EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN/TIS–RP/96–14/CF

RADIATION PROTECTION CONSIDERATIONS IN THE DESIGN OF THE LHC, CERN'S LARGE HADRON COLLIDER.

M. Höfert, M. Huhtinen, L. E. Moritz, H. Nakashima,
K. M. Potter, S. Rollet, G. R. Stevenson and J. M. Zazula,
CERN, 1211 Geneva 23, Switzerland

ABSTRACT

This paper describes the radiological concerns which are being taken into account in the design of the LHC (CERN's future Large Hadron Collider). The machine will be built in the 27 km circumference ring tunnel of the existing LEP collider at CERN. The high intensity of the circulating beams (each containing more than 10^{14} protons at 7 TeV) determines the thickness specification of the shielding of the main-ring tunnel, the precautions to be taken in the design of the beam dumps and their associated caverns and the radioactivity induced by the loss of protons in the main ring by inelastic beam-gas interactions. The high luminosity of the collider is designed to provide inelastic collision rates of 10^9 per second in each of the two principal detector installations, ATLAS and CMS. These collisions determine the shielding of the experimental areas, the radioactivity induced in both the detectors and in the machine components on either side of the experimental installations and, to some extent, the radioactivity induced in the beam-cleaning (scraper) systems. Some of the environmental issues raised by the project will be discussed.

To be presented at the Health Physics Society's 30th Midyear Topical Meeting on The Health Physics of Radiation Generating Machines, San Jose, California, January 5–8, 1997

CERN, 1211 Geneva 23, Switzerland
17 October 1996

1. The LHC Design

The Large Hadron Collider (LHC) of CERN will be a synchrotron-collider which accelerates and stores two intense beams of particles circulating in opposite directions and collides them head-on at several points where particle physics detectors can study the interactions. While CERN's present collider, LEP, collides electrons and positrons at energies up to 100 GeV, the LHC will collide two beams of protons at energies of up to 7 TeV. A luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is needed to reduce the statistical uncertainties in the measured properties of the rare, interesting events at 7 TeV. It is also planned to collide lead ions. The conceptual design of the LHC has been considerably refined over the years and a new design report was published in October 1995 (Lefèvre and Pettersen 1995). A careful cost optimization of performance has led to the main parameters of the LHC given in Table 1.

Table 1: Nominal LHC design parameters

	Protons	Pb-Ions
Centre of mass total energy (TeV)	14	1148
Magnetic field in bending magnets (T)	8.4	8.4
Initial luminosity per collision region ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	10^{34}	2×10^{27}
Number of bunches per beam	2835	608
Bunch spacing (m – ns)	7.5 – 25	37.4 – 124.8
Number of particles per bunch	10^{11}	9.4×10^{7}
Number of collision regions assumed	2	1
Beta parameter at interaction point (m)	0.5	0.5
r.m.s. beam radius at collision point (μm)	16	15
r.m.s. collision region length (mm)	54	53
r.m.s. energy spread σ_E/E	1.1×10^{-4}	1.1×10^{-4}
Beam crossing angle (μrad)	200	100
Luminosity lifetime (h)	10.0	6.7
Stored energy per beam (MJ)	334	4.8
Synchrotron radiation per beam (kW)	3.6	–

The LHC will be installed in the same underground tunnel which at present houses LEP alone (see Figure 1). Since the circumference of the LHC is given by the existing LEP tunnel, the maximum beam energy depends only on the magnetic field which can be reached in the high quality dipole magnets needed to guide the protons around the 27 km of the tunnel. These magnets will use super-conducting coils of NbTi cooled to 1.9 K. They will provide a field of 8.4 T, almost 50% higher than that presently foreseen for any other accelerator. The two opposing proton beams will circulate in ingenious "two-in-one" magnets which provide the necessary twin magnetic channels with opposite sign fields in the same yoke and cryostat. The present "Version 4" optics is based on 23 lattice periods in each of the eight arcs. Each half-period consists of three dipoles with magnetic lengths of 14.2 m and a 3.1 m long quadrupole with a field gradient of $230\,\mathrm{T\,m}^{-1}$. The coil aperture of these magnets is 56 mm and the two beam channels lie side-by-side. In the arcs they are separated horizontally by 194 mm. The beams will only cross in regions where collisions are required.

