

# Review of the radiation tolerance of LHC power converters

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**Date:** April 13 -14 2010

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**Source of Material:** <http://indico.cern.ch/internalPage.py?pageId=0&confId=85477>

**Executive summary:** *This review of the radiation tolerance of the power converters for the LHC accelerator concludes that the current power converters at their current locations introduces a significant risk for the reliable running of the LHC at high luminosities. At nominal LHC luminosity it can be estimated that radiation induced transient and destructive failures in the power converters might seriously limit the beam availability for physics.*

*For the initial 1<sup>st</sup> physics run (2010 -2011), at low luminosity, the currently implemented shielding improvements is estimated to allow the current power converters to have sufficient reliability. There is in practice no other alternative, as no major improvements can be introduced during the running period.*

*For the planned 2<sup>nd</sup> physics run (2013-2014), at increased luminosity and increased energy, radiation induced failures can become a limiting factor for the running of the accelerator (directly dependent on luminosity). Because of the limited time available only minor incremental improvements can in practice be implemented to improve this (relocation, improved shielding and minor power converter modifications). It is proposed to perform a paper vulnerability analysis of the current power converters as soon as possible. Part-level radiation tests of identified high risk components can then be made to determine where such improvements can be implemented to reduce the global risk.*

*For the long term running at full nominal luminosity the current power converters can be expected to become a serious limitation for the effective running of the accelerator. They should therefore be replaced by new radiation tolerant converters or the current converters must be relocated to areas without radiation. The design and production of new radiation tolerant power supplies will require a significant time and should therefore be started as early as possible.*

## Introduction

A large number (~1000) of 4 different types (60A, 120A, 600A, 4-8kA) of Power Converters (PC) for the LHC machine will have to work in an environment with radiation. Only the 60A power converter was designed and tested for operation under these radiation conditions (but is also known to have radiation tolerance problems). The 13kA power converters for the main dipoles are not part of this review (assumed located in areas without radiation). A transient failure (e.g. radiation induced single event upset) in one of these power converters will in most cases imply that the LHC beams will have to be dumped and therefore reduce the efficient beam time for physics. Permanent hardware failures (e.g. a component destroyed by radiation induced single event latch-up or single event burn-out) in a power converter will in many cases imply that an access must be given to make repairs, before new beams can be made available. Such an access to controlled radiation areas implies significant dead time of the whole accelerator. The reliable function of the power converters under radiation conditions is therefore considered critical for the efficient operation of the LHC accelerator and the time available for physics collisions.

The 60A power converter for orbit corrections, located under the main dipoles, has initially been designed for use in a radiation environment. Recent radiation tests of this power converter and its control have though revealed a single event latch-up problem with CPLD (Complex Programmable Logic Device) components used in its implementation and parts of the design are not fully protected against Single Event Upset (SEU) effects.

A large variety of electronics components have been used within the power converters without any radiation testing (the FGC common controller and the 60A PC is an exception to this). In general no component traceability has been assured for the design and production of the power converters. This is normally considered vital for equipment that must work with high reliability in a radiation environment. This implies that there is a large uncertainty on the actual components used to build each power converter. Commercial components with the same marking can have very different radiation behavior. This can be caused by second sourcing among IC manufacturers, or modifications that may have been introduced in a given design or manufacturing line over time.

A review was conducted with a set of external radiation and system experts to evaluate the potential problems and risks that can be encountered with the use of the existing power converters for the LHC. One day of presentations was made to the review panel and extensive additional material has been made available to the reviewers via the review agenda.

The reviewers were presented with a large set of information covering the estimated radiation environment, architecture of each power converter, global system aspects, installation locations and the general use of the power converters for LHC. Because of the large set of material presented in a short time, the complicated and delicate nature of the power converters, their radiation tolerance, and their specific use for the LHC, the reviewers will be forced to limit themselves to give general recommendations based on their past experience. A thorough review of the 4 different power converter

designs and their specific radiation tolerance is a major task outside the realistic scope of such a short 1 day review.

