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Power electronics in HEP experimental caverns

Ferdinando Giordano,* Antonio Alborini, Andrea Guatteri, Alessandro Iovene, Claudio Landi and Simone Selmi

CAEN s.p.a.,
Via Vetraia 11, Viareggio, Italy

E-mail: f.giordano@caen.it

Next generation high energy physics experiments will be more granular than those currently in operation, this means more demanding electronics to power the detectors and to process all collected data. Space constraints, cabling, cooling and, last but not least, efficiency are all parameters that need to be optimized during experiment design to have the best performance for data taking.

The CAEN R&D to develop a new generation of power supplies for hostile environment is presented and some results from test campaigns are discussed. This R&D named EASY6000, after its predecessors EASY3000 and EASY4000, was launched in 2020 designing and testing electronics capable to survive magnetic fields and mixed radiation fields (composed by gamma, neutral and charge hadrons) of the High Luminosity LHC (HL-LHC) experimental caverns at CERN.

To cover all needs, CAEN started an irradiation campaign in various steps and at various irradiation facilities, with the aim to investigate COTS (Commercial Off-The-Shelf) electronics behavior using one radiation at a time: neutron, gamma, protons, and then validate the final board design with a mixed field. Plus, we performed efficiency tests in magnetic fields up to 1 T using various orientations to exploit different symmetries in the boards design.

During this talk we will focus on test campaigns performed in the last year. Some undertaken within the RADNEXT EU project and in collaboration with INFN and CERN, that include tests with proton, neutron, and gamma sources, of various components: ADCs, DACs, RAMs, FPGAs, μControllers, Power Transistors and FETs, temperature and humidity sensors, etc. All the necessary pieces to design and build circuits and boards capable to survive in the experiments; these components alone cannot ensure the reliability to run an experiment in such conditions, thus also circuits and control loops must be tested. The results of the test campaigns will be discussed together with some mitigation techniques used to achieve the wanted reliability.

First developments of power supply circuits and devices based on these blocks will be also presented, as well as the performances achieved so far in terms of reliability, power density, energy efficiency, noise figure, etc.

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*Speaker

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1. HEP caverns environment

High Energy Physics (HEP) experiments are all different, and so are their experimental caverns. CAEN provides power supplies to experiments at CERN as well as in other international laboratories everywhere in the World, anyhow currently the focus is all devoted to HL-LHC upgrades and we have taken the most demanding conditions of the CMS and ATLAS caverns as benchmark [1].

The composition of the radiation field, as well as the intensity and direction of the magnetic field, can vary by orders of magnitude between experiments, but also within the same cavern. To cover all needs, all components and circuits are designed to work correctly at the maximum operational field (see Tab. 1), then the boards are validated in an environment that resembles the proper operational mixed field.

Type	Total
Total Ionizing Dose	200 Gy
High Energy Hadrons	10^{12} p/cm^2
1 MeV neutron equ.	10^{13} n/cm^2
Magnetic field	1.0 T

Table 1: Summary of the maximum tested values for the various radiation types, plus the magnetic field.

2. Radiation damage

Testing against one type of irradiation at a time allows us to better understand the kind of radiation damage that might be occurring, plus it gives more flexibility to find the right facility and the proper dose/flux. The two main types of radiation damages are Total Dose (TD) and Single Event Effects (SEE), as the name suggests the first depends on the accumulated dose, while the second is stochastic and occurs with a certain probability depending on flux and device(s).

The TD is deterministic and it can be easily tested, understood and calculated. There are two main contributors to the total dose damage: the Total Ionizing Dose (TID) and the Displacement Damage (DD). The TID is generally tested with high energy photons as gamma rays do not cause major damages to the silicon structure. Instead neutrons are often used as probes for DD, neutron can also cause damages since they loose energy in the material as well (so called NIEL processes).

SEE are trickier to understand, since they manifest themselves erratically it is important to have a good statistic to calculate them and, thereafter, predict their behavior. SEE can also be divided into subcategories, some SEE might be permanent (i.e. a short-circuit that burns a component) or temporary (i.e. a bit flip that changes a μC status). Permanent SEE are the most problematic ones, since they might occur anytime during the lifecycle of a product and usually make it unusable, while temporary SEE can be cured by resets and power cycles.

3. Test setup and mitigation techniques

Our test system is shown in Figure 1, it is rather simple and easy to adjust according to the Device Under Test (DUT) and the facility. The DUT can be easily changed together with the adaptor board, therefore the user needs only to adjust the setting of the power supplies and configuration of the logger (for low frequency data) and/or oscilloscope (for high frequency transient) between one test run and the following.

