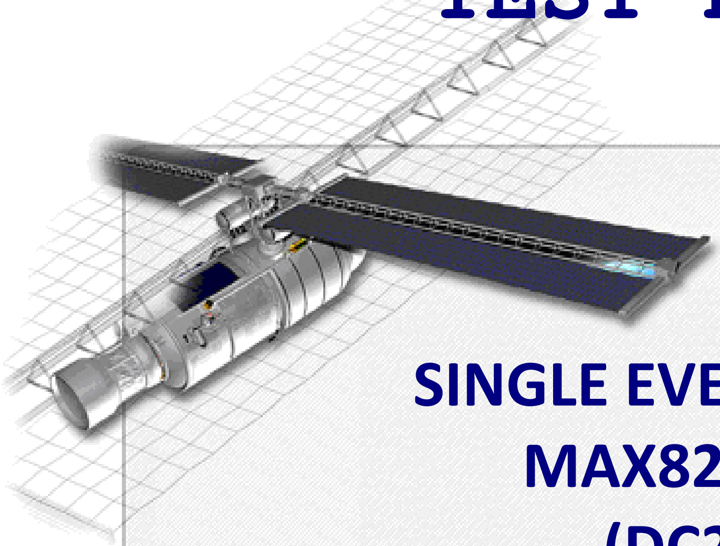
HEAVY ION and LASER TEST REPORT



SINGLE EVENT EFFECTS
MAX823TEUK+
(DC2224)
5-Pin Microprocessor Supervisory Circuits with Watchdog Timer and Manual Reset
From
Maxim Integrated

TRAD/TI/MAX823TEUK+/2224/ESA/TA/2308		Labège, August 20th, 2024
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Revision: 0	First edition of the test report. – 12/12/23	
Revision: 1	LASER testing added in Appendix B	
To:	**R. KARPOV**	Project/Program:
Company:	**European Space Agency**	

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Abbreviations and acronyms

DUT	Device Under Test
ESA	European Space Agency
LET	Linear Energy Transfer
RADEF	RADiation Effects Facility (Jyväskylä, Finland)
SEL	Single Event Latch-up
SET	Single Event Transient
VASCO	VAcuum System for Californium Operation

Abstract

The main objective of this test was to evaluate the sensitivity of the MAX823TEUK+, a 5-Pin Microprocessor Supervisory Circuits With Watchdog Timer and Manual Reset versus SEL and SET.
The irradiation was performed at RADEF with a maximum LET of 56.8 MeV.cm²/mg.
The main conclusions are the following.

The SEL test was performed under SEL test conditions (see Table 6).

In SEL test configuration
No SEL was observed with a LET of 56.8 MeV.cm²/mg, Xenon heavy ion.
No destructive events were observed.

The SET test was performed under SET test conditions (see Table 7).

In SET test configuration
SET were observed with a minimum LET of 13.3 MeV.cm²/mg, Iron heavy ion.
No lower LET was tested during this test campaign.
Different events were observed between heavy ions and LASER testing.

1. Introduction

This report includes the test results of the heavy ion SEE test sequence carried out on the MAX823TEUK+, a 5-Pin Microprocessor Supervisory Circuits With Watchdog Timer and Manual Reset from Maxim Integrated, susceptible to show SEL and SET induced by heavy ions.

This test was performed for ESA at RADEF. Irradiations were performed from October 27th, 2023 to October 28th, 2023. During this test campaign, 2 samples were irradiated.

2. Documents

2.1. Applicable documents

[AD1] Technical proposal: TRAD/P/ESA/AO17950/AR/131222 Rev 0 dated 13/11/2022
[AD2] Irradiation test plan: ITP/TRA/TI/MAX823TEUK+/SOT23-5/MAX/140923 Rev0 dated 14/09/2023

2.2. Reference documents

[RD1] ESCC Basic specification No. 25100 Issue 2 of October 2014
[RD2] Datasheet: MAX823-MAX825Z: 5-Pin Microprocessor Supervisory Circuits with Watchdog Timer and Manual Reset Data Sheet (Rev. 5)
[RD3] S. Dubos et al., "Review of Alternatives to Heavy Ions Broad Beam for SEL Screening of COTS", in RADECS 2023 proceedings

3. Organization of activities

The devices were procured by TRAD. The samples were delidded by TRAD. The testing board and testing software were developed by TRAD. Before the campaign the samples were checked-out and the test bench was validated with californium test at TRAD. The test campaign was performed by TRAD under ESA supervision. The next table summarizes the responsible entity for each activity involved in this project:

1	Procurement of Test Samples	TRAD
2	Preparation of Test Samples (delidding)	TRAD
3	Preparation of Test Hardware and Test Program	TRAD
4	Samples Check out	TRAD
5	Accelerator Test	TRAD/ESA
6	Test Report	TRAD

Table 1: Organization of activities

4. Parts information

4.1. Device description

The MAX823/MAX824/MAX825* microprocessor (µP) supervisory circuits combine reset output, watchdog, and manual reset input functions in 5-pin SOT23 and SC70 packages. They significantly improve system reliability and accuracy compared to separate ICs or discrete components. The MAX823/MAX824/MAX825 are specifically designed to ignore fast transients on VCC.
Seven pre-programmed reset threshold voltages are available (see Reset Threshold Table). All three devices have an active-low reset output, which is guaranteed to be in the correct state for VCC down to 1V. The MAX823 also offers a watchdog input and manual reset input. The MAX824 offers a watchdog input and a complementary active-high reset. The MAX825 offers a manual reset input and a complementary active-high reset. The Selector Guide explains the functions offered in this series of parts.

4.2. Identification

Part designation	MAX823TEUK+
Manufacturer	Maxim Integrated
Part function	5-Pin Microprocessor Supervisory Circuits With Watchdog Timer and Manual Reset

Table 2: Part identification

4.3. Procurement information

Package	SOT-23-5
Date code	2224
Lot code No.	0006408484
Number of tested parts	2 irradiated samples

Table 3: Part procurement information

4.4. Sample preparation

4 parts were delidded, no sample has been damaged during this operation.
5 part were thinned (back-side) for LASER testing, 2 were damaged during this operation.
A functional test was performed on delidded samples to check that devices were not degraded by the delidding operation.
Among the 4 delidded samples available for the test campaign, 2 were irradiated and 2 were not used.
Among the 3 thinned sample available for the LASER test campaign, 1 was irradiated.

4.5. Sample pictures

4.5.1. External view

The Figure 1 shows an external view of the parts. Left and right pictures are respectively the top and the bottom views of the package.

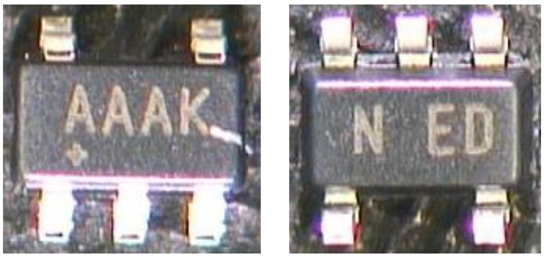


Figure 1: Pictures of the package

4.5.2. Internal view

Figure 2 gives an overview of the die. Figure 3 presents a view of the internal markings observed on the die (indicated by red rectangles on Figure 2).

