WHERE ARE WE WITH THE LONG-TERM PLANS AND THE CERN-WIDE RADIATION POLICY

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Abstract

The different options for the long term consolidation plan are presented, which should ensure that the risk of SEE in control electronics installed in the LHC is minimized. The plan will imply full (or partly) relocation of the installed electronics for some locations like US85 or UJ56 and UJ76, additional shielding in different areas where relocation is not convenient and may imply major civil engineering for Point 1 and Point 5. The possibility to avoid some of this heavy works by modifying the loss pattern or by redesigning some of the control systems to be radiation tolerant will be summarized for the major systems. Finally, the basic principles to be fixed in a CERN wide radiation policy at CERN will be proposed, with the aim of ensuring that we will never in the future be obliged again to consolidate further exposed underground installations.

CONSOLIDATION PLAN

Scope and objectives

In order to achieve a successful consolidation it is important to fix precisely its objective. Specifically we need to fix a radiation level that can be considered safe for electronics that is not proved to be radiation tolerant, and then develop a strategy to either reduce radiation levels in the underground areas below that limit, or to impose to the systems installed a strict policy to ensure radiation tolerance at the level to which they are exposed.

Estimating the MTBF due to radiation damage of electronics for the LHC machine at any level of radiation is impossible, due to the fact that too many electronic systems are installed in areas exposed to radiation and that it will be impossible to measure the sensitivity of all of them.

Apart from electronics installed directly in the tunnel and in UJ56, where total Ionization Dose (TID) and Displacement Damage from Non Ionising Energy Loss (NIEL) may represents a serious issue, the main risk for exposure of electronics to radiation in the LHC underground areas comes from stochastic effects (Single Event Effects - SEE).

For this reason the limit fixed by the Radiation To Electronics (R2E) study group should not be intended as an absolute value below which there is no risk of occurrence of SEE, but rather as the upper value for which normally a single non rad-hard electronic device, either Commercial Off The Shelf (COTS) or Custom designed has good chances to have an MTBF well above one year. It cannot be excluded that very sensitive electronics may present dramatic failures already at this level, but R2E considered that the number of equipments presenting this risk is rather limited and a workaround in case of problems can be found in a reasonable time. Reducing further the limit to come close to the yearly value normally registered at ground level (~10^5 hadrons/cm^2) would represent an investment well beyond what is reasonable. The consolidation program described below however aims at minimising the number of equipment exposed by relocating those for which no radiation tolerance data is available in properly shielded areas. For a more detailed discussion on the choice of the limit see ref. [1]. For the purpose of this paper it is sufficient to know that in the LHC we will aim at reducing the annual fluence of high energy hadrons (>20 MeV) below **10^7 hadrons/cm^2** for every year (200 days) at nominal luminosity and intensity. Where this is not possible (e.g. RRs, some of the UJs) we propose either the relocation of equipment or its replacement with radiation tolerant equipment to be designed on purpose.

Can we displace losses?

It has not been possible yet to study in details the possibility to displace losses in the machine by e.g. moving collimators. A study was conducted in 2008 by R. Assmann and his team to temporarily move the betatron cleaning from IR7 to IR3. This option would be extremely attractive if it was possible to implement it as a long term solution, but today this is not envisaged. Moreover, as presented in 2008 it will imply a further limitation by a factor 2 in intensity and use some of the positions reserved for phase 2 collimators, spoiling therefore the objective to increase the intensity to nominal within a few years. Further ideas to reduce the losses in other areas by changing the operational scenario could not unfortunately be found.

The strategy to follow to reduce the risk has therefore to rely on more pragmatic actions:

- Shielding
- Relocation to safe areas
- Creation of new safe areas
- Redesign of some of the critical systems

In the following paragraph the possible scenario to mitigate the risk in each of the exposed underground area will be presented.

Equipment installed in the tunnel

The LHC paradox consists in the fact that all the equipments directly installed in the tunnel and that are therefore the ones exposed to the highest doses and fluencies, are also those that can be considered safer for tolerance to SEE. This is because the tunnel was the only area that had been clearly identified as critical for radiation and therefore appropriate actions in terms of design, procurement of components and irradiation test were taken in due time. The most relevant systems concerned are: QPS, Power converters, Beam Loss monitors, Beam Position Monitors, some cryogenic monitoring devices, Warm Magnet Interlocks (in the transfer lines). All those equipment have been tested in the CNGS facilities or in TCC2 and they either survived the radiation level specified for the tunnel or the problems are understood and a workaround is being found. No interference with operation in 2010 and beyond is expected.

