Chapter 11

Radiation Protection Considerations

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This chapter summarizes the legal Radiation Protection (RP) framework to be considered in the design of HiLumi LHC. It details design limits and constraints, dose objectives and explains how the As Low As Reasonably Achievable (ALARA) approach is formalized at CERN. Furthermore, features of the FLUKA Monte Carlo code are summarized that are of relevance for RP studies. Results of FLUKA simulations for residual dose rates during Long Shutdown 1 (LS1) are compared to measurements demonstrating good agreement and providing proof for the accuracy of FLUKA predictions for future shutdowns. Finally, an outlook for the residual dose rate evolution until LS3 is given.

1. Radiological Quantities

The design phase of a new project includes an evaluation of radiological risks as well as their limitation and minimization by appropriate protection and optimization measures. The radiological quantities to assess comprise

- for periods of beam operation:
  (1) dose equivalent to personnel by stray radiation in accessible areas,
  (2) activation of effluents and air and their release into the environment as well as the resulting annual dose to the reference groups of the population,
  (3) dose equivalent to personnel and environment in case of abnormal operation or accidents,
- for beam-off periods:
  (4) radioactivity induced by beam losses in beam-line components and related residual dose equivalent rates,
  (5) dose equivalent to personnel during interventions on activated beam-line components or experiments,

- for decommissioning:
  (6) radionuclide inventory.

2. Regulatory Framework, Design Limits and Dose Objectives

The upgrade of the LHC studied within the HiLumi LHC Project must be optimized according to CERN's Radiation Protection rules and regulations of which the most relevant for the design and upgrade of accelerators are summarized in the following.

2.1. *Justification, optimization, limitation*

The CERN Radiation Protection legislation is detailed in the Safety Code F [1]. It stipulates that all activities involving ionizing radiation have to be *justified*, *optimized and limited* and defines respective limits:

- Any practice leading to an effective dose exceeding 100 μSv per year for individuals working on the CERN site or 10 μSv for members of the general public must be justified.
- It is obligatory to optimize radiation protection according to the As Low As Reasonably Achievable (ALARA) principle. Optimization can be considered as respected if the annual dose of a practice is below 100 μSv for persons exposed because of their professional activity and 10 μSv for members of the general public.
- The effective dose in any consecutive 12-month period is limited to 20 mSv for so-called Category A Radiation Workers, to 6 mSv for Category B Radiation Workers and to 1 mSv for not occupationally exposed personnel. The effective annual dose to any person outside of the CERN site boundaries must not exceed 300 μSv.

2.2. *Design constraints*

Design constraints for new or upgraded facilities ensure that the exposure of persons working on the CERN sites as well as the public will remain below the dose limits under normal as well as abnormal conditions of operation and that the optimization principle is implemented. In particular, the following design constraints apply:

- The design of components and equipment must be optimized such that installation, maintenance, repair and dismantling work does not lead to an effective dose, e.g., as calculated with Monte Carlo simulations, exceeding 2 mSv per person and per intervention [2]. The design is to be revised if the dose estimate exceeds this value for cooling times compatible with operational scenarios.

- The annual effective dose to any member of a reference group outside of the CERN boundaries must not exceed 10 μSv. The estimate must include all exposure pathways and all contributing facilities.
- The selection of construction material must consider activation properties to minimize the dose to personnel and the production of radioactive waste. In order to guide the user a web-based code (ActiWiz) is available for CERN accelerators [3].

2.3. *ALARA and dose objectives*

Detailed CERN-specific ALARA rules apply to any work implying risks due to ionizing radiation [4, 5]. Procedures define the optimization process to follow based on a risk-dependent classification scheme: The estimated individual and collective dose equivalent estimated for an intervention determines the so-called "ALARA category" (see Fig. 1); the dose equivalent rate at the worksite as well as contamination risks might be used as additional criteria in the definition of the category (see Fig. 2).

