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Muons and the Electronics Caverns of the LHC Experiments

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Abstract

The Technical Proposals of both ATLAS and CMS indicate caverns housing electronics on the outside of the LHC ring. This note addresses the question as to whether in this position they are exposed to unacceptable radiation levels as a result of muons created by beam losses. Both normal LHC operational conditions and credible accidents have been considered. Not only are the normal operating conditions acceptable, but no realistic accident scenario has been found which would result in unacceptably high doses for radiation workers in these caverns.

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I. INTRODUCTION

The LHC experiments all require a certain number of racks of electronics close to the detectors which are at the same time accessible during LHC operation. The necessary shielding has been defined in a general manner1) and a more refined definition specific to each experiment is currently being established 2)3). Caverns to house 200-300 racks have been included in the Technical Proposals (TP's) of both ATLAS and CMS and in both cases the chosen position is on the outside of the ring with the volume of the cavern crossing the plane of the machine. In this position it has to be expected that muons from beam losses in the machine arcs may traverse these caverns. It is the aim of this note to establish the order of magnitude of radiation doses which might result from this source and hence determine if it is necessary to make more refined estimates or perhaps resite the caverns.

II. BEAM LOSSES

For radiological purposes it is necessary to consider the loss of protons from the LHC beam under the two quite different categories:

a) continuous operational loss of a small fraction of the circulating beam

b) accidental or catastrophic loss of the whole beam or a substantial part.

At the LHC the maximum rate of the former at any one point will be limited by a monitoring system designed to extract the beam and send it to the external dump before magnets quench as a result of energy deposition in the superconducting coils. Hence the threshold of this detection system can be used as the maximum local loss during normal operation. This threshold will be set at approximately 10^6 protons per second.4)

Establishing a reliable number for the maximum local accidental beam loss is much more difficult. The "accident" is required to produce not only an unusually high loss but as shown below it must be confined to less than a 20m length of beam pipe and in addition there must be a complete failure of the beam loss detection and dumping system. This system will be constructed with considerable redundancies to ensure that its failure is a very rare event. The stored energy of the LHC design beam is 332 MJ, enough to create damage that will take many months to repair, if it is dissipated in an uncontrolled manner. It is reasonable to assume that this event will only occur once or twice during the lifetime of the LHC, if at all. Nonetheless for the purposes of this note studying a total, local beam loss is the first step to determining if a problem may exist.

III. ORIGIN OF MUONS

The possible sources of muons which will traverse the electronics caverns depends on the geometry of the LHC (version 4.1)[5] which is sketched in fig. 1. The straight section upstream of an odd numbered collision region is 263.888 m long. This is followed by the region of the dispersion suppresser 159.469 m long where the average radius of curvature is 3909 m, a short straight of 14.957 m follows and then the regular lattice where the quadrupoles are on an arc of radius of curvature 3494 m.

