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0.3.	24. 3. 2010	Added Linac 2/4 simulation part Revised all table and figure numbers Completed bibliography Completed Executive Summary	Th. Otto
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The Preparatory Phase of the Large Hadron Collider upgrade (SLHC-PP) is a project co-funded by the European Commission in its 7th Framework Programme under the Grant Agreement n^{o} 212114. SLHC-PP began in April 2008 and will run for 3 years.

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EXECUTIVE SUMMARY

The report SLHC-PP-M5.1-982404-v1.0 has identified a number of areas in the sLHC and in the injector chain where the impact of ionizing radiation on workers and the public may be elevated and which merit special consideration. Additional considerations have been made during 2009, and another area of interest for radiation protection has been added.

The present report presents these areas briefly, it describes the impact of ionizing radiation and gives recommendations for further action in order to mitigate the hazard.

On the worksite of **Linac 4**, a new injector accelerator on the critical path to sLHC, measures have been taken to protect the construction workers (not classified as radiation workers) from ionizing radiation emerging from the operating Linac 2. A combination of additional shielding walls and a radiation interlock by a monitor is assuring that ambient dose equiovalents on the worksite remain below 0.5 μSv h^{-1}, the dose rate limit for publicly accessible spaces.

SPL and **PS 2** are the injector accelerators planned to renovate CERN's aging injector complex for delivering reliably the required number of protons to sLHC. They are built with modern methodologies, minimizing beam loss. Nevertheless, all aspects of radiation protection must be studied in the planning phase of these accelerators. In SPL wide vertical shafts are needed to accommodate 16 bundled RF waveguides each. These shafts with a diameter of 2.8 metres are a pathway for neutron scattering and the ambient dose rates in the Klystron Buildings must be studied. The radiation transport calculations performed demonstrate that additional work is required to optimize the radiation impact.

The PS 2 injection dump is a planned beam loss point, a first design of its shielding is provided such that worker can access the dump for short periods of time during shut-downs of the accelerator.

The **inner triplets** are the last quadrupole magnets before the interaction points (IP) in the ATLAS and CMS detectors. In order to provide increased luminosity for sLHC, they must be replaced by new models, providing better focusing of the beams. Due to their closeness to the IP, the inner triplets are exposed to an intense bombardment of secondary particles emerging from the p-p collisions and will become strongly activated. For their dismantling (before installing new triplets), either a long waiting time after the stop of the LHC for allowing radioactive decay, or the retrofitting of remote-controlled manipulators and tools is necessary. The design of new inner triplets should include an optimized approach to dismantling.

1. LINAC 2 – LINAC 4 INTERFACE

The injector Linac 2, after having supplied protons at *E* = 50 MeV to CERN's high-energy accelerators since 1972, will be replaced by a new injector, Linac 4. Linac 4, producing negative hydrogen ion beams at an energy *E*=160 MeV is an essential element to overcome proton beam intensity limitations in the existing injector chain, and it is on the critical path of the migration towards sLHC. The envisaged date of replacement is in the period 2014 / 2015. In order to respect this schedule, it is indispensable that construction work on LINAC 4 can progress during the whole year. The transfer tunnel connecting LINAC 4 to the existing injector PS Booster, must be constructed in immediate vicinity of the LINAC 2 – PS Booster transfer tunnel (Figure 1). Before start of the construction, this area was covered by earth and thus inaccessible. The construction work made excavation necessary and the relatively thin outer wall of Linac 2 is now accessible. Civil engineering and accelerator construction work in this area must progress even when the proton beams from LINAC 2 are transported to the PS Booster.

Figure 1. Worksite of the interface between Linac 4 transfer tunnel and Linac 2. The workers are close to the outer wall of Linac 2.

For the protection of workers against the effects of ionizing radiations, the following steps had to be taken:

- Assess the radiation hazard on the newly created construction site
- Classify the worksite as a radiation area, if necessary
- Classify the workers as radiation workers, if necessary

The objective of the process was to keep the work site unclassified, with full access for members of the public, thus avoiding the classification of the construction workers as radiation workers. This objective translates into a limit of ambient dose equivalent rate of $H^*(10) = 0.5\ \mu\text{Sv/h}$ under all operating conditions of LINAC 2.