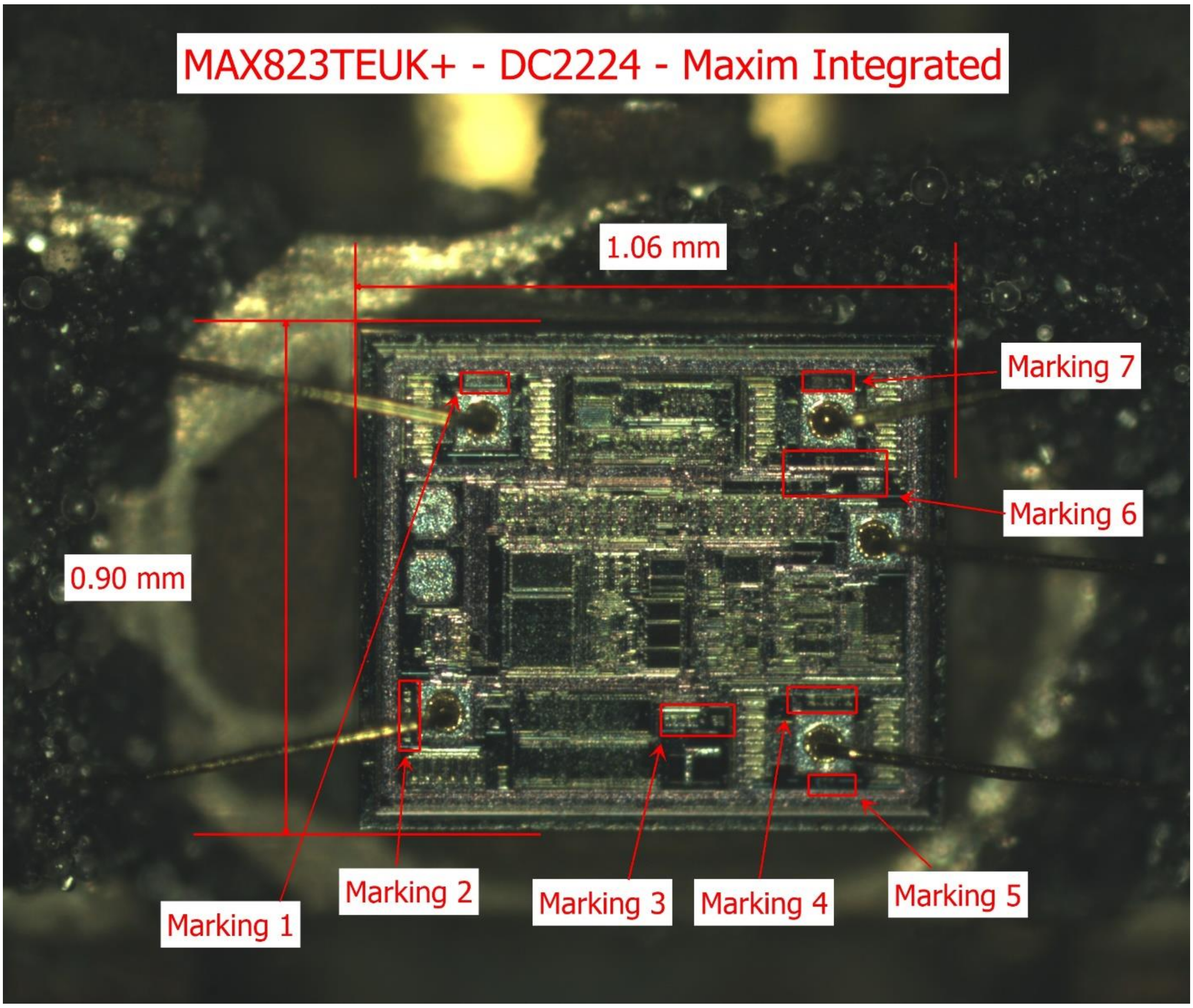


Figure 2: Picture of the internal overall view

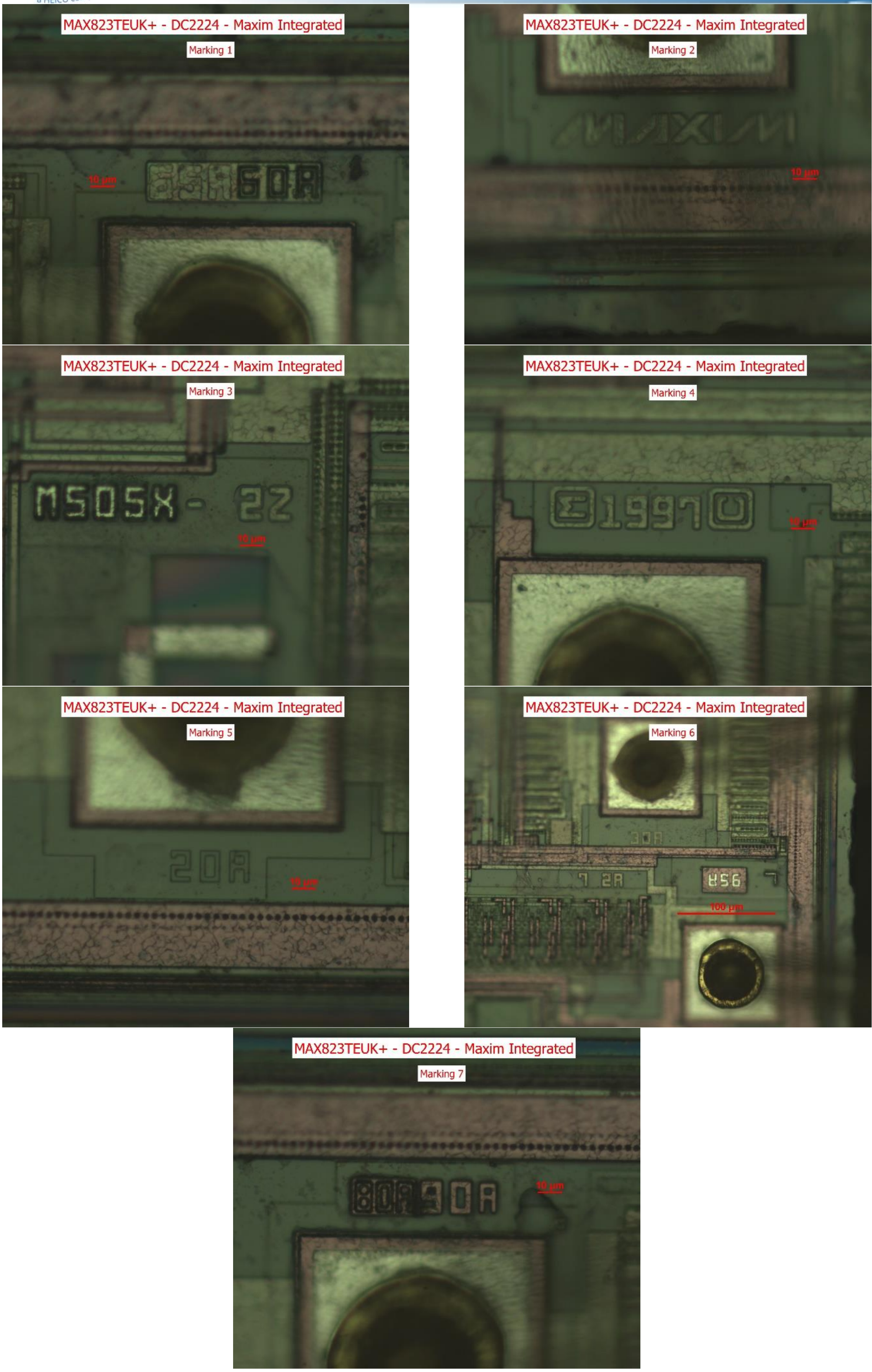


Figure 3: Pictures of the die markings

5. Dosimetry and irradiation facility

5.1. RADEF heavy ion test facility

The cyclotron used is a versatile, sector-focused accelerator for producing beams from hydrogen to xenon.

Heavy ion irradiations are performed in a vacuum chamber with an inside diameter of 75 cm and a height of 81 cm. The vacuum in the chamber is achieved after 5 minutes of pumping, and venting takes also only a few minutes. Irradiations can also be performed in air, therefore the LET and the range is calculated according the distance between the collimator and the component.
The components can be fixed on a 25x25cm^2 aluminium plate which will be mounted on the linear movement apparatus inside the chamber. The DUT can be moved in the X and Y directions and also tilting is possible.

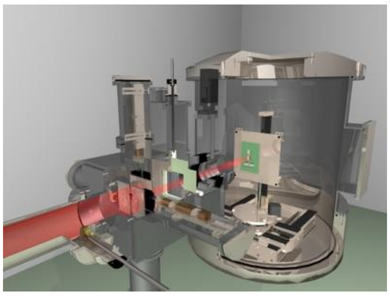


Figure 4: RADEF facility

A CCD camera with a magnifying telescope is located at the other end of the beam line to determine accurate positioning of the components. The coordinates are stored in the computer's memory allowing fast positioning of various targets during the test.

5.2. Dosimetry

To control and monitor the beam parameters, scintillation plastics connected to photomultiplier tubes are used as detectors. Four of such kinds of detectors are very close and placed around the edges of the beam. Detector can be moved to the front of the DUT and evaluate flux and homogeneity.
The spot size is 2 cm^2 and for special cases up to a diameter of 70 mm in vacuum. The Spot Homogeneity is ± 10 %

5.3. Beam characteristics

The beam flux is variable between a few particles s^{-1}cm^{-2} and 1.5E+4 s^{-1}cm^{-2} and is set depending on the device sensitivity. On special request, the users have the possibility to increase the flux up to 1E+6 s^{-1}cm^{-2}.
Characteristics of heavy ions available at RADEF during the test campaign are listed in Table 4 where heavy ions used for this test campaign are highlighted.
The tests on MAX823TEUK+ are performed in air, therefore the LET and range are calculated according to the 50 µm of Kapton degrader (used only in the case of Xenon heavy ion), and the distance between collimator and the component.

ION	Energy (MeV)	Range (µm(Si))	LET (MeV.cm²/mg)
$^{126}Xe^{44+}$	1446.48	105.71	56.8
$^{107}Ag^{37+}$	1714	158	38.8
$^{83}Kr^{29+}$	1358	185	24.5
$^{57}Fe^{20+}$	941	214	13.3
$^{40}Ar^{14+}$	657	264	7.2
$^{20}Ne^{7+}$	328	360	2.3
$^{17}O^{6+}$	284	481	1.5

Table 4: RADEF heavy ion list

6. Test procedure and setup

6.1. Test method

With respect to reference documents (see 2 Documents), runs were performed:

- Up to a fluence of 1E+7 cm^{-2} with only SEL monitoring.
- Up to 100 events for SET runs.

