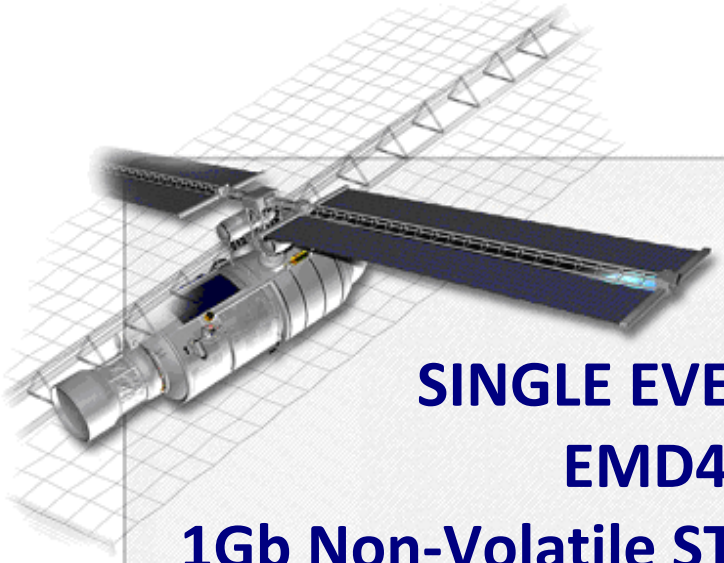
HEAVY ION
TEST REPORT



SINGLE EVENT EFFECTS
EMD4E001G
1Gb Non-Volatile ST-DDR4 Spin-transfer Torque MRAM
From
Everspin Technologies

TRAD/TI/EMD4E011G/XXX1/ASI/PC/2203		Labège, March 20th, 2024
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Revision: 1	SEU per bit cross section added to the report
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To:	**A. BERNE**
Company:	**THALES ALENIA SPACE TOULOUSE**

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Abbreviations and acronyms

DUT	Device Under Test
LET	Linear Energy Transfer
MBU	Multiple Bit Upset
RADEF	RADiation Effects Facility (Jyväskylä, Finland)
SEE	Single Event Effect
SEFI	Single Event Functional Interrupt
SEU	Single Event Upset
TAS	THALES ALENIA SPACE (Toulouse, France)

Abstract

The main objective of this test was to evaluate the sensitivity of the EMD4E011G, a 1Gb Non-Volatile ST-DDR4 Spin-transfer Torque MRAM versus SEL, SEU, MBU, Burst and SEFI.
The irradiation was performed at RADEF with a maximum LET of 39.48 MeV.cm²/mg.
The main conclusions are the following.

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

In SEL test configuration
No SEL was observed with LET of 39.48 MeV.cm²/mg, Krypton heavy ion.

The SEU test was performed under SEE test conditions (see Table 8).

In SEU_READ test configuration
SEU were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

MBU were observed with a minimum LET of 23.6 MeV.cm²/mg, Iron heavy ion.
No MBU was observed with LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.

BURST were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

SEFI were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

In SEU_WR test configuration
SEU were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

MBU were observed with a minimum LET of 23.6 MeV.cm²/mg, Iron heavy ion.
No MBU was observed with LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.

BURST were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

SEFI were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

1. Introduction

This report includes the test results of the heavy ion SEE test sequence carried out on the EMD4E001G, a 1Gb Non-Volatile ST-DDR4 Spin-transfer Torque MRAM from Everspin Technologies, susceptible to show SEL, SEU, MBU, burst and SEFI induced by heavy ions.

This test was performed for TAS at RADEF. Irradiations were performed on October the 26, 2023. During this test campaign, 2 samples were irradiated.

2. Documents

2.1. Applicable documents

[AD1] Technical proposal: TRAD/P/ASI/E-OSIP/DS/011021 Rev0 dated 09/02/2022
[AD2] Irradiation test plan: ITP_TRA_TI_EMD4E001_ASI_020323 Rev0

2.2. Reference documents

[RD1] ESCC Basic specification No. 25100 Issue 2 of October 2014
[RD2] Datasheet: EMD4E001GAS2, Rev. 1.2 by Everspin Technologies dated August 2020

3. Organization of activities

The devices were procured by TAS to 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 at TRAD. The test campaign was performed by TRAD. The next table summarizes the responsible entity for each activity involved in this project:

1	Procurement of Test Samples	TAS
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
6	Test Report	TRAD

Table 1: Organization of activities

4. Parts information

4.1. Device description

The ST-DDR4 device is a high-speed non-volatile random-access memory internally configured as sixteen banks (4 bank groups with 4 banks for each bank group) for x8 devices, and eight banks for each bank group (2 bank groups with 4 banks each) for x16 devices. The device uses double data rate (DDR) architecture to achieve high speed operation

4.2. Identification

Part designation	EMD4E001G
Manufacturer	Everspin Technologies
Part function	1Gb Non-Volatile ST-DDR4 Spin-transfer Torque MRAM

Table 2: Part identification

4.3. Procurement information

Package	FBGA-96
Date code	T002140
Number of tested parts	2 irradiated samples

Table 3: Part procurement information

4.4. Sample preparation

20 parts were delidded, 16 samples have been 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.

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.

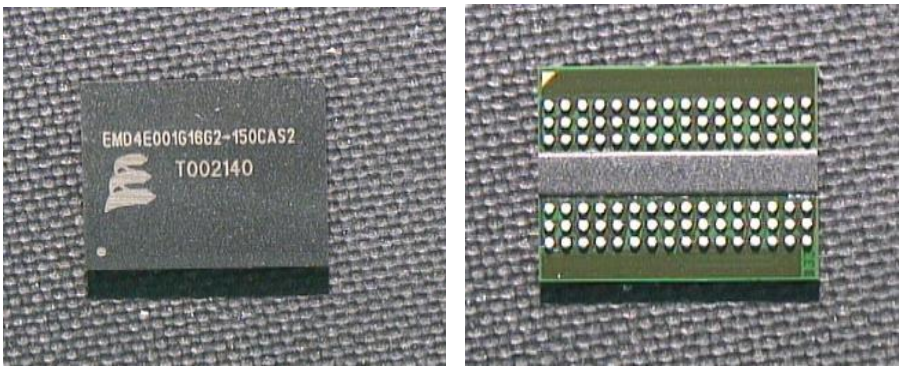


Figure 1: Pictures of the package

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.

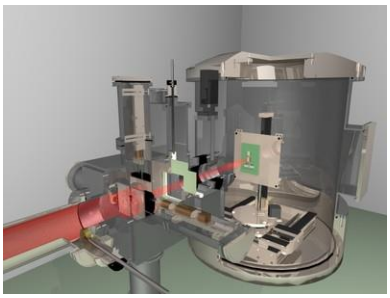


Figure 2: RADEF facility

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 EMD4E001G are performed in vacuum, therefore the LET and range are calculated according to 250µm of substrate, if there is one, and the distance between collimator and the component.

Ion	Energy (MeV)	Range (µm(Si))	Effective LET (MeV.cm²/mg)
$^{83}Kr^{29+}$	1826	274	39.5
$^{57}Fe^{20+}$	1254	283	23.6
$^{17}O^{6+}$	374	797	1.4

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 a fluence of 1E+6 cm^{-2} for the SEU, MBU, Burst and SEFI detection.

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

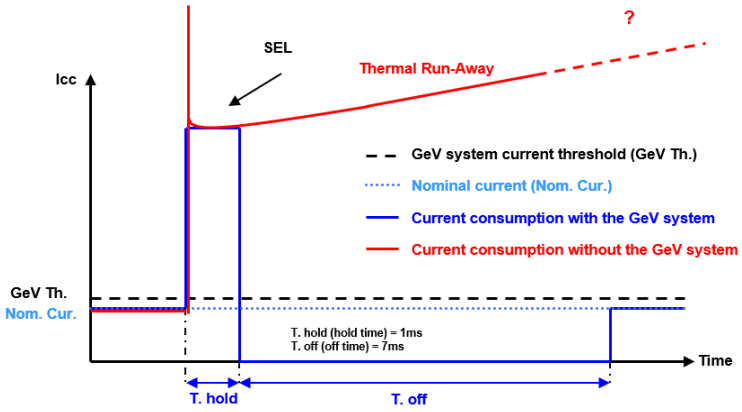


Figure 3: Common SEL characteristic

The SEL test was performed under SEL test conditions (see Table 7).
TRAD uses a dedicated system to heat and regulate the DUT temperature. The temperature is visualized and regulated from outside of the vacuum chamber during the irradiation.

6.2.2. SEE test principle

SEU, MBU, Burst and SEFI tests were performed under other SEE test conditions (see Table 8: SEE test conditions and detection thresholds).

The SEU/Burst/SEFI detection is ensured by the FPGA, driven by the remote computer. The memory is continuously read back and data are compared to the expected data set contained in the FPGA. There are three types of events recorded during this test:

- **SEU**: Any mismatch of data reading with expected data is at first considered to be a SEU and the data is sent to the computer. A counter is incremented accordingly. This process is repeated from address 0 to the last address of the memory. An SEU is an isolated upset in the data array of a memory. At normal flux under beam (until 5000 part./s.cm²), the number of SEUs induced by heavy ions in the memory should not exceed a few events (less than 10 events).
- **MBU**: An MBU is detected when several bits change from state 0 to 1 or from state 1 to 0 in a single word.
- **Burst:** If the SEU/MBU error counter reach more than 10 events and less than 500 events of SEU before the last address is reached, then a Burst is considered.
- **SEFI:** If the error counter reach more than 500 events of SEU before the last address is reached, then a SEFI is considered and a power cycle is applied to the memory.

A checkerboard pattern ''AAAA/5555'' was written in the memory before the start of irradiation. Two test modes were performed during this test campaign as listed in Table 5.

Test Mode	Test Sequence
SEL	Read loop, without feedback of erroneous data. SEU/SEFI detection is bypassed.
Read Only	Read loop with SEU/MBU/SEFI detection during irradiation.

Table 5: Test Modes

The following diagrams represent the different test modes available for the test campaign.
During the SEL test, the memory is read continuously as represented in Figure 4, but its content is ignored. The test bench only checks the presence of latch-up on the power supplies. This functionality is ensured by GeV.

