ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano–Bicocca

INFN-23-32 MIB
December 19, 2023

Heavy-ion test report of LTC1668 DAC
LiteBIRD-NOTE-84

A. Cotta Ramusino[8], S. Della Torre[2], L. Galli[4], A. Limonta[1,2], R. Malaguti[8], D. Nicolò[3,4], G. Signorelli[4], L. Silvestrin[5,6], F. Spinella[4], A. Tartari[3,4], M. Tessaro[5,6], J. Wyss[6,7] and M. Zannoni[1,2]

[1)] *Dipartimento di Fisica dell'Università di Milano Bicocca,*
[2)] *INFN, Sez. di Milano Bicocca, Milano, Italy*
[3)] *Dipartimento di Fisica dell'Università di Pisa and* [4)] *INFN, Sez. di Pisa, Pisa, Italy*,
[5)] *Dipartimento di Fisica dell'Università di Padova and* [6)] *INFN, Sez. di Padova, Padova, Italy*
[7)] *Dipartimento di Ingegneria Civile e Meccanica, Università di Cassino, Italy*
[8)] *INFN Sez. di Ferrara, Ferrara, Italy*

Abstract

This document presents the results of a heavy-ion test program carried out on the Linear Technology LT1668 16-bit 50 Msps DAC (LTC1668IG) to identify single-event effects. In particular, it was studied the detection of single-event latch-up (SEL), single-event upsets (SEU), and single-event transients (SET) due to heavy-ions radiation. The tests were performed at the heavy-ion facility Tandem-ALPI at INFN Legnaro National Laboratory (Italy) in February 2021 and June 2022 for a total irradiation time of ∼51 hours.

PACS:61.80.-x, 61.80.Jh

Published by
Laboratori Nazionali di Frascati

Contents

1 Applicable and reference documents

1.1 Applicable documents

none

1.2 Reference documents

1. ESCC Basic Specification no. 25100
2. ECSS-Q-ST-60-15C Space product assurance — Radiation assurance for EEE components
3. ECSS-E-ST-10-04C Description of space environment.
4. LiteBIRD note 056: “Guidelines for radiation test on the ground”
5. Radiation tolerance tests for DAC LTC1668 (companion paper)
6. J. Wyss et al, “SIRAD: an irradiation facility at the LNL Tandem accelerator for radiation damage studies on semiconductor detectors and electronic devices and systems”, Nucl. Instr. Meth. A 462 (2001) 426

