Development of a Radiation-Tolerant Component for the LHC Quench Protection System

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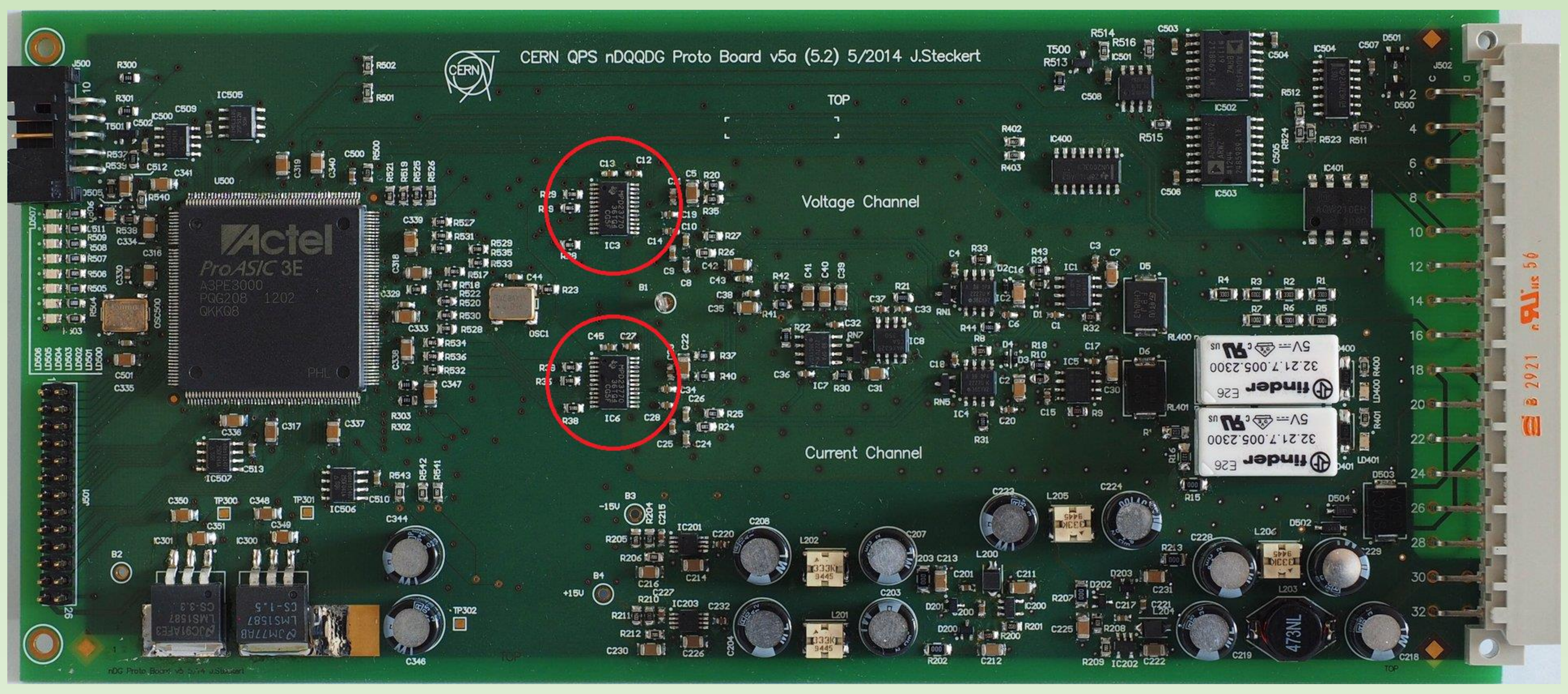
Re-design of the 600 A Quench Protectors (QPS)

