Summary of the 2009 irradiation tests and perspectives for future tests and facilities

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Abstract

Numerous radiation tests were performed during 2009, both directly at CERN in CNGS, as well as at various outside facilities. This presentation gives an overview of the test results by putting them in contrast to expected radiation levels in the exposed areas. By applying a best guess scaling of the expected development of the respective LHC radiation levels, failure rates can be estimated for both short-medium- and long-term LHC operation. Based on this, the most critical systems and mitigation options are investigated. Furthermore, future test requirements are compared to the availability and characteristic of existing test facilities.

INTRODUCTION

The electronic systems in the LHC tunnel and other underground areas will suffer from radiation induced ageing and single event effects during the operation of the accelerator due to various beam loss mechanisms.

In order to estimate the risk for the machine operation and safety, three types of information have to be known. The failure mode(s) of the device, the failure cross section or level at which it occurs in case of cumulative effects and the expected radiation level [4] at the installation point.

Most of the electronics systems located in the LHC tunnel and only few systems from the LHC alcoves were tested in the CNGS TSG4 area and in various external facilities in 2009. These tests provide the data on the sensitivities of the devices as well as the likely failure modes. The resulting numbers are combined with the Fluka simulations of the radiation levels together with the expected operational scenarios.

TEST AREAS IN THE SIDE GALLERY OF CNGS

The side gallery TSG4 beside the CNGS experiment cavern is used as the test facility for the radiation tolerance of the LHC electronics systems. The area was liberated in 2007 after many radiation induced failures of the electronics, which is vital to the operation of CNGS.

Intense radiation showers are produced mainly in the graphite target, horn and reflector of the CNGS experiment during fast extraction from SPS. These showers stream through the ventilation ducts connecting the TSG4 to the target chamber. Areas around two neighboring ducts (TSG45 and TSG46) are used as tests sites equipped with online radiation monitoring and extensive signal connectivity grouped into 4 test stations. The cables are laid up to the CNGS control room, which is about 1.5km away. The data acquisition and control systems of the test setups are located in this room.

Calibration

Thanks to the excellent beam stability throughout the year, the accumulated radiation levels are scaling linearly with the integrated number of protons on the target (pot).

The radiation levels are measured by the RadMon detectors. Each position, where electronics is being tested, was measured either with the RadMon mother box, which measures TID and high energy hadron fluence or with the deported unit if the dose rate is too high. The deported unit measures TID and 1MeV neutron eq. fluence. The remaining value is extrapolated using the simulated fluence to dose ratios.

The fluence of hadrons above 20MeV is measured with SRAM memories in the RadMon. The values measured in the line of sight of the ducts are in a very good agreement with the Fluka simulations. The measurements behind the corners start to deviate because of a small sensitivity of the memories to thermal neutrons (about 10 times lower at the nominal voltage). The dose and 1MeV n eq. fluence are measured with RadFets and PIN diodes respectively.

Radiation levels

The hottest spot in the TSG46 test area exhibits 3.3Gy(Si)/week assuming 1e18pot/week. The high energy hadron fluence at this location is $1.8{\cdot}10^{10} cm^{-2}/week$. The radiation fields around TSG45 are about 10 times higher than for TSG46. The maximum dose is 28Gy(Si)/week and $1.9 \cdot 10^{11} cm^{-2}/week$. This is equivalent to about 3 years of nominal beam operation along an ARC dipole.

TEST RESULTS AND MITIGATION OPTIONS

In case of failures produced by Single Event Errors (SEE) the Mean Time Between Failures (MTBF) is calculated by the combination of the cross section and the expected radiation levels. The result has to be divided by the total number of devices. The time to repair is assumed as zero. The failure cross section is simply the number of detected errors divided by the accumulated hadron fluence above 20MeV.

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The device lifetime is calculated for the case of errors caused by cumulative radiation effects.

Assumptions

The failure rates and lifetimes are estimated for both the initial operation period in 2010 and for the nominal operation.

The 2010 operation scenario is assuming $0.5fb^{-1}$ of integrated luminosity and 200 days of operation. The tunnel losses are assumed as 1/40th of nominal, which is a rather conservative number. Energy scaling is not considered.

The nominal operation is assumed with $100\,fb^{-1}$ per year and $10^{15}molec/m^3$ for the rest gas in the ARCs.

Due to the calibration uncertainties, large gradients and large volumes of tested electronics a safety factor of at least 2 should be applied to the measured radiation levels. For the MTBF estimation, the total number of devices is assumed as placed in the worst actual location, which produces a safety factor greater than 2.

