RADIATION PROTECTION:
HOW (RADIO)ACTIVE ARE WE GOING TO BE?

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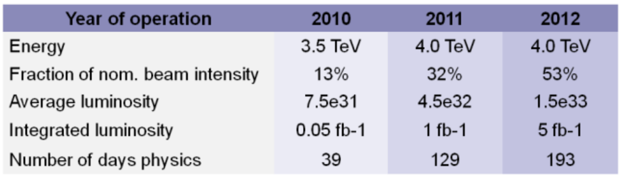
Abstract

Operation in 2010 has caused the first components to become radioactive. An overview of the present residual dose rates around the machine is given. It shows that measurable activation is presently limited to a few components only, such as collimators and absorbers. The procedures to be applied for maintenance and repair work in the tunnel and/or workshops reflect the low radiological risk. However, the comparison to calculated residual dose rates also confirms results of studies and adds confidence in predictions for operation in 2011/12. The latter are given assuming operation at 4 TeV with up to 53% of nominal beam intensity. At the same time, predictions by pure simulation have limitations which are outlined. In order to overcome them, assessments combined with measurements are planned and will be summarized. Finally, the implications of the envisaged operational scenarios for 2011/12 on maintenance and consolidation work as well as on the validity of compensatory measures are detailed.

OPERATIONAL PARAMETERS AND DERIVED SCALING FACTORS

During the year 2010 the LHC has stored beams of up to 368 bunches and a total intensity of 4.3×10^{11} protons at 3.5TeV. Peak luminosities reached values of about $1\times10^{32}/\text{cm}^2/\text{s}$. Predictions for operational conditions which might be achieved in the coming two years are summarized in Table 1 [1].

Table 1: Operational parameters [1].



Year of operation	2010	2011	2012
Energy	3.5 TeV	4.0 TeV	4.0 TeV
Fraction of nom. beam intensity	13%	32%	53%
Average luminosity	7.5e31	4.5e32	1.5e33
Integrated luminosity	0.05 fb-1	1 fb-1	5 fb-1
Number of days physics	39	129	193

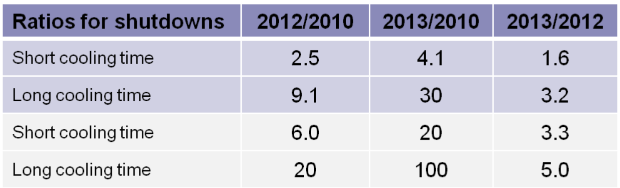
It is assumed that beam intensities will gradually increase up to about 1/3rd of nominal intensity in 2011 and about ½ of nominal intensity in 2012. Similarly, peak luminosities are expected to increase by factors of six and 20, respectively, as compared to last year. With these values, integrated luminosities of 1/fb in 2011 and 5/fb in 2012 can be obtained. Assuming that the luminosity is on average 75% of its peak value and an operational efficiency of 20%, about 129 days of physics operation would be required in 2011 to achieve the goal of 1/fb and 193 days in 2012 to reach 5/fb.

These parameters can serve as basis of a first rough estimate of the evolution of induced radioactivity. The activation in the arcs and collimation regions is determined by the beam intensity. At a certain cooling period, nuclides dominate which have half-lives of about the cooling time. Thus, residual dose rates at short cooling times (few hours to days) are determined by short-lived nuclides (of which the activities have most likely reached saturation), *i.e.*, they reflect the operational parameters of the week preceding the beam stop and roughly scale with the average beam intensity. For example, if the intensity was 32% at the end of the run in 2011 and 53% at the end of 2012, the residual dose rates at short cooling times will be higher by about a factor of 0.53/0.32=1.6. On the contrary, at cooling times of several months long-lived nuclides, that may not yet have reached saturation, dominate the dose rates. In this case, the total number of beam particles lost in the area preceding the given moment matters for dose rate estimates. Assuming that losses scale roughly with beam intensity the residual dose rates at long cooling times increase with the integrated number of circulating protons, which yields, for example, a factor of 3.2 after the run in 2012 as compared to the situation after the 2011 run.

With similar arguments, the evolution of activation around the experiments (detectors, inner triplets, *etc*.), which is dominated by secondary particles from the interaction points, can be estimated. In this case, the average luminosity of the week preceding the beam stop determines the dose rates at short cooling time while the dose rates after several months of cooling reflect the integrated luminosity.