In the course of the upgrade of the Large-Hadron-Collider (LHC) to its high luminosity state many electronics components have to be re-designed to cope with the new level of radiation. From 2010 to 2011 the percentage of premature beam dumps caused by the radiation impacting the magnet powering system rose from 35% to 46%. In the future to prevent a further rise in unnecessary down time all subsystems of the magnet powering system, including the QPS, have to be upgraded before the luminosity increase. The 600 Ampere Quench detector is one of the parts that will need to be replaced by a more radiation tolerant component [1]. One of the crucial components for a re-design of this system is a radiation tolerant high resolution (24 bit) ADC to measure voltage and current of the magnet circuit. Currently there are no ADCs of this resolution available as radiation hardened components. Therefore and also because of the high price of such components it was necessary to find a commercial-of-the-shelf (COTS) with enough radiation tolerance to be usable in this project. The selected component was the ADS1281 [2] an ADC which was proven to be immune to latch-ups in a previous irradiation campaign [3].

Radiation Test on the ADS1281

The new 600 A board was tested for using the 230 MeV Proton beam at the Paul-Scherrer Institute (PSI).



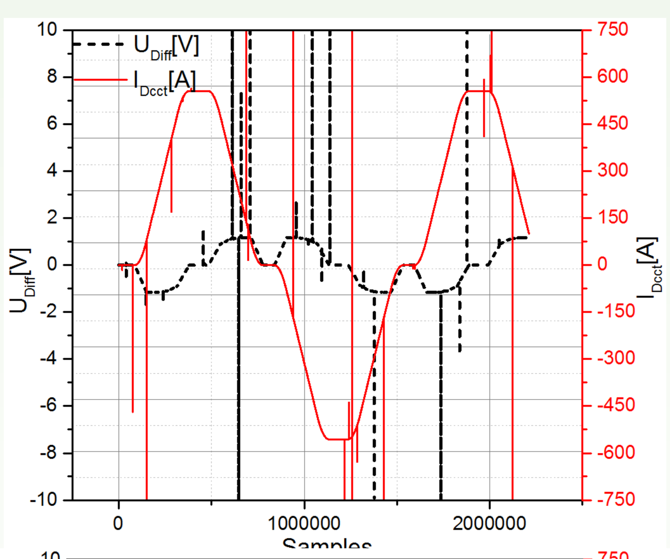
The PSI beam consists of protons with an energy of 230 MeV and a flux of $1.7 \cdot 10^{8}$ p $\cdot$ s^{-1} $\cdot$ cm^{-2} . The dose rate was 0.09 Gy $\cdot$ s^{-1}.

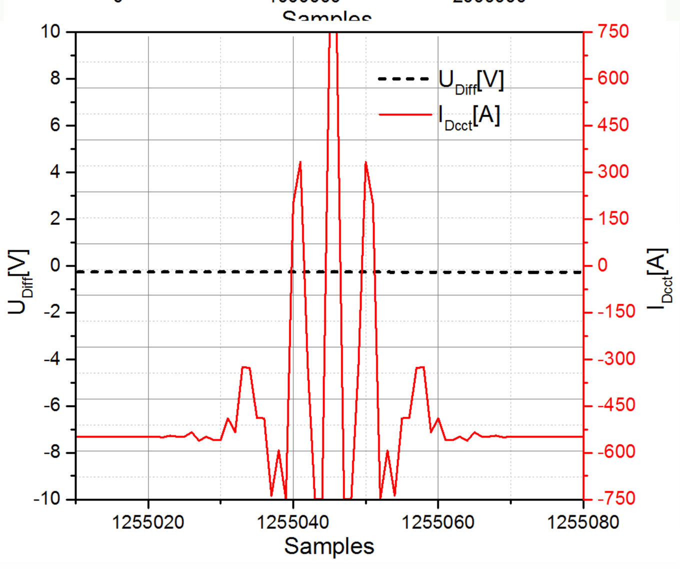
Three boards equipped with two ADCs were tested consecutively. During irradiation either a sine wave or a simulated magnet signal was sampled by the ADCs with a frequency of 4 kHz. The complete data stream was read out for later analysis.

In course of the measurement 3 boards were irradiated each with a dose of about 600 Gy.

