

Induced radioactivity and residual dose rates in the LHC experiments

I. Kurochkin^{1,2}, S. Roesler¹, C. Theis¹, C. Urscheler¹, H. Vincke¹

¹CERN, CH-1211 Geneva 23, Switzerland, ²IHEP, Protvino, Russian Federation

Abstract

The Large Hadron Collider (LHC) at CERN started beam operations in 2008 and has clearly outperformed initial expectations. At the two biggest LHC experiments, ATLAS and CMS, the delivered integrated luminosity (which refers to the number of inelastic interactions during a certain time interval) for 2011 has been exceeded by a factor of almost 6 compared with its initial goal given at the beginning of 2010. LHCb and ALICE are operating already at their nominal luminosities and even above.

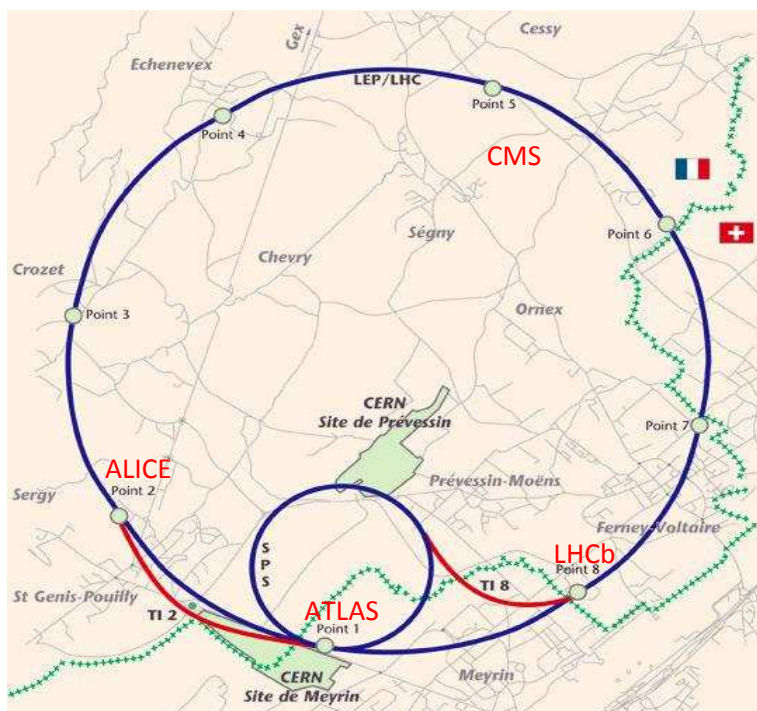
Consequently, radiation levels in the LHC experiments are increasing. Further, the amount of radioactive material inside the experiments is becoming larger. Predictions of the expected residual dose rate during accesses are necessary in order to plan and co-ordinate work activities inside the experimental caverns. The Monte-Carlo particle transport code FLUKA was used to assess the expected prompt and residual dose rates at the LHC experiments. Further, the code was used to calculate the amount of material which would become radioactive and therefore requires special treatment and alertness when being handled, modified, stored or shipped. Estimates of radiation levels are presented and compared with the first measurements. An outlook of the expected radiation levels after several additional years of LHC operation is also given.

Introduction

The superconducting Large Hadron Collider (LHC) [1] is the world's largest and highest-energy particle accelerator and is located deep underground below the Franco-Swiss border near Geneva, Switzerland, (see Figure 1). The LHC consists of a 14 TeV (centre-of-mass energy) accelerator (presently operated at 8 TeV) and is installed in a 27 km long tunnel. This tunnel was originally constructed for the Large Electron Positron (LEP) collider at CERN which operated from 1989 to 2000 before liberating the tunnel for the LHC. Two transfer lines (TI 2 and TI 8) are acting as injectors to the LHC and connect the LHC to CERN's accelerator complex. At present, seven experiments have been approved for the LHC. Four of them, ALICE [2], ATLAS [3], CMS [4] and LHCb [5], are large experiments, LHCf [6], MoEDAL [7] and TOTEM [8] and are much smaller.

