LHC POWER CONVERTERS, THE PROPOSED APPROACH*

Yves Thurel, Quentin King, Miguel Cerqueira Bastos
CERN, Geneva, Switzerland

Abstract

The LHC uses more than 1700 Power Converters to feed magnets. Some of these power converters were foreseen to be operated in a radioactive environment and that has been taken in consideration from their initial design. However there is a number of standard design Power Converters that were not foreseen for installation in irradiated areas and are now installed in irradiated areas in the LHC. This paper presents the situation for all TE-EPC Power Converters, discusses the tests performed on some of the critical components and possible solutions.

INTRODUCTION

A power converter is a combination of different sub-parts, all extensively using modern components in their design. They are therefore inherently susceptible to radiation issues. This paper describes the LHC Power Converters and their highly specific design to give an accurate picture of the present situation regarding radiation; some tests will be presented on what the TE-EPC group consider as the most susceptible equipments, and some projections will be given in the LHC context.

LHC POWER CONVERTER DESIGN

The LHC power converters design was initiated in the late 90s. At the time the design strategy that was chosen to cope with the high accuracy requirements for the LHC was based on a sub-system approach. The required part per million accuracy for the main circuits could only be achieved by separating the Power Converters in three main sub-systems:

- A complex Digital Control Electronics (FGC) in charge of the high precision current loop and of the communication with the CERN CONTROL ROOM. This part was kept in the complete responsibility of CERN to ensure required software upgrade required by the operation of the LHC machine, and to keep close control on a critical high precision unit.
- Power Part, which was in some cases internally developed and in others externally procured to profit from high quantities and specialized companies knowledge.
- High Precision Current sensor, DCCT (DC Current Transducer), which measures the output current.

LHC using a high number of different magnets or different circuits (same magnet with different length of cables), all current loop adaptation is under the responsibility of the Digital Controller. The Power Part was designed to operate on a wide variety of loads (different time constant).

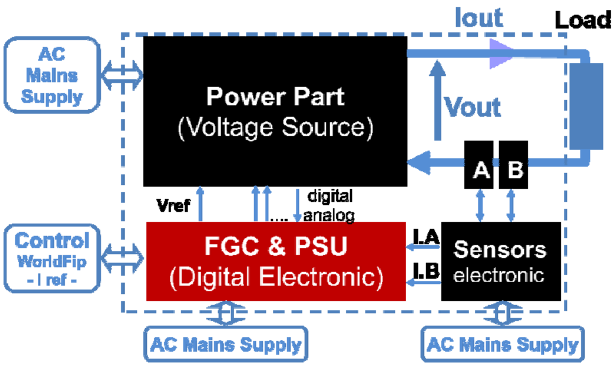

Figure 1: LHC Power Converter Architecture

What is really important to notice is that the Power Part doesn't make intensive use of high density devices like micro-processors, memories, FPGAs. The Power Converter group also oriented designers to keep the Power Part control the least sensitive possible to radiation, when it became obvious that the irradiation conditions for the standard design power converters were much harsher than initially foreseen.

Table 1: LHC Power Converter Overview*

Converter Type units	Safe Area Units	Irrad. Area Units	Rad-Tol Design	Rad. Location
60A-08V (752 Units)	000	752	yes	Tunnel
120A-10V (290 Units)	183	107	no	RR1x (36) RR5x (36) RR7x (20) UJ1x (10) UJ56 (05)
600A-10V (400 Units)	272	128	no	RR1x (28) RR5x (28) RR7x (48) UJ1x (16) UJ56 (08)
600A-40V (37 Units)	025	012	no	UJ76 (12)
4..8kA-08V (189 Units)	123	066	no	RR1x (30) RR5x (30) UJ1x (04) UJ56 (02)

* Only relevant to radiation issue power converter are presented in the table

DCCT & SIGMA DELTA

Overview

Figure 2: various DCCT

The DCCTs used in the LHC power converters are built using only analogue electronics (with the exception of the identification chip which is not a critical component) and most of the electronics is bipolar (supply regulator, opamps, power amplifier), therefore less sensitive to ionizing effects (although more sensitive to lattice displacement effects which can cause transistor gain reduction). Some junction FETs are used in the DCCTs' zero flux stage. Temporary conduction of these FETs on the millisecond scale has no effect on the output. Passive components like burden resistor and measuring head are not critical.

