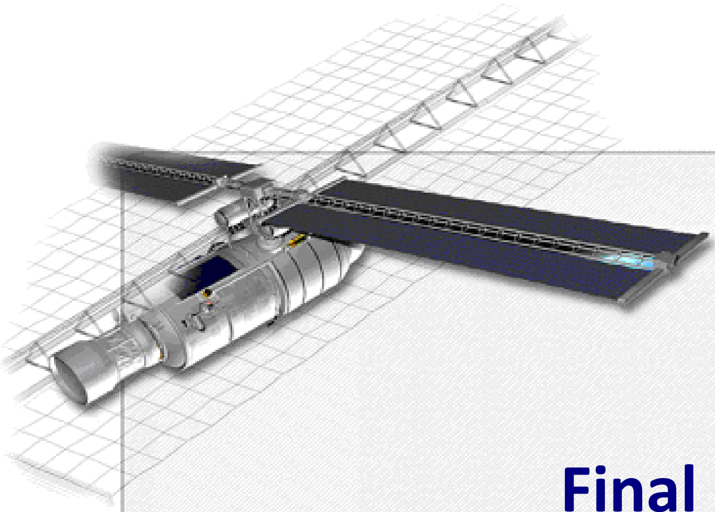
TID Influence on the SEE sensitivity of Active EEE



Final Report

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To: **ESA** **POIZAT Marc**	Projet/Programme: TID Influence on the SEE sensitivity of Active EEE Ref: ESTEC Contfract No. 4000111336

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1. INTRODUCTION

The radiation hardness of modern electronic devices regarding the space radiation environment is characterized according to two main aspects: cumulated effects and single event effects. The parts radiation qualification process includes Total Ionizing Dose (TID), Total Non-Ionizing Dose (TNID) and Single Event Effect (SEE) tests, usually performed independently. The aim of this study is to evaluate the potential synergetic effects of TID on SEE sensitivity.

Four devices have been selected for this study:

- ADC AD9042 from Analog Device
- DAC AD558 from Analog Device
- Flash NAND MT29F4G08AAC from Micron
- SRAM R1RW0416 from Renesas

Parametric tests have been performed on fifty devices of each part type. Of the fifty devices, forty were delidded and used for the TID-SEE synergy study, and 10 were not delidded. The latter were used as reference to identify possible degradation effects not due to TID, but induced by time spent in a non-controlled atmosphere.

All these devices have been irradiated under Cobalt 60 up to 150 krad for the ADC, the DAC and the SRAM and up to 100 krad for the Flash NAND. This dose level has been selected in order to evaluate if synergetic effects can be observed for standard missions (GEO, MEO or LEO) and also for the specific JUICE mission where an important final dose level is expected.

Four TID steps have been performed on Flash NAND and five TIS steps have been performed on ADC, DAC and SRAM respectively. At each TID step, parametric tests have been performed on ten devices of each reference (5 ON and 5 OFF). Following these tests, heavy ion tests were performed for both ON and OFF bias conditions under ^{60}Co. Three devices which were biased and two devices which were unbiased under ^{60}Co are tested under heavy ions to obtain sufficient part-to-part variability statistics for further analysis on the synergetic effects. A delidded reference part (not exposed to TID) is also tested under heavy ions.

Once the devices were irradiated and measured (parametric test and SEE cross section), they were no longer used for the study.

This report presents results obtained during this study.

A comparison between parametric measurements performed on delidded and undelidded parts is presented for each reference. TID measurements performed on delidded parts during the synergy study are also compared to the TID pre-characterization on delidded parts using a different dose rate. Impact of used dose rate and die ageing in a non-controlled atmosphere are then studied.

Impact of TID on SEE sensitivity is also described for each reference. Indeed standard SEE cross section, performed on non-irradiated devices, is compared to SEE cross section performed on TID irradiated parts. These comparisons are performed on SEE test results as a whole but also regarding the biased condition used during Cobalt 60 irradiation.

SEE signatures are also studied as a function of TID level:

- The impact of TID on SET number observed on ADC AD9042 from Analog Device is analyzed,
- The impact of TID on the SET shape observed on DAC AD558 from Analog Device is analyzed,,

- The impact of TID on Bad Blocks measured on Flash NAND MT29F4G08AAC from Micron and the impact of TID on SEL sensitivity are studied,
- The impact of TID on MBU multiplicity and imprint effects on the SRAM R1RW0416 from Renesas is considered.

2. DOCUMENTS

2.1. Applicable documents

[AD1].	TRAD/P/ESA/AO7751/AV/130214 Rev.0 Proposal in response to ITT/AO/1-7751/13/NL/SW

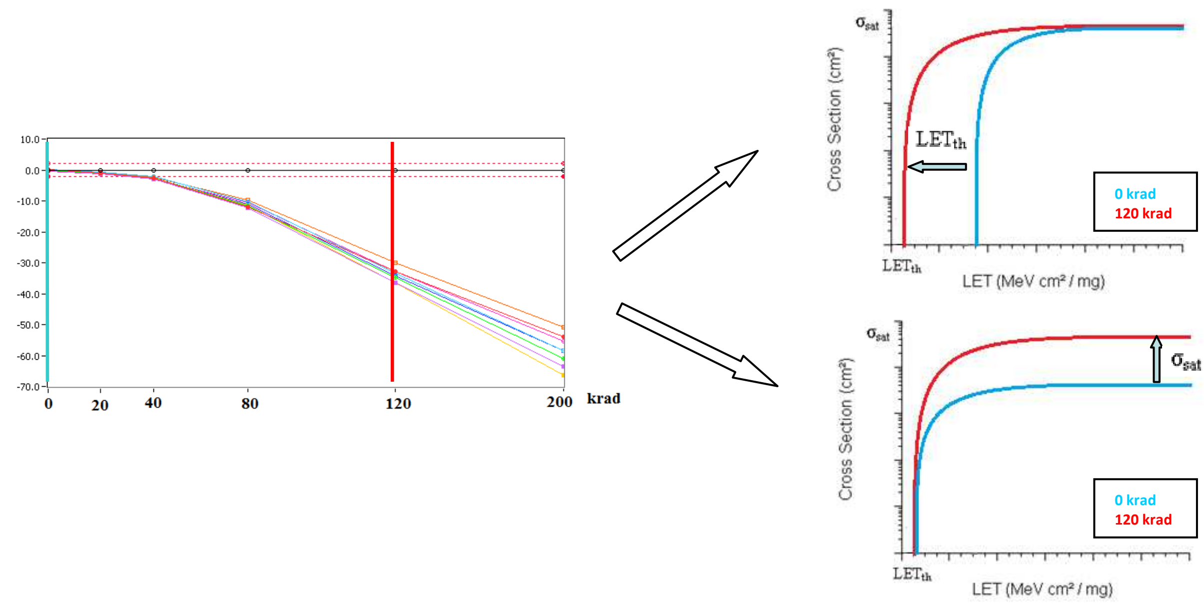
2.2. Reference documents

[RD1].	TID Influence on the SEE sensitivity of Active EEE; WP1: Part Selection; TRAD_ESA_IR_SYN_AS3_040714
[RD2].	TID Influence on the SEE sensitivity of Active EEE; Choix des ions pour les tests SEE TRAD_ESA_IR_SYN_AS3_300115
[RD3].	"Catastrophic failure in highly scaled commercial NAND flash memories," F. Irom, D. N. Nguyen, G. Cellere, M. Bagatin, S. Gerardin, and A. Paccagnella, IEEE Trans. Nucl. Sci., vol. 57, no. 1, pp. 266–271, Feb. 2010.
[RD4].	"Single event effect characterization of high density commercial NAND and NOR nonvolatile flash memories", F. Irom and D. Nguyen, IEEE Trans. Nucl. Sci., vol. 54, no. 6, pp.2547-2553, Dec. 2007
[RD5].	TRAD_TE_AD558JNZ_1116_ESA_LG_1409_lot_A_rev0
[RD6].	TRAD_TE_AD9042ASTZ_1314_ESA_LG_1409_lot_A_rev0
[RD7].	TRAD_TE_MT29F4G08ABADAWP_1350_ESA_LG_1409_lot_A_Rev0
[RD8].	TRAD_TE_R1RW0416DSB_1346_ESA_LG_1409_lot_A_rev0
[RD9].	TRAD_TI_AD558JNZ_1116_ESA_LG_1409_lot_I_rev0
[RD10].	TRAD_TI_AD9042ASTZ_1314_ESA_LG_1409_lot_I_rev0
[RD11].	TRAD_TI_MT29F4G08ABADAWP_1350_ESA_LG_1409_lot_I_Rev0
[RD12].	TRAD_TI_R1RW0416DSB_1346_ESA_LG_1409_lot_I_Rev0

3. COMPONENT SELECTION AND PROCUREMENT

The devices selected for the study should be sensitive to TID in order to display parameter drift, but not too much to remain functional during the whole test campaign.

On the other hand, devices should be sensitive to SEE, but with an LET threshold above a few MeV.cm^2/mg in order to observe a potential LET threshold drift towards zero during the test campaign. The device's saturated cross section should be low enough (regarding the available particle fluxes provided by the facility) to measure a potential increase.



Moreover, these components have to be commercially available in high quantities with the same date code, and procurement and test development need to be in accordance with the study budget.

Considering these requirements, the first step of this study was a bibliographical research to evaluate the best candidates. Available component databases as well as Data Workshop papers (NSREC, RADECS) were consulted. The result of this research is detailed in [RD1].

Considering these requirements, four device references have been selected for this study. The part selection covers data converters (ADC and DAC), SRAMs and NAND Flash memory devices commonly used in space missions.

TABLE 1. List of selected parts

Reference	Manufacturer	Type	Technology	Package	Quality level	Quantity
AD9042	Analog Device	ADC 12bit	Bip. XFCB	LQFP-44	Commercial	100
AD558	Analog Device	DAC 8bit	Bip. I2L	PDIP	Commercial	100
MT29F4G08AAC	Micron	NAND flash	SLC	TSOP	Commercial	100
R1RW0416	Renesas	SRAM 16Mb 8bit	CMOS	TSOP	Commercial	100

Around 70 parts of each reference were tested during the synergy study. One hundred devices were procured in for each reference to take into account possible losses during the delidding process.

4. IRRADIATION TEST PLAN

The flow chart on the next figure presents the different steps that were performed for each part type.

For each reference, four LOTs are considered:

- LOTP: A preliminary ^{60}Co irradiation was performed at GAMRAY (TRAD facility in Toulouse; France) in order to evaluate the device degradation up to a final dose of 250 krad(Si). Ten non delidded devices are tested: five of them are biased OFF and five are biased. All test results are available in [RD5][RD6][RD7][RD8]
- LOTI: An SEE test is performed at UCL (Louvain-la-Neuve; Belgium) on three non-irradiated devices in order to evaluate the SEE sensitivity before ^{60}Co irradiation. All test results are available in [RD9][RD10][RD11][RD12]
- LOTB, LOTC, LOTD and LOTE: Combined TID and SEE tests are performed at UCL (Louvain-la-Neuve; Belgium) in order to evaluate the synergetic effect of ^{60}Co with heavy ions.

  The UCL facility has been chosen because TID and SEE tests can be performed at the same place which minimizes the time between TID measurement and SEE tests.

  Forty devices are placed under ^{60}Co irradiation and four TID steps are performed. At each TID step, ten devices are removed from the irradiation facility and measured. Among these ten devices, three biased parts and two unbiased parts are selected for the test under heavy ions. One non-irradiated part is also tested under heavy ion to evaluate the impact of delidding on the SEE sensitivity. Each TID step corresponds to a LOT (B, C, D or E).

  Due to the high TID sensitivity of the MT29F4G08AAC NAND Flash memories, ^{60}Co irradiation has not been performed on LOTE.
- LOTA: As the devices under test need to be delidded for heavy ion irradiations, the delidding operation has to be done before the ^{60}Co irradiation. The time between the end of the TID sequence and the heavy ion test should be limited to two hours to avoid any dose annealing. This constrain does not allow to perform the delidding process between TID and heavy ion tests.

  As a consequence, all devices were delidded before the TID exposure, and will therefore remained open for a long time in a non-controlled atmosphere, in terms of temperature and moisture (the ^{60}Co irradiation room).

  The usual way to test electronic devices to TID includes a reference part to control the parametric test repeatability and potential test hardware drift over long irradiation times. In order to keep control over possible degradation effects due to the irradiation room environment, and not to TID, the experimental procedure applied to the synergetic effect study will consider ten non-delidded reference parts exposed to TID and measured at each dose step (LOTA). The irradiated non-delidded samples will help demonstrate if the delidded parts present different drifts under ^{60}Co.

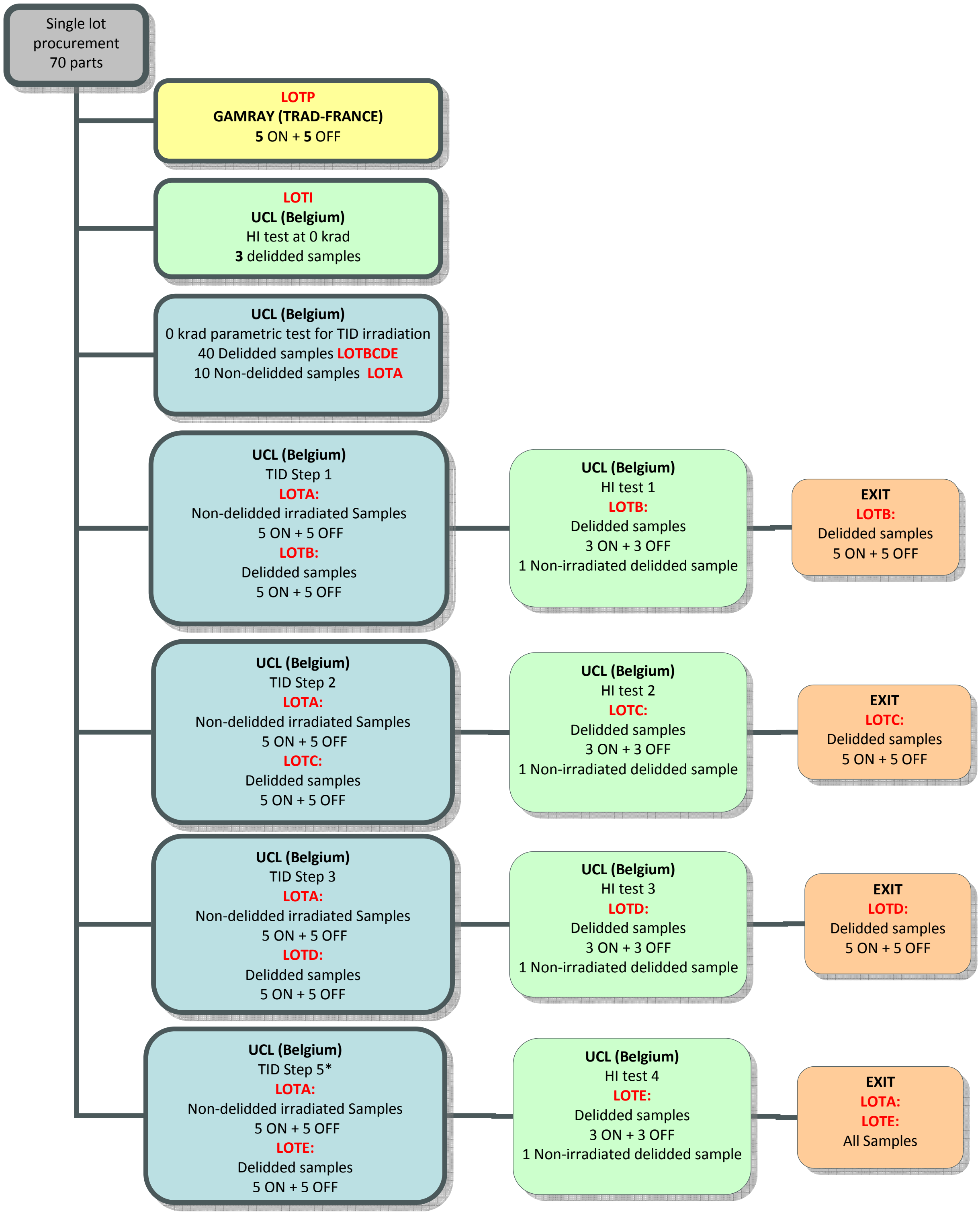
The next table resumes the part repartition:

TABLE 2 : part LOT repartition

	Facility	Test	Device Number
LOTP	GAMRAY (TRAD Toulouse; France)	TID pre-characterisation	10 (5 ON + 5 OFF)
LOTI	UCL (Louvain-la-Neuve; Belgium)	SEE test	3
LOTA	UCL (Louvain-la-Neuve; Belgium)	Non-delidded TID test	10 (5 ON + 5 OFF)
LOTB	UCL (Louvain-la-Neuve; Belgium)	TID step1	10 (5 ON + 5 OFF)
		SEE step1	6 (3 ON + 2 OFF+1 REF)
LOTC	UCL (Louvain-la-Neuve; Belgium)	TID step2	10 (5 ON + 5 OFF)
		SEE step2	6 (3 ON + 2 OFF+1 REF)
LOTD	UCL (Louvain-la-Neuve; Belgium)	TID step3	10 (5 ON + 5 OFF)
		SEE step3	6 (3 ON + 2 OFF+1 REF)
LOTE*	UCL (Louvain-la-Neuve; Belgium)	TID step4	10 (5 ON + 5 OFF)
		SEE step4	6 (3 ON + 2 OFF+1 REF)

*Not performed on the MT29F4G08AAC NAND Flash memories

Details are described below.



*Not performed on the MT29F4G08AAC NAND Flash memories

Figure 1 : Proposed test organization

4.1. TID pre-characterization

A TID pre-characterization was conducted for each part type in order to estimate the device behavior and to adjust efficiently the TID steps for the synergy study test campaign. This test campaign was performed at the GAMRAY facility (TRAD- France) up to the total dose of 250 krad(Si) for all references.

Total dose, dose rate and irradiation steps are described in the following table for the pre-characterization campaign.

TABLE 3 : Irradiation test parameters for the pre-characterization campaign.

Source characteristics		
	Source	^{60}Co
	Site	GAMRAY (TRAD facility in Toulouse - France)
	Dosimetry	Doselec
Irradiation conditions for all lots		
	Dose Rate	310 rad(Si)/h
	Total dose	250 krad(Si)
	Accumulated Dose Steps	0, 10, 20, 30, 50, 70, 100, 150, 200, 250 krad(Si)

All pre-characterization test results are available in [RD5][RD6][RD7][RD8].
The DAC AD558, ADC AD9042 and SRAM R1RW0416 remain functional at 250 krad(Si).
However, the irradiation for the MT29F4G08AAC NAND Flash memories was stopped at 150 krad(Si) due to their low TID tolerance.

4.2. SEE pre-characterization

Three delidded devices of each reference were tested under heavy ion at UCL (Belgium). These experiments provided, for each device, the reference cross section curve before TID irradiation.

All SEE test results are available in [RD9][RD10][RD11][RD12]

4.3. Combined TID and SEE tests

Parametric tests are performed on fifty devices of each part type. Of the fifty devices, forty were delidded and used for the TID-SEE synergy study, and 10 were not delidded and used as reference to identify possible degradation effects induced by long time irradiation room environment exposure, and not to TID. All of these devices are exposed to Cobalt 60 irradiation. Final dose level and dose rate are determined in accordance with each TID pre-characterization previously performed.

Four TID steps are performed for the ADC AD9042, the DAC AD558 and the SRAM R1RW0416. However, only three steps were performed for the MT29F4G08AAC NAND Flash memories. Forty NAND flash were then tested during the synergy study.

At each TID step, parametric tests were performed on ten devices of each reference (5 ON and 5 OFF). After the TID steps, heavy ion tests were conducted for both ON and OFF bias conditions under ^{60}Co. Three biased devices and two unbiased devices irradiated under ^{60}Co were tested under heavy ions to obtain sufficient part-to-part variability statistics for further analysis on the synergetic effects. A delidded reference part (not exposed to TID) is also tested.

Irradiated and measured (parametric test or cross section) devices are no longer used for the study.

TABLE 4 : Irradiation test parameters for the synergy study campaign.

Source characteristics		
	Source	^{60}Co
	Site	UCL (Belgium)
	Dosimetry	Alanine and DosElec dosimeters
Irradiation conditions for AD9042, AD558 and R1RW0416		
	Dose rate	74 rad(Si)/h
	Total dose	150 krad(Si)
	Accumulated Dose	0, 41, 78, 114, 150 krad(Si)
Irradiation conditions for MT29F4G08AAC		
	Dose rate	66 rad(Si)/h
	Total dose	100 krad(Si)
	Accumulated Dose	0, 36, 72, 100 krad(Si)

The flow chart available on Figure 2 shows the detailed planning for the TID-SEE synergy tests. The fact that the UCL heavy ion beam facility imposes a two week interval between 2 heavy ion irradiation campaigns has been taken into account.
The total ionizing dose level has been defined in accordance with the preliminary TID test. Moreover this dose level was chosen since it is high enough to cover various space missions like GEO, LEO or the JUICE mission. In addition, the dose rate was selected in order to have a sufficiently low dose rate. Considering all these requirements, a total dose of 150 krad(Si) was selected for the ADC, DAC and SRAM devices whereas 100 krad(Si) was chosen for the NAND Flash reference.