LHC operation started in 2008 and has achieved exceptional performance clearly outperforming initial expectations. As a consequence, dose rates in the LHC experiments are increasing as well as the amount of activated material is becoming larger. The Monte-Carlo particle transport code FLUKA [9] [10] was used for predications of prompt and residual dose rates and for the activation of material at the LHC experiments.

Figure 1: Location of the LHC



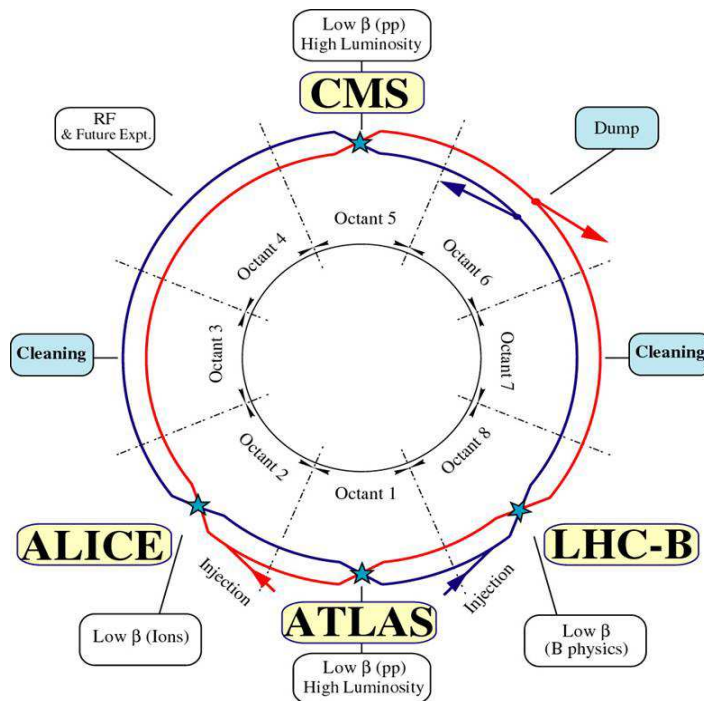
The four major LHC experiments

Four major experiments are installed at the LHC. Two of them, namely ATLAS and CMS are so called high luminosity¹ experiments. LHCb is operated at peak luminosities about a factor of 50 lower than in ATLAS or CMS whereas the peak luminosity in ALICE is about hundred times lower than in LHCb. Two counter-rotating beams are crossing each other at the 4 experiments roughly 11 000 times per second where they can be brought into collisions to study fundamental questions/laws of particle physics at high energy.

¹ Luminosity refers to the number of inelastic interactions during a certain time interval.

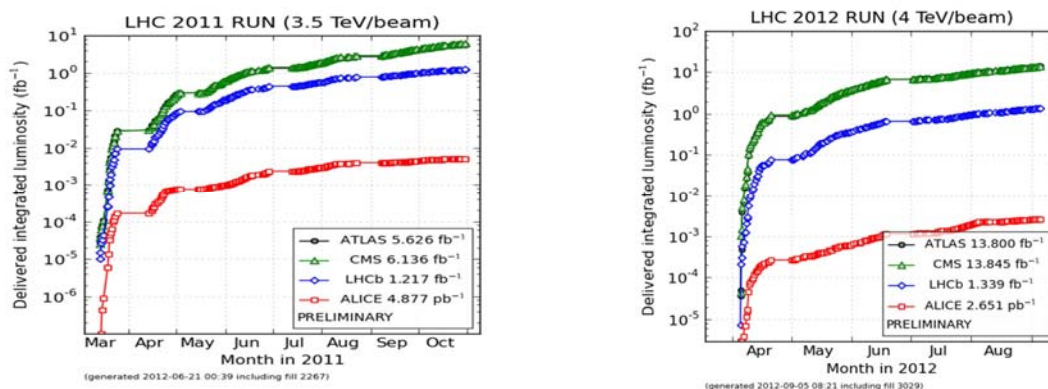
No access into the experimental caverns is possible during beam periods because the prompt dose rate is by far too high. Only well-shielded service areas and counting rooms in the underground are accessible during beam time.