## **Radiation environment**

The prediction of the radiation environment for the power converters (and for the LHC machine in general) is a very complex issue that depends strongly on many specific LHC machine parameters (beam gas, collimation, interactions and beam-beam effects in the experiments, etc.). Being a unique machine it is very difficult for the reviewers to use existing experience from other machines (e.g. Tevatron at Fermilab) to judge if the radiation estimates presented in the review are realistic. It can be mentioned that the radiation distribution in the Tevatron was not seen to change significantly with luminosity (but the absolute levels obviously did). The reviewers believe that the presented radiation simulations have included the major effects that can be expected in such an accelerator environment. Simulations will always have significant uncertainties and it is very important that radiation measurements from the first running of the LHC are used to verify and improve the radiation simulations for the future running of the machine at higher luminosities. It can in particular be mentioned that radiation monitoring equipment with sufficient sensitivity for the initial low luminosity runs will be important to obtain useful radiation measurements from the early operation of the LHC. No radiation estimates/simulations have been presented for the ion runs.

There are also significant uncertainties in the schedule for the luminosity increase of the machine and therefore uncertainty in the prediction of radiation levels in the areas of the power converters for the coming years of LHC running. The first initial running of the machine will occur at relatively low luminosities and therefore only limited problems from radiation effects can be expected. This unfortunately though also implies that the operation experience gained during this period will most likely not give much information that allows the radiation tolerance of the power converters to be estimated and use this to predict their reliability for the coming high luminosity runs.

### **Total Ionizing dose (TID)**

The estimated relatively modest TID (below 2.5 - 10Gy per year at nominal LHC luminosity) will to the best of the experience of the reviewers most likely not be a major issue for the reliability of the power converter electronics. Potential drifts in parts of the very high precision (PPM level) analog electronics may require regular calibrations of critical parts to be performed (e.g. the high precision DCCT module used by the 120A, 600A and 4-8kA converters). For very long time use (e.g. > 10 years) of the current converters, TID effects may though potentially become a problem. Increasing power supply currents for the control part of the converters can be an indication that TID effects start to become significant.

### **Non Ionizing Energy Loss (NIEL)**

The reviewers do in general not expect NIEL (displacement damage) effects to be a major worry for the electronics used in the power converters.

Opto couplers may though potentially be an exception to this as some types of opto couplers have been seen to be quite sensitive to NIEL and can become important for long term running It can be recommended to specifically verify opto-couplers used in the power converters (radiation data on different families of opto-couplers can be found in open literature).

### **Thermal Neutrons**

At the location of some of the power converters, thermal neutrons are seen in simulations to be the dominant component of the particle flux. Thermal neutrons have to the best knowledge of the reviewers only been seen to give non destructive Single Event Effects (SEE). The Single Event Upset (SEU) sensitivity to thermal neutrons can be particular high if IC technologies with borated glass (BPSG) pre-metal dielectric have been used as the emission of an alpha from a captured thermal neutron will deposit significant energy locally in the silicon of the integrated circuits. Borated glass has been used for a majority of CMOS technologies before the 180nm node. It can be recommended to verify if BPSG has been used for some of the integrated circuits used (memory, micro controller, DSP, CPLD's). A dedicated test of a FGC module in a thermal neutron test facility can be made to verify this basic assumption. For the possible system effects of SEU's please look at the paragraph below dealing with general SEU's.

In case thermal neutrons are seen to be a real problem, local shielding of specific components/sub-systems can be envisaged with appropriate materials (borated plastic).

### **Single Event Effects from high energy particles (hadrons)**

Single event effects are estimated by the reviewers to be a major risk for the operation of the power converters in the radiation environment of the LHC machine. A clear distinction must be made between destructive and non-destructive events, as this has very different consequences on the accelerator operation.

