Induced activation studies for the LHC upgrade to High Luminosity LHC

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Abstract. The Large Hadron Collider (LHC) will be upgraded in 2019/2020 to increase its luminosity (rate of collisions) by a factor of five beyond its design value and the integrated luminosity by a factor ten, in order to maintain scientific progress and exploit its full capacity. The novel machine configuration, called High Luminosity LHC (HL-LHC), will increase consequently the level of activation of its components. The evaluation of the radiological impact of the HL-LHC operation in the Long Straight Sections of the Insertion Region 1 (ATLAS) and Insertion Region 5 (CMS) is presented. Using the Monte Carlo code FLUKA, ambient dose equivalent rate estimations have been performed on the basis of two announced operating scenarios and using the latest available machine layout. The HL-LHC project requires new technical infrastructure with caverns and 300 m long tunnels along the Insertion Regions 1 and 5. The new underground service galleries will be accessible during the operation of the accelerator machine. The radiological risk assessment for the Civil Engineering work foreseen to start excavating the new galleries in the next LHC Long Shutdown and the radiological impact of the machine operation will be discussed.

1. Introduction

1.1. Introduction to CERN

CERN, the European Organization for Nuclear Research, is an intergovernmental organization with over 20 Member States. Its seat is in Geneva but its premises are located on both sides of the French-Swiss border (http://cern.ch/fplinks/map.html).

CERN’s mission is to enable international collaboration in the field of high-energy particle physics research and to this end it designs, builds and operates particle accelerators and the associated experimental areas. At present more than 11 000 scientific users from research institutes all over the world are using CERN’s installations for their experiments.

The accelerator complex at CERN is a succession of machines with increasingly higher energies. Each machine injects the beam into the next one, which takes over to bring the beam to an even higher energy, and so on. The flagship of this complex is the Large Hadron Collider (LHC) as presented in Figure 1.

Further information is available on the CERN website: http://cern.ch.
1.2. Introduction to LHC and HL-LHC

The Large Hadron Collider (LHC) is the most recent accelerator constructed on the CERN site. The LHC machine accelerates and collides proton beams but also heavier ions up to lead. It is installed in a 27 km circumference tunnel, about 100 m underground.

High Luminosity LHC (HL-LHC) is a project aiming to upgrade the LHC collider during the Long Shutdowns (LS) 2 and 3, in order to maintain scientific progress and exploit its full capacity. By increasing its peak luminosity by a factor five over nominal value it will be able to reach a higher level of integrated luminosity, nearly ten times the initial LHC design target.

2. Radiation Protection studies using FLUKA Monte Carlo code

The radiological impact of the LHC proton-proton operation in the Long Straight Section (LSS) areas of the Insertion Region (IR) in Point 1 and 5 was evaluated in order to prepare the work for the modification of the LHC machine for its upgrade to HL-LHC. Using the Monte Carlo particle transport code FLUKA [1], [2], ambient dose equivalent rate estimations for the LSS regions have been performed on the basis of available operating scenario and using the latest available machine layout.

2.1. The p-p accelerator machine operating scenario

Proton-proton collisions in the LHC experiments in Point 1 (ATLAS) and in Point 5 (CMS) produce a secondary high energy radiation field that penetrates into the adjacent accelerator tunnels and causes severe activation of beam-line elements.

The simulations are performed considering the luminosity achieved up to 2016 and the target values announced by the LHC Operation team (LHC machine) and by the HL-LHC project (HL machine).
Table 1. Operating scenario of the LHC and HL-LHC machine.

| Year of HL-LHC Operation | Peak / levelled luminosity \([\text{cm}^2\cdot\text{s}^{-1}]\) | Integrated luminosity \([\text{fb}^{-1}]\) |
|--------------------------|-----------------------------|-----------------|
| <2012                    |                             |                 |
| LS1 2015                 | 6.30\times10^33             | 4               |
| 2016                     | 5.40\times10^34             | 60              |
| 2017                     | 1.60\times10^34             | 50              |
| 2018                     | 1.60\times10^34             | 50              |
| LS2 (2 years)            |                             |                 |
| 2021                     | 2.08\times10^34             | 60              |
| 2022                     | 2.08\times10^34             | 60              |
| 2023                     | 2.08\times10^34             | 60              |
| LS3 (3 years)            |                             |                 |
| 2027                     | 5.08\times10^34             | 250             |
| 2028                     | 7.5\times10^34              | 250             |
| 2029                     | 7.5\times10^34              | 250             |
| LS4 (1 year)             |                             |                 |
| 2031                     | 5.08\times10^34             | 250             |
| 2032                     | 7.5\times10^34              | 250             |
| 2033                     | 7.5\times10^34              | 250             |
| LS5 (1 year)             |                             |                 |
| 2035                     | 5.08\times10^34             | 250             |
| 2036                     | 7.5\times10^34              | 250             |
| 2037                     | 7.5\times10^34              | 250             |

The operating scenarios as well as the integrated luminosity targets are summarized in Table 1.