Table 2 summarizes the scaling factors obtained with the arguments discussed above. For example, the 2011 run will increase the residual dose rates in the arcs by factors between 2.5 and 9.1 (depending on the cooling time) and operation in 2012 will cause a further increase by factors between 1.6 and 3.2. Around the inner triplets at Points 2 and 5 a stronger increase is expected, by factors between 20 and 100 until the end of 2012.

Table 2: Scaling factors derived from the operational parameters. The first two lines give the factors for areas where losses scale with beam intensity, the latter two lines show those where activation is caused by p-p collisions.



Ratios for shutdowns	2012/2010	2013/2010	2013/2012
Short cooling time	2.5	4.1	1.6
Long cooling time	9.1	30	3.2
Short cooling time	6.0	20	3.3
Long cooling time	20	100	5.0

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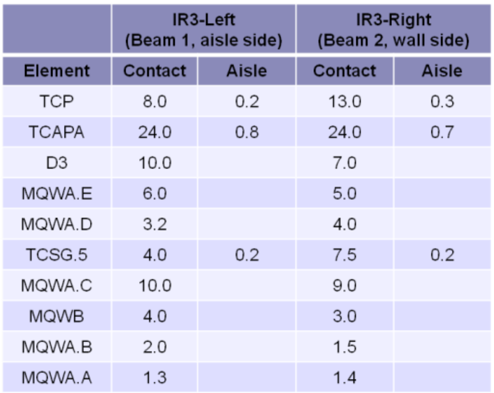
PRESENT RADIOLOGICAL SITUATION

At present (technical stop 2010/11) all LHC underground areas are classified as Supervised Radiation Areas [2], mostly not because of the residual dose rate levels but due to the fact that accelerator components are potentially radioactive. Residual dose rates at cooling times of about two months after the proton run are at background level, except for a few localised areas in the collimation regions of Points 3 and 7, the TAS absorbers at Points 1 and 5 and the beam dumps.

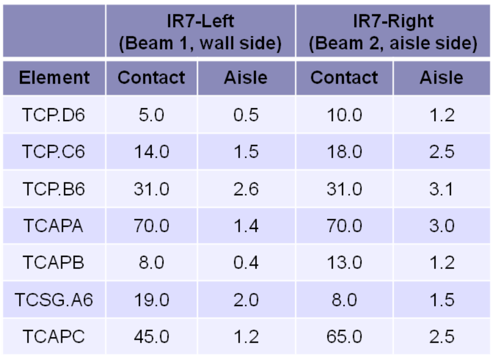
Tables 3 and 4 list residual dose rates measured with an AD6 detector on contact to the most radioactive components as well as in the aisles at Points 3 and 7, respectively. The date of the measurements (early January 2011) corresponds to about two months of cooling time after the proton run. The ion run is assumed to give a negligible overall contribution to the activation due to the much lower intensities (number of accelerated nucleons) as compared to proton operation, except for a few spots in the dispersion suppressor regions where no beam protons but ion fragments of certain rigidities are lost.

Table 3: Residual dose equivalent rates (in μSv/h) in the momentum cleaning insertion at Point 3 as measured on 1/10/2011.



	IR3-Left (Beam 1, aisle side)		IR3-Right (Beam 2, wall side)	
Element	**Contact**	**Aisle**	**Contact**	**Aisle**
TCP	8.0	0.2	13.0	0.3
TCAPA	24.0	0.8	24.0	0.7
D3	10.0		7.0	
MQWA.E	6.0		5.0	
MQWA.D	3.2		4.0	
TCSG.5	4.0	0.2	7.5	0.2
MQWA.C	10.0		9.0	
MQWB	4.0		3.0	
MQWA.B	2.0		1.5	
MQWA.A	1.3		1.4	

Table 4: Residual dose equivalent rates (in μSv/h) in the betatron cleaning insertion at Point 7 as measured on 1/7/2011.



	IR7-Left (Beam 1, wall side)		IR7-Right (Beam 2, aisle side)	
Element	**Contact**	**Aisle**	**Contact**	**Aisle**
TCP.D6	5.0	0.5	10.0	1.2
TCP.C6	14.0	1.5	18.0	2.5
TCP.B6	31.0	2.6	31.0	3.1
TCAPA	70.0	1.4	70.0	3.0
TCAPB	8.0	0.4	13.0	1.2
TCSG.A6	19.0	2.0	8.0	1.5
TCAPC	45.0	1.2	65.0	2.5

The tables show that presently the most radioactive components are the passive absorbers (TCAPA/B/C), followed by the primary (TCP) and first secondary collimators (TCSG). Dose rates on contact are of the order of tens of μSv/h, in the aisle they do not exceed 3μSv/h. The latter values justify that also the collimation regions are classified as Supervised Radiation Areas.