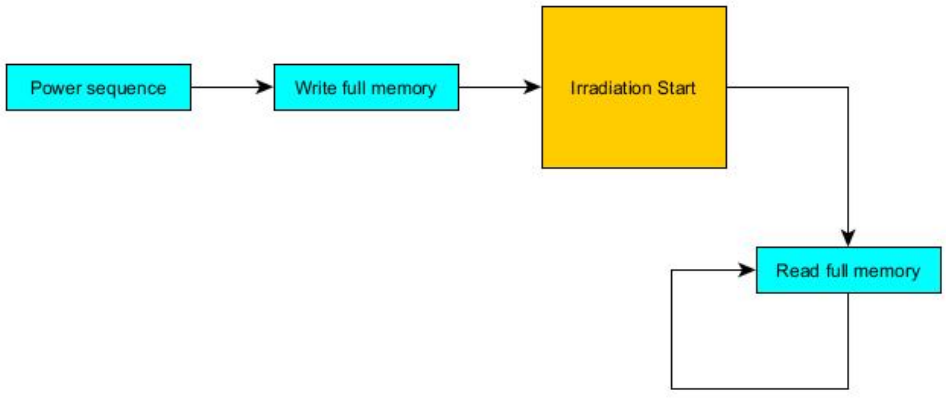


Figure 4 : SEL Test Flow Diagram.

In Read only, read operations occurs on the DUT, during irradiation. If an event occurs, the test bench tries to correct the data, implying write operation. Check Memory function is described in Figure 6.

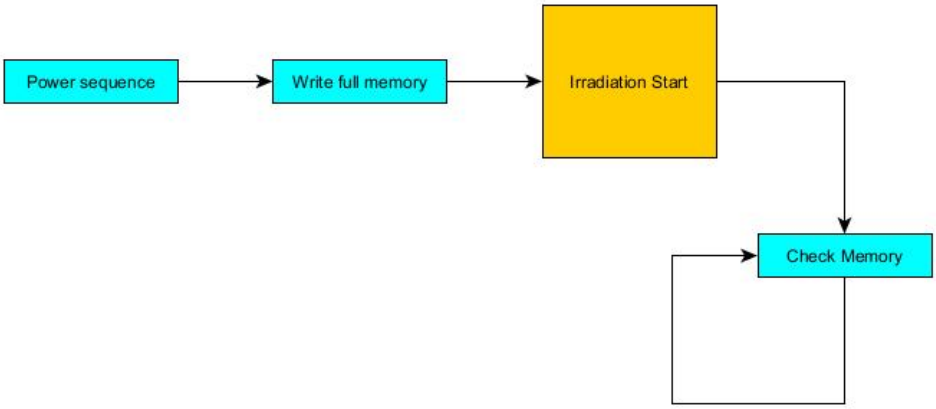


Figure 5 : Read only mode Test Flow Diagram.

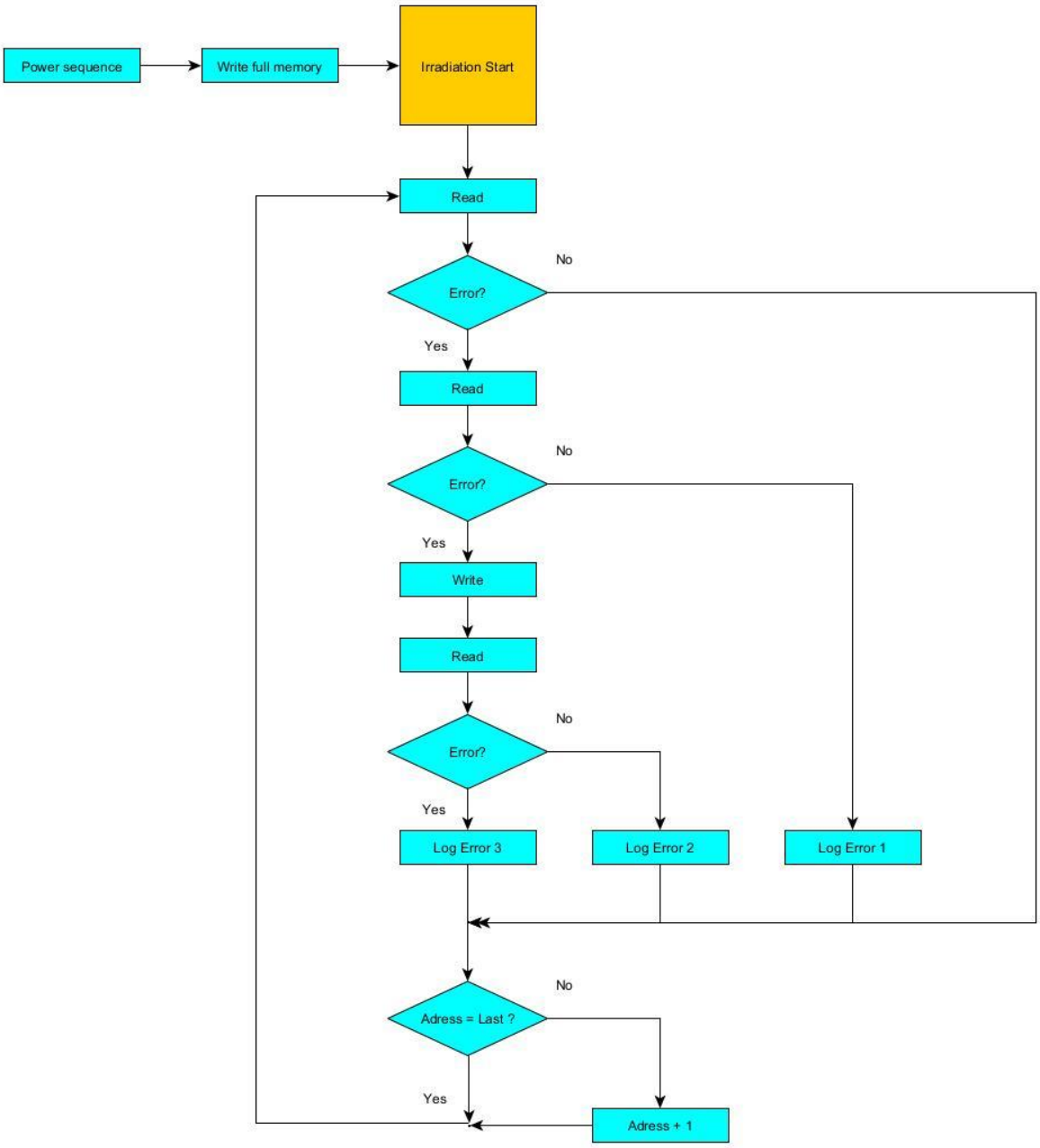


Figure 6 : Check Memory Flow Diagram.

6.3. Test bench description

6.3.1. Test bench overview

Figure 7 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 ZCU104 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.

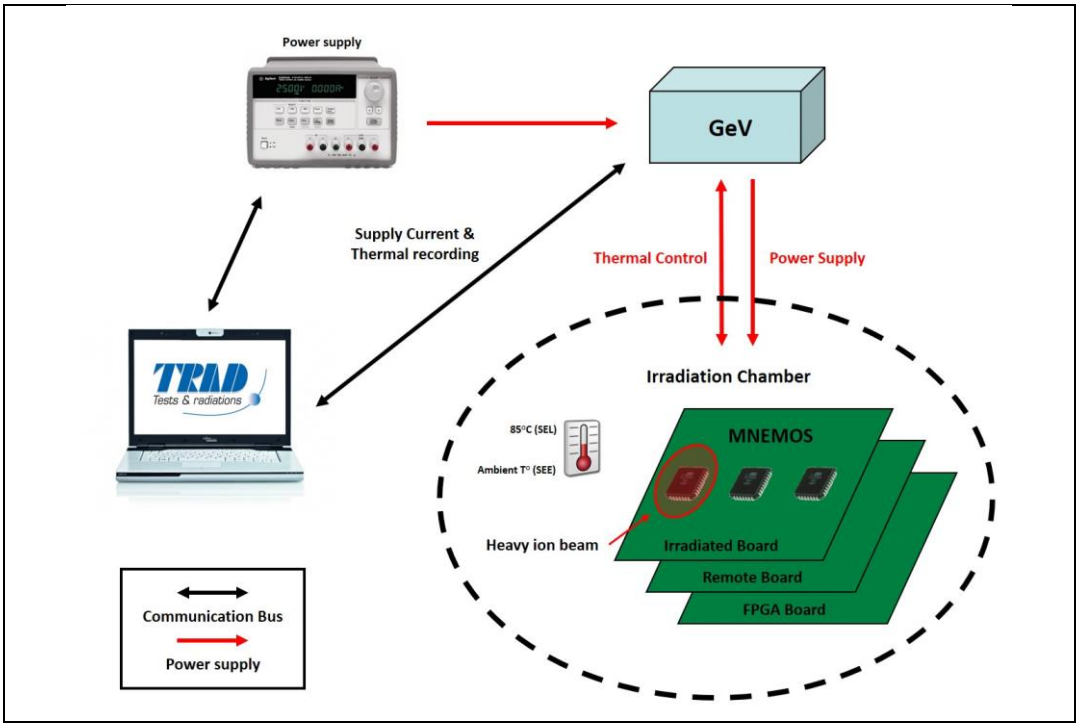


Figure 7: Test bench description

6.3.2. Heating system

TRAD has developed a specific heating system to heat and regulate the temperature of the DUT. Figure 8 shows a thermal image taken during the heating calibration of the DUT, the temperature of the die was set to 85°C as shown on the picture.

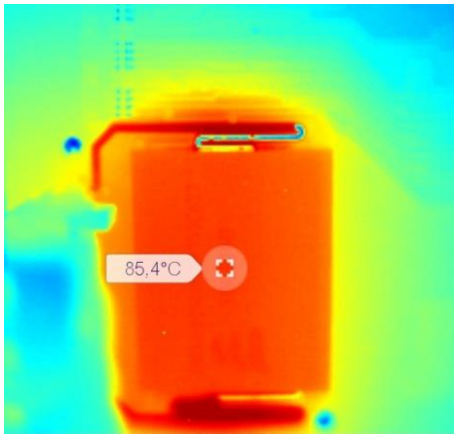


Figure 8: Thermal image of EMD4E011G heated to 85°C

6.3.3. Test equipment identification

TEST BOARD	ZCU104 XILINX TRAD/TA1/I/EDM4E011G/BGA96/PC/2205
EQUIPMENT	GeV8, ZCU104, SM-89
TEST PROGRAM	EMD4E011G_TI_XXX1_bi_V10.zip EMD4E011G_TI_XXX1_bi_V10.llb

Table 6: Equipment identification

6.3.4. Test board description

The TRAD test board schematic referenced "TRAD/TA1/EMD4E011G/BGA96/PC/2205" is illustrated in Figure 11.