From the exposed above, one can conclude that, compared to high density MOS devices, the DCCTs electronics cannot be considered critical: there are no MOS circuits, and circuitry is not sensitive to microsecond disturbances.

Testing on initial prototypes of the 120A DCCTs (used for 60A-08V and 120A-10V Power Converters) have confirmed this analysis although no tests were performed on the final DCCT versions neither on the high current models, which were initially foreseen to stay away from radiation sensitive areas.

A summary of the situation for different types of DCCTs is given below:

Table 2: General radiation Info

Type	**Rad-tol @ Design origin**	**Rad. Tests**
TOPACC 4-13kA	No @External	No Not Critical
STACC 600A	No @External	No Not Critical
MACC 120A	No @External	Tested with TID of 50Gy: no degradation of performance
RITZ 120A	No @External	Tested with TID of 50Gy: no degradation of performance

The 22 bit Delta sigma is a high accuracy ADC built with discrete components. In its design it includes both MOS logic and high density devices. This includes a CPLD which is also used in the PCs digital controller (FGC) and during previous radiation tests has shown latch-ups and even a definitive burn-out in one occasion.

The high accuracy of the 22 bit Delta sigma circuit greatly relies on good quality of the clock and on the pulse duration and pulse edge symmetry of the DS reference switches. Disturbances at the picoseconds level can generate errors of some parts per million. Since these switches are CMOS devices, they can be sensitive to ionizing effects and therefore performance degradation is likely to happen."

Table 3: General radiation Info

Type	**Rad-tol @ Design origin**	**Rad. Tests**
22 bit DS	No @CERN	No tests done CRITICAL

DIGITAL CONTROLLER (FGC)

Overview

Figure 3: Function Generator Controller (FGC)

The Function Generator Controller (FGC) is an embedded control computer used with all the power converters in the LHC and LHC experiments. It was design at CERN and 2000 were manufactured by industry. Over 1700 are operational, the vast majority in underground locations.

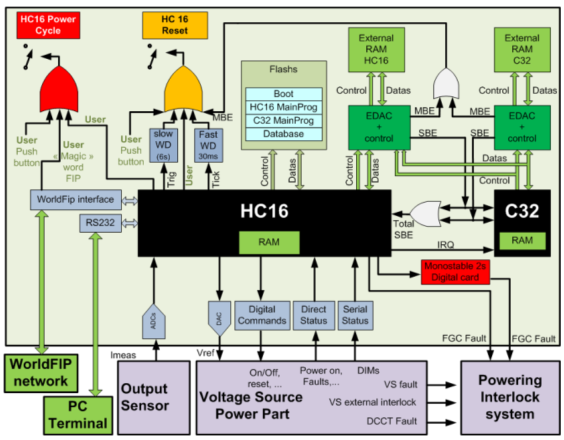

Figure 4: FGC Internal Architecture

Table 4: General radiation Info

Type	Rad-tol @ Design origin	Rad. Tests
FGC-50	No (analogue interface) @CERN	2003 UCL 60MeV p-beam 2008 Propspero 20MeV neutrons
FGC-60	Yes @CERN	2008 CNGS 2009 CNGS

Radiation status

The FGC was designed taking into account radiation. The SRAM was seen to be the most vulnerable to SEUs and error detection and correction logic was included. The processors are old (1993/4) and are manufactured with a large feature size, giving them a low cross section to SEEs, so corruptions of processor registers have been seen during tests, but very rarely. The design includes watch-dogs and the ability to power cycle the complete FGC via a request sent over the network. Various other mitigation features were included.