It should be mentioned, that systematic checks proved the absence of contamination.

GENERIC STUDY

In order to obtain more realistic scaling factors, *i.e.*, factors which take into account the actual irradiation pattern for the years 2010-12 (see Table 1) a generic study was performed with the FLUKA Monte Carlo code [3,4]. The calculations utilized a generic collimator geometry that had been used previously to assess the influence of different material choices, beam energies and particle types on residual dose rates [5]. It consists of two rectangular, vertical jaws of a length of 120 cm made of carbon. The cooling system is approximated by two copper plates with an artificially reduced density, in order to account for its actual design based on water-cooled pipes, fixed to the jaws with stainless steel clamps. The entire assembly is finally placed into a stainless steel tank. Figure 1 shows a cross sectional view through the geometry. The geometry also includes a tunnel wall which, however, is of minor importance due to its small contribution to the dose rate close to the absorber.

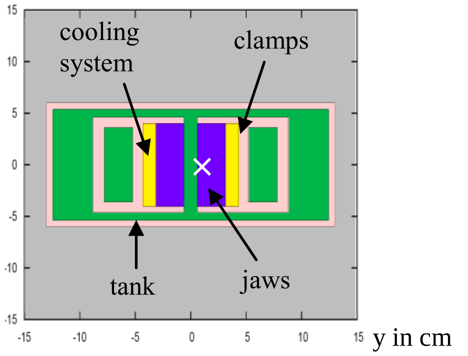


Figure 1: Cross sectional view of the absorber geometry. The beam impact point is indicated with a white cross.

For the calculations, a pencil beam of 4TeV protons was assumed to hit one of the jaws at a distance of 4mm to its edge (see Figure 1). Residual dose rates, scored in a one-dimensional, longitudinal binning (*i.e.*, in beam-direction) at 2cm above the absorber, were calculated for the operational cycle between 2010 and 2012 and cooling times between one week and four months using the parameters given in Table 1.

The scaling factors obtained from this calculation are shown in Table 5 together with those estimated by scaling beam intensities (Table 2). As expected, the values calculated for the generic absorber between one week and four months of cooling are within the ranges for short and long cooling times. Moreover, using the operational scenarios of Table 1 the run in 2012 will increase the dose rates only by about a factor of two in the arcs and at Point 3, where significant consolidation and upgrade works are planned for the next long shutdown. Thus, pre-cautions to be taken during the work to limit the radiological risks will not depend on the year of the shutdown, *i.e.*, whether it is in 2012 or 2013.

The calculations also yield the cooling time dependence of the residual dose rates which is given in Table 6 relative to one month cooling. Consequently, the dose rates drop by about a factor of two between one week and one month cooling and by another factor of 2-3 between one and four months of cooling.

Table 5: Scaling factors derived from operational parameters for short and long cooling times (first and last line, taken from Table 2) as well as obtained with the generic study.

Ratios for shutdowns	2012/2010	2013/2010	2013/2012
Short cooling time	2.5	4.1	1.6
One week cooling	3.9	7.4	1.9
One month cooling	4.9	10.0	2.0
Four months cooling	6.6	15.0	2.3
Long cooling time	9.1	30	3.2

Table 6: Ratios of residual dose equivalent rates at a certain cooling time and at one month cooling.

Dose rate relative to one month cooling	2011	2012	2013
One week cooling	2.3	1.9	1.7
One month cooling	1.0	1.0	1.0
Four months cooling	0.3	0.4	0.4

RESIDUAL DOSE RATE ESTIMATES FOR THE NEXT LONG SHUTDOWN

The above scaling factors allow one to predict residual dose rates for the next long shutdown based on the present measurements. The resulting values are given for some of the components in Points 3 and 7 in Tables 7 and 8, respectively. As can be seen, dose rates on contact to some of the passive absorbers at Point 7 may reach 1mSv/h, the dose rates in the aisle are in general of the order of tens of µSv/h. For this reason the tunnel sections at Points 3 and 7 containing the collimators will have to be classified as Controlled Radiation Areas [2] where job and dose planning becomes obligatory.