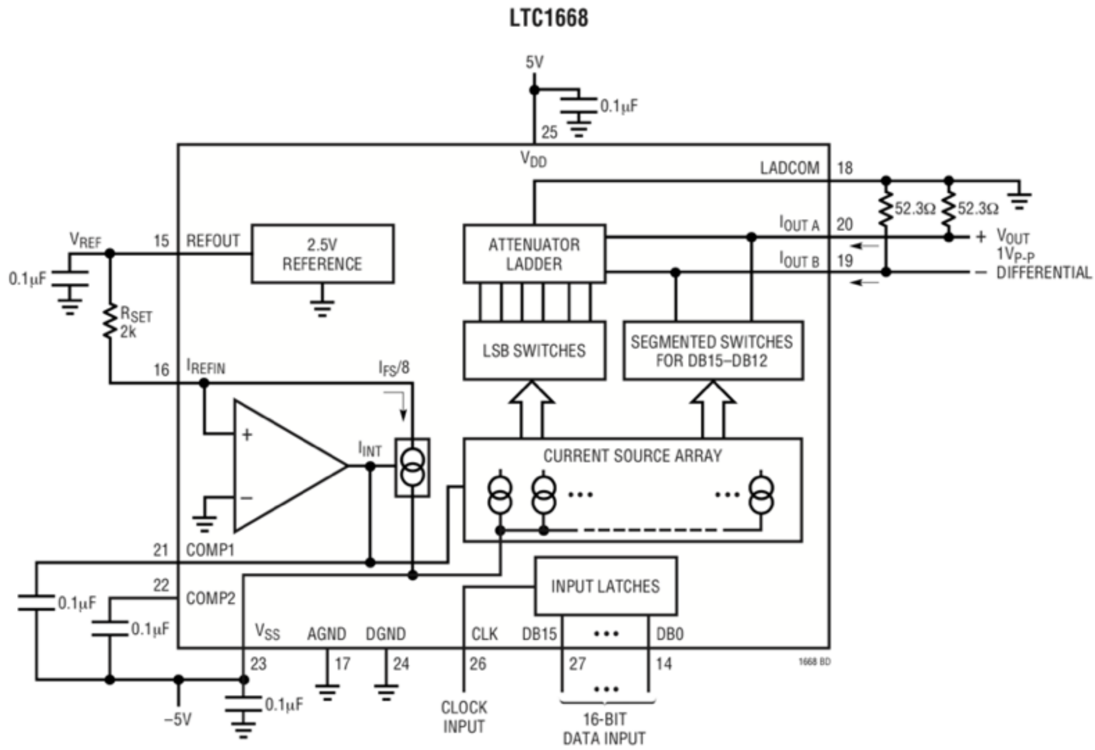
2 Device Information

2.1 Description of LTC1668

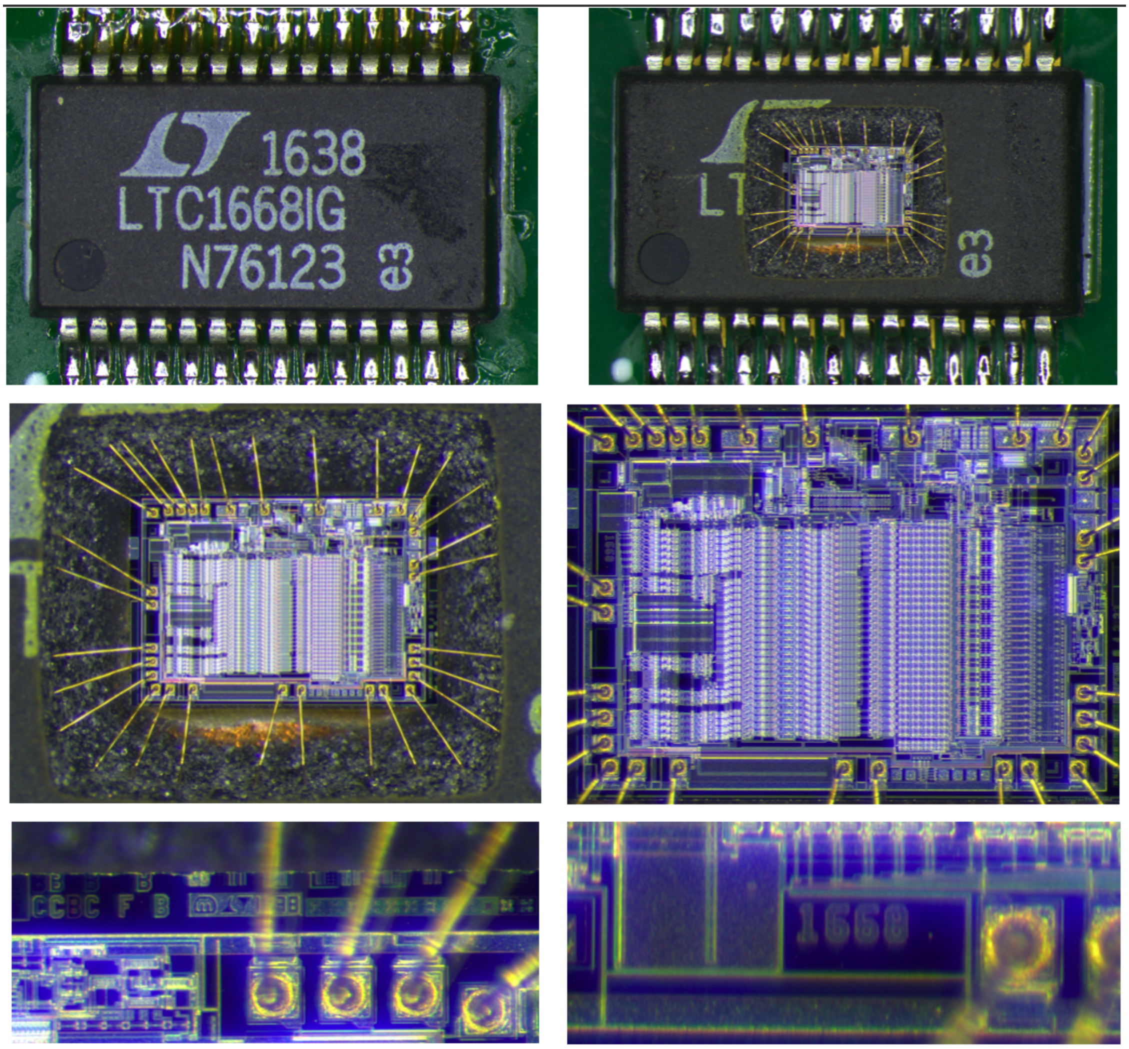
Part description:	LTC1668IG 16-bit, 50Msps DAC
Manufacturer:	Linear Technology
Package:	28-pin SSOP
Technology:	BiCMOS
Samples used:	Tested four samples out of a batch of ten.

2.2 Component schematics

We reported in the draw below the schematic of the device under test.



3 Sample identification



Die area: 2 mm $\times$ 2.95 mm = 5.9 mm^2

4 Test set-up

4.1 Test facility

4.1.1 Beamline

The SEE experiment was performed with the *Tandem-ALPI* beam at INFN Legnaro National Laboratories (Italy) with a cocktail of ions ranging in LET from 12,5 MeV cm^2/mg to 82.5 MeV cm^2/mg. Among the ions that can be accelerated by the facility, four ions have been used (Cl-35, Ni-58, Ag-107, and I-127) to span the desired LET range in the beam time allocated. Moreover, the devices under test have been rotated through several angles to increase the *Effective LET*[1].

Ion	Energy (MeV)	Range in Si (μm)	LET in Si (MeV cm2 /mg)
^{35}Cl	160*, 171**	46, 49.71	13.05, 12.68
^{58}Ni	220	37.03	29.36
^{79}Br	228	31.2	41.96
^{107}Ag	266	29.03	58.39
^{127}I	249*, 276**	27.74, 29.53	63.66, 65.37

*Energy value of the beam during the 2022 campaign

**Energy value of the beam during the 2021 campaign

4.1.2 Test chamber

Irradiation is performed in a vacuum chamber equipped with a movable and tiltable stage that allows the alignment of the DUT with the ion beam. The position and tilt of the DUT are monitored with a CCD camera looking inside the vacuum through a set of mirrors. A laser beam is used to align the various DUTs with the beam. At the same time, dedicated software allows recording the encoder data to re-position all DUTs correctly after the vacuum chamber has been closed. Vacuum feedthroughs (high-density and coaxial) are available to carry the signals out of the chamber. A picture of the test chamber with our detectors installed is shown in Figure 1.