In the long term a serious concern might come from the FIP communication cards installed in Power converters and QPS. In fact while the old chip provided by Alstom as FIP client had been selected for its radiation hardness and proved to work well in several irradiation tests, its new version (so-called microFIP) is much less tolerant and cannot be used as such in the tunnel. The new QPS system that includes the MicroFIP chip in its design had to provide a workaround to reset the chip when a SEE occurs. In this case a SEE affects only the monitoring of QPS parameters and not the safety of the machine [2]. However a long term solution is being seeked through the insourcing of the WorldFIP technology and the design of a new FIP device is now a high priority project for BE/CO [3] that coordinates an interdepartmental working group to address the problem.

The safe underground areas

The equipment installed in the underground areas of P2, P3, P4 and P6 are considered safe. In details:

P2: Following the installation of dedicated shielding in UJ23 at the exit of TI2, the initial part of the UA where power converters are installed is now below the reference limit.

P3: Levels in UJ33 are well below the reference value. UJ32 may become a problem if excessive beam-gas interaction occurs, however there is sufficient room for shielding if necessary. Dedicated radiation monitoring has been installed in the area and will tell us (in 2011?) whether we need to take any action.

P4: The level of radiation in the cavern will depend mainly on beam-gas interaction. With the assumed maximum gas density of 10^{15} molecules/cm^3 the levels of fluence will remain well below the reference value. Radiation monitors have been added to verify the assumptions.

P6: The main source of concern is the radiation coming from TCDQ and TCDD that could stream through the cable ducts and affect the controls of the Beam Dump system. To avoid that, the ducts have been filled with iron rods in 2009 therefore UA63 and UA67 are now considered safe. Dedicated radiation monitoring through RADMONs and TLD detectors has been implemented to confirm that the intervention has effectively solved the problem.

Early actions to gain time

In the most exposed areas the radiation levels may reach very soon the reference value and therefore affect at an early stage the operation of the LHC. At nominal conditions, the fluence can reach several 10^9 hadrons/cm^2 and therefore present a considerable risk for the operability of the LHC, probably preventing it completely. Solving the problem at the same time in all the areas is impossible since this would involve considerable financial resources and parallel work in too many areas from the equipment groups concerned. A pragmatic proposal is therefore to first reduce the radiation levels by shielding to the lowest possible level in order to push in time the moment where the fluence will be equal to the reference value. It has been concluded however that one cannot reduce only by shielding the radiation levels down to the reference level. The measures proposed in this section therefore, apart from the relocation in P8, only aim at giving more time to develop long term solutions as described in the following paragraphs and that may require a minimum of 3 to 4 years to be implemented. In details we propose:

- Full relocation of electronics installed in UX85, and protection of cryogenic controls by shielding in UX85. The integration study is almost completed and the action could be performed during the next shutdown (the minimum time necessary is under study). This action should solve completely the problem in P8, pending confirmation of the efficiency of the different shielding installed through analysis of RADMON and RAMSES data during operation and from the TLD installed for that purpose.
- Heavy shielding of UJ14 and UJ16: will allow decreasing the radiation levels to about 10^8 hadrons/cm2/year (at nominal) and therefore give the time to implement a solution for the full relocation of all the equipment.
- Relocation of ODH and Fire detectors everywhere, and shutdown of underground access doors controls during operation.

UJ76, RR73 and RR77

UJ76 has been the first area addressed already in 2008. A partial relocation of the most sensitive equipment has already been prepared by enlarging the TZ76 and installing part of the needed infrastructure. The actual relocation will take place in the next long shutdown. At the same time it is necessary to further optimize the shielding of the safe room, that for its specificity cannot be moved from UJ76.