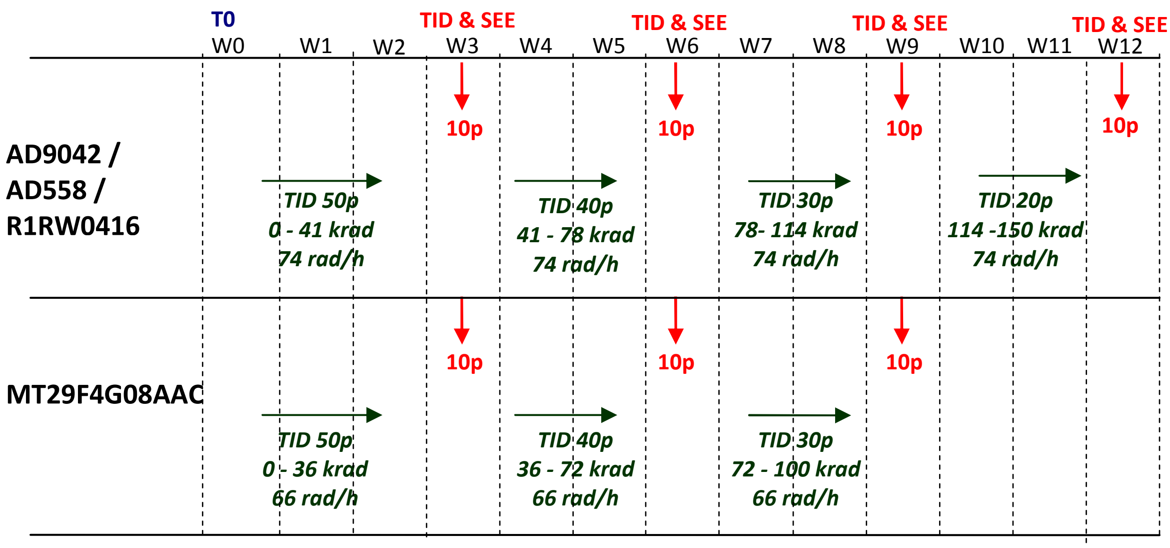


Figure 2 : Pre-defined test campaign organization

The supply current, supervised by a BILT system, was measured for each individual test group (5 parts ON = one group). BILT system provides voltage/current for biasing cards under irradiation.

5. TEST BENCH DESCRIPTION

For all references, the test was divided in two parts, with respect to reference or applicable documents:

- Runs were performed up to a fluence of 10^7 cm^{-2} with only SEL monitoring. This configuration allowed to verify the devise latchup sensitivity.
- Runs were performed up to a fluence of 1.10^6 cm^{-2} for other SEE detection. A latchup monitoring was used during these tests for component protection. This configuration allowed to verify the SEE device sensitivity.

The test was terminated when the maximum fluence was reached or when enough events were recorded to be statistically representative of the part behavior.

During SEL runs, the test was performed at nominal operating voltage.
TRAD has developed a fully integrated test bench to perform Single Event Latchup tests (SEL). The GUARD system (Graphical Universal Autorange Delatcher) allows its user to easily protect his device under test and to perform SEL characterization.
The power supply is applied to the device under test through the GUARD system.
The threshold current of the GUARD system is set according to the nominal current. If the nominal current exceeds the threshold current, the GUARD system is triggered and the event is counted as an SEL. Then, the GUARD system sends a trigger command to the oscilloscope, maintains the power supply during a defined 'Time hold' and cuts it off during a defined 'Time cut'. Then, the power supply is restarted with the nominal current consumption.
At the end of each run, the test program reads the oscilloscope's "Local Scope Counter" which represents the total event count, downloads and stores the recorded current waveforms.

The next Figure shows an example of the SEL detection.

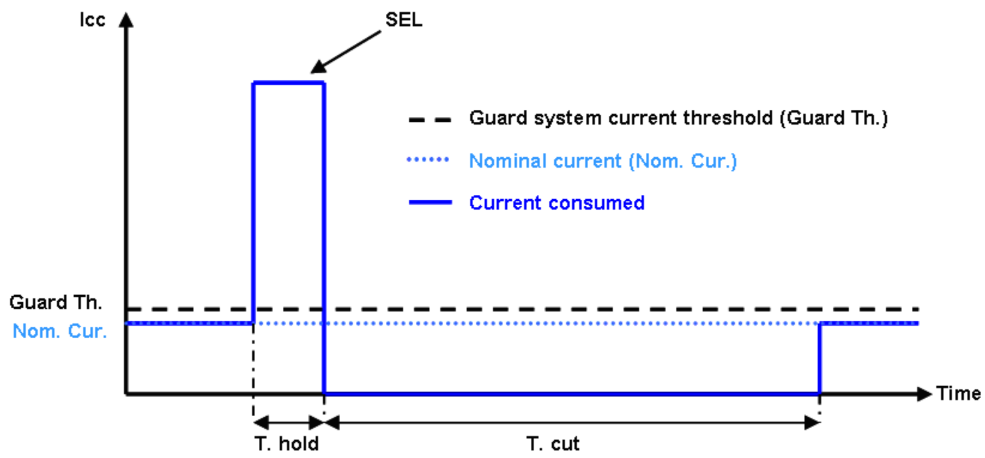


Figure 3: Common SEL characteristic.

5.1. ADC AD9042 From Analog Device

5.1.1. AD9042 Total Ionizing Dose Test Bench description

AD9042 reference has been irradiated under ^{60}Co using two different bias conditions. Half of the parts were biased during irradiation and the other half were unbiased.

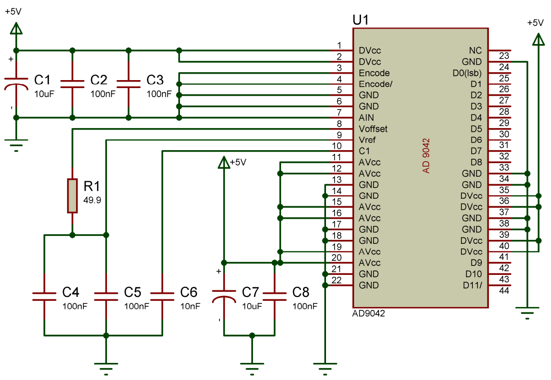


Figure 4: AD9042 ON Bias Condition

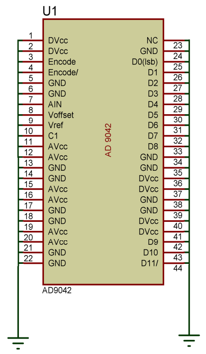


Figure 5: AD9042 OFF Bias Condition

The following parameters have been measured at each TID step:

TABLE 5 : AD9042 TID parameters

Parameters	Symbols	Test conditions
Ta = +25°C, AVcc = DVcc = +5V, Vref tied to Voffset through 50Ω, unless otherwise specified		
Differential Non Linearity	**DNL**	ENCODE = 20MSPS
Integral Non Linearity	**INL**	
Offset Error	**Offset_Error**	
Gain Error	**Gain_Error**	
Signal to Noise Ratio	**SNR**	ENCODE = 41 MSPS, Analog input at -1dBFS, F = 9.6MHz
Signal to Noise And Distortion Ratio	**SINAD**	
Worst Spur Ratio	**WS**	
DVcc Supply Current	**ICCD**	
AVcc Supply Current	**ICCA**	
Total Supply Current	**ICC_TOTAL**	
Reference Out	**Vref**	
Input Resistance	**Rin**	
Logic 1 Input Voltage	**Vih**	
Logic 0 Input Voltage	**Vil**	
Output Delay	**Tod**	ENCODE = 41 MSPS
Logic 1 Input Current	**Iih**	Vinh = 5V
Logic 0 Input Current	**Iil**	Vinl = 0V
Logic 1 Output Voltage	**Voh**	Ioh = 10µA
Logic 0 Output Voltage	**Vol**	Iol = 10µA

5.1.2. AD9042 Single Event Effect Test Bench description

During test, the DUT is operated in continuous conversions at 5MHz Frequency with a constant input signal and the digital output conversion is monitored to detect SEE events.
Before each run, 10 000 consecutive conversions are initiated to define the limits where the conversions are considered valid (to these limits, we appreciatively add a ±2,5mV band to prevent the noisy environment).
Out of these limits an error is detected as follows:

- For a single error followed by a correct conversion a SEU is counted,
- For several consecutive conversion errors (<200 errors) a SET is counted,
- For 200 consecutive false conversions a type 1 SEFI is counted,
- For a conversion value which stays exactly the same during 200 conversions a type 2 SEFI is counted.

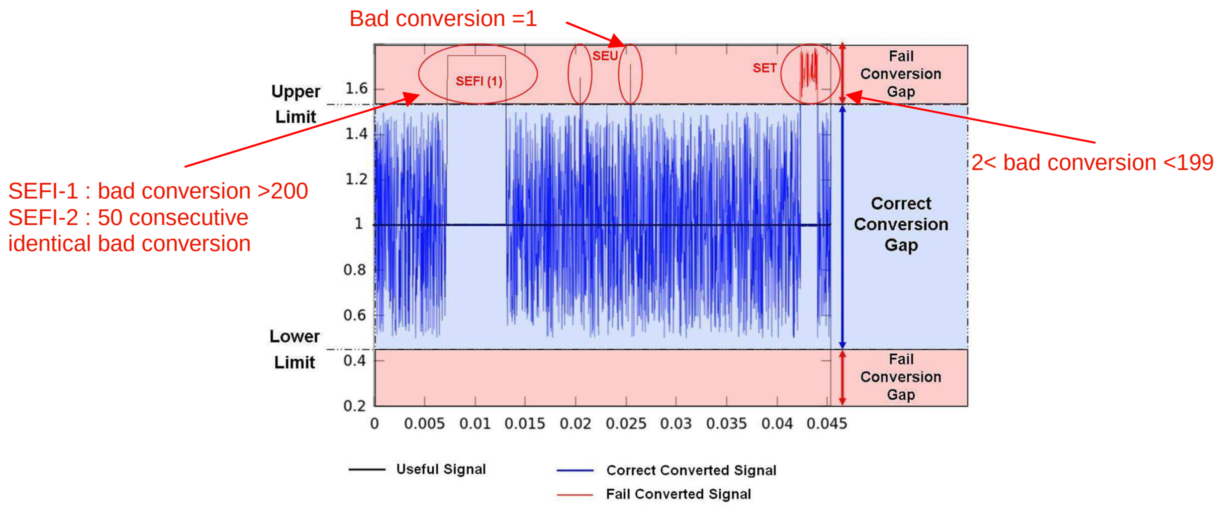


Figure 6: AD9042 SEE detection description

The following Figure presents the test bench used during SEE tests.

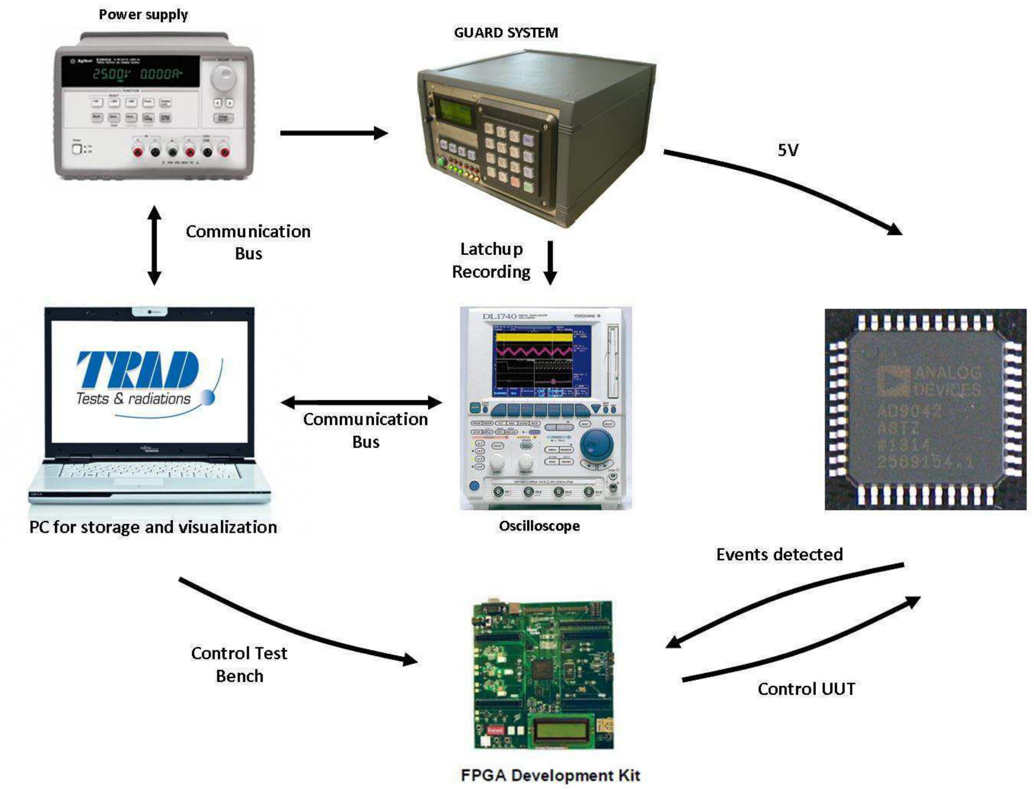


Figure 7: AD9042 Test system description

Trigger thresholds for SET test are defined in the following table:

Vcc	5V
Configuration	SET_2
V_{in}	2.4V

TABLE 6: AD9042 SEE input configurations

Trigger threshold for SEL test is defined in the following table:

Power Supply	Avcc	Dvcc
Voltage Value	5V	5V
$I_{nominal}$	110mA	15mA
$I_{threshold}$	150mA	25mA
T_{hold}	1ms	
T_{cut}	7ms	
Temperature	25°C	

TABLE 7: AD9042 SEL detection threshold

5.2. DAC AD558 FROM Analog Device

5.2.1. AD558 Total Ionizing Dose Test Bench description

AD558 reference has been irradiated under ^{60}Co using two different bias conditions.
Half of the parts were biased during irradiation and the other half were unbiased.

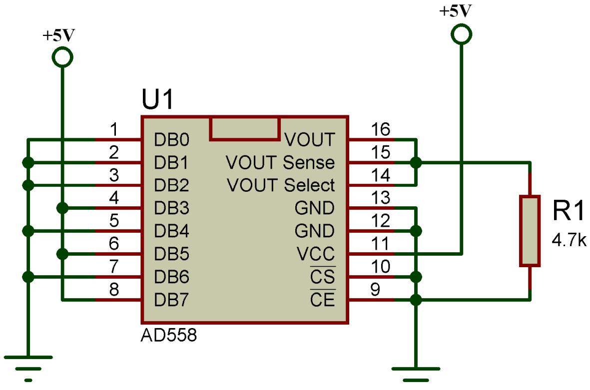


Figure 8: AD558 ON Bias Condition

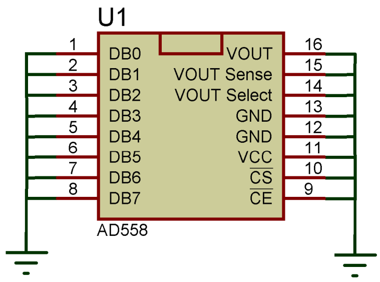


Figure 9: AD558 OFF Bias Condition

The following parameters have been measured at each TID steps:

TABLE 8 : AD558 TID parameters

Parameters	Symbols	Test conditions
Ta = 25°C, Vcc = 5V, unless otherwise specified		
Digital Input High Voltage	**Vih**	
Digital Input Low Voltage	**Vil**	
Power Supply Current	**Icc**	All bits on
Gain Error	**FSA**	
Digital Input High Current	**Iih**	Vin = 5V
Digital Input Low Current	**Iil**	Vin = 0V
Zero Error	**Vze**	
Differential Non Linearity	**DNL**	
Relative Accuracy	**INL**	

5.2.2. AD558 Single Event Effect Test Bench description

The GUARD system is always used on the component's power supply to detect SEL and to prevent the destruction of the device under test.
Single Event Transient is an event described by a voltage amplitude and a timing parameter.
the output voltage component is monitored to detect these events.

A SET can be positive or negative. Two trigger thresholds (positive and negative) are used to detect the amplitude voltage due to a SET. A SET is detected when the output device voltage becomes higher or lower than the positive trigger threshold or the negative trigger threshold respectively. During the test, the oscilloscope internal counter is incremented at each detected SET and the waveform of each transient is stored.

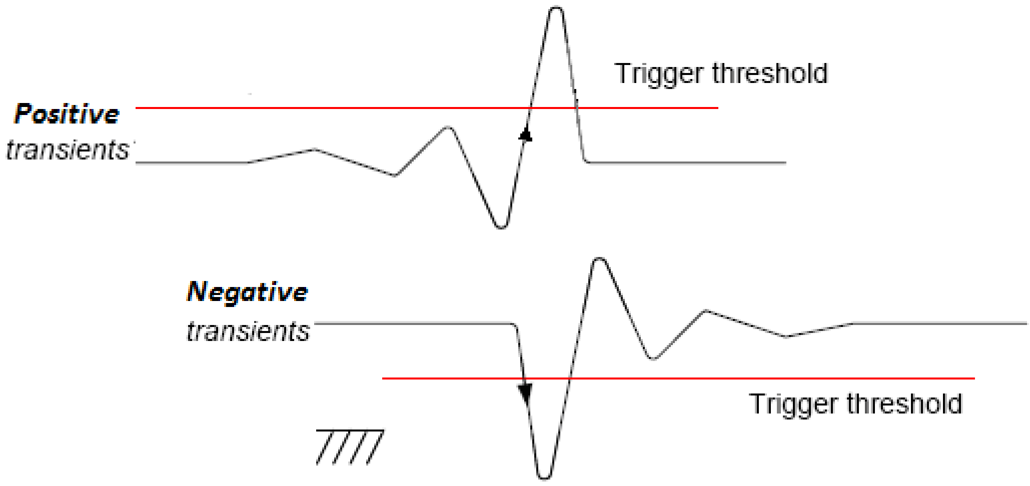


Figure 10: Positive and negative SET detection

The lower threshold for the SET detection is set to "Vout - 20 LSB" and the higher threshold is set to "Vout + 20 LSB".

A SEFI is taken into account if Vout stays out of limits during more than 100ms. The lower threshold for the SEFI detection is set to "Vout - 10 LSB" and the higher threshold is set to "Vout + 10 LSB". When a SEFI occurs the DAC is power-cycled OFF-ON.

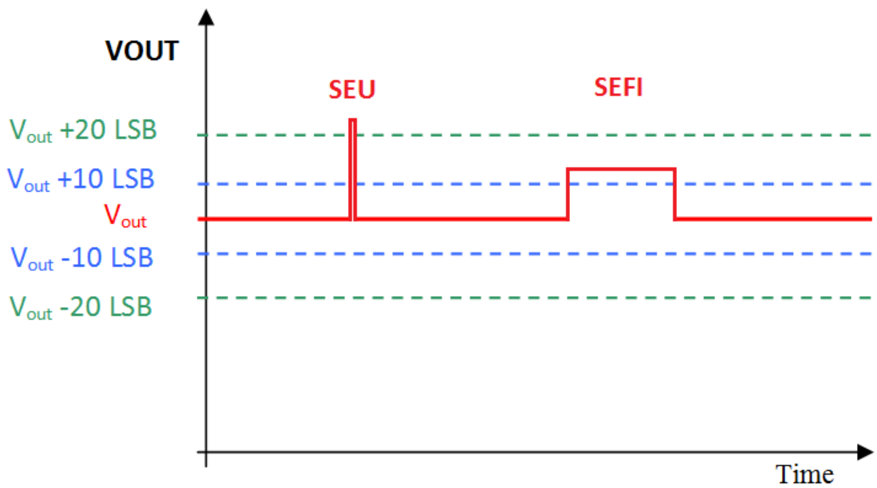


Figure 11 : AD558 SEE detection description

At the end of each run, the test program reads the oscilloscope's "Local Scope Counter" which represents the total event count and downloads the recorded current waveforms to store them.

The following figure presents the test bench used during SEE tests.

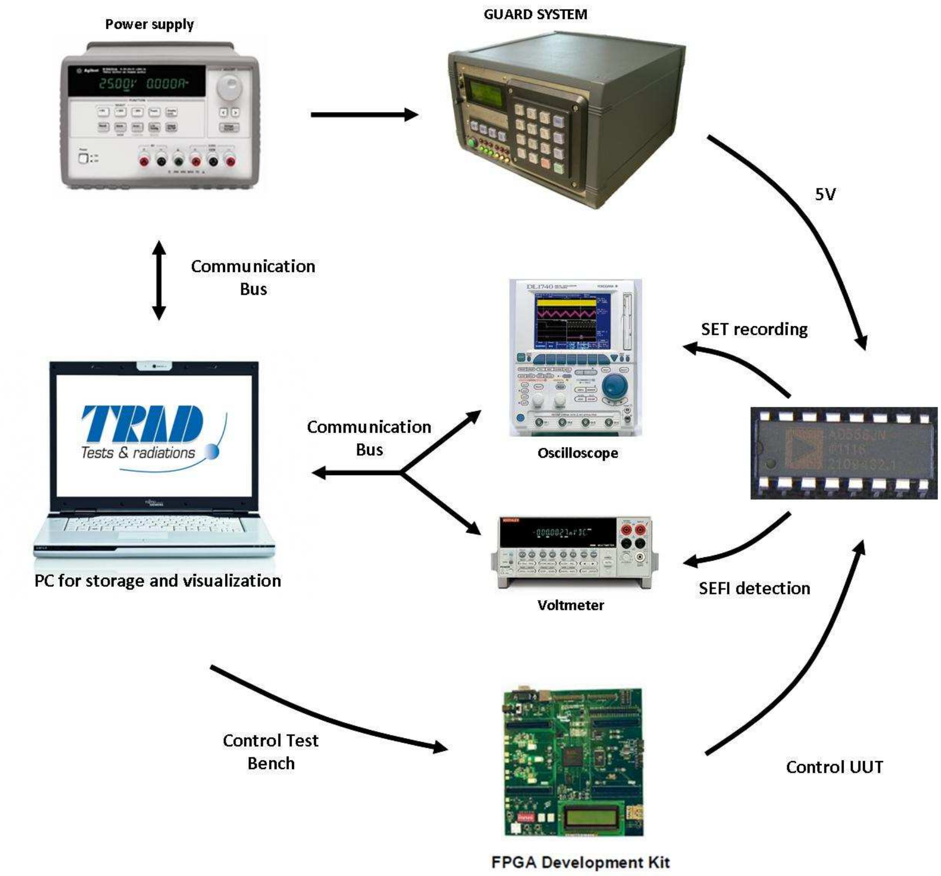


Figure 12 : AD558 Test system description

Trigger thresholds for SET test are defined in the following table:

Vcc	5V
In	BB
V_{out}	0.51
Positive trigger threshold	0.71
Negative trigger threshold	0.31

TABLE 9: AD558 static SET detection threshold

Trigger threshold for SEL test is defined in the following table:

Vcc	5V
$I_{nominal}$	15mA
$I_{threshold}$	20mA
T_{hold}	1ms
T_{cut}	7ms
Temperature	25°C

TABLE 10: AD558 SEL detection threshold

5.3. Flash NAND MT29F4G08AAC FROM Micron

5.3.1. MT29F4G08AAC Total Ionizing Dose Test Bench description

MT29F4G08AAC reference has been irradiated under ^{60}Co using two different bias conditions. Half of the parts were biased during irradiation and the other half were unbiased.