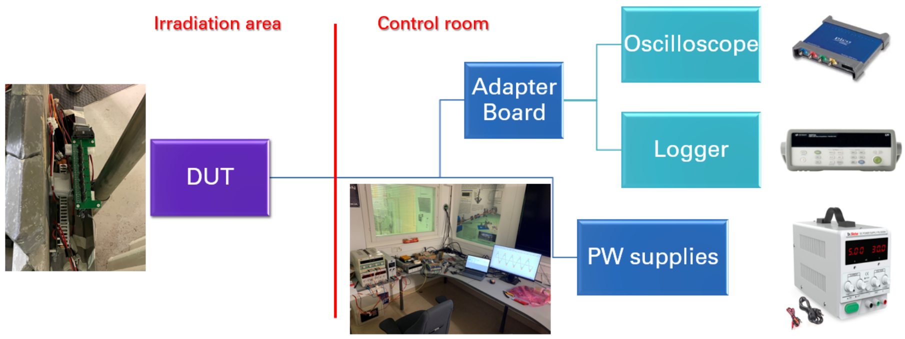

Figure 1: Graphic illustration of the test setup. The Device Under Test (DUT) is the only module inside the irradiation area, power and control are placed in the control room and connected using various cables between 20 and 50 m long. In the control room we in general have some power supply and adaptor board (easily adaptable to the DUT) to feed the signal to a logger and/or oscilloscope.

While various mitigation techniques can be implements at the hardware (HW) and firmware (FW) level, the tests described in this manuscript are mainly focused on the HW, since the FW is easier to adapt and the goal was to investigate purely the HW in order to understand its limitation and, on the other hand, estimate the amount of FW redundancies needed to properly operate each device. Thus, we will describe the HW mitigations implemented and improved during the tests, and briefly mention the FW mitigation foreseen for the final implementation.

Hardware can be made more robust at various levels and using different approaches, CAEN has decided not to use rad or space graded components, but only COTS. This choice requires carefully planned irradiation tests but helps minimizing costs while giving more freedom in terms of choice of components.

First and foremost the HW had been made robust by using less integrated circuits, as they are the most susceptible to radiation; where needed we only used integrated circuits previously tested in radiation. Otherwise, even if cumbersome, the functions implemented by integrated circuits are spread out among discrete components resilient to radiation, of which behavior is more predictable. To protect against SEE we have chosen higher grading components and implemented pulse-by-pulse protections. Besides the design and components choice it is also important the circuits are properly calibrated to take into account component degradation due to radiation, so the driving circuits can perform their function during the whole life cycle of the products. During the test some circuits had to be re-calibrated since the working window was too narrow given the degradation of the components.

4. Irradiation results

In this section we briefly describe the tests performed in the last year at various irradiation facilities, the section is divided according to the radiation damage we wanted to probe: Total Ionizing Dose 4.1, Displacement Damage 4.2, and Single Event Effects 4.3.

4.1 Total Ionizing Dose

We tested TID resilience with high energy photons as they do not inject extra charge in the silicon and/or create vacancies/interstitials. Our tests were performed at ENEA Casaccia laboratories, using the CALLIOPE facility [2] which provides a flux of high energy gammas thanks to a ^{60}Co source.

We tested various components and subparts of a power supply. In general MOSFET are the most sensitive components to TID as their characteristics can change dramatically, so we had to test the resilience of our circuits to see if they were properly designed to cope with these changes.

Probably, one of the most interesting results of this test is a trial with 8 MOSFET known to be sensitive to radiation. In general we select MOSFET that are as resilient as possible, and we test them to verify they never work in depletion ($V_{th} < 0$) but in enhancement ($V_{th} > 0$); on the other hand we wanted to use these as radiation monitors on our power supplies, to better know their actual operating conditions. In Figure 2 we can see the variation of the MOSFET threshold voltage as the TID increases, the behavior of them all is consistent and after an initial fast response of 10 mV/Gy they reach a stability of about 3.5 mV/Gy. The most difficult part of the calibration is to properly take into account the annealing periods, which happen when the MOSFET is not irradiated and it recovers part of the losses sustained during irradiation.

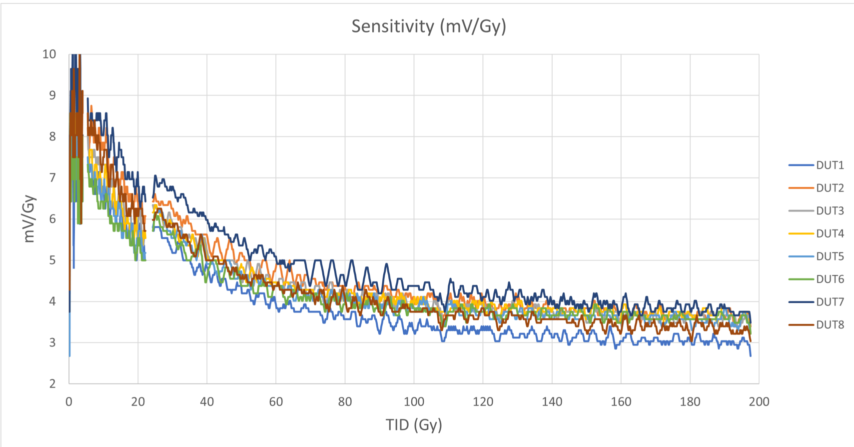

Figure 2: Sensitivity to TID of 8 MOSFET to be used as radiation monitors. On the y-axis we can see the mV/Gy variation of the MOSFET voltage threshold, on the x-axis the TID. After a rapid degradation, where the change could be up to 10 mV/Gy, we see that the values stabilize at about 3.5 mV/Gy for all MOSFET, the only caveat is the annealing that happened around 20 Gy when the test was stopped for 40 minutes.