2.2. Simulation geometry
LHC and HL-LHC geometry of the Insertion Region in Point 1 and in Point 5 has been reproduced in FLUKA [3], [4], all the machine elements as well as the tunnel are implemented in the simulation geometry.

The machine element layout and optics in the two points are the same, and from a radiological point of view the two Insertion Regions are equivalent. Figure 2 and Figure 3 show the horizontal cuts of the LHC and HL-LHC simulation geometry used, respectively.

Figure 2. FLUKA geometry models of the LHC machine used for the Monte Carlo simulation.
2.3. LHC machine simulation

Ambient dose equivalent rate maps have been calculated from around 18 m distance from the Interaction Point (IP) around the two main LHC experiment in Point 1 and 5 (ATLAS and CMS respectively) up to around 260 m distance, and for different cooling times in the LS2 and LS3 (as in Table 1). The simulations were done for 7+7 TeV pp-collisions and using DPMJET-III [5] as the event generator; for the inelastic proton-proton cross section the value of 85 mb is used, on the basis of the extrapolation from [6].

In order to benchmark the simulation results, during LHC machine operation, ambient dose equivalent rate maps have been calculated on the basis of the actual machine operating scenario and for typical cooling times during the Technical Stop of the machine.

For example, Figure 4 and Figure 5 show the comparison between the simulation results and the measurement taken in the LHC tunnel during the first Technical Stop in 2016. In the upper part of the plots the sequence of the machine elements is depicted.
Figure 5. Calculate ambient dose equivalent rate profile (yellow) and residual dose measurements taken during LHC-TS1 (in blue) along the LHC machine elements in IR1.

The simulation results are in a very good agreement with the measurements.

Figure 6 shows the ambient dose equivalent rate map after one month of cooling time during LS3 in IR1. Figure 7 and Figure 8 show the residual dose rate profiles taken at a working distance (about 40 cm) from the machine elements in the tunnel aisle, at different cooling times (1 week, 4 weeks, 4 months and 1 year) during LS2 and LS3 respectively. The higher residual dose rates are around the elements closest to the IP (element on the left in plots), with the highest levels in the aisle corresponding to the connections between elements, where the shielding effect due to self-absorption of the element is less effective, and around the collimators (element in purple in the upper part of the profile plots, where the sequence of the machine elements is depicted).

Figure 6. Ambient dose equivalent rate map in the Insertion Region 1 after one month cooling time during LHC machine Long Shutdown 3. The residual dose in the vertical dimension is averaged on 30 cm around the beam pipe.
2.4. HL-LHC machine simulation

For the HL-LHC proton operation, the ultimate scenario is considered (7+7 TeV pp-collisions at the average luminosity value of $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ with a 295 $\mu$rad half-angle crossing in the interaction point using DPMJET-III [5] as the event generator; for the inelastic proton-proton cross section the value of 85 mb is used, on the basis of the extrapolation from [6]).

Figure 9 shows the ambient dose equivalent rate maps after one month of cooling time during the first Long Shutdown during the HL-LHC era, so called LS4, in IR1 (upper plot) and in IR5 (bottom plot). The small difference in between the two ambient dose equivalent rate maps is due to the different crossing angle plane, which is vertical in IP1 and horizontal in IP5.
Figure 9. Ambient dose equivalent rate maps in the Insertion Region 1 (top plot) and in IR5 (bottom plot) after one month cooling time during HL-LHC machine Long Shutdown 4. The residual dose in the vertical dimension is averaged on 30 cm around the beam pipe.

Figure 10. Ambient dose equivalent rate profile in the Insertion Region 5 after 1 week, 4 weeks, 4 months and 1 year cooling time during HL-LHC machine Long Shutdown 4. The residual dose in the horizontal and vertical dimensions are averaged on 30 cm.

Figure 10 shows the ambient dose equivalent rate profile in the aisle at a working distance from the machine elements at four different cooling times (1 week, 1 month, 4 months and 1 year), which are typical cooling times for maintenance intervention in the machine tunnel during the scheduled technical stops, end of the year technical stops and long shutdowns. As for the LHC machine, the higher residual dose rates are around the elements closest to the IP (element on the left in plots) where the highest levels in the aisle correspond to the connections between elements, where the shielding effect due to self-absorption of the element is less effective, and around the collimators (element in purple in the upper part of the profile plots, where the sequence of the machine elements is depicted).
As reported in Table 1, for the time being, three long shutdown are schedule for the HL-LHC. The operating scenario is foreseen as three blocks of three operational years with a long shutdown in between. For the operational years, constant operating parameters are assumed.