Of course, these estimates carry significant uncertainties, also due to the underlying assumptions such as scaling with beam intensity, the identical collimator settings until 2013, *etc*.

All radiological studies for the collimation system are based on nominal performance parameters of the LHC. In order to compare to residual dose rates predicted for nominal conditions a further scaling in intensity (factor of two) and beam energy (factor of $(7.0/3.5)^{0.8}=1.7$) has to be applied to the values given in Table 8 for January 2013. For example, this would result in a dose rate on contact to the first passive absorber (TCAPA) of 3.6mSv/h ($1\text{mSv/h} \times 2 \times 1.7$, see Table 8). This agrees approximately with the FLUKA results for nominal LHC parameters presented in Ref. [6] (see values inside the black circle in Figure 2).

Table 7: Estimated residual dose equivalent rates (in µSv/h) in the momentum cleaning insertion at Point 3 for January 2012 and January 2013.

IR3-Right	January 2012 (Jan.2011 x fac.6.6)		January 2013 (Jan.2011 x fac.15)	
Element	Contact	Aisle	Contact	Aisle
TCP	86.0	2.0	195.0	4.5
TCAPA	158.0	5.0	360.0	11.0
D3	46.0		105.0	
TCSG.5	50.0	1.3	113.0	3.0
MQWA.C	60.0		135.0	

Table 8: As in Table 7, here for the betatron cleaning insertion (Point 7).

IR7-Right	January 2012 (Jan.2011 x fac.6.6)		January 2013 (Jan.2011 x fac.15)	
Element	Contact	Aisle	Contact	Aisle
TCP.D6	66.0	8.0	150.0	18.0
TCP.C6	120.0	17.0	270.0	38.0
TCP.B6	205.0	21.0	465.0	47.0
TCAPA	460.0	20.0	1050.0	45.0
TCAPB	86.0	8.0	195.0	18.0
TCSG.A6	53.0	10.0	120.0	23.0
TCAPC	430.0	17.0	975.0	38.0

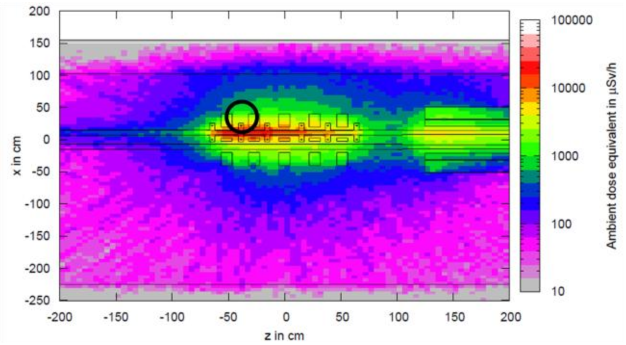


Figure 2: Ambient dose equivalent rate distribution around the passive absorber TCAPA at Point 7 (in µSv/h) for losses at nominal LHC energy and intensity [6]. The location of the measurement performed in January 2011 is indicated with a black circle.

In order to predict induced radioactivity in more detail around interconnects between cold arc magnets dedicated FLUKA studies were performed. Here, activation is dominated by beam-gas interactions. In the calculations a residual gas density of $10^{15}H_2$-equivalent/m^3 is used; results can be easily re-scaled to any other measured value. The studies are based on a sophisticated FLUKA geometry and input of the collimation and dispersion suppressor region at Point 7 developed by the FLUKA team [7].

Figures 3 and 4 show the residual dose rate distributions in the area between magnets MQ11 and MQ13 due to beam-gas interactions of beam 1 one month after the runs in 2011 and 2012, respectively. Only on contact to the innermost parts (*e.g.*, beam pipe) values exceed 1μSv/h. At locations accessible for a human body dose rates are well below that value indicating that risks due to external irradiation in the arcs should in general be low.

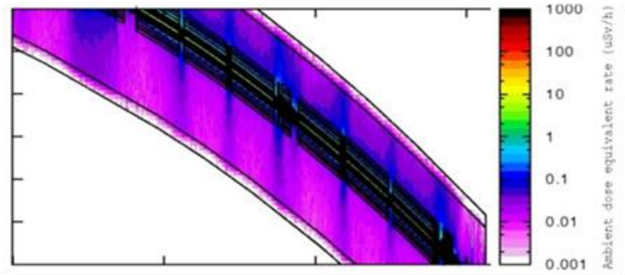


Figure 3: Ambient dose equivalent rate distribution (in μSv/h) due to beam gas interactions at Point 7 between magnets MQ11 and MQ13 one month after the run in 2011.