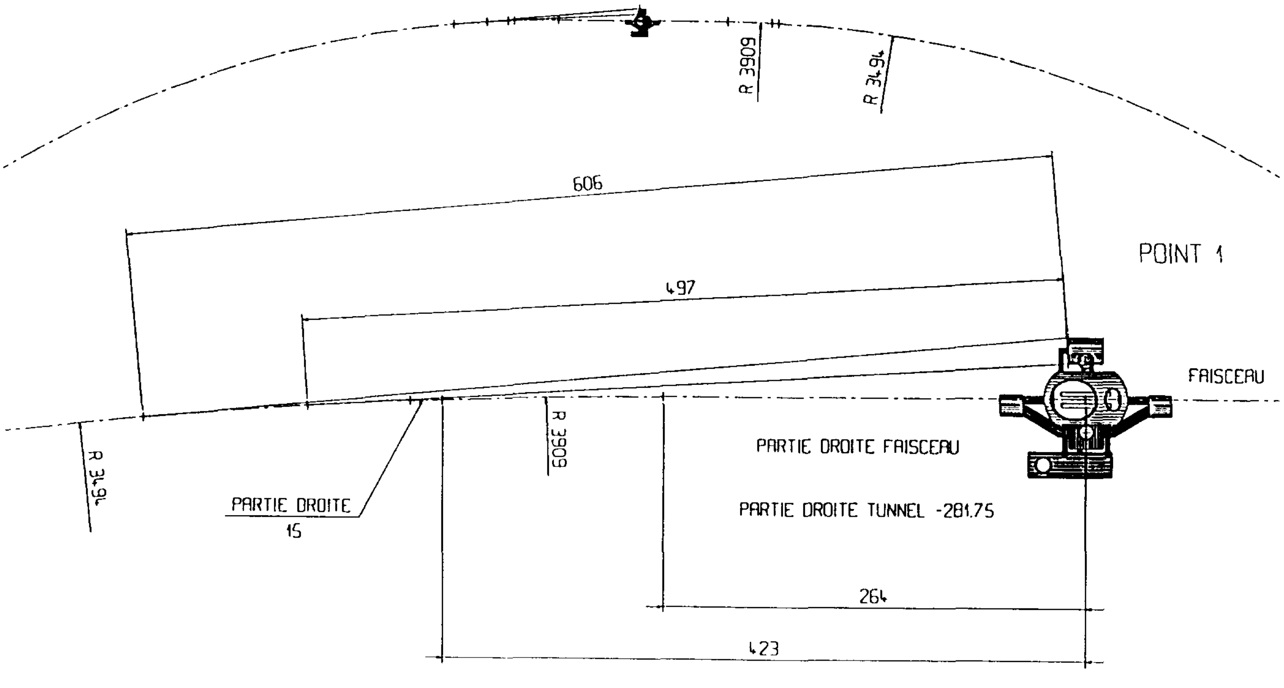

Fig. 1 The basic geometry of the LHC upstream of a collision point, for example P1 or P5.

The position of the quadrupoles is of particular interest as the beam is at its largest in the horizontal plane in a horizontally focusing quadrupole (F) and at its highest in the vertical plane in a vertically focusing quadrupole (D). This can be seen from the optical parameters of the regular lattice shown in fig. 2.

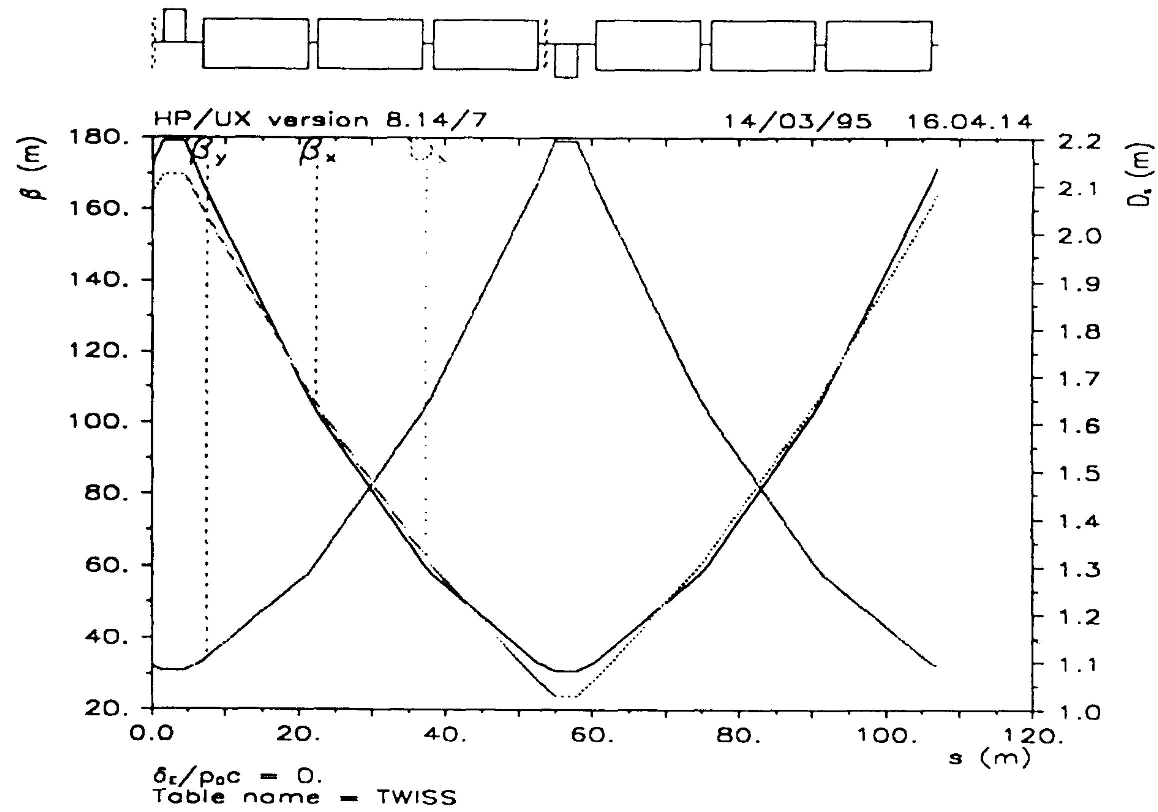

Fig. 2 The optical parameters β and momentum dispersion in the standard LHC half-cell.

