CHAPTER 4

RADIATION PROTECTION AND SHIELDING

4.1 INTRODUCTION

This chapter describes the radiation protection aspects of the LHC Project including the pre-injectors for protons (LINAC II, PS-Booster) and ions (LINAC III, LEIR), the two injectors PS and SPS, the LHC main ring and the LHC experimental areas. It gives an account of the expected radiological situation and the provisions made to minimise the radiological consequences for those working with LHC, or living in its vicinity. These precautions include adequate shielding where necessary and a state-of-the-art radiation monitoring and alarm system as well as a rigorous access control system to protect personnel.

In the assessment of possible radiological risks, due account is taken of the maximum possible performance and utilisation of the LHC installations. In the calculations and estimates, reasonable safety factors are applied with respect to the production of prompt radiation, radioactivity and to their respective attenuation, decay and decomposition.

4.2 REGULATORY BASIS FOR RADIATION PROTECTION AT CERN

CERN's standards for the protection of the environment and the workers are based on the European Council Directive 96/29/EURATOM [1]*, together with the French and the Swiss National Legislations on Radiation Protection [3][4][5][6][7]. CERN's Radiation Protection Manual [8] meets the legal radiation protection requirements of the two host states by following the most advanced regulations of the two. As all member states of the European Union (EU) committed themselves to include the EURATOM recommendations into their national legislations, France acted accordingly by releasing the Décret No 2002-460 du 4 avril 2002 « relatif à la Protection générale des personnes contre les dangers des rayonnement ionisants » [4] and the Decret No 2003-296 du 31 mars 2003 « relatif à la protection des travailleurs contre les dangers des rayonnement ionisants » [5]. Although Switzerland does not belong to the EU, the Swiss radiation protection legislation [6] is compatible with the European Directive. With the latest developments in France and Switzerland, CERN decided to revise its Radiation Protection Manual [8] and the release of the up-dated version is planned for 2004 [9].

4.2.1 Basic Rules of Radiation Protection

State of the art radiation protection is based on three principles: **Justification**, **Limitation** and **Optimisation** of any personal and collective dose.

Justification

A practice involving the exposure to ionising radiation is only considered as justified when the economic, social or other benefits clearly outweigh the health detriment it may cause.

Limitation

Yearly dose limits, expressed in terms of effective dose† received by a person are laid down in the EU, the Swiss and the French legislation. The effective dose to members of the public should not exceed 1 mSv per year. All persons who risk exceeding this limit during their professional activity have to be classified as radiation workers.

---

* The European Directive 96/29/Euratom takes into account the latest recommendations of international bodies like the International Commission on Radiological Protection ICRP [2]

† The quantity effective dose (Sievert) takes into account that

a) the biological consequences depend on the type of radiation
b) some tissues and organs are more sensitive to ionising radiation than others.

The equivalent dose of energy (Gray) deposited in an organ is therefore weighted by a radiation weighting factor and a specific risk factor for each tissue or organ to give the effective dose (Sievert). The total effective dose is the sum of the weighted equivalent doses given to the various tissues or organs.

Within the EU radiation workers are classified according to the professional risk involved in their job and are sub-divided into Category B workers (< 6 mSv/year) and Category A workers (< 20 mSv/year)[‡].

CERN's future RP Safety Manual [9] will adapt to the classification of workers which is already common practice in France and within the EU. Tab. 4.1 gives an overview of these limits.

Table 4.1: Annual limits for personal effective doses as laid down in European legislations

	Public	**Radiation Workers**	
		B	**A**
EU-Directive	< 1 mSv	< 6 mSv	< 20 mSv
France	< 1 mSv	< 6 mSv	< 20 mSv
Switzerland	< 1 mSv	< 20 mSv	
CERN from 2004	< 0.3 mSv	< 6 mSv	< 20 mSv
CERN until 2004	*< 0.3 mSv*	*< 20 mSv*	

CERN's annual effective dose limit for the public of 300 µSv has to be understood as a source related dose limit. CERN is following the Suisse Directive HSK-R-11 of the "Hauptabteilung für die Sicherheit in Kernanlagen" (HSK). This one is based on the recommendation of the "International Commission on Radiological Protection" (ICRP) [2]. Respecting a limit of 300 µSv/year permits the coexistence of several installations that might potentially contribute to the effective dose of the same critical group of members of the public.

Optimisation

Any justified job is considered as optimised when:

- Different appropriate solutions have been evaluated and judged against each other from the radiation protection viewpoint,
- The decision process leading to the chosen solution can be reconstructed at any time,
- The risk of failure and the elimination of radioactive sources have been taken into account.

Optimisation can be considered as respected if the activity never gives rise to an annual dose of more than 100 µSv for persons professionally exposed or 10 µSv for members of the public [6].

4.2.2 Consequences of Implementing the Regulatory Requirements at CERN

As society judges High Energy Physics in general and CERN's research in particular as beneficial, the consequences of radiation doses given to individuals by these activities have to be considered as justified. In order to keep the exposure low, CERN strives to respect internal guide line limits that are well below the legal ones.

Public

The effective dose resulting from CERN's activities and received by any person living or working outside the Organization's boundaries must not exceed 300 µSv per year. This limit includes both external and internal exposure to ionizing radiation. The internal exposure results from the intake of radioactive nuclides that are released from CERN's installations into the environment. Its contribution to the annual effective dose for persons living outside the Organization's boundaries must be limited so that it does not exceed 200 µSv per year.

[‡] In Switzerland only one category of radiation workers exists (< 20 mSv/year).

Non-radiation worker

The effective dose resulting from CERN's activities received by any person working at CERN without being professionally exposed should be kept below the same limits as for the public.

Radiation worker

From 2004 it is envisaged to use internal limits for the effective dose of CERN's radiation workers as presented in Tab. 4.2 [9]. The responsible persons for CERN staff or contractor's staff should make an effort to arrange the work in such a way that an effective dose of 6 mSv per year and per person will be not exceeded.

Table 4.2: CERN's internal guide line limits for the effective dose of radiation workers

	Effective Dose
per week	< 1 mSv
per month	< 2 mSv
per year	< 6 mSv

Table 4.3: CERN's classification of areas and guideline limits for ambient dose equivalent rate as valid from beginning of 2004§

Type of Area	Guide line value for ambient dose rate equivalent in µSv/h	Legal limit for annual effective dose in mSv/ year	Conditions of access and work
Public area (outside CERN fence)	<0.1 (permanently occupied) <0.5 (temporarily occupied)	<1	Free access
Supervised area (inside CERN premises)	<0.5 (permanent working place) <2.5 (temporary stay)	<1	Free access
Controlled area	<10 (without special restrictions) <25 (temporary stay)		Persons working in these areas have to be classified as radiation workers and their effective dose has to be individually monitored.
Limited stay area	<2000	<20	Persons working in these areas have to be classified as radiation workers and their effective doses have to be individually monitored by passive and active dosimetry. The access is strictly controlled.
High radiation area	$<10^5$	<20	Persons working in these areas have to be classified as radiation workers and their effective doses have to be individually monitored by passive and active dosimetry. The access is strictly controlled.
Prohibited Areas	$>10^5$	< 20	No access

§ CERN's classification of areas is presently based on the Swiss radiation protection legislation [6, 7], the corresponding classification in France is still less restrictive. The revised version of the Safety Code F will take into account the newest developments in France.

All radiation workers at CERN need medical clearance and appropriate training. They will be supplied with passive dosimeters and, where necessary, with active dosimeters. The decision on the latter depends on the risk the person is exposed to during his professional activity.

Classification of Areas at CERN

In order to fulfil its legal obligation to keep exposure of persons to ionizing radiation as low as reasonably achievable (ALARA) and in particular below legal limits, CERN is obliged to regularly monitor the ambient dose equivalent and the ambient dose equivalent rate in the various areas in and around CERN. These include the areas outside CERN's fences, the total of its premises and in particular the working places of CERN's radiation workers. Guideline values for the ambient dose equivalent rate and the classification of areas according to these limits are practical means for the operational radiation and environmental protection to guarantee that legal requirements are respected.

4.2.3 LHC Design Limits for Doses and Dose Rates

When dose and dose rate design limits for the LHC were fixed, legal requirements and in particular the optimisation principle had to be taken into account [10-14].

Design Limits for occupied areas

The specifications of LHC shielding parameters are either derived from analysis based on the consequences of a full beam loss or on continuous loss processes during normal operation. In the case of a full beam loss the following limits for effective doses are set: 20 mSv maximum for persons working in the LHC underground areas, 1 mSv for persons working within CERN's premises and 300 μSv for the persons living outside CERN's fences. The limits for ambient dose equivalent rates are based on continuous losses and should not exceed 10 μSv/h for a controlled area, 1 μSv/h for a public area within CERN and 0.1 μSv/h for a public area outside CERN. The choice of these limits is justified by:

1) The legal limits for effective doses will be not exceeded, even in the case of a full beam loss.
2) The dose rate of 10 μSv/h is the upper limit for a simple controlled area according to the Swiss legislation [7]. Taking into account that the results of Monte Carlo calculations include considerable safety margins and that the decision making is always based on the results for the worst case (loss close to the shielding wall), a reasonably low ambient dose equivalent rate can be expected for the fixed working places in these types of area.

Design Limits for Maintenance

For LHC it is sensible to plan maintenance operations with a design limit for the annual effective dose of less than 2 mSv. Based on the optimisation principle all work in radiation areas must be planned and expected doses estimated. If this estimate exceeds 100 μSv for an activity per year, an optimisation must be made, balancing the doses against the cost of protection measures (time, shielding, distance and remote handling). A more detailed list of basic principles concerning job planning and optimisation can be found in [14]. Long term experience in high-energy accelerators has proved the usefulness of the dose rate guide line values as listed in Tab. 4.4.

Table 4.4: Maintenance constraints as function of the ambient dose rate level

Ambient dose rate reference level	**Maintenance Constraints**
> 100 μSv/h	All work must be carefully planned and optimised
> 2 mSv/h	All work must be carefully planned, the intervention time in the zone must be severely limited, remote handling of the components shall be seriously envisaged. French legislation: Workers of French firms holding only a temporary contract with the firm are not permitted to intervene in such CERN areas [15].
> 20 mSv/h	In regions where dose rates are above this value, no work is allowed since dose limits would be too easily exceeded. Remote handling of objects is essential.

In case an item under repair has to be taken out of the LHC it must be immediately transferred into a properly equipped and radiologically classified workshop. Obviously, transport as well as the workshop activities has to be optimised. The legal requirements for a radioactive workshop depend strongly on the type of job and on the radionuclide inventory of the accelerator component [7]).

4.3 EVALUATION OF RADIOLOGICAL RISKS

The particles of a hadron beam interact with matter via various processes such as beam-gas, beam-beam, beam-collimator, beam-target or beam-dump interactions. The high energy nuclear reaction between the beam particles and the target atoms will result in:

- The in-situ production of ionising radiation fields (prompt, mixed radiation fields),
- The production of radioactive nuclei inside the target material (induced activity).

Prompt Radiation Fields

The so-called prompt, mixed radiation fields are composed of charged hadrons (protons, pions, kaons, etc.), neutrons, leptons (e.g. muons) and photons. The composition of the fields at a given point in or outside the LHC tunnel strongly depends on its position with respect to the beam loss and the kind of shielding in between. As a general rule radiation fields around high energy accelerators are very similar to cosmic radiation fields.

