CALCULATION OF RESIDUAL DOSE RATES AND INTERVENTION SCENARIOS FOR THE LHC BEAM CLEANING INSERTIONS - CONSTRAINTS AND OPTIMIZATION

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Abstract

Radiation protection of the personnel who will perform interventions in the CERN LHC Beam Cleaning Insertions is mandatory and includes the design of equipment and the establishment of work procedures. Residual dose rates due to activated equipment are expected to reach significant values such that any maintenance has to be planned and optimized in advance. Three-dimensional maps of dose equivalent rates at different cooling times after operation of the LHC have been calculated with the Monte Carlo code FLUKA. The simulations include a new method based on an explicit calculation of induced radioactivity and of the transport of the radiation from the radioactive decay. The paper summarizes the FLUKA-simulations for the Beam Cleaning Insertions and discusses the estimation of individual and collective doses received by personnel during critical interventions, such as the exchange of a collimator. The given example outlines the potential of the new doserate simulation method but also the potential and the need to optimize, in an iterative way, the design of components as well as the layout of the beam cleaning insertions. As result of a first benchmark test under realistic accelerator conditions measurements and simulations of residual dose rates for a collimator test recently performed at the SPS are presented.

LIMITS & CONSTRAINTS

CERN's guidelines for the protection of the environment and personnel are compiled in the CERN Radiation Safety Manual [1] which is related to the French and the Swiss National Legislation and to the European Council Directive 96/29/EURATOM [2]. They all base radiation protection on three general principles: *Justification*, *Limitation* and *Optimization* of potential human exposure due to the use and operation of equipment emitting ionising radiation.

Therein the legal limit defines a value never to be exceeded nor to be reached and differentiates between category *B* workers not allowed to work regularly in high-radiation areas (6 mSv/year) and category *A* workers (20 mSv/year).

However, these limits and constraints cannot be directly applied during the construction and design work of an accelerator. It is therefore useful to introduce a design criterion in order to ensure that the above mentioned limits and constraints will not be exceeded during operation. Therefore, for high-radiation areas a design criterion of 2 mSv per person and per intervention is applied. Estimated or calculated individual doses getting close to 2 mSv must raise awareness and imply further optimization of work procedures.

It shall be noted that optimisation is only considered as automatically respected in the case the practice never gives rise to an annual dose of more than 100 μSv for persons exposed because of their own professional activity or 10 μSv for individuals not professionally exposed.

LHC PARAMETERS AND THE SITUATION AT IR7

High-energy particle cascades induced by beam particle losses lead to the activation of material in the respective zone of the accelerator. The dump caverns, the cleaning insertions, the inner triplets and the experiments will certainly be the regions showing the highest localized losses. Out of those it was found that with respect to the amount of possible interventions, certainly the beam cleaning insertions, especially Point 7 showing the highest losses, will be the most critical regions of concern, especially due to the foreseen phased installation approach [3].

The staged machine approach will also invoke a constant increase of beam losses during the first years of operation. However, all calculations presented later in this document refer to the so-called nominal loss intensity of 2.05×10^{16} protons per beam and year, the respective loss intensity under nominal operating conditions.

MONTE CARLO CALCULATIONS

To assess remanent dose rates in the betatron beam cleaning insertion at Point 7 extensive series of FLUKA [4, 5] calculations were performed, using a detailed geometrical model of the cleaning insertion, based on its final layout in Phase 1. To reach high accuracy for the results and to be able to calculate remanent dose rate maps for any arbitrary location, an already successfully benchmarked method developed by CERN/RP was applied [6].

The geometry includes all major beamline components like bending magnets, quadrupoles, collimators, etc., to the left and right of the interaction point. Details of the geometrical model of the simulation can be found in chapter 3 of [7].

In order to overcome the limitations of previous methods to calculate remanent dose rates, for the beam cleaning insertions a more rigorous and general approach which can be applied to arbitrary irradiation configurations and geometries was followed. It is a two-step approach which has been linked to FLUKA as follows:

In a first, pure hadronic FLUKA simulation, as soon as a radioactive residual nucleus is produced by FLUKA, its build-up and decay is calculated (taking into account radioactive daughter isotopes) for a certain irradiation pattern and different requested cooling times. This information is stored together with additional necessary properties in an external file. In a second, pure electromagnetic FLUKA simulation the information on the produced isotopes is read from the file and decay photons, electrons, or positrons are generated. Particles are assumed to be emitted isotropically, with their energies sampled according to their corresponding intensities and/or energy spectra. The electromagnetic particles are tracked through the geometry allowing the scoring of dose equivalent rate at any point-of-interest or in a three-dimensional mesh covering the geometry (for more details see Refs. [6, 8]).

In addition, during a first successful full scale collimator test in the SPS-LHC transfer line (TT40) the applied FLUKA simulation method was benchmarked with measurements of remanent dose rates for two different cooling times of one week and one month [9]. Both agreed within 10% and confirmed the accuracy of the new simulation approach not only for the already existing benchmark data of specific materials but also for complex objects and geometries.