RR73 and RR77 are very difficult to address. The main systems installed there are the 120A and 600A power converters which are not radiation tolerant. It is not possible to imagine any civil engineering work in surface since the RRs are below the urban area of Ferney-Voltaire therefore we are left with the following options:

- Leave the power converters in place but redesign the most sensitive parts (the FGC at least) to be radiation tolerant to at least 10^8 hadrons/cm^2. This will represent an important workload for TE-EPC which requires also the full support of the EN-STI team for the numerous test campaigns that will be necessary to find the right components and assess the radiation performance of the entire system. The risk of not reaching the required tolerance is projected to be low, and the solution might be ready at the earliest in 2013/2014.
- Move the converters to TZ76 and use warm cables to connect them to the corresponding magnets. In this case a full reorganisation of TZ76 needs to be done since after the works done in 2008 there is no more possibility to pass any new cable to the TZ. The converters have to be installed as close as possible to the UJ76 and all the rest has to be moved further on towards the lift. This implies dismantling another part of the separation wall present on TZ76. In order to compensate for the new long cables it will be necessary to redesign the power converters to sustain a much higher voltage. The development would use some manpower in TE-EPC but the development is considered as very low risk since it uses standard technology. The solution could be ready by 2013/2014. A solution to pass all the power cables in the tunnel need to be studied and it is not guaranteed that it can be found.
- Move the converters to TZ76 and use a DFB in the TZ76 to convey all the cables into a single superconducting cable and add a junction box somewhere on the magnets. This is also conceptually a low risk solution, since would re-use the existing design already available for the converters of P3. This is however known to be a serious limitation in case of losses in P3, and a custom rad-hard solution would probably have to be developed.
- Use Superconducting links.

The cost and resources needed depend of course on the chosen solution. At this stage, none of them can be abandoned.

RRs in P1 and P5. New UAs?

At about the same level of radiation but a bit more critical are the RRs in Point 1 and Point 5. Here relocation of the power converters cannot be easily done since in addition to the 120A and 600A as in P7, also the big 4-6 KAmps are installed, and they cannot be easily displaced at long distances or redesigned, even in standard technology. The only viable options we have today is to drill new shaft from surface and create a side gallery protected from radiation and equivalent in space to the RRs. A prestudy from J. Osborne and GS-SEM [4] estimated at about 37 MCHF the cost of civil engineering for the four points, to which one has to add the cost for all the infrastructure and relocation, that can easily raise the total cost to 50÷60 MCHF. The study is too preliminary to give any credible estimate of manpower. It is worth mentioning that the study has confirmed that most of the civil engineering work can be performed even with beam in the LHC. It remains to be evaluated what level of vibrations can be accepted by the machine without perturbing the beam conditions.. Only the last 8 meters of the connection from the new gallery to the RRs need to be done during a long shutdown (see fig. 1). The shafts would also be used as a possible path in case of a massive discharge of helium in the tunnel [4].

In addition, it would be possible to further extend these new caverns to have new UA galleries in P1 and P5 [5], which would allow a comfortable relocation of all the equipment in the UJ14/16/56 and give in addition sufficient space for all the new equipment necessary for the upgrade of the LHC interaction regions. [

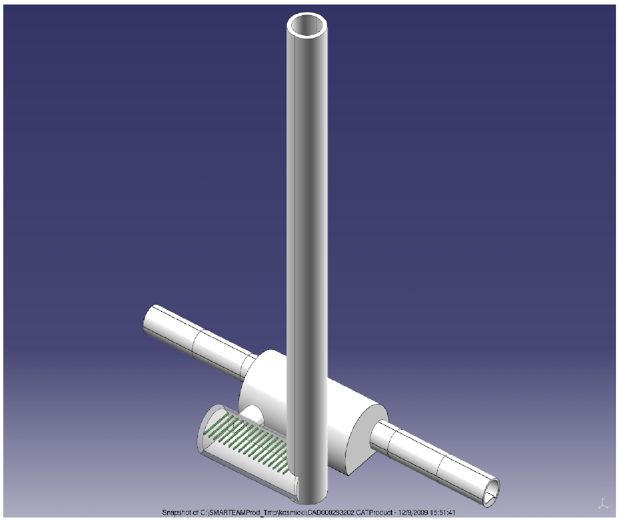

Fig. 1: the new shafts for the RRs in P1 and P5 (courtesy J. Osborne).