A first estimation of radiation levels on the worksite [1] showed that additional barriers must be provided within LINAC 2 to protect the worksite against ionizing radiation from routine beam loss in the LINAC 2 transfer line, and that a radiation monitor must provide an interlock on LINAC 2 operation, should exceptionally high beam loss occur.

Due to the complexity of civil engineering structures in the area, the simple line-ofsight approach in [1] had to be very conservative, limiting severly the use of Linac 2 as LHC injector during the construction work. Progress could be made with Monte-Carlo simulations of radiation transport from hypothetical loss points in Linac 4, explicitly taking into account all walls and galleries between Linac 2 and the worksite in the Linac 4 transfer tunnel [2].

Figure 2 shows a representation of the geometry file submitted to the simulation programme. An example of the graphical representation of a result file is given in Figure 3.

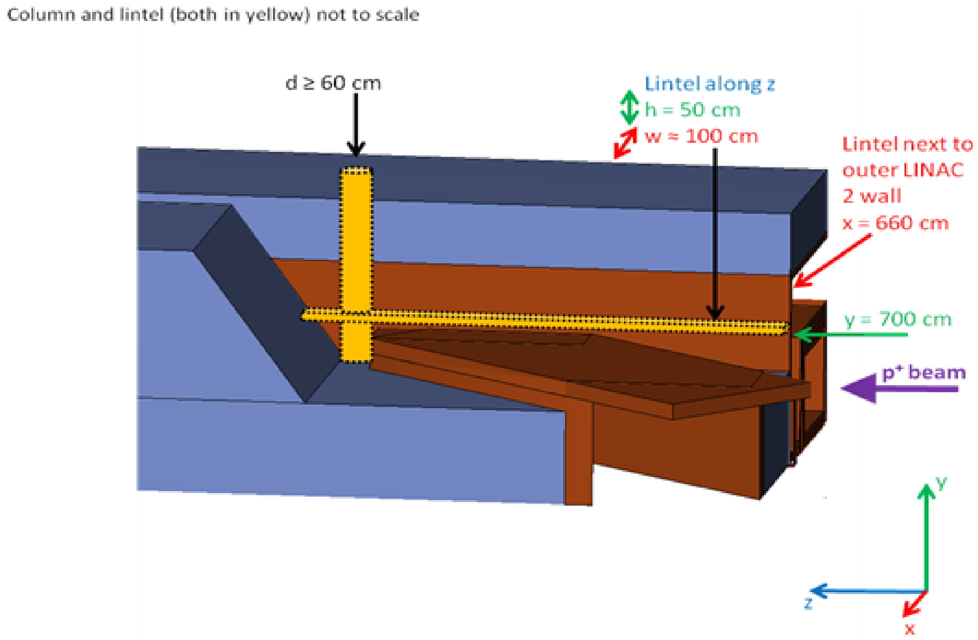

Figure 2: 3-d view of geometry file for Monte-Carlo simulation of dose rate on Linac 4 worksite.