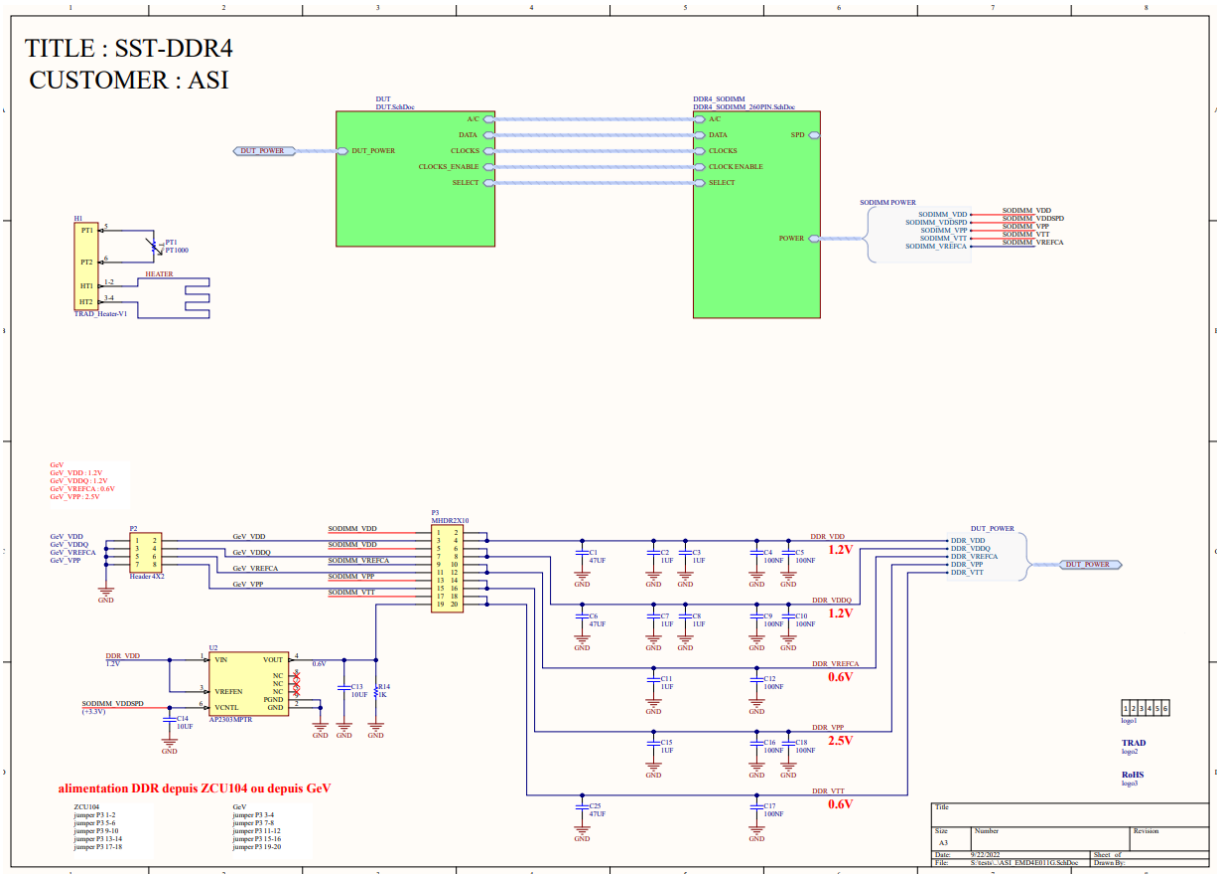


Figure 9: Test board schematic 1/3

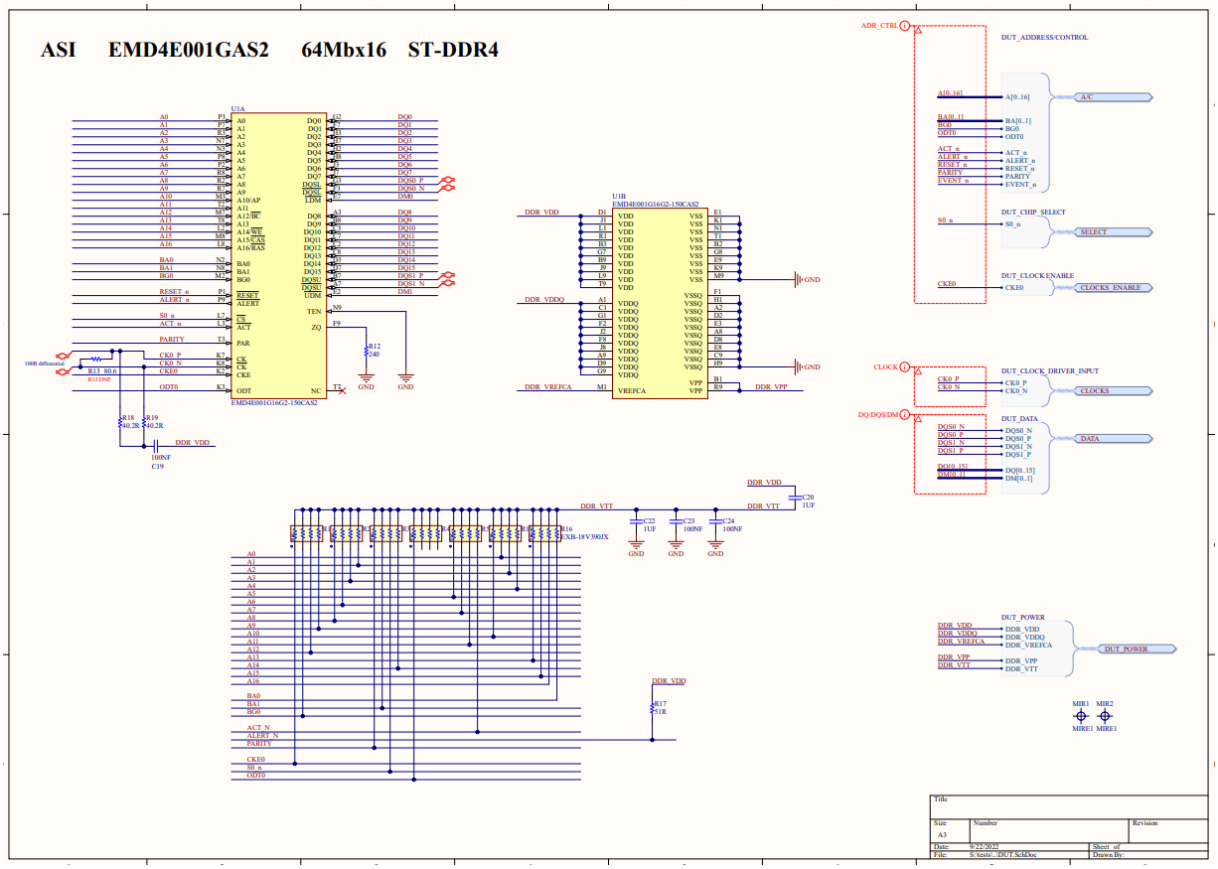


Figure 10: Test board schematic 2/3

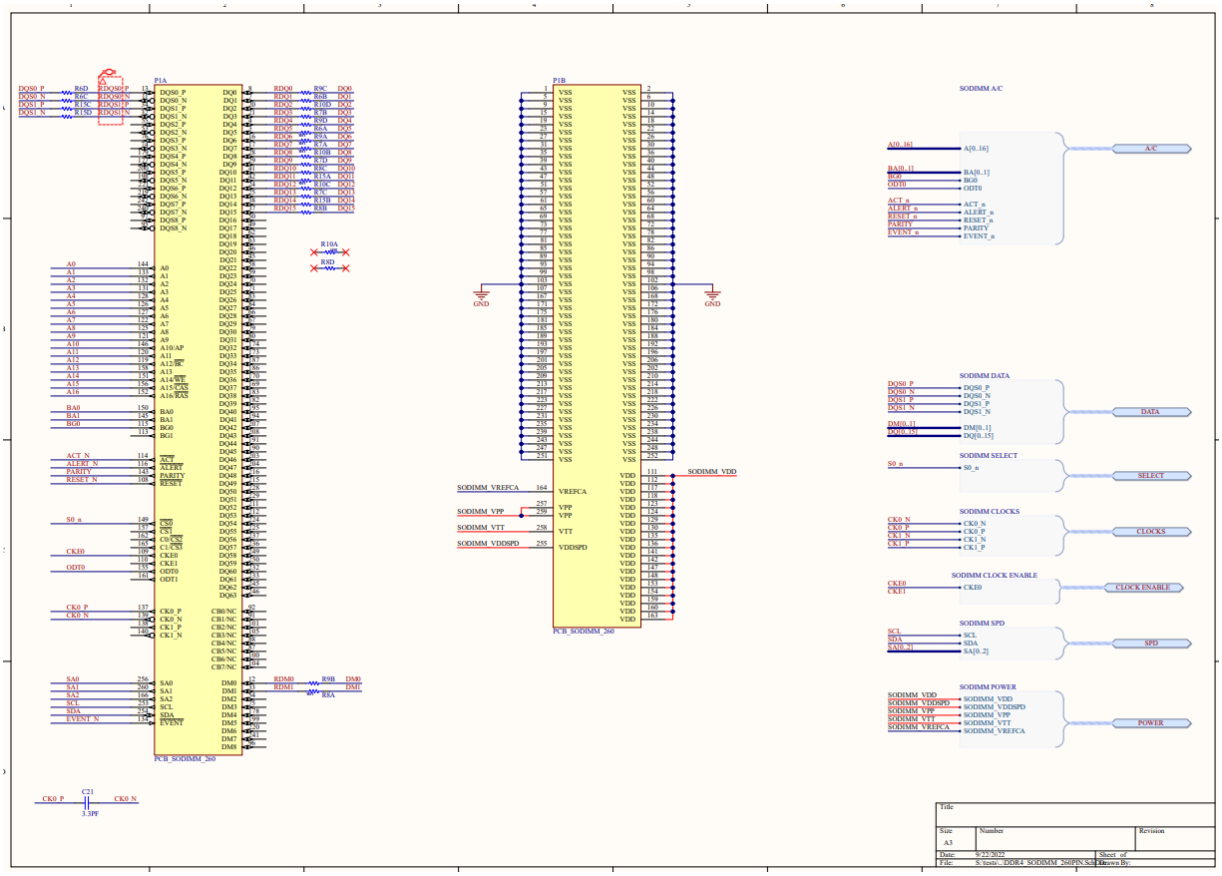


Figure 11: Test board schematic 3/3

6.3.5. Test conditions and event detection thresholds

SEL test

	EMD4E001G			
	VDD	**VDDQ**	**VPP**	**VREFCA**
Voltage	1.5 V	1.5 V	3.0 V	0.75
$I_{nominal}$	5 mA	120 mA	10 mA	1 mA
$I_{threshold}$	100 mA	300 mA	50 mA	10 mA
T_{hold}	1 ms	1 ms	1 ms	1 ms
$T_{cut\ off}$	7 ms	7 ms	7 ms	7 ms
Temperature	85°C			