### ***Non destructive single event effects***

Single bit flips in memories and registers in processors and logic chips (SEU: Single Event Upset) can disrupt the correct function of the digital control logic in the power converters. The global system effects of this will depend highly on the detailed implementation of the control logic and the sensitivity of the global system to this (e.g. required reaction speed and precision).

The memory chips used in the power controller module (FGC) have been protected with error correcting codes capable of correcting single bit errors. Multiple Bit Errors (MBE) in the used memory chips are most likely not a worry. The memory chips used are from a relatively old technology where MBE's are unlikely to be introduced in the LHC radiation environment.

Some critical parts of the Complex Programmable Logic Devices (CPLD) in the FGC have according to the material presented been protected with triple redundancy (The reviewers have though not had the time to look into this in detail).

The use of SRAM based FPGA's on the high precision generic controller (FGC-50 with SD350 analogue interface) used by the 120A, 600A and the 4-8kA converters have a high SEU cross section (CNGS tests showed data corruptions every few minutes !). A replacement of this SD350 plug-on module to the FGC

with significantly decreased SEU sensitivity has therefore already been designed and tested and should be deployed during the 2012 shut-down.

Registers in the micro controller and the DSP are unprotected and the effects of SEU bit flips in these are hard to predict and depends strongly on the system and the software used. The reviewers have not been presented with sufficient information that allows the effects of such SEU's to be estimated. The use of optimized software and self-checking functions (e.g. watchdog timers) can significantly improve the systems capability to work correctly despite such bit flips and corresponding malfunction of the processors. It has been presented in the review that the controller module has hardware features that allows the processor to make a "fast" reset/reboot in case of detected problems. This has to the reviewers understanding though not yet been used in practice and it is currently not known what system effects such a reset/reboot may have (e.g. loss of beam or not). It is the general feeling of the reviewers that the total cross section of SEU's in the processors, that will have visible system effects, is most likely limited and incremental improvements to the software can improve this if required. It is recommended that a systematic study is made to estimate the global cross section for SEU malfunctions and determine if the auto reset/reboot can be used in practice without loss of beam. Such verifications should be performed both on standalone power converters and as part of full accelerator tests with beam. The reviewers assume that both the DSP and micro controller can be reset/reboot remotely so no physical access is required for this.

SEU effects in dedicated digital control functions (e.g. CPLDs) in the different power converters (all with different implementations) are basically impossible to predict as not enough information is available for each specific implementation. This logic has no triple redundancy so a large fraction of SEU's will most likely be seen as a transient or static failure of the PC. According to the information presented the logic present should be of limited complexity (the local control has no real intelligence) so the effective SEU cross section of this should be relatively small and will most likely not be a dominating risk factor. There is though a very large uncertainty on such a simplified guess and this control logic remains a risk factor.

The effect of SEU induced signal glitches in the high power part of the power converters are estimated by the reviewers not to be a major worry, because of the relatively large signal levels used. The effects of SEU induced glitches in the high precision analog current and voltage measurements is not estimated to be a significant risk as these signals are further filtered and because the time constants of the regulation loops are relatively slow (because of very large inductance of loads).

In general it is estimated that SEU's will be a significant risk factor for the reliable operation of the power converters. It is though with the information available very difficult to guess which parts of the systems will be most prone to malfunctions from SEU effects.

Single Event Functional Interrupts (SEFI) in the integrated circuits of the power converters (e.g. non destructive single event latch-up, SEU in particular control registers, ) will normally require a power cycle to recover normal functionality of the circuit (and the power converter). The CPLD's used in the FGC have been seen to have a significant cross section for this. First estimates for these CPLD's gives a power converter mean time between failure among the 752 60A power converters, at nominal LHC luminosity,

of the order of a few days that must be considered problematic (depending on system sensitivity to this as described in later paragraph). The critical FGC module can be remotely power cycled so no physical access is required to resume normal functionality (but beams will most likely be dumped). For other parts of the power converters, containing a number of unknown/untested components, the risks of Single Effect Functional Interrupts are basically unknown. In the current installation physical access is required to power cycle the power converters. This is clearly highly undesirable and a basic means of performing remote power cycling should be implemented as soon as possible. SEFI's must therefore in general be considered to be a major risk for the reliability of the power converters.

