Radiation Tolerant Power Converter Controls

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ABSTRACT: The Large Hadron Collider (**LHC**) at the European Organisation for Nuclear Research (**CERN**) is the world's most powerful particle collider. The LHC has several thousand magnets, both warm and super-conducting, which are supplied with current by power converters. Each converter is controlled by a purpose-built electronic module called a Function Generator Controller (**FGC**). The FGC allows remote control of the power converter and forms the central part of a closed-loop control system where the power converter voltage is set, based on the converter output current and magnet-circuit characteristics. Some power converters and FGCs are located in areas which are exposed to beam-induced ionizing radiation. There are numerous radiation induced effects, some of which lead to a loss of control of the power converter, having a direct impact upon the accelerator's availability.

Following the first long shut down (**LS1**), the LHC will be able to run with higher intensity beams and higher beam energy. This is expected to lead to a significantly increased rate of radiation induced effects in materials close to the accelerator, including the FGC. Recent radiation tests indicate that the current FGC would not be sufficiently reliable. A so-called FGClite is being designed to work reliably in the radiation environment in the post-LS1 era.

This paper outlines the concepts of power converter controls for machines such as the LHC, introduces the risks related to radiation and a radiation tolerant project flow. The FGClite is then described, with its key concepts and challenges: aiming for high reliability in a radiation field.

KEYWORDS: Digital electronic circuits; Hardware and accelerator control systems; Radiation damage to electronic components.

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1. Introduction

The Large Hadron Collider (**LHC**) at the European Organisation for Nuclear Research (**CERN**) is the world's most powerful particle collider and one of the largest and most complicated machines constructed to date, having been conceived and designed over the course of the last 25 years.

Two counter-rotating beams are injected into the LHC at 450 GeV, they are then accelerated, squeezed, and brought into collision at experiments located at four of the eight insertion regions of the 27 km circumference machine. The experiments detect and analyse particles produced by the collisions, giving physicists valuable information about the properties of matter at the sub-atomic level. To reach the new frontiers of physics, each beam needs an energy of 7 TeV (10^{12} electron-Volts), giving a centre-of-mass collision energy of 14 TeV. To circulate the beams of this energy within the circumference of the machine requires a magnetic field of 8.3 Teslas. These is formed using superconducting dipole magnets with a precise forward current of 13kA (±1ppm = ±13mA). To reach the superconducting state, the magnets are cooled to around two degrees above absolute zero (about -271°C).

2. Power Converters and their Controls

The LHC has several thousand normal and super-conducting magnets with associated power converters. Circuits having high stored energy use a system of interlocks and protection to guard against uncontrolled release of magnet and powering energy. A typical example of this is a 13kA dipole circuit as shown below:

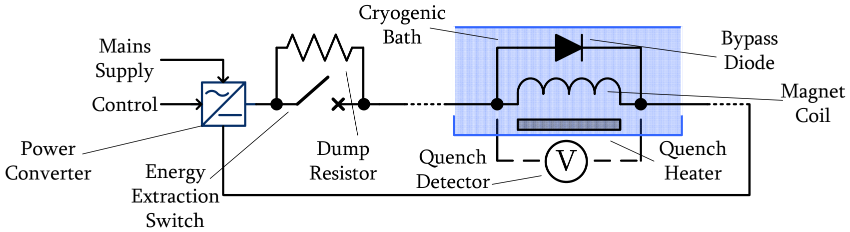

Figure 1 : Superconducting Circuit Layout

Each power converter consists of three distinct sections; a Voltage Source (**VS**) dealing with mains power conversion, current transformers (**DCCTs**) used to read back converter current and a Function Generator Controller (**FGC**):