Observed Failure Modes

The analysis of the readout data showed 4 different failure modes:

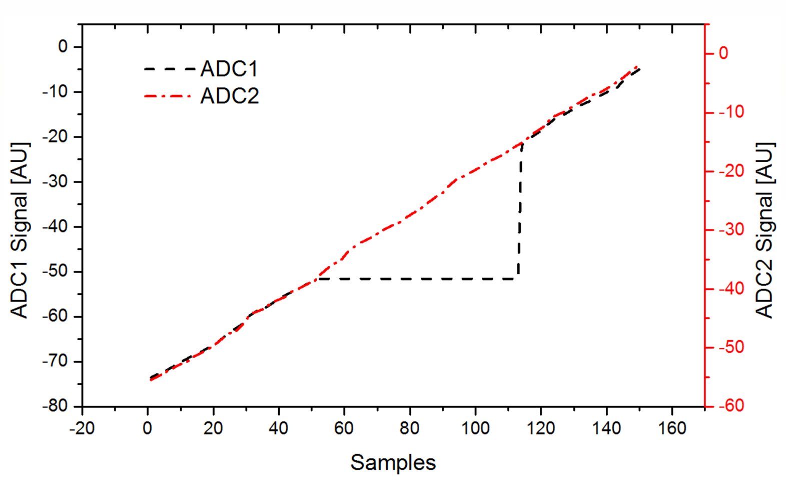


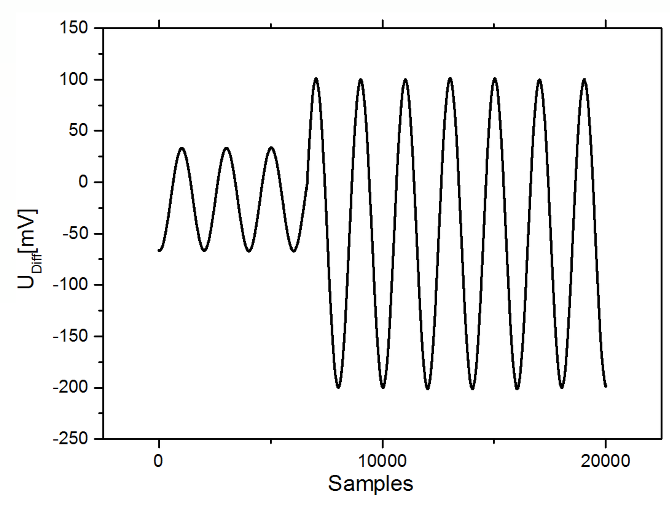


As seen in the first figure the read out signal is distorted in many places. The most frequent error mode is a single sample with very different value than the surrounding samples. Second most frequent were distortions of the signal spanning for several consecutive samples like the one shown in the second figure. These disturbances had a roughly constant duration of 60 samples.

Less frequently observed were occasions were one of the two ADCs stopped to produce new samples for some time. Most of these stops had a length of about 63 samples but some were as long as 2-3 minutes (>500,000 samples).