4.1.3 Beam quality control and dosimetry

The DUT region is surrounded by four PIN diodes that count the number of impinging ions during irradiation to estimate the received flux. A second set of four PIN diodes can be placed in place of the DUT at any time to cross-check the total flux. The beam homogeneity is guaranteed by de-focusing the beam. A flux of 10^3 to 10^5 ions/cm^2/sec is available. A beam blocker ensures the correct timing of the irradiation of the DUTs. The real-time ion flux and the total fluence are recorded by the system and stored together with the accelerator parameters.

[1] L. Silvestrin et al., "Status and prospects of the SIRAD irradiation facility for radiation effects studies at LNL," 2013 14th European Conference on Radiation and Its Effects on Components and Systems (RADECS), 2013, pp. 1-4, DOI: 10.1109/RADECS.2013.6937371.

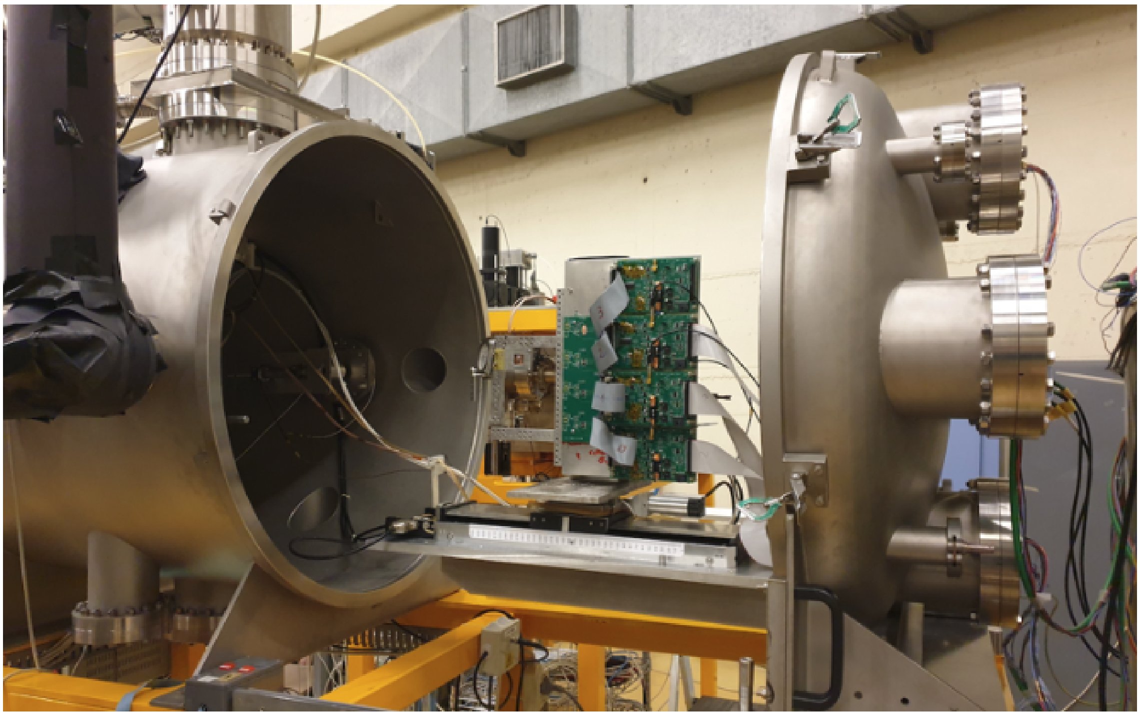


Figure 1: Test chamber at LNL SIRAD facility with the board hosting 4 DUTs installed.

4.2 Test system

The testing apparatus is based on an ArriaV GX FPGA (a GEMROC board that was developed within the framework of the BESIII experiment) that operates at 166 MHz. It is coupled with customized transition boards that facilitate the interface between the current output of the LTC1668 and the input ADCs. The system implements the high-resolution readout of four independent currents/voltages at 24 bits at 26kHz, and a lower-resolution readout of device currents and temperatures. This high-resolution, slow ADC, is used to detect SEL and SEU. The transition boards send a copy of each of the four DAC outputs to a digital scope read out at 50 MHz to detect transients (SET). The 16-bit digital scope features a sampling rate of 62.5 MS/s, with a maximum temporal resolution of 16 ns/bin. The system allowed us to be sensitive to 15 bits out of 16 with the high resolution, low-speed ADC, while 10 bits out of 16 with the low resolution, high-speed one.

4.3 Test principle

The LTC1668 has been tested with a ±5V power supply. During irradiation the contents of the irradiation registers were frozen, i.e. the input of the DAC was held constant, the CLK was stopped, and the output was digitized at 24 bits with a 16kHz rate. **The latch-up** was identified by monitoring the positive and negative current drawn by the DUT. The typical behavior of the DUT current is shown in Figure 3. During normal operation, the DUT draws I_p = 32 mA and I_n = 2.7 mA. A sudden current increase was attributed to a latch-up. At this point, the current was monitored and recorded for a few