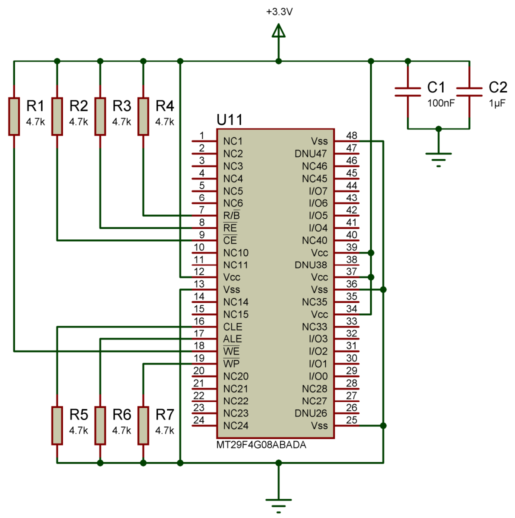


Figure 13: MT29F4G08AAC ON Bias Condition

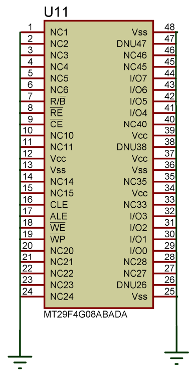


Figure 14: MT29F4G08AAC OFF Bias Condition

The following parameters have been measured at each TID step:

TABLE 11 : MT29F4G08AAC TID parameters

Parameters	Symbols	Test conditions
Ta = 25°C, Vcc = 3.3V, Vih = 2.64V, Vil = 0.66V, unless otherwise specified		
Block 0 Functionality Check	**Chk_B_Zero_Func**	Functional Test
Sequential READ current	**Icc3**	
PROGRAM current	**Icc2**	
ERASE current	**Icc1**	Trc = 20ns, CE# = Vil, Iout = 0mA
RESET current	**Icc7**	
Standby current (TTL)	**Isb1**	CE# = Vih
Low level input leakage current	**Ilil**	Vin = 0V
High level input leakage current	**Ilih**	Vin = Vcc
Output low voltage	**Vol**	Iol = 2.1mA
Output high voltage	**Voh**	Ioh = -400µA
RE# access time	**tREA**	

5.3.2. MT29F4G08AAC Single Event Effect Test Bench description

These tests are performed at nominal operating voltage and ambient temperature. Each NAND Flash memory tested was checked before the irradiation beam to evaluate its functionality. The functional test was conducted by the 4096 blocks writing and control. Tests in Retention, Standby and Read modes were performed up to a fluence of 1.00E+6 #/cm², at ambient temperature.

Before the irradiation sequence, the UUT (Unit Under Test) is written with a fixed pattern and controlled. During irradiations, the part is read continuously block by block. Events are recorded during irradiation. SEUs are defined as one or multiple differences between the read and the expected data, while a SEFI is defined as at least a half erroneous page or a loss of communication with the UUT. In case of a SEFI event, the UUT is power cycled OFF-ON and the test continues with the next block.

The following figure presents the test bench used during SEE tests.

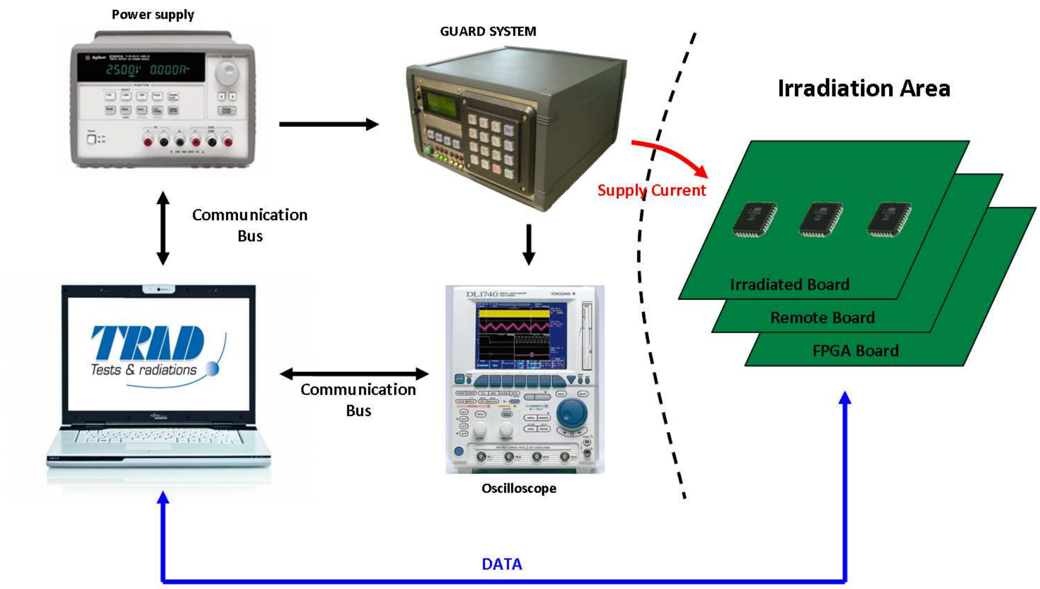


Figure 15 : MT29F4G08AAC Test system description

Trigger threshold for SEL test is defined in the following table:

Power Supply	Vcc
Voltage Value	3.3V
$I_{nominal}$	5mA
$I_{threshold}$	50mA
T_{hold}	1ms
T_{cut}	7ms
Temperature	25°C

TABLE 12: MT29F4G08AAC SEL detection threshold

5.4. SRAM R1RW0416 FROM Renesas

5.4.1. R1RW0416 Total Ionizing Dose Test Bench description

R1RW0416 reference has been irradiated under ^{60}Co using two different bias conditions.
Half of the parts were biased during irradiation and the other half were unbiased.
During TID test, all biased devices were written using the pattern AAAA.

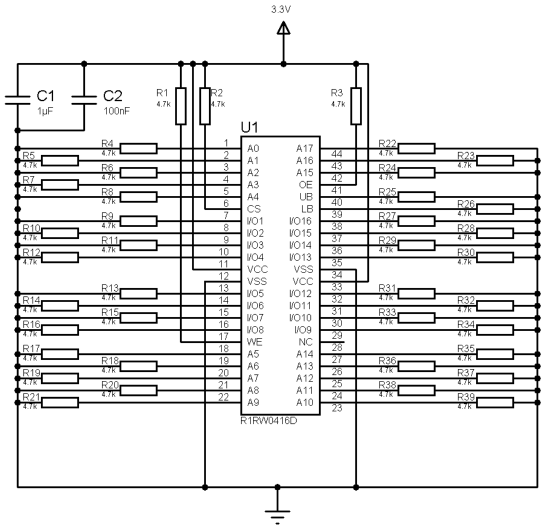


Figure 16: R1RW0416 ON Bias Condition

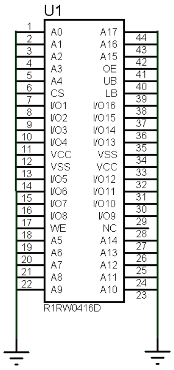


Figure 17: R1RW0416 OFF Bias Condition

The following parameters have been measured at each TID steps:

TABLE 13 : R1RW0416 TID parameters

Parameters	Symbols	Test conditions
Ta = 25°C, Vcc = 3.3V, Vih = 2.0V, Vil = 0.8V, unless otherwise specified.		
High Level Input leakage current	**Ilih**	Vin = Vcc
Low Level Input leakage current	**Ilil**	Vin = 0V
High Level Output leakage current	**Iloh**	Vout = Vcc
Low Level Output leakage current	**Ilol**	Vout = 0V
Operating power supply current	**Icc_Write_20MHZ**	CS# = Vil, read cycle = 20MHz
	Icc_Read_20MHZ	CS# = Vil, write cycle = 20MHz
Standby power supply current	**Isb_H**	CS# = Vih, Other inputs = Vih
	Isb_L	CS# = Vih, Other inputs = Vil
	Isb1_H	CS# = Vcc, Other inputs = Vcc
	Isb1_L	CS# = Vcc, Other inputs = 0V
Output voltage	**Voh**	Iol = 8mA
	Vol	Ioh = -4mA
Address access time	**tAA**	
Chip select access time	**tACS**	

Output enable to output valid	**tOE**	
Functional ZEROS	**Func_0**	Vcc = 3V, 3.3V and 3.6V, Functional test, write zeros, read zeros, full memory
Functional ONES	**Func_1**	Vcc = 3V, 3.3V and 3.6V, Functional test, write ones, read ones, full memory
Data Retention Voltage	**Vdr**	

5.4.2. R1RW0416 Single Event Effect Test Bench description

Before each run, a reference memory and the Device Under Test (DUT) is filled with a checker-board pattern (e.g AA at even addresses and 55 at odd addresses) from address 0 up to the DUT maximum addresses. An initial verification of their contents is performed off beam to ensure proper functionality of both DUT and reference.
During irradiation, the test bench reads both memories and compares their contents one address at the time. When the last address is reached, the FPGA sends a command to the Labview software in order to indicate the end of the read/compare cycle and a new read/compare order is immediately sent back to the FPGA. If no event occurs during the cycle, this operation is performed at the maximum system speed. However, if the data read from the DUT does not fit the data from the reference memory, an error is counted. If the number of bit impacted is only 1, a SEU is counted. For all other cases, an MBU is counted.

The following figure presents the test bench used during SEE tests.

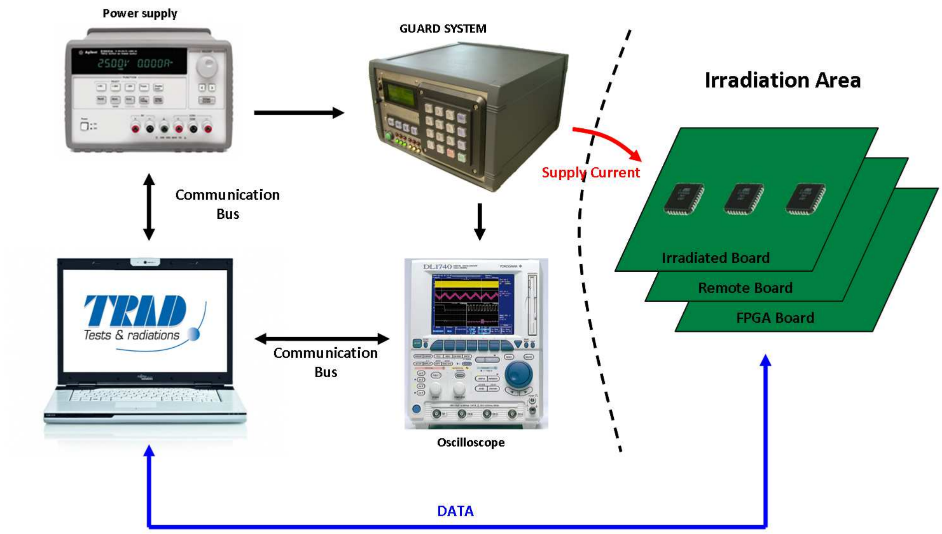


Figure 18 : R1RW0416 Test system description

Trigger threshold for SEL test is defined in the following table:

Power Supply	Vcc
Voltage Value	3.3V
$I_{nominal}$	100mA
$I_{threshold}$	150mA
T_{hold}	1ms
T_{cut}	7ms
Temperature	25°C

TABLE 14: R1RW0416 SEL detection threshold

6. IRRADIATION TEST CONDITIONS

6.1. Test conditions used for SEE characterization

6.1.1. AD9042 Test conditions used for SEE characterization

As the AD9042 reference is fairly sensitive to SEU events, the test condition representing the lowest sensitivity has to be used for the synergy study.
During the pre-characterization SEE test campaign, a set of digital inputs: quarter, half and three-quarter of the input range were used to evaluate the lowest sensitive configuration with the highest LET (67.7 MeV.cm²/mg). These configurations are respectively noted as Low (2.15V), High (2.65V) and Middle (2.4V).
The lowest sensitive configuration is then maintained for all the following tests.
As shown in the following figure, the three configurations are equivalent. As the Middle (2.4V) test condition appears to be the lowest sensitive test condition, it has been used during all the synergy study.

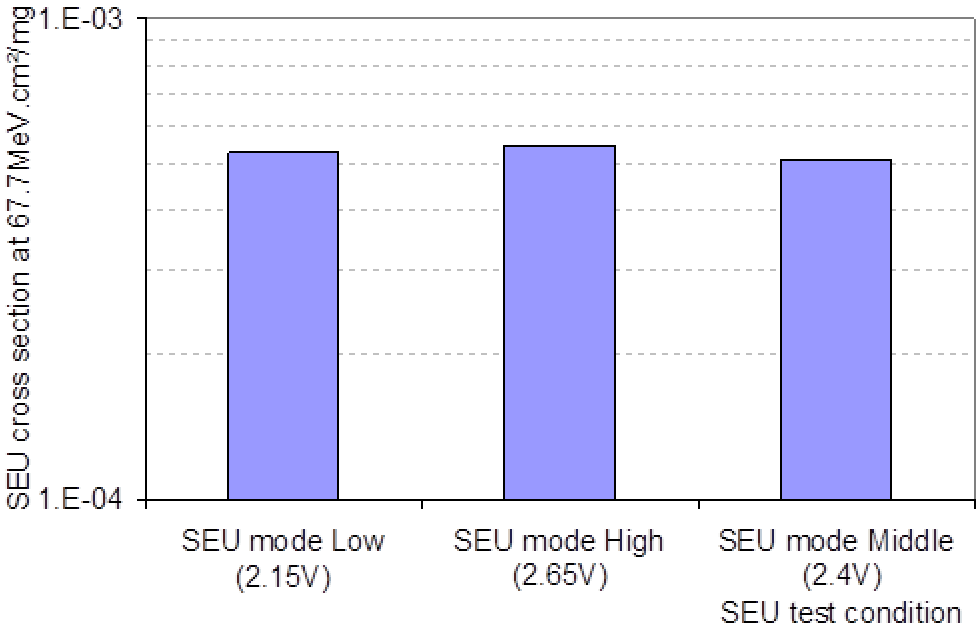


Figure 19 : AD9042 tests condition impact on SEU sensitivity using the Xenon ion (LET=67.7 MeV.cm²/mg)

6.1.2. AD558 Test conditions used for SEE characterization

As the AD558 reference is fairly sensitive to SET events, the test condition representing the lowest sensitivity has to be used for the synergy study.
During the pre-characterization SEE test campaign, a set of digital inputs: quarter, half and three-quarter of the input range were used to evaluate the lowest sensitive configuration with the highest LET (67.7 MeV.cm²/mg). These configurations are respectively noted as Low (33), High(7F) and Middle (CC).
The lowest sensitive configuration is then maintained for all the following tests.
As shown in the following figure, the three configurations are equivalent. As the Low(33) test condition appears to be the lowest sensitive test condition, it has been used during all the synergy study.

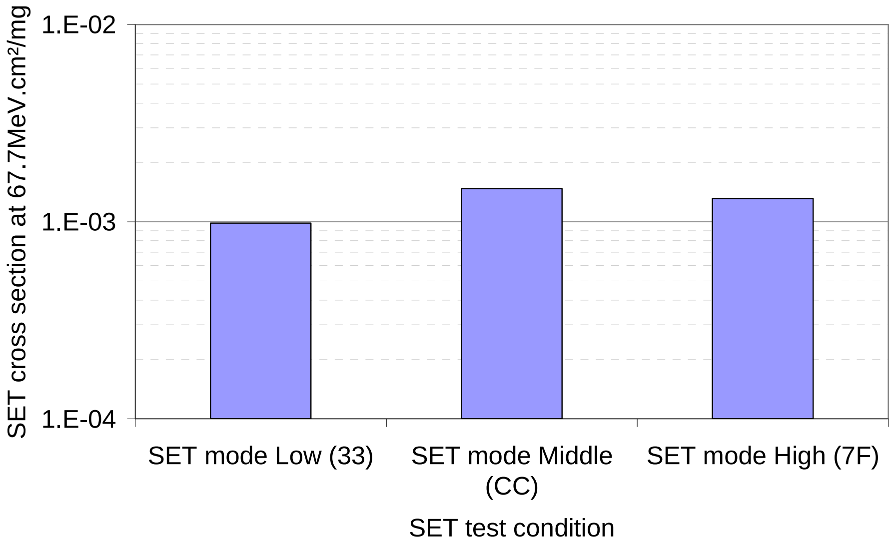
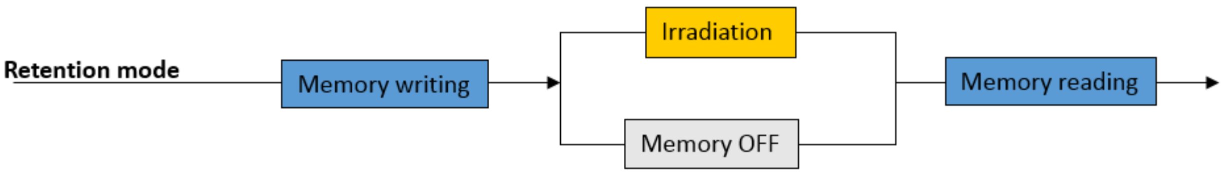


Figure 20 : AD558 tests condition impact on SET sensitivity using the Xenon ion (LET=67.7 MeV.cm²/mg)

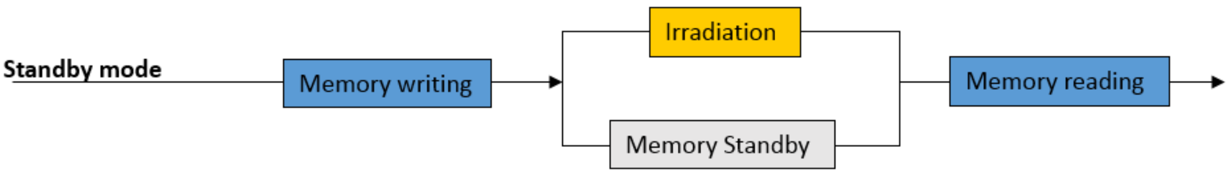
6.1.3. MT29F4G08AAC Test conditions used for SEE characterization

The MT29F4G08AAC NAND Flash reference has been tested under heavy ion to evaluate SEU and SEFI sensitivity using three different modes:

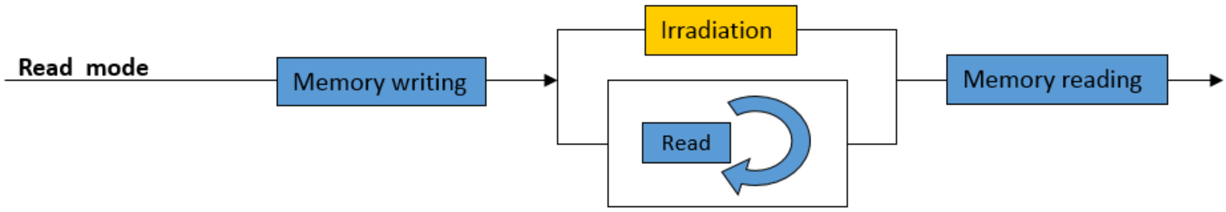
- Retention mode principle: In Retention mode, the Unit Under Test (UUT) is written with a fixed pattern and is controlled before irradiation. Then, the memory power supply is cycled OFF until the end of the irradiation sequence. The UUT is then power cycled ON and read again in order to observe if events have occurred. SEUs are defined as one or multiple differences between the read and the expected data.



- Standby mode principle: As in Retention mode, the UUT is written and controlled before irradiation. During irradiations, the memory is continuously powered in standby activity. After irradiations, the UUT is read again in order to observe if events have occurred. SEUs are defined as one or multiple differences between the read and the expected data, while a SEFI is defined as at least a half erroneous page.



- Read Only mode principle: Before irradiation the UUT is written with a fixed pattern and controlled. During irradiation, the part is read continuously block by block. Events are recorded during irradiation. SEUs are defined as one or multiple differences between the read and the expected data, while a SEFI is defined as at least a half erroneous page or a loss of communication with the UUT. In case of a SEFI event, the UUT is power cycled OFF-ON and the test continues with the next block.



As shown in the next figure, SEU sensitivities are equivalent no matter the test condition used.