Table 7: SEL test conditions and detection thresholds

SEE test

	EMD4E001G			
	VDD	**VDDQ**	**VPP**	**VREFCA**
Voltage	1.2 V	1.2 V	2.5 V	0.6
$I_{nominal}$	5 mA	120 mA	10 mA	1 mA
$I_{threshold}$	100 mA	300 mA	50 mA	10 mA
T_{hold}	1 ms	1 ms	1 ms	1 ms
$T_{cut\ off}$	7 ms	7 ms	7 ms	7 ms
Temperature	Ambient			

Table 8: SEE 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)	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)	SEFI	SEFI Cross Section (cm²)	SEU	SEU Cross Section (cm²)	MBU	MBU Cross Section (cm²)	BURST	BURST Cross Section (cm²)	SEU_bit	SEU_bit Cross Section (cm²)
1	SEL	1	85	83 Kr 29+	1826	39.5	274.0	1.01E+04	986	1.00E+07	6.32	3.92	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-16
2	SEU_READ	1	AMB	83 Kr 29+	1826	39.5	274.0	1.07E+03	935	1.00E+06	0.63	4.31	0	<1.00E-06	8	8.00E-06	234	2.34E-04	6	6.00E-06	29	2.90E-05	5.44824E-08	5.45E-14
3	SEU_READ	1	AMB	83 Kr 29+	1826	39.5	274.0	8.45E+03	1184	1.00E+07	6.32	8.23											-	-
4	SEU_READ	2	AMB	83 Kr 29+	1826	39.5	274.0	2.14E+03	467	1.00E+06	0.63	0.39	0	<1.00E-06	8	8.00E-06	143	1.43E-04	0	<1.00E-06	17	1.70E-05	3.32948E-08	3.33E-14
5	SEL	2	85	83 Kr 29+	1826	39.5	274.0	1.92E+04	520	1.00E+07	6.32	4.31	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-16
6	SEU_READ	2	AMB	57 Fe 20+	1254	23.6	283.0	1.90E+03	1052	2.00E+06	0.75	4.74	0	<5.00E-07	7	3.50E-06	437	2.19E-04	4	2.00E-06	43	2.15E-05	1.01747E-07	5.09E-14
7	SEU_WR	2	AMB	57 Fe 20+	1254	23.6	283.0	1.57E+03	638	1.00E+06	0.38	4.95	0	<1.00E-06	7	7.00E-06	55	5.50E-05	0	<1.00E-06	11	1.10E-05	1.28057E-08	1.28E-14
8	SEU_READ	1	AMB	57 Fe 20+	1254	23.6	283.0	1.30E+03	767	1.00E+06	0.38	8.44	0	<1.00E-06	5	5.00E-06	248	2.48E-04	35	3.50E-05	23	2.30E-05	5.7742E-08	5.77E-14
9	SEU_WR	1	AMB	57 Fe 20+	1254	23.6	283.0	2.05E+03	488	1.00E+06	0.38	8.66	0	<1.00E-06	4	4.00E-06	54	5.40E-05	3	3.00E-06	11	1.10E-05	1.25729E-08	1.26E-14
10	SEU_READ	1	AMB	17 O 6+	374	1.4	797.0	1.02E+04	490	5.00E+06	0.11	8.78	0	<2.00E-07	1	2.00E-07	15	3.00E-06	0	<2.00E-07	0	<2.00E-07	3.49246E-09	6.98E-16
12	SEU_WR	1	AMB	17 O 6+	374	1.4	797.0	1.16E+04	431	5.00E+06	0.11	8.90	0	<2.00E-07	1	2.00E-07	74	1.48E-05	0	<2.00E-07	5	1.00E-06	1.72295E-08	3.45E-15
13	SEU_READ	2	AMB	17 O 6+	374	1.4	797.0	1.32E+04	379	5.00E+06	0.11	5.07	0	<2.00E-07	3	6.00E-07	49	9.80E-06	0	<2.00E-07	4	8.00E-07	1.14087E-08	2.28E-15
14	SEU_WR	2	AMB	17 O 6+	374	1.4	797.0	1.32E+04	379	5.00E+06	0.11	5.19	0	<2.00E-07	1	2.00E-07	20	4.00E-06	0	<2.00E-07	1	2.00E-07	4.65661E-09	9.31E-16

Run	Test configuration	Part	T° (°C)	Ion	Energy (MeV)	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)	MBU 2 bits	MBU 2 bits Cross Section (cm²)	MBU 3 bits	MBU 3 bits Cross Section (cm²)	MBU 4 bits	MBU 4 bits Cross Section (cm²)	MBU 5 bits	MBU 5 bits Cross Section (cm²)	MBU 6 bits	MBU 6 bits Cross Section (cm²)	MBU 7 bits	MBU 7 bits Cross Section (cm²)	MBU 8 bits	MBU 8 bits Cross Section (cm²)
1	SEL	1	85	83 Kr 29+	1826	39.5	274.0	1.01E+04	986	1.00E+07	6.32	3.92	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07
2	SEU_READ	1	AMB	83 Kr 29+	1826	39.5	274.0	1.07E+03	935	1.00E+06	0.63	4.31	6	6.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
3	SEU_READ	1	AMB	83 Kr 29+	1826	39.5	274.0	8.45E+03	1184	1.00E+07	6.32	8.23														
4	SEU_READ	2	AMB	83 Kr 29+	1826	39.5	274.0	2.14E+03	467	1.00E+06	0.63	0.39	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	1	1.00E-06	0	<1.00E-06
5	SEL	2	85	83 Kr 29+	1826	39.5	274.0	1.92E+04	520	1.00E+07	6.32	4.31	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07
6	SEU_READ	2	AMB	57 Fe 20+	1254	23.6	283.0	1.90E+03	1052	2.00E+06	0.75	4.74	4	2.00E-06	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07
7	SEU_WR	2	AMB	57 Fe 20+	1254	23.6	283.0	1.57E+03	638	1.00E+06	0.38	4.95	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
8	SEU_READ	1	AMB	57 Fe 20+	1254	23.6	283.0	1.30E+03	767	1.00E+06	0.38	8.44	35	3.50E-05	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
9	SEU_WR	1	AMB	57 Fe 20+	1254	23.6	283.0	2.05E+03	488	1.00E+06	0.38	8.66	3	3.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
10	SEU_READ	1	AMB	17 O 6+	374	1.4	797.0	1.02E+04	490	5.00E+06	0.11	8.78	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
12	SEU_WR	1	AMB	17 O 6+	374	1.4	797.0	1.16E+04	431	5.00E+06	0.11	8.90	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
13	SEU_READ	2	AMB	17 O 6+	374	1.4	797.0	1.32E+04	379	5.00E+06	0.11	5.07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
14	SEU_WR	2	AMB	17 O 6+	374	1.4	797.0	1.32E+04	379	5.00E+06	0.11	5.19	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	1	2.00E-07	0	<2.00E-07

MBU 9 bits	MBU 9 bits Cross Section (cm²)	MBU 10 bits	MBU 10 bits Cross Section (cm²)	MBU 11 bits	MBU 11 bits Cross Section (cm²)	MBU 12 bits	MBU 12 bits Cross Section (cm²)	MBU 13 bits	MBU 13 bits Cross Section (cm²)	MBU 14 bits	MBU 14 bits Cross Section (cm²)	MBU 15 bits	MBU 15 bits Cross Section (cm²)	MBU 16 bits	MBU 16 bits Cross Section (cm²)
0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07
0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07

Table 9: EMD4E001G test run tables

Setting run not taken into account

SEE detailed results are described in the following sections.

9.2. Cumulated dose table

Part No.	Cumulated Dose (krad)
1	8.9
2	5.19

Table 10: 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 7).

In SEL test configuration

No SEL was observed with LET of 39.5 MeV.cm²/mg, Krypton heavy ion.

9.3.2. SEL cross sections

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

In SEL test configuration

	EMD4E001G 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 (+)
39.5	0.00E+00	<1.00E-07	3.69E-07	0.00E+00	<1.00E-07	3.69E-07

Table 11: EMD4E001G SEL cross section values in SEL test configuration

9.4. SEU test results

9.4.1. SEU LET threshold

The SEU test was performed under SEE test conditions (see Table 8).

In SEU_READ test configuration
SEU were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

In SEU_WR test configuration
SEU were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

9.4.2. SEU cross sections

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

In SEU_READ test configuration

	EMD4E001G SEU Cross Section (cm²) in SEU_READ test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
39.5	2.90E-05	2.34E-04	3.20E-05	2.25E-05	1.43E-04	2.55E-05
23.6	2.99E-05	2.48E-04	3.29E-05	2.00E-05	2.19E-04	2.15E-05
1.4	1.32E-06	3.00E-06	1.95E-06	2.55E-06	9.80E-06	3.16E-06