Cryo - tunnel electronics

The cryo electronics located in the tunnel was designed with radiation as a constraint and the CNGS test results are excellent.

In total 58 channels were tested together with several WorldFip cards and power supplies.

No errors were observed and the test was stopped at 500 Gy(Si) with the cards fully functional. The upper limit on the cross section was calculated assuming 1 error on a single channel. The cards with 9500 channels in total are installed under the MBBs in the ARCs ($< 1\,Gy/y$ nominal), while several cards are located in the DS up to MBB 8 (40 Gy/y).

Table 1: cryo tunnel cards

	measurement	MTBF/lifetime
cross section	$5 \cdot 10^{-15}\,cm^2$	$> 5.2\,y$ nominal $> 200\,y$ 2010
TID	$> 500\,Gy(Si)$	$> 500/12\,y(DS)$

Cryo - alcoves

The AC supply of the QRL heater (45 in LHC) and Insulated temperature conditioners (2400 in LHC) were tested. The supply failed very soon, but shielding will help to mitigate in the UJs (relocation could be needed in 1st floor of UJ56). The heaters are required only during the cool down of the LHC. The conditioners are OK for TID but suffer from SEEs in the digital isolator. The errors are mitigated through an automatic reset via the WorldFip interface.

Table 2: cryo cards in alcoves

QRL heater	measurement	lifetime
TID	$10\,Gy(Si)$	2 y nominal 400 y 2010
Conditioner	**measurement**	**lifetime/MTBF**
TID cross section	$140\,Gy(Si)$ $2 \cdot 10^{-9}\,cm^2$	28 y nominal $0.2\,h$ nominal $1.7\,days$ 2010

Interlock Controllers

The two types of XILINX CPLDs used in the interlock controllers were tested in CNGS.

The XC9500XL part is powered at 3.3V and is used in the signal path of the Beam Interlock Controller. This device has a very high cross section, but the 36 concerned systems are installed in relatively low radiation areas (i.e. UA87,23). In 80% of cases the SEE leads to a false dump but in 20% of the cases, the crate fails in an unsafe way (blind to incoming dump request). Nevertheless, the risk for the machine is marginal thanks to the redundancy of the system. The shielding of the concerned areas should considerably decrease the risk.

Table 3: CPLD test for interlock controllers

BIS controllers (CPLD at 3.3V)	
SEE cross section	$2.8 \cdot 10^{-10}\,cm^2$
MTBF redundancy loss	$10\,y$ nominal
MTBF false dump	$2.5\,y$ nominal
BIC/PIC (CPLD at 5V)	
SEE cross section	$3.8 \cdot 10^{-13}\,cm^2$
MTBF monitoring problem	$8\,y$ nominal
MTBF false dump	$72\,y$ nominal

The XC9500 CPLD is powered at 5V and is a part of the monitoring paths in the power interlock controllers (36 in LHC) and the BIC CIBUs (300 mostly in RRs). The measured failure cross section is very small. 90% of the SEEs cause only a monitoring problem and the remaining percentage issues a false dump. Given the low failure rate, no mitigation is needed.

The CPLDs can be subject to destructive Single Event Latchups (SEL) as observed in CNGS in 2008 and confirmed by recent heavy ion tests[1]. Nevertheless, the probability of such event in shielded environments should be very low, as high energy hadrons are required (i.e. no SEL observed with 60MeV p+ beam[3]).

BLM tunnel electronics

The BLM tunnel card (BLECF) was designed with radiation as a constraint. Two types of handmade power supplies located in the RRs were also tested (Haltec 2.5 and 5V).

The power supplies failed after more than 30Gy(Si) which results in more than 30 years of lifetime in the RRs.

Only one SEFI (single event functional interrupt) was observed during the whole irradiation period. The fault issued a false dump and a remote reset via the HV line was required. An ionisation chamber was connected to the card to constantly verify the functionality of the system.

Table 4: BLM tunnel card and power supplies

Haltec power supplies (2.5/3V)	
TID	85/33 Gy(Si)
lifetime in RRs	85/33 y nominal
BLECF tunnel card	
SEE cross section	$1.9 \cdot 10^{-13}\, cm^2$
MTBF false dump	44 days nominal
MTBF false dump	8.8 y 2010
TID	750 Gy(Si)
lifetime under MQ	75 y nominal

BPM tunnel cards

Two samples of the WBTN tunnel cards (2160 in LHC) which are located under the MQs in the ARCs were tested in CNGS together with Intensity cards (330x in LHC), WorldFip cards and power supplies.