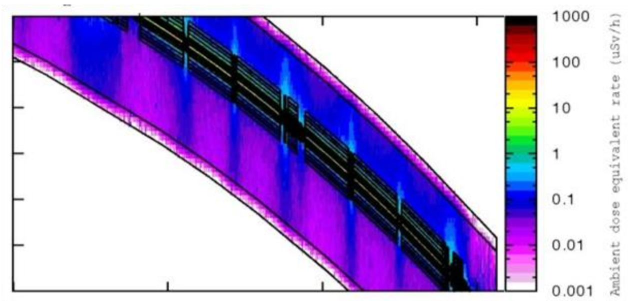


Figure 4: As in Figure 3, here one month after the run in 2012.

In addition to activation by beam gas interactions, localised areas of increased radioactivity exist where protons diffractively scattered in primary collimators or ion fragments are lost. Results of related studies were presented elsewhere [8] and showed that contact dose rates of the order of 10μSv/h can be expected in these locations after one month of cooling. Due to the limited number of such spots, the risk due to external irradiation during consolidation work still remains low.

CONSOLIDATION OF INTERCONNECTS

The consolidation of the LHC interconnects also involves machining and soldering with the associated risk of releasing radioactivity as dust, in fumes, *etc.* Thus, a risk analysis is imperative based on an estimate of the nuclide inventory. At present, the latter can only be obtained by means of FLUKA calculations; later on (prior to the work) measurements will add further information.

Figure 5 shows the FLUKA geometry of the simulated interconnect between two dipole magnets. It includes a detailed representation of the M-lines taking into account the actual material compositions [9].

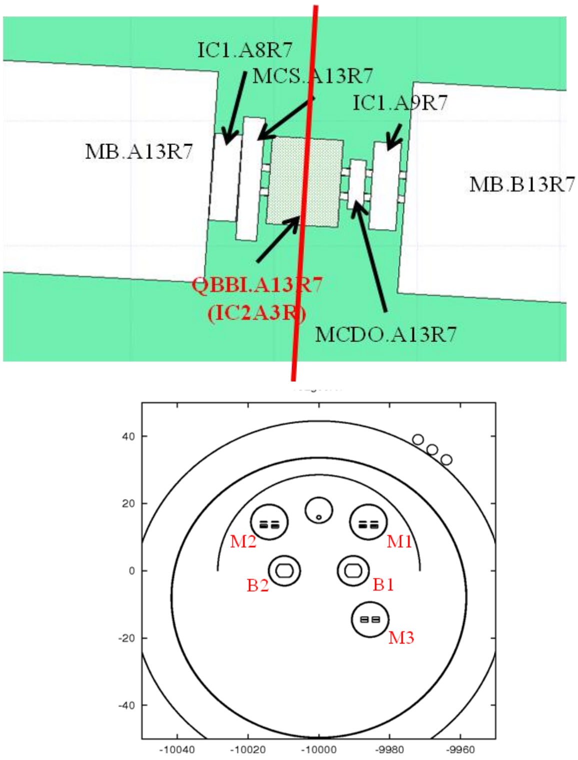


Figure 5: Top view of the FLUKA geometry of the interconnect between the dipole magnets MB.A13R7 and MB.B13R7 (top) and transverse section (bottom) at the position of the red line indicated in the top panel.

In each of the components the specific activity due to beam-gas interactions in beam 1 was scored and divided, for each nuclide, by the CERN exemption limit for radioactive material [10]. By definition, if the sum of these ratios over all nuclides exceeds unity for both total and specific activities the component is classified as radioactive material. It is also radioactive if the residual dose rate at 10cm distance is larger than 100nSv/h after subtraction of the background. Assuming a residual gas density of $10^{15}H_2$-equivalent/m^3 the above mentioned sum-rule for specific activity yields for both the M1-pipe (stainless steel) and the super-conduction cable (copper), see Figure 5, a value of 0.3 one month after the run in 2012. The contribution of trace elements and solder is difficult to assess with reasonable statistical significance.

However, generic studies showed that, for example, for silver this value is about a factor of 20 higher. Taking into account the small amount of such elements they should not add a significant contribution.