Induced Radioactivity

Radioactive isotopes are produced in the accelerator components and the accelerator tunnel structure during the nuclear reactions between a high energy primary or secondary particle with the nucleus of target atoms. The radioactive (“unstable”) isotopes decay, mainly by emitting betas and gammas, until they reach the “Valley of Stability”. Since the half-lives of the radioactive isotopes range from fractions of seconds to years and beyond, the radiation fields will always be present in the machine once it becomes operational and are the source for the remanent dose rates.

4.3.1. Radiological Studies by Monte Carlo Techniques

The radiological studies discussed in this Chapter are based on Monte-Carlo (MC) simulations of the particle interactions and transport in matter. Most of these calculations were performed with the FLUKA code [16][17]. FLUKA is a multi-purpose Monte Carlo code which is capable of simulating all components of hadronic and electromagnetic cascades from TeV-energies down to that of thermal neutrons. Its predictive power has been confirmed by a large number of benchmarking studies, comparing FLUKA results against experimental data [18]. The code has its roots in the field of radiation physics and is thus the most appropriate choice for LHC Radiation Protection studies. In the following, a brief summary is given of the methods used with FLUKA for the evaluation of radiological risks.

Dose equivalent

Dose equivalent can be estimated from the physical quantities obtained with FLUKA by one of the following methods:

- Multiplication of dose (energy deposition) with an average quality factor,
- Multiplication of the density of inelastic interactions with energies above a certain threshold, typically 50 MeV (“stars”), with pre-determined factors
- Folding particle fluence with particle type and energy dependent conversion factors.

For LHC studies the third method is used most frequently. In particular, fluence to effective dose and fluence to ambient dose equivalent conversion factors [19] are used. These have been calculated with the FLUKA code and are based on recommendations of the International Commission of Radiation Protection (ICRP).

Induced radioactivity

Three methods exist for the calculation of the specific activity induced by hadronic interactions in beam line, shielding components and in the environment (air, rock, water, etc.). These are:

1) Multiplication of star density with pre-determined factors,
2) Folding of particle fluence with energy-dependent cross sections for the production of certain isotopes,
3) Direct calculation of isotope production with FLUKA.

Each method has its advantages and limitations and is used correspondingly for LHC studies. The first approach allows easy implementation and fast estimates, but is limited to high-energy reactions. Furthermore, the factors have been determined for a certain radiation environment (particle composition and spectra) and are therefore only valid for similar conditions. The second method is considered to be most reliable if experimental cross sections are available. In addition, it is the only option for the estimation of activities in regions of low density (e.g. air). Finally, the prediction of isotope production with FLUKA provides the most universal and problem-independent method although its reliability is strongly dependent on the quality of the hadronic interaction models in FLUKA.

Remnant dose rates

Methods for the calculation of remanent dose rates are either based on the so-called omega factor approach or on an explicit simulation of the production of radioactive isotopes and the transport of radiation from radioactive decay. Using the omega-factor approximation means to determine the surface dose rate by multiplying the number of inelastic interactions ("stars") produced in a material with pre-determined factors that are characteristic for a specific material. This technique allows estimations of dose rates on the surface of extended, uniformly activated objects. The results depend strongly on the particle environment as well as on irradiation and cooling time. Although the omega factor approach is rather limited in its range of application, it is considered to be reliable if used appropriately. The explicit simulation method has, in principle, no limitations with regard to the geometry or complexity of the problem. However, it is more time-consuming and depends on the quality of the prediction of isotope production with FLUKA. It has only recently been used for estimating remnant dose rates around the LHC machine.

Interaction rates and loss assumptions

Radiological assessments of environmental parameters and shielding use ultimate parameters for the LHC proton beam current (850 mA, 4.7×10^{14} protons/ring) and luminosity (2.5×10^{34} $cm^{-2}s^{-1}$) whereas nominal parameters (536 mA, 1.0×10^{34} $cm^{-2}s^{-1}$) are applied in assessments of radiation damage and induced radioactivity in the accelerator [10][20]. The studies assume an annual operation cycle of three 60-day periods separated by 10 days of shutdown and having two daily fill scenarios, one fill of 20 hours duration or two fills each of 8 hours duration, respectively. Environmental assessments are therefore based on the following intensities [10][20]:

- Inelastic proton-proton interaction rate at the high-luminosity insertions: 1.6×10^{16} y^{-1} (1.0×10^{9} s^{-1}),
- Total number of dumped protons: 1.0×10^{17} y^{-1},
- Total proton loss rate per LHC beam in the beam cleaning insertions: 4.0×10^{16} y^{-1} (2.5×10^{9} s^{-1}),
- Total proton loss rate per LHC beam in the Main Ring: 3.4×10^{15} y^{-1} (2.2×10^{8} s^{-1}).

Further details as well as the intensities for internal assessments can be found in [10]

Heavy-ion operation

The radiological importance of ion operation at the LHC has been found to be generally lower than that of proton operation [21]. The estimate is based on LHC performance parameters as given in the Conceptual Design Report of the LHC [22] and the Technical Proposal for the ALICE experiment [23].

4.4 THE INJECTOR CHAIN

As already indicated the radiological concerns for the LHC injector concentrate on two issues:

- The operation with ions and its consequences in particular for LINAC3 and LEIR.
- Operation of the SPS with the LHC beam and in particular the ejection of the proton beam into the LHC.

4.4.1 Ions in the Injector Chain

As the radiation protection aspects of LHC ion beams in LINAC3 and LEIR are already discussed in detail in Volume III of the LHC Design Report [24], only a short summary will be given here.

LINAC3

Three radiation sources have to be taken into account: neutrons, X-rays from the ion source and X-rays from the LINAC3 itself.

When the beam intensity is increased by two orders of magnitude, additional shielding will be required around the dump for neutrons. The improvement of the present 100 μA current to the potential 500 μA with the ECR source means an increase of the X-ray dose rate at the ion source by a factor of three. Additional shielding of 1 cm lead or 10 cm concrete will be sufficient. The X-ray dose rate around LINAC3 is expected to increase by a factor five and consequently some extra shielding of 2 mm lead or about 10 cm concrete are recommended.

LEIR

Given the expected beam intensity in LEIR, the 1.6 m thick concrete walls enclosing the accelerator will be sufficient to shield LEIR sideways and to allow access to the rest of the South Hall during operation. The gangway can remain accessible during operation of LEIR with Pb ions (10^{+9} $^{208}Pb^{54+}$ ions at 72 MeV/u every 3.6 seconds) – providing that special precautions are taken (e.g. fast beam abort) in case of accidental conditions. The decision on top-shielding for LEIR will be taken as soon as more experimental data become available. This data is needed to verify the theoretical models.

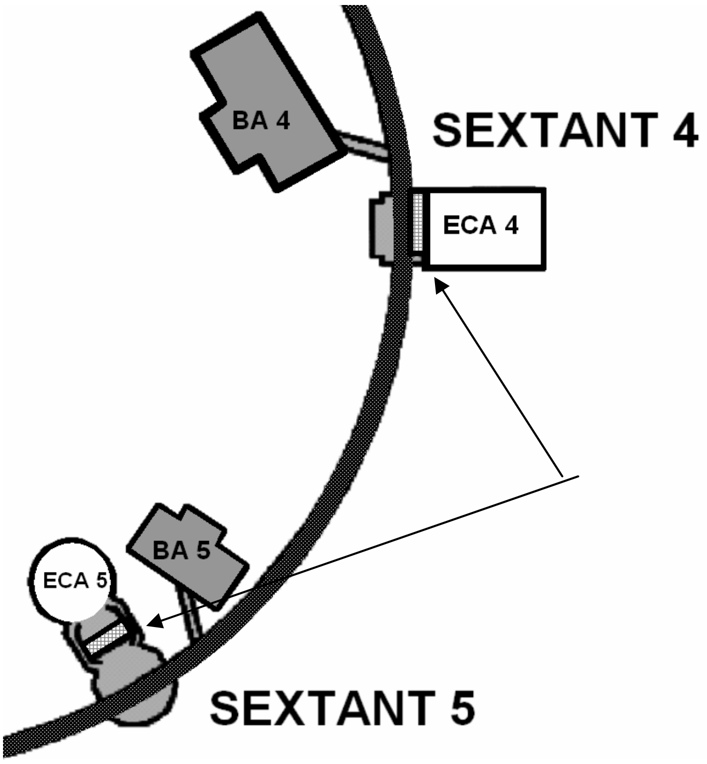

Figure 4.1: Schematic lay-out of ECA 4 and EC5 of the SPS, the arrows point to the mobile shielding walls.

4.4.2 Protons in the Injector Chain

Whereas the LHC beam in LINAC, Booster and PS will not cause major radiation protection problems, the present shielding in the ECA4 and ECA5 areas of the SPS will have to be redesigned.

SPS

In the late 1970s two caverns were excavated in point 4 and point 5 of the SPS to house the detectors of UA1 and UA2. The former assembly areas of UA1 and UA2 (ECA5 and ECA4) are shielded towards the SPS machine by mobile concrete walls, up to 5 m thick (see Fig. 4.1) and are presently classified as simple controlled areas [8]. Nowadays, they are used for various purposes: ECA5 as a storage area for accelerator components and ECA4 for the installation of power supplies and various control equipment for the SPS machine.

The radiation level in ECA4 will increase during the ejection of the beam into LHC and CNGS when compared to “normal” SPS operation. This is because the ejection will be initiated by kicker and septum magnets installed in LSS4 to direct the beam into TT40. Monte-Carlo studies were performed to evaluate the radiological risks in ECA4 under LHC and CNGS beam conditions [25][26][27].

Two scenarios were calculated: beam losses in the septum magnets [25] and in the spoiler protection unit installed in ECX4 [26]. Assuming loss rates under normal operation of 10^{-3} at the spoiler and 10^{-4} at the magnets, the losses at the spoiler determine the upgrade of the shielding of the concrete wall between ECA4 and ECX4. The calculations give dose rates of the order of some tens of μSv/h for the present shielding wall. Adding additional shielding will reduce the dose rate but not sufficiently low to classify ECA4 as a radiation controlled area during LHC and CNGS operation. In case it turns out that the loss factor at the spoiler is really as high as assumed (10^{-3}), the shielding of the wall or around the spoiler has to be re-enforced as much as possible and the area classified as a limited stay area with many consequences (strict access control, job planning, passive and active dosimetry).

The first results on dose rate calculations for ECA5 show similar tendencies [28].

4.5 LHC UNDERGROUND AREAS

With circulating beam, the radiation doses in the LHC underground areas reach high levels and therefore access during beam operation has to be prohibited for the major part of the underground structure. However, access during beam operation is required for a few underground areas (USA15, upper part of PX24, USC55, part of UX85) and therefore extensive shielding calculations had to be performed.

4.5.1 Shielding Design

A summary of design values of doses and dose rates outside the shielding of the LHC is given in Ref. [11]. Three loss conditions have to be considered in the shield design:

1) A full loss of a circulating LHC beam of 4.7×10^{14} protons at a point,
2) Proton-proton interactions at an intensity of 10^{9} s^{-1},
3) A continuous loss of the injected beam of 450 GeV at a maximum rate of 4×10^{12} s^{-1}.