6.2. Test principle

6.2.1. SEL test principle

A SEL is a permanent event that results from the activation of a parasitic thyristor structure creating low impedance conduction path in the device. The consequent high current can potentially damage the device, possibly even leading to its destruction due to overcurrent. A power cycle is required to correct this situation.

GeV is a specific equipment developed by TRAD to protect the DUT and to perform SEL characterization. The power supply is applied to the DUT through GeV which protects the DUT against over consumption. Indeed, GeV continuously monitors and records the current. A programmable threshold current is set above the nominal operating value of the supply current. During irradiations, if the current consumption exceeds the threshold during a defined “hold time”, a SEL is counted and the DUT is switched off during a defined “off time”. Once the event is defused, the power supply is switched ON again with the nominal current consumption expected.

Figure 5 shows a common SEL characteristic, with and without the GeV system protection.

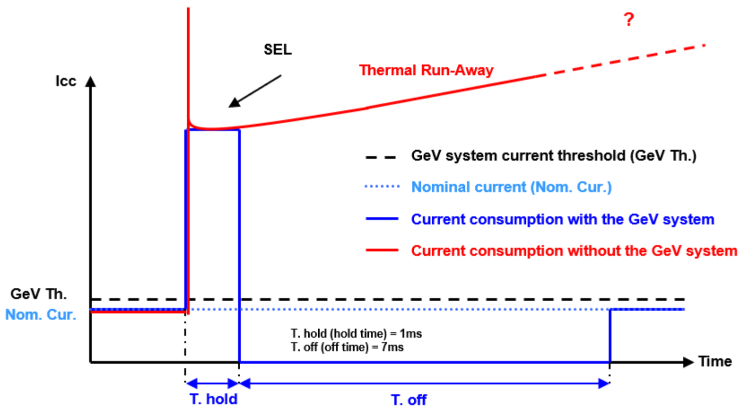


Figure 5: Common SEL characteristic

The SEL test was performed under SEL test conditions (see Table 6).
TRAD uses a dedicated system to heat and regulate the DUT temperature. The temperature is visualized and regulated.

6.2.2. SET test principle

A SET event is a temporary voltage excursion (voltage spike) at a node in a logic, or linear, integrated circuit, caused by a single energetic particle strike.

On static output signals, the SET can be a positive or negative amplitude variation. Two trigger thresholds (positive and negative) are used to detect the event when the monitored signal is out of the detection range (Figure 6). All SET are counted and their waveforms are recorded using an oscilloscope.

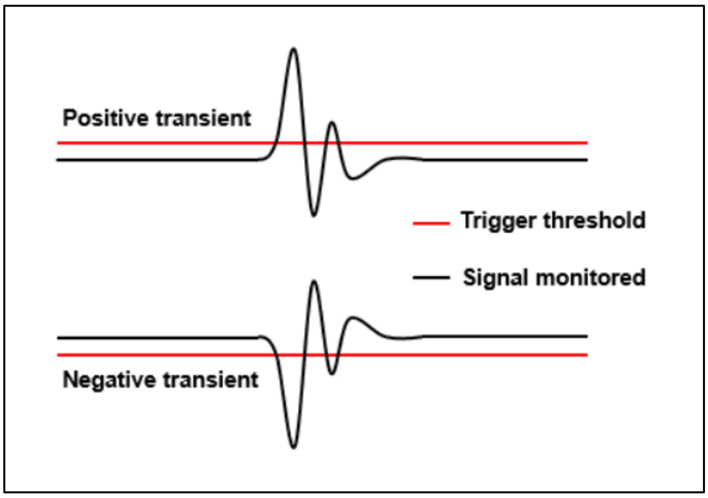


Figure 6: SET in static mode characteristic

SET were monitored on the /RESET pin during this test campaign and were triggered as downslopes front from 5.5V to 0V (see Appendix A for worst cases). Figure 7 shows a SET example on /RESET pin.

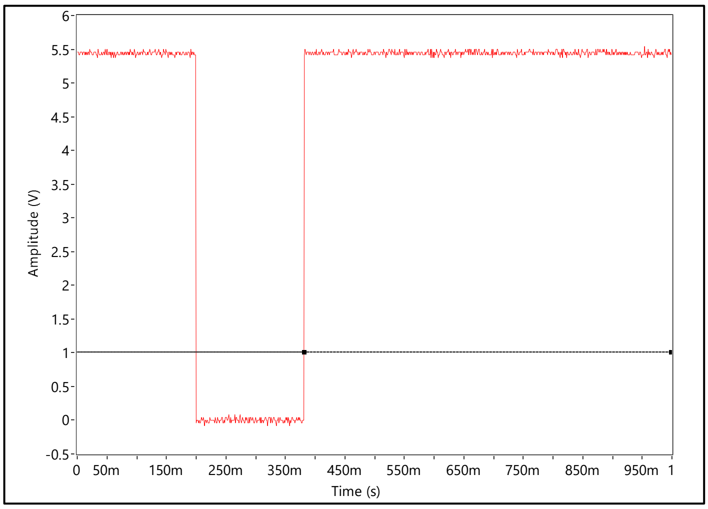


Figure 7: SET example

6.3. Test bench description

6.3.1. Test bench overview

Figure 8 provides a global view of the test bench. It is composed by:

- A computer to control the test equipment and to record the SEE.
- A test board to bias and operate the DUT (schematic is shown in Figure 11).
- A power supply for the DUT and auxiliary components.
- A GeV System to protect the DUT, detect and record SEL.
- An oscilloscope to detect and record SET.

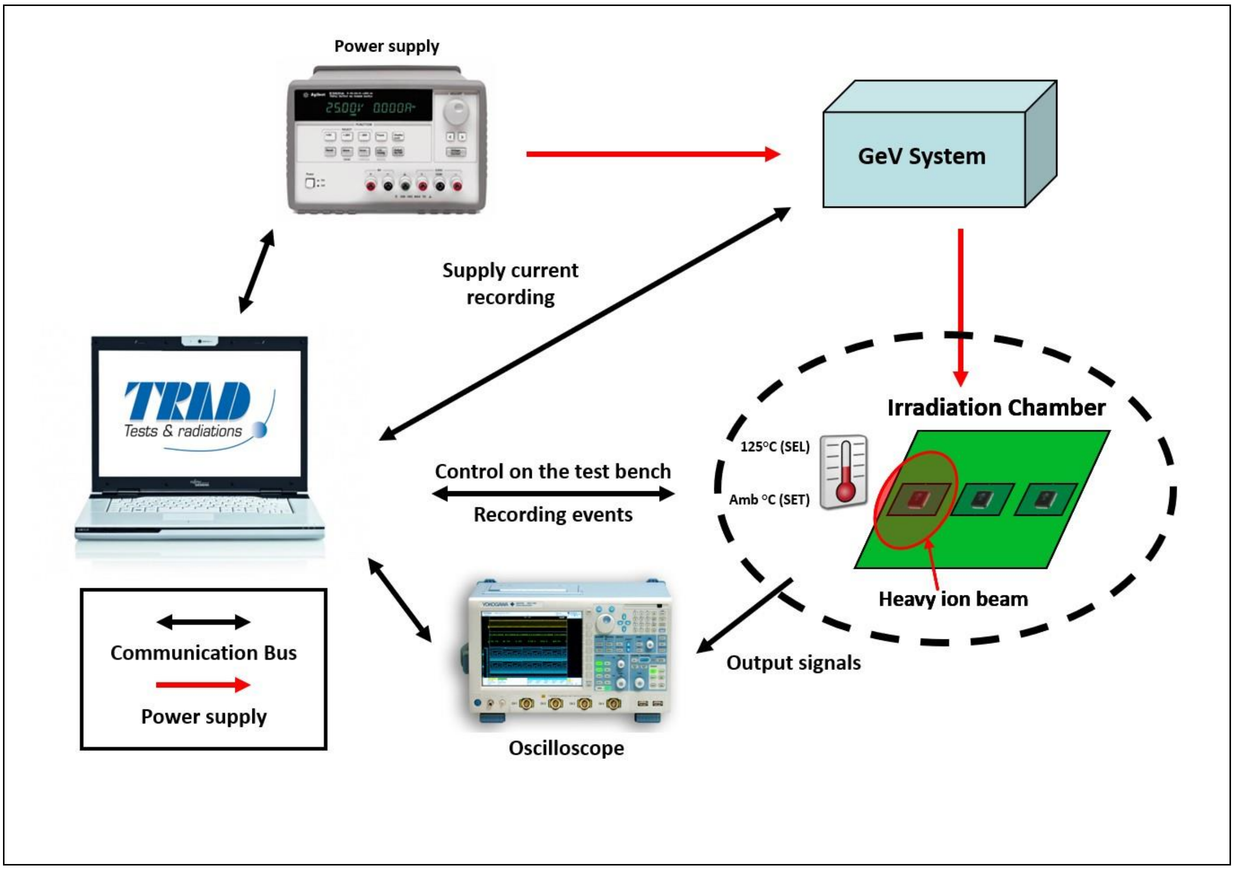


Figure 8: Test bench description

6.3.2. Validation of test hardware and program

Before performing the heavy ion test, the whole system (delidded sample, test board and software) was assembled and tested by TRAD in VASCO.