Figure 2: The LHC and the 4 major experiments



LHC performance

The LHC is presently operating at performances well beyond first expectations. Estimates given in January 2010 about the integrated luminosity for 2011 were exceeded by a factor of 6. The LHC has delivered almost 6 fbarn^{-1} by the end of 2011 to ATLAS and CMS, (see Figure 3). In 2012 (not adding up the values from the past) the delivered luminosity is expected to reach $\sim 25 \text{ fbarn}^{-1}$ (by beginning of September 2012 almost 14 fbarn^{-1} were delivered already, see also Figure 3). In 2012, the peak luminosity has reached nearly 80% of the nominal luminosity of $1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with an average integrated luminosity of 1 fbarn^{-1} per week to ATLAS and CMS. ALICE and LHCb are operating already at nominal luminosities and even above.

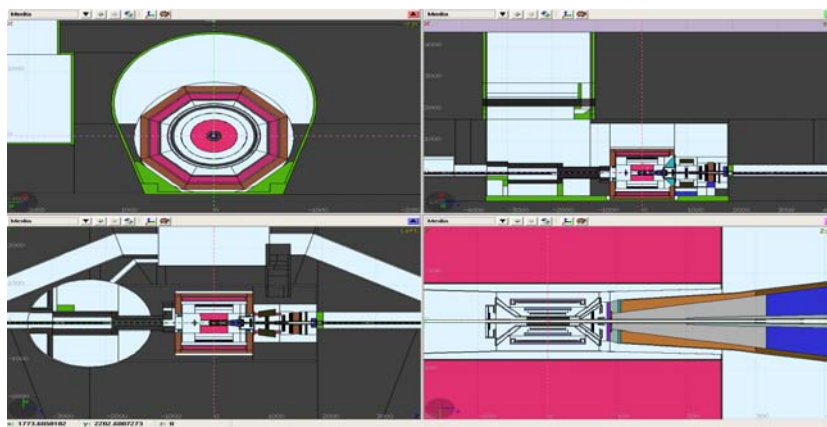
Figure 3: Luminosities delivered to the LHC experiments in 2011 and 2012, respectively

Radiological assessments for the LHC

Many radiological studies have been performed for the LHC experiments. This paper reports on residual dose rate up to 2022 inside the experimental cavern to which personnel could be exposed during access and maintenance work of detector components. An activation chart is also presented indicating which parts of the detectors are radioactive according to CERN's radiation protection legislation and therefore, require special treatment and alertness when being handled, modified, stored or shipped.

FLUKA simulations

All four major experiments have been modelled in detail with FLUKA, (see Figure 4). It should be mentioned that these geometries are very complex and are partially derived from work developed and updated by several contributors². Magnetic fields inside the magnets of the experiments were also well described and modelled within FLUKA.

Figure 4: FLUKA geometry of the ALICE experiment (shown with FLAIR³)

An important input for the radiological calculations is the proper description of beam intensities as well as beam operation and cool-down periods. Table 1 represents the

² Contributors: I. Dawson, A. Ferrari, A. Morsch, M. Huhtinen, L. Shekhtman, M. Karacson, Z. Zajacova, N. Ludovic, M. Guthoff, S. Mueller, M. Brugger, R. Veenhof and others.