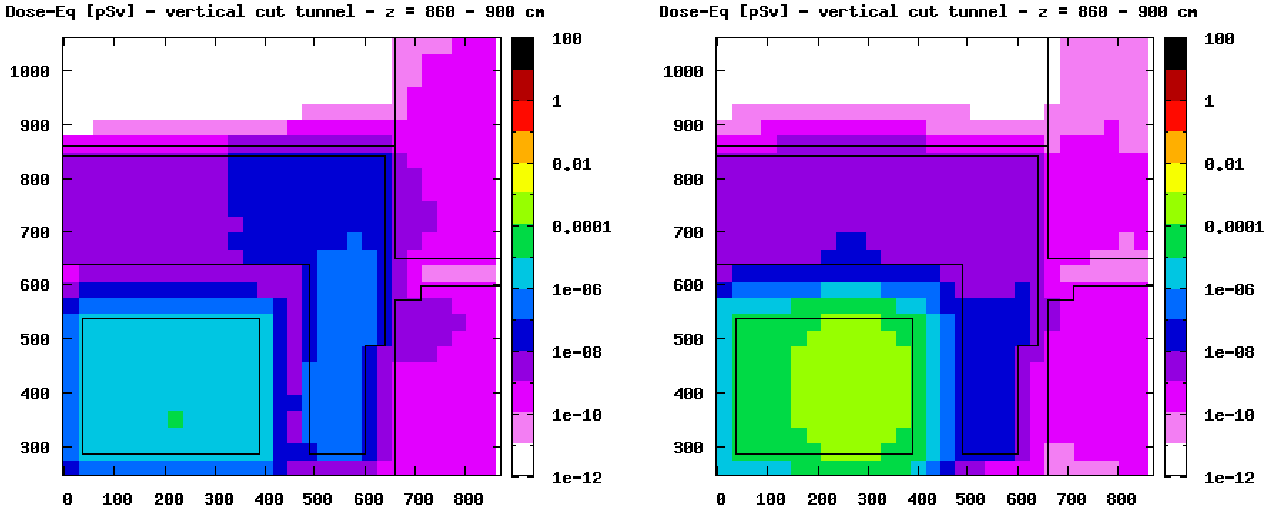

Figure 3: 2D projections of tunnel section LINAC 2 – LINAC 4 interface: Maps of dose equivalent including the LINAC 2 tunnel (left structure on bottom) with the klystron gallery (middle layer) and the LINAC 4 tunnel (the roof is visible on the right). In this plot, the bins are 30 cm in x and 30 cm in y averaged over the bins z = 860 – 900 cm. The beam loss points are either in front of the entrance to the klystron gallery (TP1) [left figure] or 5 meters upstream (TP2) [right figure].

The result of the refined estimations is, that the interlock level of the radiation monitor inside the klystron gallery can be modified depending on the completion of certain construction steps. The values given in Table 1 for the radiation monitor are reduced by about 25 % to account for measurement uncertainties of the monitor. The uncertainties of the simulations are already considered within the “minimum attenuation factor”.

At the first construction stage (until covering of the hole in the LINAC 4 roof), the interlock value for the radiation monitor is set to 6.0 µSv/h. If the backfill towards the LINAC 2 tunnel is finished, the radiation monitor limit can be raised to 13.5 µSv/h. The beam loss in L:inac 2 hypothetically required to reach these ambient dose rate equivalents at the monitor position are far higher than routine losses. Normal operation of Linac 2 in spite of the work site is thus assured.

Table 1: List of attenuation factors for LINAC 4 building site and recommended interlock values for the radiation monitor.

Construction stage	Minimum attenuation factor	Recommended attenuation factor	Interlock value for radiation monitor
	[-]	[-]	µSv/h
Hole in LINAC 4 roof	15.84	12.0	6.0
Completed LINAC 4 roof	20.41	15.5	7.7
Completed backfill	35.71	27.1	13.5

2. NEUTRON STREAMING THROUGH SPL RF DUCTS

In one of the scenarios for the upgrade of CERN's injectors towards sLHC, a superconducting linear accelerator for protons (SPL) with an energy of up to 5 GeV and a new Proton Synchrotron (PS2) with an energy of up to 50 GeV are planned to replace the PS Booster and the PS. A tentative layout of the planned accelerators, integrated into the CERN accelerator complex, is shown in Fig. 4.