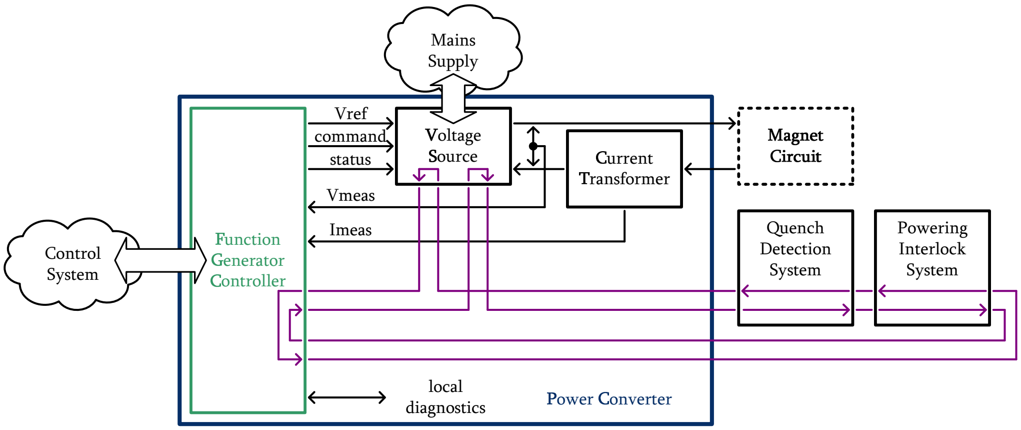

Figure 2 : Key Components of a Power Converter

The FGC is a purpose-built electronic module having several functions, most notably it [1]:

- Implements **closed-loop regulation** of the magnet current, reading the measured current, $\mathbf{I}_{\mathbf{meas}}$, to establish the reference voltage, $\mathbf{V}_{\mathbf{ref}}$, needed for reference current, $\mathbf{I}_{\mathbf{ref}}$.
- **Controls** the converter, by issuing digital commands such as ON, OFF and RESET.
- Implements low-level **interlock logic** as part of interlock loops between the VS, Quench Detection and Powering Interlock systems [2].
- Allows **remote control** and **surveillance** of the converter and associated sub-systems.

The FGC currently used in the LHC machine is the 2nd generation FGC, called **FGC2**.

3. Radiation Effects on Electronics

Particles from the two circulating proton beams in the LHC can escape the closed orbit, leaving the confines of the accelerator and interacting with local materials. A single escaping proton has the potential to create a significant shower of particles which propagate from the machine into the surrounding area. Electronics in the path of this shower are at risk from three principle types of radiation induced effects: single events, total dose and displacement damage.

3.1 Single Event Effects

A Single Event Effect (**SEE**) is prompt, having a certain probability or cross-section of occurring with every particle interaction. An SEE manifests in several ways, the two most relevant to the FGCs are:

1. Single Event Upset (**SEU**) – a particle interacts with a digital circuit, causing a stored bit to change in value. This erroneous value persists until it is re-written. The effect of an SEU on the system level depends upon the location of the flipped bit.
2. Single Event Latch-up (**SEL**) – parasitic transistors within some C-MOS circuits can be activated by radiation. This creates a low-impedance short-circuit between power supply and ground. An SEL has the potential to be catastrophic for the circuit if the fault is not mitigated [3].

3.2 Total Ionising Dose

An incident particle can cause direct or indirect ionisation of the semi-conductor, this occurs when a charged particle passes through material, liberating electron-hole pairs as it does so. In the case of direct ionisation, the primary particle causes the ionisation, indirect ionisation occurs when a primary particle causes a cascade of nuclear reactions which then lead to ionisation. This causes electrons and holes to collect within the semiconductor elements, changing device characteristics. The absorbed dose or Total Ionising Dose (**TID**), measured in Grays [**Gy**], increases over time causing gradual degradation of the device performance. This leads to several adverse effects: N-MOS semiconductors have a decrease in their switch-on voltage, whereas P-MOS devices exhibit an increase. Timing margins will change, leakage currents and board level power consumption will both increase. All active components are potentially susceptible to TID and after sufficient dose devices will completely fail.

3.3 Displacement Damage

Displacement damage (**DD**) occurs when particles interact with the silicon lattice, striking fixed atoms and displacing them from their original location causing Frenkel Defects. Damage to the lattice is proportional to the integrated flux of particles which have passed through the atomic structure, therefore DD gradually increases over time. The effects of DD generally reduce device gain which eventually leads to complete failure of the device.

DD is measured as the total number of 1MeV equivalent neutrons which have passed through a given surface area [**1 MeV eq. N / cm^2**]. The term Non Ionising Energy Loss (**NEIL**) can also be used for this metric.