4.2 Displacement Damage

The main probe to investigate DD are neutrons, which thanks to their properties are mainly responsible for creating vacancies and interstitials. We were able to perform neutrons test using 0-30 MeV white spectrum neutron at NPI-CAS [3] and 13 MeV neutron using D-T fusion at the ENEA Frascati research center [4]. During these tests we where able to test High Voltage and Low Voltage channels, plus the components needed for control: memories and controllers.

During the tests we did not notice any problems with the channels, only spurious events where detected at very high rates, i.e. 10^8 n/cm^2/s, due to SEE. Anyhow, this instantaneous flux is so high that it would never be reached during normal operations of the power supplies, we decided to set this flux in order to accumulate 10^{13} n/cm^2 in a reasonable time during tests.

Thanks to a good statistics of memories and controllers tested we are able to calculate also a Mean Time Between Failure (MTBF) relative to neutrons: a Mean Neutron Dose Between Failure of 1.1×10^{13} n/cm^2 and an error rate for the memories of 2.2×10^{-4} error/kB/Gn.

4.3 Single Event Effects

SEE were instead tested with protons at the Proton Irradiation Facility (PIF) at PSI [5] and RADEF at the physics department of the University of Jyväskylä [6]. The PIF facility has a powerful proton beam at 230 MeV with intensity (tunable by the user) up to 10^9 p/cm^2/s, also the intensity of the RADEF beam is tunable but the energy is instead 55 MeV, as we will later see protons of this energy have large ionizing potential and therefore the TID was larger than expected in our DUT.

At PSI we tested mainly controls and memories, in more details we tested a known rad-tolerant FPGA, in which the high-level micro-controller has been istantiated as an IPCore inside the FPGA fabric. While the FPGA itself was robust enough, the μC showed a lot of SEE since it runs on a SRAM which is, on the other hand, known to be susceptible to SEE like single event upsets.

In Jyväskylä instead we tested mainly the channels and converters of the power supply, we aimed at 10^{12} p/cm^2 as this value covers most of the needs we foresee for HL-LHC, including some safety margin. As for neutrons we set various instantaneous fluxes from 10^5 to 10^7 p/cm^2/s, to cover "normal" use and reach the total dose in a reasonable time. During the first irradiation step we did not see any SEE or any major problems, but we noticed some failures already at 2×10^{11} p/cm^2, way earlier than the wanted 10^{12} p/cm^2. These failures proved to be permanent, also during post-mortem analysis, and not related to SEE. Eventually we looked at the TID equivalent and not only the number of protons, and we realized that the TID was already exceeding 200 Gy, so the MOSFET and their circuits reached their limit already.

5. External magnetic field impact

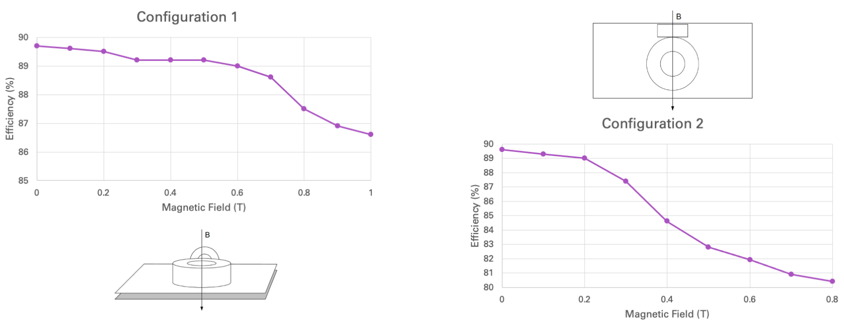

Figure 3: Two opposite configurations used during the efficiency test in a variable magnetic field: on the left the field is parallel to the toroid axis, while on the right it is perpendicular. The efficiency of the DC-DC conversion is plotted in both cases against the field intensity.

We performed some detailed tests using a magnetic field up to 1 T, where our goal was to understand if there was any preferable orientation to minimize the efficiency losses due to the saturation of the inductors used in the DC-DC converters. As visible in Figure 3 when the applied field is parallel to the main inductor axis the efficiency loss is moderate, while when the magnetic field is perpendicular to the axis of symmetry the losses are much higher at lower intensities. These results could be predicted thinking about how the external field brakes the symmetry of the magnetic field inside the toroid.

The efficiency is not the only parameter to take into account, there are other effects on the currents as well that have to be monitored and understood as they might damage the modules.

6. Conclusions

We summarized our test campaign to validate our PS design for HL-LHC, all tests were carefully planned and results analyzed, unfortunately only a few details could be presented in this manuscript. We are already planning more tests in a mixed field to validate new components with old designs, as well as completely new designs. This R&D will continue until the first HL-LHC beam.

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