Figure 11 compares the ambient dose equivalent rate after one month of cooling time during the first HL-LHC long shutdown (LS4) and the last (LS6). The ratios for all the considered cooling times are reported in Table 2; the ratio is almost 1 for the shortest cooling time and it increase with the longer cooling times due to the accumulation in the activated equipment of the induced radionuclides with longer half-lives.

![Figure 11. Ambient dose equivalent rate profiles in the Insertion Region 1 after one month cooling time during HL-LHC machine LS4 and LS6. The residual dose in the horizontal and vertical dimensions are averaged on 30 cm.](image)

**Table 2. Comparison residual dose rate ratios between LS4 and LS6 results for different cooling times.**

| Cooling time | LS6/LS4 |
|--------------|---------|
| 1 hour       | 1.02    |
| 1 day        | 1.03    |
| 1 week       | 1.06    |
| 1 month      | 1.09    |
| 4 months     | 1.18    |
| 1 year       | 1.29    |

Figure 12 compares the ambient dose equivalent rate after one month of cooling time during the first HL-LHC long shutdown (LS4) between the nominal and the ultimate case (as reported in Table 1). The ratios for all the considered cooling times are reported in Table 3; the ratio is higher for the shortest cooling time due to the higher production in the activated equipment of the induced radionuclides with shorter half-lives, and it decreases with the longer cooling times.
Figure 12. Ambient dose equivalent rate profiles in the Insertion Region 5 after one month cooling time during HL-LHC machine LS4 for the Nominal and Ultimate operating scenarios. The residual dose in the horizontal and vertical dimensions are averaged on 30 cm.

Table 3. Comparison residual dose rate ratios between Nominal and Ultimate results for different cooling times.

| Cooling time | Ultimate/Nominal |
|--------------|------------------|
| 1 hour       | 1.50             |
| 1 day        | 1.46             |
| 1 week       | 1.35             |
| 1 month      | 1.30             |
| 4 months     | 1.24             |
| 1 year       | 1.23             |

2.5. HL-LHC new underground galleries

In order to accommodate the new technical infrastructure needed for the upgrade of the LHC machine to HL-LHC, new caverns and 300 m long galleries along the Insertion Region of IP1 (ATLAS) and IP5 (CMS) are required. The new underground service galleries, showed in red in Figure 13, will be on a higher level with respect to the LHC tunnel.

Figure 13. Schematic of HL-LHC with the new infrastructure galleries in red.
The new service galleries will be accessible during the operation of the accelerator machine. For this reason, the radiological impact of the machine operation has to be assessed.

Two different scenarios are kept into account in the study: an accidental scenario, represented by one full proton beam lost into a bulky object in front of the most exposing connection to the galleries, and the stray radiation from the normal operation of the machine. For both cases the ultimate beam intensity (2808 bunches and $2.2 \times 10^{11}$ ppb) and luminosity ($7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$) are considered. The requirements are set by the two considered scenarios. In the accidental case the effective dose delivered to personnel has not to exceed the legal annual limit for the class B radiation worker, i.e. 6 mSv. During normal operation of the accelerator machine, in the new service galleries the ambient equivalent dose has to be the lowest possible, and in any case, it has to be lower than 15 µSv/h, in order to classify the areas at the lowest Radiation Area level, i.e. Supervised Radiation Areas.

In Figure 14, the two scenarios and the corresponding operational parameters considered are summarized.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure14.png}
\caption{Operational parameters and scenarios considered.}
\end{figure}

In the FLUKA geometry model used for the previous LHC and HL-LHC studies (Ch. 2.3. and Ch. 2.4. in this proceeding), the new underground service galleries were not included at the time of this study. For this reason a standalone model of the service galleries was developed (Figure 15). In order to assess the impact of normal operation, the results from the accidental scenario study are used combined with the results from the study on the HL-LHC IR1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure15.png}
\caption{Different view of the new underground service galleries FLUKA model.}
\end{figure}
Figure 16 shows on the left the effective dose map and on the right effective dose profile in the area indicated by the red square, due to the full loss of a full proton beam on a bulky object in front a connection to the new galleries. The implemented shielding provide an attenuation of a factor of about $10^{-8}$ from the LHC tunnel to the closest accessible area in the new galleries (indicated by the blue line in profile plot, on the right of Figure 16), where the effective dose level drops to a delivered dose lower than 0.1 mSv.

Figure 16. Effective dose delivered in the new underground galleries due to a full proton beam lost on a bulky object.

The ambient dose equivalent rate in the tunnel during the accelerator machine operation at ultimate intensity is shown in Figure 17, top part.

Figure 17. Ambient dose equivalent rate map in the tunnel during the HL-LHC machine operation at ultimate intensity, on top, and corresponding ambient dose equivalent rate profile next to the tunnel wall, on the bottom.