3.4 Power Converter Installation and Associated Radiation Risk

Power converters and their associated equipment can be installed in five different types of area, having different risks related to radiation:

1. **Surface** – surface buildings, which are typically used for gateway computers, and normal-conducting circuits in the injector complex. Aside from atmospheric effects, there is no increased risk of radiation induced damage to components from the accelerator. *Radiation risk: none*.
2. **Perpendicular Galleries** – in parts of the LHC, equipment galleries have been constructed running perpendicular to the LHC tunnel. Their orientation and the

addition of concrete chicanes mean that local equipment is almost completely protected from the radiation field of the machine. *Radiation risk: none - low*.

3. **Parallel Galleries** – in parts of the LHC, equipment galleries have been constructed in a dedicated tunnel running in parallel to the machine. Their orientation and separation does allow a small amount of radiation to reach local equipment. *Radiation risk: low*.
4. **Alcoves** – alcoves are in the same principle tunnel as the LHC, alongside the machine. In places there is no physical barrier between the two. *Radiation risk: medium – high*.
5. **LHC Tunnel** – power converters for corrector circuits are installed directly beneath the accelerator between magnet supports. These converters are in the direct path of particle showers from the LHC. *Radiation risk: high*.

Converters which are exposed to a medium or high risk are to have their controls electronics upgraded from FGC2 to FGClite, representing around 1000 converters in total.

4. Design Flow for Radiation Tolerant Designs

The design flow of the FGClite has been optimised to address risks specific to the development of electronics for use in radiation. Steps and loops particularly relevant to radiation tolerant designs are shown in green:

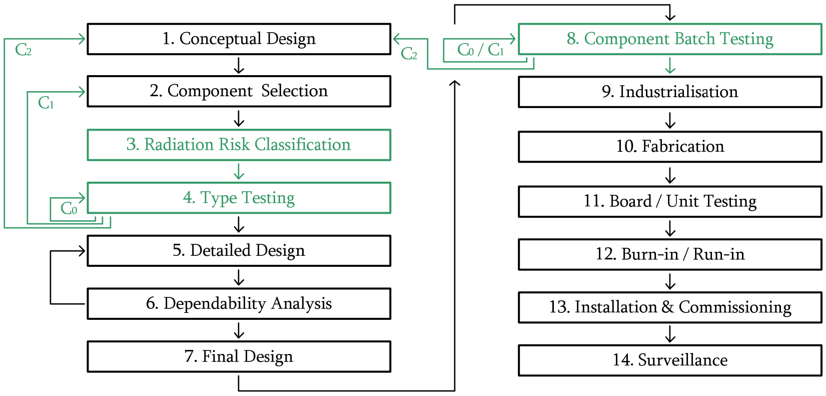

Figure 3 : Design Flow for Radiation Tolerant Electronics.

1. **Conceptual Design** – A basic design for the system is selected, with solutions proposed for the implementation of each required function.

2. **Component Selection** – The *conceptual design* is broken into sub-systems, and a component inventory is established, with components organised by requirements.

3. **Radiation Risk Classification** – Each component to be used is classified into one of three criticality classes (**$C_{0\text{-}2}$**) based on a risk-matrix, cross-referencing the likelihood and impact of radiation induced failure. A summary of each class is as follows:
   Class 0: components known to be resistant to radiation, or easily replaced if found to be weak. The basic design of the system is not influenced by these parts.
   Examples: resistors, capacitors, diodes, transistors…
   Class 1: components potentially susceptible to radiation, in less-critical parts of the system. Substitution of parts or mitigation of issues is possible with a re-design.
   Examples: regulators, references, drivers, level translators, Digital-to-Analogue Converters (**DACs**), memory…

Class 2: components are potentially susceptible to radiation, in more-critical parts of the system. The basic design is compromised if these parts do not perform well, and would require a significant re-work of the *conceptual design* if found to be weak. Substitution of parts or mitigation of issues would be difficult.

> ***Examples:*** Analogue-to-Digital Converters (**ADCs**), programmable logic, mixed circuits for field-bus…

4. **Type Testing** – the selected components are subject to radiation testing to identify cross-sections and to predict component lifetime.
    - **C_0** parts are minimally tested as many candidate parts fulfil the functional needs.
    - **C_1** parts are tested, it is preferred that two or more candidate parts for each C_1 position pass *type testing*. If this cannot be ensured, it is possible that a return to *component selection* is needed to find more candidate parts.
    - **C_2** parts are extensively tested and at least one must be found which meets requirements. If this is not the case the *conceptual design* must be revised. **Type testing failure of a C_2 part is a critical case for the project.**

5. **Detailed Design** – the remainder of the design is established, using components which performed well in *type testing*.