Table 12: EMD4E001G SEU cross section values in SEU_READ test configuration

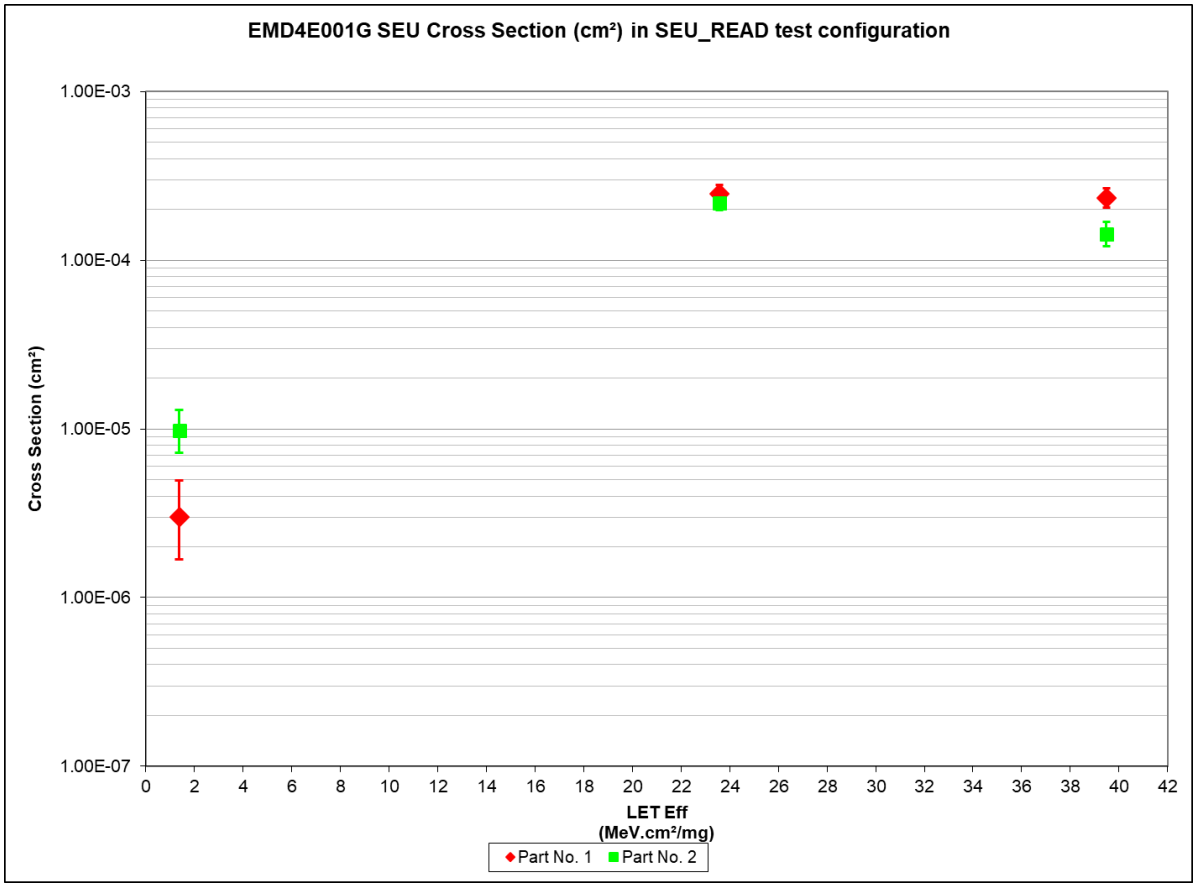


Figure 12: EMD4E001G SEU cross section curve in SEU_READ test configuration

In SEU_WR test configuration

	EMD4E001G SEU Cross Section (cm²) in SEU_WR test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
23.6	1.34E-05	5.40E-05	1.65E-05	1.36E-05	5.50E-05	1.66E-05
1.4	3.18E-06	1.48E-05	3.78E-06	1.56E-06	4.00E-06	2.18E-06

Table 13: EMD4E001G SEU cross section values in SEU_WR test configuration

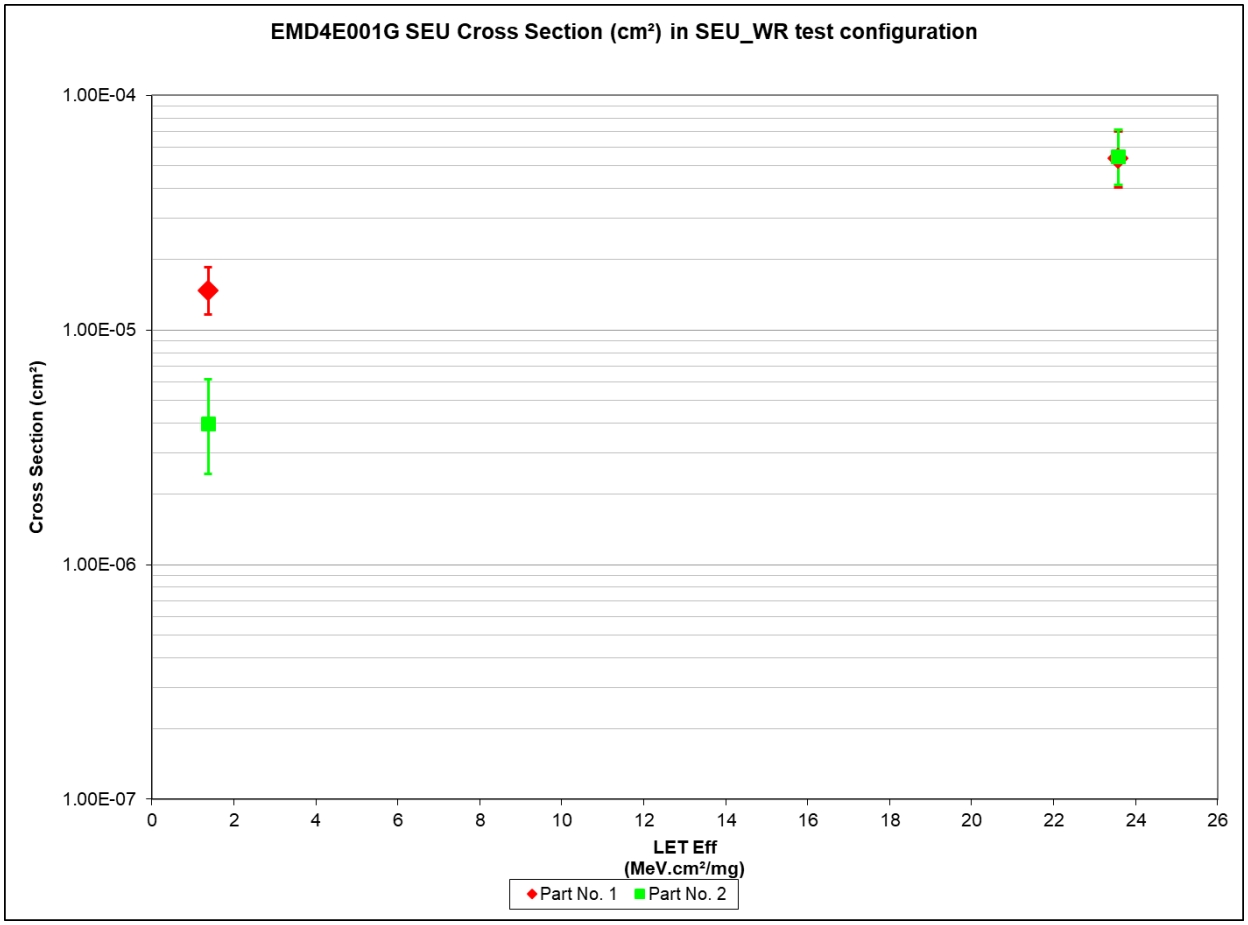


Figure 13: EMD4E001G SEU cross section curve in SEU_WR test configuration

Hereafter are shown the SEU per bit cross section values for each tested component.

In SEU_READ test configuration

	EMD4E001G SEU_bit Cross Section (cm²) in SEU_READ test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
39.5	-	5.45E-14	3.69E-06	-	3.33E-14	3.69E-06
23.6	-	5.77E-14	3.69E-06	-	5.09E-14	1.84E-06
1.4	-	6.98E-16	7.38E-07	-	2.28E-15	7.38E-07

Table 14: EMD4E001G SEU per bit cross section values in SEU_READ test configuration

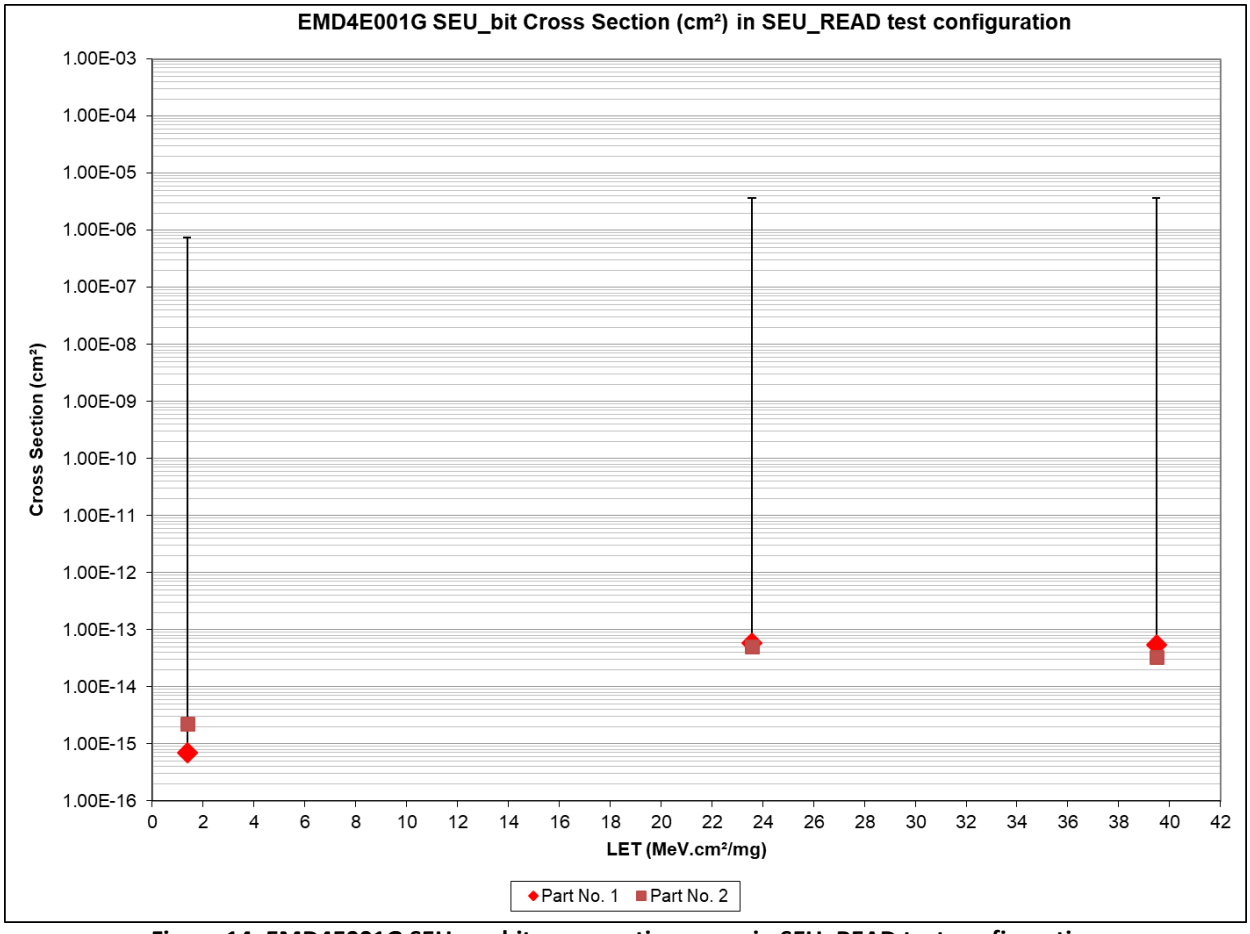


Figure 14: EMD4E001G SEU per bit cross section curve in SEU_READ test configuration

In SEU_WR test configuration

	EMD4E001G SEU_bit Cross Section (cm²) in SEU_WR test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
23.6	-	1.26E-14	3.69E-06	-	1.28E-14	3.69E-06
1.4	-	3.45E-15	7.38E-07	-	9.31E-16	7.38E-07

Table 15: EMD4E001G SEU per bit cross section values in SEU_WR test configuration