As can be seen in the profile plot on the bottom part of Figure 17, the maximum dose rate next to the tunnel wall is 50 Sv/h, which applying the attenuation factor of $10^{-8}$, lead to a value of 0.5 μSv/h ambient dose equivalent rate due to stray radiation in the new underground gallery closest accessible point.
3. Activation studies using ActiWiz3 Creator code

In order to assess the level of activation of the spoil when the new underground galleries will be excavated (LS2), the results obtained with the FLUKA Monte Carlo code (particle fluence spectra) were used as input for the ActiWiz3 Creator code [7].

An activated material is defined as radioactive if the specific or total activity of any radionuclides of artificial origin exceed the corresponding exemption limit, i.e.:

$$\sum_{i=1}^{n} \frac{a_i}{LE_i} < 1$$

where $a_i$ is the specific activity (Bq/kg) or the total activity (Bq) of the $i^{th}$ radionuclide of artificial origin in the material, $LE_i$ is the respective CERN exemption limit for the radio-nuclide $i$ in the material and $n$ is the number of radionuclides present. The CERN exemption limits (LE) are adopted from the Swiss legislation [6]. By the end of the current year (2017), these limits will be updated and the new version of this limits (LL) is taken into account for the estimation of the spoil activation in LS2.

During last end of the year technical stop of the LHC machine (EYETS 2016-17), some concrete and rock samples were taken out from the LHC tunnel wall, in the place where the excavation will occur (Figure 18.).

$\gamma$-spectrometry measurements were performed on the rock and concrete samples, after a cooling time of about 3 months. The activation of the samples was also evaluated using ActiWiz3 Creator code. The results are reported in Table 4, in the form of the sum of specific activity over exception limit.

| $\sum_{i=1}^{n} \frac{a_i}{LE_i}$ | EYETS 2016-17 (~3 months cooling time) |
|----------------------------------|----------------------------------------|
|                                  | UPR $\gamma$ spectrometry measurements | ActiWiz3 Creator© only $\gamma$ full |
| concrete                         | 1.15E-01                                | 9.70E-02 4.96E-01                     |
| soil                             | 8.17E-03                                | 5.30E-03 1.65E-02                     |
In the last column of Table 4, the results of all the radionuclide is reported, including the ones that cannot be measured with the $\gamma$-spectrometry technique. The $\gamma$ results, second and third column in Table 4, are in good agreement. The induced radionuclide list calculated is reported in Table 5 (concrete sample) and in Table 6 (soil sample) with the contributing percentages to the sum; the most contributing radionuclide in both cases is Ca-45, which is a pure $\beta$-emitter, thus not measurable with the $\gamma$-spectrometry technique.

| Table 5.                  | Table 6.                  |
|---------------------------|---------------------------|
| Concrete sample           | Soil sample               |
| radionuclide              | radionuclide              |
| Contribution to $\Sigma \frac{a_i}{E_i}$ | Contribution to $\Sigma \frac{a_i}{E_i}$ |
| Ca-45                     | Ca-45                     |
| 80%                       | 68%                       |
| Na-22                     | Na-22                     |
| 7%                        | 28%                       |
| Zn-65                     | S-35                      |
| 3%                        | 2%                        |
| Fe-55                     | Mn-54                     |
| 3%                        | 1%                        |
| S-35                      |                           |
| 1%                        |                           |
| Mn-54                     |                           |
| 1%                        |                           |

The activity over limit sum was evaluated for the spoils coming from the excavation of the new underground galleries where they are connected to the existing LHC tunnel (Figure 19).

![Figure 19. Snapshot of the new underground galleries (UPR) where they connect to the existing LHC tunnel.](image)

The results of the calculation, for the first three meters of excavation spoils is reported in Table 7, for one and four months cooling times; the first meter of excavated spoils will be radioactive, the second and the third meters are below the legal limits in both the cases.
Table 7. Activation level of excavated spoils.

| Layer          | Activation Level |
|----------------|------------------|
| UPR            | ActiWiz 3 Creator© |
| 1st meter      | 5.19E+00         |
| 2nd meter      | 3.19E-01         |
| 3rd meter      | 1.87E-02         |

4. Summary
Fluka Monte Carlo code is extensively used to perform induced activation studies for the LHC accelerator machine and its High Luminosity upgrade. The simulations are performed using a very long and detailed geometry which reproduce the accelerator elements and the tunnel environment in great detail. The simulation results are continuously benchmarked with the radiation measurements performed in the LHC machine.

ActiWiz3 Creator© were used in order to predict the level of activation of excavation spoils and the radionuclide inventory in view of the excavation work in order to build the new underground galleries for the HL-LHC additional infrastructure and services.

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