The Diagnostic Module (DIM) using the same type of CPLD's will also suffer from the SEFI problem seen. The DIM module can not be locally power cycled and will therefore require a global power cycling of the converter to recover normal functionality. The basic power converter can continue to function when a DIM module failure occur but the particular fault diagnostics monitoring functions will not be available. It must at the system level be determined if it is acceptable to keep running with a power converter when a DIM module is not functional.

#### *Destructive single event effects.*

Destructive Single Event Latch-up (SEL) of integrated circuits in the power converters will require the whole PC or sub-modules to be exchanged/repaired. The relative old types of chips (5 V IO) used in the common controller (FGC) and dedicated control functions will have a significant risk of single event latch-up. The FGC, that is the only module that has been extensively radiation tested, have recently been measured to have destructive latch-ups in the Xilinx CPLD's when exposed to high energy hadrons (test with 230 MeV protons and at mixed radiation field at CNGS). Based on the number of CPLD's of this type in the power converters and the coarsely estimated cross-section this will at nominal LHC luminosity give an estimated hardware failure rate of one 60A power converter per 4 months (comparable to expected MTBF of such power electronics). Such a hardware failure rate of the 60A supplies seems acceptable, especially if they are not all required to be functional (see section on global system aspects). Components used in the 120A, 600A and the 4-8kA power converters have not been radiation tested and their failure rate can therefore not be estimated. Destructive Single event latch-ups are globally a risk factor for the high luminosity operation of LHC which is difficult to evaluation because of limited radiation tests.

Bill Bartholet has in discussions with the Xilinx radiation expert (Gary Swift) verified that the 95000 family CPLD used was not designed for latch-up immunity. It is also possible that purchased samples could come from different foundries, with potentially different radiation behavior. This CPLD is an older part, and predates Mr. Swift's time at Xilinx, but it is also possible that it was not originally a Xilinx design, but was purchased by Xilinx. Current spaced-qualified Xilinx parts are manufactured in a special epi-layer process for latch-up-immunity, which is not the case for this old 95000 family parts.

Radiation induced Single Event Burnout (SEB) of power devices (power MOS and IGBT) is a known problem for the use of power electronics in radiation environments. It is generally known that selected commercial devices can be used in specialized radiation tolerant power supplies if their maximum voltage parameters are de-rated by a given factor (1.5 - 2). The necessary radiation tolerance of such

de-rated devices can though only be guaranteed after an appropriate radiation qualification program. For the 60A power supply such a de-rating principle has been assured for the power devices used and successful radiation testing of the full power converter has been made (but no detailed radiation qualification of the individual power devices). The other power converters have been designed to cope with ~2 times higher mains input over-voltages so they have in practice a de-rating applied (assuming that such over-voltages only occur rarely). The effective radiation tolerance has though not been verified with appropriate radiation tests. Power devices can also suffer from Single Event Gate-Rupture (SEGR) failures. It is currently basically impossible to estimate the risk of this without detailed radiation tests of the devices used. Destructive single event burn-out and gate-rupture is therefore a significant risk factor for the 120A, 600A and 4-8kA converters.

It is proposed to make specific radiation tests of the power devices used in the different converters to determine their basic radiation behavior at the operation voltage they are used (Specialized companies can make such tests at a reasonable cost). Such tests will also be required to identify possible candidate devices for new radiation tolerant power converters.