UJ14, UJ16 and UJ56

UJ14, UJ16 and even more UJ56 will present very high level of radiation at nominal intensity (~$5\cdot10^9$ hadrons/cm^2/year). However while in P1 a solution to add heavy shielding in order to reduce radiation by a factor 10 and therefore gain a few years before the situation becomes critical, in P5 there is no possibility to effectively shield, so alternative solutions (relocation) have to be urgently found.

For the long term, in P1 full relocation can be foreseen in the space that has been reserved for the IR upgrade (which means that a different solution has to be studied in collaboration with the IR upgrade project).

In P5 there is no more useable space and the only possible solution today for relocation consists in modifying the destination of the pit PM56. A full study for the integration in PM56, including its impact on safety aspects, needs to be conducted to ensure that we can use the pit for that purpose, install the necessary infrastructure and relocate the electronics there. The base floor of UJ56 can be shielded to reduce the annual fluence to 10^8 hadrons/cm^2, and can therefore be used to host SEE tolerant equipment (new power converters?). At the level of dose foreseen today without additional shielding (~10 Gray/year), the materials of electronic systems would very quickly degrade for TID effects.

In conclusion:

P1: UJs can be shielded to reduce the fluence down to 10^8 hadrons/cm^2/year at nominal. This is not sufficient for standard electronics therefore full relocation has to be foreseen. A detailed integration study needs to be done, however it is probable that by using the space reserved for the LHC IR upgrade all the presently installed electronics should fit, while a small part (4-6 kAmp converters) cannot be relocated but can be further shielded locally once the UJs are emptied. If such a scenario would be accepted, a new strategy for the upgrade shall have to be studied. This might include new civil engineering works.

P5: The critical installation is UJ56. There is no integration study available today, but a possibility is to use PM56 to host all the electronics. A detailed integration and safety study has to be launched quickly.

In both points it will be necessary to create new areas in correspondence of the RRs, by major civil engineering work.

With full relocation the underground installation in P1 and P5 will become extremely crowded, and their operability and maintainability may become a concern on the long term. A safer and more flexible approach calls for further civil engineering works, that would solve at the same time all the problems of the approved and future upgrades, including eventually the possibility to install crab cavities in P1 and P5.

RADIATION POLICY FOR THE LHC MACHINE

Most of the problems listed in the previous section were originated by the lack of consciousness that some of the areas foreseen for control electronics were exposed to high levels of high energy hadrons even if the total annual dose was quite low. When the problem became clear, several groups were also missing the know-how necessary to quantify their own risk and to prepare an action plan to solve eventual problems. While a small team has been built in EN-STI to centralise some activities (mainly simulation, coordination and testing), a considerable effort still remain to be done by every group.

The policy for the radiation tolerance of electronics in the LHC machine proposed in this section aims at helping the electronic and controls engineer with guidelines of good practice to satisfy all the requirements of the underground areas. At the same time, it gives the rules for quality assurance, including test procedures to ensure that a common approach is used to qualify the exposed systems. It is largely inspired by the radiation policy adopted by ATLAS [6].

The policy will be organised in a main document, providing all the definitions and the principles, and then in addenda that will give all the information specific to the LHC (e.g. limits, procedures, working groups). In this way the policy can be adopted as is, if necessary, by other projects, installations or experiments, by only adapting the addenda. The following sections describe the main points that will be detailed in the policy.

Principle “0”: responsibility

Every equipment owner is responsible for assuring the radiation tolerance of its own equipment. It is the equipment owner’s responsibility to decide on the best strategy to avoid problems (typically he will have to decide whether to (re)design or (re)locate at distance his system in a safe area). It is the responsibility of the Organisation to set-up centralised working groups and services to help the equipment owners in this process.

Principle “1”: Knowledge of the environment.

