HOW RADIATION WILL CHANGE (Y)OUR LIFE

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Abstract

The paper addresses radiological risks during the LHC operation and maintenance as expected for the first year of the LHC operation. Data on ambient dose equivalent rates and induced radioactivity will be presented as function of beam parameters and “cooling times”. The radiological risks result in radiation protection requirements and constraints for operation and maintenance. In case of LHC air management both, general safety and radiation protection requirements and constraints are presented.

INTRODUCTION

In September 2008, the LHC beam operation had been stopped due to a technical problem. The damaged material had been repaired and in parallel - after thorough and detailed studies - measures were taken to protect personnel and material against risks from similar incidents. In November 2009 the LHC beam operation was resumed for a few weeks until 17th December 2009. Both, the beam energy and total number of protons used during these few weeks in 2009 were orders of magnitude lower than the beam parameters foreseen for the nominal LHC operation. The radioactivity produced in the LHC and the resulting ambient dose equivalent rates had been very low when compared to the future LHC operation. The ambient dose equivalent rates measured in the collimator regions - the areas mostly prone to beam losses - did not exceed few μSv/h. After the stop of LHC in December 2009 the entire machine tunnel and all experimental LHC caverns were classified as “Supervised Radiation Area”.

By resuming the LHC commissioning, the beam energy and intensity are supposed to increase, the levels of prompt radiation and the production of radionuclides in accelerator components, tunnel structure, gases, air and water will increase accordingly.

The paper summarizes the radiation protection studies that have been performed for various LHC operation scenarios and gives an ALARA-conform prioritising of the LHC consolidation and maintenance work.

RADIATION RISKS

The radiation protection studies for the first year of the LHC operation are based on input beam parameters as defined by LHC operation [1], assuming a maximum number of protons per beam of few \(10^{13}\) protons, a maximum beam energy of 3.5 TeV and a maximum luminosity of \(10^{32}\) cm\(^{-2}\) s\(^{-1}\). In case the beam parameters will change, the corresponding radiological risk can be forecasted by simple extrapolation. The radiation risks during the LHC operation are different than those during maintenance periods and will be addressed in the following paragraphs.

Radiation risks during the LHC operation

The main radiation risk during the LHC operation is the exposure of workers and public to prompt ionising radiation and to radioactivity released in air and water. During the LHC operation only some areas close to the beam tunnel are accessible (e.g. service areas of the experiments). The workers in the service areas might be exposed to high-energetic, mixed radiation fields (hadrons, leptons, photons) with energies up to GeV. About 90 % of the received personal dose will be due to neutrons, about half of the neutron dose will be due to neutrons with energies above 20 MeV. The expected ambient dose equivalent rates due to prompt ionising radiation are low, even under nominal conditions – due to thick shielding walls between the experimental caverns and service areas. In USA15 the ambient dose equivalent rate will reach 2 to 4 μSv/h for the nominal operation, in 2010 levels are expected not to exceed the natural background radiation level by a factor of two as luminosity will reach only about 2% of its nominal value. In 2010, persons working in USA15 will receive individual doses of less than 100 μSv/year and a collective dose of about 2.5 mSv/year. The radiological conditions for workers in the service caverns of CMS, ALICE and LHCb are more favourable when compared to the ATLAS experiment, due to a very thick shielding wall in case of CMS and due to much lower luminosities in case of ALICE and LHCb.

During the LHC beam operation, activated air might be released into the environment. The amount of radioactivity scales with beam energy and beam losses in case of the tunnel air or with luminosity in case of the air from the experimental caverns or the inner triplet. Mainly short-lived radionuclides (\(^{11}\)C, \(^{13}\)N, \(^{14}\)O, \(^{15}\)O, \(^{41}\)Ar) are produced and result in the risk of mainly external exposure of members of the public. In 2010 the individual dose to a person of the respective reference group might be, under the most unfavourable conditions, in the order of 100 nSv/year for LHC Point 1 and about 1 μSv/year for LHC Point 7. For the nominal operation the dose to the person of the reference group may reach about 5 μSv/year for LHC Point 1 and 4 μSv/year for LHC Point 7 – assuming that the requested modifications of the air management system at LHC Point 7 have been implemented until then. The modifications foresee a...
confinement of the air activated around the collimators in Point 7 to allow short-lived radionuclides to decay before the air will be released into the environment after beam stop.

**Radiation risks during the LHC maintenance and repair**

The main radiation risk during the LHC maintenance is the external exposure of workers to gamma radiation. The photons are emitted during the decay of radionuclides which have been induced in accelerator-, detector components and tunnel structure by beam losses (accelerator) or beam-beam interactions (experiment detectors, inner triplets) during the operation. The gamma energies of these photons do not exceed 2.7 MeV (emitted by $^{24}$Na). The risk of external exposures has to be assessed for all types of LHC maintenance and repair works, the additional risk of internal exposure of workers needs to be assessed in case of destructive activities (cutting, welding, etc.), maintenance of some mobile equipment (presence of grease or other lubricants), change of filters, etc.