The VASCO is a vacuum chamber developed by TRAD in order to test the complete setup in vacuum with all cables length and electrical feedthroughs as used on the irradiation site.
The VASCO main characteristics are:
Chamber dimensions: 400x400x400mm, pressure 5.10^{-2} mbar.
Electrical feedthroughs available:
16 isolated BNC, 16 isolated SMA, 16 isolated SMB, 4 DB25, 3 HE10-40.
Other possibility on request

Validation runs are performed using Californium-252 source.
Californium-252 is a fissionable, transuranic radionuclide which decays by alpha particle emission with a half-life of 2.72 years.
The source emits alpha particles, fission fragments and fast neutrons. The fission fragments are used for SEE testing and these have a mean LET of 43 MeV.cm²/mg (Si) with 95% of the particles having LETs between 41 and 45 MeV.cm²/mg (Si). The mean range of the fission particles in silicon is 14.2µm.

Figure 9: VASCO picture

6.3.3. Heating system

TRAD has developed a specific heating system to heat and regulate the temperature of the DUT. Figure 10 shows a thermal image taken during the heating calibration of the DUT, the temperature of the die was set to 125°C as shown on the picture.

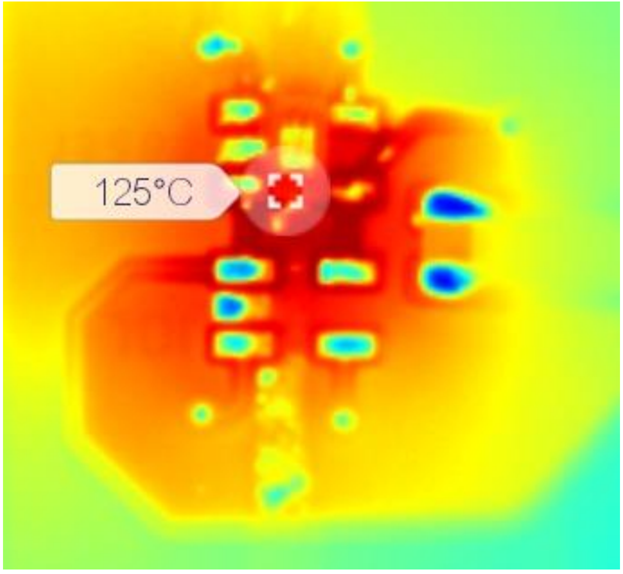


Figure 10: Thermal image of MAX823TEUK+ heated to 125°C

6.3.4. Test equipment identification

TEST BOARD	TRAD/TA1/I/MAX823TEUK+/SOT-23/AA/2309
EQUIPMENT	SM-87; SM-96; GR-27; GeV-3
TEST PROGRAM	MAX823TEUK+_I_2224+5_B-MTP_V10; MAX823TEUK+_I_2224+5_B-MTP_V11; MAX823TEUK+_I_2224+5_B-MTP_V12

Table 5: Equipment identification

6.3.5. Test board description

The TRAD test board schematic referenced "TRAD/TA1/I/MAX823TEUK+/SOT-23/AA/2309" is illustrated in Figure 11.

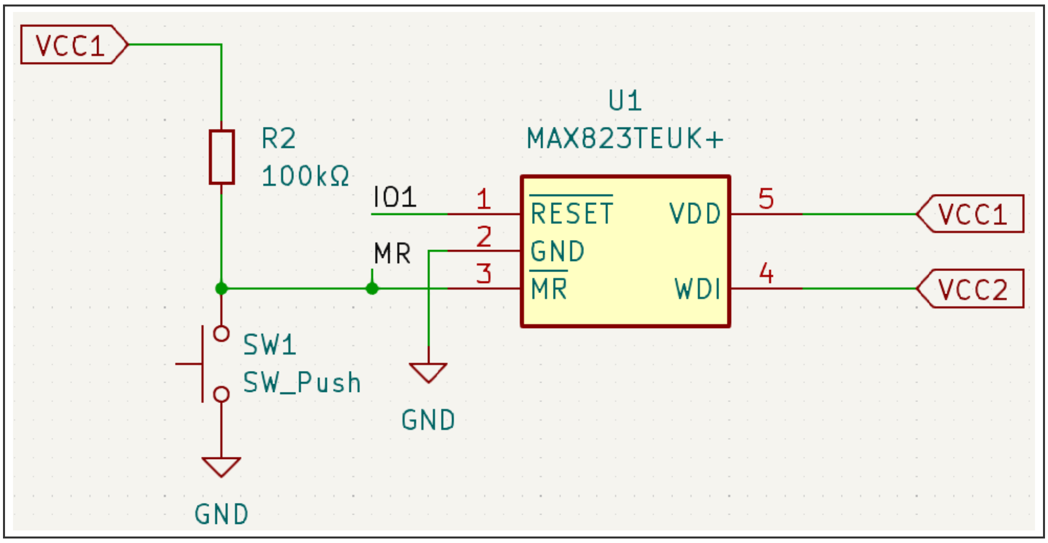


Figure 11: Test board schematic

6.3.6. Test conditions and event detection thresholds

SEL test

	VCC
Voltage	5.5 V
$I_{nominal}$	<5 mA
$I_{threshold}$	5 mA
T_{hold}	1 ms
$T_{cut\ off}$	7 ms
Temperature	125°C

Table 6: SEL test conditions and detection thresholds

SET test

	VCC = 5.5V
	/RESET
$V_{nominal}$	5.5 V
Negative trigger threshold	4 V
Temperature	Ambient

Table 7: Static SET test conditions and detection thresholds

7. Test story

No atypical behaviour during the test to report.

8. Non conformance

Test sequence, test and measurement conditions were nominal.

9. Results

In this chapter are presented the SEE test results.
First, test runs summary tables provides details of the runs performed during this campaign, their parameters and results.
Then, for each event type are given their corresponding LET threshold, cross section and worst cases when it is applicable.
On the cross section curves are plotted their corresponding error bars.
The following formulas is used to calculate these error bars. It can be found in ESCC Basic specification No. 25100.

$$\delta\sigma \times F = \sqrt{(\delta Nevents)^2 + (\mathrm{Nevents} \times \frac{\delta \mathrm{F}}{F})^2}$$

where :

- F is the fluence
- $\sigma = N_{events} / F$
- $\delta F/F$ is the uncertainty on the measured fluence (±10%).
- δN_{events} is the variance on the measured number of events.

Assuming that SEE events are random, the probability of events follows a Poisson distribution. The variance on the number of events is calculated from the chi-square distribution for a given confidence level. In this test report, we used a confidence level of 95%.

9.1. Test run summary

Run	Test configuration	Part	T° (°C)	Ion	Energy (MeV)	Tilt (°)	Eff. LET (MeV.cm²/mg)	Eff. Range (µm Si)	Flux (φ) (cm⁻².s⁻¹)	Time (s)	Run Fluence (cm⁻²)	Run Dose (krad)	Cumulated Dose (krad)	SEL	SEL Cross Section (cm²)	SET	SET Cross Section (cm²)
1	SEL	1	125	Ag	1714	0	38.8	158.0	9.91E+03	1009	1.00E+07	6.21	6.21	0	<1.00E-07	-	-
1	SEL	2	125	Ag	1714	0	38.8	158.0	9.91E+03	1009	1.00E+07	6.21	6.21	0	<1.00E-07	-	-
2	SEL	1	125	Xe	1446.5	0	56.8	105.7	1.41E+04	707	1.00E+07	9.09	15.30	0	<1.00E-07	-	-
2	SEL	2	125	Xe	1446.5	0	56.8	105.7	1.41E+04	707	1.00E+07	9.09	15.30	0	<1.00E-07	-	-
3	SEL	1	amb	Fe	941	0	13.3	214.0	3.82E+03	217	8.28E+05	0.18	15.48				
4	SEL	1	amb	Fe	941	0	13.3	214.0	6.53E+02	17	1.11E+04	0.00	15.48				
5	SEE Watchdog	1	amb	Fe	941	0	13.3	214.0	7.37E+02	1356	1.00E+06	0.21	15.69	-	-	108	1.08E-04
6	SEE Watchdog	1	amb	Xe	1446.5	0	56.8	105.7	6.02E+03	109	6.56E+05	0.60	16.29	-	-	110	1.68E-04
7	SEE Watchdog	1	amb	Ag	1714	0	38.8	158.0	6.20E+03	115	7.13E+05	0.44	16.73	-	-	108	1.51E-04

Table 8: MAX823TEUK+ test run table

SEE detailed results are described in the following sections.

9.2. Cumulated dose table

Part No.	Cumulated Dose (krad)
1	16.73
2	15.3

Table 9: Cumulated dose table

9.3. SEL test results

9.3.1. SEL LET threshold

The SEL test was performed under SEL test conditions (see Table 6).

In SEL test configuration
No SEL was observed with LET of 56.8 MeV.cm²/mg, Xenon heavy ion.