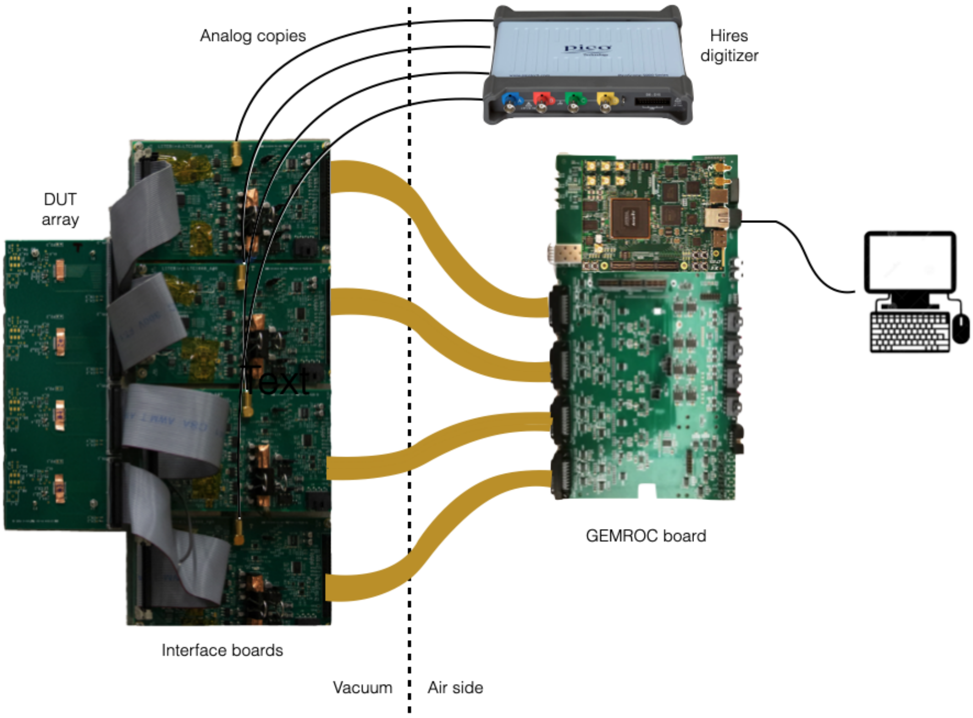


Figure 2: Schematics of the test set-up

seconds, after which the DUT was switched off, waited for 10 to 20 seconds according to the test conditions, and switched on again. The setup allowed the distinction between the **transient** errors (glitch at the device output) and the permanent errors (Single Event **Upset** in the device registers). A static digital input has been applied during the irradiation (about mid-scale, DUT output=2V). With this setup, we have been able to test the 15 (9) most significant bits out of the 16-bit device resolution for SEU (SET) respectively. Upsets or transients are identified by changes in DAC output: SEU is defined as a definite change of output, identified using the high-resolution, low-speed, DAC; SEL is defined as glitches in the output observed with the lower resolution, high-speed, ADC. The data stream of the high-resolution ADC is written to a file which is eventually analyzed offline, while the digital-scope-based high-speed DAQ is triggered whenever the DAC level exits a window centered around the mean output voltage. Since the average output level can change following SEUs, the average level is continuously monitored by a moving-average algorithm, which also computes the signal RMS. A transient is triggered whenever the signal exits a 5σ window centered around the moving average. A 2240 μs sample is therefore recorded to disk.

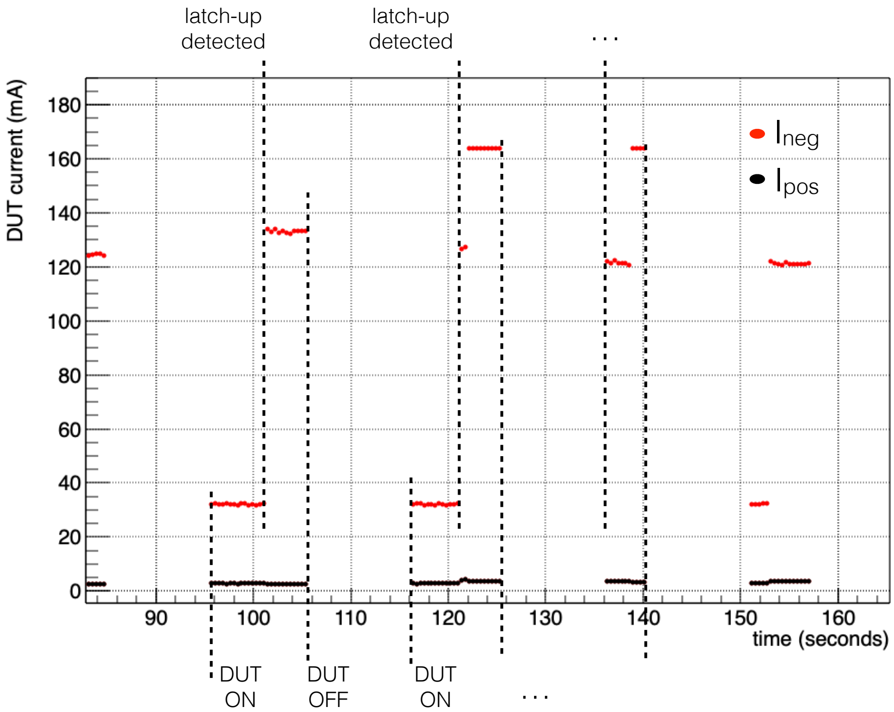


Figure 3: Typical behaviour of positive and negative current of LTC1668 during irradiation.

5 Test condition

Each DUT received, at the end of the campaign, a minimum irradiation fluence of $\sim 7.5 \times 10^5$ cm^{-2} from at least two different ions covering a LET range from 12 to 85 MeV cm^2 mg^{-1} (see section 6.1). The flux was kept constant in the range 3×10^4 to 4×10^4 cm^{-2}s^{-1}. We monitored positive and negative currents, reference voltage, and DUT temperature. The DUTs were tested at room temperature, i.e. the temperature they reached in the vacuum when switched on. This turned out to be in the range of 28 to 35 °C (see Figure 4). Trigger follows different strategies according to the different SEE observed. A typical sequence of data acquisition with both SELs and SEUs visible is presented in Figure 5.

SEL

A latch-up was triggered with the following parameters:

- Negative or positive threshold 40 mA;
- Temperature threshold 50°C;
- Hold time $\sim$4 sec (the time before switching off the DUT);
- Detector re-armed after 10 sec.