The functionality of the FGC is divided into six small circuit boards. One is the analogue interface which has two variants, while the other five have only one variant. One type of analogue interface uses two SRAM based Spartan 20 FPGAs which are known to be vulnerable to SEUs and for this reason a second design was made that has lower performance but avoids the FPGAs. This variant is more tolerant to radiation and is included in the FGC-60 which was conceived specifically for use in the LHC tunnel with the 60A-8V converters.

The high performance analogue interface is used in the FGC-50 which was designed to work in non-radiation areas. Unfortunately 313 FGC-50s will be in radiation areas and may have problems due to the FPGAs becoming corrupted. Remediation in software will be implemented with regular reprogramming of the FGPA.

All the cards in the FGC use the 5V Xilinx 95000 series flash-based CPLDs for their programmable logic. This device was tested in a 60MeV proton beam at Louvain la Neuve in 2003 without signs of latch-up. Subsequent tests in CNGS showed that the device does latch up with higher energy particles.

Four FGCs have been tested in CNGS, each containing 11 CPLDs. One device failed destructively and several system freezes were seen that were recovered by a power cycle. The cross section based on the combined results is estimated to be $2.10^{-11}/cm^2$ E>20MeV.

A detailed study of the CPLD using an ion beam and a higher energy proton beam has suggested a figure for the cross section for latch-up at $4.10^{-12}/cm^2$ which is significantly higher when the 11 CPLDs in one FGC are considered. Based on this figure, the total cross section for the FGC should be over $4.10^{-11}/cm^2$.

Table 5: Rad-Performances table

Type	T.I.D Limit	Cross Section	Events @ LHC Nominal Fluence
FGC	60Gy	$2.10^{-11}/cm^2$ (CNGS) $4.10^{-11}/cm^2$ (CPLD tests)	$5.10^9/cm^2/yr$ E>20MeV

Radiation mitigation possible options

The consequences of radiation on the FGCs are very complex. We will have crashes that can be cleared by a reset, and interruptions that will require a power cycle. Sometimes we will have component failures that will require replacement of the component.

Estimating the rate of each of these for the different areas is very hard since the sensitivity for latch-up to the radiation spectra is high.

Based on the results so far, it seems that the combined rate of all failures should be low enough not to impact significantly upon the nominal operation of the LHC, provided that all the shielding and relocation measures being considered are implemented.

Finally, if the failure rate is worse than our estimations suggest, then a new design will be required. If we are correct in believing that the CPLDs are the weakest link, and if the other components are still available with the same fabrication techniques as now, then it could be imagined to redesign the FGC by replacing only the CPLDs with something with a lower cross section for latch-up. However, no affordable equivalent device has been identified so far. Simply finding 5V devices is almost impossible.

A complete redesign with a new rad-tol processor and only certified rad-tol devices could be done, but the resulting FGC would cost around 10 times more than the current design (25KSF rather than 2.5KSF). The design and development would require substantial effort and several years.

DIAGNOSTIC INTERFACE MODULE

Overview

The diagnostic interface module (DIM) is a daughterboard that is implanted in the power converter electronics to recover first fault information and to provide basic analogue signal monitoring. It has 24 digital inputs, plus a trigger input, and 4 analogue inputs that are sampled at 50Hz with a 12-bit ADC. When the trigger input is activated, the state of the 24 digital inputs is memorized by the CPLD, enabling the FGC to read out the first fault. The trigger is created in the converter electronics from the OR of all the fault signals. A 125 kHz counter is also stopped when the trigger occurs so that the time of the fault can be known to 8 µs.

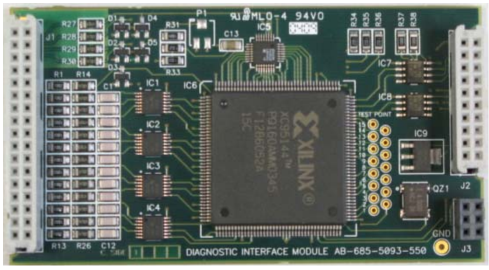

Figure 5: Diagnostic Input Module

Up to 30 DIMs can be connected to the FGC via a serial daisy chain, though the most used in practice is 18.