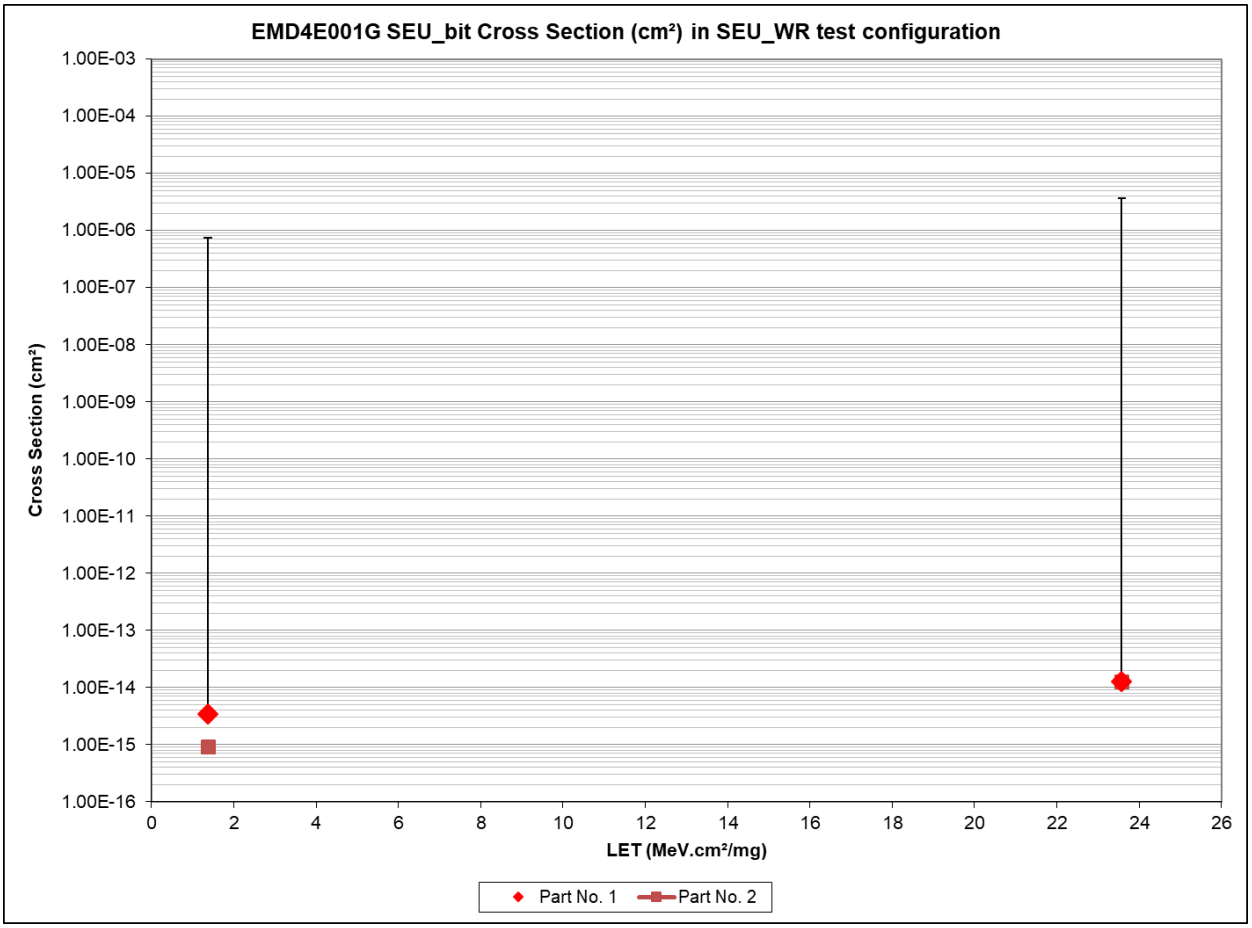


Figure 15: EMD4E001G SEU per bit cross section curve in SEU_WR test configuration

9.5. MBU test results

9.5.1. MBU LET threshold

The MBU test was performed under SEE test conditions (see Table 8).

In SEU_READ test configuration

MBU were observed with a minimum LET of 23.6 MeV.cm²/mg, Iron heavy ion.
No events were observed with LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.

In SEU_WR test configuration

MBU were observed with a minimum LET of 23.6 MeV.cm²/mg, Iron heavy ion.
No events were observed with LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.

9.5.2. MBU cross sections

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

In SEU_READ test configuration

	EMD4E001G MBU Cross Section (cm²) in SEU_READ test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
39.5	3.80E-06	6.00E-06	7.06E-06	0.00E+00	<1.00E-06	3.69E-06
23.6	1.06E-05	3.50E-05	1.37E-05	1.46E-06	2.00E-06	3.12E-06
1.4	0.00E+00	<2.00E-07	7.38E-07	0.00E+00	<2.00E-07	7.38E-07

Table 16: EMD4E001G MBU cross section values in SEU_READ test configuration

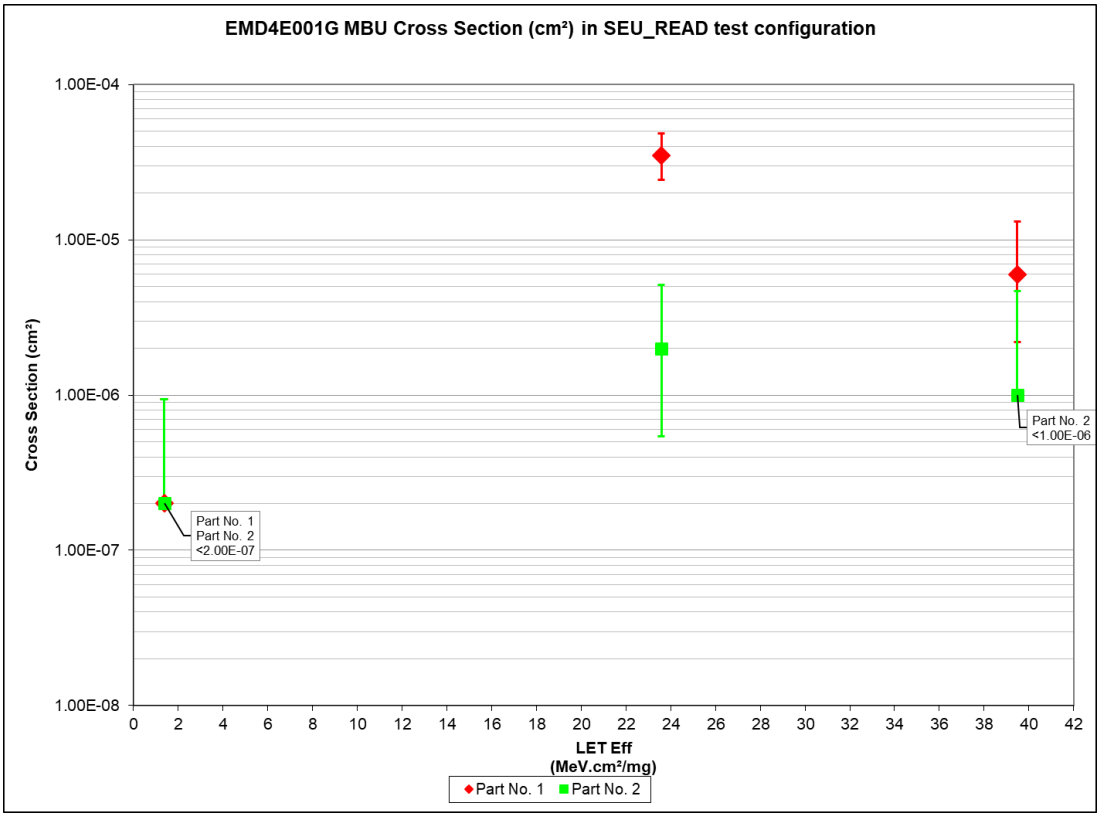


Figure 16: EMD4E001G MBU cross section curve in SEU_READ test configuration

In SEU_WR test configuration

LET Eff (MeV.cm²/mg)	EMD4E001G MBU Cross Section (cm²) in SEU_WR test configuration					
	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
23.6	2.38E-06	3.00E-06	5.77E-06	0.00E+00	<1.00E-06	3.69E-06
1.4	0.00E+00	<2.00E-07	7.38E-07	0.00E+00	<2.00E-07	7.38E-07

Table 17: EMD4E001G MBU cross section values in SEU_WR test configuration

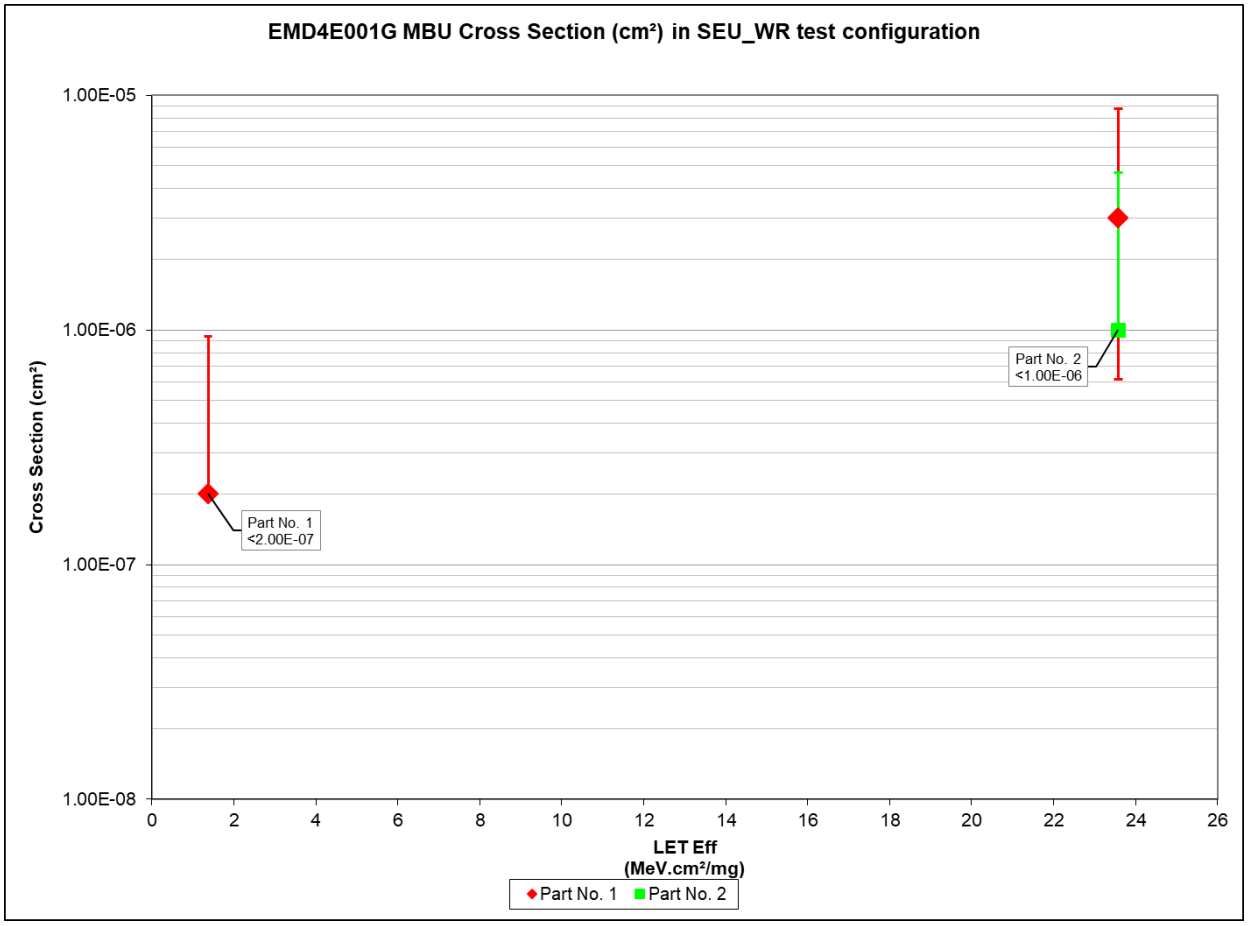


Figure 17: EMD4E001G MBU cross section curve in SEU_WR test configuration

MBU distribution

Table 18 and 19 give the MBU distribution observed during the test campaign.