³ <http://www.fluka.org/flair/index.html>.

beam operation schedule for ATLAS⁴ up to 2021/2022. In general, LHC operation starts in March/April with proton-proton (p-p) runs until end of October. Afterwards, the LHC programme continues with a heavy ion period of about 4 weeks followed by either a winter shutdown period (winter SD) for ~4 month or a so-called long shutdown (LS) which can last up to 2 years. These LSs are used for major upgrade activities of the LHC accelerator as well as for upgrade activities of detectors of the LHC experiments. It should be noted that the luminosity during the ion operation is considerable lower than during p-p operation. Consequently, the radiological conditions are dominated by the p-p run periods (with the exception of ALICE). Peak luminosity during the p-p collisions is up to a factor 1×10^7 higher in ATLAS and CMS than during Pb-Pb collisions periods.

Table 1: ATLAS beam operation schedule

Year	Period Run/SD/LSx	Peak luminosity $\text{cm}^{-2} \text{s}^{-1}$	Period length (months)	Efficiency	Collect $\text{fbarn}^{-1}/\text{period}$	Integrated fbarn^{-1}	Cooling (months)
2011	run	3E+33	3	0.25	5.8E+00	5.8	0
2011/2012	Winter SD	0	5	0.25	0.0E+00	5.8	5
2012	run	6.00E+33	8	0.2	2.5E+01	30.7	0
2012	LS1	0	2	0.2	0.0E+00	30.7	2
2013	LS1	0	12	0.2	0.0E+00	30.7	12
2014	LS1	0	12	0.2	0.0E+00	30.7	12
2015	run	1.00E+34	10	0.2	5.2E+01	82.6	0
2015/2016	Winter SD	0	4	0.2	0.0E+00	82.6	4
2016	run	1.00E+34	8	0.2	4.1E+01	124.0	0
2016/2017	Winter SD	0	4	0.2	0.0E+00	124.0	4
2017	run	1.00E+34	8	0.2	4.1E+01	165.5	0
2017/2018	LS2	0	16	0.2	0.0E+00	165.5	15
2019	run	2.00E+34	8	0.2	8.3E+01	248.4	9
2019/2020	Winter SD	0	4	0.2	0.0E+00	248.4	4
2020	run	2.00E+34	8	0.2	8.3E+01	331.4	0
2020/2021	Winter SD	0	4	0.2	0.0E+00	331.4	4
2021	run	2.00E+34	8	0.2	8.3E+01	414.3	0
2021/2022	LS3	0	24	0.2	0.0E+00	414.3	0

Residual dose rates in the experimental caverns

Detector equipment as well as beam line components located close to the beam pipe will get significantly activated in the high-luminosity experiments ATLAS and CMS. Therefore, significant shielding was placed aside these components in order to allow access into the cavern while preventing unjustified exposure. Both ATLAS and CMS have enough shielding around the beam pipe to reduce the radiation levels outside shielded areas to acceptable levels. For example, if an access is required to the cavern, the radiation level immediately after the beam stop at the end of 2012 will be below $1 \mu\text{Sv/h}$ in the ATLAS cavern outside of the shielded areas, (see Figure 5). The highest dose rate of 10 to $20 \mu\text{Sv/h}$, in accessible detector areas of the four major LHC experiments, is being measured at the VELO location of LHCb shortly after a beam stop. Very similar values have been predicted also with FLUKA, (Figure 6). The radiation levels at ALICE are considerably lower than in all other experiments.

⁴ Provided by the ATLAS Radiation Safety Officer.