Furthermore, with different loss contributions at each collimator, it is important to know the correct loss at each single one. They have to be accurately included in the simulation using pre-calculated source distributions, typically obtained with so-called tracking codes which are used for the accelerator design, *e.g.*, for the prediction of cleaning efficiencies.

In order to retrieve three dimensional maps of remanent dose rate distributions, for the entire beam cleaning insertion at IR7 and accounting for all above mentioned details, FLUKA simulations were performed. Figure 1 shows an exemplary spatial distribution of remanent dose rates for a horizontal cut through the upstream part of the geometry, after 180 days of operation and an assumed cooling time of one day. In order to reach results of high statistical significance also for smaller objects and for all cooling times ranging from 1 hour two 4 months, separate simulations were performed for different contributors to the total remanent dose rate, *i.e.*, the beamline elements, the magnets and the concrete structures.

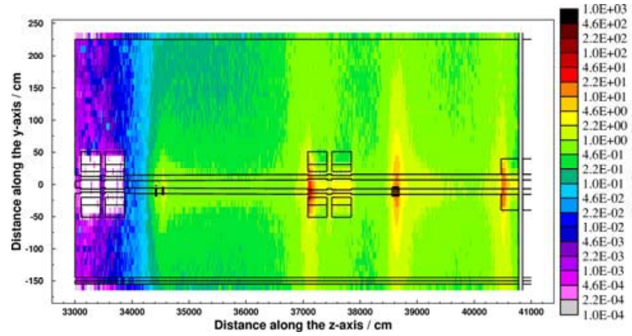

Figure 1: Remanent dose rate distribution after 180 days of continuous operation and one day of cooling period shown for a horizontal cut through the geometry at the height of the beam axes.

As can be seen, the first dipole module (centre), the secondary collimator and the front face of the downstream magnet module of the first quadrupole (right) become highly activated by the secondary particle shower and constitute the main contributors to the dose rate close to the beam-line. For short cooling times in the order of hours and days the remanent dose rates close to the most radioactive objects range from 1 to 10 mSv/h.

INDIVIDUAL AND COLLECTIVE DOSES

Various groups will have to perform interventions in the beam cleaning insertion at IR7. In order to estimate individual and collective doses it is necessary to develop intervention scenarios as detailed and complete as possible, including the following information:

- kind of intervention
- location of the intervention
- typical cooling period before intervention
- number of persons involved
- steps of the intervention
- time estimate for each step (including the respective location)
- annual frequency of the intervention
- verify if external contractors are involved

The collimators will be among the most radioactive components at IR7, thus their exchange has to be studied in detail. Different groups will be involved in this operation and various options were already evaluated. Therefore, this scenario serves as a suitable example to present the methodology of the calculation, point out possible and already performed optimizations and show the need to apply an equivalent approach to other critical interventions.

For the exchange of the collimator the dose received per person was calculated based on the given information of the work procedure, the respective location and duration. Results for the most radioactive collimator in Phase 1 (the first secondary collimator) are shown in Table 1 for six different cooling times. Two persons are

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involved in this operation and it becomes apparent that immediate interventions (within a few hours after shutdown) will not be possible. In order to stay below the 2 mSv constraint a minimum cooling time of one day will have to be considered.

Table 1: Dose per person and intervention (in mSv) as accumulated during the exchange of a collimator. Results are given separately for each work step (time in minutes) and for cooling periods between one hour and four months. All values are normalized to losses at nominal intensity.

Exchange of a Collimator - People Intervening on the Collimator only								
Actions	Time per person	Individual Dose / Person [mSv]						# of Persons
		1h	8h	1d	1w	1m	4m	
Transport material	10	0.129	0.084	0.045	0.010	0.006	0.003	2
Close manual water valve	1	0.063	0.041	0.034	0.020	0.010	0.005	1
Connect water circuit to pressurized air	1	0.063	0.041	0.034	0.020	0.010	0.005	1
Purge water circuit with air	5	0.232	0.136	0.085	0.032	0.020	0.010	1
Position transport material	2	0.117	0.073	0.057	0.030	0.017	0.007	1
Fix lifting equipment to collimator tank	3	0.375	0.304	0.239	0.153	0.086	0.035	2
Lift the collimator	2	0.125	0.082	0.068	0.040	0.021	0.010	1
place the collimator on the transport unit	2	0.117	0.073	0.057	0.030	0.017	0.007	1
Move the faulty collimator	1	0.046	0.027	0.017	0.006	0.004	0.002	1
Position replacement collimator	1	0.059	0.036	0.028	0.015	0.008	0.003	1
Fix lifting equipment to collimator tank	3	0.176	0.109	0.085	0.045	0.025	0.010	2
Lift the collimator	2	0.135	0.096	0.077	0.042	0.024	0.010	1
Install the collimator with quick plug in	5	0.625	0.506	0.398	0.254	0.143	0.058	2
Check electrical connections	2	0.250	0.202	0.159	0.102	0.057	0.023	1
Open manual water valve	1	0.063	0.041	0.034	0.020	0.010	0.005	1
Check water connections, flow	2	0.125	0.082	0.068	0.040	0.021	0.010	1
Other Person Waiting	22	1.287	0.799	0.623	0.329	0.183	0.077	1
Transport out of material	10	0.129	0.084	0.045	0.010	0.006	0.003	2
1st Person	**53**	**2.7**	**1.9**	**1.4**	**0.8**	**0.5**	**0.2**	
2nd Person	**53**	**2.8**	**2.0**	**1.5**	**0.9**	**0.5**	**0.2**	
Collective Dose	**106**	**5.5**	**3.9**	**3.0**	**1.7**	**0.9**	**0.4**	