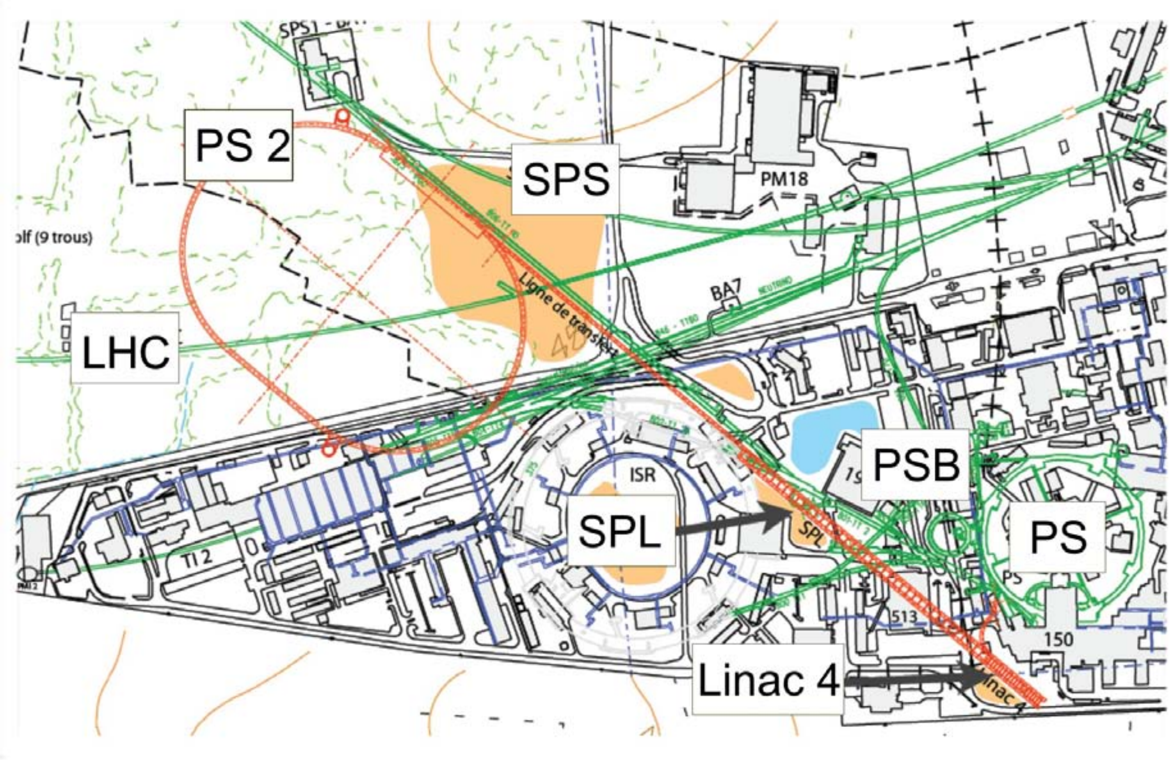

Figure 4. Layout of the LHC injectors at present and in the future.

The underground construction of the SPL shields the environment effectively against stray radiation from beam loss in the accelerator, with exception at the vertical shafts for the RF waveguides.

Injected 160 MeV H- ions from the Linac 4 into the SPL will be accelerated up to 4-5 GeV. The SPL tunnel will be situated in the earth at a depth between 20 and 30 meters. The expected uncontrolled losses are 1 W/m at each section of the SPL. Thus the radiobiological study has been started with the estimation of the dose rate level at the surface at the exit of the waveguide, caused by uncontrolled losses in the SPL [3].

The calculations of the prompt dose rate were performed by using the Monte Carlo code FLUKA. The first calculation was done for a proton beam energy of 5 GeV. The total length of the SPL is 550 meters, for the calculation 100 meters were taken. Along 100 meters three waveguide ducts (shaft) will be situated. The target in which the beam is lost was assumed by a 0.02 × 0.02 × 100 m^3 iron block placed at the beam height. The dose rate was calculated from the superposition of 11 sources, which were equally distributed all over the target. In Fig. 5 the radiation streaming in the SPL tunnel and in one of the shafts is presented. The most conservative case is for the shaft number 3 which is shown in the lower part of Fig. 5. Without implementing any waveguides in the calculations the dose rate on ground level is less than 50 µSv/h.