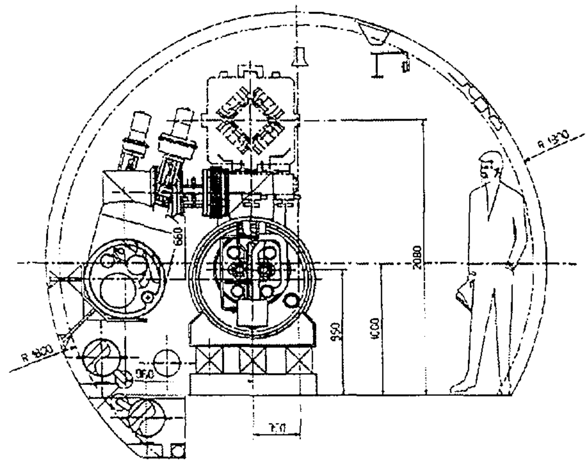

Figure 1: A cross-section of the machine tunnel with the twin aperture super-conducting magnet of the LHC installed below a LEP quadrupole. The separated cryogenic feed-line and connecting valve box can be seen on the left.

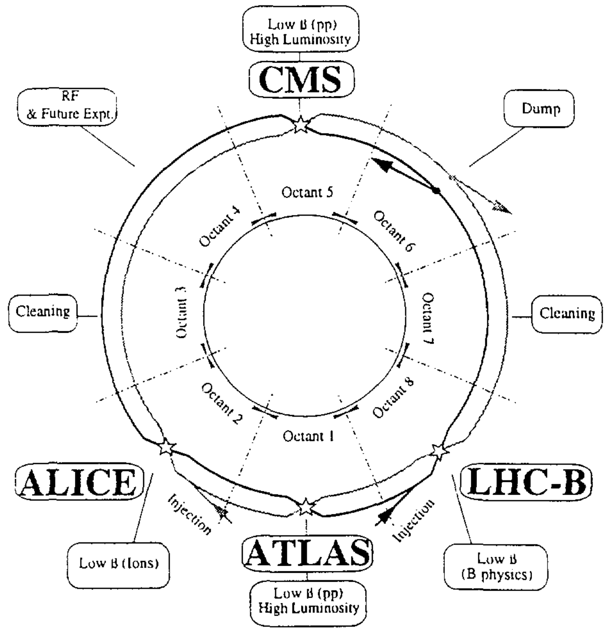

Figure 2: A schematic layout showing the assignment of the eight long straight sections of the LHC to experiments and utilities

The layout of the LHC, indicated in Figure 2, is given by the form of the LEP ring which consists of eight arcs with a bending radius close to 3.5 km linked together with 550 m long straight sections to form a regular structure. The two high-luminosity general-purpose detectors ATLAS and CMS will be installed on opposite sides of the collider in new underground areas at P1 and P5. It is planned to install a dedicated heavy-ion detector ALICE in the existing LEP experimental facilities at P2 where the present L3 detector is housed. It is expected that a specialized B-physics detector LHC-B will be installed at P8 where, in order to make the best use of the existing cavern, it is planned to displace the normal collision point by 11.2 m. With this modification the 18 m long spectrometer of LHC-B will just fit into the cavern presently occupied by the LEP experiment DELPHI.

The remaining straight sections will be used for LHC machine utilities, one to provide safe external abort systems for the beams at the end of each run, one for the accelerating system of Radio Frequency cavities and the other two for the beam cleaning systems. The straight sections around P3 and P7 will be used for these beam cleaning sections; systems of collimators which will ensure that all particles which fall outside the dynamic aperture of the machine in any of the six dimensions of phase space, will be safely removed and absorbed in suitable shielding. If these halo particles were to be allowed to circulate until they struck the vacuum pipe near superconducting magnets they would deposit their energy in the coils and cold masses of the magnets causing superconducting to normal transitions, or "quenches". The efficiency to be achieved in these cleaning sections is of order 99.9%, as the LHC halo is expected to be about 3×10^9 protons per second while as few as 10^6 may cause a quench. Two beam halo cleaning insertions are foreseen, both using a FODO lattice of classical magnets with a dogleg at either end where the beam separation is increased from 194 to 224 mm. These insertions will be equipped with two stage collimator systems consisting of three scattering blocks at each stage, designed to remove the betatron halo in P3 and off-momentum particles in P7. The doglegs are required to prevent off-momentum particles from inelastic interactions in the collimator blocks being lost in the adjacent superconducting machine elements.

