RADIATION PROTECTION AT THE LHC, CERN'S LARGE HADRON COLLIDER

K. M. Potter, M. Höfert and G. R. Stevenson

CERN, Geneva, Switzerland

ABSTRACT

After a brief description of the Large Hadron Collider (LHC), which will produce 7 TeV on 7 TeV proton collisions, some of the radiological questions it raises will be discussed. The machine will be built in the 27 km circumference ring-tunnel of an existing collider at CERN. It aims to achieve collision rates of 10^9 per second in two of its high-energy particle detectors. This requires two high-intensity beams of more than 10^{14} protons each. Shielding, access control and activation in addition to the high power in the proton-proton collisions must be taken into account. The detectors and local electronics of the particle physics experiments, which will surround these collisions, will have to be radiation resistant. Some of the environmental issues raised by the project will be discussed.

THE DESIGN CONCEPT OF THE LHC

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 two or more 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. 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, which will use superconducting coils of NbTi cooled to 1.9 K are the subject of a vigorous R and D programme as they need to provide a field of 8.4 T, almost 50% higher than that presently foreseen for any other accelerator.

The LHC is designed to study quark-quark interactions whose point-like nature implies that cross-sections decrease as the energy E increases. To maintain a constant detection probability for a given type of event, the luminosity, which is proportional to collision rate, should increase at least as E^2. To explore rare processes such as Higgs$\rightarrow 2Z^0 \rightarrow 4\mu$ the LHC must be able to provide luminosities of the order of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (interaction rates of approximately 10^9 per second). To achieve this, high intensity circulating beams are needed with very small cross-sections at the collision point. The LHC will circulate two opposing proton beams in ingenious "two-in-one" magnets which provide the necessary twin magnetic channels with opposite sign fields in the same yoke and cryostat.

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 beams of the LHC will lie side by side in the horizontal plane in the arcs, 194 mm apart, and will cross over in the centre of each straight section where collisions are required. Two such regions, P1 and P5, will be used for large general purpose LHC detectors, called ATLAS and CMS. The Technical Proposal for each of these has been prepared by collaborations of some 1500 particle physicists from all over the world. Two smaller and more specialised experiments, ALICE which will study lead-ion collisions and LHC-B which will study particles with the fifth "beauty" quark and CP violation, will be installed at P2 and P8, respectively. The remaining straight sections will be used for LHC machine utilities, one to provide safe external beam dumps 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 which will be needed to ensure that halo particles cannot reach the vacuum chamber walls and deposit their energy in the superconducting magnets.

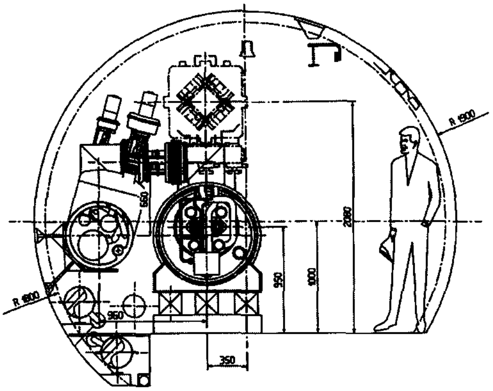

Figure 1: A cross-section of the machine tunnel with the twin aperture super-conducting magnet of the LHC installed below a LEP quadrupole. The separated cryogenic feed-line and connecting valve box can be seen on the left.

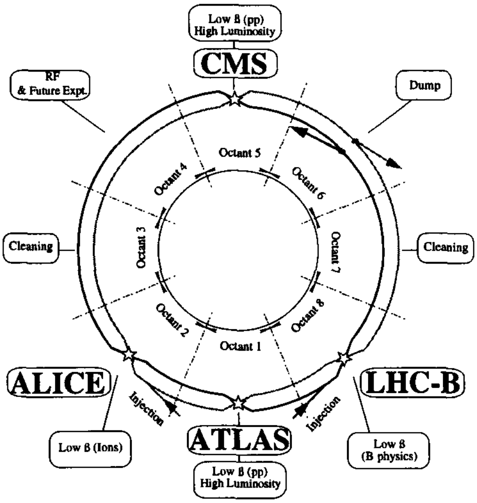

Figure 2: A schematic layout showing the assignment of the eight long straight sections of the LHC to experiments and utilities