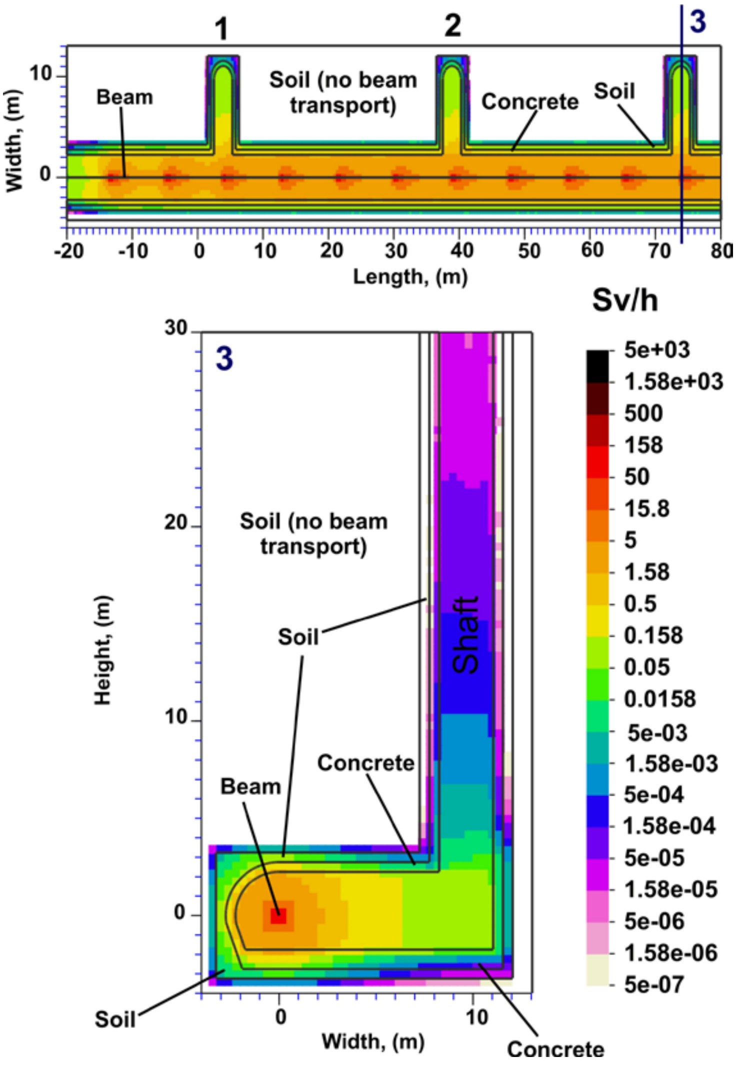

Figure 5: Neutron streaming through three waveguide ducts of SPL. Uncontrolled losses are assumed to be 1 W/m. The primary beam energy is 5 GeV. The importance biasing technique was used to improve the transport of the neutrons. The beam transport in the soil was switched off.

The same calculations were performed for the beam energy of 1 GeV. Assuming in this case also the beam losses of 1 W/m it was found out that the dose rate at ground level is by a factor of 3 higher than for the beam energy of 5 GeV. This lower energy is overcompensated by the higher intensity.

3. SPL-PS2 INJECTION DUMP

The PS 2 accelerator is proposed to replace the existing PS complex, to provide more reliable operation and improved basic beam parameters for the foreseen LHC luminosity upgrade. In the projected PS 2 accelerator various beam dumps will absorb beams. One of the beam absorbers, which has been studied in detail [4], will serve for stopping of unstripped H^0/H^- ions. It is planned to strip the H^- ions coming from SPL to PS 2 by using a charge-exchange H^- system. After a 500 µg/cm^2 foil 95 % of stripped H^+ ions will be accelerated in the SP 2 and the unstripped H^0/H^- ions will be dump. The beam load for the H^- dump is $6.4x10^{19}$ particles per year at the energy of 4 GeV .

3.1. THE BEAM DUMP DESIGN

As the starting point a design of the H- injection dump like the one proposed for Project X at Fermilab is studied The same parameters and materials were taken for the SP 2 beam dump. In Fig. 6 schematic geometry of the dump is shown.

