Investigation of Radiation-Induced Effects in a Front-end ASIC Designed for Photon Counting Sensor Systems

Romanian LHCb Group

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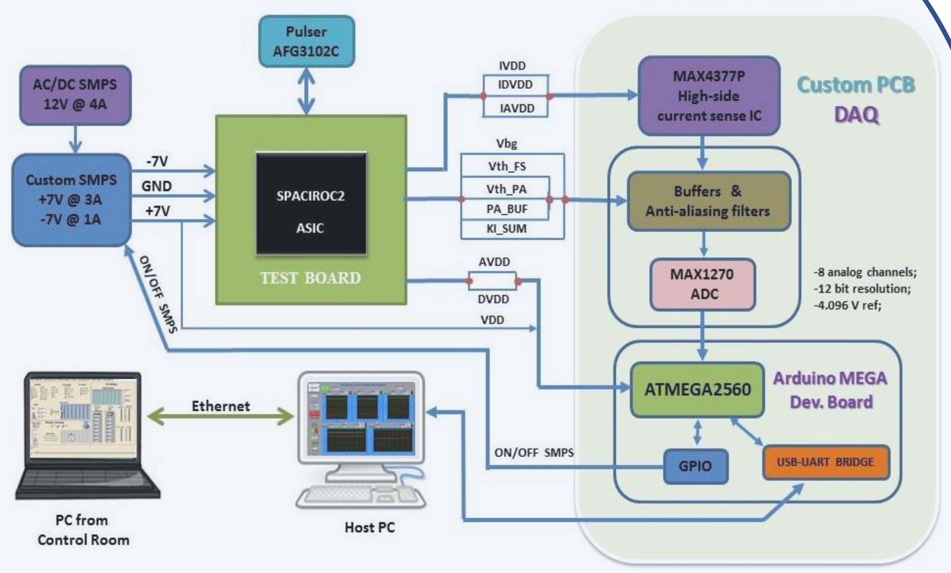
Introduction

- The Spatial Photomultiplier Array Counting and Integrating Readout Chip (SPACIROC) is a mixed signal and full readout front-end ASIC:
  - Designed by Omega Microelectronics Center from Ecole Polytechnique;
  - 0.35 µm SiGe BiCMOS technology;
  - 100% trigger efficiency at very low charge (50 fC ~ 1/3 photoelectron charge);
  - Radiation tolerant (TMR in configuration registers);
  - Device Under Test (DUT): SPACIROC2; (prototype version)
- Proposed for JEM-EUSO mission onboard at the International Space Station (ISS);
  - A very similar ASIC, the MAROC3, was considered as a backup ASIC for the LHCb experiment for the *Upgrade Phase Ia*;
- A custom experimental setup was designed to measure and to characterize the functionality of the DUT while exposed to a radiation environment equivalent to the following case:
  - Space experiments (e.g. JEM-EUSO at the ISS);
  - Accelerator/LHC experiments (e.g. LHCb at the LHC from CERN);
- Different particle beams were used to measure the DUT radiation tolerance:
  - 35 MeV and 200 MeV protons; (Juliech FZJ and PSI)
  - Ions with Linear Energy Transfer (LET) from 2.85 to 11.2 MeV · cm^2/mg; (Legnaro LNL);
  - 8-50 KeV X-ray photons; (Padova University)
- JEM-EUSO expected radiation environments (~ 5 years of operation):
  - TID: ~1 krad;
  - Dose rate: ~6 · 10^{-6} rad/s;
  - LET: in range of 0.01 MeV·cm^2/mg and 40 MeV·cm^2/mg;
- LHCb-RICH during *Upgrade Phase Ia* expected radiation environments (~7000 h of operation):
  - TID: ~200 krad;
  - Dose rate: ~8 · 10^{-3} rad/s;
  - HEH fluence: ~1.2 · 10^{12} HEH/cm^2;
  - LET: < 15 MeV·cm^2/mg;