**Figure 5: Ambient dose equivalent rate in ATLAS
(only the upper part of the detector is shown, symmetric layout)**

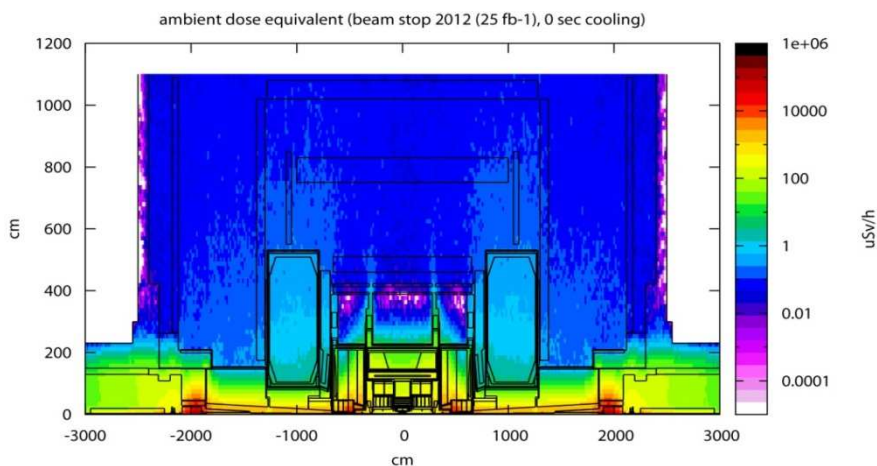
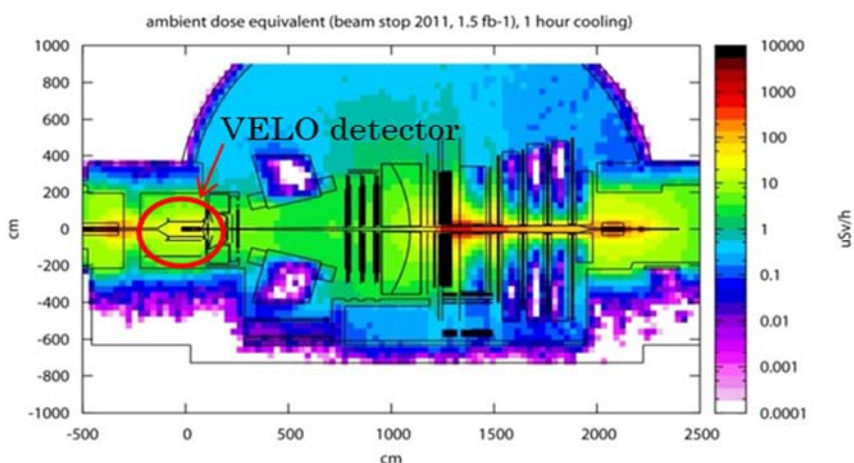


Figure 6: Ambient dose equivalent rate in LHCb



As shown in Figure 5, the radiation levels outside of the shielded components are small. However, this changes as soon as the shielding is opened to allow for access and the repair of components. This is illustrated in Figure 7, which shows the dose rate averaged over the first 14 cm around the beam line as a function of cooling time after the beam stop in 2012. It can be seen that the dose rate is about a factor of 100 lower at the end of LS1 (after 2 years of cool down) compared to the time when the beam will be stopped at the end of 2012 and about a factor of 50 lower compared to a cool down time of 1 week. It should be noted here, that the heavy ion run (due to the low luminosity) does not contribute significantly to the activation levels and can be considered as cool down time for ATLAS, CMS and LHCb.

A similar plot is shown in Figure 8, here, for a cool down time of 1 month following the beam stops in 2012, 2015, etc. up to the stop for the long shutdown 3 (LS3) at the end of 2021. It can be seen that the dose rate in LS2 (end of 2017) will be ~2 times higher than in LS1 and ~3 times lower than in LS3. The high dose rates at the Target absorber for secondaries (TAS) and the forward calorimeter FCAL are values inside the opening for the beam pipe and are normally not accessible unless being dismantled.