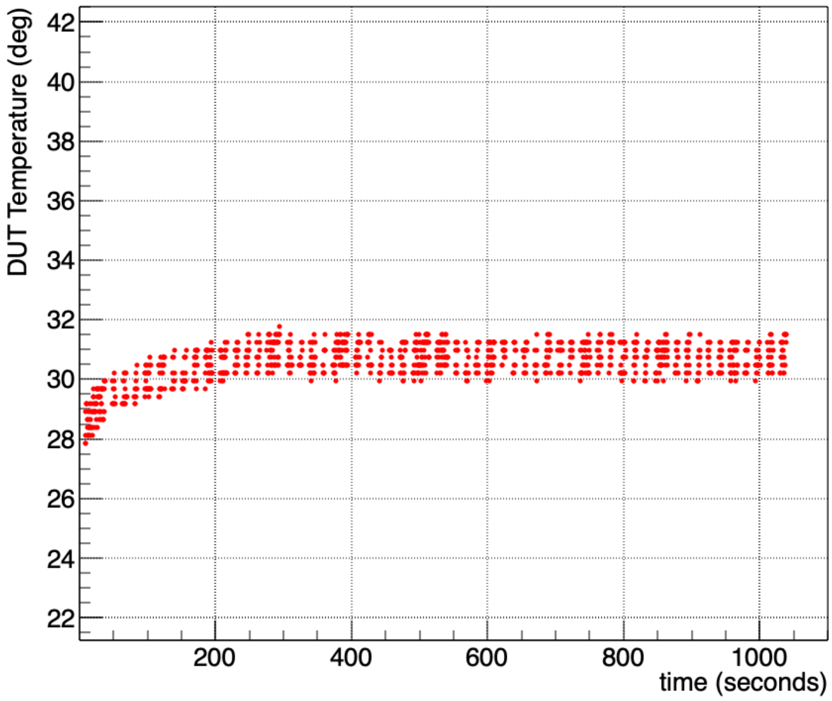


Figure 4: Typical temperature of a DUT during the test. The DUT is switched on at t=0.

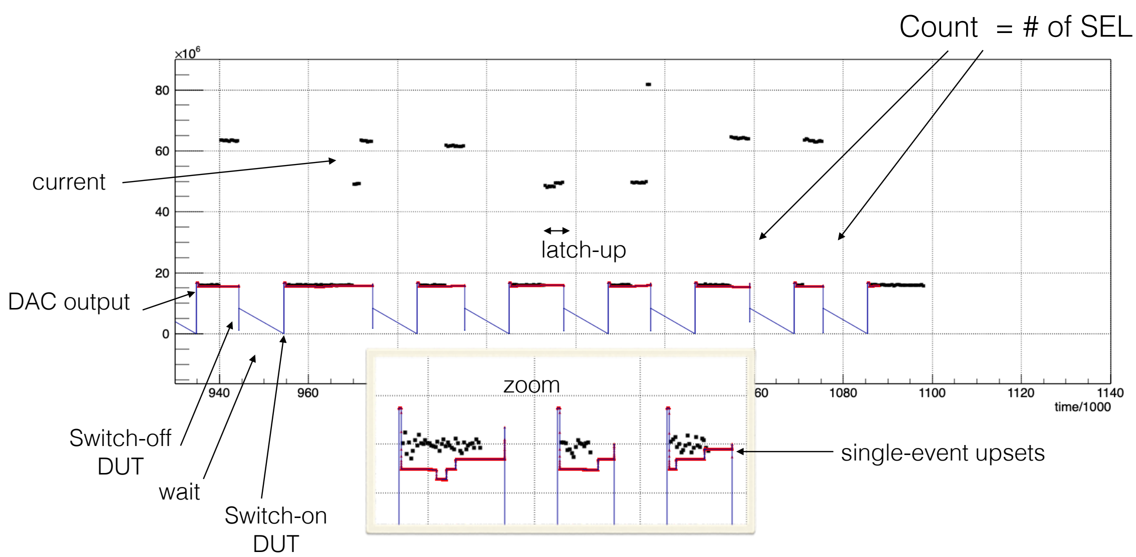


Figure 5: Typical sequence of data acquisition during one test run.

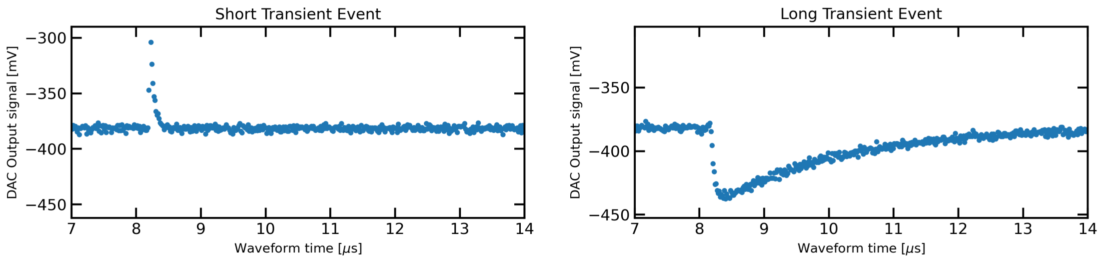


Figure 6: Examples of transient events recorded during the test.

SEU

The DAC pattern was alternatively programmed with the content 0xA5A5 or 0x5A5A, for which the output of the DAC was set at the mid-range of the high-resolution ADC. Heavy-ion Event Upsets were recognized offline by analyzing the DAC output data stream and identifying the sudden changes in the DAC level. The RMS of the 24-bit ADC readout was $\sim$100 ADC counts while the total span of the DAC as recorded by the ADC was $\sim$0x61A800 corresponding to 23 bits. We were then effectively sensitive to 15 out of 16 bits of the DAC.