ATLAS and CMS

Shield design in the areas around the ATLAS and CMS experiments is determined by stray radiation from the collimators protecting the first superconducting low-beta quadrupole magnet. Each collimator absorbs approximately 2 TeV of the colliding 7 TeV protons. It can be shown that the attenuation provided by the shield must be better than 10^{-5} pSv per 7 TeV proton [10]. Results of detailed FLUKA simulations are available [11] and demonstrate that the design is adequate to meet the requirements for the classification of the experimental service caverns as Controlled Areas.

ALICE and LHC-b

Because of the lower luminosity, shield design in the ALICE and LHC-b areas is dominated by a full beam loss or a continuous loss during injection. Both scenarios require the same attenuation of about 10^{-4} pSv per

7 TeV proton [11]. As an example, Fig. 4.2 shows the total dose equivalent per lost proton for a vertical longitudinal section through the PX24 shaft at Point 2 [29]. The loss point was assumed to be at the bottom of the shaft in the first quadrupole magnet of the low-beta insertion. The values shown on the contour plot have to be multiplied by 4.7×10^{14} protons in order to obtain the total dose for a full beam loss. The design constraints for the upper part of PX24 which houses the ALICE counting rooms (Controlled Area) are fulfilled.

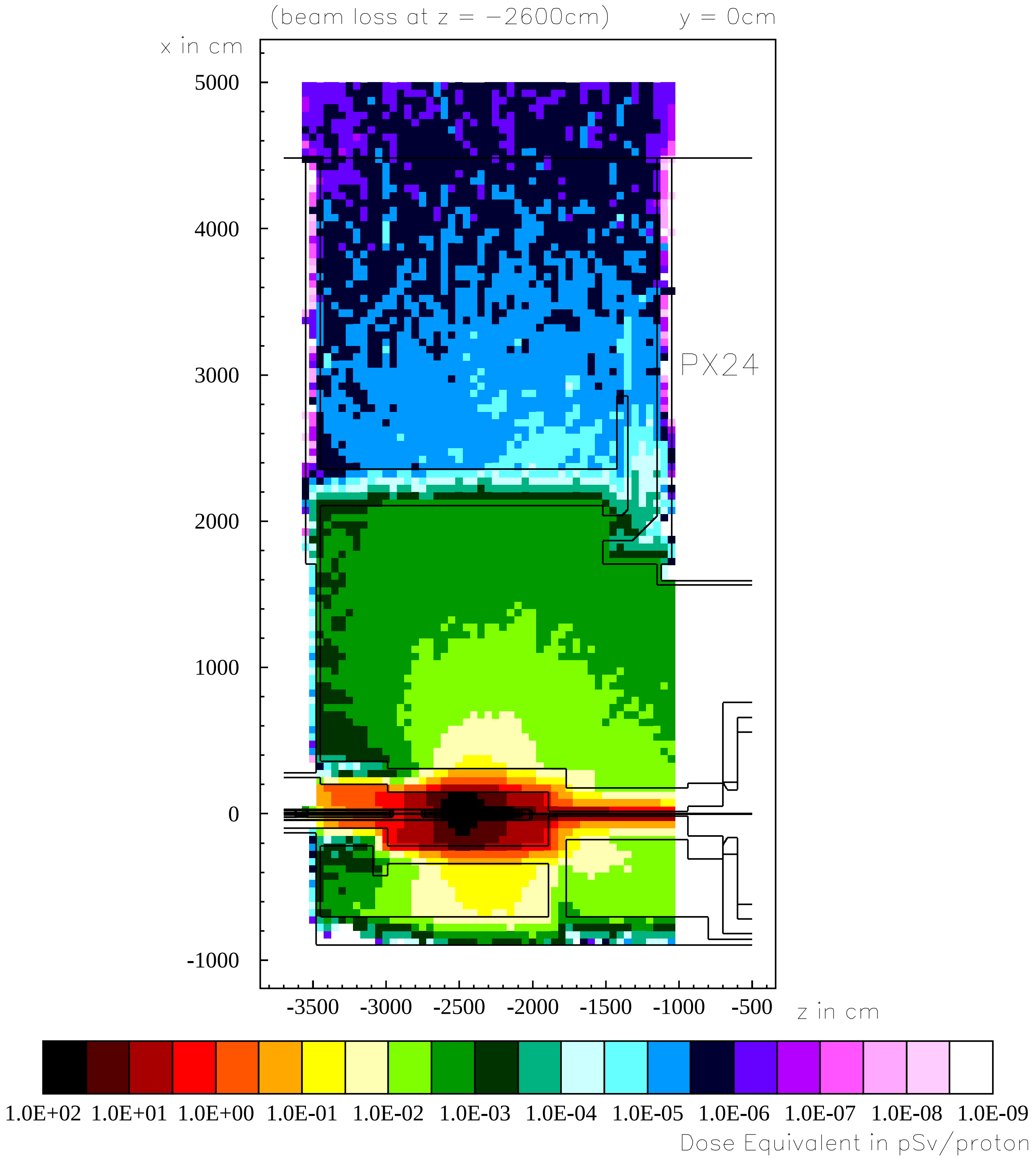

Figure 4.2: Dose equivalent per lost proton in the PX24 shaft.

The shield wall in the UX85-cavern at Point 8 separates the counting rooms from the LHC-b detector area. The wall consists of a large movable central part of about 3 m thickness covering the access opening, a fixed part (~4 m thick) on either side of this opening and a thinner top part. A complex system of ducts allows the passage of cables and pipes through the wall. At the UX floor level a labyrinth provides access to the detector. Among other considerations, the final design of this wall has been optimised with respect to a minimisation of dose equivalent in the counting room area based on detailed FLUKA calculations [30].

Point 4 – LHC RF cavities

The LHC superconducting RF cavities will be installed in Point 4. Whereas the access into these underground areas will be prohibited during beam operation, people may be present in UX45 and US45 during the conditioning of the cavities. A study of the radiological risk caused by the high energetic bremsstrahlung was necessary to design the shielding. For this, experimental results measured during the conditioning of 2, LHC modules in the SM18 test facility were combined with detailed Monte Carlo simulations [31]. According to the study a roof shield as well as a second, 80 cm thick shielding wall towards UX45 is required. With these in place, access will be possible to the US cavern and to the ground floor of UX45 during RF cavity conditioning. The access to the upper floors in UX45 will be restricted.

4.5.2 Remnant Dose Rates and Maintenance

In general, all equipment installed in the LHC tunnel will become radioactive as a result of particle showers induced by interactions of the beam with the residual gas in the vacuum chamber. In addition to these distributed losses there are localised areas which will become radioactive as a result of interactions of the beam with accelerator components. In the following the most affected areas will be addressed.

TAS Collimators

Calculated residual dose rates for the TAS collimator can be found in [32][33]. Close to the beam pipe dose rates may reach tens of mSv/h and require careful job planning and the provision of some means of remote or easy handling for maintenance operations. The dependence of the residual dose rate - averaged over the IP-side surface of the collimator - on irradiation and cooling time is shown in Fig. 4.3 [33]. Except for very short irradiation times, dose rates are comparable within a factor of two up to one day of cooling and within an order of magnitude for several months of cooling. Even after one week of cooling time the dose rates are of the order of several mSv/h.

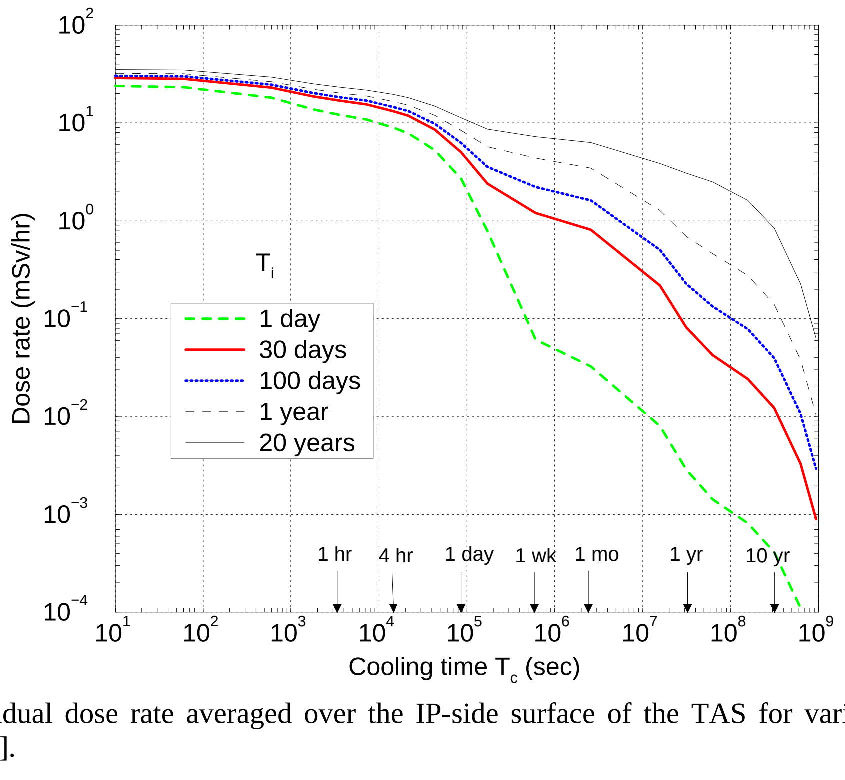

Figure 4.3: Residual dose rate averaged over the IP-side surface of the TAS for various irradiation and cooling times [33].

Low-β Insertions and TAN Absorbers

As for the TAS the magnets of the low-β insertions at IP1 and IP5 together with all the vacuum equipment and the TAN absorber will become highly radioactive from secondary particles emerging from the interaction point. Estimates of residual dose rates at the IP5 inner triplet vacuum vessel [33] are shown in Fig. 4.4. It should be noted that these values are valid for the outside of the vessel, whereas dose rates close to the vacuum pipe will reach several tens of mSv/h [33].

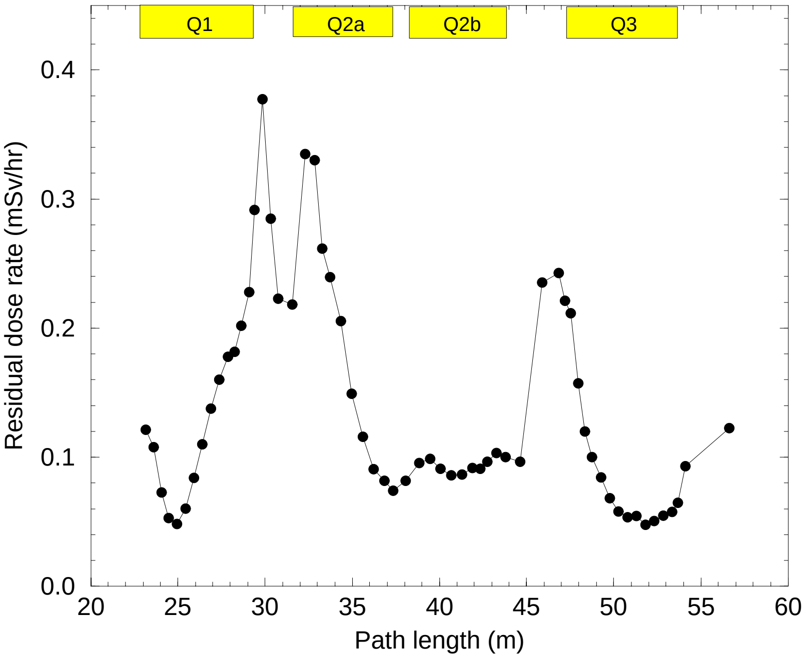

Figure 4.4: Residual dose rate on the outside of the IP5 inner triplet vacuum vessel after 30 days of irradiation and 1 day of cooling [33].