Table 6: General radiation Info

Component	Rad-tol @ Design origin	Rad. Tests
DIM	Yes @ CERN	2008 CNGS 2009 CNGS

Radiation status

The DIM was designed using the Xilinx 95144 CPLD in the belief that this was radiation tolerant based on the 2003 tests results from at Louvain la Neuve. In CNGS it was seen that latch-ups occur which block the operation of the DIM and no power-cycle ability is available since the DIM is powered from the power converter electronics card on which it is mounted.

We can therefore anticipate losing the operation of some DIMs, however they provide diagnostic information only and are not essential for the operation of the converter.

Table 7: Rad-Performances table

Type	T.I.D Limit	Cross Section	Events @ LHC Nominal Fluence
DIM	60G	$4.10^{-12}/cm^2$	$5.10^9/cm^2/yr$ E>20MeV

FGC AUXILIARY POWER SUPPLIES

While the LHC60A-08V Power Converter is composed only of the Power Part and the FGC, other Power Converters use a fully equipped electronics crate to house the FGC. This electronics crate provides up to two FGC slots with forced air cooling (an FGC Fan Tray), and depending on the type chassis can also provide DCCT (high precision current sensor) electronics slots. Powering of the FGC and DCCT electronics is done by a AC-DC Module (3 phases – 48Vdc) followed by a dedicated DC-DC PSU (48V input).

The AC-DC Power Module being a traditional 3-phases 50Hz transformer followed by rectifier and low frequency filtering is assumed to be rad-tolerant by design.

On the other hand, the FGC and DCCT PSU are made of several DC-DCs modules with additional circuitry to provide a redundant system, which controls the power level of each DC-DC to be at 50% of the total output power delivered by the 2 DC-DC when both are running well, maintaining safe operation conditions regarding the lifetime of these components. In case one DC-DC fails, the other one will run at full power indicating through remote signal that conditions are not optimum anymore. These PSU can be susceptible from a radiation point of view since they use DC-DC modules and additional circuitry which are not rad-tolerant by design.

Table 8: General radiation Info

Converter Type	Rad-tol @ Design origin	Radiation Tests	Radiation Status
AC-DC 48V	No @ CERN	Not needed	Partially Tested NOT CRITICAL
PSU DCCT	No @ CERN	Yes (DC-DC Only)	Partially Tested NOT CRITICAL
PSU FGC	No @ CERN	Yes (DC-DC only	Partially Tested NOT CRITICAL

Radiation status

Some (between 2-3) DC-DCs from each type of the ones being used in both FGC PSU and DCCT PSU were tested in CERN CNGS irradiation facility. Result clearly shows that they are not susceptible to Single Event, but are affected by the Total Ionizing Dose, which is often the case, and often coming from the reference voltage device being used in the control regulation.

Concerning the other components being commonly used in the PSU ensuring the redundant mode, they need more investigations and were not tested.

Table 9: Rad-Performances table

Type	**T.I.D Limit**	**Cross Section**	**Events @ LHC Nominal Fluence**
AC-DC 48V	unknown	unknown	No Event expected
PSU DCCT	50 Gy	n.a.	No Event expected
PSU FGC	50 Gy	n.a.	No Event expected

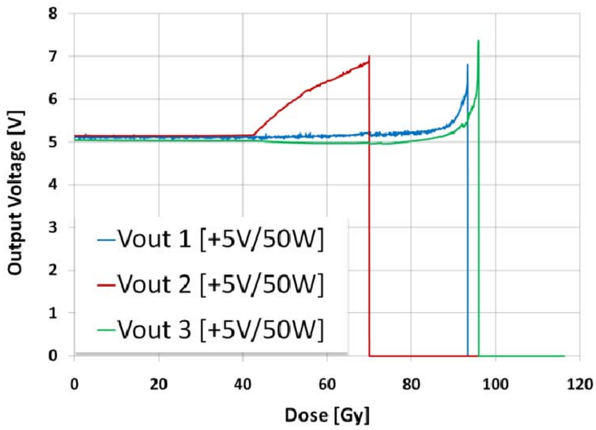

Figure 6: Typical DC-DC results under radiations of 3 same reference DC-DCs

LHC60A-08V POWER CONVERTER

Figure 7: LHC60A-08V Power Converter

Overview

These Power Converters are placed below dipoles in the tunnel, in radioactive areas. The compact design only uses a Power Part 19'' chassis, which also integrates the FGC. Only one AC-DC auxiliary Power Supply is used for both Power Part and FGC controller.