The radiation fields to which the equipment will be exposed have to be understood in order to decide on the strategy for a given equipment. In particular the different mechanisms of damage that a designer shall take into account are defined by the following parameters:

- **Total Ionising Dose (TID)**: cumulative effect of ionising energy loss in the lattice caused by coulomb scattering from energetic particles or by gamma radiation. It is a quite predictable effect and should be tested for equipment exposed to high level of dose (> few Grays), typically by exposing it to a Co source. Standard electronics normally fails at levels starting from few Grays up to hundreds of Grays for rad-tolerant equipment. Measured in Grays.
- **Non Ionising Energy Loss (NIEL)**: caused by accumulation of displacement damage in the lattice following collision with neutrons or very low energy heavy ions. It is a cumulative and reproducible (predictable) effect, measured in fluence of 1 MeV equivalent neutrons. Can be tested in reactors with neutrons at a fixed energy.

- **Single Event Effects (SEE)**: stochastic effect created by a localised energy deposition from a single high energy hadron (>20 MeV). In the last years however a certain sensitivity to thermal neutrons has been observed, for example in devices powered with low voltage (3V) without specific precautions. For this reason this mechanism is described with two parameters:
    - **High energy hadron flux**: measured in hadrons/cm^2;
    - **Ratio thermal neutrons vs. High energy hadrons flux:** dimensionless number that provides a figure of merit to decide whether to test against sensitivity to thermal neutrons.

The project, or installation responsible, will be responsible to provide the values for the above parameters via simulations or measurements (for existing installations). For the LHC this process will be coordinated through the R2E study group, and the information made available through the R2E website [7]. The equipment owner shall be responsible to evaluate the failure rate for a given radiation field and take a decision on how to reduce it down to an acceptable level.

Principle "2": Component selection.

Radiation levels in the LHC machine are generally lower than those found in the detectors. Use of "hard-by-design" components is generally not a necessity and therefore most of the systems that will have to remain in radiation areas may use COTS components properly selected to resist to a given level of fluence. This section will provide guidelines on how to proceed with the selection. In practice:

- Only known (tested) rad-tolerant components shall be used.
- When planning a design, the designer shall acquire a sufficient number of components from a same batch to ensure that all the components to install and all spares come from the same batch.
- A statistically relevant number of components needs to be tested (at least 10).
- Depending on the level of TID, NIEL and >20 MeV to which the component will be exposed during operation, perform test to assess each relevant parameter.

It is the responsibility of the equipment owner to test the components he wants to use, in this process he will be supported by the RADWG, while test organisation shall be centralised in the EN/STI group. A central procurement of the most popular components (e.g. FPGAs, CPLDs etc...) is under discussion.

Principle "3": Classification of systems and their reviews.

While all the systems deserve identical attention from the project and equipment owners, it is important to establish a priority criteria in order to be able to assign the available common resources (design support, test etc..) according to a well established guideline.

The proposed priority order is based on the function of the system:

1) **Systems relevant for personnel security**: e.g. fire detectors, oxygen detectors, access etc...
2) **Systems relevant for machine protection**: e.g. BIS/BIC, LBDS, collimators, BLMs etc...
3) **System relevant for beam downtime**: e.g. power converters, instrumentation used for feedback, RF etc...
4) **Systems used for monitoring**: e.g. some beam instrumentation, some cryogenic instrumentation, etc...

Systems for personnel and machine protection should never be installed in radiation area if possible. Where this is not possible, the equipment owners shall have to demonstrate the radiation tolerance. They shall have to pass reviews, organised by the RADWG, in particular design reviews before starting the prototyping, but more important the readiness review, that will give the green light for final production and installation. During readiness reviews the equipment owners shall have to produce test results as described in the next paragraph.

Principle "4": System test.

Component and system test are the most important basic element of quality assurance. Procedures for component and system test will depend on the radiation levels that one wants to address, and on the nature of the component itself, therefore they will be specified either in addenda or discussed in details in the RADWG when necessary. On the contrary, the final test that can validate the design of the entire systems (or of the most sensitive part of it) has to be performed in a facility with a radiation field very similar to the final environment. For the LHC the reference facility will be the CNGS irradiation facility. Other similar facilities may be needed if redesign work has to be done, and additional facilities might be made available if necessary in nTOF and HiRadMat.

It is important that test results are well documented to be able to trace back the real limitation of every system. It is a general experience that it is extremely difficult to provide a generic template for the test reports since every system has different specificities. All the people working on this subject since years [8, 9] agree that it is more efficient to have presentations either in working groups (RADWG for the LHC) or in annual events (like the radiation days)

Principle "5": Quality assurance.