SET

Single Event Transients are detected using a 16-bit digital scope receiving one copy of the DAC output. The trigger logic is set when the DAC signal exceeds a window of $\pm 5\sigma$ on a moving baseline (calculated using the first 512 pre-trigger samples, corresponding to 8.192μs). With this exit window trigger, we could detect both positive and negative excursions. With these settings, we were sensitive also to SEUs, SELs, and spurious events. Data were re-processed offline to eliminate spurious triggers and to classify different types of transients. We found that, during the acquisition time, a high number of short transient events were triggered. These events are probably due to the tails of the noise distribution, which increase in the harsh environment of the experimental cavity. Since we are interested in long transients only, during the offline analysis we reject all events shorter than 80 ns (corresponding to 5 samples). Examples of SET events measured during the test are reported in Figure 6.

6 Test Results

The irradiation test was performed in two separate periods in February 2021 and June 2022 for a total irradiation time of $\sim$51 hours. The complete campaign involves 96 runs, considering both data acquisitions and instrument calibrations. To compute the SEE cross-sections, the number of observed events was normalized to the acquisition lifetime and taking into account the effective flux in the tilted situation. The so-obtained values were fitted using the Weibull function:

$$\sigma(L) = \sigma_f \left[1 - e^{-\left(\frac{L-L_{th}}{w}\right)^s}\right] \tag{1}$$

Where L is the LET of incident particle, L_{th} is the threshold value for producing the single event effect, σ_f is the cross-section plateau value for high LET, w and s are parameters describing the transition smoothness from threshold to high LET plateau. Results are presented in Figures 8 (SEL), 8 (SEL), and 9 (SET). For SET analysis, we discard the time in which the system was in Latch-up. Furthermore, we notice that the fast SET acquisition was affected by dead times (probably associated with data dump from the oscilloscope RAM to the computer storage disk), which occurred unpredictably. The combined effect was a systematic uncertainty that we couldn't properly assess. The run in which this problem has been identified was excluded from the analysis. Furthermore, for the same reason, we also excluded runs at high LET (i.e. the ones with a greater number of SELs) with less than 2 SET occurrences. This also explains why data points are sparser and more scattered in Figure 9 than in Fig. 8 and 7. Nevertheless, a threshold value of LET, together with plateau values of $\sigma(L)$ never exceeding 2×10^{-4} cm^2, can be neatly spotted. The fit proposed in Fig. 9 was evaluated with an iterative procedure where, at first, all parameters of the Weibull function were free; then we fix w and s parameters while performing again the fit and exploring the 2σ band. In the same figure, we define as the *safety threshold* the result of the Weibull fit considering σ_f and L_{th} values in the worst 2σ case. Using the computed cross-section, we estimated the number of events per device per day (see table 1) that could be statistically experienced during the on-orbit operations for three different conditions: i) during a solar minimum, ii) during a solar maximum, and iii) during the worst day. The three cases cover respectively: i) the pessimistic scenario (i.e. the highest galactic cosmic rays flux intensity), ii) the optimistic scenario (i.e. the lowest galactic cosmic rays flux intensity), and, finally, iii) the scenario for 18 hours of exposure at the most intense SEP registered. This estimation was done using CRÈME[2] software, a set of online tools for SEE rate prediction developed in collaboration with NASA. The computed fluences in the three scenarios are then transported through 100 mils of aluminum to account for the effects due to standard shielding. Finally, the Direct-

[2]Tylka et al (1997) "CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code", IEEE Trans. Nucl. Sci., vol. 44, no. 6, pp. 2150-2160, Dec. 1997. [online] available at https://creme.isde.vanderbilt.edu/ [Oct. 2023]

	SEL	SEU	SET (safety threshold)
Solar minimum [SEE/device/day]	5.37×10^{-5}	8.41×10^{-5}	5.28×10^{-5} (2.83×10^{-4})
Solar Maximum [SEE/device/day]	1.92×10^{-5}	3.04×10^{-5}	3.36×10^{-5} (1.05×10^{-4})
SEP WORST-DAY [SEEs/device in 18 hours]	4.02×10^{-1}	6.49×10^{-1}	7.25×10^{-1} (2.33)

Table 1: Number of SEE/device/day in case of a parallelepiped with X = 2.00 mm, Y = 2.95 mm, and Z = 1 μm. In the SET column, we report in parenthesis the value using the safety threshold cross-section. For the SEP worst day the number of SEE is evaluated for an exposition of 18 hours.

Ionization-heavy-ion-Induced SEE was evaluated using the HUP module that calculates direct-ionization rates using the integral rectangular parallelepiped (IRPP) method[3].

6.1 Dosimetry

In table 2 we evaluate the total ionizing dose (TID) received during the test through the equation:

$$D = F \cdot LET \cdot 1.6 \cdot 10^{-5}. \tag{2}$$

Where D is the deposited dose in rad, F is the fluence measured in the plane normal to the beam in cm^{-2} and LET is the linear energy transfer expressed in MeV cm^{2}mg^{-1}. This formula assumes that the energy lost by the incoming particle is fully absorbed by the medium. For instance, the medium is supposed to be thick enough to fully absorb the kinetic energy of emitted delta rays and the particle energy is almost constant while traversing the absorber.