Table 10: General radiation info summary

Converter Type	**Rad-tol @ Design origin**	**Radiation Tests**	**Radiation Status**
60A-08V	Yes @ CERN	Yes @ CNGS	SAFE

Radiation status

This Power Converter was designed at CERN taking in account its future radioactive environment. Tests performed in CNGS demonstrated that the overall design was suitable for its LHC operation.

SEE susceptibility of the overall Power Converter is given by the FGC, when the TID limit is driven by the Power Part.

Radiation tests

Several tests were done in CNGS @ CERN on both parts: FGC and Power Part. FGC was also tested in other places as described in its section. Results are:

Table 11: Rad-Performances table summary

Converter Type	**T.I.D Limit**	**Cross Section**	**Events @ LHC Nominal Fluence**
60A-08V	50	See FGC section	1 / 3..5 days

LHC120A-10V POWER CONVERTER

Figure 8: LHC120A-10V Power Part

Overview

These air-forced cooled Power Converters are CERN design. 107 are installed in RR1x (28), RR5x (28), RR7x (48), UJ1x (16), UJ56 (08). Both DCDC PSU FGC and DCCT are used in this Power Converter.

Table 12: General radiation info summary

Converter Type	**Rad-tol @ Design origin**	**Radiation Tests**	**Radiation Status**
120A-10V	No @ CERN	No	UNKNOWN CRITICAL?

Radiation status

This Power Converter was designed at CERN and even if not rad-tolerant design, it was designed taking advantages from LHC60A-08V development, and then could be considered as relatively safe.

Nevertheless, the Power Part (Voltage Source) internal digital card was designed using the FGC critical CPLD (latch-up problem). It can then be expected that:

- It will be sometimes required to manually power cycle this digital card (no remote function implemented), by a local and complete power recycle of the power converter.
- It could happen that some critical interlock like protection of the current leads can be not operating as designed: stopping action is relying on CPLD feature, and then deserves deeper analyze.

Radiation tests

TE-EPC doesn’t consider a radiation test of this Power Converter to be mandatory since being CERN design, corrective actions can be taken relatively quickly (months) in case LHC operation shows radiation issue on the Power Part.

Radiation mitigation possible options

Re-design of some internal part of the power converter is highly recommended and feasible since original CERN design. Majority of cards are expected to run without any trouble since originally designed taken in account the radiation potential issue. (CPLD base Power Part digital card exception)

Re-location of these converters can also be a valid solution and would make the operation and maintenance of these converters a lot easier. Additional voltage drop would not be a big problem since cables used at the moment can be thicker relatively easily, and then could compensate a longer length for a same total cable resistance.

LHC600A-10V POWER CONVERTER

Figure 9: LHC600A-10V Power Converter

Overview

128 of these water-cooled Power Converters are located in RR1x (28), RR5x (28), RR7x (48), UJ1x (16), UJ56 (08). Both DCDC PSU for FGC and DCCT are used in this Power Converter.

Table 13: General radiation info summary

Converter Type	**Rad-tol @ Design origin**	**Radiation Tests**	**Radiation Status**
600A-10V	No @ External	No	UNKNOWN CRITICAL

Radiation status

They are complex external design and deserve a lot of attention, since using CPLDs, DC-DC, AC-DC and other possible sensitive devices.

No test have been performed on these Power Converter regarding radiation issue up to now, since these water cooled converter are very hard to test as a single piece. Another point to consider is that rack contains some cards, and a full radiation test should include the Power Module and the cards located in the rack.