Run	Part	Ion	Run Fluence (cm^{-2})	MBU 2 bits	MBU 2 bits Cross Section (cm^2)	MBU 3 bits	MBU 3 bits Cross Section (cm^2)	MBU 4 bits	MBU 4 bits Cross Section (cm^2)	MBU 5 bits	MBU 5 bits Cross Section (cm^2)	MBU 6 bits	MBU 6 bits Cross Section (cm^2)	MBU 7 bits	MBU 7 bits Cross Section (cm^2)	MBU 8 bits	MBU 8 bits Cross Section (cm^2)
1	1	83 Kr 29+	1.00E+07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07
2	1	83 Kr 29+	1.00E+06	6	6.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
3	1	83 Kr 29+	1.00E+07														
4	2	83 Kr 29+	1.00E+06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	1	1.00E-06	0	<1.00E-06
5	2	83 Kr 29+	1.00E+07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07
6	2	57 Fe 20+	2.00E+06	4	2.00E-06	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07
7	2	57 Fe 20+	1.00E+06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
8	1	57 Fe 20+	1.00E+06	35	3.50E-05	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
9	1	57 Fe 20+	1.00E+06	3	3.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
10	1	17 O 6+	5.00E+06	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
12	1	17 O 6+	5.00E+06	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
13	2	17 O 6+	5.00E+06	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
14	2	17 O 6+	5.00E+06	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	1	2.00E-07	0	<2.00E-07

Table 18: EMD4E001G Test runs MBU distribution

MBU 9 bits	MBU 9 bits Cross Section (cm^2)	MBU 10 bits	MBU 10 bits Cross Section (cm^2)	MBU 11 bits	MBU 11 bits Cross Section (cm^2)	MBU 12 bits	MBU 12 bits Cross Section (cm^2)	MBU 13 bits	MBU 13 bits Cross Section (cm^2)	MBU 14 bits	MBU 14 bits Cross Section (cm^2)	MBU 15 bits	MBU 15 bits Cross Section (cm^2)	MBU 16 bits	MBU 16 bits Cross Section (cm^2)
0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07	0	<1.00E-07
0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07	0	<5.00E-07
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06	0	<1.00E-06
0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07
0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07	0	<2.00E-07

Table 19: EMD4E001G Test runs MBU distribution

9.6. SEFI test results

9.6.1. SEFI LET threshold

The SEFI test was performed under SEE test conditions (see Table 8).

In SEU_READ test configuration
SEFI were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

In SEU_WR test configuration
SEFI were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

9.6.2. SEFI cross sections

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

In SEU_READ test configuration

	EMD4E001G SEFI Cross Section (cm²) in SEU_READ test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
39.5	4.55E-06	8.00E-06	7.76E-06	4.55E-06	8.00E-06	7.76E-06
23.6	3.38E-06	5.00E-06	6.67E-06	2.09E-06	3.50E-06	3.71E-06
1.4	1.95E-07	2.00E-07	9.14E-07	4.76E-07	6.00E-07	1.15E-06

Table 20: EMD4E001G SEFI cross section values in SEU_READ test configuration

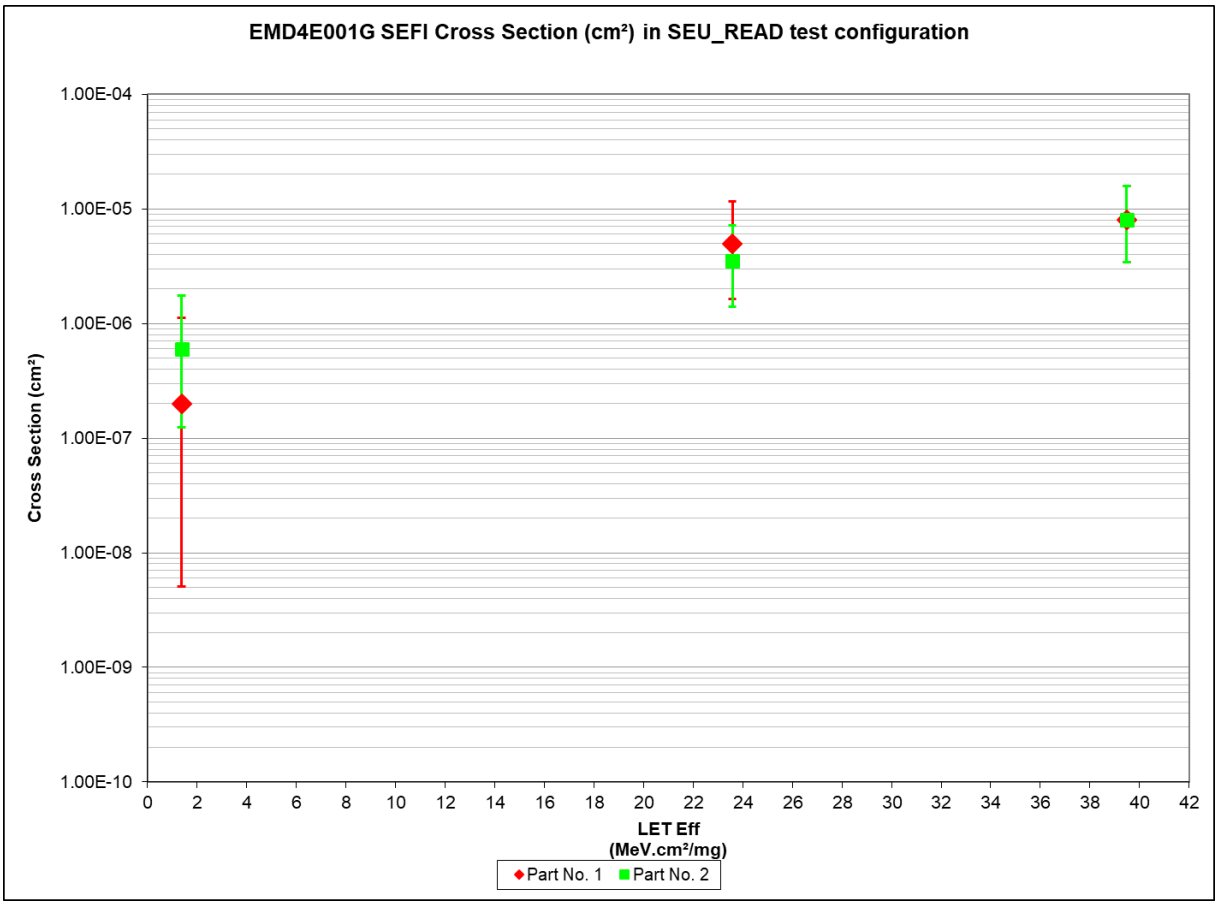


Figure 18: EMD4E001G SEFI cross section curve in SEU_READ test configuration

In SEU_WR test configuration

	EMD4E001G SEFI Cross Section (cm²) in SEU_WR test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
23.6	2.91E-06	4.00E-06	6.24E-06	4.19E-06	7.00E-06	7.42E-06
1.4	1.95E-07	2.00E-07	9.14E-07	1.95E-07	2.00E-07	9.14E-07

Table 21: EMD4E001G SEFI cross section values in SEU_WR test configuration

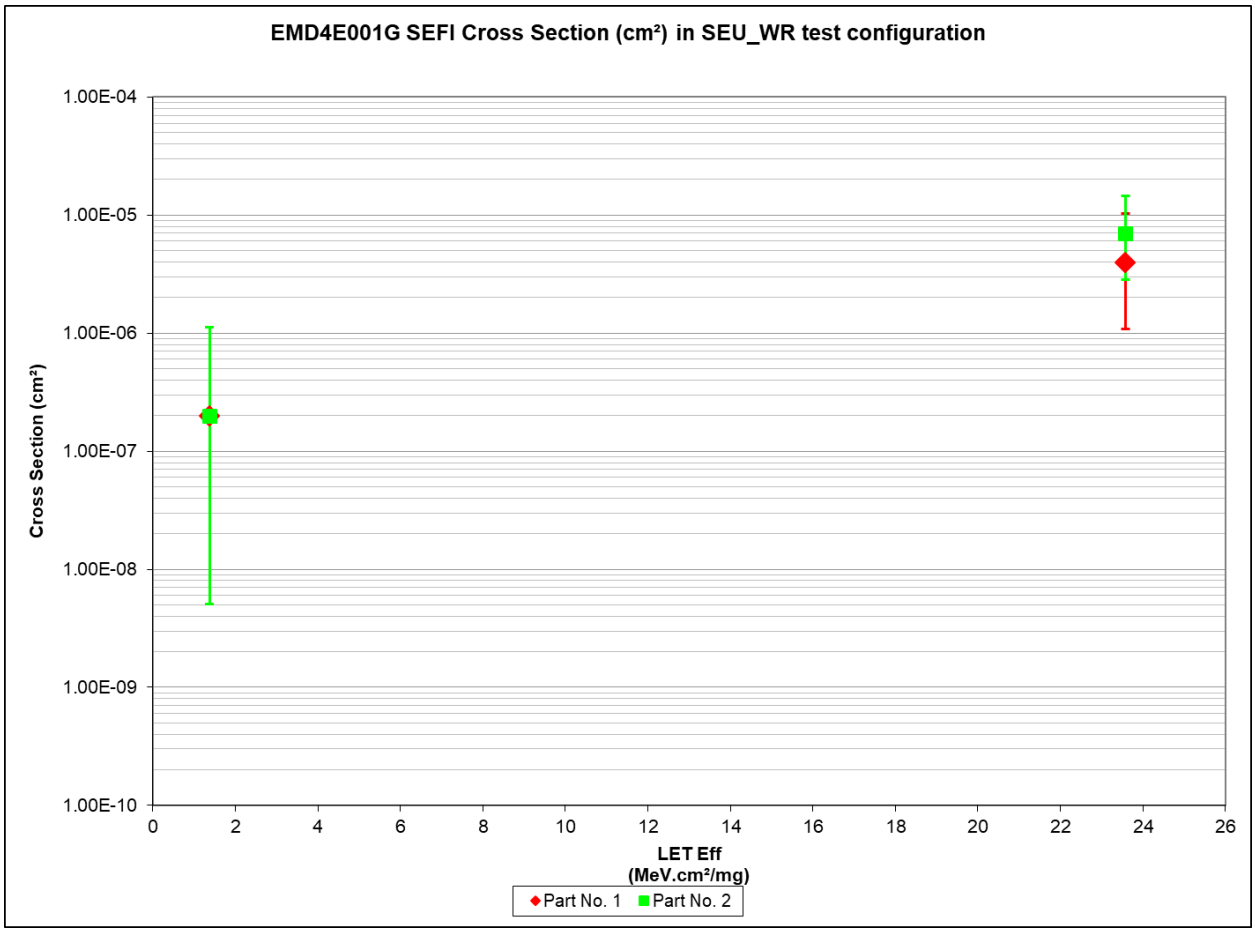


Figure 19: EMD4E001G SEFI cross section curve in SEU_WR test configuration

9.7. Burst test results

9.7.1. Burst LET threshold

The Burst test was performed under SEE test conditions (see Table 8).