[3]This method is compliant to ECSS guidelines — ECSS-E-HB-10-12A Space engineering — Calculation of radiation and its effects and margin policy handbook (2010)

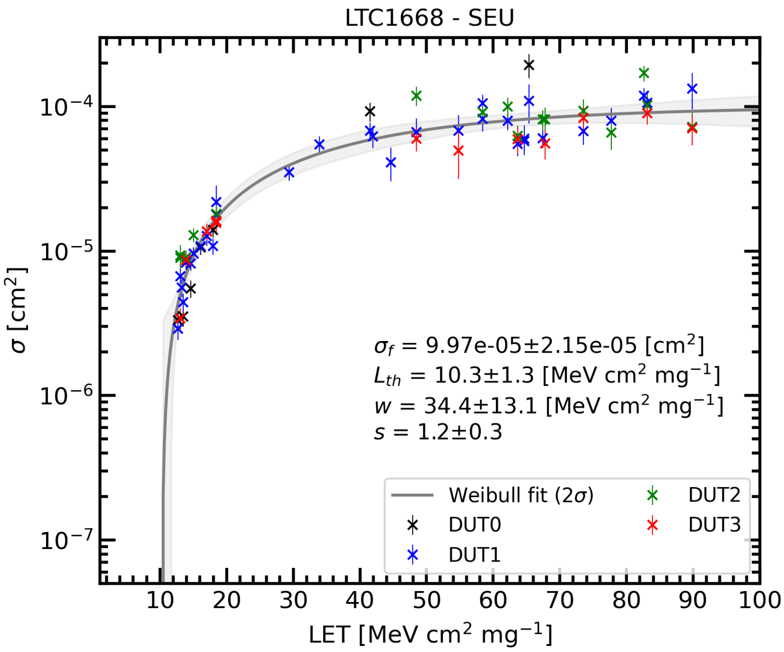


Figure 7: Single-Event Latch-up cross-section measurement for three samples of LTC1668, along with the Weibull function describing the data set.

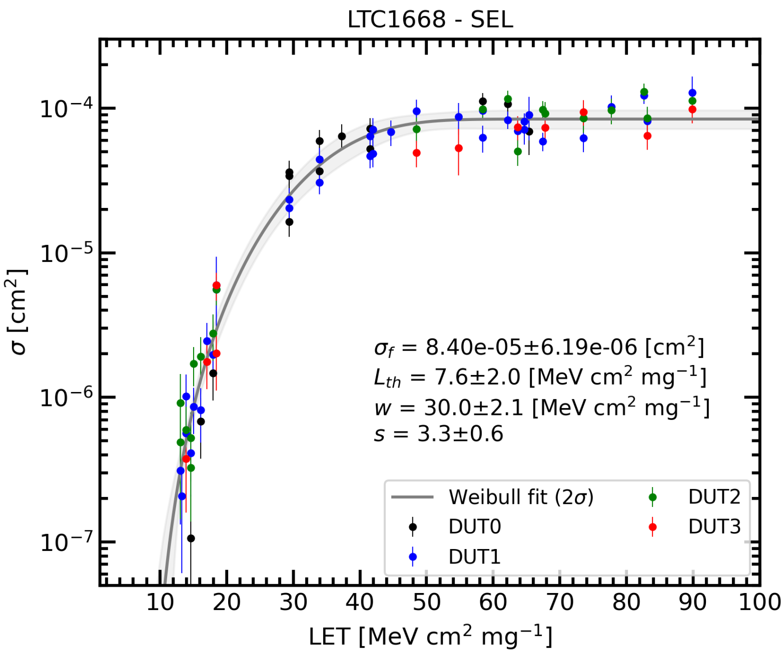


Figure 8: Single-Event Upsets cross-section measurement for three samples of LTC1668, along with the Weibull function describing the data set.

DUT	Ions	Energy [MeV]	Total Fluence [cm^{-2}]	Ionizing Dose [rad]
DUT0	Cl-35	171	6.09E+07	1.46E+04
DUT0	Ni-58	220	5.29E+07	2.74E+04
DUT0	Ag-107	266	4.96E+06	4.76E+03
DUT0	I-127	276	7.49E+05	7.84E+02
	TOTAL		1.19E+08	4.68E+04
DUT1	Cl-35	160	5.91E+07	1.37E+04
DUT1	Cl-35	171	6.02E+07	1.44E+04
DUT1	Ni-58	220	2.44E+07	1.38E+04
DUT1	Br-79	228	3.19E+06	2.30E+03
DUT1	Ag-107	266	1.17E+07	1.24E+04
DUT1	I-127	249	1.19E+07	1.27E+04
DUT1	I-127	276	4.60E+05	4.81E+02
	TOTAL		1.70E+08	6.94E+04
DUT2	Cl-35	160	3.84E+06	9.34E+03
DUT2	Cl-35	171	4.80E+07	1.22E+04
DUT2	Br-79	228	6.69E+05	5.19E+02
DUT2	Ag-107	266	8.14E+06	8.79E+03
DUT2	I-127	249	4.23E+06	5.04E+03
	TOTAL		9.94E+07	3.58E+04
DUT3	Cl-35	160	4.53E+07	1.15E+04
DUT3	Br-79	228	9.13E+05	7.31E+02
DUT3	I-127	249	3.00E+06	3.64E+03
	TOTAL		4.92E+07	1.59E+04

Table 2: Heavy Ions Fluence and Ionizing dose absorbed by DUTs during the test period