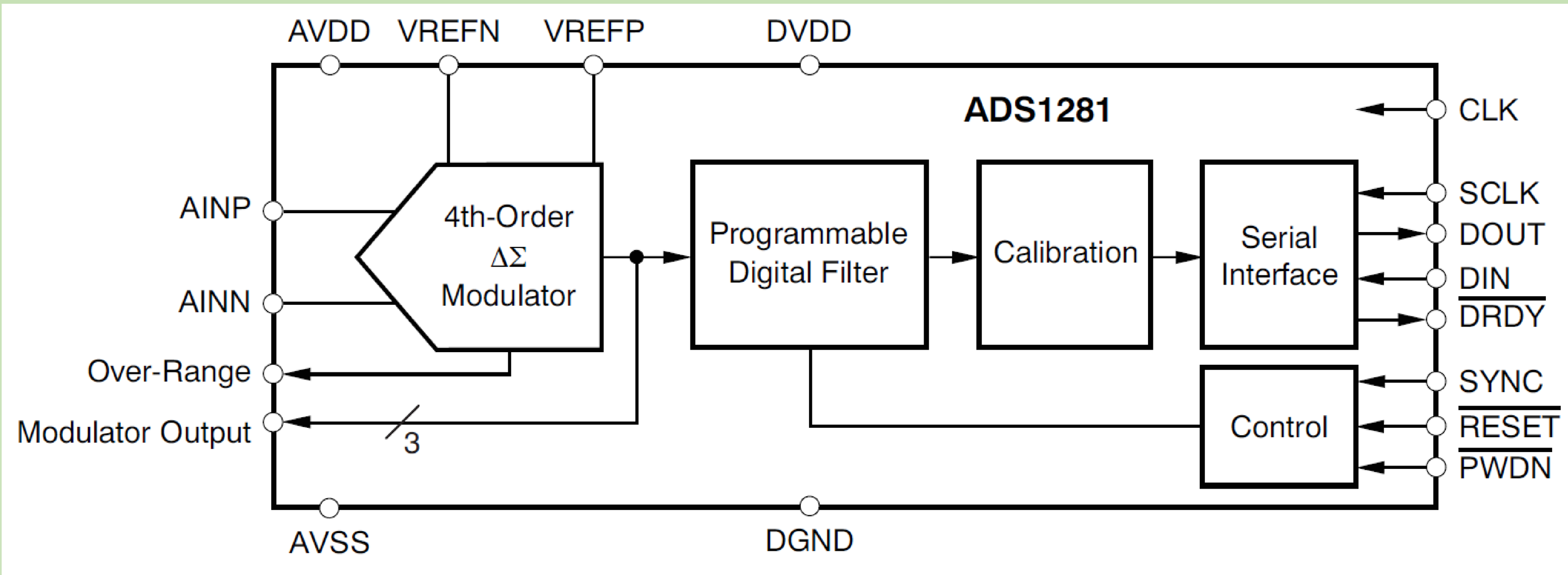
Two times during measurement the gain of the signal changed and stayed that way until restart of the ADC.





Error Analysis

Distortions in the readout signal are flipped bits in the data word propagating inside the ADC caused by SEUs. If the SEU occurs before the digital filter stage the error is spread over multiple consecutive samples while if it occurs after the filter it appears as only one single sample. Changes in gain or offset are caused by SEUs in the configuration registers inside the calibration stage of the ADC. Finally stops of the ADC are caused by SEFIs inside the Delta-Sigma-modulator stage.



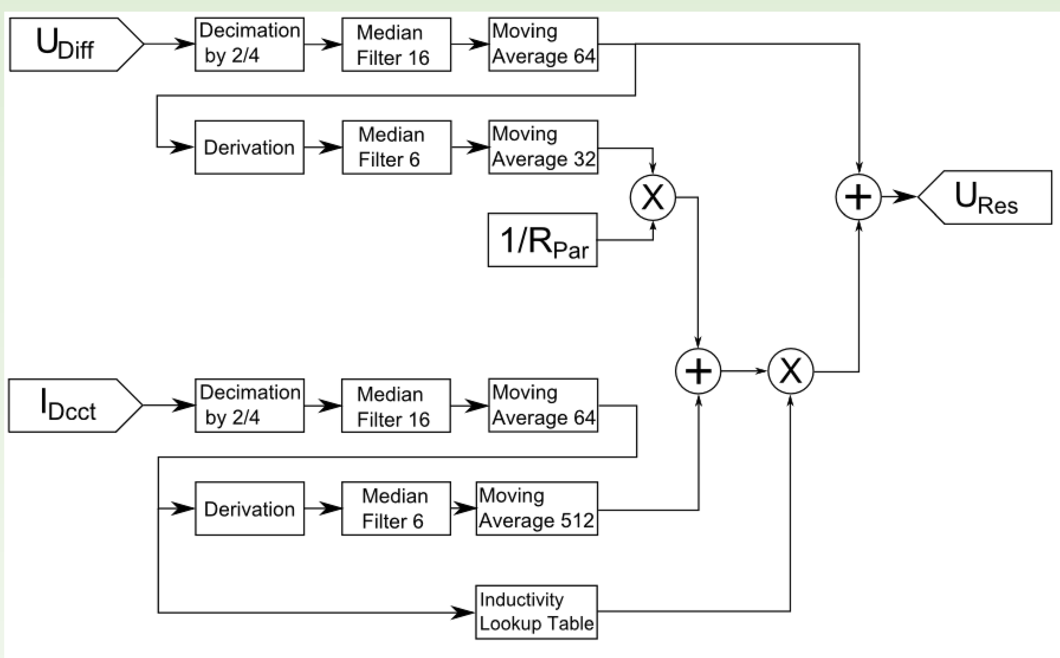
The table below shows the counts of all 4 failure modes. By comparing these counts with the dose over which they were counted a statistical probability for each error mode in relation to the dose was calculated.