Momentum and Betatron Cleaning Insertions

Apart from the beam absorbers in IR6 the cleaning insertions will become the most radioactive zones of the LHC. For radiation studies it is assumed that about 30% of all stored LHC protons will be lost in the cleaning insertions at points 3 and 7. Expected dose rates depend strongly on various factors, such as the collimation layout, local shielding, the materials chosen and the cooling time. The question of whether and where to implement shielding is still a matter for further studies.

First detailed studies related to contact dose rates on the surface of a possible iron shield and magnets in the momentum cleaning section (IP3) were obtained with the omega-factor approach (see above). The simulations [34] are based on machine layout version 6.2 (one primary aluminium collimator, six secondary copper collimators and local thick iron shielding). The results are normalised to 10^9 protons per second and per ring, interacting in the momentum cleaning insertion and refer to 30 days of irradiation and 1 day of cooling.

Fig. 4.5 shows contact dose rates on the outer surface of the iron shield and magnets as a function of the longitudinal position for both rings. The contact dose rate reaches a maximum value of 3 mSv/h near the first secondary collimator TCS1 and near the bare coil ends of the dipole and orbit corrector magnets. In most of the regions the dose rates significantly exceed the reference value of 100 µSv/h (Tab. 4.4) therefore work must be carefully planned and optimised. In case the shielding has to be removed for maintenance of the vacuum components, the dose rates from induced radioactivity in the collimator jaws, the front bare coils and the beam pipes will exceed 100 mSv/h [34].

As a result of the new collimation layout in the cleaning insertions and ongoing design work (in particular with respect to shielding) the first generic studies have been performed to estimate the induced activity for different proposed collimator materials [35]. Possible candidates for low-Z materials have been identified as beryllium and carbon composites; copper is kept in the generic study for comparison with results of earlier simulations. Dose rates have been estimated by two different approaches; the omega-factor approach and the explicit method of calculating and transporting the radioactive decay products (see Sec. 4.3.1). It has to be noted, that the omega-approach could include rather large uncertainties in the case of the very thin beam pipe or the tunnel wall. The dose rates as calculated clearly exceed 20 mSv/h near the copper collimator, whereas beryllium and carbon composite give dose rates of few mSv/h. In all cases values are reached which require dose optimisation in design and maintenance of the beam cleaning insertions.

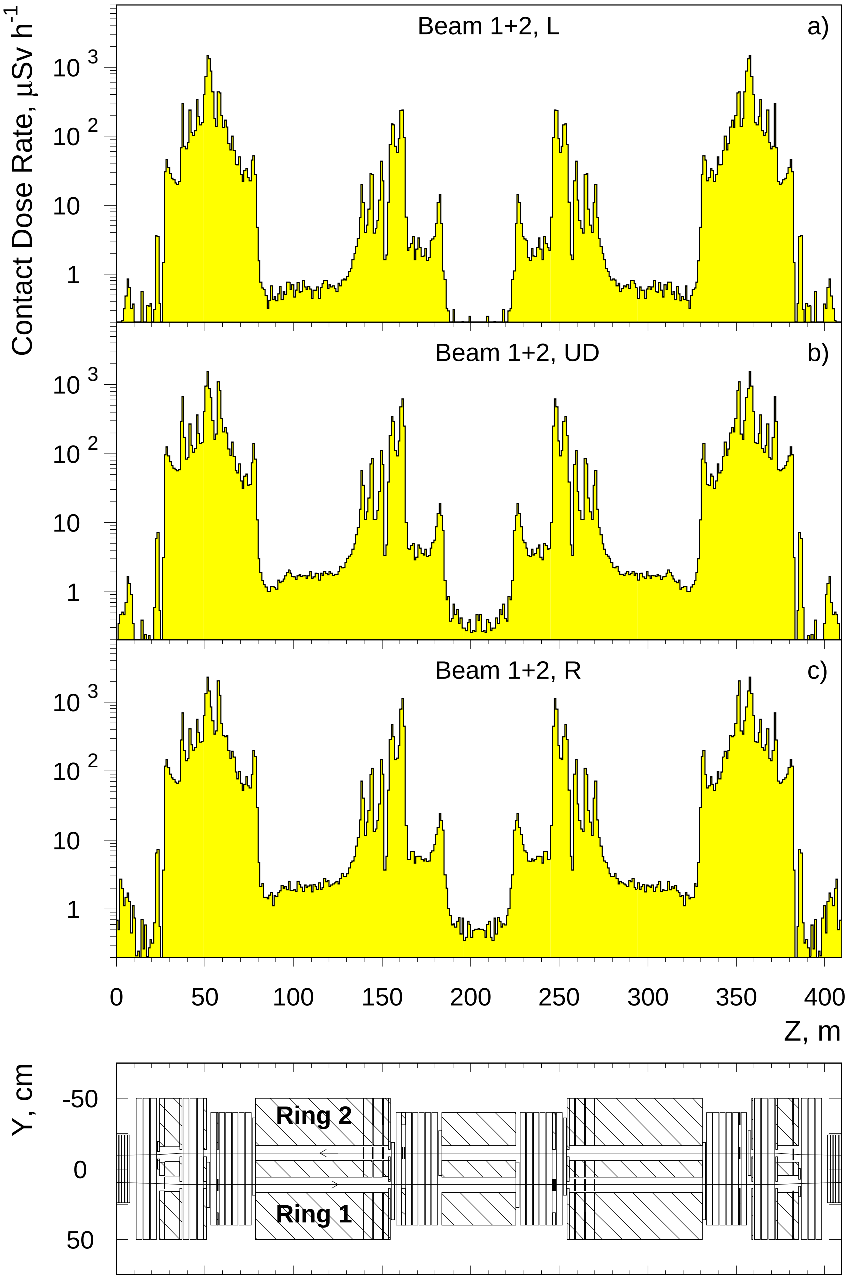

Figure 4.5: Contact dose rates on the surface of the iron shield and magnets in the momentum cleaning sections: a) left surface L; b) up-down surface UD; c) right surface R [34].

Generic Monte Carlo simulation studies were performed to compare different choices of material and to study the effect of shielding. Fig. 4.6 shows results comprising a very simplified geometrical model, which was used to obtain fast first estimates for dose rate distributions: the residual activation can be significant, thus imposing restrictions on human interventions [36]. In the case where the collimators are shielded, high dose rates in the order of several tens of mSv/h are to be expected on the inside of the iron shield after 180 days of operation and one day of cooling. The situation is much more relaxed in the unshielded scenario, where dose rates reach values of several mSv/h. The results are normalised to 10^9 protons per second and per ring and refer to a full beam loss at a single collimator.

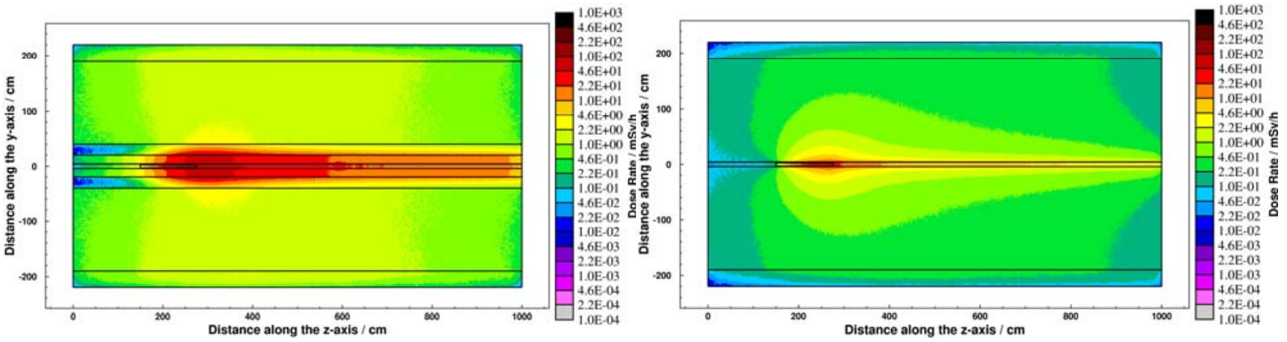

Figure 4.6: Spatial dose rate distribution after 180 days of operation and one day of cooling for the shielded (left) and unshielded (right) configuration of a carbon composite collimator.

Any kind of intervention in this kind of radiation area requires a detailed job and dose planning. The results strongly depend on the particle losses at the particular collimator, the collimator material and the surrounding local shielding [37]. More detailed calculations will have to be performed in order to optimise the final layout of the collimators and its implication on collective doses (see [38] and Fig. 4.7).

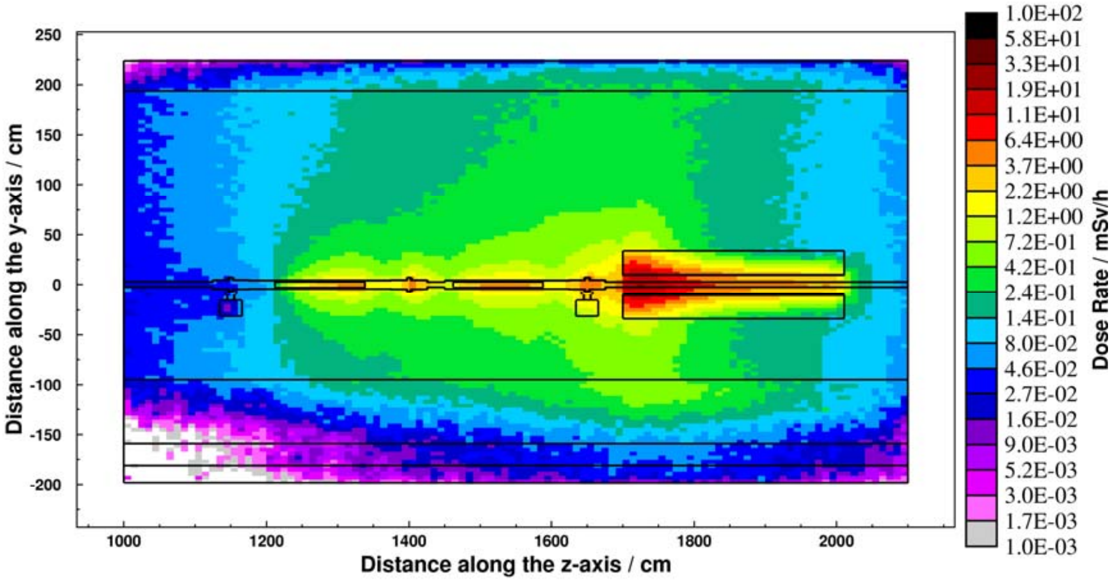

Figure 4.7: Spatial dose rate distribution for a vertical projection of the collimator geometry for 180 days of irradiation and 1 hour of cooling [38].