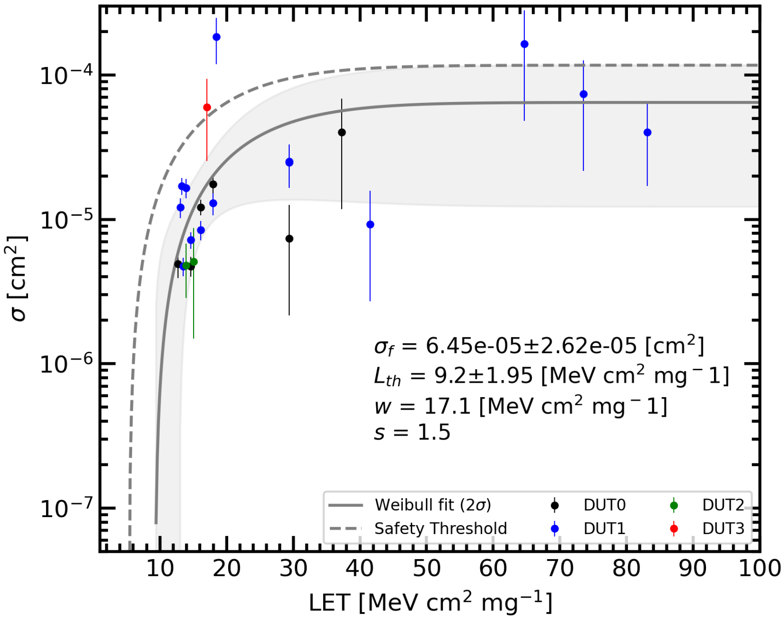


Figure 9: Single-Event Transient cross-section measurement for three samples of LTC1668, along with the Weibull function describing the data set.

7 Conclusion

We tested the 16-bit DAC LTC1668 from Linear Technology at room temperature under a beam of different ions spanning LET range from 12 to 80 MeV cm^2 mg^{-1}. The SEE test on the LTC1668 shows that the device is sensitive to

SEL: SELs have been observed at LET$>$ 14 MeV cm^2 mg^{-1}. SEL has a relatively low cross-section but cannot be considered as a rare event, therefore a suitable SEL circumvention circuitry should be implemented.

SEU: A significant number of SEUs is observed, which induces the wrong output value. The output should be reset after reprogramming the DAC registers.

SET: Numerous SETs were observed with different time characteristics and populations. They show up as a blend of short ($< 1\mu s$) and long ($> 1\mu s$) pulses. Overall, the cross-section of transient events exhibits a threshold around 10 MeV cm^2 mg^{-1}, reaching rapidly a plateau value $\leq 2 \times 10^{-4}$ cm^2.

Appendix: Total Irradiation Dose test

A preliminary total irradiation dose test was performed on a sample of LTC1668 at the gELBE facility in Dresden. In the gELBE facility photons are produced by bremsstrahlung by 17 MeV electrons hitting a 12.4 μm niobium foil, at a current of 600 μA. The energy spectrum of the photon is shown in Figure 10, and the dose rate is up to 18 krad/hour. The sample was placed in the irradiated area and a 1 MHz sinusoid spanning the full

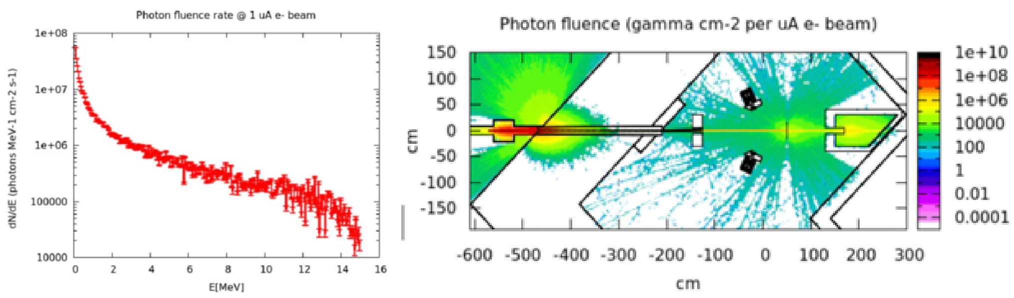


Figure 10: Photon spectrum at the gELBE facility and photon fluence in the experimental area.

DAC range was generated and recorded every 30 seconds. A 10-hour acquisition was performed, the sample being irradiated for 6.5 hours, during which the dose was monitored with a calibrated rad FET. The total dose on the DAC was found to be 70 krad. No significant decrease in amplitude nor difference in the acquired waveforms and Fourier transforms were observed. Figure 11 shows the amplitude variation as a function of the time during irradiation.

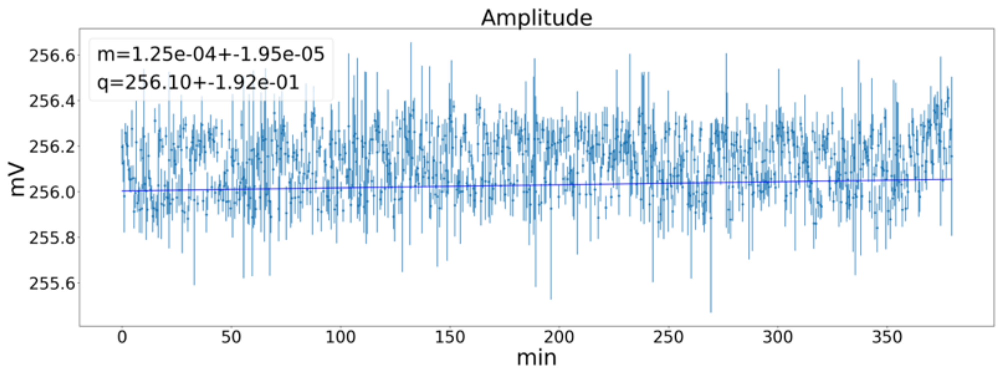


Figure 11: Amplitude of the 1 MHz sinusoid as a function of the time during irradiation