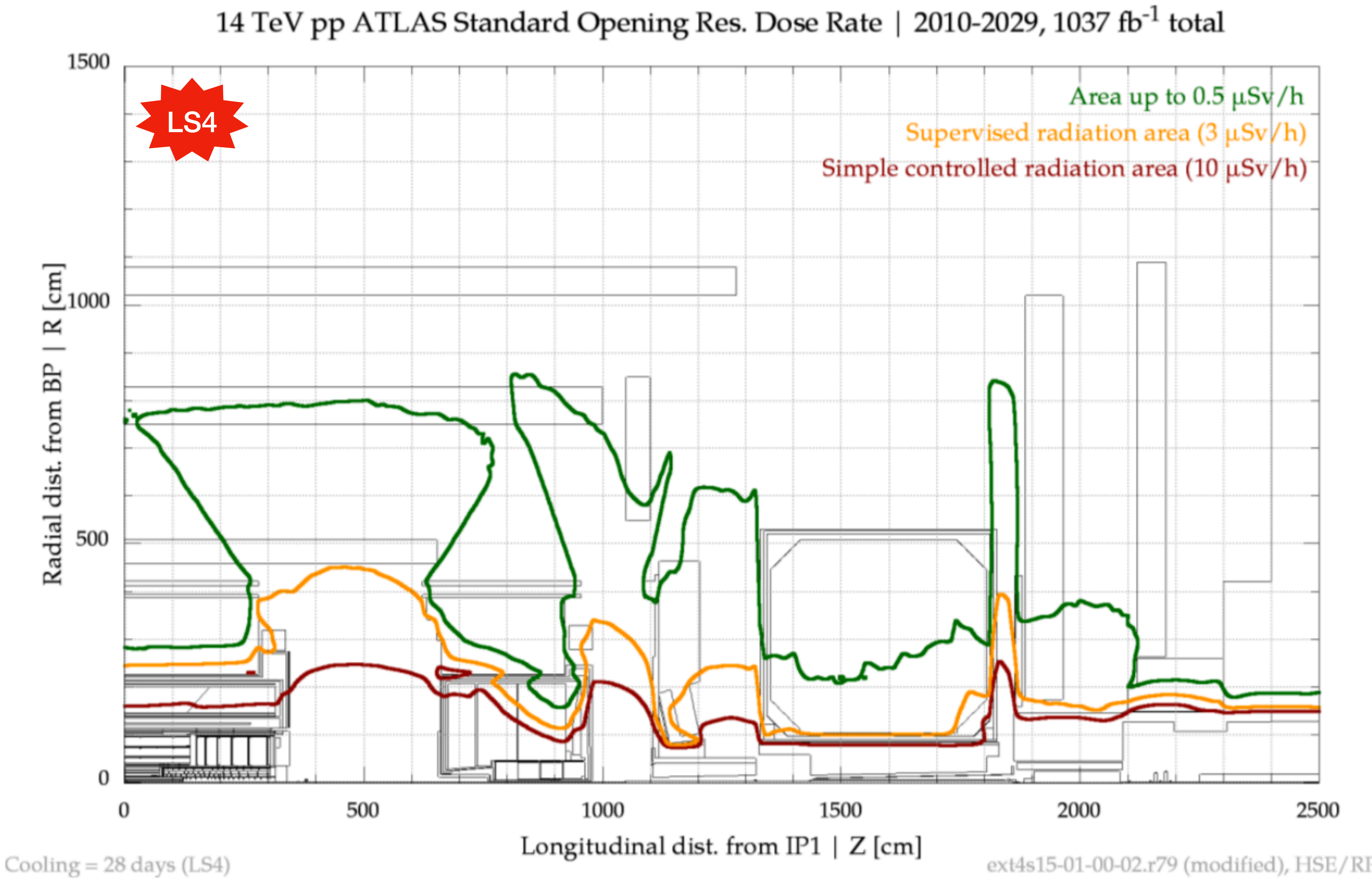


Radiation Classification - LS3



Area	Dose limit [year]	Ambient dose equivalent rate: permanent	Ambient dose equivalent rate: low occupancy	Plot colours
Non-designated	1 mSv	0.5 μSv/h	2.5 μSv/h	
Radiation Area: Supervised	6 mSv	3 μSv/h	15 μSv/h	
Radiation Area: Simple	20 mSv	10 μSv/h	50 μSv/h	
Radiation Area: Limited Stay	20 mSv		2 mSv/h	
Radiation Area: High Radiation	20 mSv		100 mSv/h	
Radiation Area: Prohibited	20 mSv		> 100 mSv/h	


14 TeV pp ATLAS Standard Opening Res. Dose Rate | 2010-2023, 297 fb-1 total
LS3
Area up to 0.5 μSv/h
Supervised radiation area (3 μSv/h)
Simple controlled radiation area (10 μSv/h)
Radial dist. from BP | R [cm]
0
500
1000
1500
0
500
1000
1500
2000
2500
Longitudinal dist. from IP1 | Z [cm]
Cooling = 28 days (LS3)
ext4s15-01-00-02.r79 (modified), HSE/RP


14 TeV pp ATLAS Standard Opening Res. Dose Rate | 2010-2029, 1037 fb-1 total
LS4
Area up to 0.5 µSv/h
Supervised radiation area (3 µSv/h)
Simple controlled radiation area (10 µSv/h)
Radial dist. from BP | R [cm]
1500
1000
500
0
0
500
1000
1500
2000
2500
Longitudinal dist. from IP1 | Z [cm]
Cooling = 28 days (LS4)
ext4s15-01-00-02.r79 (modified), HSE/RP