9.3.2. SEL cross sections

Hereafter are shown the SEL cross section values for each tested component.

In SEL test configuration

	MAX823TEUK+ SEL Cross Section (cm²) in SEL test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
56.8	0.00E+00	<1.00E-07	3.69E-07	0.00E+00	<1.00E-07	3.69E-07
38.8	0.00E+00	<1.00E-07	3.69E-07	0.00E+00	<1.00E-07	3.69E-07

Table 10: MAX823TEUK+ SEL cross section values in SEL test configuration

9.4. SET test results

9.4.1. SET LET threshold

The SET test was performed under SET test conditions (see Table 7).

In SET test configuration

SET were observed with a minimum LET of 13.3 MeV.cm²/mg, Iron heavy ion.
No lower LET was tested during this test campaign.

9.4.2. SET cross sections

Hereafter are shown the SET cross section values for each tested component.

In SET test configuration

	MAX823TEUK+ SET Cross Section (cm²) in SET test configuration		
LET Eff (MeV.cm²/mg)	Part No. 1		
	error (-)	cross section	error (+)
56.8	2.99E-05	1.68E-04	3.44E-05
38.8	2.72E-05	1.51E-04	3.14E-05
13.3	1.94E-05	1.08E-04	2.24E-05

Table 11: MAX823TEUK+ SET cross section values in SET test configuration

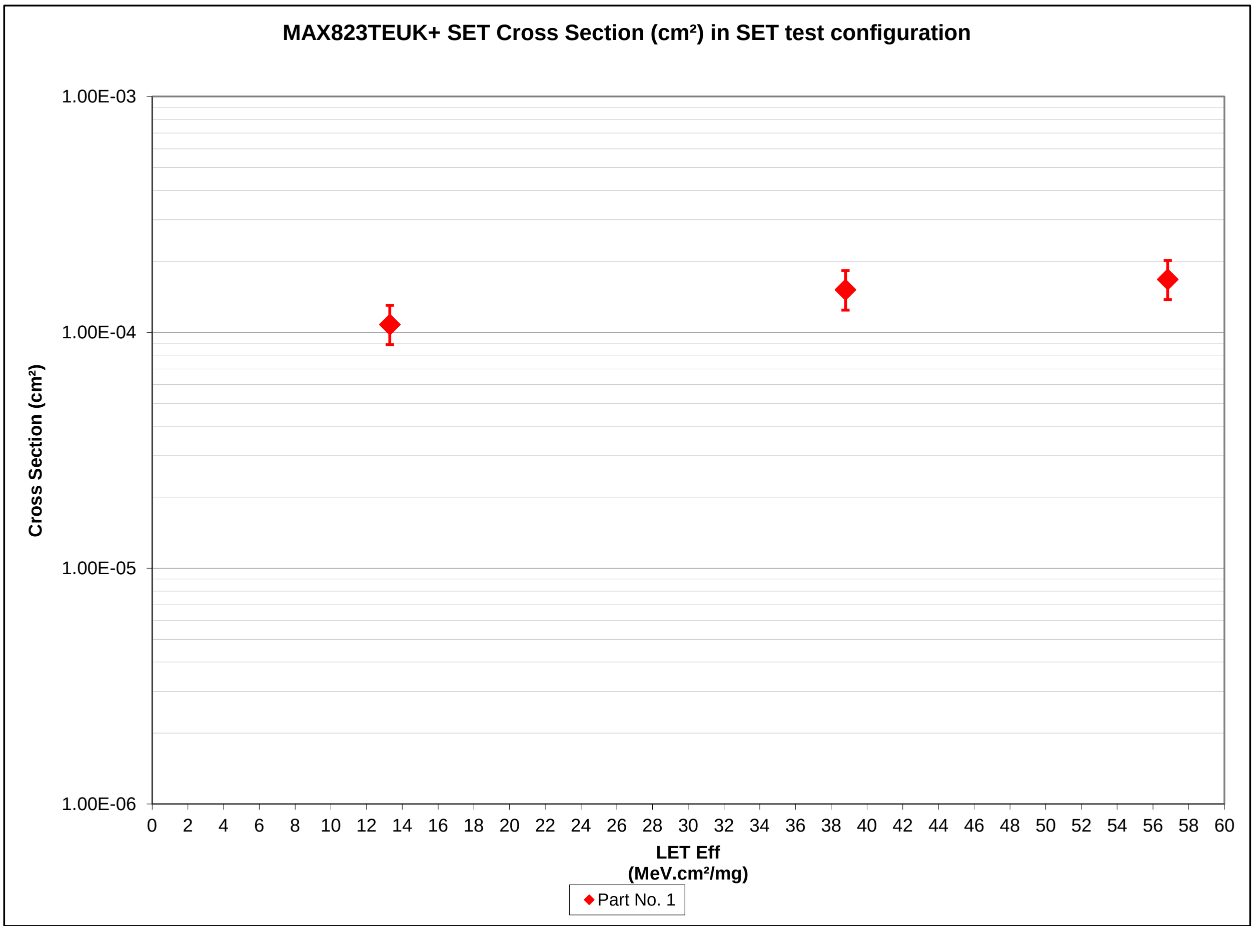


Figure 12: MAX823TEUK+ SET cross section curve in SET test configuration

In SET test configuration

The worst complete SET observed on /RESET occurred during run No. 5 on part No. 1 event No. 78.

Run No.	5
Part No.	1
Test condition	**SET**
Type event	**SET**
Ion LET (MeV.cm²/mg)	13.3
Absolute amplitude	0 V
Relative amplitude	5.45 V
Duration	298 ms

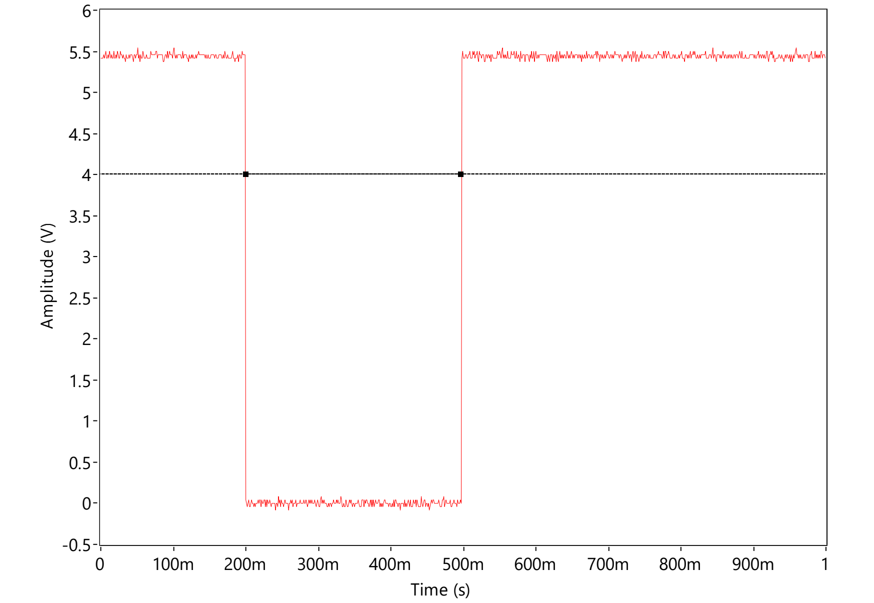


Figure 13: SET worst case

10. Conclusion

The heavy ions test was performed on MAX823TEUK+. The aim of the test was to evaluate the sensitivity of the device versus SEL and SET. SET were observed under SET test conditions,.

The SEL test was performed under SEL test conditions (see Table 6).

In SEL test configuration
No SEL was observed with a LET of 56.8 MeV.cm²/mg, Xenon heavy ion.
No destructive events were observed.

The SET test was performed under SET test conditions (see Table 7).