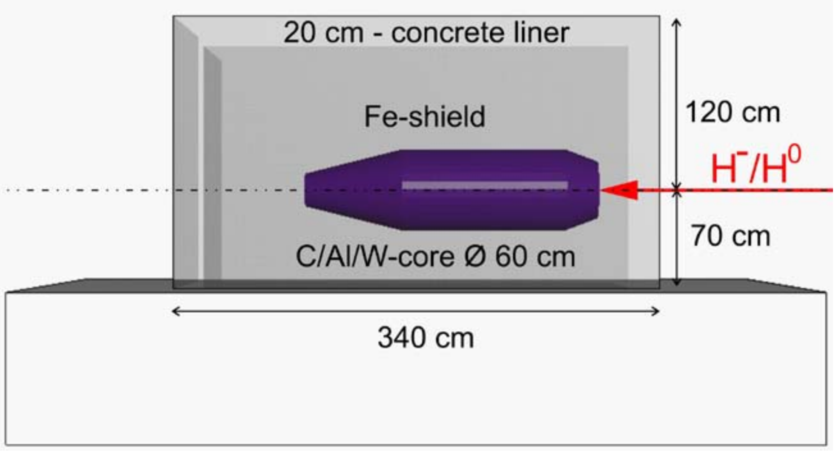

Figure 6: Geometry of the beam dump. The inner core consists of graphite, aluminium and tungsten. The core is surrounded by iron shielding. The outer layer of the shielding is concrete.

3.2. RESIDUAL DOSE CALCULATIONS

The design goal of the beam absorber is after irradiation and 8 hours of cooling, to have in the close vicinity of the absorber the residual ambient dose rates is not higher than 10 µSv/h. For the optimization the Monte Carlo code FLUKA was used. First of all, the geometry, as it is shown in Fig. 1, was taken for the calculation. The beam is assumed as a pencil beam. The intensity is $6.4E10^{19}$ protons uniformly distributed during 8 months of operations. The irradiation period is 10 years of operation, each of 8 months of beam operation and 4 months of shutdown. The dose is scored for 5 different cooling down periods after the last 8 months of irradiation: 8 hours, 1 day, 1 week, 1 month and 4 months. First calculations have shown that for reaching of our design goal the sizes of the dump had to be modified: the height of the iron part had to be increased by 20 cm, the width had to be 40 cm wider on each side; the tungsten core had to be shortened by 20 cm. The last result of the optimization is presented in Fig. 7. The residual dose rate after 8 hours of cooling is already below 10 µSv/h.

Only at the beam entrance of the dump the dose rate is above the limit. It can be solved by closing the entrance after the shut down.

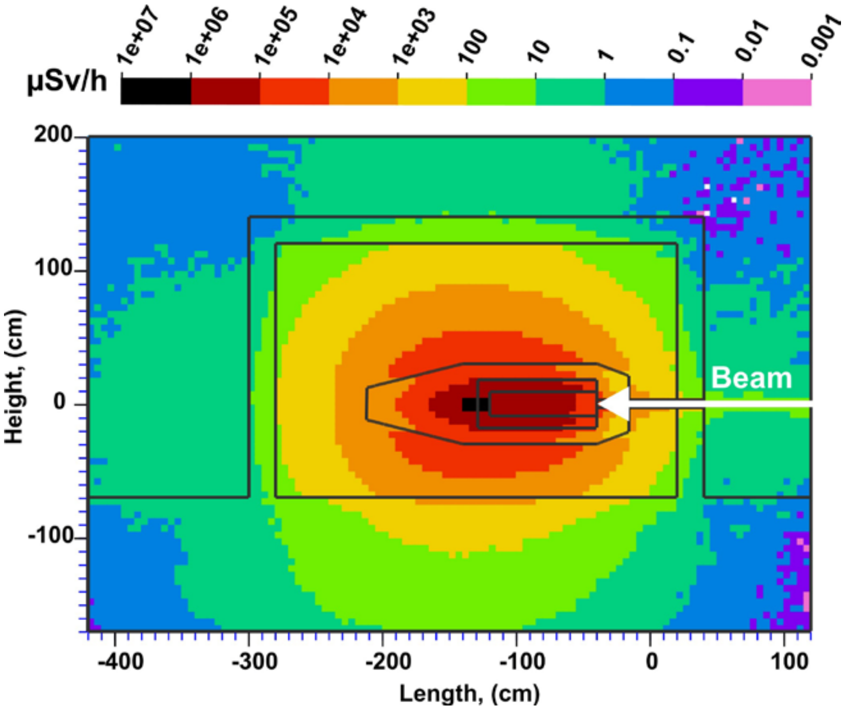

Figure 7: Plot of the residual dose rate after the irradiation period described in the text and a cooling time of 8 hours.