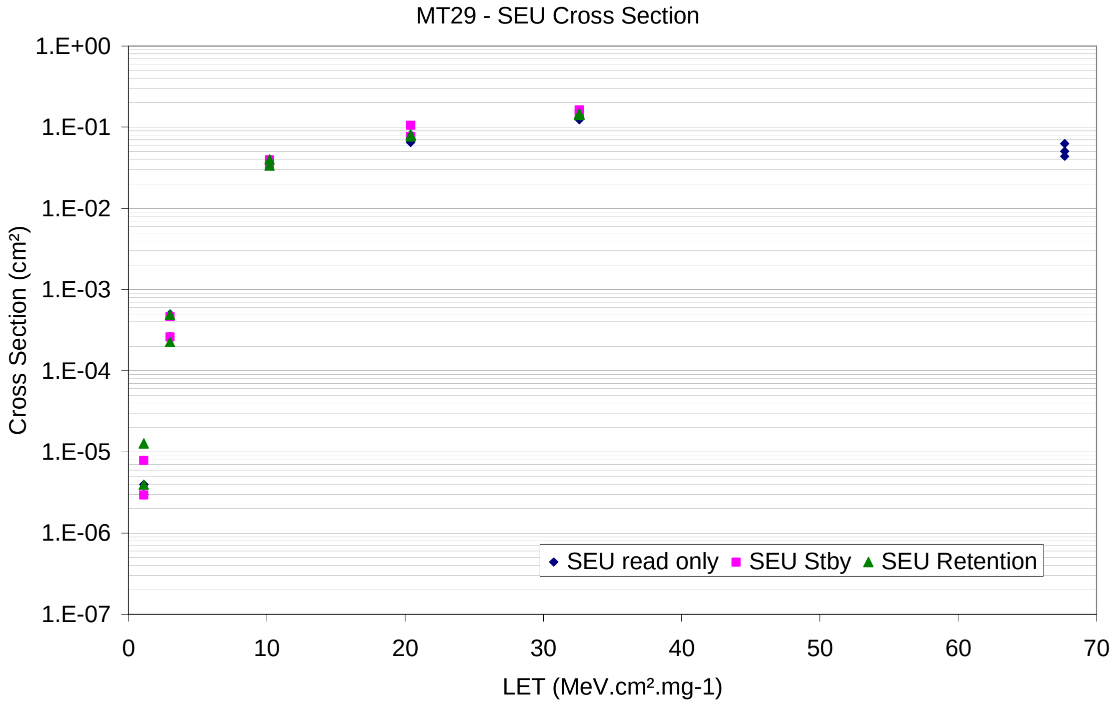


Figure 21 : MT29F4G08AAC tests condition impact on SEU sensitivity

However, different SEFI sensitivities are observed for different of test conditions.
No SEFI are recorded using the retention mode. Indeed, as the memory is unpowered during irradiation, SEFI could not occur on the device.
Moreover, the SEFI sensitivity is higher using the Standby mode than using the Read Only mode. This result could be explained by the SEFI detection method which is different for these two modes. Indeed when a half page is detected in error a SEFI is counted. Using the Read Only mode, a power ON/OFF is performed for each SEFI detection, whereas the entire memory is read after irradiation using Standby mode.
Using the Standby mode, no temporal information is given on the SEFI occurrence. Several SEFI could then be counted while they correspond to a single, unique event.

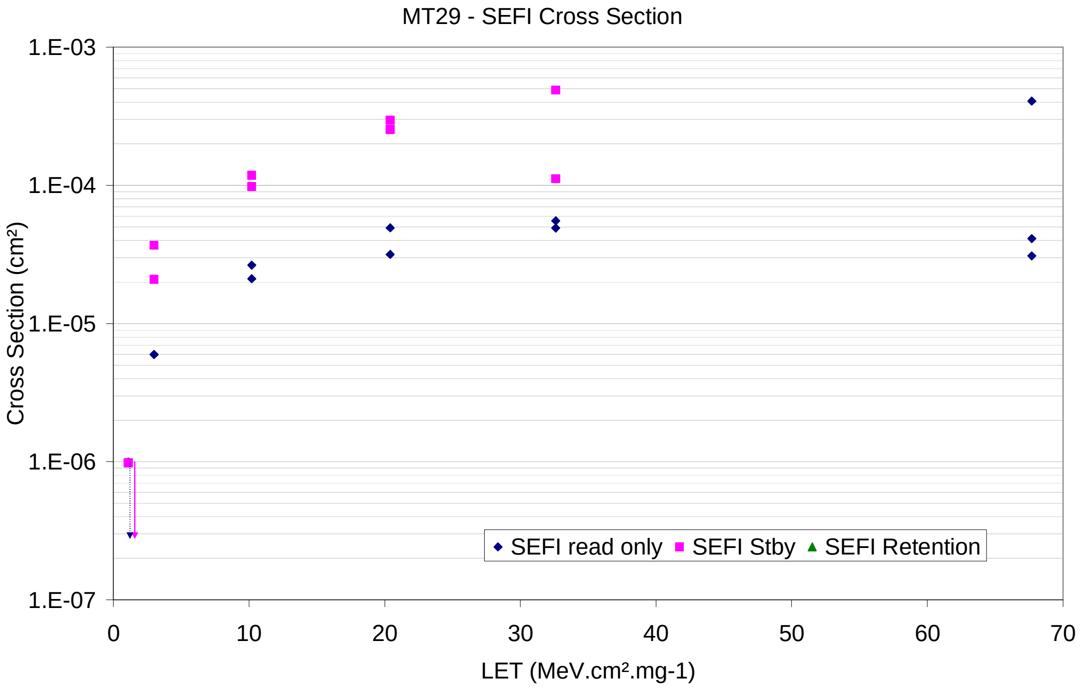


Figure 22 : MT29F4G08AAC tests condition impact on SEFI sensitivity

As the MT29F4G08AAC reference is fairly sensitive to SEU no matter the mode has been used, the test condition has been selected based on the SEFI test results.
As shown in the previous figure, the Read Only test condition appears to be the one for which the memory shows the lower sensitivity. For that reason it has been used during all the synergy study.

6.2. Heavy ion choice used for SEE characterization

A complete SEE characterization was performed for the SEE pre-characterization. Several ions were used in order to evaluate the device sensitivity.
During SEE test performed on ^{60}Co irradiated devices, the LET threshold, the Weibull curve shape and the saturation cross section have to be evaluated in order to observe a possible synergetic effect impact. To evaluate a possible parameter drift, the same cross section points have to be measured at each received dose. Five ions, and then five LET, have to be selected for each reference.
Considering these hypotheses, the points shown on the following figures have to be performed during the synergy study:

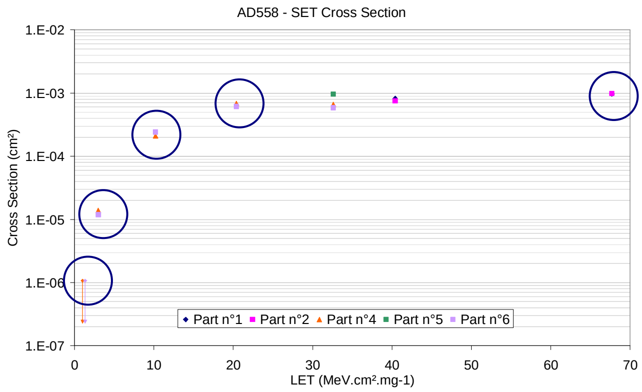


Figure 23 : preferential ions for AD558 SEE test

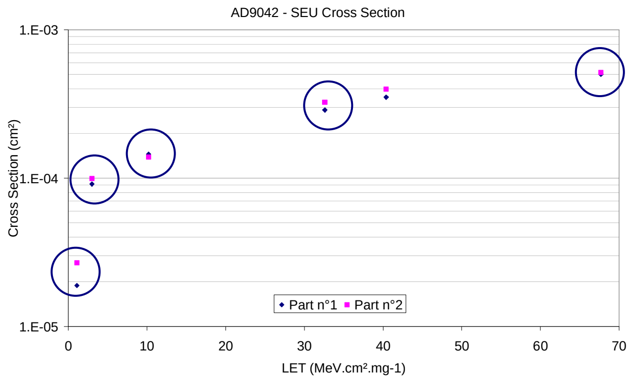


Figure 24 : preferential ions for AD9042 SEE test

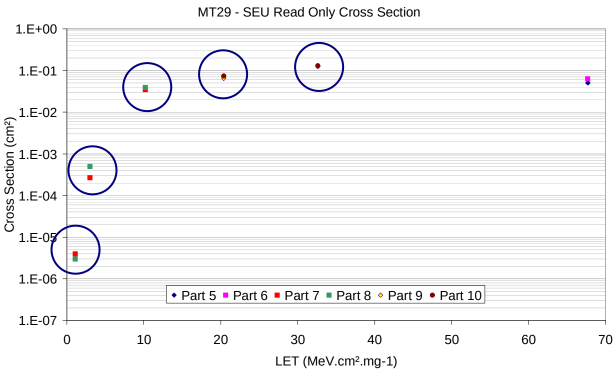


Figure 25 : preferential ions for MT29F4G08AAC SEE test

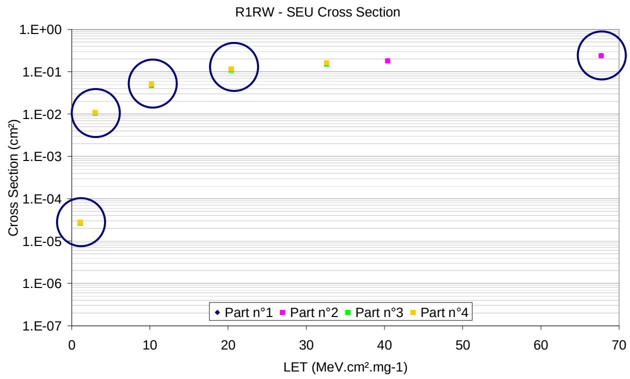


Figure 26 : preferential ions for R1RW0416 SEE test

The SEE test using the Xenon ion (67.7 MeV.cm²/mg) was not performed for NAND Flash devices during the synergy study. Indeed during the SEE pre-characterization, devices were non-functional after the Xenon runs.

Following the selection of the ions as described here above, 40 hours of high range cocktail and 6 hours of high LET cocktail were needed, as shown in the following table:

TABLE 15 : distribution of beam hours needed for SEE characterizations during the synergy study

High LET			
Xe	67.7		
Kr	40.4		
Ar	15.9		
Ne	6.4		
N	3.3		
R1RW	01:30	Setup	00:30
		Xe	01:00
AD558	02:00	Setup	01:00
		Xe	01:00
AD9042	02:30	Setup	01:30
		Xe	01:00
MT29F4G08	00:00		
Total	6:00:00		

High Range			
Kr	32.6		
Ni	20.4		
Ar	10.2		
Ne	3		
C	1.1		
R1RW	04:00	Setup	00:30
		C	00:30
		Beam setup	00:30
		Ar	00:30
		Beam setup	00:30
		Ne	00:30
		Beam setup	00:30
		Ni	00:30
AD558	06:45	Setup	01:00
		C	01:15
		Beam setup	00:30
		Ar	01:15
		Beam setup	00:30
		Ne	00:30
		Beam setup	00:30
		Ni	01:15
AD9042	07:25	Setup	01:30
		C	01:15
		Beam setup	00:30
		Ar	01:15
		Beam setup	00:30
		Ne	00:40
		Beam setup	00:30
		Kr	01:15
MT29F4G08	21:50	setup	00:30
		C	03:40
		Beam setup	00:30
		Ar	03:40
		Beam setup	00:30
		Ne	03:40
		Beam setup	00:30
		Ni	03:40
		Beam setup	00:30
		Kr	04:40
Total	40:00:00		

However, this sharing out was not compatible with the beam time schedule and staff constraint. The distribution of beam hours was revised to obtain an equivalent number of hours between high range cocktails and high LET cocktails.

In order to reduce the number of hours during the high range cocktails and to keep the coherence between 0 krad characterization and the following tests, the Neon Ne ion (LET=3 MeV.cm²/mg, high range cocktail) has been replaced by the Nitrogen N ion (LET=3.3 MeV.cm²/mg, high LET cocktail) for all devices.

High Range M/Q=3.3			
Ion	Energy (MeV)	Range (µm)	LET (MeV.cm²/mg)
$^{22}Ne^{7+}$	235	216	3

⇨

High LET M/Q=5			
Ion	Energy (MeV)	Range (µm)	LET (MeV.cm²/mg)
$^{15}N^{3+}$	60	59	3.3

These two ions present an equivalent LET but different ranges.

Indeed the Nitrogen range is lower than the Neon range, but is still sufficient to perform SEE tests without any range effect.

The cross section curve following TID steps will then be equivalent to the curve performed before the TID exposure.

Finally, the following schedule was considered:

TABLE 16: distribution of beam hours used for SEE characterizations during the synergy study

High LET			
Xe	67.7		
Kr	40.4		
Ar	15.9		
Ne	6.4		
N	3.3		
R1RW	**02:30**	Setup	00:30
		Xe	01:00
		Beam setup	00:30
		N	00:30
AD558	**03:25**	Setup	01:00
		Xe	01:00
		Beam setup	00:20
		N	01:05
AD9042	**04:05**	Setup	01:30
		Xe	01:00
		Beam setup	00:20
		N	01:15
MT29F4G08	**04:00**	setup	00:30
		N	03:30
Total	14:00:00		

High Range			
Kr	32.6		
Ni	20.4		
Ar	10.2		
Ne	3		
C	1.1		
R1RW	**03:00**	Setup	00:30
		C	00:30
		Beam setup	00:30
		Ar	00:30
		Beam setup	00:30
		Ni	00:30
AD558	**05:25**	Setup	01:00
		C	01:15
		Beam setup	00:20
		Ar	01:15
		Beam setup	00:20
		Ni	01:15
AD9042	**05:55**	Setup	01:30
		C	01:15
		Beam setup	00:20
		Ar	01:15
		Beam setup	00:20
		Kr	01:15
MT29F4G08	**17:40**	setup	00:30
		C	03:40
		Beam setup	00:30
		Ar	03:40
		Beam setup	00:30
		Ni	03:40
		Beam setup	00:30
		Kr	04:40
Total	32:00:00		
		Ar	03:40
		Beam setup	00:30
		Ne	03:40
		Beam setup	00:30
		Ni	03:40
		Beam setup	00:30
		Kr	04:40
Total	40:00:00		

The following slots have been scheduled during the high LET cocktails:

- 6 hours : AD558 and AD9042tests
- 8 hours : R1RW0416 and MT29F4G08AAC tests

The following slots have been scheduled during the high range cocktails:

- 11 hours : AD558 and AD9042tests
- 11 hours: R1RW0416 and MT29F4G08AAC tests
- 10 hours: MT29F4G08AAC tests

The next figures show the entire LET range performed during the synergy study for all the tested references. Points encircled by a blue ring mean that the same ion has been used during the 0 krad(Si) characterization and the following tests. Points encircled by a red ring show LET which were not used during the 0 krad(Si) characterization.

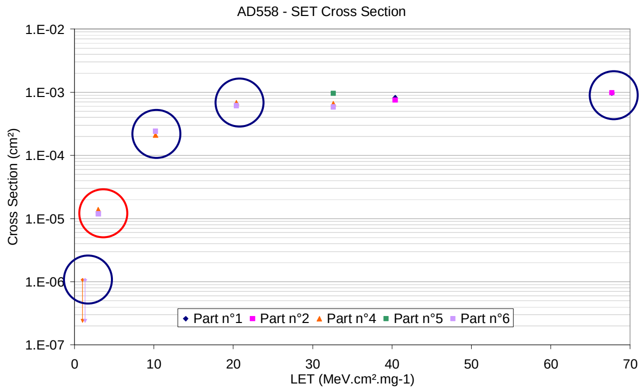


Figure 27 : ions used for the AD558 SEE test

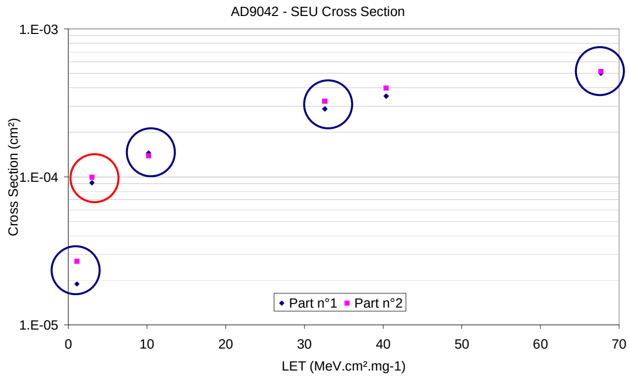


Figure 28 : ions used for the AD9042 SEE test

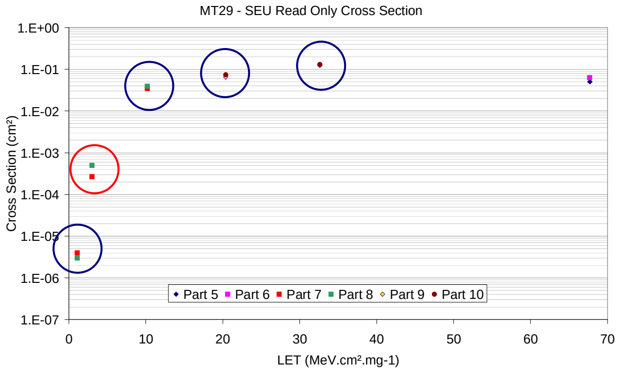


Figure 29 : ions used for the MT29F4G08AAC SEE test

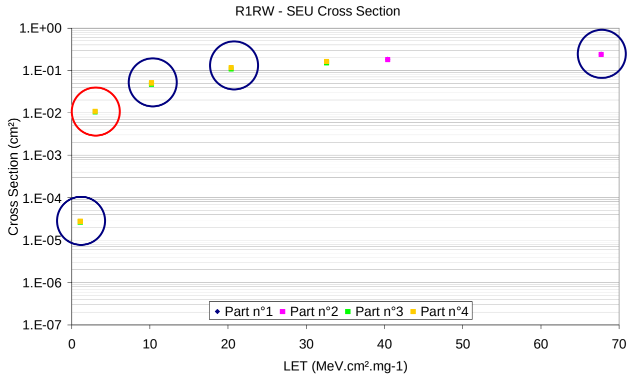


Figure 30 : ions used for the R1RW0416 SEE test

7. IRRADIATION TESTS RESULTS

7.1. ADC AD9042 FROM Analog Device

7.1.1. ADC AD9042 TID tests results

Six AD9042 Lots have been irradiated under ^{60}Co:

- LOTP : 10 non delidded parts (5 ON + 5 OFF) up to 250 krad (Si) at 310 rad(Si)/h at GAMRAY
- LOTA: 10 non delidded parts (5 ON + 5 OFF) up to 150 krad (Si) at 74 rad(Si)/h at UCL
- LOTB: 10 delidded parts (5 ON + 5 OFF) up to 42 krad (Si) at 74 rad(Si)/h at UCL
- LOTC: 10 delidded parts (5 ON + 5 OFF) up to 78 krad (Si) at 74 rad(Si)/h at UCL
- LOTD: 10 delidded parts (5 ON + 5 OFF) up to 114 krad (Si) at 74 rad(Si)/h at UCL
- LOTE: 10 delidded parts (5 ON + 5 OFF) up to 150 krad (Si) at 74 rad(Si)/h at UCL

No intermediary TID steps have been performed for LOT B, C, D and E. Results for these lots are then summarized on the same graph where each represents a TID step LOT.
The next Figure presents the comparison between LOTA and the compilation of LOT B, C, D and E (named LOTBCDE).

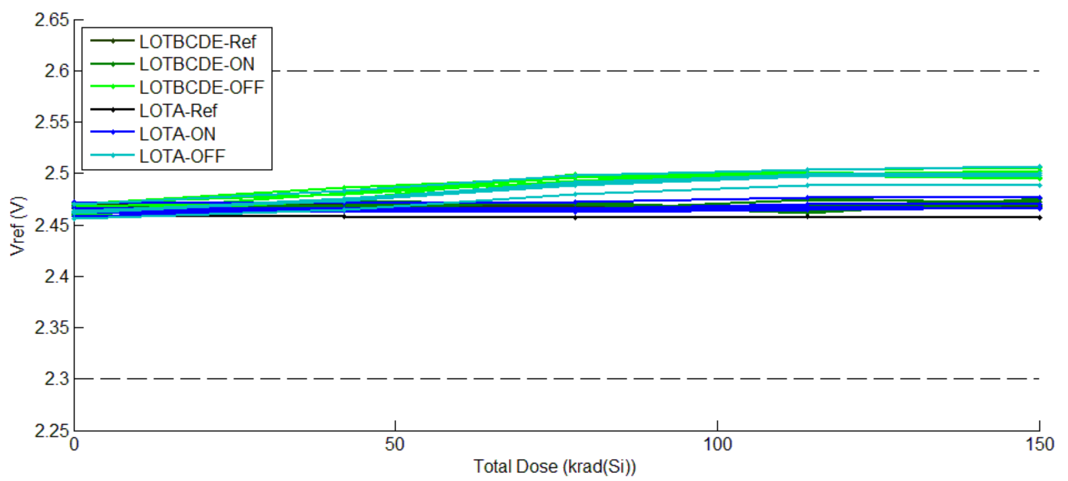


Figure 31 :AD9042 Vref function TID - LOTA compare to LOT BCDE

As shown here above, no difference is observed between LOTA (non delidded parts) and LOTBCDE (delidded parts): the long time opened condition in a non-controlled atmosphere has no impact on the degradation for this reference.

The next figure presents the comparison between LOTA and LOTP.

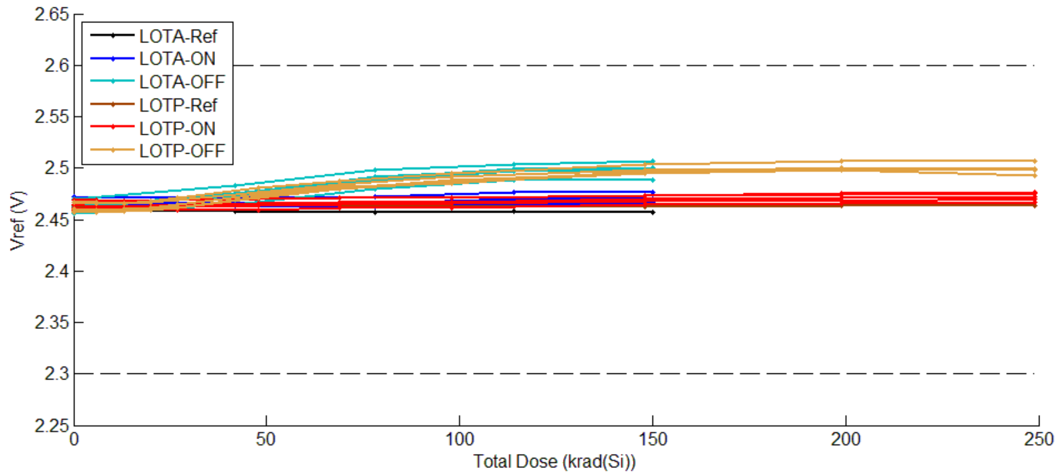


Figure 32: AD9042 Vref function TID - LOTA compare to LOT P

As it can be seen, no difference is observed between LOTA (74 rad/h) and LOTP (310 rad/h): the ^{60}Co dose rate has no impact on the degradation for this reference.

However, a difference is observed between ON and OFF parts. Indeed the Vref degradation is more important on the parts which are biased OFF than on the parts which are biased ON.