Beam Dump Caverns

Photon dose rates coming from the graphite, aluminium and concrete of the dump have been estimated for various locations in the dump cavern (see Fig. 4.8) [39]. Assuming a total number of $4.5\times10^{+16}$ protons dumped per year, the dose rate will reach a maximum value of 84 μSv/h after one hour of cooling at position 4 above the dump. Since it is possible that the top shielding blocks will have to be removed to allow a core-sleeve assembly or a base-plate to be exchanged, dose rates have also been estimated for this case. The dose rates range from 380 μSv/h at position 4 (see Fig. 4.8) to 1 μSv/h at position 1 after one day of cooling. After one month cooling values ranging from 100 μSv/h to 0.4 μSv/h are reached.

Beam Dump Assembly

Details of the dump and shielding have been reproduced to the nearest millimetre; details of the cavern walls, floor, tunnels etc. to the nearest centimetre. The beam-dump comprises the cylindrical graphite core (length 700cm and diameter 70cm), surrounded by the aluminium sleeve (outer dimensions 94×94×700 cm). This core ensemble, along with the aluminium end-block (100×110×100 cm), sits on a 16 cm thick aluminium base plate. The densities of the graphite and aluminium are 1.85 g/cm^3 and 2.7 g/cm^3 respectively. The shielding for the dump is made from decommissioned magnet-yokes, partially filled with concrete, and an outer 20 cm layer of concrete. The densities of the iron and concrete are 7.88 g/cm^3 and 2.35 g/cm^3 respectively. The cavern ceiling, walls and floor are composed of the same concrete; the ceiling and wall thickness is taken to be 60 cm while the floor is 200 cm deep. In order to speed up the calculations the volume of the cavern is assumed to contain a vacuum. The rock (molasse) with a density 2.40 g/cm^3 surrounds the cavern-concrete.

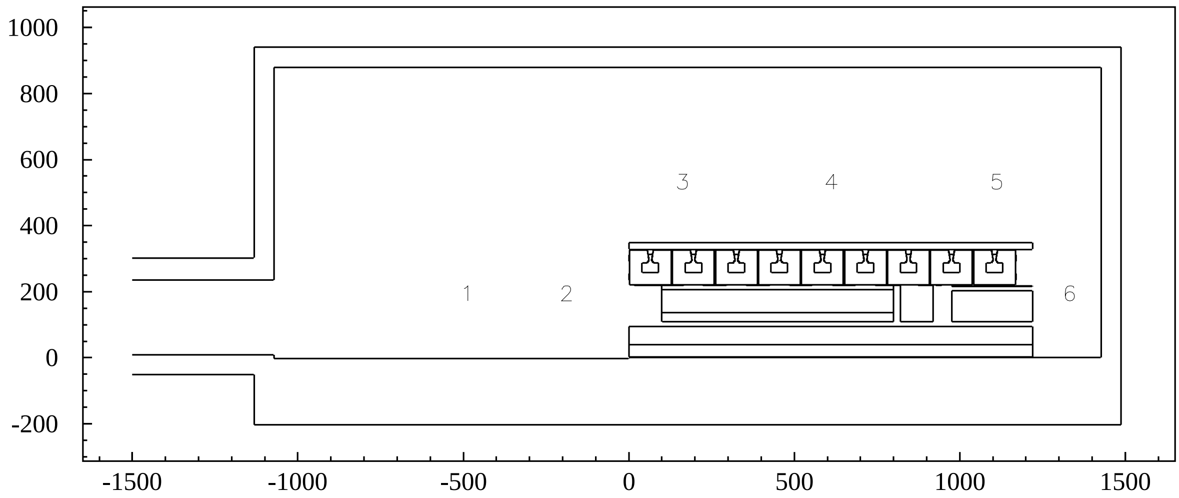

Figure 4.8: Vertical slice through the centre of the dump. The positions where dose has been determined are indicated. Dimensions are in cm.

Dispersion Suppressor Regions

No explicit calculations exist for remanent dose rates around the dispersion suppressor (DS) regions at Points 1 and 5. However, a rough estimate of the remanent dose rates in these areas can be obtained by scaling the results for dose rates from beam-gas interactions in the arcs [40] to the proton loss density in the DS region [41]. The latter loss densities were calculated based on optics Version 6.2 and an interaction rate at the IP of 3.5×10^8 s^{-1}. The dose rates depend strongly on the amount of self-shielding provided by the beamline elements and may reach several mSv/h at isolated spots.

4.6 RADIATION DAMAGE TO ELECTRONIC EQUIPMENT

4.6.1 Electronic Equipment in the LHC Tunnel

The LHC is technically more complex than any of the previous accelerators built at CERN and the physics operation margins are very tight. This has had a clear impact on the design and the integration of the controls electronics for the machine.

A large amount of low-level controls electronics is located close to the beampipe to improve the signal quality, to reduce cabling costs and to reduce ohmic losses in the power cables. In total, there will be around 10 000 crates installed under the cryostats of the main magnets and containing the low level electronics for beam instrumentation (BPMs, BLMs), quench protection, cryogenics, power converters (orbit correctors), vacuum and magnet position surveying. Other electronic systems such as junction boxes or local control electronics will be attached to the cable trays.

There are some trends in the selection and use of microelectronics for the LHC machine components that have raised questions concerning the radiation tolerance of this equipment:

- Most systems use complex programmable devices such as ASICs (Application Specific ICs), Memory (EEPROM) based CPLDs (Complex Programmable Logic Devices), SRAM based microprocessors or devices with flash memory. Although this gives more flexibility and allows easy switching between operational modes (calibration, proton run, ion run), it is difficult to predict how an error may propagate through the whole system.

- There is a preference for using complete commercial off-the-shelf systems (COTS) whenever possible. Complete COTS systems eliminate the need for a specific custom development and may lead to overall reduction of costs. For example, the use of PLCs (Programmable Logic Controllers) in combination with digital or analogue remote I/O modules is presently envisaged for the cooling and ventilation system, the electrical distribution system, interlocks, vacuum and the RF system.
- Modern designs use the latest technology that has the highest performance, meaning a high density of bits and low power supply voltage.

The scale of the LHC project excludes the use of specific radiation-hard components such as those used in space or military applications. Instead radiation tolerance of electronic equipment is ensured at the system level, using multiple identical circuit paths, error correction codes, current protection and radiation tolerant power supplies.

4.6.2 Radiation Damage to Electronic Equipment

In the complex radiation field of the LHC machine, electronics will degrade via 3 different damage mechanisms [42]:

- Surface damage caused by ionizing radiation (in the tunnel mainly gamma rays and electrons) proportional to the total absorbed dose in the device.
- Displacement damage caused by energetic particles (in the tunnel mainly neutrons) that create damage in the bulk of electronic devices and that is proportional to the number of particles incident on the device per unit of surface.
- Single Event Errors caused by hadrons (mainly neutrons in the LHC tunnel) with energy above 10 MeV. This number of these errors is proportional to the number of particles incident on the device per unit surface.

Surface and displacement damage are cumulative effects. It is not expected that electronics will degrade significantly from cumulative effects during the first years of LHC operation. Single Event Errors (SEE), however, are caused by individual ionizing particles and will appear as soon as there is a circulating beam.

4.6.3 Radiation Spectra and Shielding

The “radiation map” of the LHC has been constructed over the last 10 years or so and results have been obtained with various simulation codes, optics versions, assumptions about the proton-proton collision rate, beam gas densities, beam life times and proton loss rates [44][45][46][47][48]. The evolution of the parameters over the years has relatively little impact on the radiation levels in the arcs where the magnetic lattice is regular. In the dispersion suppressor (DS) regions however, radiations levels may be higher, which is why safety factors are used in all radiation tests of electronics.

Most electronic equipment is located under the cryostats in the regular arcs of the machine. To compute the radiation levels in the arcs, it was assumed that the machine is operating at nominal conditions and that there is a loss rate of 1.65×10^{11} protons $m^{-1}y^{-1}$ for the 2 beams [44]. To compute the radiation levels close to the interaction regions, the point loss distribution from [45] was taken.

To estimate the radiation damage to electronics, it is very useful to have an idea of the highest hadron energy that can be expected in the tunnel. This is because hadrons at very high energies (>1 GeV) may cause destructive (hard) single event errors in the machine electronics. Fig. 4.9 shows that the spectra in the DS regions have more high energetic hadrons than those in the arc. This is due to the fact that some of the beam pipes in the DS are not shielded with a magnet core. The maximum hadron energy in the dispersion suppressor regions reaches several hundred GeV.

Fig. 4.9 also gives an impression on the effect of shielding which leads to a reduction in the number of protons and charged pions at high energy. However, many more neutrons appear in the MeV energy range. A proposal to shield the electronic equipment in the RRs around Point 1 and Point 5 is described in [46].

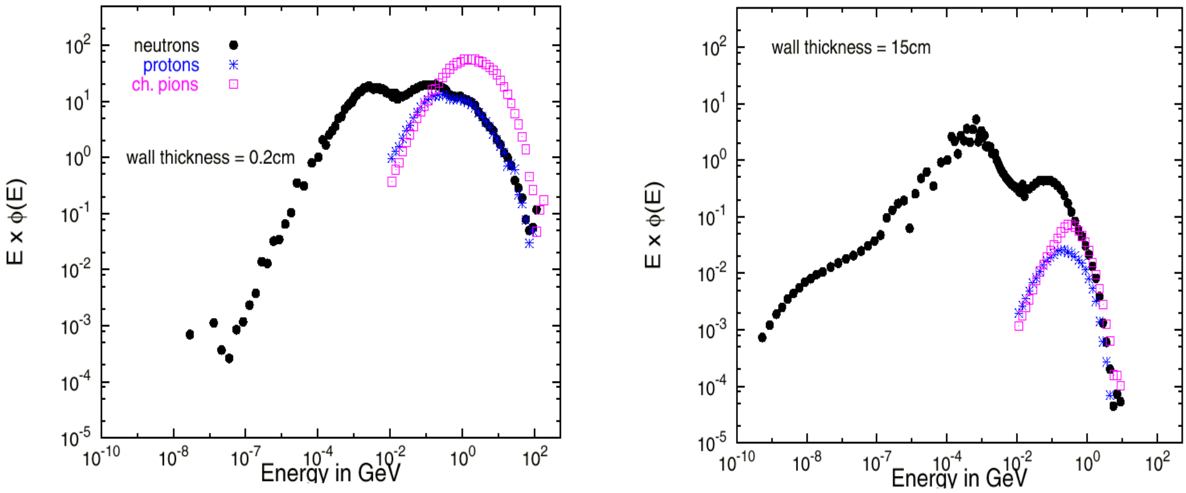

Figure 4.9: Simulated particle spectra for the LHC tunnel (left: DS region, right: regular arc).