4. REPLACEMENT OF INNER TRIPLETS IN ATLAS, CMS

The inner triplet, consisting of three superconducting quadrupole magnets, focuses and directs the beam towards the interaction point. It is foreseen to replace the inner triplet by an upgraded version at the latest when the integrated luminosity has reached 400 fb^{-1}. The dismantling of the current triplet magnets has to be planned accurately due to the high dose rates in the interconnections regions. Monte-Carlo radiation transport calculations were performed with the code FLUKA for the vicinity of the inner triplets. In Figure 8 the horizontal dose rate distribution at beam height of the space in-between and around the interconnection of the quadrupoles Q1 and Q2 is shown. In the graph in Figure 9, the dose rate in the center between the two quadrupoles is shown as a function of the distance to the center of the counter-rotating beams. The discontinuities in the dose rate distribution at a distance of ± 50 cm from the beam axis originate mainly from shielding effects of the cryostat vacuum vessel and at ± 15 cm from the overlapping of the scoring bins with the beam pipes.

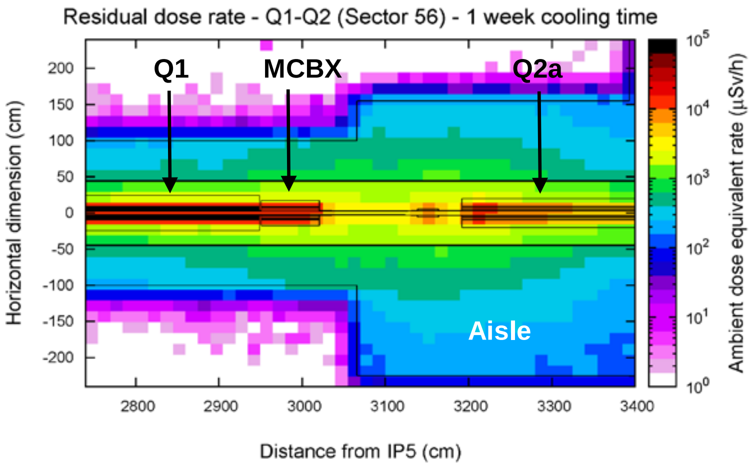

Figure 8. Ambient dose equivalent rate distribution in the area between the quadrupoles Q1 and Q2 after one week cooling and 180 days continuous LHC operation with 10^9 pp/s. The horizontal scoring layer was 30 cm thick and centered at beam height.

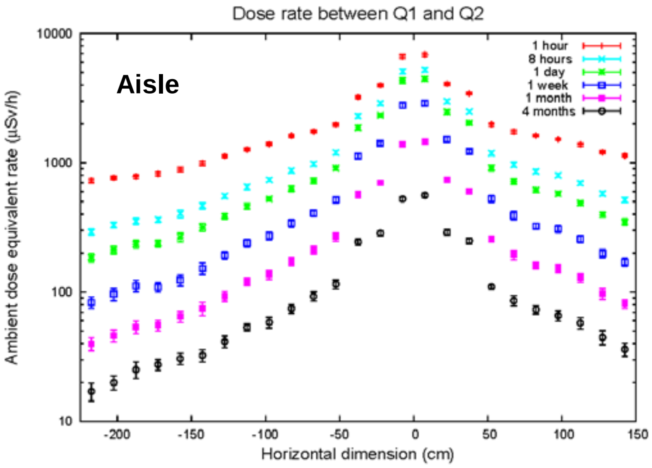

Figure 9. Ambient dose equivalent rates after 180 days continuous LHC operation with 109 pp/s for different cooling times between Q1 and Q2 in a distance of 3090 cm from the IP5. The dose rates are plotted as a function of the distance to the center between the two beams (the aisle is at negative values).