Figure 7: Ambient dose equivalent rate around the beam pipe of ATLAS (detector and shielding closed, averaged over 14 cm radius from the beam line)

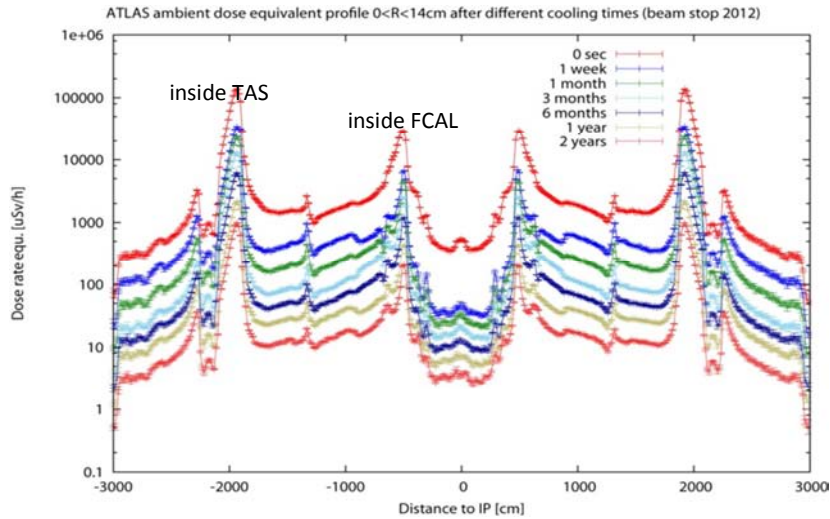
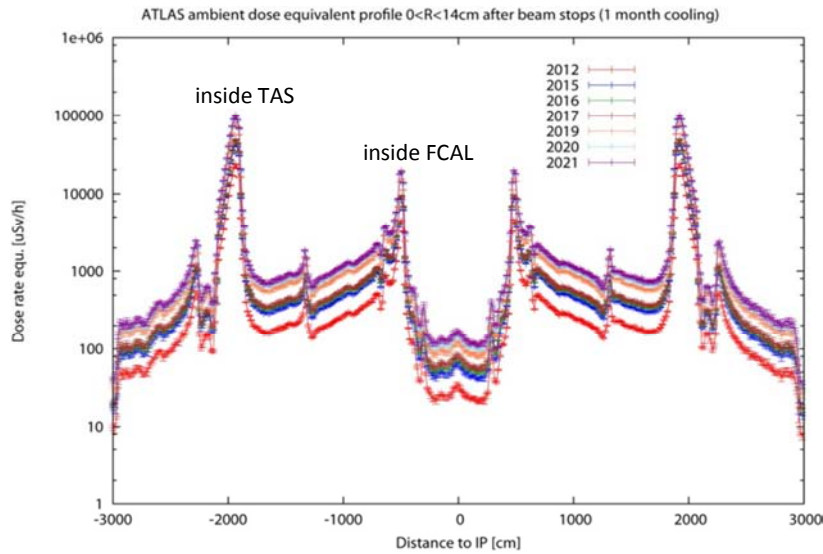


Figure 8: Ambient dose equivalent rate around the beam pipe of ATLAS



Calculation of specific activities inside the experimental caverns

FLUKA was also used to calculate the specific activity of components inside the detector and shielding material and these activities were compared afterwards with Swiss exemption limits. The following sum rule was used;

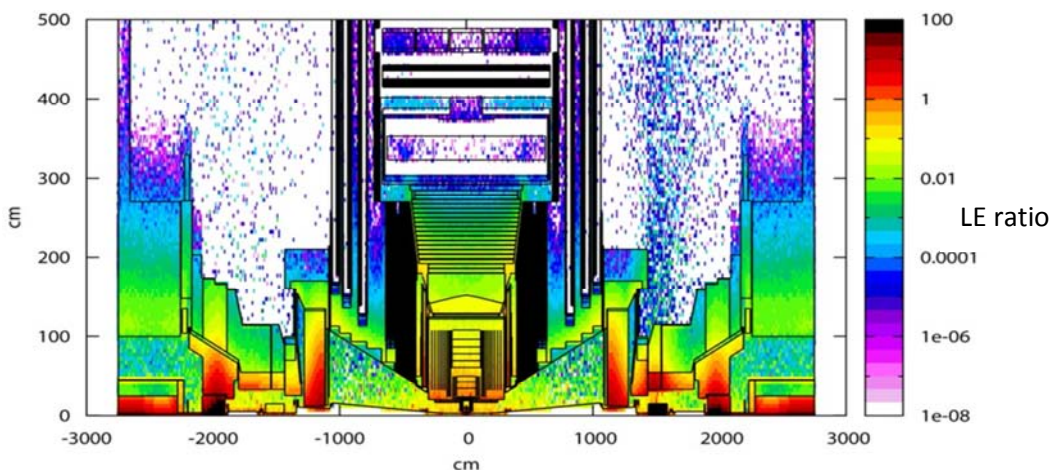
$$\sum_i \frac{a_i}{LE_i} \geq 1 \quad (1)$$