4.6.4 Ensuring Radiation Tolerance of LHC Machine Electronics

All electronic devices installed in the LHC tunnel must be tested for their radiation tolerance. Because of the relatively short time available and the quantity and volume of the items to test, it has not been possible to adopt the standard radiation hardness assurance methods as used in space and military applications as well as for the LHC detectors. Instead, a method has been developed based on testing components and systems in a radiation facility (the LHC radiation test facility) in the SPS North area. This region has a complex radiation field similar to that expected in the LHC tunnel but with much higher dose rates [48][49]. During the selection phase, a trial and error method was used to determine whether the use of COTS (commercial off the shelf) components can be envisaged. In the second stage, irradiation tests in calibrated facilities outside the laboratory are conducted using proton beams, neutrons sources or Cobalt irradiation. Such tests are needed to determine the radiation tolerance of specific components in detail and to define the tolerance limits with sufficiently high precision. More than 90% of the radiation tests outside CERN are dedicated to solving Single Event Errors. The remainder concern cumulative damage effects (TID and displacement damage).

Final prototypes and randomly picked samples of completed pre-series systems are also tested in the complex field of the LHC radiation facility. If the radiation tolerance is consistent with observations in earlier experiments, series production and installation can be started.

4.6.5 Dosimetry for the LHC Machine Electronics

Any method to ensure radiation tolerance can only provide a reduction of the risk of inducing radiation damage to electronics: it cannot completely eliminate it. In order to monitor the degradation of electronics and materials in the tunnel, an on-line radiation-monitoring system will be used. The aim of the system is:

- To monitor the total dose (the 1 MeV equivalent neutron fluence and the hadron (E>20 MeV) fluence) on line at locations underground where electronics are located,
- To compare measured radiation levels to simulated radiation levels,
- To predict long term radiation induced failure from cumulative damage and hence anticipate replacement,
- To distinguish between radiation induced Single Event Errors and normal MTBF failure,
- To provide radiation tolerance requirements for new electronic designs,
- To evaluate the efficiency of the shielding and to assess the possibility of staged implementation,
- To provide feedback to LHC operations on the beam confinement.

The system is composed of 125 radiation monitors distributed around the ring. There are approximately 200 junction boxes and 125 dosimeters which make it possible to position dosimeters at various locations. In the areas that are cabled, there is one junction box per half cell and the default location of the junction box in the half cell is next to the Beam Loss Monitor station. The local cable length is 15 m, which means that the radiation monitors can be placed at virtually any location in the half cell. A maximum of 32 monitors per half cell can be obtained if the devices are connected in series from a junction box.

The monitors are based on 3 extremely sensitive semiconductor electronic components that measure the three radiation damage parameters:

- The RADFET, which is a special MOSFET, sensitive to the ionizing radiation component of the mixed radiation field. The change in threshold voltage of the transistor can be calibrated in terms of the total absorbed dose in Silicon, in units of Gray.
- The PIN (p+/n/n+) diode that is sensitive to displacement damage in Silicon. The forward voltage over the diode is calibrated in terms of the 1 MeV equivalent neutron fluence.
- SRAM memory that is sensitive to Single Event Errors. The number of corrupted bits can be calibrated in terms of the hadron fluence with energy above 20 MeV (Fig. 4.10).

The dosimeter components have been calibrated in dedicated test facilities. A small-scale system test is currently installed in the SPS North experimental area.

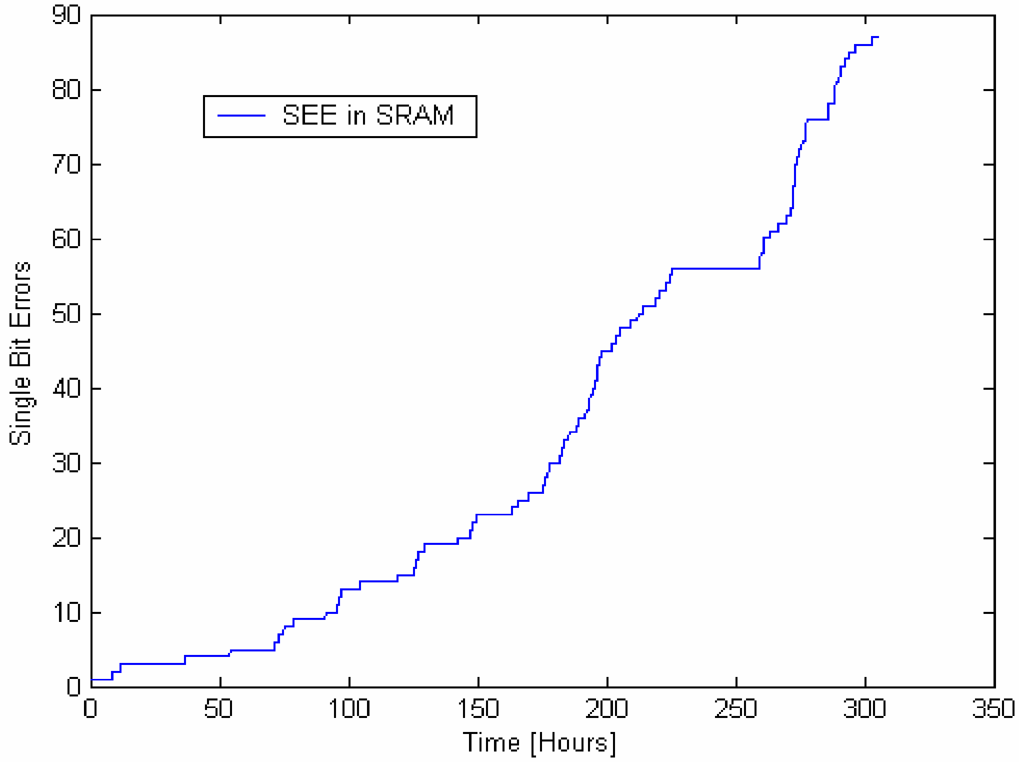

Figure 4.10: On-line observation of Single Event Upsets in standard SRAM memory as observed in the LHC radiation test facility (TCC2).

4.7 ENVIRONMENTAL MONITORING PROGRAMME

The objective of the environmental monitoring programme is to prove that the facility complies with the regulatory limits in force and to provide early warning if violation of these limits is imminent. The programme can be divided into three parts: (1) monitoring of radioactivity in released fluids (air, water) – the source term, (2) monitoring and measurements of dose rate levels in the environment and measurement of activity densities in various environmental matrices – the receptor term, and (3) evaluation of the effective dose to critical groups of the population – the radiological impact.

The crucial technical infrastructure required to meet the above-mentioned objectives is formed by the instrumentation and the data acquisition system included in the RAMSES system [50] (see Sect. 4.8).

4.7.1 Monitoring of Radioactivity in Air

Each air extraction duct likely to contain radioactivity produced in the facility will be equipped with a ventilation monitoring station. Each station consists of an on-line real-time monitor of short-lived radioactive gases together with an aerosol sampler. Whilst the readings of the monitor will be stored in a database, the aerosol filters will be replaced twice a month and analyzed in an off-line laboratory for longer-lived beta and gamma activity. Alarm thresholds will be set for the activity density of the short-lived radioactive gases. Tritium in ventilation ducts will not be measured on-line but conservatively estimated on the basis of sporadic measurements. Such measurements will be carried out especially after upgrades in the facility. The very low radiological impact of Tritium justifies such a simplified approach. There will be 5 stations for the LHC machine (PA1, PA3, PA5, PA6, PA7), 2 stations for the transfer tunnels (TI-2 and TI-8), and 11 stations for the experiments (4 in ATLAS, 3 in ALICE, 3 in CMS, 1 in LHC-b).

4.7.2 Monitoring of Radioactivity in Water

All water discharge points likely to receive water containing radioactivity produced in the facility will be equipped with water monitoring stations. In a similar configuration to the ventilation monitoring stations, each water monitoring station will consist of a radioactivity monitor with on-line alarm functions (positron emitters, ^{7}Be, ^{24}Na) and an automatic water sampler. Monthly samples will be analysed in the laboratory for tritium, total beta activity and gamma activity. There will be one station dedicated to the outlet of the LHC cooling water loop (PA1) and 8 stations located at the end of the drainage networks covering the 8 main LHC sites. The water monitoring stations will also include probes for pH, temperature, conductivity and turbidity of discharged water with alarm functions ensuring a quick detection of potential conventional pollution.

The radioactivity monitors will work with a time resolution adjustable from 10 to 60 minutes. The monitors of the physical and chemical parameters of the released water will work with a time resolution of 1 minute. The detection limits will be low enough to recognise any releases to be considered as radioactive (Ventilation: short-lived radioactive gases: <5 kBq/m^3, total beta: <0.03 mBq/m^3, gamma radionuclides: <0.1 mBq/m^3; Discharged water: short-lived positron emitters: <400 Bq/l, ^{3}H: <2 Bq/l, total beta: <0.02 Bq/l, ^{22}Na: <0.3 Bq/l, ^{24}Na: <20 Bq/l.).

Combined with the records of released fluid amounts, balance sheets of activity released into the environment will be compiled on a monthly basis. These will be used in the evaluation of the effective doses to the public due to the releases of radioactive substances into the environment.

4.7.3 Monitoring of Stray Radiation

The dose rate and doses in the environment will be monitored and measured with environmental stray radiation monitoring stations, located either at critical, or, at representative places. Each station will consist of a pressurised ionisation chamber (photons, penetrating charged particles) and a rem-counter (neutrons). These work as on-line monitors with a time resolution adjustable from 10 to 60 minutes. The sensitivity is better than 10 nSv/h for the ionisation chambers and better than 5 nSv/h for the rem-counters. The environmental monitoring stations generate alarms when dose-rate thresholds are exceeded. Twelve stray radiation monitoring stations will be dedicated to the LHC, placed around the LHC sites and at reference places. To obtain even more detailed spatial information about the dose levels on and around the LHC sites, up to 100 thermo-luminescence dosimeters will be placed in the environment and evaluated annually.

4.7.4 Sampling Programme

To check the environmental impact of releases of radioactive substances from the LHC facilities, an extensive sampling programme will be carried out. Aerosol samples will be taken at three critical places and at two reference places by using aerosol sampling stations. Exposed aerosol filters will be analysed off-line in the laboratory for total beta activity and gamma activity. Four stations will be needed to reach the same detection limits as for the ventilation aerosol samplers to be reached (see above). A high-volume aerosol sampling station, which will be alternatively placed at PA5 and PA7, will allow detection limits of fractions of μBq/m^3.

The deposition of aerosol-bound radioactivity on the ground will be checked by analysing grass and/or soil samples for gamma radionuclides. The samples will be collected downwind from the ventilation outlets close to all main LHC sites once per year. The detection limits will be several Bq/kg of dried matter.

The impact on the aquatic environment will be controlled by analysing samples of water, sediment and bryophytes taken annually in all watercourses receiving water from the LHC facilities. All samples will be analysed for gamma activity and water samples will be analysed for tritium and total beta activity in addition. The detection limits will be between 1 and 10 Bq/l or Bq/kg, depending on the sample type and the radionuclide in question.

The LHC-specific environmental monitoring programme will be complemented by the CERN-wide environmental monitoring programme including analyses of reference samples of all types, precipitation samples (2 sites), samples of agricultural products, and groundwater samples (5 wells). Detection limits will be low enough to clearly recognise any pollution with radioactive substances.