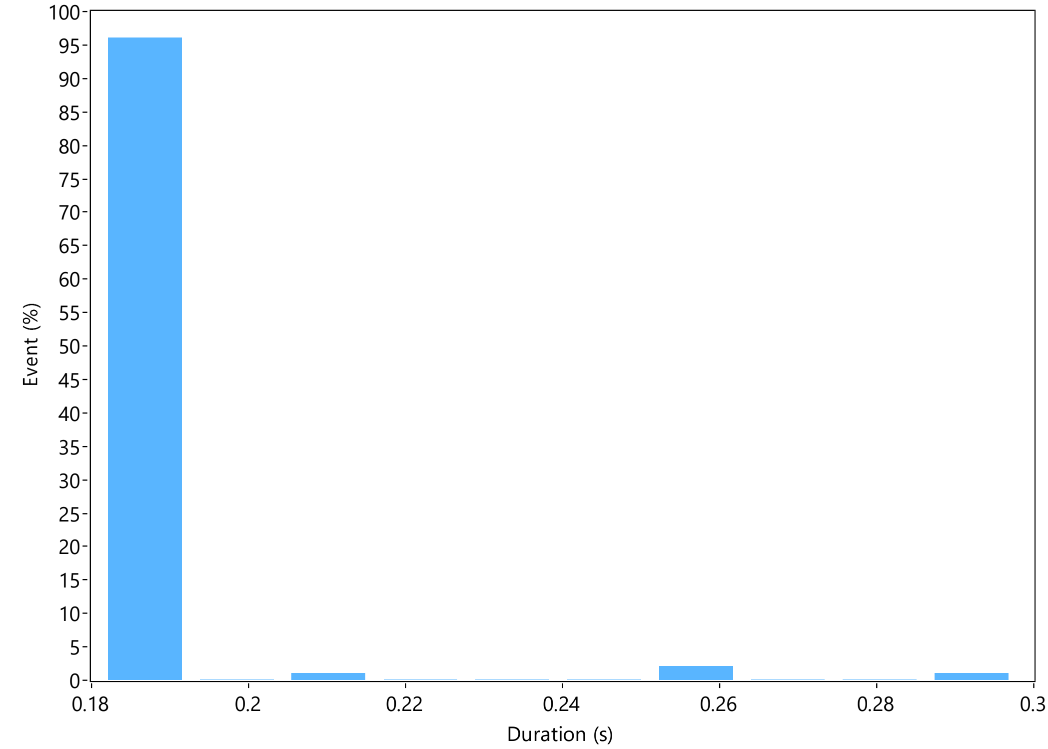
In SET test configuration
SET were observed with a minimum LET of 13.3 MeV.cm²/mg, Iron heavy ion.
No lower LET was tested during this test campaign.
Different events were observed between heavy ions and LASER testing.

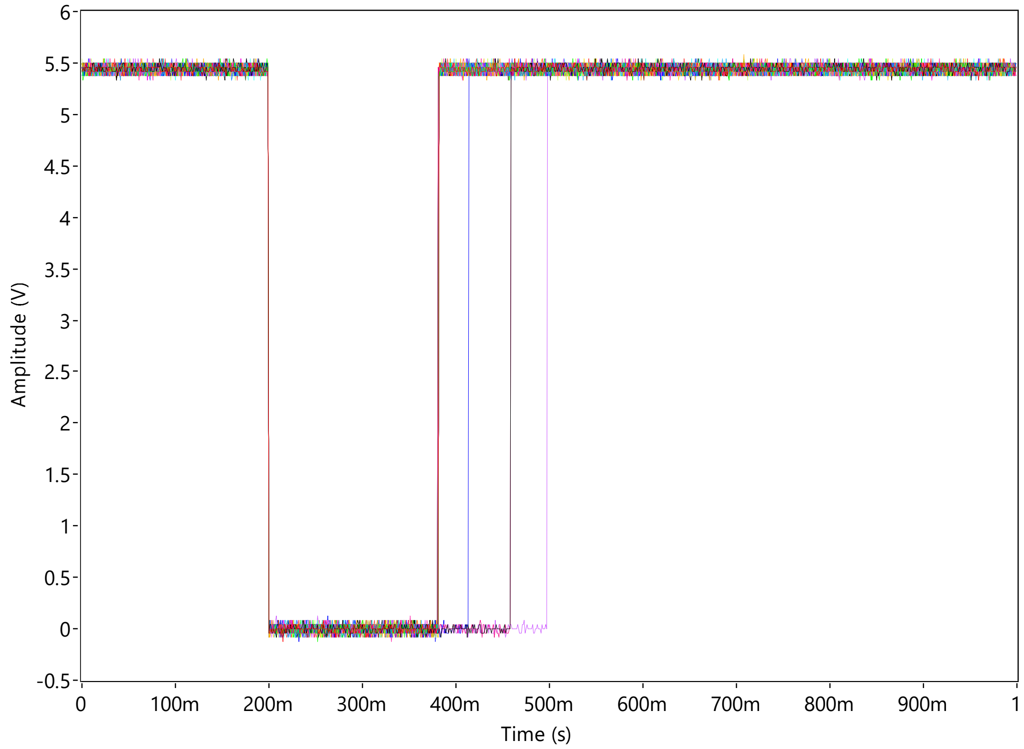
Further analysis on each run can be found in appendixes with:

- Cumulative charts representing on the same chart all the detected events,
- Distribution charts representing event amplitude versus events duration,
- Histograms representing the durations of all detected events,
- Histograms representing the amplitudes of all detected events.

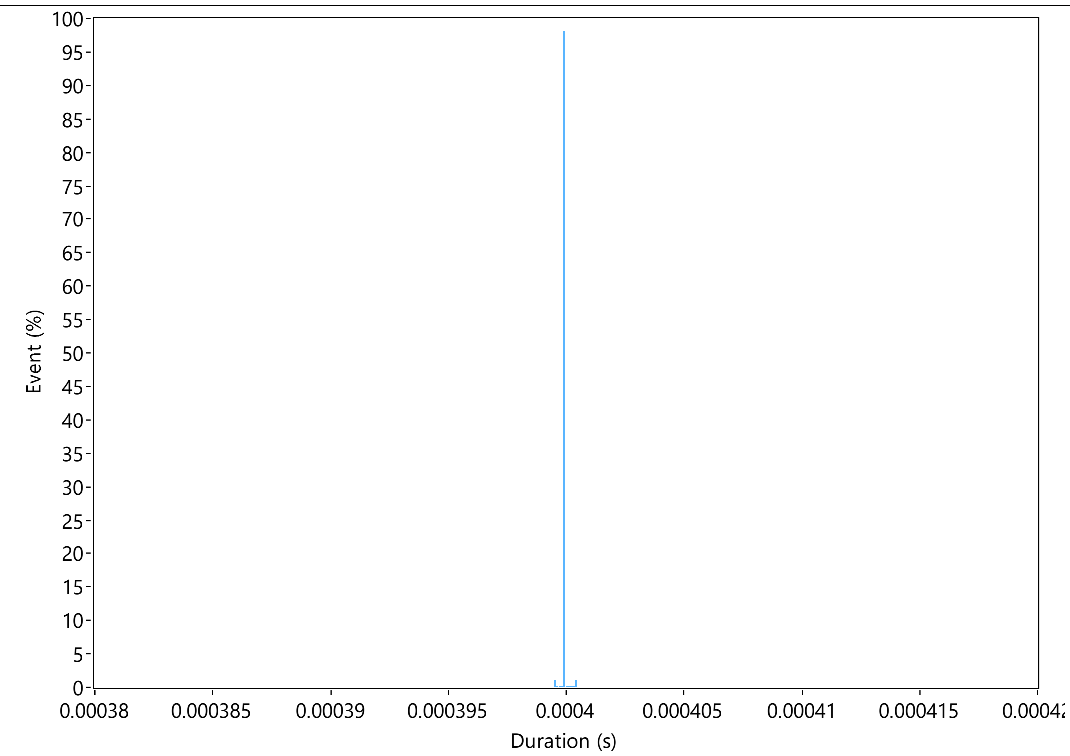
Appendix A. SET results analysis

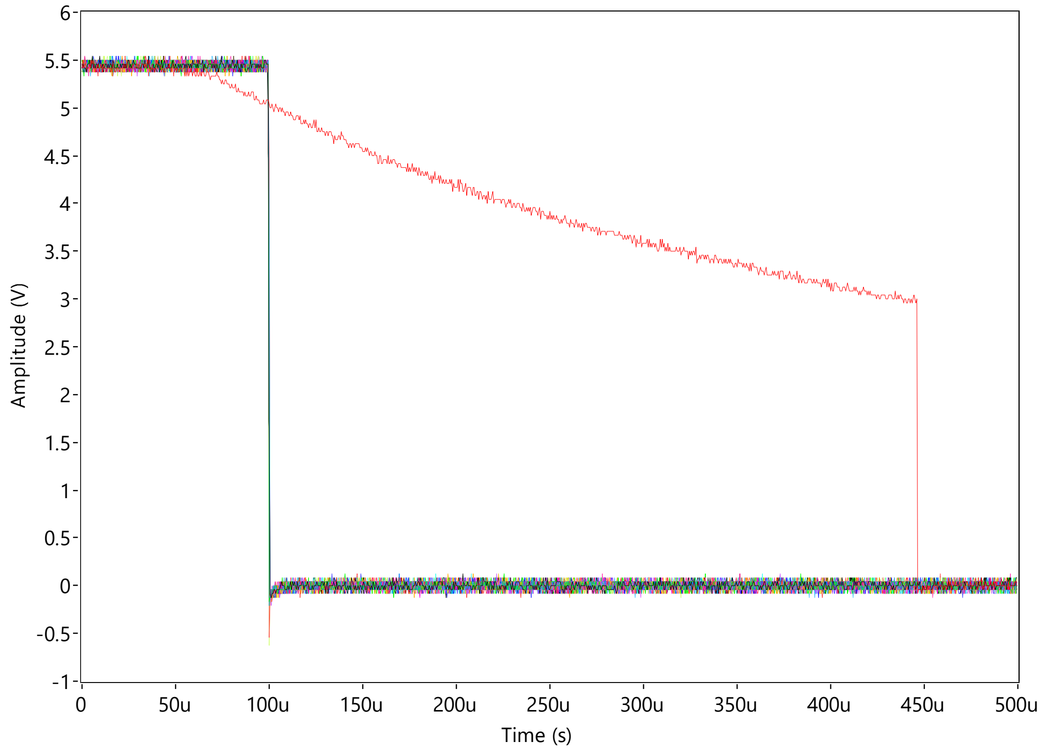
Curves at 5.5 V represent the /RESET signal.