The LHC will obtain its protons from the existing CERN accelerator chain of 50 MeV Linac, 1.4 GeV Booster, 26 GeV PS (Proton Synchrotron) and the 450 GeV SPS (Super Proton Synchrotron). The requirements of the LHC, large numbers of high intensity proton bunches with the correct small emittance, are only slightly beyond the routine performance of this injector chain and the necessary development is well underway. As these same injectors frequently operate with other particles, notably heavy ions such as lead, the LHC will also be able to accelerate and collide heavy ions. Luminosities of up to 10^{27} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ should be reached with lead ions in the LHC with the total energy of the collisions between these nuclei being about 1150 TeV.

The luminosity, $\mathcal{L}$, per collision point with two equal beams is given by:

$$\mathcal{L} = N^2 k f \gamma / 4\pi\epsilon\beta^*$$

where N is the number of protons in each of k circulating bunches, f is the revolution frequency, β^* is the value of the betatron function at the collision point and ϵ is the emittance corresponding to the 1σ contour of the beam, normalized by multiplying by the Lorentz factor $\gamma = (E/m_0c^2)$.

It is easy to see that high luminosity requires as many high density bunches as possible with the smallest possible transverse cross-section at the collision point (N and k large, $\epsilon\beta^*$ small). The main limit to such a simple approach comes from the so called beam-beam effect which results from the extremely non-linear fields seen by the particles of one beam as they pass through the bunches of the other. The long range interaction between the bunches of each beam which occurs on either side of the crossing points where the beams pass through a common length of vacuum pipe, about 100 m long, is reduced by introducing a small but finite crossing angle. A careful cost optimization of performance has led to the main parameters of the LHC given in Table 1.

Table 1: Main LHC 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 ($cm^{-2}s^{-1}$)	10^{34}	2×10^{27}
Bunch spacing (m/ns)	7.5/25	37.4/124.8
No. 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 (mm)	16	15
r.m.s. collision region length (mm)	54	53
r.m.s. energy spread $\delta E/E$	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	–

For the reasons given above the LHC requires the highest possible magnetic field, which makes the twin aperture superconducting dipoles the most technologically challenging components. The development of these magnets was started in 1985, in close collaboration with European Industry and other Accelerator Laboratories, with the aim of achieving 10 T fields. Progress has been impressive and five 10 m prototypes built in industry have been delivered and tested. Three of these magnets were assembled in a "string-test" during 1995 to verify the cryogenic system needed to bathe the coils of all 1344 dipoles and some 2000 smaller magnets in superfluid helium and maintain them at 1.9 K. As a result of a year's successful testing, the basic concepts of cooling and powering the LHC magnets have been well validated and a number of changes have been incorporated into the latest design report (1).

The massive cryogenic system needed will be based on that already installed to cool the superconducting accelerating cavities of the LEP 200 project. The system will need a considerable upgrade, however, to lower the temperature from the 4.5 K used for the LEP cavities to the 1.9 K needed for the LHC magnets and to provide the increased cooling power needed to cool down 31,000 tons of cold mass in a reasonable time. A total of about 400,000 litres of liquid helium will be needed, but nonetheless the LHC will be extremely energy-efficient, providing twenty times the collision energy and ten thousand times the luminosity of the SPS p-pbar collider which operated in the 1980s, for a similar energy consumption.

During the whole LHC operation cycle of particle injection, acceleration, colliding and finally extracting and dumping the beams, one of the most critical systems will be the beam cleaning system. A series of collimators must intercept the beam halo particles and prevent them from depositing energy in the coils of the magnets and causing the superconducting strands of the coils to become resistive *i.e.* to quench. If this should happen, for whatever reason, the stored energy in the coils of the magnets will be rapidly extracted to avoid destroying them. It is estimated that a point loss of as few as 10^6 protons per second could quench a magnet, while the losses from small angle elastic scattering in the collision regions alone will scatter of the order of 10^9 protons per second into the halo region.