4.7.5 Monitoring of Wind and Atmospheric Turbulence

In order to make use of atmospheric dispersion models needed for calculations of the effective dose to the population (see below), site-specific wind and atmospheric turbulence data must be collected. Five ultrasonic anemometers will be installed around the LHC sites. Two of them, in Maisonnex (downwind from PA1 and the CERN Meyrin site) and close to PA5, will be synoptic and measure the 10-minute averages of the wind speed, wind direction and turbulence parameters necessary for assignment of the atmospheric stability class. They will be installed on dedicated 10-metre high masts. Three anemometers installed on roofs of buildings at the sites PA3, PA7, and BA4 (TI-8 + CNGS) will measure 10-minute averages of the wind speed and wind direction. This arrangement will generate a suitable data set for the large LHC area whilst keeping the number of anemometers reasonably small.

4.7.6 Monitoring of Noxious Gases

There will be two emission monitoring stations for nitrogen oxides and ozone, which may be produced in the accelerator and released from the ventilation outlets. One station will be located in Maisonnex, downwind from PA1, and the second in Cessy. The station in Cessy will serve as a background station, as it is located far away or crosswind of all accelerator ventilation outlets. Experience with LEP and hadron accelerators confirmed that emissions of noxious gases from accelerator facilities are well below any regulatory concern and their environmental impact, if any, is negligible. Therefore, only sporadic controls of levels of these gases will be carried out in the ventilation ducts, mostly after major changes in the facility.

4.7.7 Effective Dose to the Population

The effective dose to critical groups of the population will be estimated annually from the readings of the stray radiation monitors and from the activity of radioactive substances released from the LHC facilities with air and water. For the latter exposure pathway, methodology is available [51], which is based on widely accepted environmental and radiological models [52][53].

4.8 THE RADIATION MONITORING SYSTEM (RAMSES)

The Radiation Monitoring System for the Environment and Safety (RAMSES) for LHC will be a new, state of the art system that at a later stage will replace the ARCON (Area Control System) currently used at CERN. RAMSES will take into account the latest legal requirements, international standards, the results of the preliminary hazard analysis [54], the latest technical developments and in particular the specific requirements at CERN such as the time structure or the special composition of the radiation fields.

RAMSES provides continuous measurements of the ambient dose equivalent and the ambient dose rate equivalent in the LHC underground areas together with the surface areas inside and outside the CERN perimeter. If preset radiation levels are exceeded within radiation controlled areas, an alarm will be triggered for the evacuation of personnel. RAMSES generates operational interlocks (e.g. in case of the LHC injection or the LHC RF system during tests) and transmits remote alarms to the CERN control rooms. It will permanently monitor the level of radioactivity in water and air released from the LHC installations. For radiation protection purposes RAMSES will also include hand-foot monitors, site gate monitors, tools and material monitors. In total 350 monitors of 15 types will be installed for LHC, a major part, i.e. about 150 plastic ionisation chambers will be installed inside the machine tunnel to allow remote dose rate measurements necessary for job and dose planning and subsequent decisions on access.

RAMSES provides remote supervision, long term database storage and off-line data analysis. A more detailed description of RAMSES' functions and engineering specifications can be found in [40][45]. A synoptic of RAMSES is given in Fig. 4.11 and examples for the installation are given in Figs. 4.12 and 4.13. As others might be interested in the data, the system is kept open and the data will be accessible for clients via the WEB.

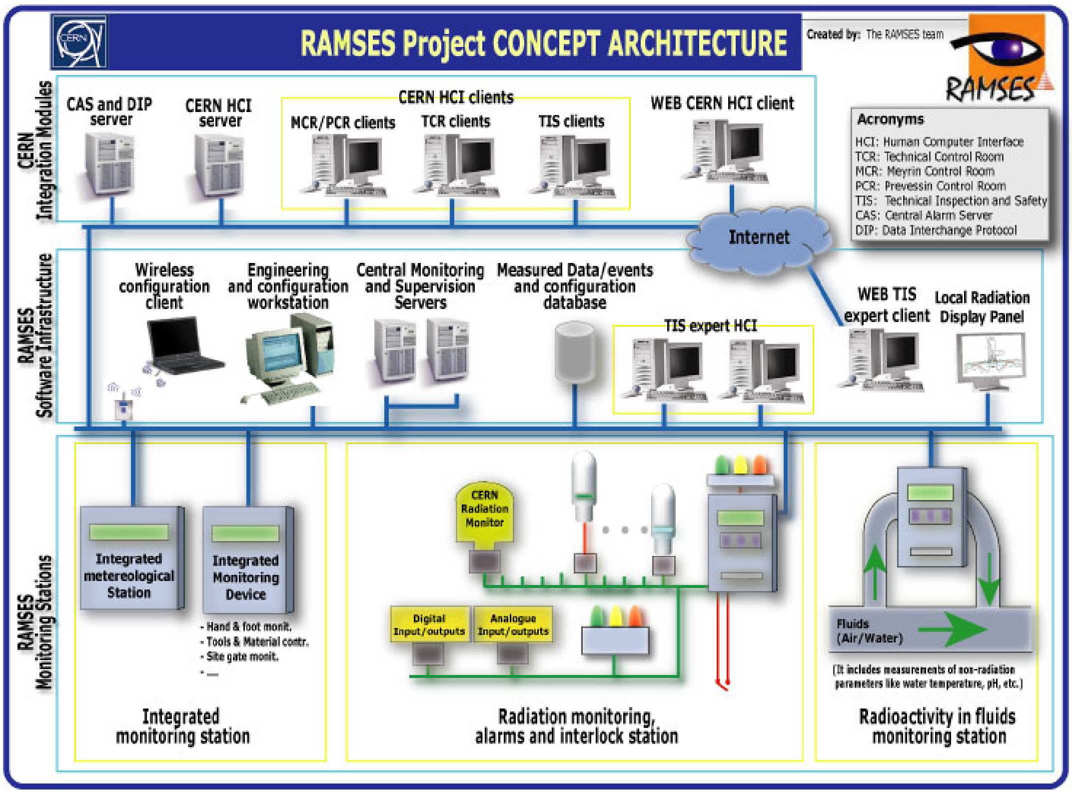

Figure 4.11: Ramses Project Concept Architecture

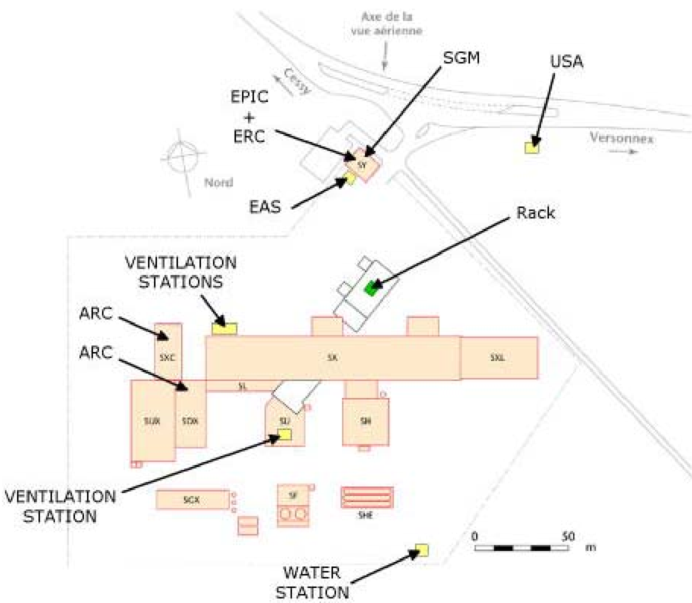

Figure 4.12: LHC point 5 surface buildings

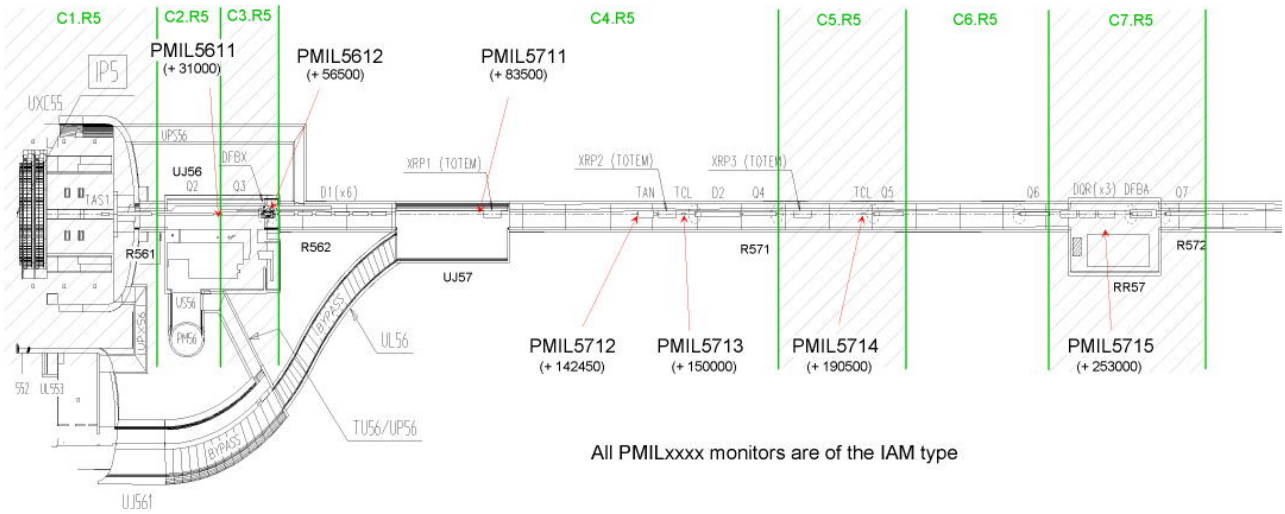

Figure 4.13: LHC point 5 underground tunnel

4.9 MANAGEMENT OF RADIOACTIVE MATERIAL AND RADIOACTIVE WASTE

Radioactive accelerator components as well as radioactive items from general services will be a product of the operation of the LHC and of the chain of injector accelerators. As a result of the interaction of the particle beams with matter, various nuclear processes will develop and in consequence, parts of the accelerator structure and its surroundings will become radioactive.

4.9.1 Classification of Radioactive Items

Radioactive material leaving the accelerator tunnel and injection lines will fall into two categories:

- Accelerator components which are meant to be reused for future re-installation in LHC (e.g. after repair) or in other CERN installations. In this context the category will be named "radioactive material".
- Radioactive items that will be considered as radioactive waste.

4.9.2 Radioactive Material

All items that belong to the category of radioactive material remain under the responsibility of the relevant department. The radiation protection group classifies the material radiologically, gives advice on the transport and where to store the material properly and safely. The RP group also performs radiological checks of the storage centres. However, the management of the stored radioactive material remains the responsibility of the owner department.

4.9.3 Radioactive Waste

Components that are considered as radioactive waste are handed over to the RP group which has full responsibility for treatment, temporary storage and, eventually, elimination of this material. In the case of massive or strongly radioactive items with dose rates above the 100 μSv/h at 10 cm, the components are directly transferred from the accelerators to the central Radioactive Temporary Storage Facility. Whereas in the case of lower dose rates, the material is sorted and separated as far as possible into radioactive and non-radioactive components, before it is sent to the central Temporary Storage Facility.

4.9.4 Management of Radioactive Waste

With respect to radioactive waste management, CERN must comply with the relative legislations of the two Host-States (France and Switzerland) [7][56]. The legal requirements that are common to the two national legislations can be summarised as follows:

- The temporary storage of radioactive material in safe conditions,
- The establishment of a radionuclide inventory (qualitative and quantitative specification of the radionuclide content in each object),
- An update of a register (book-keeping) of the information related to the radioactive waste temporarily stored in CERN.