where a_i is the specific activity of the i -th radionuclide in the material and LE is the specific exemption limit given in Bq/kg for the corresponding radionuclide. In order to avoid over-conservative classification for very small quantities of material, the same ratio is also calculated based on total activity and the exemption limit in terms of Bq. As soon as the sum is greater or equal to 1 for both results (specific and total activity), the

material is considered as radioactive according to CERNs legislation (this is in line with the Swiss regulation). It should be emphasised that the specific activity is just one criterion for the classification of a material as radioactive. The two others are dose rate and surface contamination.

Figure 9 shows the “activation” chart for CMS which was used in 2011 to assess the boundary of radioactive vs. conventional material, as shown here, for a cool down time of 4 months. As said before, values above 1 indicate radioactive material.

**Figure 9: Specific activities/LE ratios at CMS
(4 month after beam stop in 2011)**



Measurements and comparison with calculations

Measurements at CASTOR

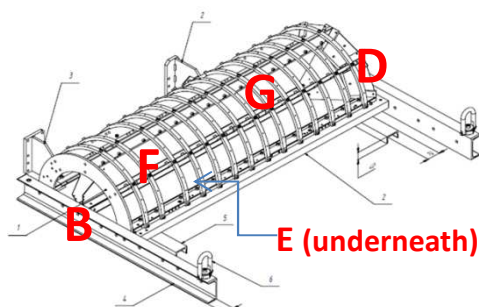
The removal of the CASTOR detector at CMS has provided a good opportunity to verify the estimates of residual dose rate with real measurements taken during the removal of the detector. The CASTOR detector was taken out in March 2012, 149 days after the end of the p-p run in 2011. CASTOR itself has a cylindrical shape and consists of 2 half cells which were removed separately from the beam line, (see Figure 10). Ambient dose equivalent rate measurements were performed after the removal of CASTOR. The dose rate was measured at 5 positions around one half cell of the cylinder, (see Figure 10). These results are shown in Table 2 together with the FLUKA estimates. Although the detector was not modelled in detail, the results are rather good. For example, the measurement at location E (on contact) showed 100 $\mu\text{Sv/h}$ whereas we predicted 89 $\mu\text{Sv/h}$.

Table 2: Ambient dose equivalent rate at CASTOR (measurement and calculation)

Position	Measurement in \cdot Sv/h	Calculation in \cdot Sv/h
F on contact	35	30
F at 100 cm	3	3
G on contact	14	11
G at 40 cm	5	4
G at 100 cm	2.5	2
E on contact	100	89
E at 10 cm	53	40
E at 40 cm	16	10
E at 100 cm	3.5	2.4

Figure 10: Specific activities/LE ratios at CMS

CASTOR detector at CMS.



Measurement locations.