7.1.2. ADC AD9042 SEE tests results

Five AD9042 Lots have been irradiated under heavy ions:

- LOTI : 3 parts
- LOTB: 5 parts following TID irradiation up to 42 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTC: 5 parts following TID irradiation up to 78 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTD: 5 parts following TID irradiation up to 114 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTE: 5 parts following TID irradiation up to 150 krad (Si) (3 ON + 2 OFF) and 1 reference

7.1.2.1. *Impact of long time opened condition on SEE sensitivity*

The following figures present the SEU and SET cross section curve comparison between devices not tested against TID irradiation. One non-irradiated device was tested at each TID step and is then named LOTI, LOTB, LOTC, LOTD and LOTE.

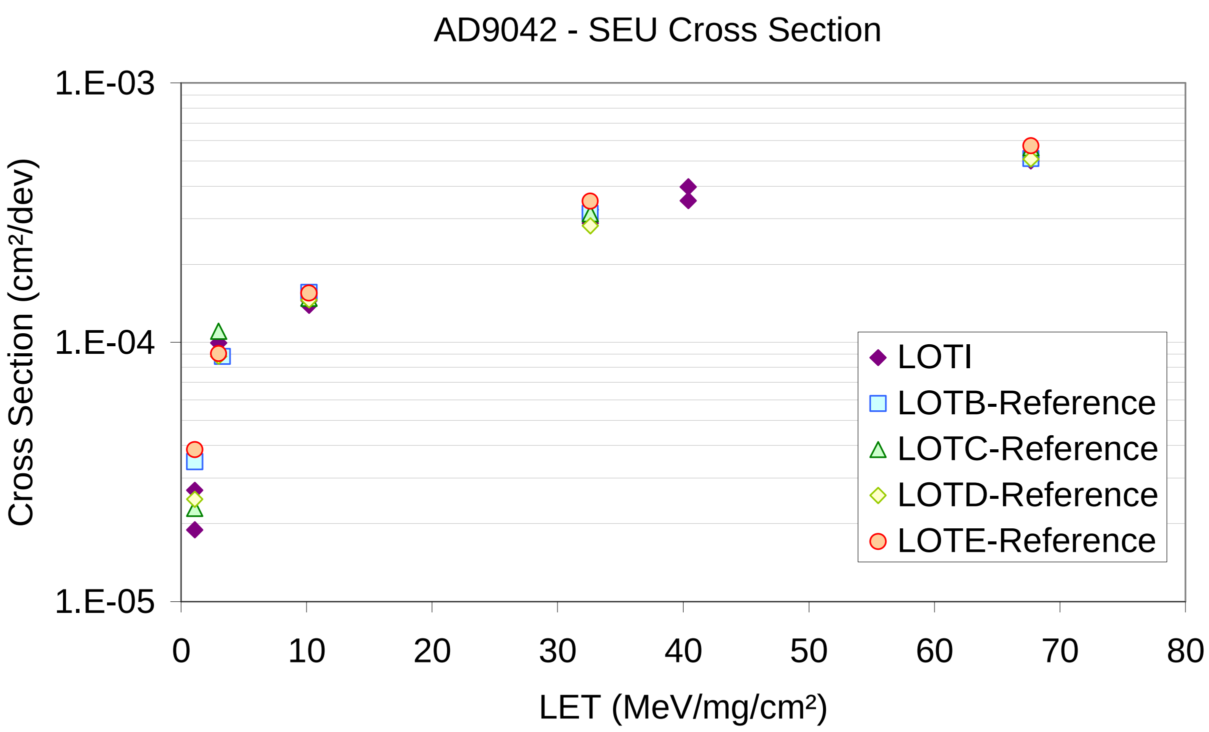


Figure 33 : AD9042 SEU cross section curve comparison between non ^{60}Co irradiated devices

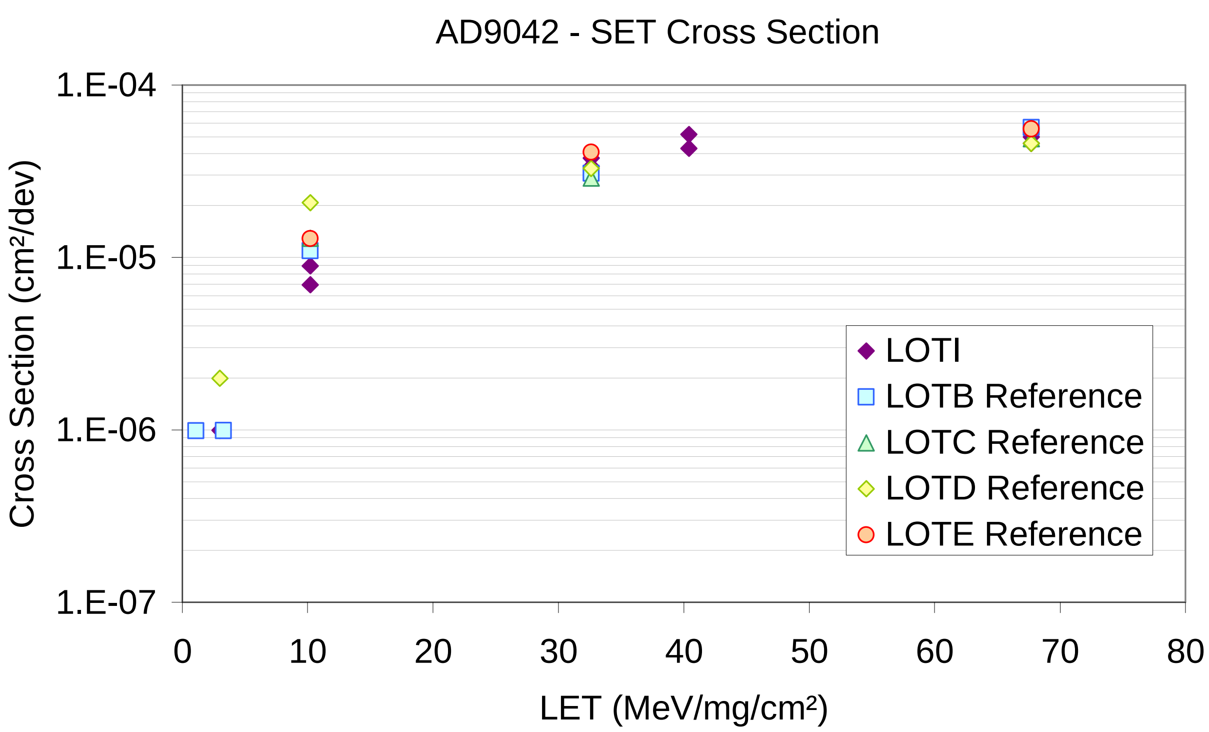


Figure 34 : AD9042 SET cross section curve comparison between non ^{60}Co irradiated devices

As it can be seen, no difference is observed between LOTI (first SEE characterization) on the following characterizations. The long time opened condition in a non-controlled atmosphere has no impact on the SEE sensitivity.

7.1.2.2. Impact of Total Ionizing Dose on SET and SEU sensitivity

The following Figures present the SEU and SET cross section curve comparison between devices subject to synergetic effect. LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)).

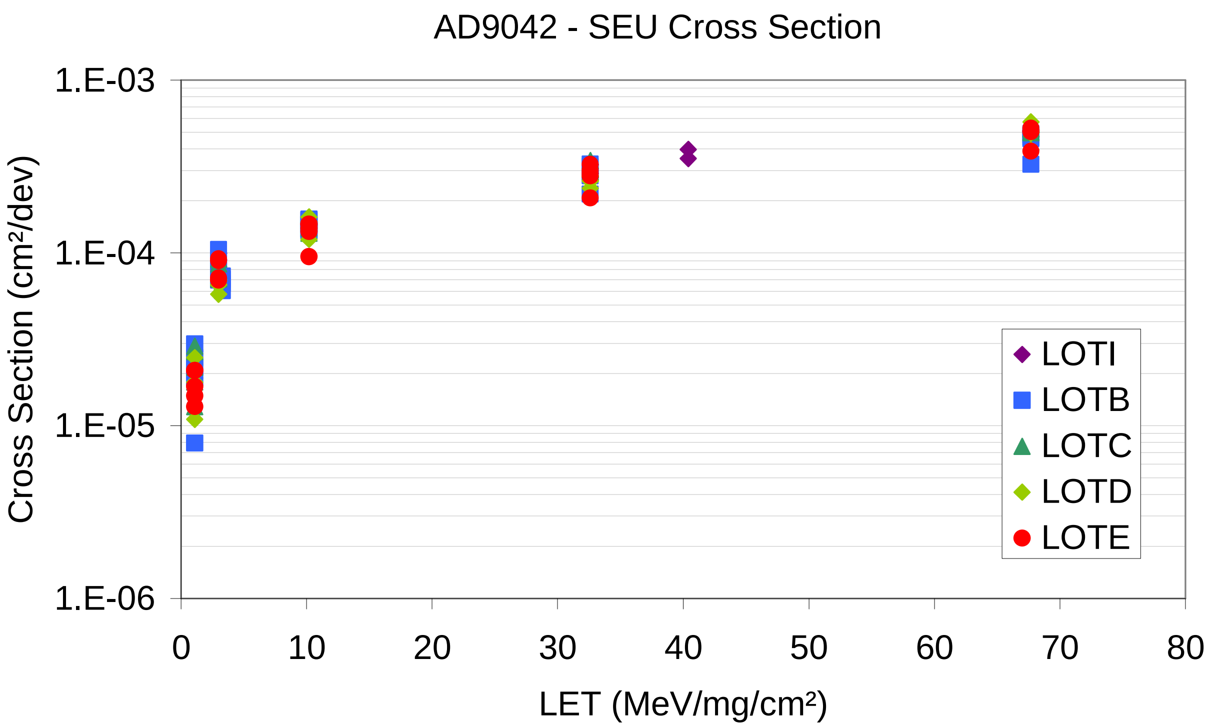


Figure 35 : AD9042 SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si))

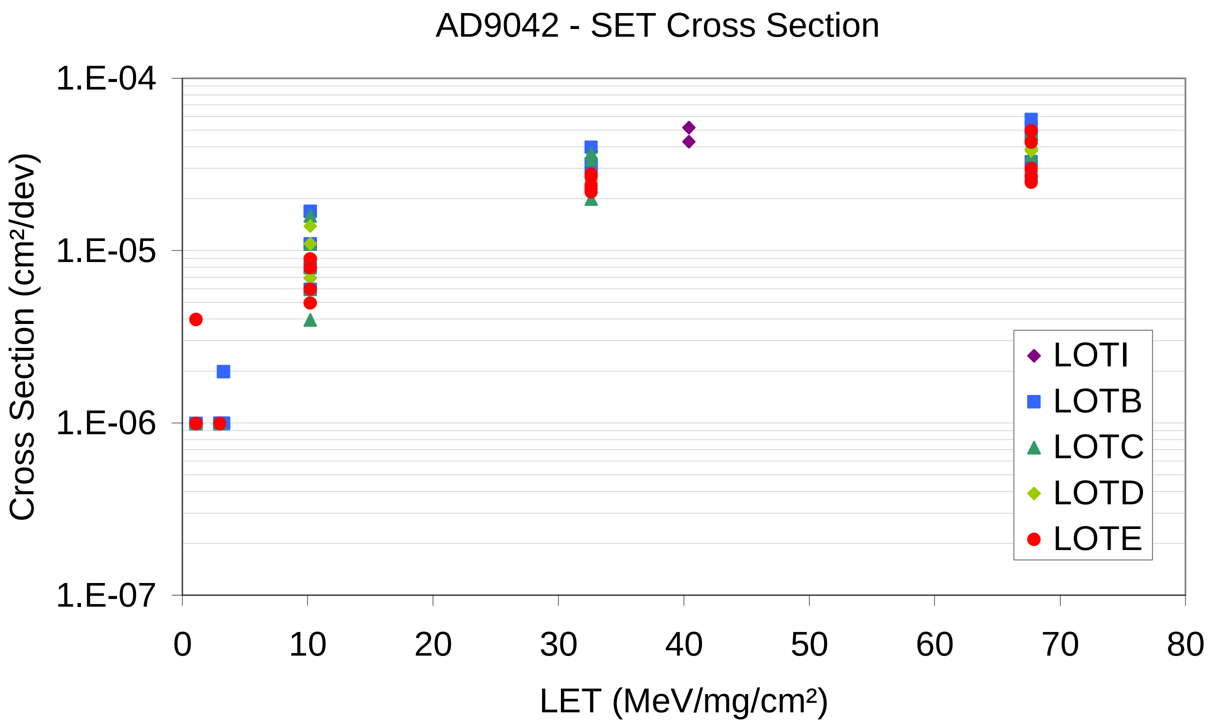


Figure 36 : AD9042 SET cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si))

As it can be seen, there is no significant effect of TID on the SEE sensitivity. Indeed saturation cross sections and LET thresholds are equivalent no matter the dose level.

7.1.2.3. *Impact of Total Ionizing Dose on SET and SEU error bars*

Error bars are calculated as described in the ESCC25100, using 95% confidence level and 10% fluence uncertainty.
The following figures represent the SEU and SET AD9042 cross section before TID irradiation including error bars.

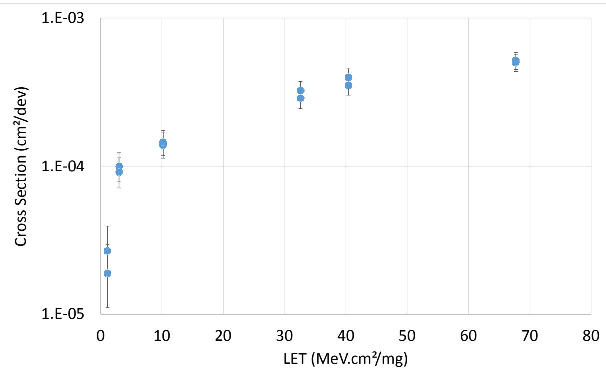


Figure 37 : AD9042 SEU cross section and error bars for 95% confidence level and 10% fluence uncertainty at 0krad(si)

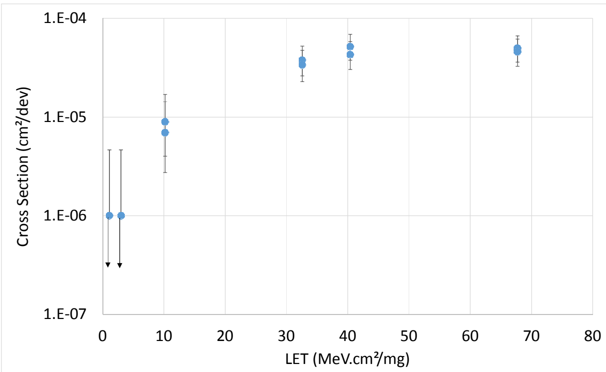


Figure 38 : AD9042 SET cross section and error bars for 95% confidence level and 10% fluence uncertainty at 0krad(si)

As shown in the previous figures, error bars are more important for lower LET due to the small statistics of events. Therefore, the impact of total ionizing Dose on error bars is evaluated for the lower LET where events are detected. LET where no event are recorded are not considered.
Following figures represent, total ionizing dose impact on error bars for:

- 1.1MeV.cm²/mg for SEU
- 10.2MeV.cm²/mg for SET

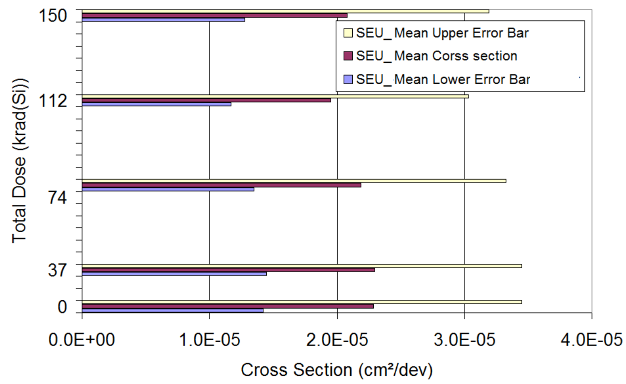


Figure 39 : AD9042 SEU error bars for 95% confidence level and 10% fluence uncertainty at 1.1 MeV.cm²/mg function of Total Dose

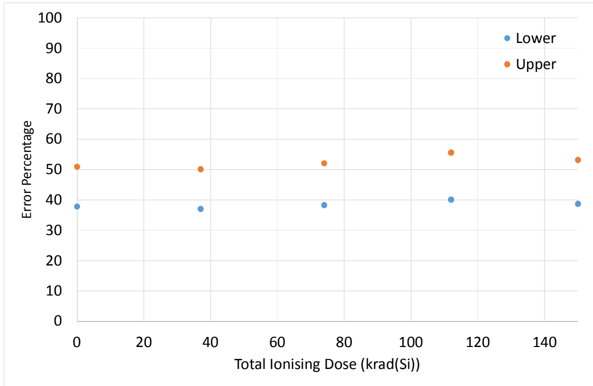


Figure 40 : AD9042 SEU percentage of error at 1.1 MeV.cm²/mg function of Total Dose

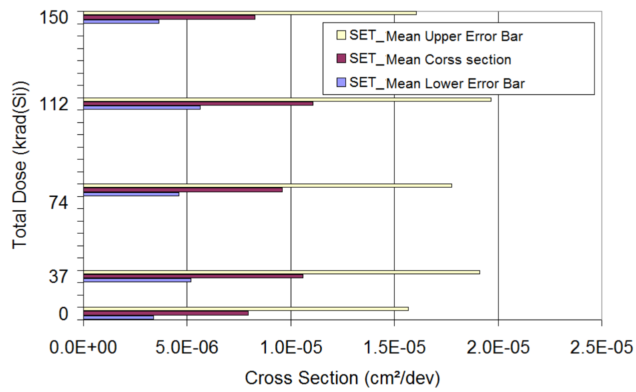


Figure 41 : AD9042 SET error bars for 95% confidence level and 10% fluence uncertainty at 10.2 MeV.cm²/mg function of Total Dose

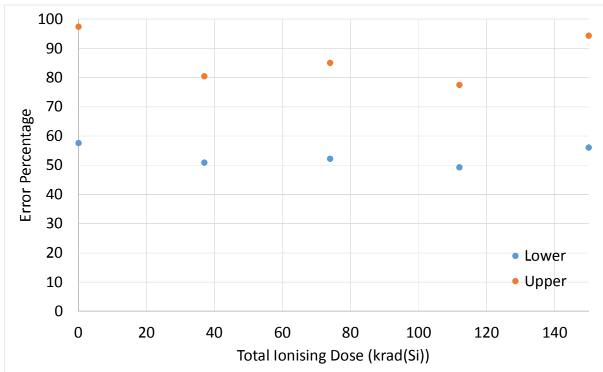


Figure 42 : AD9042 SET percentage of error at 1.1 MeV.cm²/mg function of Total Dose

As shown in the previous figures, errors on SEE cross sections are more important for SET than for SEU event. This observation is due to the number of SET observed during test which is higher than the SEU number.
Moreover the received dose does not have any impact on the error bars close to the Let threshold.

7.1.2.4. Impact of bias condition during TID irradiation on SEE sensitivity

Figure 43, Figure 44, Figure 47 and Figure 48 represent the SEU and SET cross section curve according to the received dose and the bias condition used during ^{60}Co irradiation.
Figure 45, Figure 46, Figure 49 and Figure 50 show the corresponding Weibull cross section parameter evolution with Total Ionizing Dose. The Weibull parameters are determined using the automatic fit available in the OMERE software.