The intensity card failed (probably due to a hard SEE) very soon, which brought its output out of range. The card is anyway required only for the initial commissioning of LHC at low intensities, so its failure will not impact on the later operation. For the calculation, the failure is assumed as cumulative effect.

Table 5: BPM and intensity cards and power supply

WBTN, power supply, WorldFip	
TID	$> 230\, Gy(Si)$
lifetime under MQ	$> 23\, y$ nominal
Intensity card [if cumul eff.]	
TID	$4\, Gy(Si)$
lifetime under MQ	$0.4\, y$ nominal
lifetime under MQ	$16\, y$ 2010
Intensity card [if hard SEE]	
SEE cross section	$4 \cdot 10^{-11}\, cm^2$
MTBF	0.4 days nominal
MTBF	15 days 2010
WorldFip card	
SEE cross section	$4 \cdot 10^{-12}\, cm^2$
MTBF calib. lost	3.8 days nominal
MTBF calib. lost	152 days 2010

The WorldFip card has a moderate sensitivity to SEE, in which case the WBTN card looses the calibration and switches to a high gain state. Thus the worst possible error is 250 μm offset for 1 minute. This offset can be automatically masked by the beam orbit feedback system.

The test was stopped when 230Gy were accumulated and the WBTN cards including the power supply were still functional and no errors were observed.

nQPS

The new QPS layer electronics of type DQAMGS (450 cards under MBBs in ARCs) was tested at CNGS in 2009 together with power supplies behind a corner at TSG46.

The cards use the new batch of the μFip^{TM} and FieldDrive^{TM} WorldFip^{TM} communication chips, which have a high SEE cross section. In case of error, the supervision path is frozen and an access is required prior to next fill to restart the card. The total dose resistance of the cards was not tested in CNGS and the detailed evaluation of the results still has to be done.

A temporary hardware solution was found to mitigate the SEE problem. It consists in regular resets of the μFip^{TM} chip, which is not influencing the operation of the card. The solution was validated in CNGS and will be implemented as soon as the errors start to appear in the system.

Table 6: nQPS tunnel cards

DQAMGS tunnel card	
SEE cross section	$2.8 \cdot 10^{-10}\, cm^2$
MTBF blocked supervision	10 h nominal
MTBF blocked supervision	16 d 2010

CL heaters

The Current Lead (CL) heater system (408 devices in UJs and RRs) is measuring the temperature of the top of the CL and turns on a heating via a solid state relay to prevent the formation of ice when the current is too low i.e. after a dump. 7 commercial regulators together with several relays were tested in CNGS at low dose rate behind a corner in TSG46.

Table 7: CL heater regulators

SEE cross section	$2 \cdot 10^{-11}\, cm^2$
MTBF broken regulator	5 days nominal
MTBF broken regulator	5 years 2010

The regulators have an elevated susceptibility to destructive single events. In case of such event the card has to be replaced otherwise the "CryoStart" is most likely removed. The system relies on shielding for the nominal operation.

WorldFip™ repeaters

Two samples of the Cu-Cu repeaters from the LHC tunnel (320 units on the cable trays in ARCs) were tested in CNGS in 2009 at high dose rate in TSG45.

One device failed after 165Gy(Si), while the second accumulated 250Gy and remained functional. The analysis found a too large drift in an auxiliary circuit, which caused the malfunction of the device. The annual dose in the ARCs is conservatively assumed alongside the dipoles and the resulting lifetime is satisfactory.

Table 8: Cu-Cu WorldFip™ Repeaters

TID (2 samples)	$165 \,/ > 250\, Gy(Si)$
lifetime	16 years nominal

Power Converters

The Generic Function Generator Controller (FGC - 189 units in UJs and 256 in RRs) of the power converters (PC) was tested together with the COD (752 units of 60 A orbit correctors under MBBs) version of the FGC in a high dose rate area of TSG45 in CNGS. A prototype high precision card SD360 was tested as well.

The memories of the FGC are protected by EDAC and have shown no problems. There were however several unexplained system crashes, which required a power cycle. The most likely cause is a non destructive half-SEL in the CPLD (or an SEU in registers). All the crashes occurred only at relatively low fluence. If the total fluence was considered, the MTBF would increase by almost a factor 4.