Applying the same scheme to all remaining parts of the operation (*e.g.*, vacuum handling, RP survey, etc.) and in order to calculate the collective dose for the entire intervention all individual parts have to be summed up. Since more than one possible scenario exists, for a better comparison, Table 2 groups all individual doses together, also including the respective contribution for the corresponding radiation protection surveys.

Table 2: Individual doses for each step of the intervention (time in minutes) are shown together with the respective collective dose (all values in mSv).

Actions	Individual Dose / mSv							Collective Dose / mSv						
	Time	1h	8h	1d	1w	1m	4m	Number	1h	8h	1d	1w	1m	4m
Collimator Exchange (Collimator)														
Collimator exchange (old scenario!)	80	4.8	3.4	2.7	1.6	0.9	0.4	2	9.5	6.9	5.4	3.2	1.8	0.8
Collimator exchange (new scenario!) 1st person	53	2.7	1.9	1.4	0.8	0.5	0.2	1-2	5.5	3.9	3.0	1.7	0.9	0.4
Collimator exchange (new scenario!) 2nd person	53	2.8	2.0	1.5	0.9	0.5	0.2							
Vacuum Intervention (CF flanges with bolts)														
Collimator exchange (due to a failure)	155	5.1	3.5	2.6	1.2	0.7	0.3	2	12.3	8.5	6.2	2.9	1.7	0.7
Dismounting of 2nd beam-line	150	4.9	3.3	2.4	1.1	0.6	0.3	2	9.7	6.6	4.9	2.3	1.3	0.6
Vacuum Intervention (CF flanges with chain clamps)														
Collimator exchange (due to a failure)	111	3.1	2.1	1.5	0.6	0.4	0.2	2	10.2	7.0	5.1	2.4	1.4	0.6
Dismounting of 2nd beam-line	106	2.8	1.9	1.4	0.6	0.3	0.2	2	9.7	6.6	4.9	2.3	1.3	0.6
Vacuum Intervention - Bakeout (different work group)														
not permanent	360	13.1	9.5	6.2	2.7	1.6	0.7	2	26.2	18.9	12.3	5.4	3.2	1.4
permanent	90	2.5	1.8	1.1	0.5	0.3	0.1	2	5.0	3.5	2.2	0.9	0.5	0.2
Radiation Protection (Estimate as getting half of the dose of one person participating in each step)														
Collimator exchange	53	1.4	0.9	0.7	0.4	0.2	0.1	1	1.4	0.9	0.7	0.4	0.2	0.1
1st Vacuum Intervention - bolts	155	2.6	1.7	1.3	0.6	0.3	0.2	1	2.6	1.7	1.3	0.6	0.3	0.2
1st Vacuum Intervention (2nd b.)- bolts	150	2.4	1.7	1.2	0.6	0.3	0.1	1	2.4	1.7	1.2	0.6	0.3	0.1
1st Vacuum Intervention - chain cl.	111	1.5	1.1	0.8	0.3	0.2	0.1	1	1.5	1.1	0.8	0.3	0.2	0.1
1st Vacuum Intervention (2nd b.)- ch.cl.	106	1.4	1.0	0.7	0.3	0.2	0.1	1	1.4	1.0	0.7	0.3	0.2	0.1
during bakeout (not permanent)	360	6.6	4.7	3.1	1.3	0.8	0.3	1	6.6	4.7	3.1	1.3	0.8	0.3
during bakeout (permanent)	90	1.2	0.9	0.6	0.2	0.1	0.1	1	1.2	0.9	0.6	0.2	0.1	0.1

Depending on the finally implemented installations, with respect to the use of chain clamps and a possible installation of a permanent bakeout system, the collective dose for the exchange of the most radioactive collimator can be expected to be within 5.9-26.5 mSv for a cooling time between one day and one week. In case the second beamline would have to be dismantled as well, these values would almost double.

CONCLUSION

Individual and collective doses for different scenarios were successfully calculated using a new and accurate approach. To keep individual and collective doses low, as a result of the optimization process, the following measures were already taken or are at the moment under discussion:

- no local heavy shielding (not remotely removable)
- reorientation of magnets in order to facilitate the access to the connection boxes
- new design of fixations for protection covers of the warm magnets which enable fast removal
- easy plug-in system for collimators allowing a fast exchange
- fast connect flanges
- remote bakeout equipment for critical parts of the machine

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