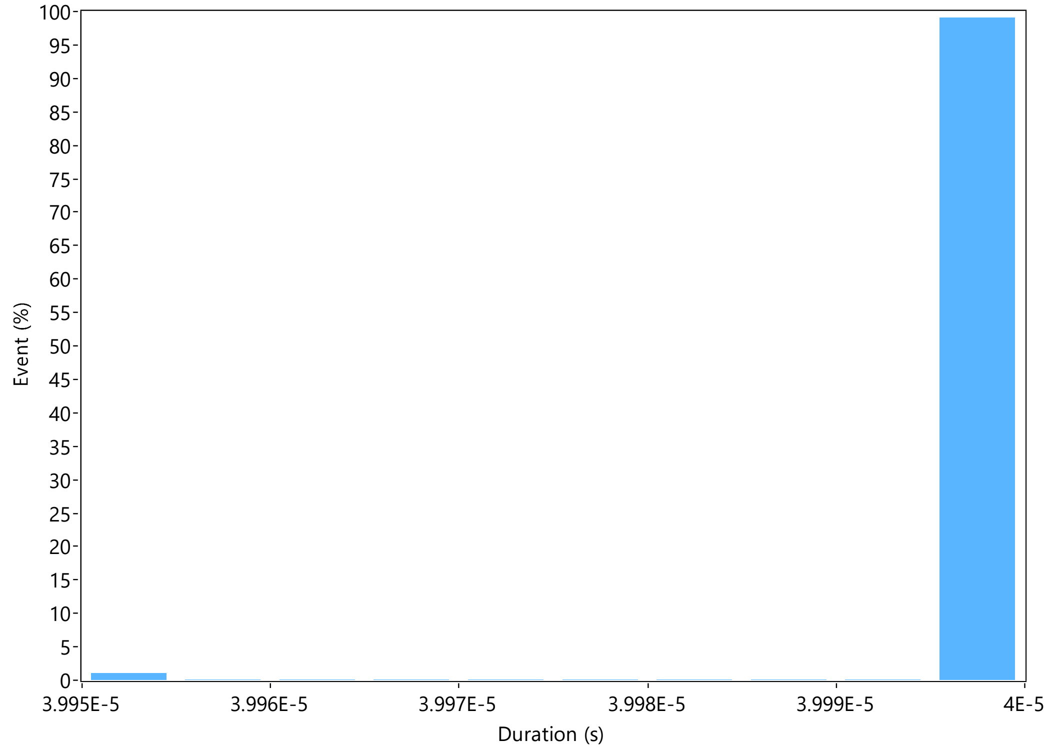


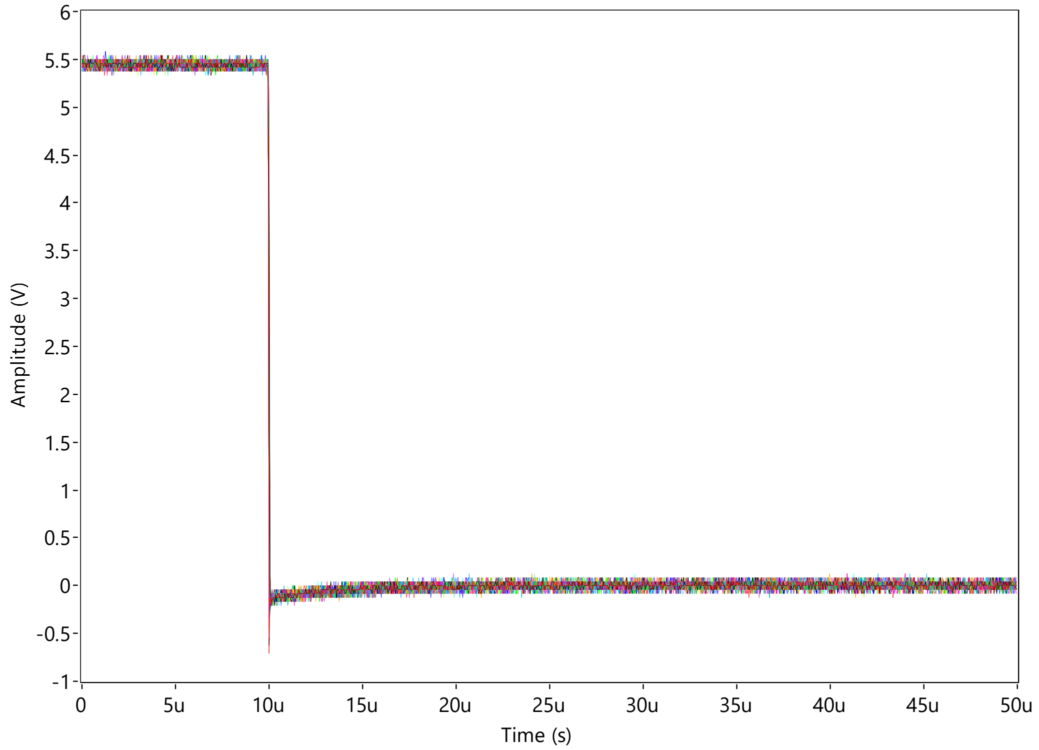
Run 5. Event recap





Run 6. Event recap





Run 7. Event recap

Appendix B. LASER testing

B.1. LASER parameters

The LASER test bench LISA developed at TRAD is dedicated to Single Event Effects testing. The LISA facility is based on a Nd:YAG pulsed LASER. Its overview and specifications are given in Table 12 and a schematic of the optical bench is given in Figure 14 below.

Reference	Coherent Helios 1064	
Wavelength	1064 µm	
Pulse duration	400 ps	
Pulse energy at output	50 µJ.pulse^{-1}	
Frequency	Single shot to 50kHz	
Shot to shot stability	± 5%	

Table 12: Overview of LISA and specifications of the Nd:YAG pulsed LASER from LISA

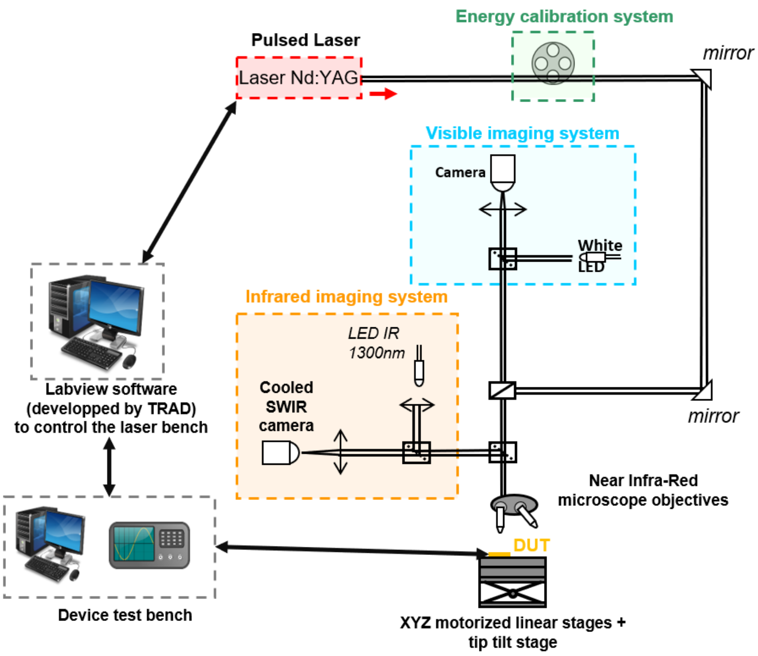


Figure 14: LISA laser test bench

The LASER spot is focused into the device active layer using apochromatic objective lens allowing to reach spot diameters of:

- 8 µm with the X10 objective
- 2.6 µm with the X50 objective

Motorized stages are used to move the LASER spot on the device under test with a great precision (minimal increment of ± 0,1 µm). The pulse energy can be modified in a continuous way using a motorized half-wave plate between two polarizers, and the energy range is comprised between ~0.3nJ/pulse and 150 nJ/pulse (depending on the objective used). Finally, an imaging system, including a visible and an infrared camera, is used to localize precisely the LASER spot focused on the device, and to monitor the "irradiation" of the part.

Several test modes are accessible with the dedicated LabVIEW software:

- Fast scan mode (S-scan): a pulse frequency, a step between two shots and an area are defined, and the moving stages proceed to scan the area at constant speed, calculated such that a pulse is shot for every step defined (ex: f=500Hz, dx=2µm, v=1000µm.s^{-1}). This mode is used prior to the others to localize the sensitive area(s) of the DUTs, before going further. It is however limited by the maximum speed of the moving stages, i.e. 2000µm. s$^{-1.}$
- Manual mode: the DUT is scanned manually, by moving the stages with the LabVIEW software, and shooting at low frequency (below 1kHz to avoid cumulative effects). This is usually used to determine precisely the location of the sensitive areas, once a fast scan has been performed.
- Step-by-step mode: the DUT is scanned with precision in a selected area. In this mode, an area is defined as well as a step between two pulses. The moving stages moves step by step on the selected area and a single shot is triggered for each position.