Typical treatment procedures that will be performed on LHC radioactive waste comprise separating the materials of different natures, a reduction in volume and temporary storage in appropriate containers.

As required by the legislation radioactive waste will be disposed of by sending it to the long-term repositories for low and intermediate level radioactive waste of the host states.

4.9.5 Precautions for Dismantling

The Specific Activity of the radioactive components coming from of the LHC tunnel will vary considerably. This depends on the material composition, the location of the material with respect to beam losses, the irradiation history and on the elapsed decay time. The RP group assesses the radionuclide inventory of each item in the machine. Most of the radioactive waste will be metallic. In addition, specific estimates for the non-metallic solid waste (insulation of power and signal cables, electronic components, etc.) will be performed. As long as machining and corrosion are avoided, all this material can be considered non-contaminating.

Liquid waste (oils, water etc.) will be classified and treated according to the specific risks.

REFERENCES

[1] Council Directive 96/29/EURATOM of 13 May 1996, Office Journal of the European Communities, Vol. 39 (1996), L159

[2] *"1990 Recommendations of the International Commission on Radiological Protection"* ICRP Publication 60, Annals of the ICRP 21, 1-3, Pergamon Press (1991)

[3] *"Protection contre le rayonnement ionisants"*, J.O. de Republique francaise no 1420, edition mise a jour 31 aout 2000

[4] Decret No 2002-460 du 4 avril 2002 « *relatif à la Protection generale des personnes contre les dangers des rayonnement ionisants* », J.O. de la Republique francaise no 81, du 6 avril 2002

[5] Decret No 2003-296 du 31 mars 2003 « r*elatif a la protection des travailleurs contre les dangers des rayonnement ionisants* », J.O. de la Republique francaise no 78, du 2 avril 2003

[6] Ordonnance sur la radioprotection (ORaP) du 22 juin 1994 (Etat le 4 avril 2000) 814.501

[7] Ordonnance sur l'utilisation des sources radioactives non-scellées du 21 Novembre 1997 (Etat 23 Decembre 1997), 814.554

[8] Safety Code F, *Protection against Ionising Radiations*, Radiation Safety Manual, Rev. 1996, CERN.

[9] Safety Code, to be released in 2004

[10] M. Höfert, K. Potter, G.R. Stevenson, "*Summary of Design Values, Dose Limits, Interaction Rates etc. for use in estimating Radiological Quantities associated with LHC Operation"*, CERN/TIS-RP/IR/95-19.1, (1995)

[11] G.R. Stevenson, *"Design values of doses and dose rates outside the shielding of the LHC"*, CERN/TIS-RP/IR/99-28, (1999)

[12] G.R. Stevenson, *"Dose Limits for Shielding Estimation at the LHC"*, CERN-TIS-2003-003-RP-TN, (2003)

[13] G.R. Stevenson, *"Dose and Dose-rate Guidelines for LHC Maintenance Operations"*, CERN-TIS-2003-004-RP-TN, (2003)

[14] M. Brugger, D. Forkel-Wirth, S. Roesler, G.R. Stevenson, "*Constraints from induced radioactivity on design and maintenance"*, Proc. LHC Performance Workshop, Chamonix XIII, 2003, page 360.

[15] Arrete du 12 mai 1998 modifiant l'arrete du 8 octobre 1990 modifie fixant la liste des travaux pour lesquels il ne peut etre fait appel aux salaries sous contract de travail a duree determinee ou aux salairies des enterprises de travail temporaire, J.O. de la Republique francaise No. 118, du 23 Mai 1998, page 7849

[16] A. Fassó, A. Ferrari and P. R. Sala, “*Electron-photon transport in FLUKA: status”*, in: A. Kling, et al. (Eds.), Proceedings of the International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, Monte Carlo 2000, Lisbon, Portugal, October 2000, Springer-Verlag Berlin, Heidelberg, pp. 159-164 (2001).
[17] A. Fassó, A. Ferrari, J. Ranft and P. R. Sala, *“FLUKA: Status and Prospective for Hadronic Applications”*, in: A. Kling, et al. (Eds.), Proceedings of the International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, Monte Carlo 2000, Lisbon, Portugal, October 2000, Springer-Verlag Berlin, Heidelberg, pp. 955-960 (2001).
[18] A. Ferrari and P. R. Sala, *“Physics of showers induced by accelerator beams”*, Lecture given at the 1995 “Frederic Joliot” Summer School in Reactor Physics, Cadarache, France (1995).
[19] M. Pelliccioni, “*Overview of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for high energy radiation calculated using the code”*, Radiat. Prot. Dosim. 88, pp. 279-297 (2000).
[20] Y. Baconnier, G. Brianti, P. Lebrun, A. Mathewson and R. Perin (Eds.), *“LHC: The Large Hadron Collider Project”*, CERN/AC/93-03(LHC) (1993).
[21] S. Roesler and G. R. Stevenson, *“Simple estimates of the radiological importance of heavy-ion operation at the LHC”*, CERN/TIS-RP/IR/98-30 (1998).
[22] P. Lefèvre and T. Petterson (Eds.), *“The Large Hadron Collider - Conceptual Design”*, CERN/AC/95-05(LHC) (1995).
[23] ALICE Collaboration, *“ALICE: Technical Proposal for A Large Ion Collider Experiment at the CERN LHC”*, CERN/LHCC/97-51 (1995).
[24] LHC design report Vol. III chapter 34 and 35, CERN 2004
[25] H. Vincke, G.R. Stevenson, D. Forkel-Wirth, *“Radiation Levels in ECA4 caused by beam losses in the septum magnets to be installed in ECX4”*, CERN-TIS-2002-025-RP-TN, (2002)
[26] H. Vinkce, G.R. Stevenson, D. Forkel-Wirth, *“Radiation in ECA4 caused by beam losses in the dummy protection unit installed in ECX4”*, CERN-TIS-2002-026-RP-TN, 2002
[27] G.R. Stevenson, H. Vincke, *“Studies of the Dose Rate in ECA4 due to Beam Losses in TT40”*, CERN-TIS-2002-034-RP-TN, (2002)
[28] M.J. Muller, G.R. Stevenson, *“Radiation Levels in ECA5 due to proton losses in ECX5”*, CERN/TIS/2003/020/RP/TN (2003)
[29] S. Roesler and G. R. Stevenson, *“The radiation environment at the LHC Insertion Point 2 (ALICE) in beam loss situations”*, CERN/TIS-RP/IR/98-10 (1998).
[30] S. Roesler and G. R. Stevenson, *“Radiation studies for LHC Point 8”*, CERN/TIS-RP/IR/99-22 (1999).
[31] S. Roesler, I. Brunner, presentation to the LHC-TCC, 14 June 2002, to be published
[32] I. Dawson and G.R. Stevenson, *“Radiation Studies in the Collimator Region of the ATLAS Experimental Area”*, CERN/TIS-RP/IR/98-01 (1998)
[33] N.V. Mokhov, I.L. Rakhno, J.S. Kerby and J.B. Strait *“Protecting LHC IP1/IP5 Components against Radiation Resulting from Colliding Beam Interactions”*, Fermilab (2003)
[34] I. I. Azhgirey et al., *“Towards a Shielding Design for the Momentum Cleaning Insertion of the LHC”*, LHC Project Note 297 (2002).
[35] M. Brugger, S. Roesler and G. R. Stevenson, *“Constraints to handling of collimators, shielding and vacuum installation”*, in Minutes of Meeting on Status of Collimation Insertion (6.12.2002).
[36] M. Brugger. Proposal to the AB LHC Technical Committee (LTC) on June 25th, 2003.
[37] M. Brugger, S. Roesler, *“Remanent Dose Rates in the LHC Beam Cleaning Insertions”*, CERN-TIS-2003-026-RP-TN, 2003.
[38] M. Brugger, S. Roesler, *“Accumulated Doses during Interventions on the Vacuum System in the LHC Beam Cleaning Insertions”*, CERN-TIS-2003-027-RP-TN, 2003.
[39] I. Dawson and G. R. Stevenson, *“Radiological Impact of the LHC Beam Dumps”*, CERN/TIS-RP/IR/98-27 (1998).
[40] G. R. Stevenson, A. Fassó and J. M. Zazula, *“The Estimation of Parameters of Radiological Interest for the LHC Main Ring*”, CERN/TIS-RP/IR/92-08 (1992)
[41] I. Baichev, *“Proton Losses in the Dispersion Suppressors of IR1 and IR5 of LHC”*, LHC Project Note 240 (2000).
[42] G. Messenger, M. Ash, *“The effects of Radiation on Electronic Systems”*, Van Nostrand Reinhold Company New York, 1986.

[43] C. Fynbo, G. Stevenson, *“Radiation environment in the main ring of the LHC”*, LHC project seminar, Nov. 2001 http://cern.ch/LHC-radwg/LHC_Radiation_Studies/Radiation_in_the_LHC_main_ring.pdf
[44] K. Potter, H. Schönbacher and G.R. Stevenson, *“Estimates of dose to components in the arcs of the LHC due to beam-loss and beam-gas interactions”*, LHC Project Note 18 1995.
[45] I. Baishev, J.B. Jeanneret and G.R. Stevenson, *“Beam losses far downstream of the high luminosity interaction points of LHC - intermediate results”*, LHC Project Note 208 1999.
[46] I. Baishev, *“Radiation Levels in the LHC RRs at point 1 and 5”* http://cern.ch/LHC-radwg/LHC_Radiation_Studies/RR_IB1404.pdf
[47] http://cern.ch/SL/HRFgroup/LHC_RF_Mtgs/LHCRF_030910.htm
[48] A. Tsoulou et al., *“Monte Carlo Simulaions of the TCC2 test facility at CERN”*, LHC project note 317, June 2003.
[49] T. Wijnands et al., *“Large Scale Radiation Tolerance Assurance for LHC machine electronics”*, 7th European RADECS conference, Noordwijk, The Netherlands, September 2003.
[50] D. Forkel-Wirth, D. Perrin, L. Scibile, G. Segura and P. Vojtyla, *“RAMSES Technical Requirements”*, LHC-P-CI-0002.00, CERN/TIS-ST, Geneva (2003).
[51] P. Vojtyla, *“Models for assessment of environmental impact of radioactive releases from CERN facilities”*, CERN-TIS-2002-013-TE.
[52] *“Berechnung der Strahlenexposition in der Umgebung aufgrund von Emissionen radioaktiver Stoffe aus Kernanlagen”*, HSK-R-41/d, Hauptabteilung für die Sicherheit der Kernanlagen, Villigen (1997).
[53] *“Generic Models for Use in Assesing the Impact of Discharges of Radioactive Substances to the Environment”*, Safety Reports Series No. 19, IAEA, Vienna (2001)
[54] Preliminary Hazard Analysis, EDMS No: 361934
[55] Functional specification *“Radiation Monitoring System for the Environment and Safety”*, LHC-P-ES-003.00
[56] Arrêté du 31-12-1999 fixant la reglementation technique generale destinée à prévenir et limiter les nuisances et les risques externes résultant de l’exploitation des installation nucléaires de base.