The geometry described can be used to determine where tangents to the beam in each quadrupole, in the machine plane, crosses the plane orthogonal to the beams at the collision point. The transverse distance from these tangents to the collision point is plotted against the distance to the quadrupole in fig. 3. It can be seen immediately that since the inner walls of the ATLAS and CMS electronics caverns are at 20 m from the collision point the first quadrupole of interest is the F quadrupole, 53.460 m beyond Q10 and approximately 500 m from the collision plane. In effect unless the half-width of the muon distribution from 7 TeV protons in a fixed target configuration is more than 5 m at 500m (10 mrad), no quadrupole in the dispersion suppresser or straight section can be an important source of muons for the electronics caverns.

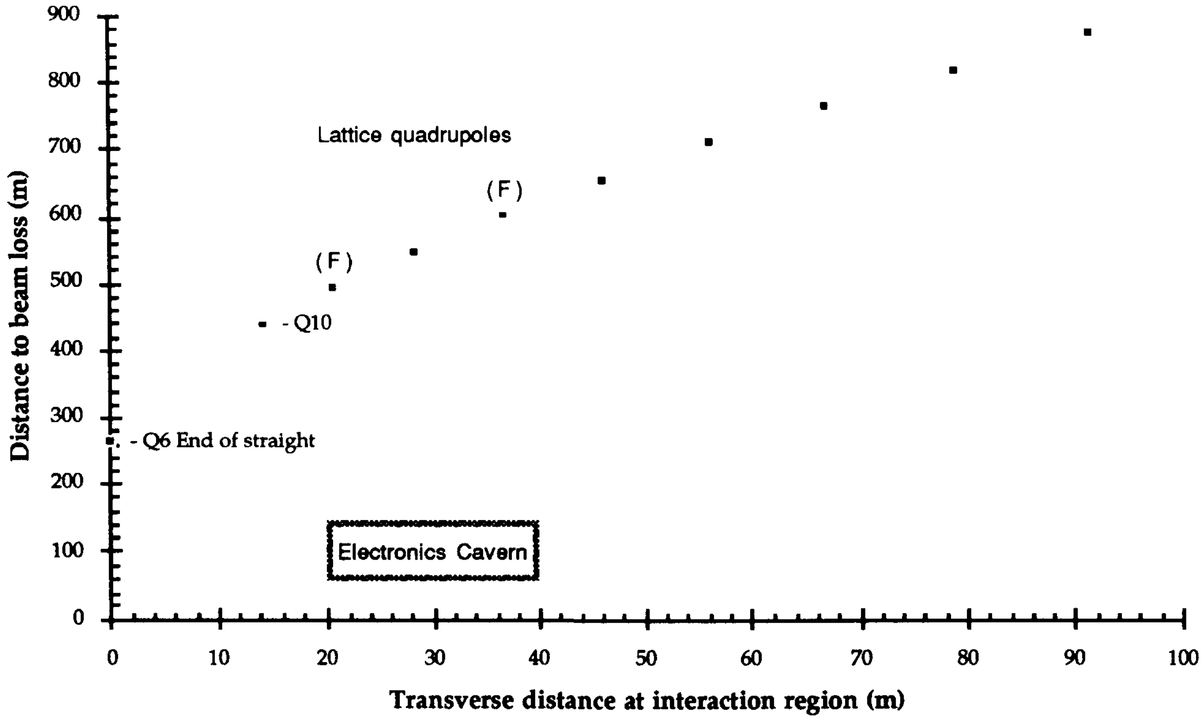

Fig 3 Transverse distance at an LHC collision point to tangents to the beam in successive upstream quadrupoles.