## Global system aspects

To estimate the global reliability of a complex machine like the LHC it is a prerequisite to know which sub-systems are required to be fully operational. The first iteration of such a global system analysis is to understand which subsystems must be “statically” operational for the beam acceleration and maintain stable beams. A second step in such an analysis is to understand which “dynamic failures” will provoke a beam dump and therefore introduce a loss of beam time. During the review it became clear that there is not yet sufficient information available to allow such a failure analysis to be made. It was presented that a few percent of the 60A power converters do not need to be operational, but it was also mentioned that some specific 60A converters must be operational. For the other power converters it generally appeared that all converters must be 100% operational to allow the accelerator to work. It can be mentioned that the 4-8kA power supply has a N+1 redundant power stage, which in principle should allow it to be functional with one broken output stage (depending on its failure mode).

The dynamic failure analysis is obviously even more complex and uncertain. Will a failing power converter (assuming some kind of graceful failure where the power supply slowly shuts down or maintains its power at a fixed level) always result in a beam dump or will the accelerator be capable of maintaining beams by having other compensating mechanisms setting in? The relatively slow time constants of the power systems (determined by the large inductance of the power supply loads) will potentially allow compensation for a dynamic failure in a PC. It was also mentioned that relatively fast protection systems (e.g. QPS) may force a beam dump in such situations anyway.

With the limited time available for the review, and also the currently limited operational experience with the full accelerator, it is basically impossible for the reviewers to give any assessment of these vital global system dependencies. There are potentially significant reliability gains possible at this level and

this needs to be better understood during the coming running of the machine. Dedicated system test should be envisaged for this when possible.

### **Protection systems**

An extremely important part of analyzing possible failures in the power converters is to determine if a power converter failure can provoke destructive failures in other parts of the accelerator. From the presented material it appears to the reviewers that equipment safety functions in the power converters are taken care of by very simple circuits (e.g. free-wheel diodes and crow bar circuits) that will have a very low risk of radiation induced failures. According to the presented material, the fast power converter abort signal from the power interlock system reacts directly on the power converter output stage without the implication of the FGC and its complicated control logic. The protection of accelerator equipment is also to a large extent taken care of by other independent systems (e.g. Quench Protection System and Power Interlock System) that are not evaluated for radiation tolerance in this specific review. It is therefore the general feeling that the equipment safety functions of the power converters are not prone to significant radiation effects.

## **Relocation and shielding**

As the 120A, 600A and 4-8kA power converters have not been constructed for reliable function in a radiation environment the option of relocating them to protected locations or decrease the radiation levels by improved shielding must be pursued to the maximum extent possible before the 2<sup>nd</sup> physics run. Any improvement on this will give direct and immediate improvements to the general reliability of the PC's. All possible short term options for this should be seriously considered. Even relatively modest radiation level reductions may be significant for the overall efficiency of the accelerator, if the power converters turn out to be weakest part of the chain.

As basic guidelines for shielding improvements the following recommendations can be given:

- Elimination of "line of sight" and "one bounce" topologies between the radiation sources and the sensitive parts of the power converters.
- Elimination of thermal neutron "conduction holes" between the beam and possibly sensitive components (e.g. FGC).

At long term, the use of very expensive means for relocation/shielding must be compared to the costs and potential risks in designing and install new radiation tolerant power converters (see later paragraph on this).

## **Radiation assessment of current power converters**

The very large uncertainty on the radiation tolerance of the power converters mainly comes from the fact that no radiation tests have been performed (excluding the 60A PC). This is particularly the case for the LHC power converters as no rigorous radiation qualification has been made of individual components and sub-systems and no component tracing have been used. Full power converter radiation tests can in the current situation give some indications if particular parts of the power converters have very high radiation sensitivity. The fact that no rigorous component tracing methodology has been used in their design and production gives a large uncertainty if such test will actually be representative for all the installed systems. As the power converters are large and expensive systems it will in practice only be possible to test a few units, so obtained results will also have large statistical uncertainties.