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

Fig. 1. Criteria and threshold values that determine the ALARA category and, thus, the optimization process [5].

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

Fig. 2. Criteria that provide further guidance to the definition of the optimization process [5]. The quantities CA (Concentration dans l'Air) and CS (Contamination Surfacique) are guidance levels for airborne and surface contamination defined in the Swiss radiation protection legislation [6] that are adopted by the CERN regulations. For example, the exposure to air with an activity concentration of 1 CA during 2000 hours results in a committed effective dose of 20 mSv. A similar definition exists for 1 CS.

Specific optimization procedures are associated with each ALARA category. For example, Level-II and -III interventions require a detailed work-and-dose planning, a documented optimization process and a formal approval. In addition, Level-III interventions have to be reviewed by an ALARA committee.

In order to evaluate their later impact on the accelerator operation it is useful to consider these ALARA rules already during the design phase for interventions that may lead to considerable individual or collective doses.

Furthermore, CERN defines personal dose objectives for consecutive 12-month periods (presently 3 mSv).[a]

3. The FLUKA Monte Carlo Code for Radiation Protection Studies

The use of general-purpose particle interaction and transport Monte Carlo codes is often the most accurate and efficient choice for assessing radiation protection quantities at accelerators. Due to the vast spread of such codes to all areas of particle physics and the associated extensive benchmarking with experimental data, the modeling has reached an unprecedented accuracy. Furthermore, most codes allow the user to simulate all aspects of a high energy particle cascade in one and the same run: from the first interaction of a TeV particle over the transport and re-interactions (hadronic and electromagnetic) of the produced secondaries, to detailed nuclear fragmentation, the calculation of radioactive decays and even of the electromagnetic shower caused by the radiation from such decays.

FLUKA [7, 8] is a general-purpose particle interaction and transport code with roots in radiation protection studies at high energy accelerators. It therefore comprises all features needed in this area of application:

- Detailed hadronic and nuclear interaction models cover the entire energy range of particle interactions at the LHC, from energies of thermal neutrons to interactions of 7 TeV protons. Moreover, the interface with DPMJET3 [9] also allows the simulation of minimum-bias proton–proton and heavy ion collisions at the experimental interaction points which enormously facilitates calculations of stray radiation fields around LHC experiments.
- Numerous variance reduction techniques are available, among others, weight windows, region importance biasing as well as leading particle, interaction and decay length biasing.
- FLUKA includes unique capabilities for studies of induced radioactivity, especially with regard to nuclide production, their decay and the transport of

[a]The values are not to be confused with the dose constraints applied during the design phase as defined in Section 2.2.

residual radiation. Particle cascades by prompt and residual radiation are simulated in parallel based on microscopic models for nuclide production and a solution of the Bateman equations [10] for activity build-up and radioactive decay. The decay radiation and its associated electromagnetic cascade are internally flagged as such in order to distinguish them from the prompt cascade. This allows the user to apply different transport thresholds and biasing options to residual and prompt radiation and to score both independently.

- Particle fluence can be multiplied with energy-dependent conversion coefficients to effective dose or ambient dose equivalent [11] at scoring time. Prompt and residual dose equivalent can thus be computed in three-dimensional meshes, the latter for arbitrary user-defined irradiation and cooling profiles.
- Integral part of the FLUKA code development is benchmarking of new features against experimental data. It includes both the comparison of predictions of individual models to measurement results (e.g., nuclide production cross sections) as well as benchmarks for actual complex situations as, for example, arising during accelerator operation.

4. Benchmark of Radiological Assessments with Measurements

Since the design phase of the LHC the FLUKA code has been extensively used in the assessment of radiological quantities up to ultimate parameters of operation. With the completion of the first operational period in early 2013 and the opening of the experimental detectors for maintenance comprehensive benchmarks of FLUKA predictions are now possible. For a most accurate comparison, FLUKA simulations have been performed for the operational parameters of the past three years, including beam energy, intensity as well as instantaneous and integrated interaction rates in the high-luminosity experiments ATLAS and CMS and annual shutdown periods.