1. S. Ahmad et al., *"SPACIROC2: a front-end readout ASIC for the JEM-EUSO observatory"*, Journal of Instrumentation, vol. 8, no. 01, pp. C01006–C01006, Jan. 2013, JINST 8 C01006
2. V. M. Placinta, L. N. Cojocariu, and C. Ravariu, *"Test Bench Design for Radiation Tolerance of Two ASICs"*, Romanian Journal of Physics, vol. 62, no. 903, p. 12, 2017, link
3. V. M. Placinta , L. N. Cojocariu , C. de la Taille, S. Blin Bondil, S. Mattiazzo, L. Silvestrin, A. Candelori and F . Maciuc, "*Radiation effects in a SPACIROC2 ASIC and long-term reliability*", Journal of Instrumentation, vol. 16, July 2021, JINST 16 P07028

Testing Results

- Several parameters were monitored:
  - Power consumption (analog + digital blocks);
  - Internal voltage reference;
  - DACs output voltages and their linearities;
  - Trigger efficiency measurements;
  - Slow control registers readback (the output of TMR voter) for SEU detection (without configuration);



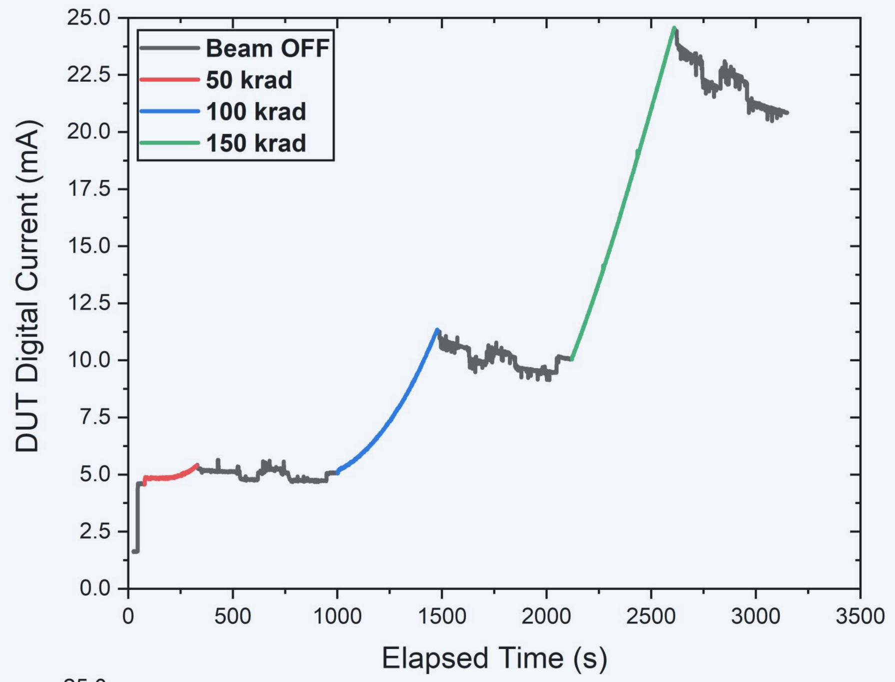
Test Bench

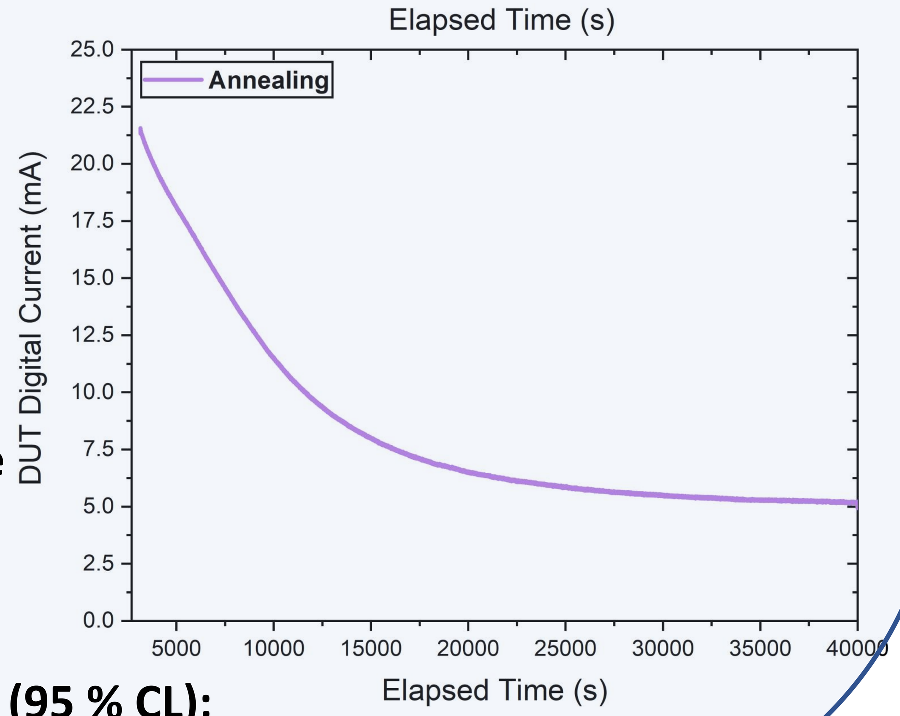
Results with ions beam:

- SEU threshold: between (4.5 ± 0.45) MeV · cm^2/mg and (8.6 ± 0.86) MeV · cm^2/mg;
  - All SEUs were mitigated by a full reconfiguration;
- No SEL was observed up to an LET of (11.2 ± 1.1) MeV · cm^2/mg;
- SEU cross-section for (8.6 ± 0.86) MeV · cm^2/mg: between 0.16 · 10^{-6} cm^2/DUT and 7.23 · 10^{-6} cm^2/DUT; (95 % CL)
- SEU cross-section for (11.2 ± 1.1) MeV · cm^2/mg: between 0.16 · 10^{-5} cm^2/DUT and 1.5 · 10^{-5} cm^2/DUT; (95 % CL)

Results with 35 MeV protons beam:

- Maximum fluence of (6.9 ± 0.33) · 10^{11} protons/cm^2 that corresponds to a TID of ~150 krad (Si);
  - Delivered in three runs of 50 krad each with different dose rates: 200 rad/s (first 50 krads) and 100 rad/s (for the rest);
- Threshold TID from where the TID induced leakage current is visible:
  - 70 krad for the analog block;
  - 20-25 krad for the digital block;
  - 12 krad for the slow control block;
- DACs showed loses of their linearity (monotonicity) starting with 50 krad delivered TID:
  - Complete failures after 150 krad;
- Trigger efficiency (S-curves) failures were observed starting with 50 krad delivered TID:
  - Corelated with DAC failures;
  - 4 DAC units shift to a lower region after 50 krad;
  - Complete failures after 150 krad;
- Partial recovery-already after 10 h of room-temperature annealing;
- No SEUs nor SELs were observed:
  - Upper limit of SEU cross-section: 0.6 · 10^{-11} cm^2 /DUT (95 % CL);





Results with 200 MeV protons beam:

- Maximum fluence of (2 ± 0.3) · 10^{12} protons/cm^2 that corresponds to a TID of ~100 krad (Si);
  - Delivered to three samples with 100 krad each and different average dose rates: 34 rad/s, 60 rad/s and 63 rads/s;
- No SEL was seen, however few SEUs were observed:
  - Lower limit of SEU cross-section: 0.32 · 10^{-12} cm^2/DUT (95 % CL);
- Same failures were observed in DACs and in the trigger efficiency measurements:
  - Recovered completely after one week of annealing;

Results with 8-50 KeV X-rays beam:

- Up to 117 krad delivered TID with a dose rate of 330 rad/s;
- Confirmed the TID effects seen in the proton beams;
  - Indication of DUT recovery onset was observed after 1 h of room-temperature annealing;

Conclusions

- No SEL was observed up to an LET of (11.2 ± 1.1) MeV · cm^2/mg:
  - The threshold LET is above this value and has to be further investigated in future irradiation test beams;
- The threshold LET for SEU in configuration (slow control registers) was measured, and the observed SEUs seem to not do any permanent damage to the DUT:
  - Mitigated by a full reconfiguration of the DUT and without power cycle;
- Expected to operate with very low error rates (if any) in the JEM-EUSO radiation environment;
  - Experiment dose rate is very low compared with the 150 krad/h in our experiment, hence no cumulative/TID effects are expected;
  - There is still an open question for high-Z (high-LET) cosmic rays which may cause SEE in triplicated registers or SELs, but in essence no SEEs are expected in the triplicated ASIC registers, and the very low SEL probability makes it easy to mitigate or even ignore;
- In the LHCb-RICH radiation environment (for 50 fb^{-1}), DUT would operate with very low error rates (if any) and no TID effects should be expected.