The RF accelerating system, consisting of eight 400.8 MHz superconducting cavities per beam, will be installed in a special insertion at P4. The beams will be separated to be 420 mm apart so as to allow the installation of separate superconducting cavities for each beam. The cavities have been placed at the ends of the straight section in such a way as to leave the central region clear for an additional collision region and experiment if necessary. Since the beams do not cross at P4 a scheme with additional bending magnets to bring the beams together into one vacuum chamber and back out again will be required if collisions are needed for an additional experiment.

At the start of a coast the beams are planned to have total stored energies of up to 334 MJ. It must be possible at any time to extract the beams from the ring and absorb the protons in external beam dumps. The beam abort system will be installed at P6 where it will require the full straight section to reliably and cleanly extract each beam with a system of horizontally deflecting fast kicker magnets and a vertically deflecting double Lambertson septum magnet in the centre of the straight section. A 3 μs gap left in the bunch train of each beam will be sufficient for the rise time of the kickers and with the proper synchronisation will ensure that no particles strike the septum. The dump blocks will be placed in special caverns alongside the arc tunnel some 750 m downstream of the septum magnet. To limit the local energy deposition in the carbon core of the dump blocks to reasonable values the 86 μs long bunch train will be swept over the front face of the block by a pair of orthogonally deflecting kicker magnets.

The CERN Council of nineteen European countries approved the LHC project in December 1994. For financial reasons it was approved on the basis of a two stage machine with first colliding beams in 2004, but at a lower energy using a missing magnet scheme. Full energy would not be achieved before 2008. It was decided, however, that the detailed construction schedule would only be formally approved in 1997, when it will be known how many non-member countries have responded to the CERN Council's invitation to join the project. If the required funds were to be available it might be possible to have 7 TeV proton beams colliding much earlier than 2008.

The proposal now being prepared by the CERN management for presentation to Council at the end of this year (1996) follows this approach and will propose a single stage construction to achieve full energy collisions before the end of 2005. This plan reflects the progress which has been made in negotiating special agreements with non-member countries and the consequent scheduling of financial expenditure. Recent work on the details of this schedule suggests that from a technical point of view it is perfectly feasible for both the collider and the experiments, including the construction of the new large experimental areas. It is assumed that LEP will stop at the end of 1999 although the schedule for LHC construction does not foresee any major dismantling of equipment in the LEP tunnel before October 2000. According to this schedule, while civil engineering starts in 1998, the main production run of the cryogenic magnets only starts in 2001, following a two year period for a pre-series. An interesting milestone will be an injection test into the first two octants to be completed, from access point P8 to P6. According to the present planning this will take place before the end of 2003. The detailed engineering design is now underway and the first substantial contracts have been placed, notably for the civil engineering design consultants.

2. LHC Shielding

Shielding requirements for high-energy proton storage rings with superconducting magnets have normally not been based on the estimates of beam loss that will occur around the ring under standard operating conditions since these losses must be kept to a minimal level for the storage ring to work at all. One of the criteria for estimating shield thicknesses is the potential exposure in the case of an unexpected loss of the circulating beam (or beams) at a single point. The damage caused to the accelerator by such a loss would be dramatic, and every effort will be made to ensure that a full beam loss will not occur. However, although the probability of such an event is extremely small, a full beam loss cannot be excluded from consideration.

One of the design constraints chosen for the LHC was that the loss of one circulating beam at full intensity should not give rise to an *ambient* dose equivalent of more than 50 mSv at the outer surface of the shield leading to a Controlled Radiation Area. This is expected in the real exposure situation to lead to an *effective* dose equivalent of less than 20 mSv. This would not then involve any declaration of a radiological incident or accident to a controlling authority and would not jeopardize the future work with radiation of the persons involved.