As an example, Fig. 3 shows ambient dose equivalent rates around the ATLAS detector one week after completion of the proton physics run in 2012. As the simulations made use of the rotational symmetry of the detector around the beam axis, only its upper half is displayed. Dose rates are well below natural background level outside of the detector while they increase towards the beam axis ($r = 0$ in Fig. 3) reaching several hundreds of μSv/h at the most radioactive locations.

After several weeks of cooling the so-called "forward shielding" around the beam-pipes was opened in order to allow for maintenance and repair interventions. Detailed radiation surveys accompanied each step of the shielding removal and allowed first benchmarks of FLUKA simulations. Figure 4 shows the locations (labeled "1–5") for which measurements were compared to FLUKA predictions. The numerical values are presented in Table 1 and demonstrate remarkable agreement taking into account measurement uncertainties as well as geometrical approximations in the calculations.

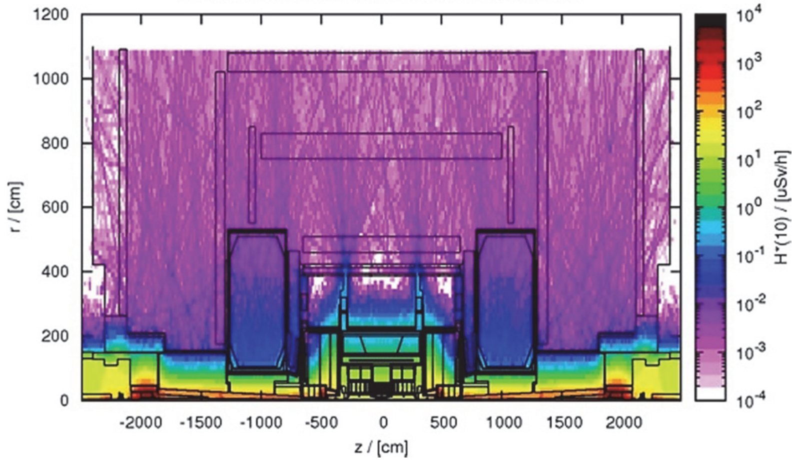

Fig. 3. Ambient dose equivalent rates (H*(10)) in μSv/h around the ATLAS detector one week after completion of the proton physics run in 2012.

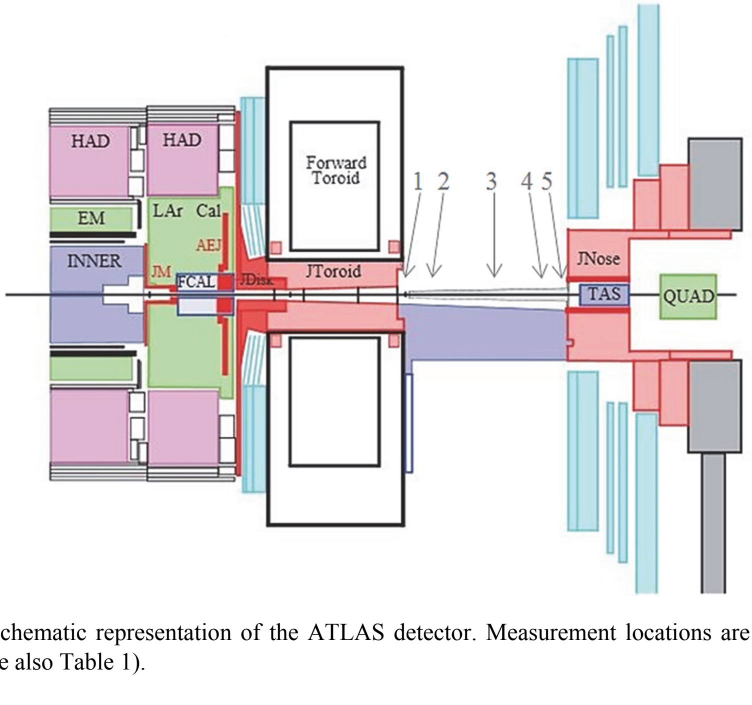

Fig. 4. Schematic representation of the ATLAS detector. Measurement locations are labelled by "1–5" (see also Table 1).