Radiation tests

TE-EPC doesn’t envisage to test the whole Power Converter since too complex to organize (water cooled converter, complex design, costly units). A pragmatic approach is envisaged listing all possible sensitive devices to get a better idea of what can cause trouble. From this first analyze still to be done, a plan will then be possible.

Radiation mitigation possible options

A complete redesign is a considerable and costly work, since design is highly complex, and quantities are important. This option can be a valid solution if a synergy with other future like LHC Inner Triplet Ugrade can be found. TE-EPC doesn’t have the required manpower for launching such a project, and a rad-tolerant design of this kind of converter cannot be externalized.

A partial redesign can be a valid option considering the following points:

- Only some cards in the Power Converter can be susceptible to Single Event, but they are obviously the most complex (up to 5x CPLDs in the digital control card)
- At least 2 years are needed to develop new version (retro-engineering + electronic design + test / validation + manufacturing + exchange of the cards)

Re-location option is a valid option also, but a special care must be taken on the additional cable voltage drop which would potentially lead to too high voltage requirements at the level of the power converter. Solution like new cryo-lines could fix this issue.

LHC600A-40V POWER CONVERTER

Figure 10: LHC600A-40V Power Converter

Overview

These water-cooled Power Converters are located in UJ76 and UJ33 only. If the 12 units in UJ76 are exposed to a relatively high level of radiations, this issue will be solved thanks to TZ76 relocation. Both DCDC PSU FGC and DCCT are used in this Power Converter.

Table 14: General radiation info summary

Converter Type	**Rad-tol @ Design origin**	**Radiation Tests**	**Radiation Status**
600A-40V	No @ External	No	UNKNOWN SAFE by relocation

Radiation status

They are complex external design using CPLDs, DC-DC, AC-DC and other possible sensitive devices. A relocation plan at CERN in UJ76 where 12 Power Converter are installed will clean the situation without further tests or analyzes being required.

LHC4..8KA-08V POWER CONVERTER

Figure 11: LHC4..8kA-08V Power Converter

Overview

66 of these water-cooled Power Converters are located in RR1x (30), RR5x (30), UJ1x (04), UJ56 (02). Only FGC DCDC PSU card (+ AC-DC power module always needed) is used since DCCT electronic is powered directly from mains.

Table 15: General radiation info summary

Converter Type	**Rad-tol @ Design origin**	**Radiation Tests**	**Radiation Status**
4..8kA-08V	No @ External	No	UNKNOWN CRITICAL

Radiation status

They are complex external design and deserve a lot of attention, since using CPLDs and other possible sensitive devices.

No test have been performed on these Power Converter regarding radiation issue up to now, since these water cooled converter are very hard to test as a single piece (large dimensions).

These converters are highly critical since some are used in the vital complex LHC Inner Triplet systems. These specific systems are also using a very high precision Analog to Digital converter (22 bits Sigma-Delta) using same CPLD in its design than the critical one used in FGC.

Level of the operational currents (up to 7kA) is a major issue when exploring all different scenarios.

Radiation tests

TE-EPC doesn’t envisage to test the whole Power Converter since too complex to organize (big size water cooled converter, complex design, costly units). A pragmatic approach is envisaged listing all possible sensitive devices to get a better idea of what can cause trouble. From this first analyze still to be done, a plan will then be possible.

Radiation mitigation possible options

A complete redesign is a considerable and costly work, since design is highly complex, and quantities are important. This option is not considered as a valid option. TE-EPC doesn’t have the required manpower for launching such a project, and a rad-tolerant design of this kind of converter cannot be externalized.

A partial redesign can be a valid option considering the following points:

- Only some cards in the Power Converter can be susceptible to Single Event, but they are obviously the most complex (up to 10x CPLDs of the same king in total). Moreover the modularity of the power converter makes possible to redesign some whole crates or modules (mainly control module) for a fast exchange of the units to get a rad-tolerant voltage source
- Several months (14-18) are needed to develop new version of some sub-parts or complete modules (retro-engineering + electronic design + test / validation + manufacturing + exchange of the crates or removable modules)

Re-location option is a valid option also, but a special care must be taken on the additional cable voltage drop which would potentially lead to too high voltage requirements at the level of the power converter. Solution like new cryo-lines could fix this issue.