Other criteria are that the dose rate from a continuous source under the worst credible circumstances should never exceed 100 mSv h^{-1} and that the design dose rate for normal, expected situations should be below 10 μSv h^{-1}.

Simulation studies suggest that a concrete shield of 4 metres thickness would be needed in places close to the accelerator ring in order to meet the requirement concerning the loss of the injected or accelerated beam (Huhtinen and Stevenson 1995). These requirements dominate over most of the circumference of the main ring, including the ALICE and LHC-B experimental areas. However the principal source of radiation to be shielded in the high-luminosity experimental areas is given by the inelastic p-p collisions. These provide a source which slowly varies in time according to the luminosity. Inside the detector during operation, radiation levels can be high enough to damage the detectors and their associated equipment. Typical fluence levels inside the ATLAS detector are given in Figure 3 for neutrons having energies above 100 keV (Ferrari et al. 1995). The total neutron fluence, including thermal neutrons, is typically a factor

2-3 higher. While the fluence in the external region is considerably attenuated by the calorimeters themselves, the neutron fluence in the inner detector remains a concern and efforts to reduce it, for example by adding low-Z material close to the calorimeters walls, coupled with radiation hardness studies, continue. It must be noted that radiation damage is always a radiological concern at high-energy accelerators since the replacement of damaged components can lead to significant exposure of personnel.

In the very-forward regions of the experiment, special shielding-collimators must be placed in front of the first superconducting quadrupoles of the accelerator to avoid excessive energy deposition in the magnets. These collimators act as strong secondary sources of stray radiation and have to be specially shielded in order to avoid serious background problems in the muon chamber systems installed around the main detector. As a consequence of the shielding provided around the collimators and by the detectors themselves, the experimental regions do not require additional heavy shielding. The main concrete shield wall for the ATLAS experiment will be only 2 m thick. The counter-consequence is that the shielding provided by the experiments must always be in position.

In common with all accelerator installations, great care is being taken to match the attenuation of equipment ducts and access labyrinths to that of the primary shields.

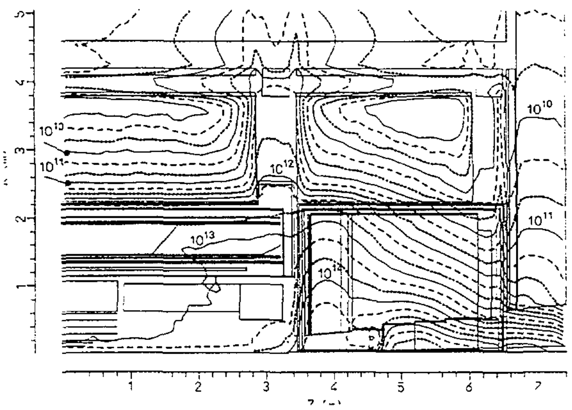

Figure 3: The annual fluence of neutrons (in cm^{-2}) having energies above 100 keV in the inner detector and calorimeter system of ATLAS (reproduced from Ferrari et al. 1995).

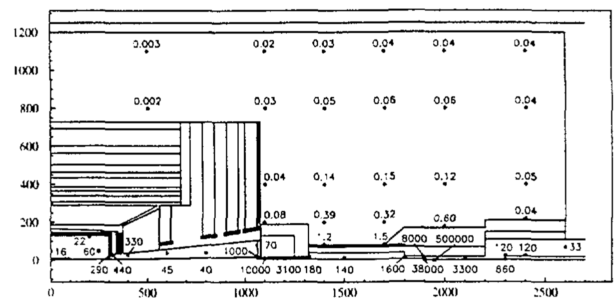

Figure 4: Estimated dose rates from induced radioactivity (in μSv/h) 1 day after the stop of a 60 day operating period for the CMS detector region (reproduced from Huhtinen 1995).

3. Induced Radioactivity in the Accelerator Structure

The fact that beam losses in the superconducting magnets of the LHC must be low to avoid quenches means that high radiation levels from induced radioactivity cannot occur in the arcs of the LHC. It has been estimated however that losses arising from inelastic interactions of the circulating protons with the residual gases in the vacuum chamber will give rise to a dose rate from induced radioactivity close to the cryostats of $\lesssim 1\ \mu$Sv/h (Stevenson 1992).