Table 1. Comparison of measured and calculated ambient dose equivalent rates along the ATLAS beam pipe at the locations as indicated in Fig. 4. The uncertainties indicated for the FLUKA results include statistical errors only.

Location	Measurement [μSv/h]	FLUKA [μSv/h]
1	19	13 (±0.3)
2	10	13 (±0.3)
3	7.2	10 (±0.2)
4	47	46 (± 0.5)
5	42	72 (± 0.5)

Similarly, detailed calculations were performed for the CMS detector and adjacent beam-line elements. Figure 5 shows the calculated ambient dose equivalent around the TAS absorber and Q1 magnet for one week of cooling after the LHC operation with proton beam in 2012. They can be compared to the radiation survey results presented for the long-straight section at LHC Point 5 (LSS5) in Fig. 6. The two measurement locations close to the TAS and inner triplet magnets showing values of 85 μSv/h and 20 μSv/h, respectively, are marked in Fig. 5 with crosses. From the color coding of the dose equivalent rates it can be seen that the simulations predict dose rates that agree well with those measured.

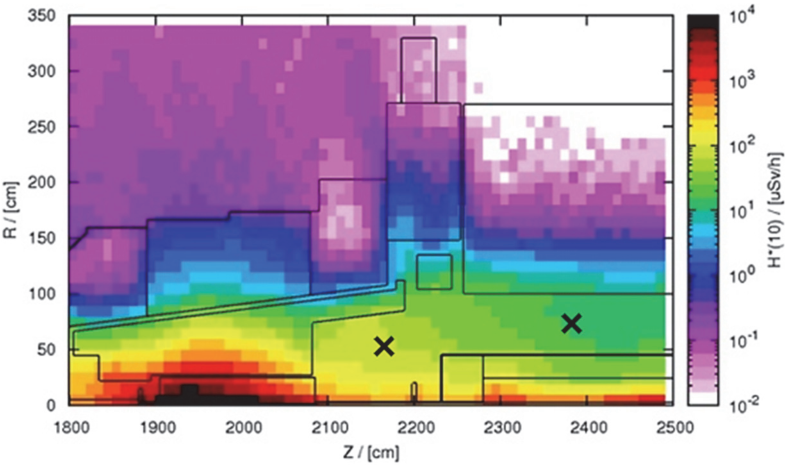

Fig. 5. Ambient dose equivalent rates (H*(10)) in μSv/h around the TAS absorber and Q1 magnet adjacent to the CMS experiment one week after completion of the proton physics run in 2012.

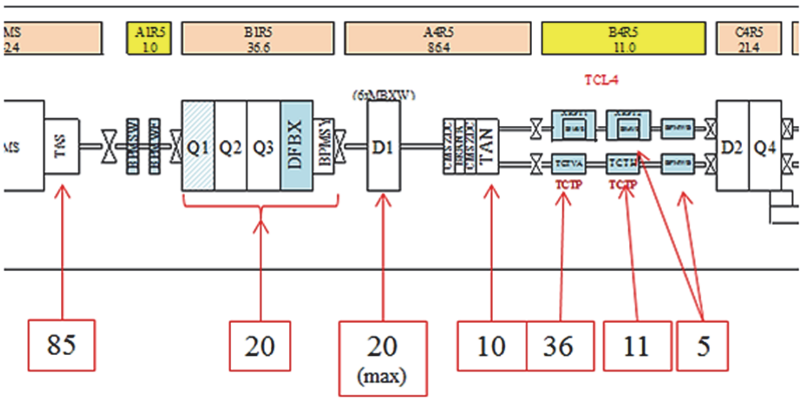

Fig. 6. Ambient dose equivalent rates in μSv/h measured in LSS5 at 40 cm distance to the respective components one week after completion of the proton physics run in 2012.