At the end of a colliding beam run, the two beams will be deflected by fast kicker magnets, providing 18 Tm with a 3 μsec rise time, into extraction channels leading to dump blocks about 750 m away. An appropriate gap will be left in the normal bunch structure during injection so that with proper time synchronization the kicker magnet can extract the beam without excessive losses. The extraction channels will have to be equipped with sweeping magnets to spread the beams over the dump blocks. Even so the inner core of the dumps will have to be made of graphite in order to withstand the very high ($\sim$ 2000°C) temperatures generated by the intense proton beams during the dumping operation. By diluting the beam in this way, the 330 MJ of each beam can be safely absorbed without incurring a risk of destroying the absorber block by the thermal shock. The absorbers will be 14 m long blocks of iron with central cores of graphite encased in aluminium. The iron may have to be water-cooled to allow repeated use during setting up and machine studies and the assemblies will be installed in caverns, designed to cope with the induced radioactivity. Like most of the rest of the LHC, these caverns will be some 100 m underground.

A Conceptual Design Study of the Large Hadron Collider (1) was published in October 1995, less than 12 months after the CERN Council approved the project in December 1994. Technical studies suggest that, with adequate funding, the LHC could be built and installed by the year 2004, but the exact time scale will depend on how many non-member countries accept CERN Council's invitation to join the project. If funding is inadequate, a two stage programme with first operation in 2004 at a lower energy and luminosity is envisaged. In that case full performance might not be reached before 2008.

LHC SHIELDING

Shielding requirements for high-energy proton storage rings are normally not been based on the estimates of loss that will occur around the ring under standard operating conditions. As explained above, these losses must be kept to a minimal level for the storage ring with superconducting magnets to work at all. Estimates of shield thicknesses are based more on 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. This shielding philosophy is explored in more detail in (2). The design constraint 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. 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 jeopardized the future work of the persons involved in radiation areas. Simulation studies suggest that 4 metres of concrete would be needed to shield the accelerator ring to meet this requirement (3). Similar simulation studies have been made for a full beam loss occuring in the ALICE experiment; the results from one of these studies is given in Figure 3 which shows dose equivalent contours in the experimental cavern and in the occupied area in a deep pit above a shield plug. The numbers indicate the dose in mSv from a full loss on one side of the experiment and show that with the shield configuration under study at the time, the dose constraints were not achieved (4). Access to the top of the shield plug must therefore be restricted.

The layout of one of the two high-luminosity experiments, ATLAS, is indicated in Figure 4. In these experiments the main source of radiation to be shielded is given by the inelastic p-p collisions. These provide a source which slowly varies in time according to the luminosity. The experiments themselves provide some shielding around the interaction point. However 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 5 for neutrons having energies above 100 keV (5). The shielding provided by the detector is clearly visible, as is the fact that survival of silicon-based semiconductor devices is not at all assured inside the inner detector assemblies. It must be noted that radiation

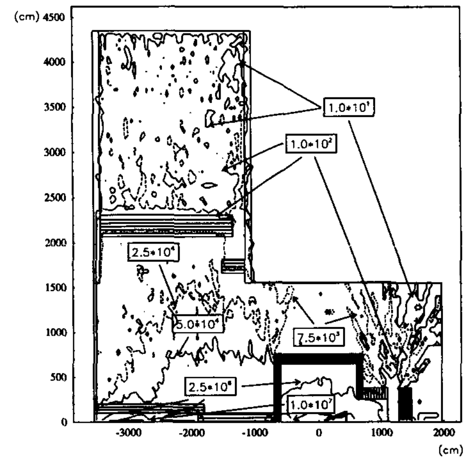

Figure 3: The radiation environment of the ALICE experimental region resulting from a full beam loss. Dose contours are in units of mSv (reproduced from reference (4)).