The dose rate distribution after a cooling time of 1 week in the connection space between the quadrupoles Q2b and Q3 is displayed in Figure 9. In general, the dose rates are slightly lower as between Q1 and Q2a even with the rather massive TASB cylinder (∅outer 12.5 cm, ∅inner 6.7 cm x 120 cm) located between Q2b and Q3. The distribution in the center between Q2b and Q3 as a function of the distance to the beam axis can be seen in Figure 10. In this graph, discontinuities appear for the same reasons as in Figure 8. The stronger increase of the two data points, which are closest to the beam axis, is due to the overlap of the scoring bins with the massive TASB in addition to the overlap with the beam pipe.

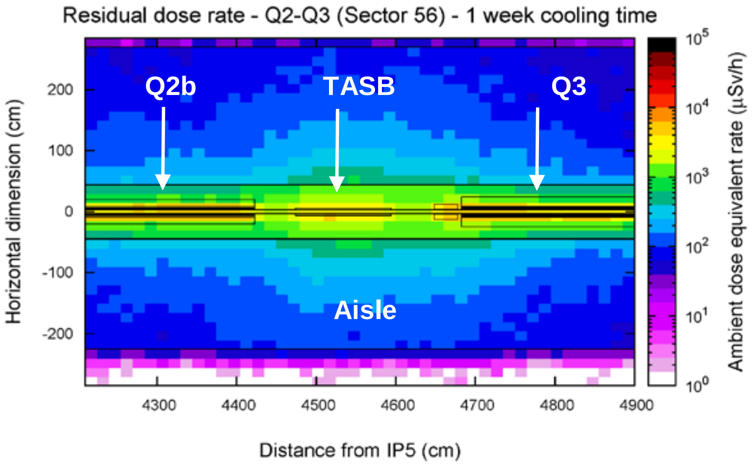

Figure 10. Ambient dose equivalent rate distribution in the area between the quadrupoles Q2b and Q3 after one week cooling and 180 days continuous LHC operation with 10^9 pp/s. The horizontal scoring layer was 30 cm thick and centered at beam height.

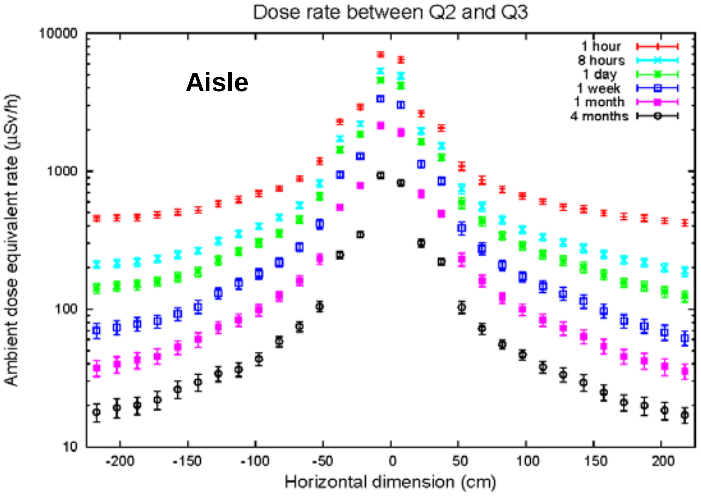

Figure 11. Ambient dose equivalent rates after 180 days continuous LHC operation with 109 pp/s for different cooling times between Q2b and Q3 in a distance of 4550 cm from the IP5. The dose rates are plotted as a function of the distance to the center between the two beams (the aisle is at negative values).

As can be seen from Figures 9 and 11, the ambient dose equivalent rates in the triplet inner region will attain values of several mSv h^{-1} for short waiting times for radioactive decay. The plots are prepared for one year (180 days) operation at nominal beam intensity (10^9 p-p collisions per second, corresponding to 50 fb^{-1} per year). While the exact value of integrated luminosity accumulated by 2015, when the triplets could be exchanged, is as yet unknown, the figures give a first appreciation of the problem. Even if the dose equivalent rates would be a factor of 2 smaller than those estimated, no continuous access by workers is possible to the worksite earlier than a few months after the stop of the LHC beams. Early dismantling of the present triplets would require the use of manipulators, which have not been planned and would have to be retrofitted at the dismantling stage. Otherwise, a delay in the installation of new triplets of several months must be taken into account.

5. REFERENCES

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