5. Estimation of Residual Dose Rates Around ATLAS Until LS3

The above mentioned comparisons between FLUKA results and radiation survey measurements support the reliability of predictions for future operational periods. Simulations have been performed for both ATLAS and CMS until Long Shutdown 3 (LS3), presently planned for the year 2022. As an example, the present Chapter presents the evolution of residual dose rates around the ATLAS experiment.

It has been assumed that the present Long Shutdown 1 (LS1) is followed by three years of operation with a peak luminosity of 1.0×10^{34} cm^{-2}s^{-1} and an integrated luminosity of 134 fb^{-1} until Long Shutdown 2 (LS2) in 2018. LS2 is then followed by another three years of operation at 2.0×10^{34} cm^{-2}s^{-1} and 249 fb^{-1} peak and integrated luminosities, respectively, until LS3 in 2022 when the HiLumi LHC upgrade will be implemented. Predictions for LS3 are of particular importance for the HiLumi LHC Project as they give an indication of waiting times and precautions to be taken during the upgrade.

Ambient dose equivalent rate maps are available for a wide range of cooling times between one week and several years; Figs. 7 and 8 show them for four months of cooling after the last high luminosity proton operation in the years 2017 and 2021, respectively. Calculating ratios between dose equivalent rates to be expected during the different LS for identical locations yields an increase of dose rates by a factor of about 4 until LS2 and by about a factor of 8.5 from LS1 until LS3. It follows that dose rates close to the beam-pipe or interaction point may reach several mSv/h until the installation of the HiLumi LHC upgrade which has to be taken into consideration in the design and planning.

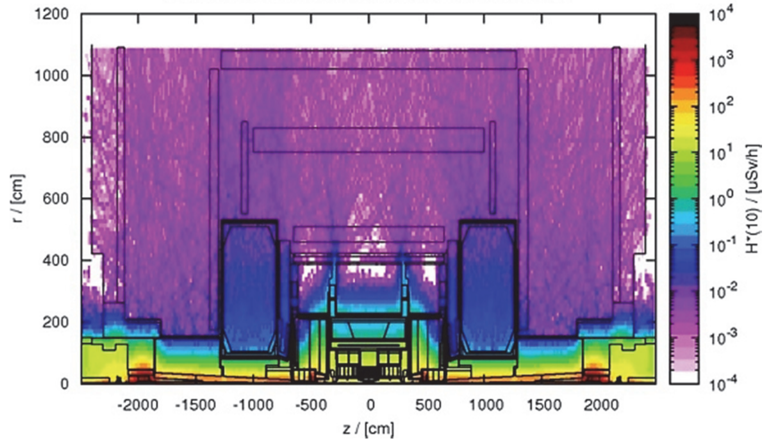

Fig. 7. Ambient dose equivalent rates (H*(10)) in μSv/h around the ATLAS detector four months after completion of the proton physics run in 2017 (Long Shutdown 2).