Local areas of high radioactivity will be concentrated in three distinct areas, i.e. close to the interaction points of the experiments, at the dumps and at the collimators.

Figure 4 indicates the dose rates from induced radioactivity that are to be expected in the CMS experimental region (Huhtinen 1995). It will be seen that the levels outside the detector and the forward shielding are not significant. However dose rates inside the shielding will imply that maintenance work inside the inner detector region will have to be strictly controlled and special handling procedures will be necessary for work on equipment in the very-forward regions close to the beam-pipe. This is especially true for the very-forward detector in the ATLAS experiment which is inside the forward calorimeter of the main detector and thus very much closer to the interaction point than the very-forward detector of CMS.

At the maximum possible intensity of the LHC, up to 540 MJ may have to be intercepted in 86 μs by each of the two LHC beam dumps at any stage of the filling or colliding process, These dumps will be constructed with a graphite core of $70 \times 70\,\mathrm{cm}^2$ cross-section surrounded by an aluminium sleeve 12 cm thick with the whole core contained in an iron shield. The graphite core is 7 m long and this is followed by 1 m of aluminium and 2 m of iron to attenuate the cascade sufficiently. A nearly circular sweep pattern about 120 cm in circumference is required to maintain the temperature of the graphite in the core to reasonable values. Even with this sweep, peak temperatures are expected to reach nearly 2000°C which may require several hours to cool after a beam abort. The effect of natural cooling by convection in the air has been studied and, at the nominal intensity of the 7 TeV beam, the dump can be used safely with a frequency not exceeding once per 3 hours. At the maximum intensity possible for the LHC, the use of a water cooling system would be indispensable. The dumps will be installed in caverns which are separated from the main ring tunnel, some 700 metres away tangentially from P6. Dumping will take place once or twice a day. Since the dumps will be heavily shielded with about 1 metre thickness of iron, the induced activity will only lead to dose-rates of the order of several tens of μSv/h alongside the dumps.

The four cleaning sections, installed in octants 3 and 7, consist of five strategically placed collimators. The three primary collimators will probably consist of 200 mm long aluminium jaws and the two secondary collimators of 500 mm copper jaws. These collimators will concentrate beam losses and the whole region around these scraper elements will become highly radioactive. Iron shields of approximately 1 metre thickness will be required in some places to reduce dose rates from induced activity to tolerable levels in the passage-way alongside the machine elements.

It should be remembered that approximately one-tenth of the initial number of protons in a circulating beam is "used" in each high-luminosity experiment, three-tenths will be "lost" at the scrapers, and the remainder will be dumped at the end of a fill. Only a few percent of the protons will be lost around the ring due to inelastic beam-gas interactions. These considerations will be reflected in the distribution of induced radioactivity in the ring but not in the importance of dose rates due to the induced radioactivity. The dumps can be designed to "absorb" the radioactivity and to be essentially self-shielded objects. This cannot be the case for the scrapers and the high-luminosity experiments. The LHC will probably be the first accelerator where the designers of the physics experiments will have to meet the same design goals for the handling and maintence of radioactive objects that accelerator builders, especially those concerned with the design of ejection septa, have been meeting for the last thirty years.

4. The environment

In common with all proton accelerators, the environmental concerns for the LHC installations are the propagation of prompt radiation (muons and neutron skyshine) and the activation of air, cooling-water, soil/rock and ground-water.

Due to the fact that the LHC is installed at some 60–100 m below ground level, prompt radiation levels will not be measurable at the surface. Strongly directional beams of high-energy muons will propagate over several kilometres behind the beam dumps and close to the scrapers, but the muons remain underground and thus present no radiation hazard for the environment. The underground machine tunnel, the experimental areas and the service galleries are connected to the surface by access shafts of 10–20 metres in diameter. Studies are in progress which show that even without the addition of local shielding, in most cases the length and position of the shafts ensure that radiation levels from neutrons at the ground surface-level will always be low and the propagation of these neutrons via skyshine to the site boundaries will not lead to detectable radiation levels.

The activation of soil is generally of concern for the environment if some of the radionuclides formed can dissolve in the ground water. Here the particularity of the LHC is that the machine is mostly situated more than 80 m underground in a geological formation of compressed sandstone called molasse that does not contain any mobile water and in particular has no exchange with the groundwater contained in the moraine layers near the surface from which the local drinking water supply is taken.