The radioactivity of a component is a function of its chemical composition, its impurities, the radiation field which the component was exposed to, the beam energy, and beam losses or luminosity. Typically, the ambient dose equivalent rates at a certain cooling time are dominated by the decay of nuclides with half-lives of the order of the respective cooling time, i.e., short-lived radionuclides shortly after the beam stop and by longer-lived radionuclides after few months of cooling.

During the first year of operation the ambient dose equivalent rates will be low. Three examples are given:

1) **LHC ARCs**: the ambient dose equivalent rates have been calculated, assuming 180 days of operation, a beam gas interaction rate of 2400 protons/m/s at 3.5 TeV assuming a H$_2$-equivalent beam gas density of $4.5 \times 10^{14}$/m$^3$. Under these assumptions, the ambient dose equivalent rates inside the arc magnets, close to the beam line will reach 5 μSv/h after one day of cooling. On the surface of the arc magnet not more than 50 nSv/h are expected. The ambient dose equivalent rate close to the beam line will decrease to 1 μSv/h and on the surface to 20 nSv/h after one week of cooling (see Figure 1).

2) **Inner Triplet**: the ambient dose equivalent rates have been calculated assuming one month of operation and a luminosity of $10^{32}$/cm$^2$/s. The expected dose rates on the surface of the cryostat will be 10 μSv/h after one week of cooling, few μSv/h after one month and 1 μSv/h after 6 months of cooling time (see Figure 2).

![Figure 1: Monte Carlo results for ambient dose equivalent rates in the LHC arcs, assuming 180 days of operation, an H$_2$ equivalent beam gas density of 4.5 $10^{14}$/m$^3$ and a beam gas interaction rate of 2400 protons/m/s at 3.5 TeV.](image-url)
3) **Collimator Region**: After one year of operation at the nominal beam intensities the ambient dose equivalent rate in the aisle close to the collimators at Point 7 will reach some mSv/h after few days of cooling. At the end of 2010 the ambient dose equivalent rate is expected to reach about 100 μSv/h, i.e. a factor of 20 lower (see Figure 3).

**RP REQUIREMENTS FOR THE LHC MAINTENANCE AND REPAIR**

*Repair and maintenance of accelerator and detector components*

All LHC underground areas with exception of USC55 are presently classified as “Supervised Radiation Areas”. With increasing beam intensity and energy, the radiological classification will change due to increasing ambient dose equivalent rates. Only radiation workers are allowed to work in the LHC underground areas or to maintain radioactive material from the LHC in auxiliary areas. Any destructive work like machining, cutting, drilling, etc. on machine components and tunnel infrastructure requires a radiological risk assessment in collaboration between DGS-RP and the maintenance team. Work procedures and choice of tooling need to be discussed with and approved by DGS-RP prior to the start of the work. These RP requirements might have a strong impact on consolidation works like the opening of the interconnects or the installation of safety valves, in particular as techniques causing contamination risks like grinding will not be permitted.
Maintenance and repair work in areas like the collimator regions, inner triplets, TAN, TAS, beam dump areas, etc. will be the first ones to become subject to CERN’s formal approach to ALARA [2]. Prior to each job and with the aim to optimise the dose to personnel, a detailed job and dose planning might be necessary and will be elaborated in collaboration between DGS-RP and the respective RSO and maintenance team. The approach to minimise the individual and collective doses comprises optimised work coordination, editing and respecting of maintenance and repair procedures, use of optimised tools, design and material. In case the predicted, individual dose will exceed 1 mSv or the predicted collective dose will exceed 10 mSv the job needs to be submitted to the ALARA committee for approval [3].

All material and components that have been inside the LHC tunnel or inside the operational zone of the LHC experiments during the beam operation are subject to a mandatory radiological control by DGS-RP. Only controlled material will be permitted to leave the LHC premises. The owner transports portable material into one of the buffer zones where he will register it. RP will control the material and inform the owner on the radiological risk due to the foreseen handling of the material. Heavy material and material from radiation areas with increased risks (Limited stay area and above) will be controlled in situ by DGS-RP. DGS-RP follows up closely the maintenance and repair of items with considerable radioactivity. All radioactive material has to be maintained in appropriate workshops – but presently only few, adequate workshops are available at CERN like the mechanical workshop in Building 109. As a consequence, compensatory measures need to be implemented, like limiting the number of maintenance and repair jobs to the absolute minimum, applying sophisticated and time consuming risk assessments to ensure safe working conditions at temporary, suboptimal work places and a very tight and close control by DGS-RP. The lack of properly equipped and grouped workshops results in measures which are costly in manpower, time and budget for all parties involved. The refurbishment of Building 867 as a central work area for maintenance of radioactive equipment will mark a big step towards a state-of-the-art infrastructure for handling of radioactive material.