TE-EPC PROPOSED APPROACH

The LHC60A-08V Power Converter is the only Power Converter in the LHC complex where the radiation susceptibility is known and considered as safe for LHC operation needs.

All other Power Converters: 120A, 600A, 4-6-8kA present an unknown status regarding the radiation susceptibility. If the power part is generally using safe components per design, and following strict specifications (severe AC network conditions require over-voltage rating on power semiconductors), some components like CPLDs or integrated ones: DC-DC, AC-DC are not qualified versus radiation susceptibility.

TE-EPC proposes a rational approach, mainly to limit re-design options, since cost and manpower would be extremely high:

On CERN-Design converter or sub-systems, it is recommended

- To analyze all possible critical components, to propose re-design sub-parts and to produce some replacement rad-tolerant cards. The goal is to use the following years to design, test, and produce cards to be ready when expected problem comes.
- To use LHC operation as a "test-bed" to identify non-expected troubles if any and to solve the problems as they arrive. Strategy is to count on the design being at CERN, and on the ability to re-design cards relatively easily and quickly. A redesign-test-production of a sensitive card can be estimated to 5-6 months for most of the cards (surely longer for high precision card if radiation affected).
- Not to test the whole power converter under radiation, since difficult to achieve and results would be difficult to analyze in case of a crash. A crash would indeed create a possible chain of damaged components, making difficult to understand what the initial failure was.
- Test some components like CPLDs or integrated ones: DC-DC, AC-DC since highly critical and delivery time could be potentially long.

On external-Design converters, it is recommended

- To analyse all possible critical components through a deep review (already organized and planned in April 2010) and to estimate the list of possible sensitive to radiation devices and their criticality with regards to LHC operation. (Some converters are operating in a redundant configuration, and some are not highly critical for operation which means operation could potentially tolerate a higher failure rate on these, in case a simple reset would clean the situation).
- To organize component tests only to get the real sensitivity on the selected devices
- To evaluate cost, manpower and possible sub-part redesign and propose some pin-to-pin replacement boards or modules to be ready in case of.
- Not to test the whole power converter for same reasons as described above.

Global approach proposed above would then lead to this situation

On CERN-Design converter or sub-systems:

- TE-EPC can be well prepared and can be proactive to limit the troubles for operation.
- TE-EPC can organize the re-design of some cards with current manpower
- Crash programs are still possible in case unexpected troubles occur.

On external-Design converters:

- Situation will always be a lot more critical, since all mitigation redesign of any card or sub-system will take time and require more manpower (additional retro-engineering work).

- Since they are medium and high current converters, their criticality is assumed to be very high for operation.
- Even if some issues can be cured before they perturb converter operation, based on an analytical review of all possible sensitive components, the risk is not entirely covered since not all power converter components will be tested, and therefore the status of the power converter will only be discovered through LHC operation failure events.
- Only limited cost and limited manpower are required since redesign action will be limited to the known components., but real needs still to be quantified following the review outputs,

Proposing a more secure plan will definitively require a total power converter redesign, which has to be made at CERN (current experience shows that all CERN-Design are manageable while external design projects are a lot more complex to manage). Choosing this option would implicate to redesign both 600A-10V and 4-6-8kA-08V to get a coherent result with regards to potential risks. Such a choice is tremendous in term of manpower (4 man x year per project, not counting the required radiation test on all components to be used in the new design).

CONCLUSION

A pragmatic approach is proposed, based on test of the small size converters and analytic analysis of bigger ones. Some tests will be performed on some specific devices for big size power converters only.

This approach can leave some open points untreated since an analytical-only approach can not be compared with a full test approach; on the other hand, this approach still seems realistic even if it surely requires substantial money and manpower.