IV. MUON PRODUCTION

Muon distributions have been given by A. Van Ginneken in a Fermilab document 6). The results from MUSIM (A Program to Simulate Production and Transport of Muons in Bulk Matter), given in reference 6, include an isodose contour map due to 8 TeV protons incident on homogeneous rock of density 2.24 g.cm^{-3}. This map has been used to obtain the logarithmic plot of fig. 4 where the dose in Sievert per incident proton is plotted against the transverse distance after 500 m. It can be seen that this distribution is extremely narrow, the dose falling by two orders of magnitude in 2 m, which corresponds to an angular distribution with $\sigma = 1.5$ mrad. Hence the assumption that losses in all quadrupoles up to and including Q10 can be ignored seems reasonable and the angular distribution of the beam, $\sigma = 1.7$ μrad, which should be folded into this plot can be ignored.

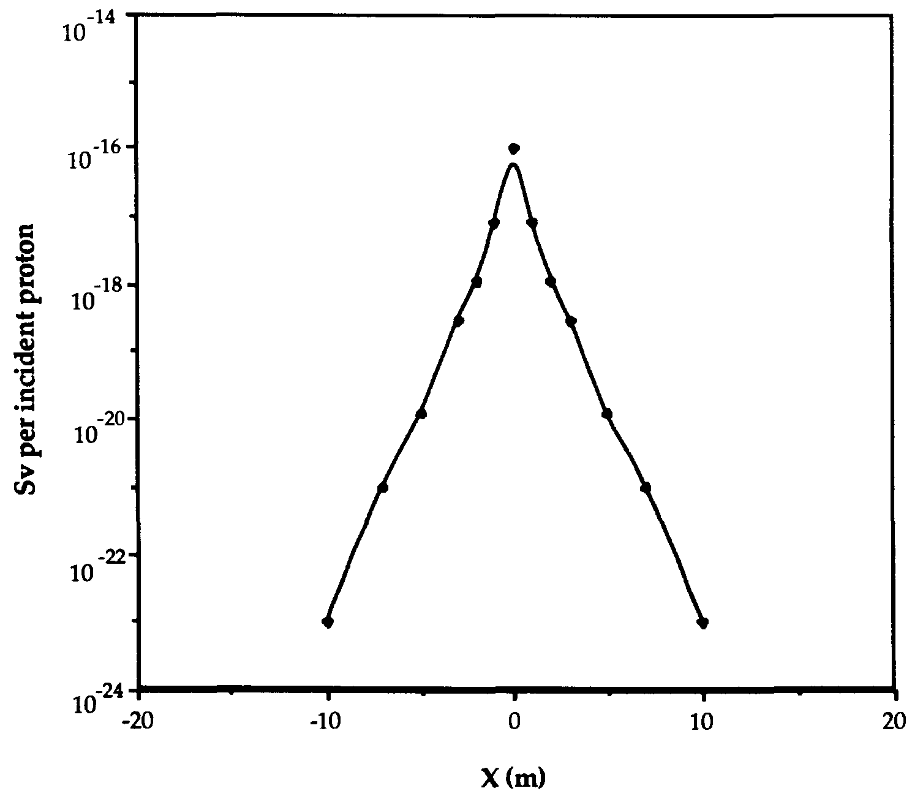

Fig. 4 Log plot of transverse dose distribution from muons after 500 m.

However, it must be remembered that the quadrupoles, which themselves have magnetic fields of 3 T at the vacuum chamber are followed by the high field (8.4 T) dipoles of the LHC and these different magnetic fields will modify the angular distributions of pions and kaons which subsequently decay to muons, as well as those of prompt muons (muons from D, η and several vector mesons are all included in MUSIM). A. Van Ginneken6) recognised this and included an isodose map for muons from 8 TeV protons incident on the outside of the vacuum chamber of a continuous dipole with an appropriate magnetic field placed in the LEP tunnel. A transverse distribution after 500 m, obtained from this plot is shown in fig. 5.

The half-width at half height of this distribution is approximately 3.6 m, (σ = 10 mrad) still small enough to ensure that only losses from one or two quadrupoles need be taken into account and there is no significant overlapping of the distributions from adjacent quadrupoles.