The operation of the LHC will double the total amount of radioactive material at CERN. Parts of the material will be taken out of the experiments and the accelerator for maintenance and repair inside and outside of CERN. The material will be transported, repaired and maintained, stored and in some case even sent to collaborating institutes and companies outside CERN. At the end of its lifetime it will be declared as waste. At each of these single stages of its lifecycle the radioactive item or parts of it risk to be mixed with non-radioactive material, due to various reasons like the lack of appropriate infrastructure or the need to test radioactive and non-radioactive material at the same, highly expensive test bench, etc. Obviously all radioactive material will be marked with the appropriate warning stickers, but the implementation of a modern traceability system of material leaving the LHC will allow for following up the history of a radioactive item. It will increase the overall efficiency of the laboratory with respect to the separation of radioactive and non-radioactive material, the transport inside and outside CERN, the storage and waste management of radioactive items. The LHC experiments developed and are implementing a modern traceability system for all items leaving the experimental caverns. In case of the accelerator a functional specification has been released [4], however, the technical implementation is pending as responsibilities for the overall maintenance of the accelerator traceability system still need to be defined.

**Water management**

Cooling water of accelerator and detector components will be either directly activated by the interaction of hadrons with the stable nuclei of hydrogen, oxygen and chemical impurities (e.g. $^3$H, $^7$Be) or contaminated by radionuclides removed from radioactive accelerator or detector components (e.g. $^{60}$Co). Ion exchangers installed within the demineralised water circuits will filter and retain a major part of the radioactivity. The radioactivity of the demineralised water will most likely not exceed the limit above which it needs to be treated as radioactive water but the ion exchangers need to be treated as radioactive.

The risk of a direct activation of infiltration water will be low – according to estimates. Potential contamination (e.g. by $^{22}$Na, $^{24}$Na) due to leaking from activated concrete is difficult to predict.

The Radiation Protection Group will perform regular sampling campaigns of demineralised and infiltration water to keep control over the risk for workers and the public. In addition, retention basins at LHC Point 3 and Point 8 will decrease the radioactivity released in water.

**Air management**

The air in the accelerator tunnel and the experimental caverns will be activated during the beam operation, due to the direct interaction between hadronic particles and the stable nuclei of e.g. oxygen, nitrogen and argon. The activated air has to be confined within the tunnel and experimental caverns, no activated air should penetrate into adjacent areas like service galleries, service caverns and the LHC surface area. The activated air has to be conducted and released into the environment via well defined pathways and release points. All air releases potentially containing radioactivity need to be monitored with respect to the total air volume and total radioactivity. The contribution to the dose of the public is calculated from measured released activities.

The LHC air management scheme is supposed to mitigate three risks: oxygen deficiency hazards due to
accidental gas releases, in particular helium releases, fire and the dispersion of radioactive air. Oxygen deficiency hazards (ODH), fire and air activation require very similar protection measures: compartmentalisation of the installation, confinement of air and gas, controlled air and gas flow as well as well defined release points. After the incident in Point 3-4 in September 2008 compensatory measures had to be taken to protect workers against an accidental release of helium. The ventilation doors between the tunnel and the UA service galleries had to be removed to enable depressurisation and fast release of helium gas from the tunnel. This action resulted in a partial loss of compartmentalisation, confinement and controlled air flow. Consequently, a second set of compensatory measures had to be applied:

- the LHC beam power needs to be limited to about a tenth of the value for the nominal operation to avoid possible, undue and uncontrolled releases of radioactivity into the environment (radiation protection requirement). This constraint will be lifted upon the reestablishment of the compartmentalisation.
- any access into the service galleries needs to respect a 30 minutes waiting time to allow for the decay of potentially present radioactivity in the air (radiation protection requirement)
- during the power testing in one sector, the adjacent sectors need to be closed (ODH mitigation requirement)

With respect to fire protection no measure can be applied to compensate for the loss of compartmentalisation.

In order to restore state-of-the-art safety and radiation protection conditions the following requirements have to be implemented:

- Overpressure in machine service areas (UA, UL, US) when compared to the machine tunnel (reinstallation of the ventilation doors, closure of cable ducts and holes, etc.)
- Overpressure in service areas accessible during the beam operation when compared to the experimental caverns and accelerator tunnel
- Continuous monitoring of the pressure differences, and air flow with its direction
- Monitoring of activated air in experimental areas – spot-wise at the beginning, if required permanent in at a later stage
- Monitoring of all released radioactivity will require additional monitoring stations at LHC Point 4 and Point 6

CONCLUSION
The first year of the LHC operation foresees a rather low beam intensity, beam energy and luminosity. As a consequence the associated radiological risks for workers and public are limited and the doses to workers and public have been extrapolated.

CERN’s infrastructure is not yet completely optimised with respect to the transport, maintenance, repair and storage of radioactive items. Work areas for radioactive material need to be properly refurbished and grouped, an efficient traceability system for all radioactive material from the LHC accelerator shall be implemented.

The LHC air management scheme shall meet the requirements of ODH mitigation, fire and radiation protection which are compartmentalisation, confinement and controlled air flow. The required actions to be taken during the next shut-down are sealing of areas, implementation of pressure cascades, the installation of ventilation and fire doors and the installation of additional air monitoring stations at Point 4 and Point 6.

REFERENCES
[2] Critères et Exigences ALARA applicable aux Interventions (EDMS 810176)
[4] Equipment Traceability (EDMS 1012291)