It was during the review discussed if a vulnerability analysis of the current power converters, based on schematics and parts lists, is a viable addition/alternative to radiation testing of the current power converters. Some of the reviewers, that have extensive experience within this domain, think that such an analysis is clearly difficult, but not necessarily impossible and can give useful indications of potential weak components in the designs. Such a vulnerability analysis must be done as a team work between the power converter designers and a specialized company/institute that has extensive experience in this domain and have access to extensive information about radiation tolerance of commercial components. The review panel can be contacted directly to better understand the feasibility of such an analysis and its potential costs and manpower needs.

If an appropriate radiation test facility (spectrum, infrastructure, access, etc.) for full (or major parts of) power converters can be found, it can be proposed to make some basic radiation tests of their general function and reliability in a radiation environment. This can help to identify particular radiation sensitive parts of the converters. Such full power converter radiation tests must be made rather quickly to have any practical value to determine possible incremental improvements that can be implemented for the 2<sup>nd</sup> physics run. In a pragmatic approach it can be proposed to test early and late production samples to assess major differences in their radiation tolerance. To determine if such an appropriate radiation facility is (or can be made) available it can be recommend to contact people with a wide knowledge of existing radiation facilities.

## **1<sup>st</sup> physics run 2010 – 2011**

For the initial 2 years (2010 – 2011) of the physics running period there is clearly not much that can be done to significantly improve the radiation tolerance of the power converts themselves (except incremental improvements to DSP and microcontroller software and possibly CPLD firmware). There will possibly be opportunities to minimize the effects of dynamic and static failures on the operation of the LHC machine. All encountered failures of power converters should be carefully traced and diagnosed to determine if it is potentially radiation related and from this get better radiation tolerance estimates that can be used to determine possible actions that can be implemented during the following 1 year shutdown (2012) to improve the radiation tolerance for the following higher luminosity and higher

energy physics run. To allow such a diagnosis to be made in practice appropriate radiation monitoring equipment must be present in all power converter locations.

## 2<sup>nd</sup>. Physics run 2013-14

For the second physics running, when the machine luminosity will potentially be significantly higher, the radiation tolerance of the PC's can become a critical issue. There will though most likely be opportunities to make incremental improvements to their reliability and their effect on the global running of the accelerator. Information from the dedicated radiation tests and from the 1<sup>st</sup>. physics run will be important to determine if such opportunities exist and prepare for such improvements to be implemented efficiently during the 1 year shutdown in 2012. Such improvements can be:

- Deployment of new SD 360 module for FGC's.
- Install redundant PSU for all FGC's and DCCT's.
- Replacement of particular radiation sensitive components.
- Improvements to shielding.
- Additional relocations where possible.
- Improvements to soft and firmware.
- Capability to do remote power cycling of the DIM and full power converters.
- Global system optimizations to make LHC less sensitive to failures in single PC's (e.g. 60A PC). (The replacement of the current FGC in the 60A PC with a new radiation tolerant version should be seriously considered if the global system can not deal with transient failures and the use of its automatic reset/reboot)
- Etc.

## Long term options

It is clear that the radiation tolerance problem of the current power converters must be resolved to allow a reliable operation of the LHC with high luminosity. For a long term solution there seems to be two basic options that can be pursued: complete relocation or complete power converter redesign. With the current information available both options must be investigated seriously to determine the best/affordable solution.

A complete relocation of power converters to locations without radiation will intrinsically be the safest route to take. It though seems that it will not be possible to relocate the 60 A PC's and for the other power converters it appears that the civil engineering costs related to their full relocation may possibly be exceedingly high.

The only realistic alternative to a complete relocation is to develop a new family of radiation tolerant power converters using an appropriate design and test/qualification radiation assurance methodology (please see appendix). As proposed by the CERN power converter group during the review, an architecture of very modular power converters based on a few and very thoroughly radiation qualified modules appears to be an attractive approach. The reviewers based on their experience in the domain of radiation tolerant electronics believe that this will be feasible for the radiation environment expected. The design and production of such highly modular radiation tolerant power converters will clearly need a significant effort from a competent design and production team with the appropriate experience in power converters and radiation effects. It is recommended that a more detailed architecture and implementation of such a design approach is worked out immediately and then reviewed by external experts after a ~6 month's period. The members of the current review panel are all willing to participate to such a feasibility review.