	Error Count	Fluence in P·cm^{-2}	Dose in Gy	Error Rate in Gy^{-1}
Single Sample	191	$1.718 \cdot 10^{12}$	1000	0.191
Multi Sample	97	$1.718 \cdot 10^{12}$	1000	0.097
ADC Stops	35	$5.804 \cdot 10^{12}$	3378	0.0104
Gain or Offset	2	$5.804 \cdot 10^{12}$	3378	0.0006
Combined				0.299

In total one ADS1281 ADC will cause one error every 0.3 Gy.

Mitigation Measures

The 600 A QPS will consists of 200 boards with two ADCs each. In the R-R sections of the LHC were the cards will be mounted a yearly radiation exposition of at least 1 Gy is to be expected. The combined error rate of the whole system is therefore about one error every 3 days. Since every of these errors could lead to a trigger in the QPS which would lead to a premature beam dump this error rate is not acceptable.



$$U_{res} = U_{diff} + L(i)\left(\frac{dI}{dt} + \frac{dU_{diff}}{dt} * \frac{1}{R_{PAR}}\right)$$

To suppress these error modes several mitigation measures were implemented. To mitigate SEU distorted samples an array of digital filters was included into the algorithm. The base function of the algorithm is to compute the expected voltage in a magnet circuit and compare it with the measured voltage. Disturbances in U_{Res} above a certain threshold would trigger the QPS.

A combination of decimating the input signal, median filters and moving average filters is able to either eliminate or sufficiently suppress single and multi sample errors.

In case of the corruption of the configuration registers of the ADC it is necessary to constantly check the contents of these registers. The settings are read out over the SPI interface of the ADC and if corruption is discovered the correct settings are re-written onto the ADC.

ADC stops have to be mitigated using two different methods. Most stops are short enough to not impede the functionality of the QPS. The algorithm was changed so no triggering will occur until the restart. However due to the existence of longer stops it is necessary to activate a hardware power cycle of the ADC as soon as a stop is detected. A power cycle using the power down pin of the ADC is not sufficient. The algorithm does not trigger until the power cycle is finished.

Conclusions

The ADS1281 has proven to withstand doses up to 600 Gy without damage. Several failure modes caused by SEEs were found but it is possible to mitigate those nearly completely. The device is therefore a viable component for use in the R-R areas of the LHC with a dose rate of a few Gy every year. In case of usage in with higher flux other options, like the usage of an oversampled lower resolution ADC, should be considered.

References

[1] R. Denz, K. Dahlerup-Petersen, A. Siemko, J. Steckert, "Upgrade of the Protection System for the Superconducting Elements of the LHC during LS1", MT23, Boston, July 2013.

[2]Texas Instruments High-Resolution Analog-to-Digital Converter ADS1281 http://www.ti.com/lit/ds/symlink/ads1281.pdf

[3] Slawosz Uznanski, Benjamin Todd, Arend Dinius, Markus Brugger ADS1281: SEL/SEFI test set-up and cross section evaluation, Oct. 2013