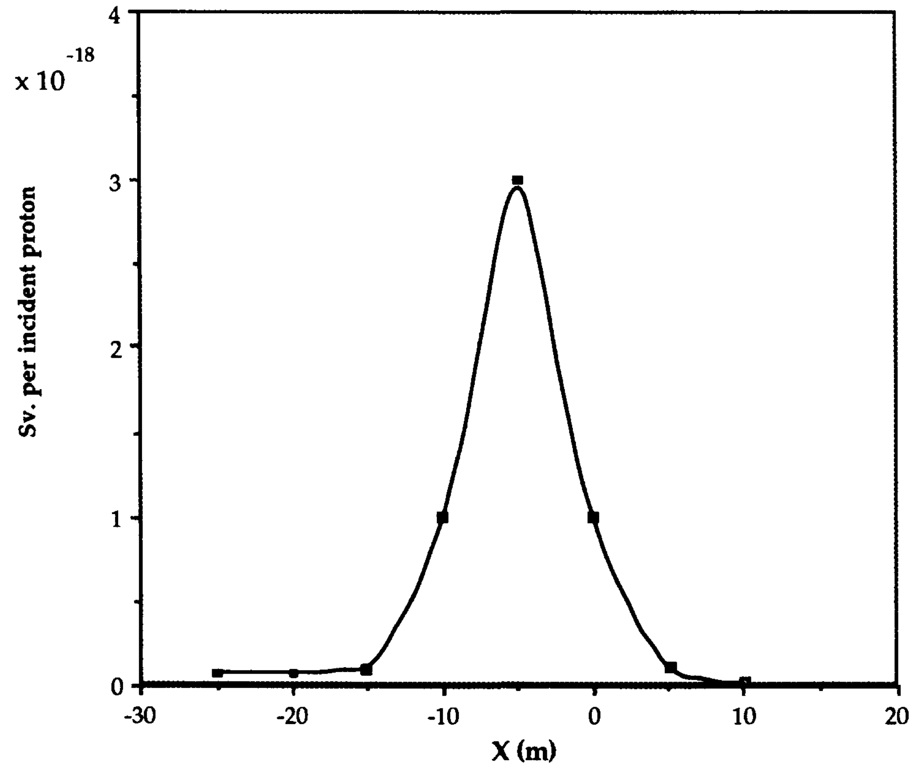

Fig. 5 Transverse distribution of the dose from muons after 500 m for a proton loss in a continuous dipole placed in the LHC tunnel.

V. APPROXIMATE RADIATION DOSES.

The dose distribution of fig. 5 can be used to estimate maximum radiation doses from muons in the electronics caverns of ATLAS and CMS. In both P1 and P5 the first quadrupole after Q10 will be an F quadrupole, where the horizontal beam size and the momentum dispersion are both at maxima. Hence this will be the most likely local loss point. In the worst possible case, 10^6 protons per second may be striking the vacuum chamber wall in this quadrupole which according to fig. 5 will give a peak dose of

$$3 \times 10^{-18} \times 10^6 \times 3600 \approx \mathbf{0.01\ \mu Sv/hour}$$

To be compared with the limit of 10 μSv/hour for a controlled radiation area[7]. It appears that even if the threshold of the beam loss detection monitor is raised by a factor of ten, perhaps because the LHC magnets prove to be more resistant to losses than expected, there is still a substantial margin of two orders of magnitude.

The maximum possible accidental loss is the complete stored beam of 2.8 x 10^{14} protons, although no realistic scenario whereby this can happen locally has been found. Nonetheless using a total design beam loss at one point suggests a peak at the worst possible point in an electronics cavern of:

$$2.8 \times 10^{14} \times 3 \times 10^{-18} = \mathbf{0.84\ mSv.}$$

This has to be compared with "the design limit appropriate to a Controlled Radiation Area involving the full loss of one circulating beam (in the LHC) should be an ambient dose of 50mSv" from reference 7). Once again there appears to be a substantial margin of more than an order of magnitude.

VI. DISCUSSION

The MUSIM simulation results used for this note must, of course be treated with some care, in particular because A. Van Ginneken published a second paper, an erratum in September 1993. However, the error discovered in MUSIM concerned the treatment of multiple scattering and the result was to make the muon distribution slightly narrower than before. The peak value also increased by about 25%. Both very minor effects when compared to the three orders of magnitude of conservatism for the maximum continuous beam loss case. This correction should also be largely irrelevant for the simulations with magnetic field where the spreading of the muon distribution is totally dominated by the field effects. In fact the plot used to obtain fig. 5 (Fig. 11 of the original paper of reference 6) was not corrected in the erratum, apparently because it came from an earlier version of the simulation programme which did not have the same error.