6. **Dependability Analysis** – the reliability of the system hardware is predicted, using cross-sections, lifetimes and electrical characteristics. Traditional reliability engineering techniques can be used to meet system requirements.

7. **Final Design** – the *final design* is established.

8. **Component Batch Testing** – randomly selected components from every batch are tested in radiation to validate cross-sections and predicted lifetimes from *type testing*. If any C_0 or C_1 component does not meet expectations, the alternative candidate components are *batch tested*. **A C_2 component batch testing failure is a critical case for the project, as it would require revisions to the *conceptual design*.**

9. – 14. **Industrialisation → Surveillance** – the usual steps to deliver the project.

5. FGClite

From the operational point of view power-converters are to behave in the same way regardless of whether an FCG2 or an FGClite controller is used. To optimise cost, the existing fieldbus infrastructure will be re-used and the FGClite will be plug-compatible with the FGC2. This makes significant savings but means that fundamental changes to the FGC philosophy are not possible. Effort has been put into the optimisation of software, programmable logic and hardware partitions to minimise complexity of the FGClite, whilst meeting system level requirements.

5.1 Hardware Partition Optimisation

In FGC2, the current reference as a function of time is stored locally in each FGC. A function table and regulation circuit use circuit settings specific to the magnet circuit being powered to drive the voltage reference point. The gateway sends simple commands such as *start regulation* to each FGC. The most significant hardware change for the FGClite is the relocation of the DSP into the gateway, with the FGClite acting as remote input/output module.

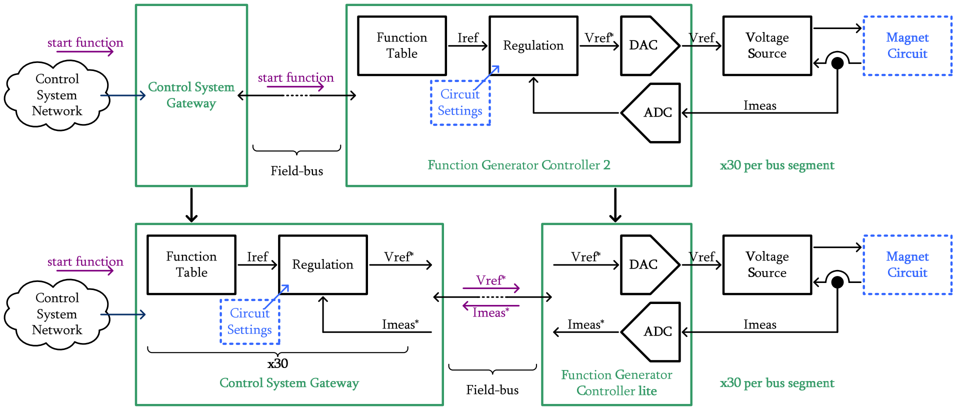

Figure 4 : FGC2 Closed Loop Control [4] vs. FGClite Architecture.

The gateway complexity is significantly increased as it is required to implement the regulation calculations for all FGClites connected on the same field-bus segment.

5.2 Software / Programmable Logic Partition Optimisation

The FGC2 depends on both software and programmable logic to achieve its functional requirements. Embedded software is used both for closed-loop signal processing and converter supervision. In the FGC2, eleven programmable logic devices are used for sub-functions such as timer circuits, access to coefficients and digital multiplexing, amongst others.

The FGClite is to have no locally executed software as the signal processing functions are to be moved to the gateway. The remaining supervision requirements, as well as FGC2 functions implemented in programmable logic, are to be implemented in three flash-based Field Programmable Gate Arrays (**FPGAs**) having functionality described in VHDL.