Material samples

Different material samples were placed next to the CASTOR detector for another benchmark experiment. A similar set of samples were also placed on the opposite side of the CMS detector (here called “no-castor-side”) since CASTOR is installed only on one side of the CMS detector. The samples were Cu, Al, Pb and stainless steel with a well-known chemical composition and were put in place from the beginning of 2009 and were retrieved from their locations after the winter shutdown in 2011. Due to time constraints, only stainless steel samples could be taken out and were analysed with a Gammascintometer. The dominating 3 isotopes in the stainless steel samples are ^{54}Mn , ^{58}Co and ^{60}Co . With the exception of the ^{60}Co sample on the “no-castor” side the ratio between the FLUKA results and the measurements is very close to one, indicating a very good agreement, (see Table 3). Because ^{60}Co is produced by thermal neutron capture, a possible reason for the divergence of ^{60}Co production might be an underestimation of the low-energy neutrons in the “no-castor” side due to simplified geometry implementation.

Table 3: Measured and calculated activity in stainless steel samples

Sample	Radionuclide	Measured activity in Bq/g	Ratio FLUKA/measurement
Samples on the CASTOR side	^{54}Mn	7.3 ± 3.3	1.0 ± 0.5
	^{58}Co	6.1 ± 2.8	0.9 ± 0.4
	^{60}Co	0.7 ± 0.2	0.9 ± 0.3
Samples on the “no – castor” side	^{54}Mn	77 ± 35	0.9 ± 0.3
	^{58}Co	68 ± 24	0.9 ± 0.3
	^{60}Co	24 ± 7	0.3 ± 0.1

Summary

The LHC at CERN has produced sensational performance and is operating at almost nominal luminosities at ATLAS and CMS and even above at ALICE and LHCb. The Monte-Carlo particle transport code FLUKA was used extensively for radiation protection studies. A few of them, the ambient dose equivalent rates during beam down times, as well as charts, show which parts of the detector will become radioactive or not. Dose rates inside the experiment cavern are (and will be even in the future) reasonably low during accesses as long as the detectors are closed. As soon as the detectors are opened, the radiation levels are considerably higher and will reach mSv/h levels at the high luminosity experiments of ATLAS and CMS. Benchmark experiments showed very good agreement between calculated and measured values.

References

- [1] LHC design report (CERN-2004-003-V-1), <http://cdsweb.cern.ch/record/782076>.
- [2] ALICE collaboration, ALICE: Technical proposal for a Large Ion collider Experiment at the CERN LHC, CERN-LHCC-95-71, <http://cdsweb.cern.ch/record/293391>.
- [3] <http://cdsweb.cern.ch/record/290968> ATLAS Collaboration, ATLAS: technical proposal for a general-purpose pp experiment at the Large Hadron Collider at CERN, CERN-LHCC-94-43.
- [4] <http://cdsweb.cern.ch/record/290969>, CMS collaboration, CMS technical proposal, CERN-LHCC-94-38.
- [5] <http://cdsweb.cern.ch/record/622031>, LHCb collaboration, LHCb technical proposal, CERN-LHCC-98-004.
- [6] LHCf collaboration, Technical Proposal for the CERN LHCf Experiment, CERN-LHCC-2005-032, LHCC-P-007, 12 October 2005, <http://cdsweb.cern.ch/record/887108>.
- [7] MoEDAL Collaboration (2010), Technical design report of the MoEDAL experiment, CERN-LHC-2009-006, MoEDAL-TDR-1, 27 February 2010.
- [8] W. Kienzle *et al.* TOTEM collaboration, Total cross section, elastic scattering and diffractive dissociation at the LHC: Technical Proposal, CERN-LHCC-99-007, <http://cdsweb.cern.ch/record/385483>.
- [9] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso`, J. Ranft (2006), The FLUKA code: Description and benchmarking, *Proceedings of the Hadronic Shower Simulation Workshop 2006*, Fermilab 6--8 September 2006, M. Albrow, R. Raja (2007), eds., *AIP Conference Proceeding* 896, 31-49.
- [10] A. Ferrari, P.R. Sala, A. Fasso, J. Ranft, (2005), FLUKA: a multi-particle transport code, CERN-2005-10, INFN/TC_05/11, SLAC-R-773.