In SEU_READ test configuration

Burst were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

In SEU_WR test configuration

Burst were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

9.7.2. Burst cross sections

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

In SEU_READ test configuration

	EMD4E001G BURST Cross Section (cm²) in SEU_READ test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
39.5	9.58E-06	2.90E-05	1.26E-05	7.10E-06	1.70E-05	1.02E-05
23.6	8.42E-06	2.30E-05	1.15E-05	5.94E-06	2.15E-05	7.46E-06
1.4	0.00E+00	<2.00E-07	7.38E-07	5.82E-07	8.00E-07	1.25E-06

Table 22: EMD4E001G Burst cross section values in SEU_READ test configuration

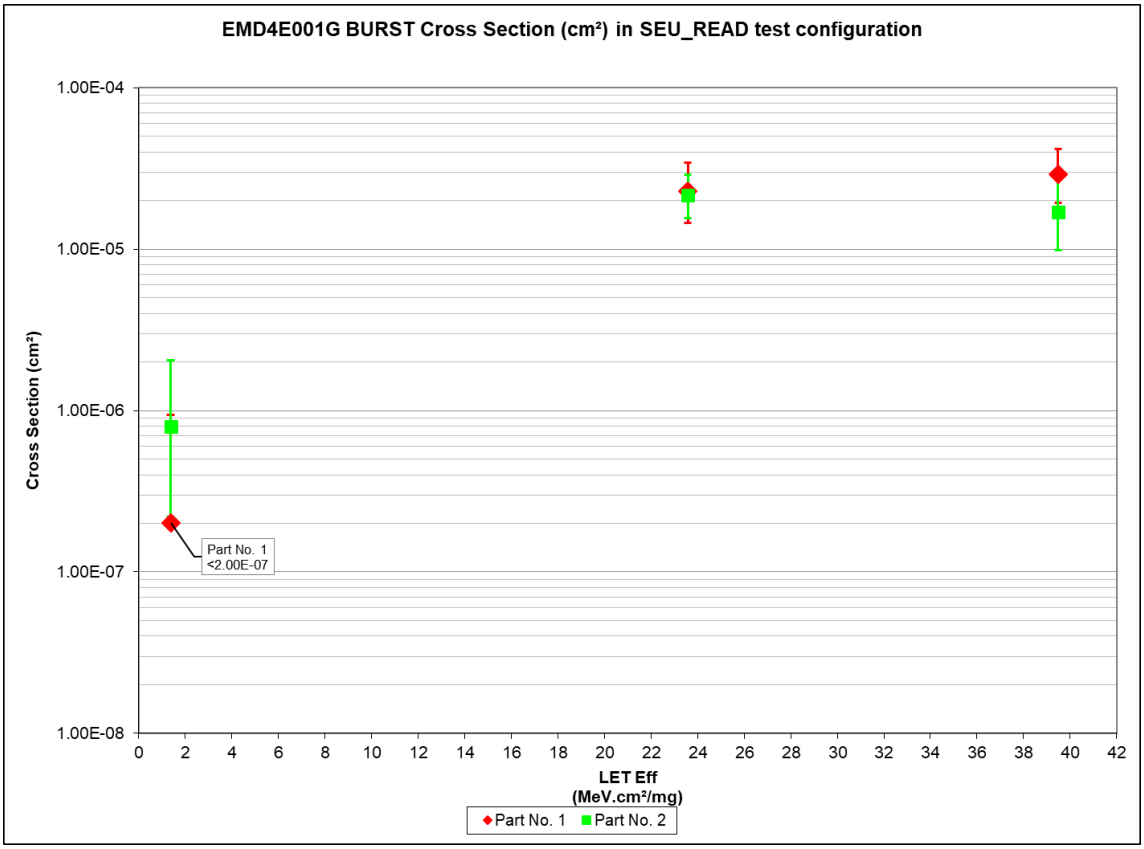


Figure 20: EMD4E001G Burst cross section curve in SEU_READ test configuration

In SEU_WR test configuration

	EMD4E001G BURST Cross Section (cm²) in SEU_WR test configuration					
LET Eff (MeV.cm²/mg)	Part No. 1			Part No. 2		
	error (-)	cross section	error (+)	error (-)	cross section	error (+)
23.6	5.51E-06	1.10E-05	8.68E-06	5.51E-06	1.10E-05	8.68E-06
1.4	6.75E-07	1.00E-06	1.33E-06	1.95E-07	2.00E-07	9.14E-07

Table 23: EMD4E001G Burst cross section values in SEU_WR test configuration

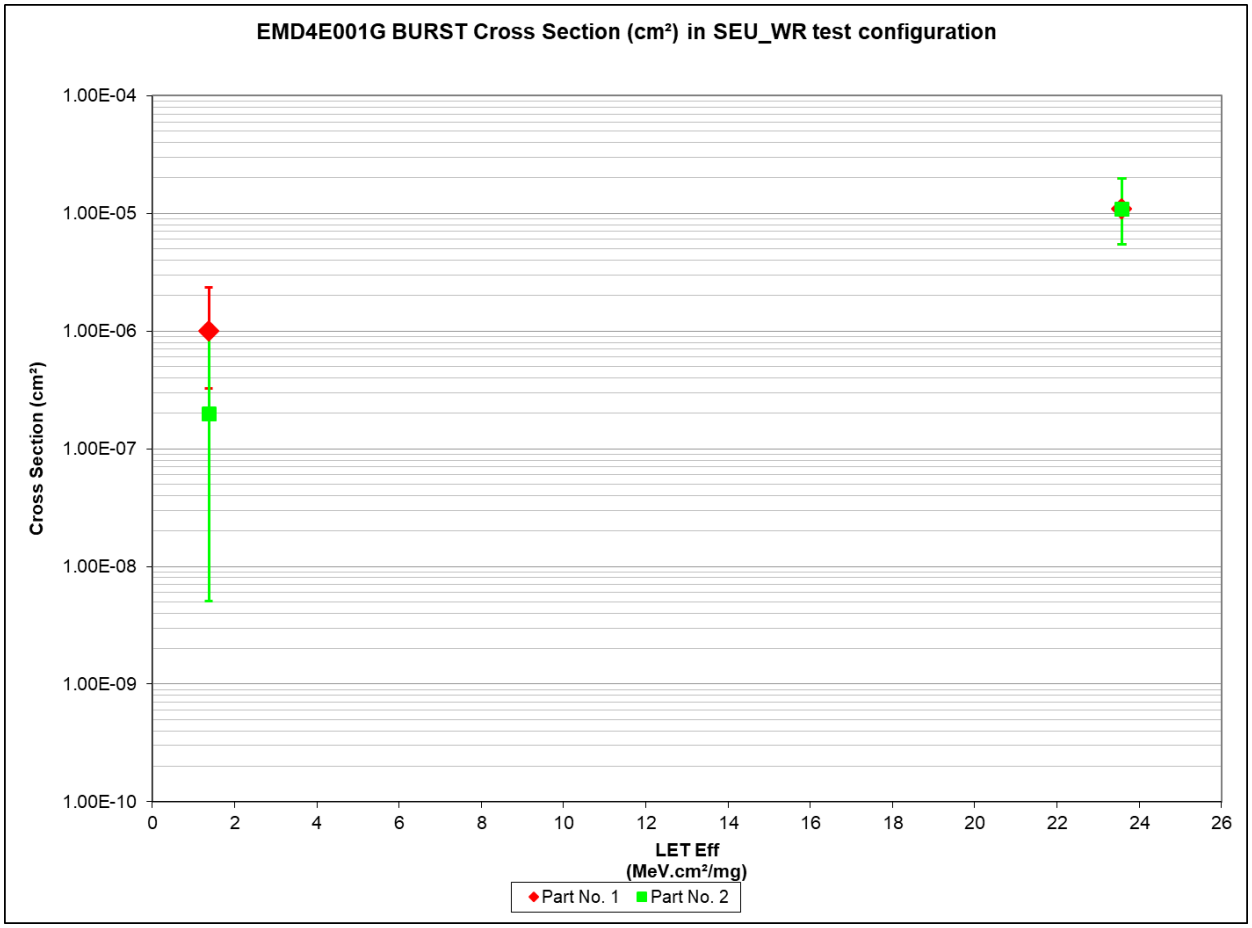


Figure 21: EMD4E001G Burst cross section curve in SEU_WR test configuration

10. Conclusion

The heavy ions test was performed on EMD4E001G. The aim of the test was to evaluate the sensitivity of the device versus SEL, SEU, MBU and SEFI.

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

In SEL test configuration
No SEL was observed with LET of 39.48 MeV.cm²/mg, Krypton heavy ion.

The SEU test was performed under SEE test conditions (see Table 8).

In SEU_READ test configuration
SEU were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

MBU were observed with a minimum LET of 23.6 MeV.cm²/mg, Iron heavy ion.
No MBU was observed with LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.

BURST were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

SEFI were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

In SEU_WR test configuration
SEU were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

MBU were observed with a minimum LET of 23.6 MeV.cm²/mg, Iron heavy ion.
No MBU was observed with LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.

BURST were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.

SEFI were observed with a minimum LET of 1.4 MeV.cm²/mg, Oxygen heavy ion.
No lower LET was tested during this test campaign.