Quality assurance is a key factor to ensure the tolerance of electronics to radiation. For example once a component is tested to be radiation tolerant, one has to ensure that only components from the same batch are used, since significant changes can occur from batch to batch in the architecture without modifying the external characteristics. Strict respect of the LHC (or equivalent for other machines) quality assurance plan will have to be enforced. The main guidelines will be:

- establishment of a comprehensive MTF folder to track all the design, production and test history of a given system.
- Provide a clear procedure to ensure that operational limitations are known to the operation's team.
- Properly document test campaigns, providing information that can be used from anybody or for future reference in case of problems. This means mainly to provide test reports including all the test conditions, procedures and results.

Resorting to the experience of ATLAS, it will be fundamental for the success of the policy to have enough resources (at least 1 person at full time: Mr "Radiation Tolerance") to follow up and control that the full documentation is produced and properly stored. Also it is necessary to control that test procedures are relevant to reveal the effect under test. Depending on the workload, another person might be necessary for that.

Implementation of the policy.

While the main body of the policy defines the general principle, its application to the LHC will require detailed specification of test procedures, of information flow and responsibilities. This will be specified in the annexes. In particular the structure coordinating and supporting the mitigation effort which is already in place for the LHC (see fig. 2) will be clearly explained in one of the annexes. In practice:

- For LHC Machine, the **LMC** will oversee and give priorities.
- **R2E** will coordinate technical work at different level and give coherence between simulations, design, test, machine integration.
- **RADWG** will support equipment groups for design (component selection, design reviews) and radiation test.
- **Equipment owners** are responsible for implementation and quality assurance.
- **Point owners** (<u>or persons to be identified</u>) shall be informed of installed equipment and in charge of organising control. Ensure that OP is aware of special procedures suggested for a given equipment.

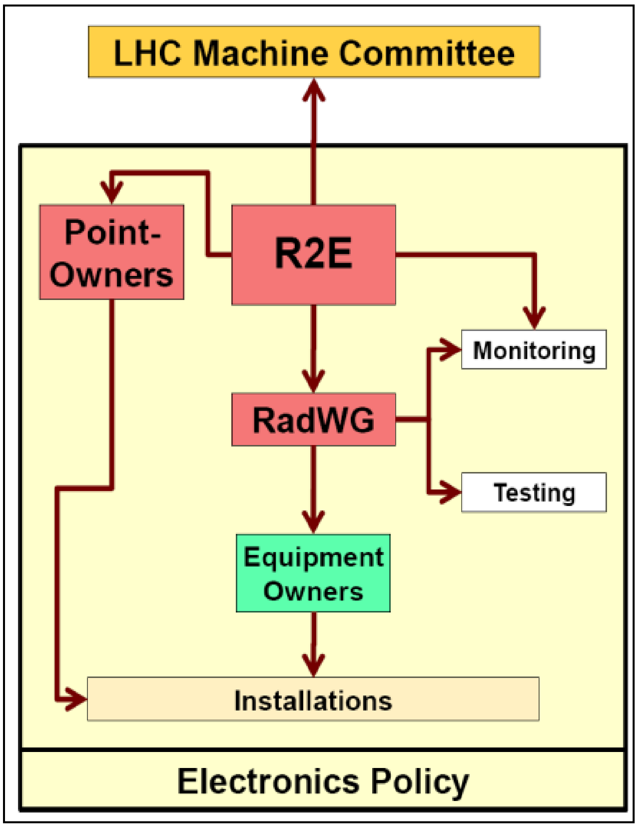

Fig. 2: organisation of the coordination of mitigation efforts in the LHC.

CONCLUSIONS

There is a relevant risk of occurrence of Single Event Effects in several areas of the LHC machine. A dedicated strategy is required to reduce it to a level that will allow a smooth operation at nominal and ultimate luminosity. Very relevant resources, both in terms of material and of personnel, will be needed to implement it. The main lines have been presented in the first part of the paper, while a radiation tolerance policy, aimed at giving guidelines and define a proper structure to avoid problems in the future has been outlined in the second part. A more detailed policy document to be approved by all the parties involved and by CERN management will be produced soon.

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