Thus, the study indicates very low activation of the interconnects in the arcs and, consequently, a low risk of contamination and internal exposure should the radioactive nuclides be released during the consolidation work. Nevertheless, the ALARA principle requests pre-cautions to be taken that contain any released particles or dust and avoid spreading it, *e.g.*, vacuum cleaners, plastic foils to protect the work-site *etc*.

Unfortunately, the estimates of specific activities in the interconnects carry large uncertainties of various sources, such as

- beam-gas pressure,
- activation by so-called scrubbing runs,
- loss assumptions (sharing of losses between IR3 and IR7, losses in heavy ion runs),
- differences between actual and simulated geometries (collimator settings, imperfections, *etc*.),
- statistical uncertainties,
- models for predicting induced activity.

Thus, verification by measurement becomes essential. This includes systematic RP-survey measurements during technical stops in order to monitor the evolution of residual dose rates as well as the analysis of BLM-readings, integrated over the year, in order to identify loss points. Furthermore, samples of materials, especially those which have to be machined during the consolidation works (copper, stainless steel, tin, silver), will be placed outside of the interconnects (see Figure 6). Gamma-spectroscopy measurements together with FLUKA simulations (providing the gradient in activation between bus-bar and sample location) would then allow a verification of the present estimates and the assessment of the actual risks well before the work starts.

Figure **6**: Position of material samples to be placed outside of the interconnects (red boxes).

CONFINEMENT OF ACTIVATED AIR

At Point 7, air venting Sectors 6-7 and 7-8 is extracted and released into the environment. In order to reduce the annual dose to the reference group of population below the optimization goal of 10μSv it was decided to enclose the areas with the highest particle losses at Point 7 by ventilation doors such that the release of short-lived nuclides is minimized [11]. Up to now, bypass ducts, guiding the air from the adjacent sectors through the loss areas, are installed and the ducts in the TZ76 gallery have been removed. As outlined in Ref.[12] the optimized ventilation scheme must be fully functional as soon as losses exceed one half of the value predicted for nominal operation. Thus, the installation must be completed in the next long shutdown or latest in 2013. Of course, in order to minimize job doses time-consuming modifications close to radioactive components (installation of door frames, *etc*.) should be implemented as soon as possible.

Furthermore, a complete separation of the air volumes in service areas and machine tunnel should be achieved during the next long shutdown [13]. This concerns mainly the re-installation of ventilation doors in the UP galleries (*e.g*., UP63/67), which had been removed to provide a path for an accidental helium release, and the sealing of the ducts between UA galleries and machine tunnel.

CONCLUSIONS

Based on the operational scenarios for the LHC during the years 2011/12, beam-intensity-dependent activation and residual dose rates are expected to increase by about a factor of 4-7 during the 2011 run and by another factor of two during 2012. Thus, radiation protection constraints and recommendations for shutdowns in 2012 and 2013 are quite similar. Of course, it assumes that losses scale linearly with beam intensity and neglects the contributions from scrubbing or ion runs. The luminosity-dependent activation (mainly the detectors and inner triplets) will increase by a factor of 20-100 until 2013.

Presently the entire LHC is classified as Supervised Radiation Area with low activation and dose rate levels (January 2011: maximum dose rate in the aisle: 3μSv/h, maximum dose rate on contact to a passive absorber in Point 7: 70 μSv/h). During technical stops and shutdowns in 2012 and 2013 a few limited areas (*e.g*., IR3/7) will have to be classified as Controlled Radiation Areas where job and dose planning is obligatory.

Residual dose rates in the arcs after the 2012 run are estimated to be very low (no limitation in duration of work). A few localised areas in the dispersion suppressor regions (loss points of protons or heavy fragments “leaking” from the straight section) might show measurable residual dose rates (<10 μSv/h). Despite low residual dose rates in these areas, components might become “radioactive” according to CERN regulations and dissipation or incorporation of this radioactivity must be prevented (ALARA principle).

Due to significant uncertainties it is important to continuously monitor the evolution of activation (*e.g.*, survey measurements, material samples) to be able to further optimise work plans and schedules. In areas where civil engineering will be required (*e.g.*, dispersion suppressor regions in IR3) concrete samples should be placed in order to demonstrate absence of activation prior to the work.

The full functionality of the ventilation bypass in IR7 has to be established in the next long shutdown. The separation of the LHC tunnel and service area air volumes has been improved and additional monitoring at Point 4 and 6 is being added. However, a full sealing between service areas and machine tunnel has to be established in the next long shutdown.

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