If an approach is taken to only redesign particular parts of the power converters (FGC, DIM, dedicated control, etc.) then the remaining sub-systems must be appropriately radiation qualified and component traceability must be verified (which is very difficult/impossible to do afterwards).

If the power converters are not fully relocated then opportunities for improved shielding must be exploited wherever possible, within a reasonable economic envelope. This will in all cases be beneficial for the overall reliability of the power converters (and other systems).

## Summary and recommendations

Radiation induced failures of the current power converters are considered to be a serious risk for the reliable running of the LHC machine during the 2<sup>nd</sup> physics run and a major risk for long term (high luminosity). The current power converters can not be considered appropriate for the reliable long term running of the LHC at high luminosities and their replacement/relocation should be seen as a necessary consolidation effort.

The radiation level estimates for concerned areas should be improved based on initial radiation measurements and opportunities and options for equipment relocation and improvements to the radiation shielding should be determined and implemented before the 2<sup>nd</sup> physics run.

If the power converters can not be fully relocated, a design/feasibility study for highly modular radiation tolerant power converters should be started as soon as possible and be reviewed by external experts. Even in case the 120A, 600A and 4-8kA power converters can be relocated, the overall radiation tolerance of the 60A power converters must be improved.

It is recommended to make a paper radiation vulnerability analysis of the current power converters as soon as possible to identify potential radiation sensitive components. Identified components can then be radiation tested if considered particular problematic for the reliability of the power converters. Radiation tests of complete power converters can also be used to identify particular critical parts of the

converters, if an appropriate radiation test facility can be found. Results from such tests and operational experience from the first physics run can be used to estimate the power converter reliability for high luminosity runs and determine if incremental improvements can be made on the current power converters for the 2<sup>nd</sup> physics run.

## **Acknowledgements**

The reviewers would like to thank the members of the power converter group (and others) to have prepared an excellent set of presentations and made extensive material available to the reviewers. There is clearly now a high awareness of the serious problems to face with the use of the current power converters in a LHC radiation environment.

## Appendix: Radiation assurance methodology

Short list of radiation assurance plan as kindly made by Bill Bartholet:

- Controlling, and keeping as small as possible, a preferred parts list for the design phase
- More complete environment definition
- Part acceptance criteria for the preferred parts list
  - Single Event Effects pass criteria
    - Mono-energetic testing criteria
      - High energy/ MeV scattering/ thermal neutrons
  - Radiation testing vs. analysis need criteria
  - Identification of most sensitive part types and assessment methodology
    - Total Ionizing Dose
      - Analog MOS functions
      - At 10 Gy/yr perhaps skip ELDRS
    - Displacement Damage
      - Photonic devices
    - SEE
      - High voltage power transistors/diodes
      - Optical fibers and optical detectors
      - Opto-isolators
      - Complex control devices
      - Software/Firmware hardening elements
      - Memory
  - Control methodology for commercial part acquisition
    - Controls for multiple chip sources of supply
    - Controls for hybrid multiple die sources of supply
    - Lot purchasing and lot acceptance radiation testing policy
- System level hardness assurance issues
  - Higher level radiation test requirements
    - Circuit board level
    - Module level
    - Full system level
  - Available test facilities
  - Circuit/system analysis of radiation failure impact
    - Creation of design hardness requirements
  - Design/controls for non-part-hardness critical design features
    - Software/Firmware implemented SEU hardening
    - End-of-life predictors for total dose failing parts
    - Reset design without beam dump
    - Remote recovery without tunnel entry
    - Redundancy
  - On-going spares replacement plan