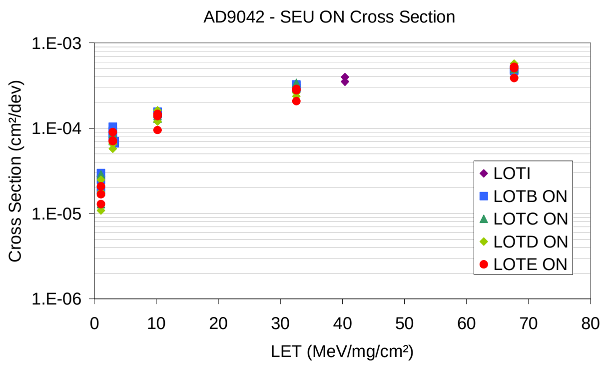


Figure 43 : AD9042 SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) Biased during TID irradiation

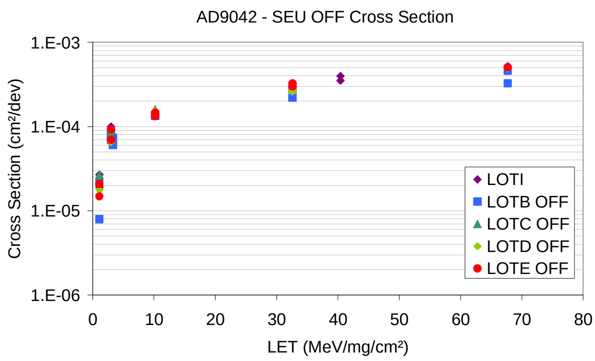


Figure 44 : AD9042 SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) Unbiased during TID irradiation

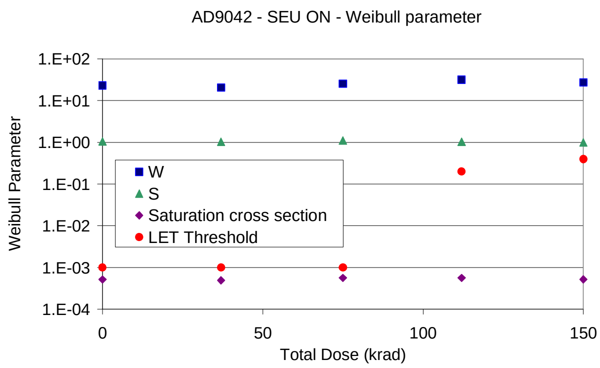


Figure 45 : AD9042 Weibull SEU cross section curve parameter in function of dose level for the biased parts during TID irradiation

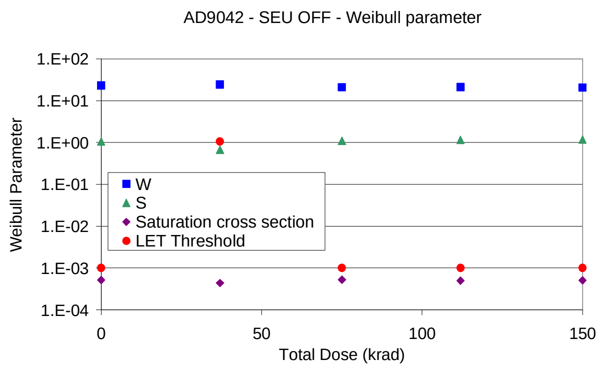


Figure 46 : AD9042 Weibull SEU cross section curve parameter in function of dose level for the unbiased parts during TID irradiation

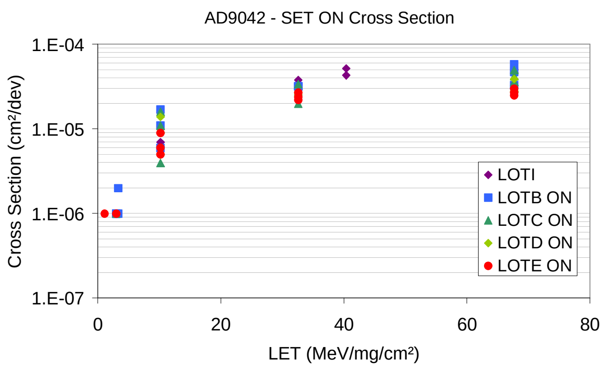


Figure 47 : AD9042 SET cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) biased during TID irradiation

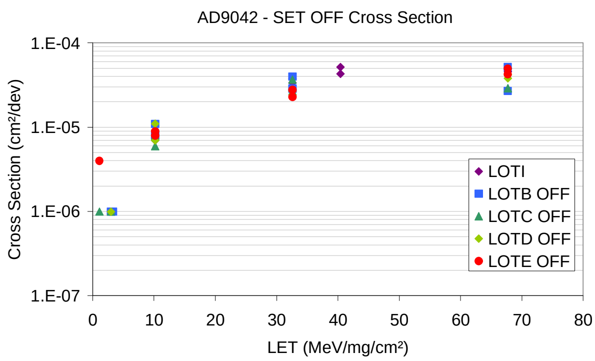


Figure 48 : AD9042 SET cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) unbiased during TID irradiation

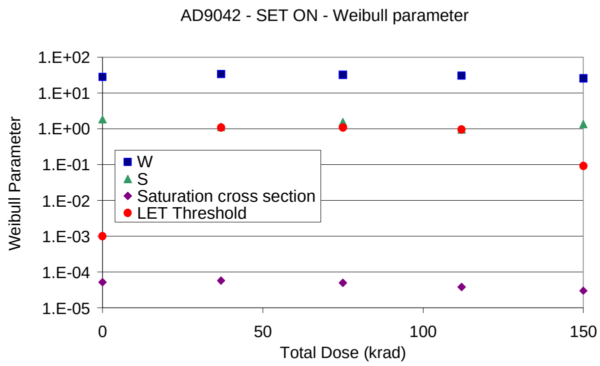


Figure 49 : AD9042 Weibull SET cross section curve parameter in function of dose level for the biased parts during TID irradiation

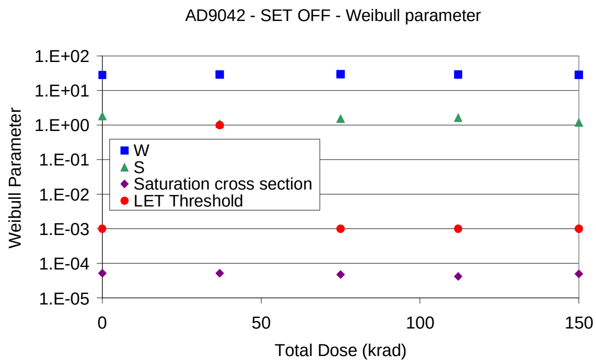


Figure 50 : AD9042 Weibull SET cross section curve parameter in function of dose level for the unbiased parts during TID irradiation

These results show that SEU and SET cross section curves are equivalent no matter the received dose and the bias condition during TID exposure.

As shown in Figure 48, the SET LET threshold seems to be higher at 150 krad(Si) for the unbiased parts, however as this phenomenon is not progressive with dose level, this observation is probably due to the low SET statics at low LET.

As shown in Figure 45, Figure 46, Figure 49 and Figure 50, Weibull parameters are constant with the dose level whatever the event or the bias condition except for the LET threshold. Indeed the LET threshold varies from 1E-3 MeV.cm²/mg to 1 MeV.cm²/mg. These variations are not induced by the dose level but by the automatic fit. SEE test results indicated that the LET threshold is lower than the value of 1.1 MeV.cm²/mg whatever the dose applied.

7.1.2.5. Impact of Total Ionizing Dose on SET signature

SET are defined as several consecutive false conversions.

SET test results are treated in order to evaluate if the total ionizing dose could have an impact on the number of consecutive false conversions. A maximum of 4 consecutive false conversions are observed.

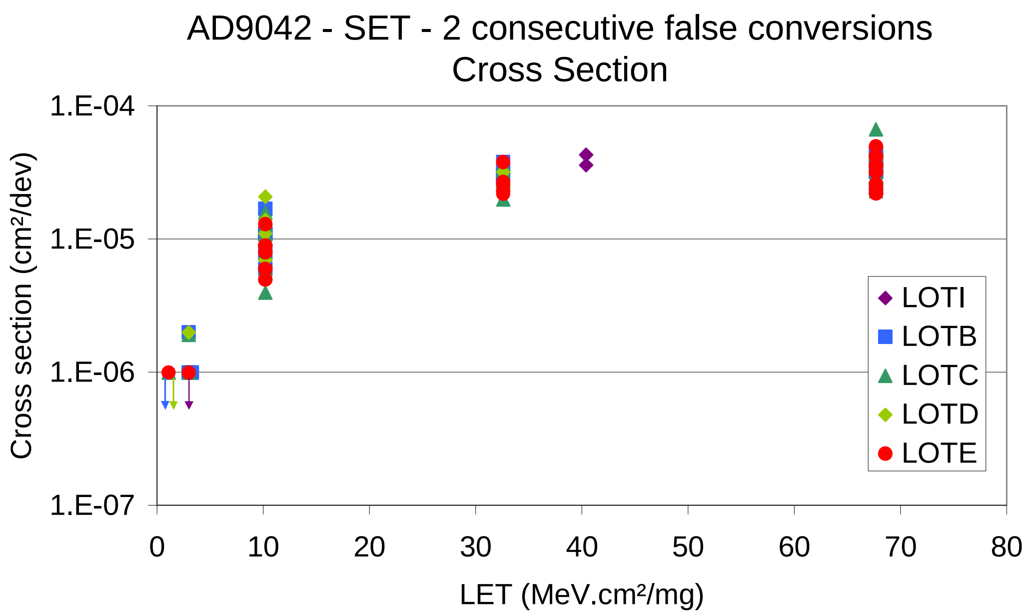


Figure 51 : AD9042 2 consecutive false conversions SET cross section curve comparison between LOTI, LOTB, LOTC, LOTD and LOTE

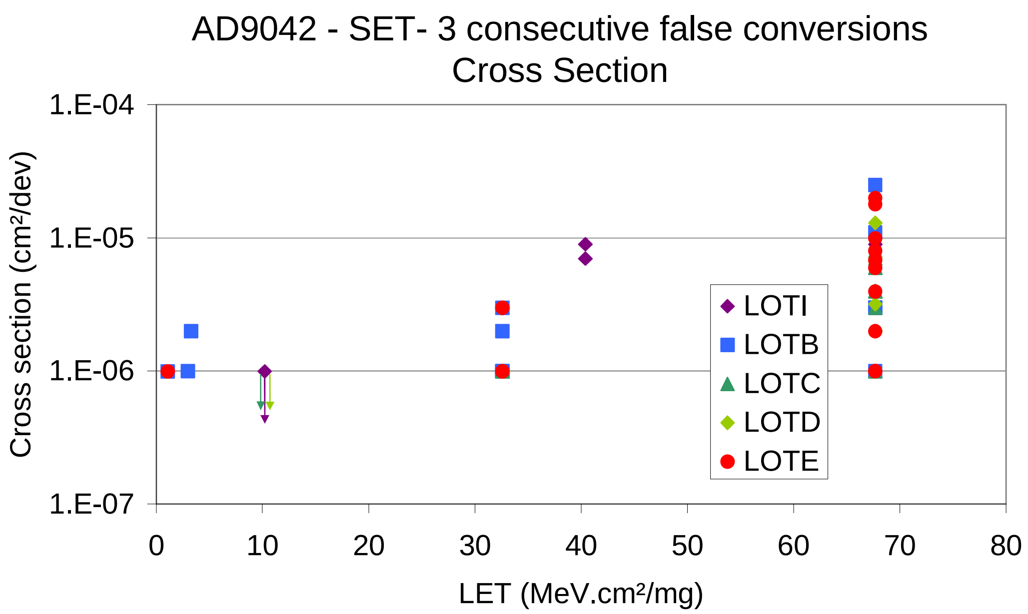


Figure 52: AD9042 3 consecutive false conversions SET cross section curve comparison between LOTI, LOTB, LOTC, LOTD and LOTE

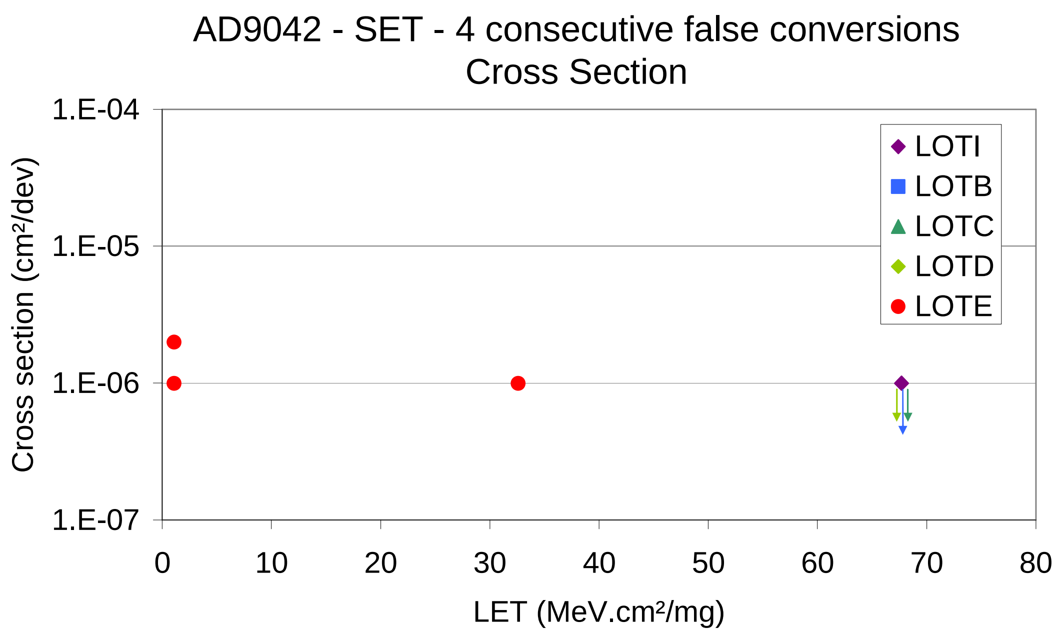


Figure 53: AD9042 4 consecutive false conversions SET cross section curve comparison between LOTI, LOTB, LOTC, LOTD and LOTE

SET corresponding to 4 consecutive false conversions are observed at 150 krad(Si).
However due to the low sensitivity of this effect, no conclusion can be drawn.

7.1.2.6. Impact of Total Ionizing Dose on SEL sensitivity

No SEL has been observed on this reference no matter dose received.

7.2. DAC AD558 FROM Analog Device

7.2.1. DAC AD558 TID tests results

Six AD558 Lots have been irradiated under ^{60}Co:

- LOTP : 10 non delidded parts (5 ON + 5 OFF) up to 250 krad (Si) at 310 rad(Si)/h at GAMRAY
- LOTA: 10 non delidded parts (5 ON + 5 OFF) up to 150 krad (Si) at 74 rad(Si)/h at UCL
- LOTB: 10 delidded parts (5 ON + 5 OFF) up to 42 krad (Si) at 74 rad(Si)/h at UCL
- LOTC: 10 delidded parts (5 ON + 5 OFF) up to 78 krad (Si) at 74 rad(Si)/h at UCL
- LOTD: 10 delidded parts (5 ON + 5 OFF) up to 114 krad (Si) at 74 rad(Si)/h at UCL
- LOTE: 10 delidded parts (5 ON + 5 OFF) up to 150 krad (Si) at 74 rad(Si)/h at UCL

No intermediary TID steps have been performed for LOT B, C, D and E. Results for these lots are then summarized on the same graph where each represents a TID step LOT.
The next Figure presents the comparison between LOTA and the compilation of LOT B, C, D, E (named LOTBCDE).

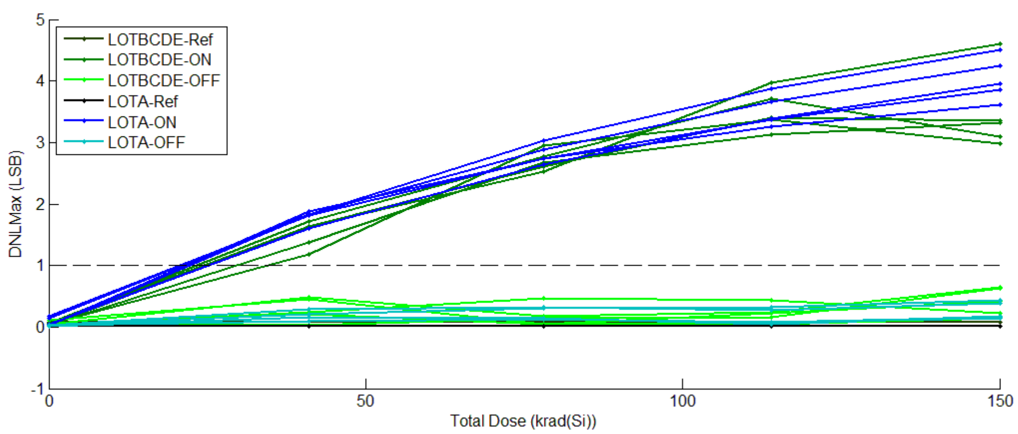


Figure 54 : AD558 DNL Max (LSB) function TID - LOTA compare to LOT BCDE

As it can be seen, no difference is observed between LOTA (non delidded parts) and LOTBCDE (delidded parts): the long time opened condition in a non-controlled atmosphere has no impact on the degradation for this reference.

The next Figure presents the comparison between LOTA and LOTP.

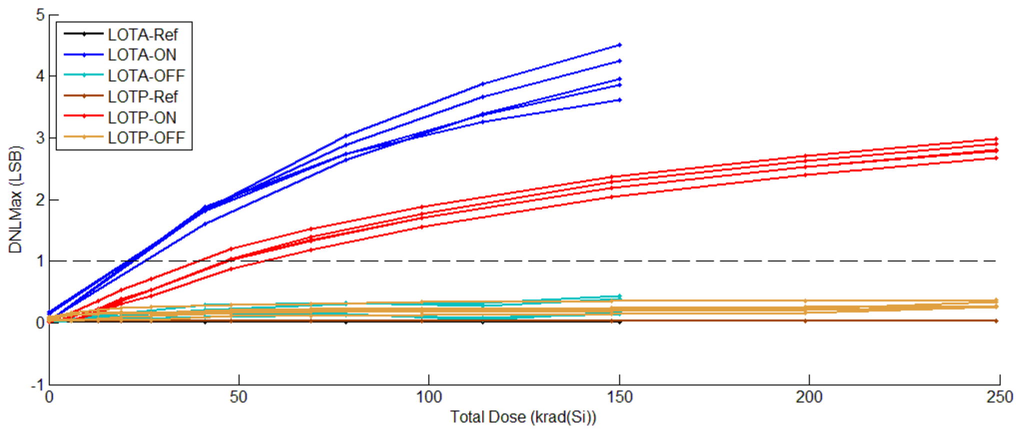


Figure 55: AD558 DNL Max (LSB) function TID - LOTA compare to LOT P

A difference is observed between ON and OFF parts. Indeed DNLmax(LSB) degradation is more important on parts biased ON than on OFF parts.

In addition, a factor of ~ 2 is observed between LOTA (74 rad/h) and LOTP (310 rad/h) at 150 krad(Si). Indeed the degradation observed under 74 rad/h ^{60}Co irradiation is higher than the one observed using a dose rate of 310 rad/h.
The first hypothesis is that this reference is Dose rate sensitive. To validate this, a new irradiation, named LOTV, has been performed at GAMRAY (TRAD) up to 150 krad(Si) using the same dose rate as the one used at UCL (74 rad/h).
The next Figure presents these results:

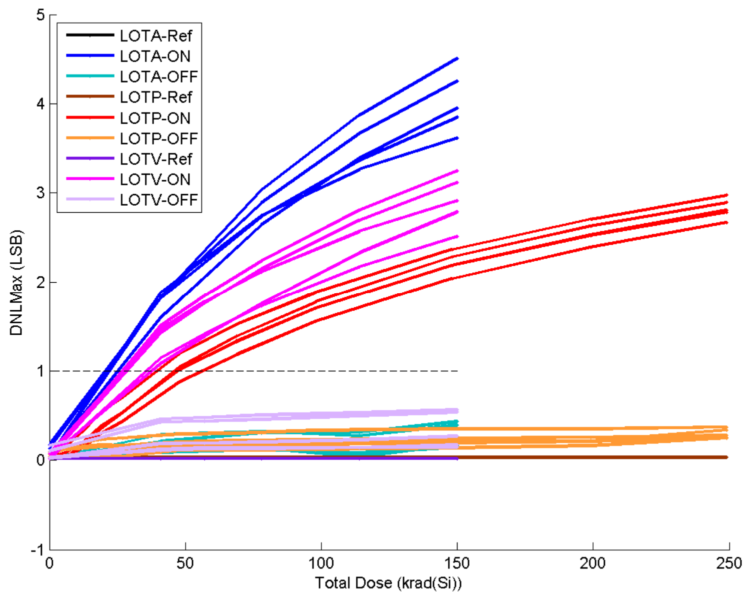
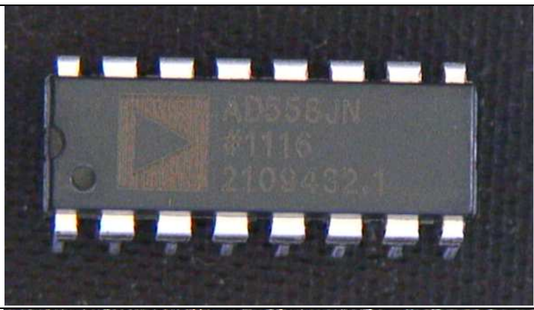
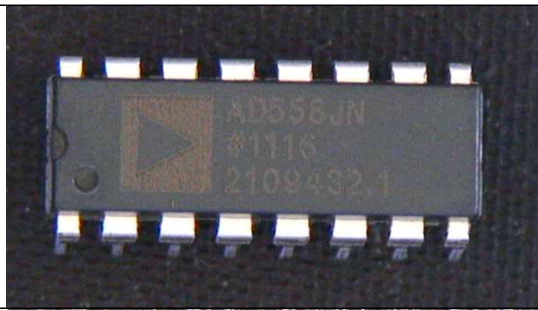


Figure 56: AD558 DNL Max (LSB) function TID – LOTA and P compare to LOTV

These results show that the difference is not induced by Dose rate effect. It looks like different lots, with different TID sensitivity, have been used for the synergy study.
Four devices: two from LOTA and two from LOTP, have been delidded and observed.
As shown in the following figures, no difference between mask, die dimension, metallization or packaging are observed.

For both lots, there is an inscription mentioning that these devices have been packaged in Malaysia. These devices have probably been packaged in the same factory.
The two procurement packages do not show any indications.
The only difference has been observed during the delidding phase. Indeed a difference in the time needed to open the two lots with chemical solution has been noted. We can suspect that different epoxies have been used to package these parts.
This observation supports that LOTA and LOTP are probably not from the same diffusion lot.