Correspondence between Laser pulse energy and heavy ion LET is not straightforward, because two very different processes and interactions are involved in charges creations in the semiconductor: the ionization process under heavy ions and the photoelectric effect under pulsed Laser.

However, an empirical correspondence has been established in the frame of a TRAD/CNES study on the LISA facility ([RD3]). Indeed, several devices with known sensitivity to SEL under heavy ions were also tested under Laser at TRAD, and a linear dependence was observed between their SEL LET threshold and SEL LASER Energy threshold. It was thus identified that the {0 – 2.5} nJ/pulse energy range (energy in sensitive volume) is representative of the {0 – 60} MeV.cm²/mg LET range. Note that this comparison is only valid with SEL effect and with the X50 objective.

The pulse energy used under Laser and given in the test result tables in this report is measured just before entering substrate, using a power meter. However, to provide comparative results between several devices, absorption by the silicon substrate, with various thicknesses, must be considered. Indeed, as the pulse propagate through the substrate to reach the active layer, a fraction of the pulse energy is lost and not used for triggering Single Event Effects. This estimation of remaining energy in the active layer is done using a Beer Lambert law, as described below:

$$\boldsymbol{Ef = Ei(1 - R)e^{-\alpha d}} \qquad \textbf{10.a}$$

With :

- R : the reflection of the beam at the Air/Si interface, which is ~31%
- d : the substrate thickness, indicated in each results' table for each reference
- α : the absorption coefficient in silicon (considered as undoped)

As a result, the classification given in Abstract of this document, is based on these pulse energies and on results obtained in [RD3], by recalculating the energy used during the tests (considering the substrate thicknesses). Note that this classification may be only valid for SEL effect.

During LASER testing, the whole die is scanned with the same test bench used during heavy ions testing with same test conditions for SEL and SET detections. The objective of this test campaign is to reproduce the set of events observed under heavy ion with LASER. LASER parameters used during this test campaign were:

- In SEL test configuration: Objective x50 and an energy of ≈ 2.5nJ/pulse in the sensitive volume.
- In SET test configuration: Objective x10 and an energy of 10nJ/pulse.

B.2. Test results

Run	Duration (s)	Part	T (°C)	Objective	Beam diameter (µm)	Pulse energy (nJ/pulse)	Pulse energy in active area (nJ/pulse)	Test mode	f (Hz)	dx (µm)	Scan speed (µm.s-1)	SEL	SET
1	4200	1	Amb	X10	8	5.04	-	Scan	-	10	-	0	402
2	600	1	125	X50	2.6	6.05	2.51	S-scan	1000	2	2000	0	120
Conclusion: no SEL/DSEE observed in SEL test config. / Sensitive areas identified in SET test config.													

Table 13: MAX823TEUK+ LASER test results

B.3. Sensitive areas on die

Each sensitive area identified is numbered and worst cases are given for each area.

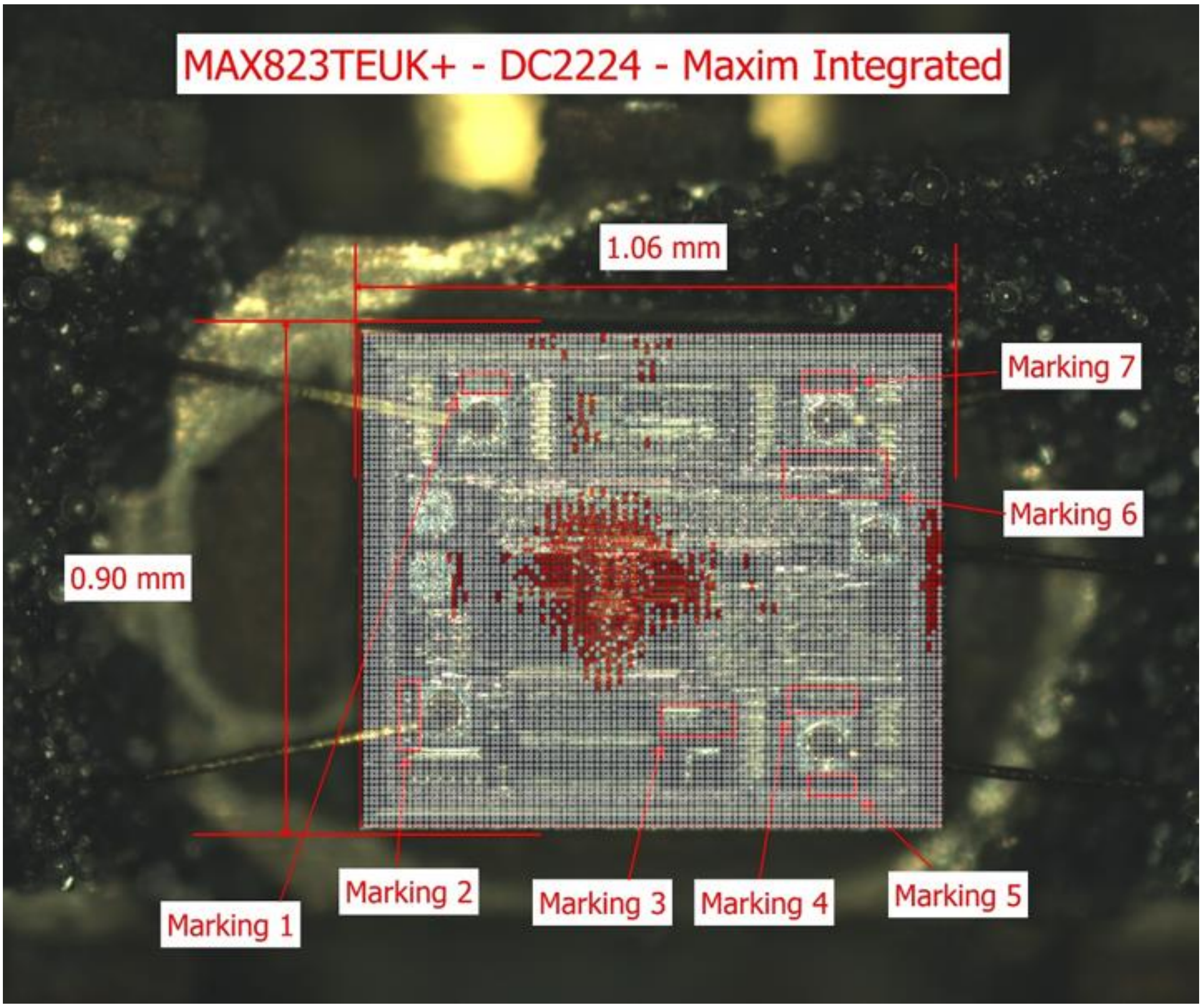


Figure 15: LISA laser test bench

B.4. Event worst case

SET worst case

Part No.	1
Test Conditions	SET
Type event	Negative SET
nJ/pulse	5.04
Absolute amplitude	5.25 V
Duration	186 µs

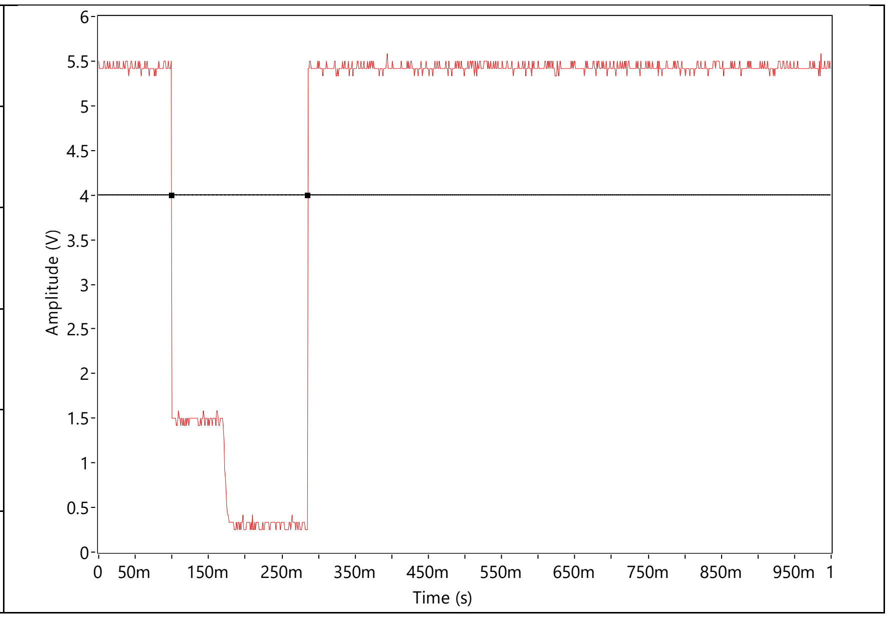


Figure 16: SET worst case