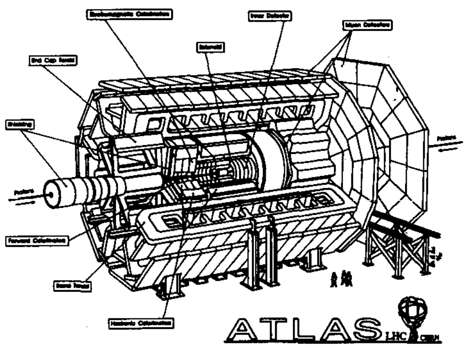

Figure 4: The ATLAS layout.

damage is always of concern to persons concerned with radiological protection at high-energy accelerators since damage goes hand-in-hand with high levels of induced radioactivity. Thus 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 quandrupoles 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 to avoid serious background problems in the muon chambers installed around the main detector. The result of the shielding provided around these collimators and by the detectors themselves is that the experimental regions give the false appearance of being only lightly shielded against beam losses in relation to the LHC main ring, with only 2 m as the thickness of the lateral shield around ATLAS and 3 m around CMS.

INDUCED RADIOACTIVITY IN THE ACCELERATOR STRUCTURE

As explained above, a proton accelerator equipped with superconducting bending magnets and quadrupoles such as the LHC has to be protected from beam losses to avoid quenches. The fact that beam losses in the superconducting magnets must be low means that high radiation levels from induced radioactivity cannot occur in the arcs of the LHC. It has been estimated however that the dose rate from induced radioactivity close to the cryostats will be $\lesssim 1\,\mu$Sv/h (6), arising from inelastic interactions of the circulating protons with the residual gases in the vacuum chamber.

It therefore appears to be prudent to expect the need to designate the LHC ring during shut-downs as a Controlled Radiation Area on this consideration alone. This level of dose rate can be considered as a minimum base level. Local areas of high radioactivity will be concentrated in three distinct areas of beam losses, *i.e.* the interaction points of the experiments, the dumps and the collimators.

Figure 6 indicates the dose rates from induced radioactivity that can be expected in the CMS exper-

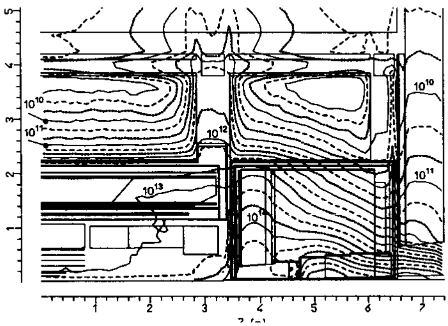

Figure 5: The annual fluence of neutrons (in cm^{-2}) having energies above 100 keV in the inner detector and calorimeter system of ATLAS (reproduced from reference (5)).

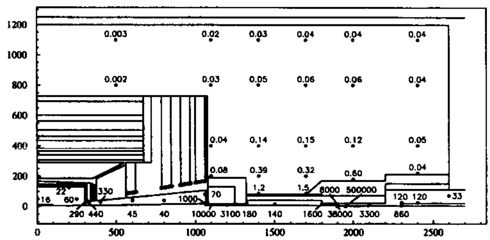

Figure 6: Estimated dose rates from induced radioactivity (in μSv/h) 1 day after the stop of a 60 day operating period for the CMS detector region (reproduced from reference (7)).

imental region (7). It will be seen that the levels outside the detector and the forward shielding are not significant. However 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.

The dumps are essential for absorbing the protons when emptying the rings of the circulating beams once these are no longer useful for physics experiments. These dumping operations will take place once or twice a day, and since the dumps will be heavily shielded with iron, the induced activity in the dump caverns will only lead to dose-rates of the order of several tens of μSv/h.

Scraper-collimators are essential for the successful operation of the LHC. They are needed to remove off-momentum protons which otherwise would be lost in sectors of the LHC containing superconducting magnets. A system of well adjusted beam apertures is required around the machine in specific places, limiting the beam size by scraping off the halo that builds up with time due to the proton-proton collisions in the experiments. The cleaning sections installed in octants 3 and 7 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.