The activation of air in high-energy proton accelerators mainly gives rise to short-lived radionuclides such as ^{13}N, ^{15}O and ^{11}C formed by spallation reactions and ^{41}Ar which is formed by a thermal neutron reaction. Air from the LHC underground areas will be released at four points equally spaced around the ring with distances of about 7 kilometres between them. One of the realistic approaches when calculating the new radionuclide specific release figures has been to assume that the plumes from the ventilation are not superimposed and thus the hypothetical member of the general public could never receive the dose from the sum of the individual releases. Studies of the production and release of radioactivity from the different regions of the LHC are nearing completion, and most have already been published (see for example Huhtinen et al. 1996)

^{41}Ar is normally detected only in small quantities at accelerators. In the LHC however particular attention has been paid to this radionuclide due to the presence of some 100 tonnes of liquid argon in the ATLAS detector where the direct formation of ^{41}Ar is possible. This could escape into the air of the experimental caverns in case of leakage from the argon calorimeters. However, since its half life is quite short (1.82 h) the build-up to equilibrium while the beam is on and the decay after shutdown is very fast. For the total forward calorimeter assembly, the ^{41}Ar activity has been predicted to stay almost constant at 3 GBq while the beam is on (Waters and Wilson 1994).

In the floor of the LEP tunnel are pipes which distribute raw water to the various surface buildings at the eight surface sites. Attention has been paid to the possible activation of this water to ensure that there is no release of any significant radioactivity (Stevenson 1995). Water that is collected in the drains that run all around under the floor of the LHC tunnel also becomes activated. There is a particularly abundant water flow in the drains in the tunnel which runs through the limestone at the foot of the Jura mountains and which will be activated by the known beam losses in the collimator region of point 3. The water which is pumped to the surface may have an activity that is too high to allow its immediate release into the environment. A delay of several hours will ensure that this water meets drinking-water standards, the necessary delay being automatically provided by the passage of the water through decantation tanks to remove any suspended solid matter (mainly sand).

5. Conclusions

It is not possible in such a short review to cover in depth all aspects of the radiological situation of the LHC. These are treated in detail in many reports published by the Radiation Protection Group at CERN and which are available to the public. The final design of the accelerator is still being determined, but sufficient studies have already been completed to show that it will be possible to operate the LHC well within the host-state limits of radiation exposure for both the personnel of CERN and persons living in the region of the LHC.

References

Ferrari, A.; Potter, K.; Rollet, S.; Sala, P. Radiation calculations for the ATLAS detector and experimental hall. CERN Divisional Report CERN/EST-LEA/01/96 1996.

Huhtinen, M. Radiation environment simulations for the CMS detector. Presented at: The Second Workshop on Simulating Accelerator Radiation Environments, 9–11 October 1995, CERN. CERN Internal Report CMS TN 95–198 1995.

Huhtinen, M.; Stevenson, G. R. Geometry effects on shielding requirements for the LHC main ring. CERN Internal Report CERN/TIS–RP/IR/95–17 1995.

Huhtinen, M.; Moritz, L. E.; Potter, K. M.; Rollet, S.; Stevenson, G. R. Radiological implications of the release of air from the LHC experimental regions. CERN Internal Report CERN/TIS–RP/IR/96–06 1996.

Lefèvre, P.; Petterson, T. (Editors). The Large Hadron Collider – Conceptual Design. CERN Divisional Report CERN/AC/95–05(LHC) 1995.

Stevenson, G. R.; Fassò, A.; Zazula, J. M. The estimation of parameters of radiological interest for the LHC main ring. CERN Internal Report CERN/TIS–RP/IR/92–08 1992.

Stevenson, G. R. Provisional estimate of radioactivity in the raw-water supply pipes of the LHC due to beam-gas interactions. CERN Internal Report CERN/TIS–RP/TM/95–25 1995.

Waters, L.; Wilson, W. LAHET/MCNP/CINDER90 activation alculations for the ATLAS Integrated Forward Calorimeter concept. CERN Internal Report ATLAS Int. Note CAL–NO–047 1994.