It is also worth noting that the simulation used a single aperture magnet while with the present preferred LHC layout the losses in question will be from the inner aperture of a twin aperture magnet. Hence the integrated magnetic field in the path of the loss will be much larger than those used for the simulation. Indeed it is clear that the peak muon dose which could be recorded in a counting room on the outside of the LHC ring is a strong function of this integrated magnetic field, since with no field at all, the distribution of fig. 4 would approximate to the situation and suggest peak doses of as much as 30 mSv. Although in this case the simulated shower development is taking place in homogenous rock with a density of 2.34 gm.cm^{-3} instead of in the very inhomogenous magnets, where the materials encountered will be Fe, NbTi/Cu, Al, Fe, in that order and where the average density will be approximately 5 gm.cm^{-3}, even taking into account the drift lengths between magnets. Since there is no way 7 TeV protons can be circulating in the LHC without the presence of the magnetic fields, whose time constants are very long compared to the proton orbit time of 88 μs, it would be overly conservative to use fig. 4 to estimate the peak possible dose.

In the event of loss of any magnet power supply, or more likely a magnet quench, the LHC beam dump will be triggered within a few turns. If the dump fails to fire the particle orbits will gradually change as the fields in the magnet or magnets affected change. The time constants involved in quench detection are of the order of milliseconds while the quench heaters which are used to increase the natural propagation time operate in about 35 ms (400 turns). The fast rundown of other magnets which is then triggered has a time constant of 100 s [8]. Hence, there is plenty of time for the beam to be cleanly dumped and if that fails the protons will be lost over hundreds, if not thousands, of turns. The magnetic field changes during this process will have a negligeable effect on the muon distributions.

In the event of the fast kicker of the dump failing to fire correctly, protons from the unstable circulating beam will start to strike the collimators in P3 and P7, until the primary collimators melt, followed by the secondary and tertiary collimators. Only after that can a substantial number of the remaining beam particles reach other obstacles around the ring, the next smallest apertures, all of which are in the insertions. In the absence of special collimators or other aperture restrictions at the critical points near the ends of the arcs there seems to be no way that even this catastrophe could lead to a substantial fraction of the beam being lost there and hence create a significant dose due to muons in the electronics caverns.

The last quadrupoles of an arc are in some sense in a privileged position, as regards beam loss, as they are protected by the previous arc quadrupoles, some twenty positions were the nominal beam size and apertures are identical. Hence they can only be struck by particles deviated locally by residual gas scattering or which have exceedingly rapidly growing betatron amplitudes. The cause of the latter must be an essentially incoherent process, as there are no rapidly changing magnetic fields in an arc, and the resulting losses will be spread over long distances. It would require a major misalignment to make one of the critical quadrupoles a privileged loss point and it is reasonable to suppose that this would be detected and subsequently corrected by observing the loss monitors under normal operating conditions.

Perhaps the most credible accident which could cause the local loss of at least a fraction of a circulating beam would be the undetected closing of a fast acting vacuum valve, which could close in as few as 10 beam revolutions. In such a case the dump kickers would normally be triggered by the interlock system, or by the loss detection system, but if both of those failed the interaction of the beam particles in ~3% of an interaction length of material might lead to muon doses of perhaps 10% of the maximum estimated in section V. In the critical region, which is at 2K, there is no such valve. Neither is there a sector valve which in addition is slow and takes seconds to close.

VII. CONCLUSION

The above results show that there is no serious radiological problem at the LHC which can arise as a result of the position of the electronics caverns in the TP's of ATLAS and CMS, on the outside of the ring. This is essentially because of geometry and in particular the 20 m minimum transverse distance of the electronics cavern from the beam. A distance which should not be reduced. It would also be wise to avoid placing collimators, vacuum valves or other objects which could move accidentally into the beam, or create aperture restrictions in the arcs before Q10. However, such a possibility is unlikely to be even considered as the whole of this region is in the main 2 K cryostat.

Although there is no indication of a serious radiological problem, moving any occupied caverns to the inside of the ring, or out of the plane of the machine by at least 3 m, would be indicated by the ALARA principle, all other considerations being equal.

Acknowledgements

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