The FGCs in the alcoves will have to profit from enhanced shielding, which is not possible for the tunnel systems. But the PCs of the correctors are redundant and a crash of one doesn't lead to a beam dump in contrary to the generic FGC. All the FGCs have a remote reset capability, however in case a SEL occurs in the voltage source, the power cycle has to be done in-situ.

Table 9: FGCs of Power Converter systems

TID	100 Gy(Si)
lifetime in UJs/ARC	100/20 y nominal
SEE cross section	$2.3 \cdot 10^{-11}\, cm^2$
MTBF	1.8 days nominal
MTBF	72 days 2010

The prototype card SD360 exhibited no errors during the test, so it is a potential candidate for the replacement of the SD350 containing the SPARTAN™ FPGA, which is very sensitive to SEEs.

Survey

There are 6 controller crates for the Survey system installed in UJ56 and one was tested in CNGS in 2009 in the high dose rate environment of TSG45.

The system failed after 100Gy(Si) which is satisfactory for UJ56. There were several crashes of the system most likely due to an SEE in the μFip™chip. As the system is not critical, no dump will be issued and only a remote reset is required.

Table 10: Survey controller crate

TID	100 Gy(Si)
lifetime in UJ56	20 y nominal
SEE cross section	$8 \cdot 10^{-12}\, cm^2$
MTBF	4 years nominal

The crate in UJ56 contains also the triplet motor driver electronics and its radiation tolerance should be studied as well.

TESTS IN EXTERNAL FACILITIES

There were several component or system tests performed in outside irradiation facilities in 2009 and coordinated through RadWG [5].

The PSI 60 and 250 MeV proton beams have a relatively good availability and were used for

- nQPS components tests
- Siemens remote I/Os of the Warm Interlock Controllers
- calibrations of the RadMon detectors

The CEA Valduc [8] facility offers a 1MeV neutron field from an air cooled ^{235}U Prospero reactor and 14 or 2.5 MeV high intensity beams in the SAMES accelerator. The facilities were used for the tests of

- the BLM tunnel cards
- the CRYO tunnel cards
- the calibration of the RadMon hadron counters

The heavy ion tests of the Xilinx CPLD were performed in UCL [7] in order to determine the latchup cross-sections.

The epithermal neutron reactor beam in NRI [9] was used for the thermal neutron tests for

- the RadMon hadron counter calibration
- WorldFip Cu-Cu repeater SEE test

The RadMon detectors were calibrated with a very precise low dose rate ^{60}Co source in IRA [10] Lausanne.

Possible future facilities

The CNGS TSG4 radiation facility was found to be very useful for the system tests of the LHC electronics. The doses to the personnel during the interventions are very low and certainly much smaller than in the former TCC2 facility.

In case if the facility cannot handle the future test demands, a similar facility could be set up in the HiRadMat test area. Another option is the n_TOF facility where a mixed field test area could be set up close to the target and a low flux neutron beam area could be available upstream of the experimental area for small devices.

ACKNOWLEGMENT

The author would like to thank to the CNGS experimental facility, DGS/RP, EN/MEF, the RadMon team and the Fluka team.

CONCLUSIONS

Most of the electronics systems located in the LHC tunnel and only few systems from the LHC alcoves were tested in the CNGS TSG4 area and in various external facilities in 2009.

The overview of the results from the CNGS campaign was presented and put in contrast to the expected radiation levels in the exposed areas. By applying a best guess scaling of the expected development of the respective LHC radiation levels, failure rates were estimated for both the initial operation in 2010 and for the nominal operation.

The errors resulting from cumulative effects were translated into the device lifetime estimations. The statistics of the single event errors was translated into the corresponding failure rates taking into account the total number of devices in the critical areas. Mitigation actions were identified for the systems with too low lifetime or high failure rate. Many systems will profit from the radiation level reduction thanks to the foreseen shielding to extend their lifetime beyond 20 years. Several groups implemented firmware or hardware modifications mostly allowing for automatic resets.

Many systems suffer from the WorldFIP client card errors, which aggravated by at least two orders for the new batch used in the nQPS layer. The mitigation of the SEE induced crashes of the FGC in the power converters should be further studied. The tests in CNGS TSG4 will continue in 2010 and will include mostly the potentially very sensitive systems from the LHC alcoves. At the same time many test facilities are available outside CERN for component or system tests. If necessary, n_TOF and HiRadMat could provide dedicated electronics test areas, however the respective need would have to be brought forward in the RadWG.

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