Failure of DCDC modules in the CMS pixel system during the 2017 run
- Executive Summary -

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1200 DCDC converters modules and based on the FEST2.1 ASIC have been installed in the CMS pixel detector system to power the front-end modules during the 2017 run. After a few months of smooth operation, some converters started to fail once the luminosity of the accelerator was increased, at the beginning of October. In the following 2 months, about 5% of the deployed converters failed. Additionally, when during the consequent winter shutdown the pixel system was opened, another about 35% of the converters were found affected by a damage mechanism that did not prevent them to work correctly.

A large series of experiments was conducted in the following months to uncover the origin of the problem, but this was complicated by the large number of unique features of the CMS pixel system (radiation background, operation temperature, magnetic field, proximity to the LHC beam line, grounding and shielding details) and by the difficulty in reproducing the same damage outside it. The turning point of the investigation was a very dedicated test at the CERN IRRAD facility in May, when it was possible to expose 32 converters to a mixed field of radiation in proximity of the PS beam and at -25^{o}C. The results of this experiment clearly indicated a strong correlation between the radiation background and the failures, as well as the functional sequence necessary for the damage to happen. With this information, and using this same functional sequence during X-ray irradiations, it was possible to reproduce the damage while observing the waveforms of the relevant circuit's nodes, hence to understand the mechanism originating it.

Total Ionising Dose (TID) is known to open source-drain leakage current paths in CMOS transistors. The FEAST2.1 ASIC uses a 350nm CMOS technology whose n-channel transistors are subject to this radiation effect. To prevent the opening of the leakage current path, transistors are laid out with a special geometry (called Enclosed Layout Transistors, ELT). Unfortunately, high-voltage transistors can not be designed this way and are subject to TID-induced leakage current. To protect the circuit from the consequences of the leakage, various design provisions are used in FEAST2.1. One high-voltage n-channel transistor in the circuit has however not been protected for all functional sequences, in particular the leakage current can flow when the converter is disabled (which is done via a dedicated pin of the FEAST2.1 circuit). This current is amplified and integrated on a capacitor, originating a large voltage transient in a critical node of the circuit. Since this transient can approach the input voltage (up to 12V), largely exceeding the 3.3V specified for most of the devices connected to the node, this over-voltage can eventually lead to irreversible damage to the circuit. This mechanism has been confirmed by multiple observations.

Having ascertained the origin of the damage, it was possible to propose solutions to prevent its further occurrence in systems where the FEAST2.1 converter is exposed to large radiation backgrounds (TID>500krad) at high dose rates. These consists in either:

- the addition of a 3kOhm resistor in the converter module, that ensures a path to ground to the amplified leakage current and prevents the voltage transient
- the reduction of the input voltage during the disable/enable sequences, that reduces the maximum voltage of the transient
- the avoidance of the disable/enable sequence during operation. In case of need, the converter can be turned off by a power cycle, although this is not a very elegant alternative
- the reduction of the DC input voltage of the module during regular operation at least below 8V. This has to be seen as a mitigation technique only, because there is no data with statistical significance certifying that the converters are 100% safe in this case.

A revised version of the ASIC, FEAST2.2, was designed at the beginning of 2018. Although at the time the failure was still a mystery, the modifications dictated by educated intuition turned out to be very effective in rendering the circuit more robust agains TID-induced effects as well as ESD discharge events. During X-ray exposures, no voltage transient was observed at either room T or at -30°C when the dose rate was below 180krad/hour (almost 2 orders of magnitude above the rate in the CMS pixel system). FEAST2.2 will hence replace version 2.1 as production-ready converter ASIC.

With more than 60,000 FEAST2.1 converters already distributed to the LHC detector teams in view of system upgrades, it was vital to reach a conclusion on the possible risks associated to their use. Most or all of these converters will be installed in detector systems where the radiation background is considerably milder than in the pixels. X-ray irradiation tests as well as a second run at the IRRAD facility, during which 64 modules were exposed, indicated that the converters are safe when the dose is below 500krad - with quite some margin.

This very concise summary is complemented by a full report "Summary of measurements on FEAST2 modules to understand the failures observed in the CMS pixel system" available for download at http://project-dcdc.web.cern.ch/project-DCDC (under the tab "publications -> reports").