All items inside the LHC tunnel during operation must be considered as and in most cases are slightly radioactive, and must be treated as such when removed from the machine *e.g.* properly marked. In the case of the LHC, the dispersion of machine and experimental components taken out for repair and maintenance, and moved into non-radioactive areas like normal workshops, must be careful controlled. By no means can such items be eliminated from the site as normal scrap material so long as it has not been shown that the activity contained therein is below the exemptions limits for the specific materials concerned. Due to the sheer number of items that are installed in the machine not all maintenance and repair operations can be closely followed by a radiation protection technician. Maintenance staff for the machine and experiments therefore need careful education in radiation matters.

CONCLUDING REMARKS

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 laboratory reports which are available to the public. The final design of the accelerator has yet to be determined, but sufficient studies have already been completed to show that it will be possible to operate the LHC well within the limits of radiation exposure for both the personnel of CERN and persons living in the region of the LHC.

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REFERENCES

1. Editors: P. Lefèvre and T. Petterson, *The Large Hadron Collider – Conceptual Design*, CERN Divisional Report CERN/AC/95–05(LHC) (1995) especially p. 48.

2. M. Höfert and G. R. Stevenson, *Potential exposures at high-energy proton storage rings*, CERN Divisional Report CERN/TIS–RP/95–13CF (1995): presented at the International Seminar on Advancements in the Implementaion of the New Basic Safety Standards – Experience in Applying the 1990 Recommendations of the ICRP, 20–24 November 1995, IAEA, Vienna.

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

4. G. Chabratova, *Some aspects of the shielding for the ALICE experimental region*, presented at the Second Workshop on Simulating Accelerator Radiation Environments, 9–11 October 1995, CERN.

5. A. Ferrari, K. Potter, S. Rollet and P. Sala, *Radiation calculations for the ATLAS detector and experimental hall,* CERN Divisional Report CERN/EST-LEA/01/96: presented at the Second Workshop on Simulating Accelerator Radiation Environments, 9–11 October 1995, CERN.

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

7. M. Huhtinen, *Radiation environment simulations for the CMS detector* presented at the Second Workshop on Simulating Accelerator Radiation Environments, 9–11 October 1995, CERN.

THE ENVIRONMENT

As for other proton accelerators, the topics that are of concern for the environment of 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.

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 100 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.

Thanks to the depth of the implementation of the LHC, radiation levels from prompt radiation will not be observed at the surface. Although strongly directional beams of high-energy muons *e.g.* behind the beam dumps propagate over several kilometers they always 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. Due to the length of these shafts and the presence of local shielding in the underground areas, or additional top shielding at the top of the shafts, the radiation levels from neutrons at the ground surface-level will always be low and the propagation of these neutrons via skyshine will not lead to radiation levels of any significance.

As far as the release of airborne and liquid radioactivity into the environment is concerned, CERN has fixed annual release limits that have been agreed upon by the Host State authorities. With the advent of new dose factors in the recently published Swiss Ordinance on radiation protection that relate the release of a specific radionuclide to the effective dose of an exposed member of the public the original limits are actually under review at CERN.

The activation of air in high-energy proton accelerators 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 in air by a thermal neutron reaction, and hence is normally detected only in small quantities at accelerators. In the LHC however particular attention has to be 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.

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 will be to assume that the four 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 four releases.

Water that is collected in the drains that run all around under the floor of the LHC tunnel becomes activated due to proton beam losses. There is a particularly abundant water flow in the drains of the part of the machine tunnel which runs through the limestone at the foot of the Jura mountains and which will be activated particularly by the known beam losses in the collimator region of point 3. The water which is pumped to the surface will have an activity that will not allow its immediate release into the environment but requires a delay of several hours to ensure that any activity in this water meets drinking-water standards. The necessary delay is automatically provided by the passage of the water through decantation tanks to remove any suspended solid matter (mainly sand).