The obsolete WorldFIP chip-set is also to be replaced by CERN nanoFIP, which also uses a flash FPGA:

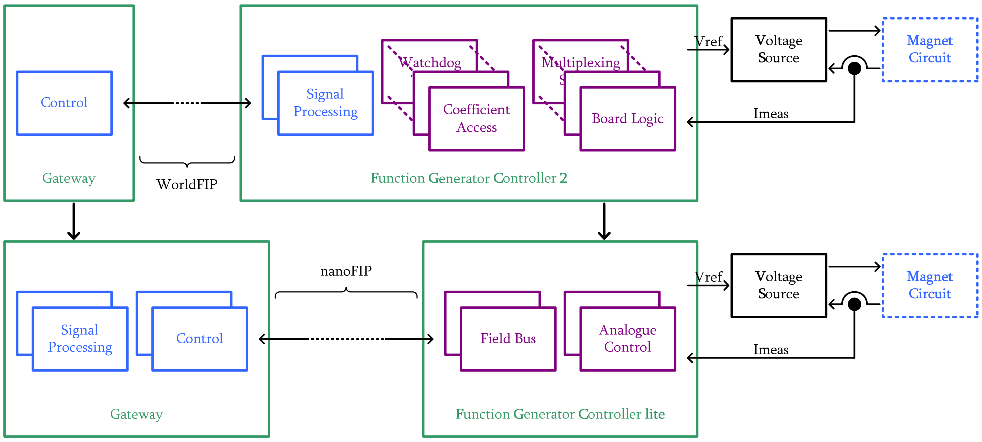

Figure 5 : FGC2 to FGClite Architecture Changes.

6. FGCLite Lifetime and Reliability

Failures of the power converter hardware can be split into two categories: basic failures corresponding to the bathtub-curve and those related to radiation damage.

6.1 Basic Failures

The first source of failure is expected to follow the typical hazard function for the failure of non-complex electronic systems, the so-called bathtub curve. This hazard function has three sections; Early-Life, Useful-Life and Wear-Out:

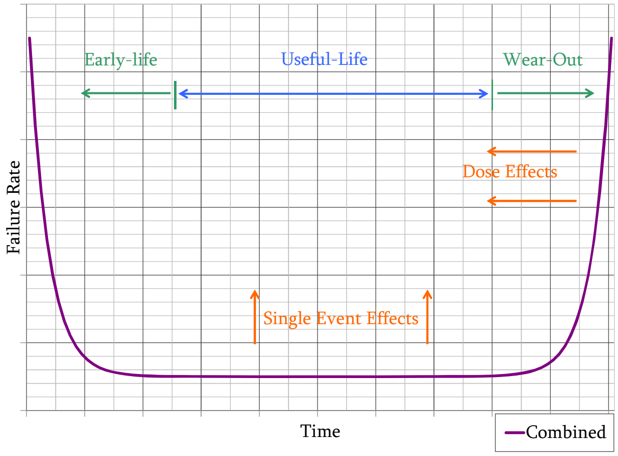

Figure 6 : Qualitative Bathtub Curve.

Early-Life failures are caused by latent defects and are avoided by processes such as stress-screening and running-in.

The Useful-Life failure rate is one of the biggest concerns for the success of the FGClite project in meeting its reliability goal. Failures of this nature can occur at any moment in time and are not correlated. This is to be minimised by following design practices promoting reliability, such as over specification and redundancy. The base failure rate of the FGClite will be determined using a combination of past experience and the handbooks (**MIL-217-F**).

Wear-Out failures are due to the gradual wear-and-tear of electronic systems in use. In the FGClite these are to be minimised by following the most appropriate maintenance plan, either preventive, or Reliability Centred Maintenance (**RCM**).

6.2 Radiation Induced Failures

The second source of failure is that related to radiation. Radiation induced damage manifests itself in two manners: cumulative or prompt. Cumulative, or Total Dose (**TD**) effects reduce the effective system lifetime by advancing the wear-out phase and SEEs increase the random-in-time failure rate of the system across its whole lifetime. These two influences can be seen as modifications to the bath-tub curve, as indicated on Figure 6.

Prompt effects, such as SEU or SEL can cause the system to malfunction, having the effect of increasing the random-in-time failure rate of the FGClite. The predicted number of failures per year can be seen as a function of the fluence of particles in the areas the FGC is installed, and the cross-section of each FGClite. With an LS1 – LS2 estimated fluence of $\mathbf{9 \times 10^9}$ High Energy Hadrons (**HEH**) per square centimetre per year in tunnel installations, characteristics for a sub-set of converters are [5]:

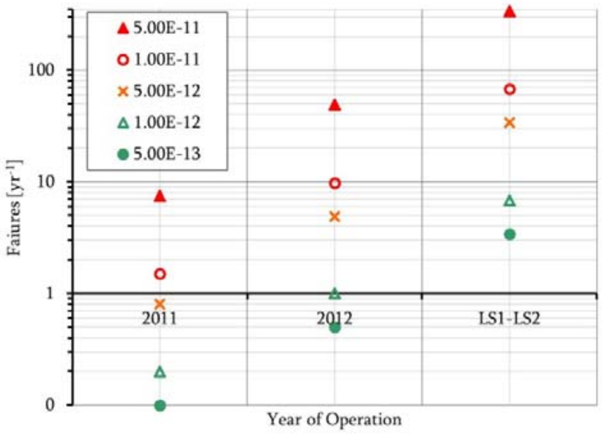

Figure 7 : Tunnel Converters Failure-Rates with Different Cross-Sections, 9 x 10^9 HEH per year LS1-2.

The **FGC2** device is predicted to have a cross-section leading to unacceptable loss of LHC availability in the LS1-LS2 era.

6.3 Overall FGClite Requirements

Lifetime Requirements: The FGClite must be designed to outlast the LHC. Current planning extends into the 2030s, so an FGClite installed in 2015 would need **20-25 years lifetime**. In addition to the electrical requirement, radiation dictates that every component in the FGClite must remain within specification after absorbing around **200Gy**, giving margin for error for both TID and DD effects (each component must survive **1 x 10^{11}** 1 MeV eq. N / cm^2).

Reliability Requirements: Power converters have a direct influence on the availability of the LHC machine. Every year the LHC is expected to run for 200 days, with two ten-hour fills, and two recovery periods of two hours every day [6]. This gives 400 *LHC missions* per year. No more than 10% of these should be aborted due to failures of power converters. Taking the pessimistic view of operation all year round and considering that a single failure of a power converter causes a premature mission abort, this requirement means each power converter must have a Mean Time Between Failure (**MTBF) in excess of 200,000 hours**.

This can be split between electrical and radiation induced failures. Electrical MTBF is therefore required to be **in excess of 300,000 hours**, with radiation effects dictating that each FGCLite needs a cross-section of better than **1 x 10^{-12}** cm^2. As each FGClite is to be made from many components, individual components must have somewhat better characteristics or must be employed using redundancy and voting to achieve the required figures.

Combining these requirements means all FGClites in operation are expected to fail **less than 10 times** per year due to radiation induced errors, and **less than 30 times** due to electrical effects, meeting the combined requirement of less than **40 failures** per year.

7. Outlook and Conclusions

FGClites are required to be installed in LHC at the end of 2015. The first six months of the FGClite project have been centred around planning and in establishing project risk. The most significant risk to the successful completion of the project concerns class $\mathbf{C_2}$ components, any problems related to them can jeopardise the delivery of the FGClite. Optimisation of the component selection has yielded only three C_2 parts:

1. The **ADC** used to determine I_{meas}.
2. The **mixed analogue-digital IC** used for the fieldbus interface.
3. The **Flash-FPGA** used throughout the design.

Early effort will focus on the *type testing* and *component batch testing* of these parts to determine their suitability for the FGClite.

The quality of statistics is critical for reliability calculations, as they drive both the mitigation techniques and overall FGClite reliability, of particular importance is the predicted HEH fluence in the LHC tunnel. In this context there is a risk of over-engineering the FGClite by taking an excessively pessimistic view: layers of redundancy and power cycling options could be in excess of the project needs, reducing overall reliability.

The shift away from software towards programmable logic has many implications, ranging from the skills required from the project team, to the quality assurance of the FGClite. Reliability calculations explained in this paper assume a non-complex system, free from systematic faults. The programmable logic engineering must be of the highest quality, matching that used elsewhere at CERN, following guidelines for dependable VHDL design that have been developed in the course of other systems developments at CERN [7].

Overall, the replacement of the FGC2 with FGClite is feasible. At the same time, it is clear the development of radiation tolerant electronics requires a special approach. The challenges which exist in building a normal electronics project are compounded by radiation risks.

Acknowledgments

The authors wish to express their thanks to Y. Thurel, who has established the baseline methods and guidelines for the power converter group’s work in developing radiation tolerant systems. Thanks also to the vital research and on-going work by the radiation to electronics working group (**R2E**) and associated experts, in particular; M. Brugger, A. Masi and G. Spiezia.

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