<table>
<tr><th>LOT-A</th><th>LOT-P</th></tr>
<tr><td>
</td><td>
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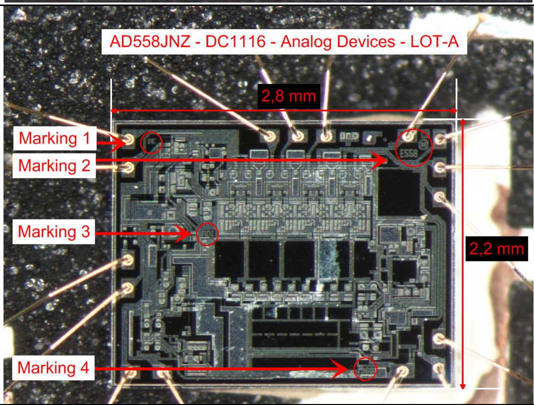
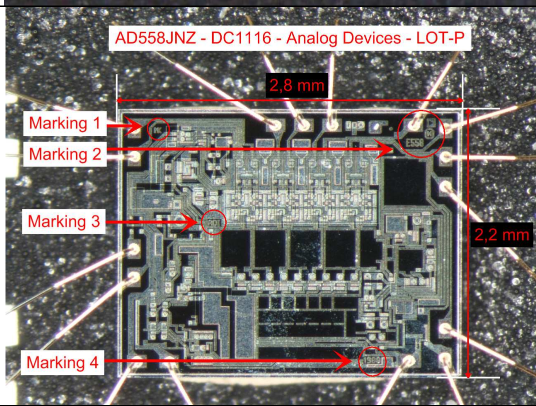
<tr><td>
</td><td>
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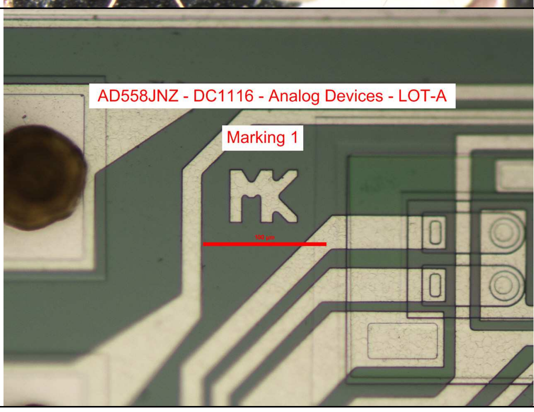
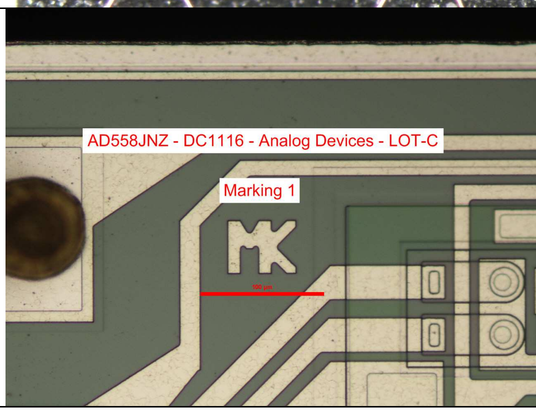
<tr><td>
</td><td>
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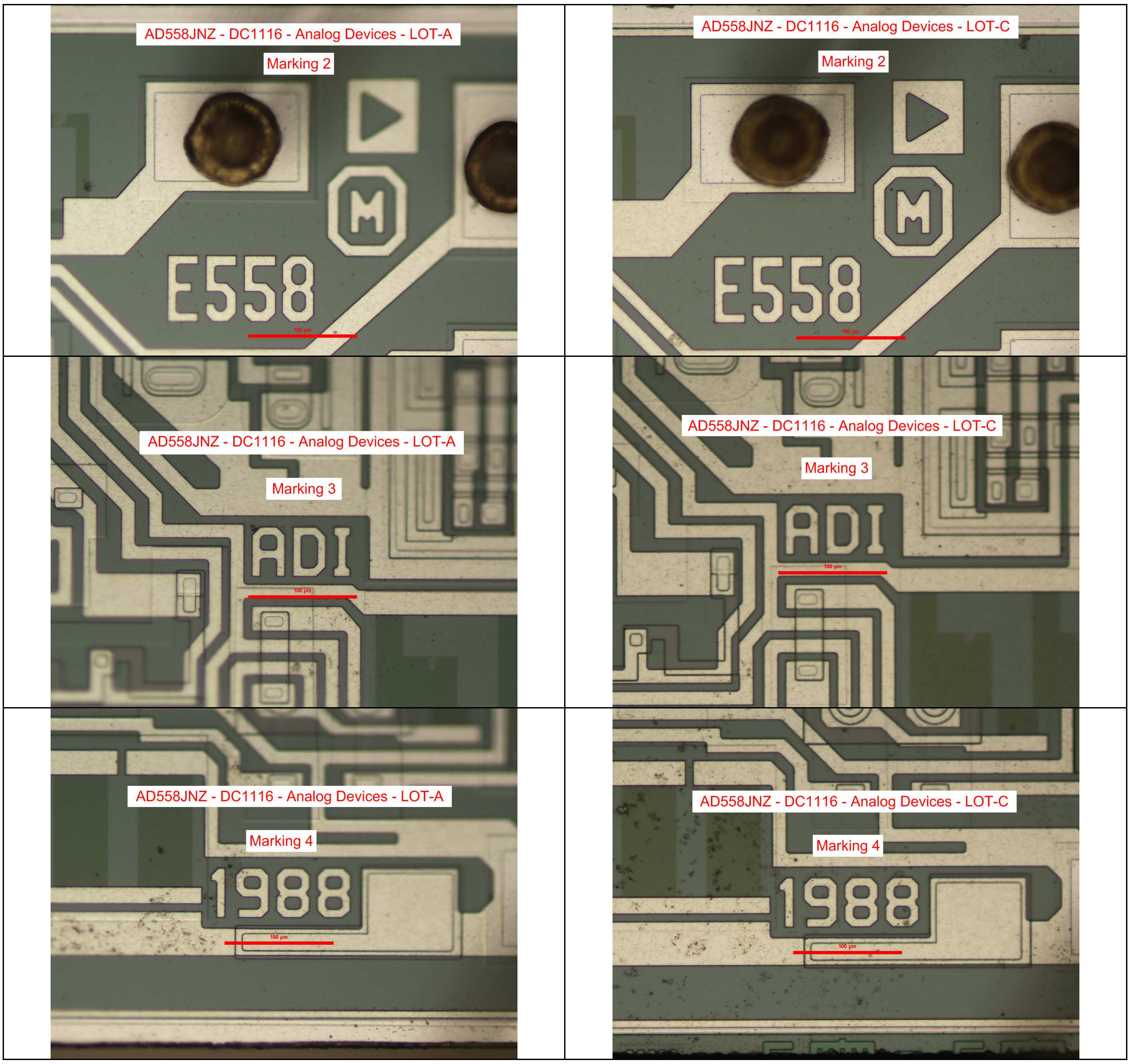


These results are still under investigation.
However as shown in Figure 56, the worst degradation is observed on the lot used for the synergy study.

7.2.2. DAC AD558 SEE tests results

Five AD558 Lots have been irradiated under heavy ions:

- LOTI : 3 parts
- LOTB: 5 parts following TID irradiation up to 42 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTC: 5 parts following TID irradiation up to 78 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTD: 5 parts following TID irradiation up to 114 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTE: 5 parts following TID irradiation up to 150 krad (Si) (3 ON + 2 OFF) and 1 reference

7.2.2.1. Impact of long time opened condition on SET sensitivity

The next figure presents the SET cross section curve comparison between devices not tested against TID irradiation. One non-irradiated device was tested at each TID step and is then named LOTI, LOTB, LOTC, LOTD and LOTE.

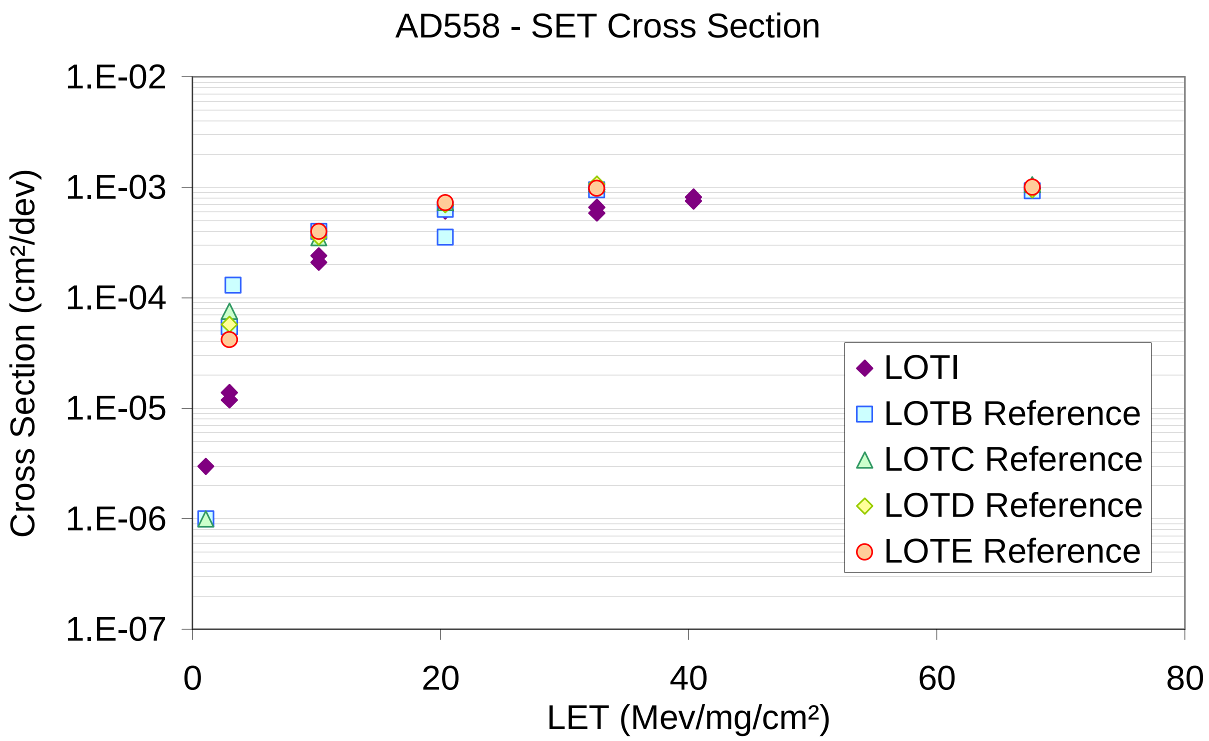


Figure 57 : AD558 SET cross section curve comparison between non ^{60}Co irradiated devices

As it can be seen, the cross section curve shape is slightly different for the LOTI than for the others LOTs.

7.2.2.2. Impact of Total Ionizing Dose on SET sensitivity

The next figure presents the SET cross section curve comparison between devices subject to synergetic effect: LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)).

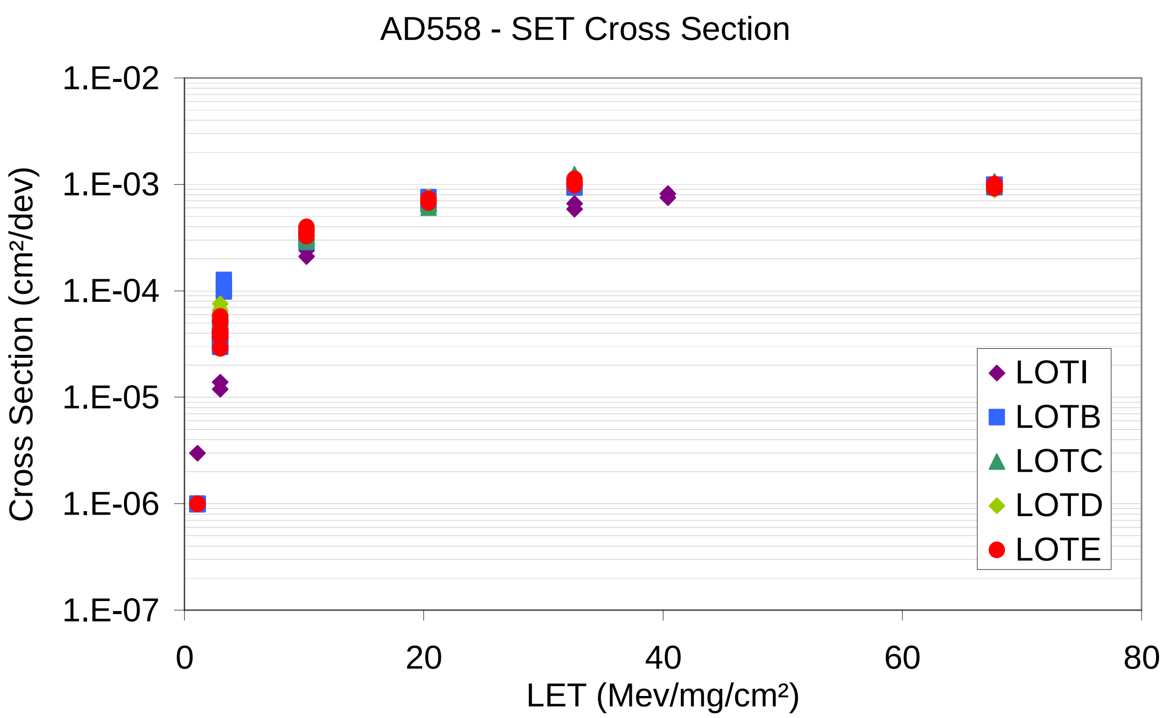


Figure 58 : AD558 SET cross section curve comparison between LOTI (0krad(Si)), LOTB (42krad(Si)), LOTC(78krad(Si)), LOTD(114krad(Si)) and LOTE (150krad(Si))

Cross section curves after TID exposure are equivalent to the reference tested at each TID step (Figure 57). As for the non-irradiated parts, a small difference is observed between LOTI and following LOTs.

7.2.2.3. *Impact of Total Ionizing Dose on SET error bars*

Error bars are calculated as described in the ESCC25100, using 95% confidence level and 10% fluence uncertainty.
As explained before, the impact of total ionizing Dose on error bars is evaluated for the lower LET where events are detected at each test.
The following figures represent, total ionizing dose impact on error bars for 3MeV.cm²/mg for SET

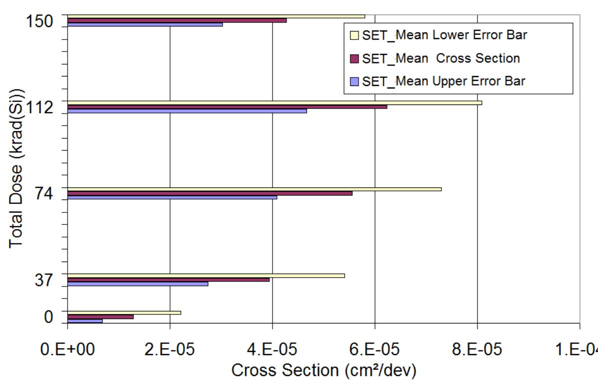


Figure 59 : AD558 SET error bars for 95% confidence level and 10% fluence uncertainty at 3MeV function of Total Dose

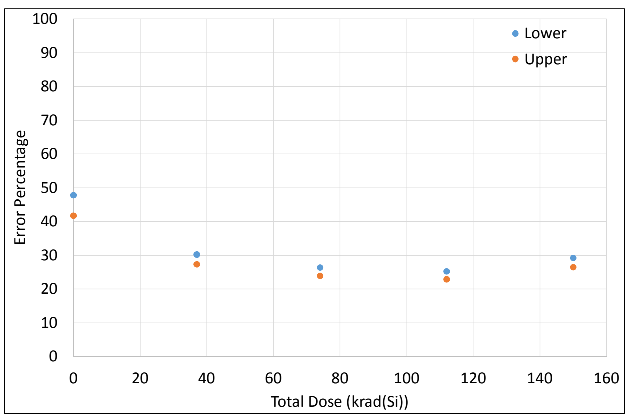


Figure 60 : AD558 SET percentage of error at 3MeV function of Total Dose

As shown in the previous figure, the measured cross section increases with total dose as the percentage error decreases. This behavior is not induced by TID but is dependent of the number of SET observed during test.

7.2.2.4. Impact of bias condition during TID irradiation on SEE sensitivity

Figure 61 and Figure 62 represent the SET cross section curves acoording to the received dose and the bias condition used during ^{60}Co irradiation.
Figure 63 and Figure 64 show the corresponding Weibull cross section parameter evolution with Total Ionizing Dose. The Weibull parameters are determined using the automatic fit available in the OMERE software.

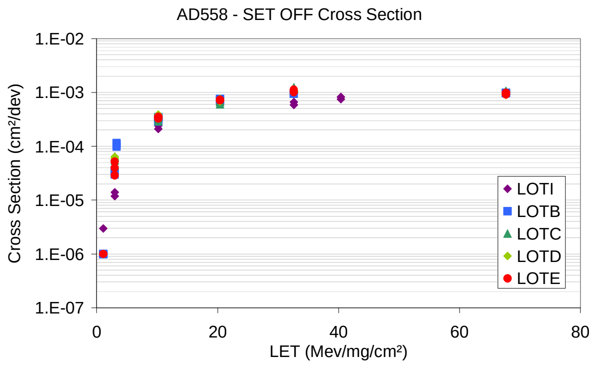


Figure 61 : AD558 SET cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) biased during TID irradiation

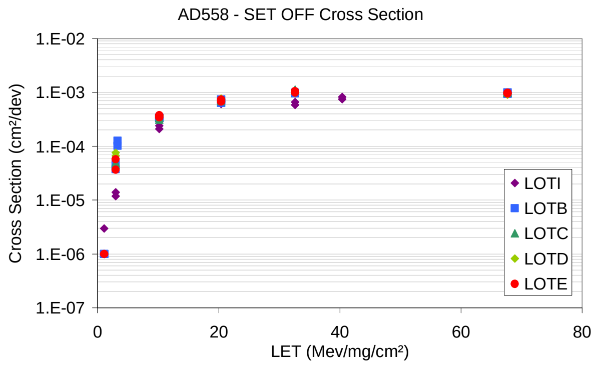


Figure 62 : AD558 SET cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) unbiased during TID irradiation

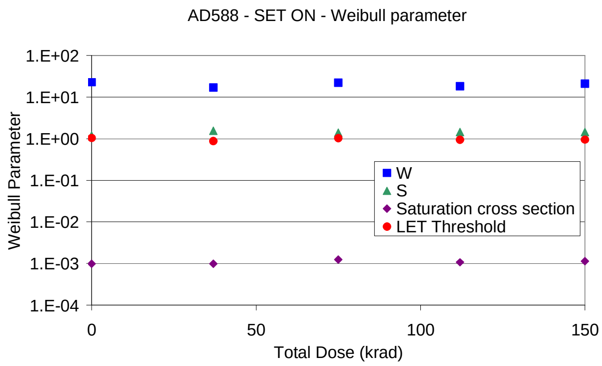


Figure 63 : AD558 Weibull SET cross section curve parameter in function of dose level for the biased parts during TID irradiation

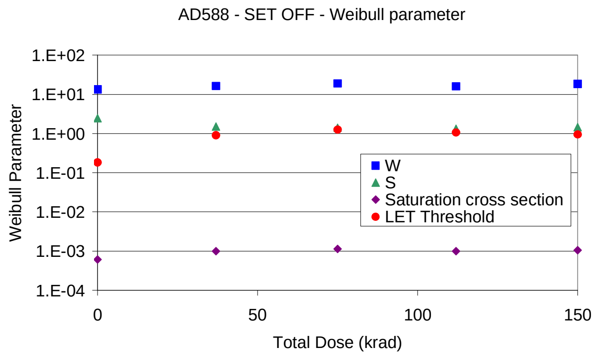
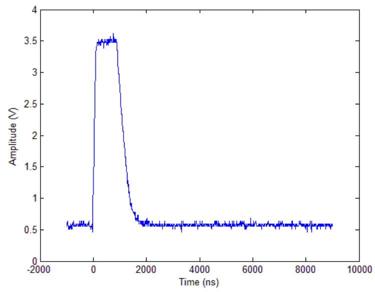


Figure 64 : AD558 Weibull SET cross section curve parameter in function of dose level for the unbiased parts during TID irradiation

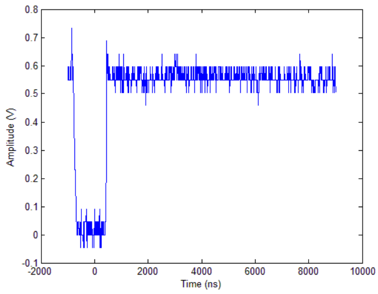
These results show that SET cross section curves and Weibull parameters are equivalent no matter the received dose and the bias condition used during TID exposure.

7.2.2.5. *Impact of Total Ionizing Dose on SET signature*

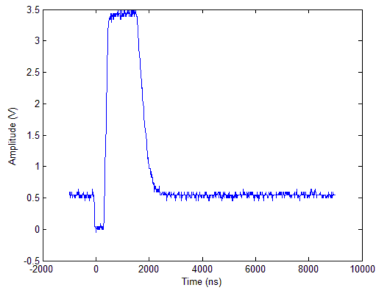
SET test results are treated in order to evaluate if the Total Ionizing Dose could have an impact on the amplitude or the duration of SET events.
Three different signatures are observed during the SET test as shown in the following figures:



Positive SET



Negative SET



Double SET

SET test results have been treated in order to evaluate if the dose level could have an impact on the SET signature and their proportion.

The next figures present SET cross section curves of non-irradiated and irradiated devices according to their SET signature. Figure 57 and Figure 58 have been post-processed in order to divide it into three cross section curves.

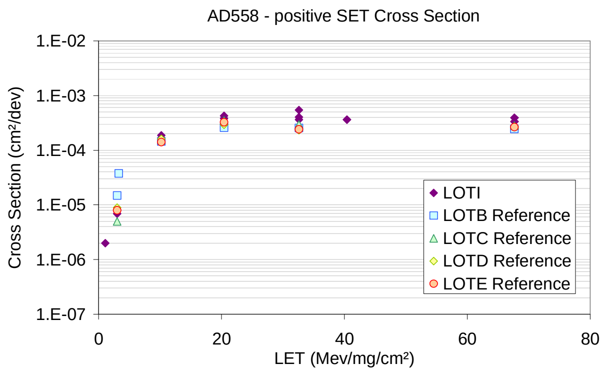


Figure 65 : AD558 positive SET cross section curve comparison between non ^{60}Co irradiated devices

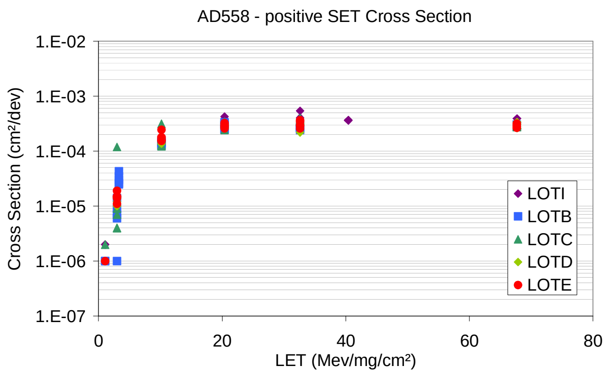


Figure 66 : AD558 positive SET cross section curve comparison between ^{60}Co irradiated devices

As shown by these results, there is no impact of the ionizing dose on the positive SET cross sections. Moreover, the following figure represents the amplitude and the duration of all detected SET according to the previous received dose. This representation shows that positive SET signal is equivalent no matter the dose level applied.