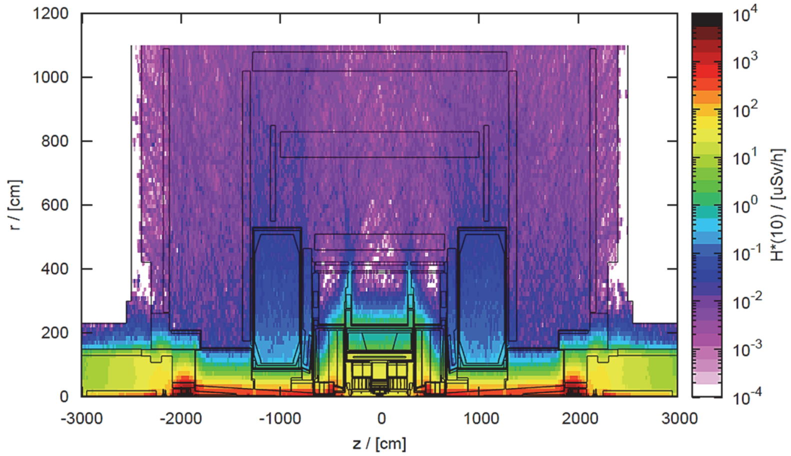

Fig. 8. Ambient dose equivalent rates (H*(10)) in μSv/h around the ATLAS detector four months after completion of the proton physics run in 2021 (Long Shutdown 3).

The FLUKA simulations for different cooling times indicate a decrease of residual dose rates due to radioactive decay by a factor of two from one month to four months of cooling and by another factor of two from four months to one year of cooling (see Table 2). Dose rate maps, as shown in this Chapter, along with intervention scenarios can be used to compute individual and collective doses that can then be compared to above mentioned design constraints. It gives an indication of the required cooling time before the intervention can start and may trigger design modifications for fast or remote handling if the work would otherwise be impossible during the planned shutdown period.

Table 2. Scaling factors for residual dose rates around the ATLAS detector in LS3. The factors have been obtained by dividing the dose rate at the respective cooling time by the dose rate at one month cooling.

Cooling time	Scaling factor
1 week	1.6
1 month	1.0
4 months	0.47
6 months	0.35
1 year	0.2

Furthermore, the methodology of residual dose rate and job dose predictions with FLUKA will be extended to operational periods beyond LS3 as soon as a first upgrade design for the detectors and adjacent beam-line components is available.

References

[1] Safety Code F, Radiation Protection, CERN (2006).
[2] M. Brugger *et al.*, The estimation of individual and collective doses for interventions at the LHC beam cleaning insertions, in *Proceedings of the LHC Project Workshop*, Chamonix XIV, 17–21 January 2005 (2005).
[3] H. Vincke and C. Theis, ActiWiz – optimizing your nuclide inventory at proton accelerators with a computer code, in *Proceedings of the ICRS-12 & RPSD 2012 Conference*, Nara, Japan, 2–7 September 2012, Progress in Nuclear Science and Technology, Volume 4 (Atomic Energy Society of Japan, 2014), pp. 228–232.
[4] General Safety Instruction, *ALARA criteria and requirements applicable to interventions,* RGE section 9/S5-GSI1, EDMS No. 810176 (2006).
[5] ALARA Review Working Group, *Final Report*, EDMS No. 1244380 (2012).
[6] Swiss Radiation Protection Ordinance, revision 1 January 2009.
[7] A. Fassò, A. Ferrari, J. Ranft, and P. R. Sala, FLUKA: a multi-particle transport code, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.
[8] G. Battistoni, S. Muraro, P. R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fassò, J. Ranft, The FLUKA code: Description and benchmarking, in *Proceedings of the Hadronic Shower Simulation Workshop 2006*, Fermilab 6–8 September 2006, M. Albrow, R. Raja eds., *AIP Conference Proceeding* **896**, 31–49 (2007).
[9] S. Roesler, R. Engel, J. Ranft, The Monte Carlo event generator DPMJET-III, in *Proceedings of the Monte Carlo 2000 Conference*, Lisbon, 23–26 October 2000, A. Kling, F. Barao, M. Nakagawa, L. Tavora, P. Vaz eds. (Springer-Verlag Berlin, 2001) pp. 1033–1038.

[10] H. Bateman, Solution of a system of differential equations occurring in the theory of radioactive transformations, *Proc. Cambridge Philos. Soc.* **15**, 423–427 (1910).

[11] M. Pelliccioni, Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the FLUKA code, *Radiation Protection Dosimetry* **88**, 279–297 (2000).