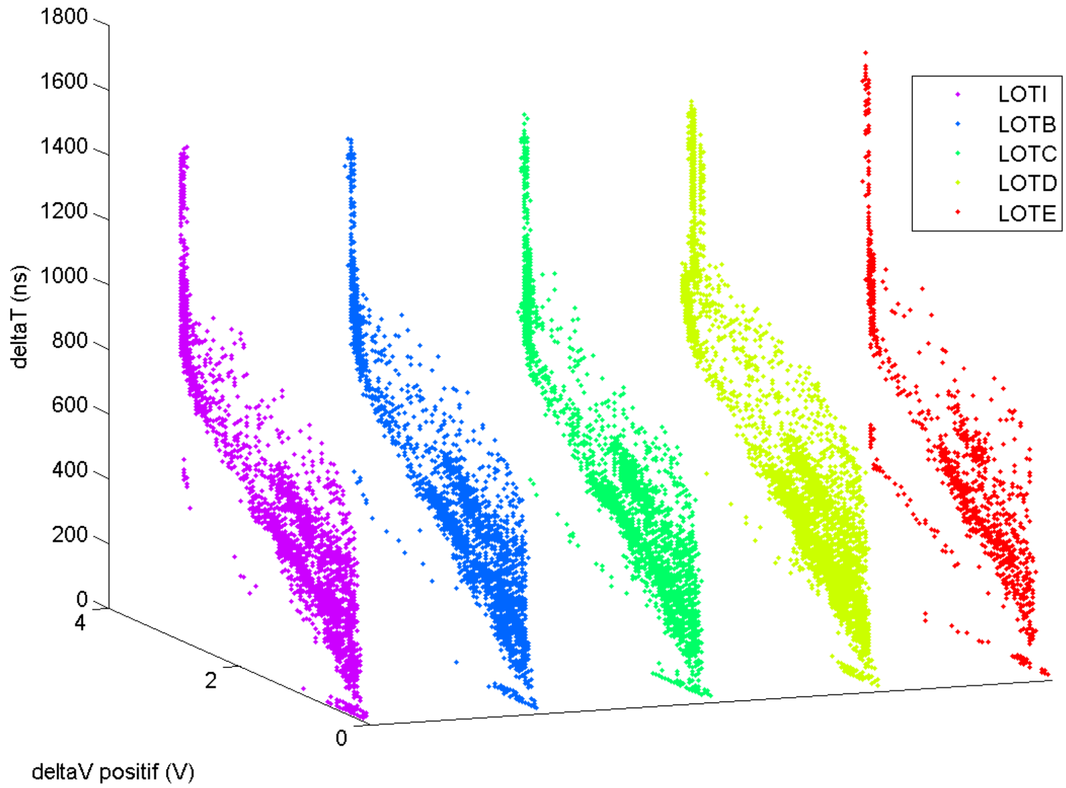


Figure 67 : the amplitude and the duration of positive SET in function of Total Ionizing Dose for LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si))

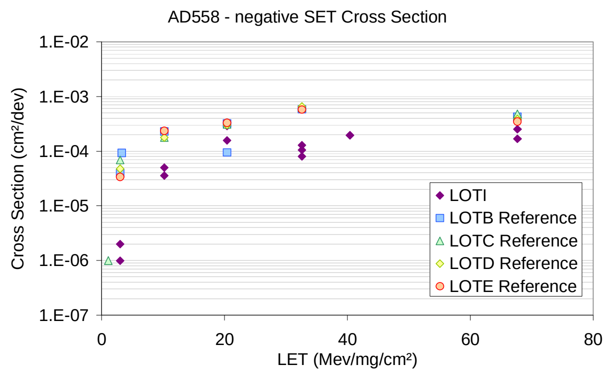


Figure 68 : AD558 negative SET cross section curve comparison between non ^{60}Co irradiated devices

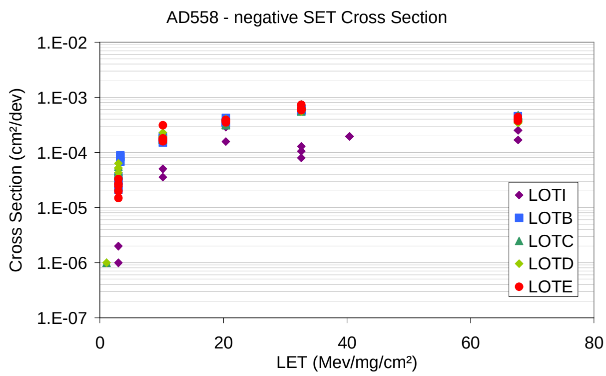


Figure 69 : AD558 negative SET cross section curve comparison between ^{60}Co irradiated devices

As shown by these results, the cross section curve shape is different for the LOTI compared to the others LOTs considering non-irradiated devices and irradiated parts. Indeed after three weeks in the open condition, the cross section curve measured is higher than the one obtained during the first heavy ion campaign. The delidded condition in a non-controlled atmosphere seems to impact the negative SET cross section curve.

Moreover, the following figure represents the amplitude and the duration of all detected SET according to the previous received dose. This representation shows that negative SET signal is equivalent no matter which dose level has been applied.

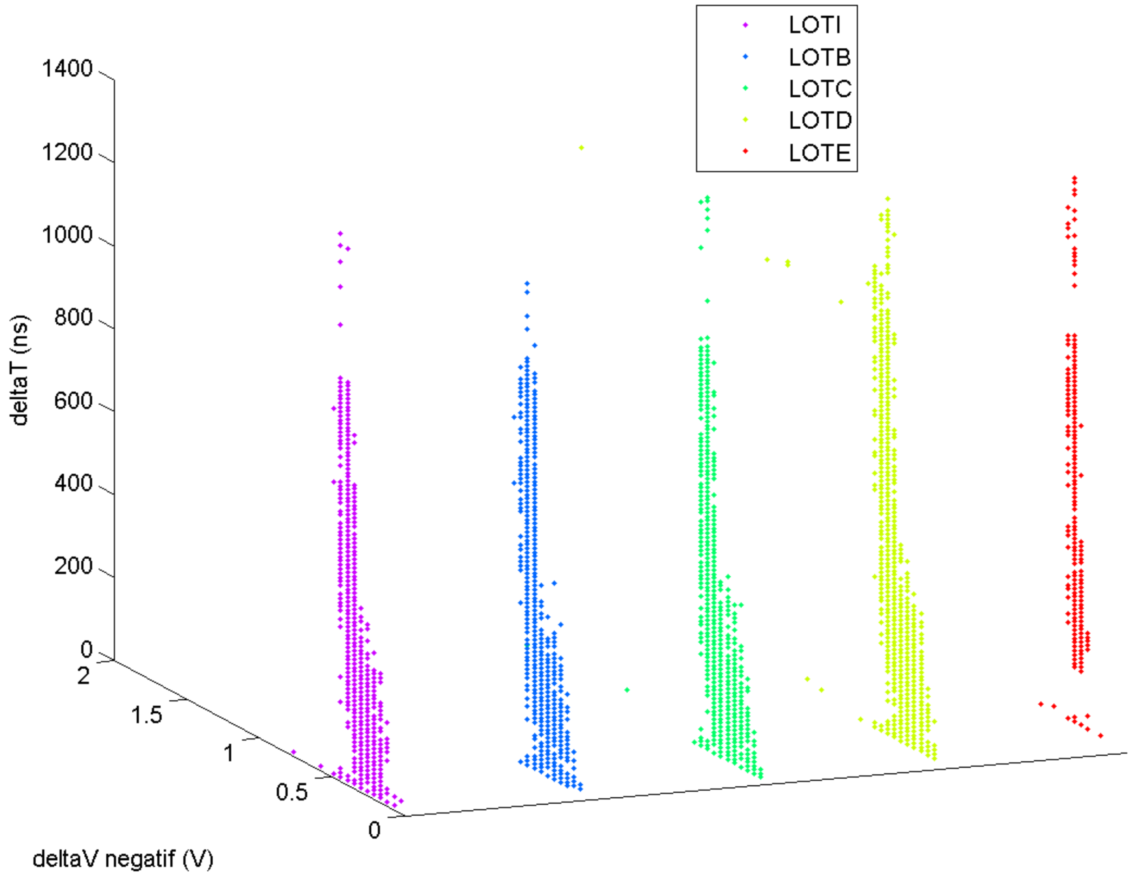


Figure 70: the amplitude and the duration of negative SET in function of total ionizing dose

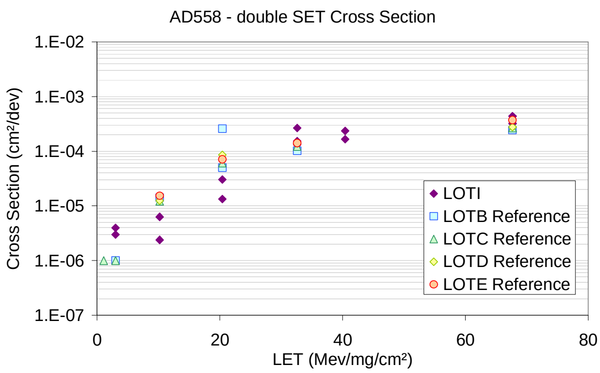


Figure 71 : AD558 double SET cross section curve comparison between non ^{60}Co irradiated devices

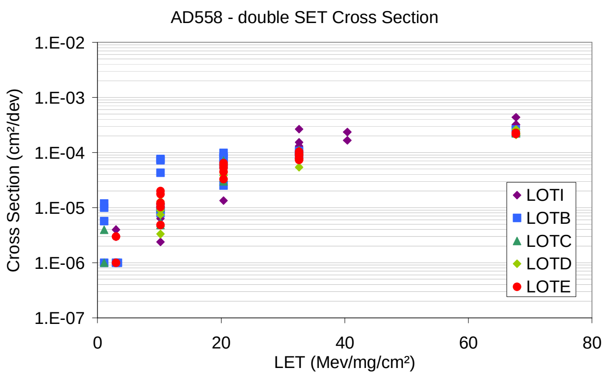


Figure 72 : AD558 double SET cross section curve comparison between ^{60}Co irradiated devices

These results show that SET results are more dispersive for irradiated devices but are still equivalent to non-irradiated devices. Moreover double SET signatures are equivalent no matter the dose level received, as shown in the next figure.

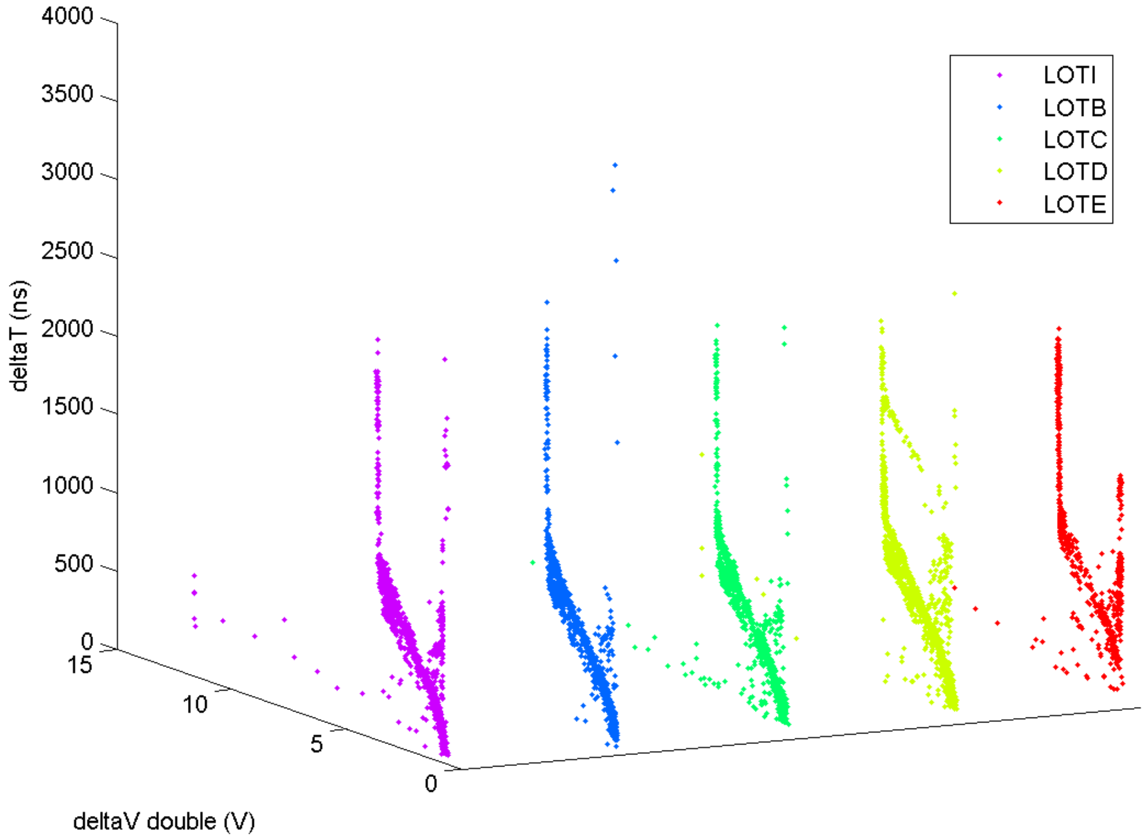


Figure 73: the amplitude and the duration of double SET in function of total ionizing dose

7.2.2.6. Impact of Total Ionizing Dose on SEL sensitivity

No SEL has been observed on this reference no matter the dose level received.

7.3. Flash NAND MT29F4G08AAC FROM Micron

7.3.1. Flash NAND MT29F4G08AAC TID tests results

Five MT29F4G08AAC Lots have been irradiated under ^{60}Co:

- LOTP : 10 non delidded parts (5 ON + 5 OFF) up to 150 krad (Si) at 310 rad(Si)/h at GAMRAY
- LOTA: 10 non delidded parts (5 ON + 5 OFF) up to 100 krad (Si) at 66 rad(Si)/h at UCL
- LOTB: 10 delidded parts (5 ON + 5 OFF) up to 36 krad (Si) at 66 rad(Si)/h at UCL
- LOTC: 10 delidded parts (5 ON + 5 OFF) up to 72 krad (Si) at 66 rad(Si)/h at UCL
- LOTD: 10 delidded parts (5 ON + 5 OFF) up to 100 krad (Si) at 66 rad(Si)/h at UCL

No intermediary TID step have been performed for LOT B, C and D. Results for these lots are then summarized on the same graph where each represents a TID step LOT.
The next figure presents the comparison between LOTA and the compilation of LOT B, C and D (named LOTBCD).

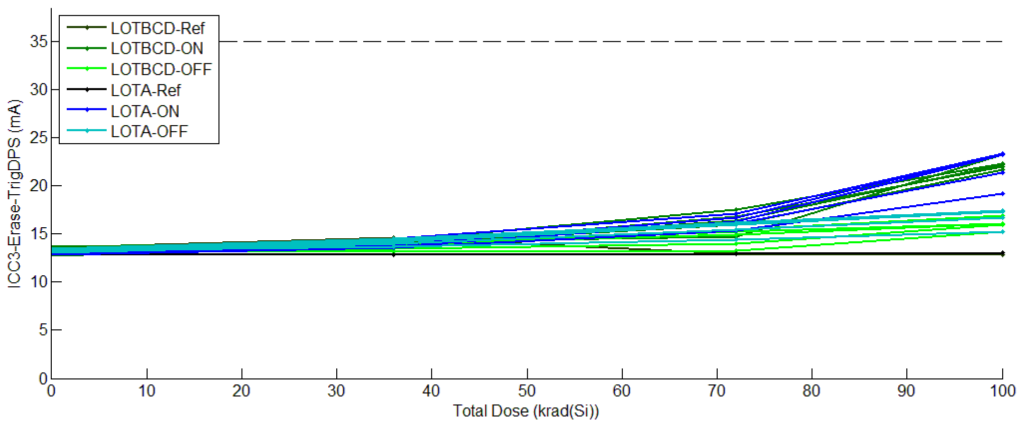


Figure 74 : MT29F4G08AAC ICC3_Erease_TrigDPS function TID LOTA compare to LOT BCD

As it can be seen, no difference is observed between LOTA (non delidded parts) and LOTBCD (delidded parts): the long time opened condition in a non-controlled atmosphere has no impact on the degradation for this reference.

The next figure presents the comparison between LOTA and LOTP.

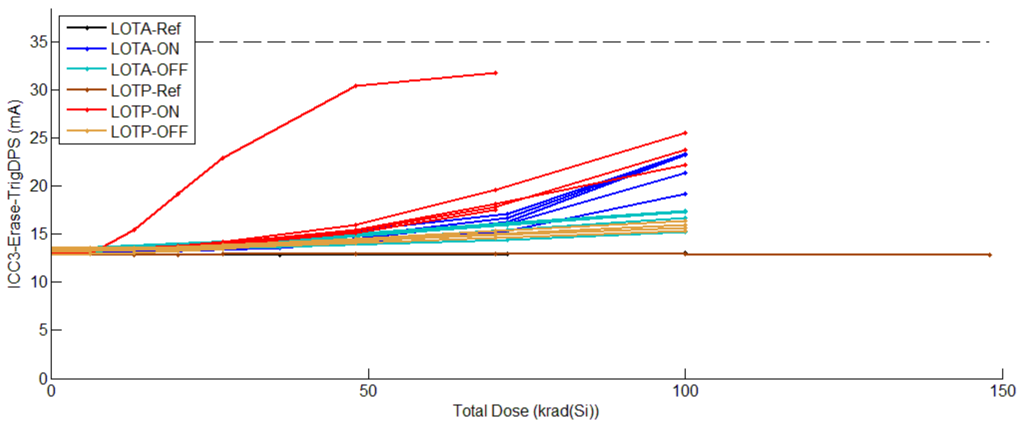


Figure 75: MT29F4G08AAC ICC3_Erease_TrigDPS function TID LOTA compare to LOT P

We notice that, no significant difference is observed between LOTA (66 rad/h) and LOTP (310 rad/h). Indeed no difference is observed for OFF biased parts, whereas degradation of ON biased is slightly higher for LOTP than the LOTA. However, as shown in the previous graphs, a disparity is observed between Nand Flash parts. Considering this disparity, degradations could be considered as equivalent. By consequence we consider that the ^{60}Co dose rate has no impact on the degradation for this reference.

7.3.2. Flash NAND MT29F4G08AAC SEE tests results

Four MT29F4G08AAC Lots have been irradiated under heavy ions:

- LOTI : 3 parts
- LOTB: 5 parts following TID irradiation up to 36 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTC: 5 parts following TID irradiation up to 72 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTD: 5 parts following TID irradiation up to 100 krad (Si) (3 ON + 2 OFF) and 1 reference

7.3.2.1. Impact of SEE test on NAND Flash Functionality

During the first test campaign, several runs have been performed on 6 NAND Flash devices using the Xenon ion, corresponding to the highest LET (67.7 MeV.cm²/mg).
These runs have been performed in order to evaluate SEL and SEU sensitivity at high LET.
The next table resumes all these runs and gives information on the status of the part after the run. As it can be seen most of the devices are non-functional after SEE test with the Xenon ion.
The test has then been stopped when the non-functionality of the part was detected. Following this failure a test has been performed again to evaluate the functionally of the device after a power ON/OFF.
Indeed, at the beginning of each SEE test, a functional test has been performed on NAND Flash memories.
All the 4096 blocks are written with the pattern AA55 and read again. If an error is detected the block is defined as a Bad Block and is not used during the following SEE test. If more than 25% of the 4096 blocks are detected as Bad Block, the device is then considered as not functional anymore. The status “functional failure” is then applied.
If the number of blocks is sufficient for test, an SEE test is then performed. However, if an atypical behavior is observed, like out of beam errors, then this device is considered as not functional anymore and the status “functional failure” is also applied.

TABLE 17 : MT29F4G08AAC SEE pre characterization using Xenon ion (67.7 MeV.cm²/mg) and post run part status

MT29F4G08ABADAWP Vcc = 3.3V T = 25°C											LATCHUP		SEE				Post Run Part Status
Run	Part	Config	Ion	Energy (MeV)	Range (µm)	LET (MeV.cm²/mg)	Flux (φ) (cm⁻².s⁻¹)	Time (s)	Run Fluence (Φ) (cm⁻²)	Run Dose (krad)	Cumulated Dose (krad)	Vcc	Cross Section	SEU	Cross Section	SEFI	Cross Section	
High LET M/Q=5																		
1	1	SEL without GUARD	124Xe 26+	420	37	67.7	7.93E+03	112	8.88E+05	0.962	0.962	-	-	-	-	-	-	Failure
2	1	Functional Test	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4096 Bad Block Functional Failure
3	2	SEL without GUARD	124Xe 26+	420	37	67.7	1.00E+04	1000	1.00E+07	10.853	10.853	-	-	-	-	-	-	Failure
4	2	Functional Test	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4096 Bad Block Functional Failure
5	3	SEU Ro	124Xe 26+	420	37	67.7	9.51E+03	17	1.62E+05	0.175	0.175	0	<6.18E-06	3084	1.91E-02	49	3.03E-04	Functional
6	3	SEL 50mA	124Xe 26+	420	37	67.7	9.81E+03	1020	1.00E+07	10.843	11.018	22	2.20E-06	-	-	-	-	Failure
7	3	Functional Test	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1124 Bad Block Functional Failure
8	4	SEU Ret	124Xe 26+	420	37	67.7	9.09E+03	112	1.02E+06	1.103	1.103	-	-	-	-	-	-	Failure
9	4	Functional Test	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	out of beam errors Functional Failure
10	5	SEU Ro	124Xe 26+	420	37	67.7	2.23E+02	497	1.11E+05	0.120	0.120	0	<9.03E-06	4848	4.38E-02	45	4.06E-04	Functional
11	5	SEU Ro	124Xe 26+	420	37	67.7	5.32E+02	411	2.19E+05	0.237	0.357	0	<4.58E-06	11042	5.05E-02	9	4.12E-05	Functional
12	5	SEL 50mA	124Xe 26+	420	37	67.7	9.80E+03	1022	1.00E+07	10.852	11.209	21	2.10E-06	-	-	-	-	Failure
13	5	Functional Test	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1172 Bad Block Functional Failure
14	6	SEU Ro	124Xe 26+	420	37	67.7	4.62E+02	350	1.62E+05	0.175	0.175	0	<6.19E-06	10159	6.28E-02	5	3.09E-05	Functional
15	6	Functional Test	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Functional

These results seem to show that heavy ion tests increase the number of Bad Blocks.
This tendency is observed for various fluences (from 1.65E5 p/cm² to 1E7 p/cm²) and then for various cumulated doses due to heavy ions.

The next figure presents the number of functional blocks before SEE test, after SEE test using the Xenon ion, after 36 hours of annealing at room temperature and after 128 hours of annealing at room temperature.

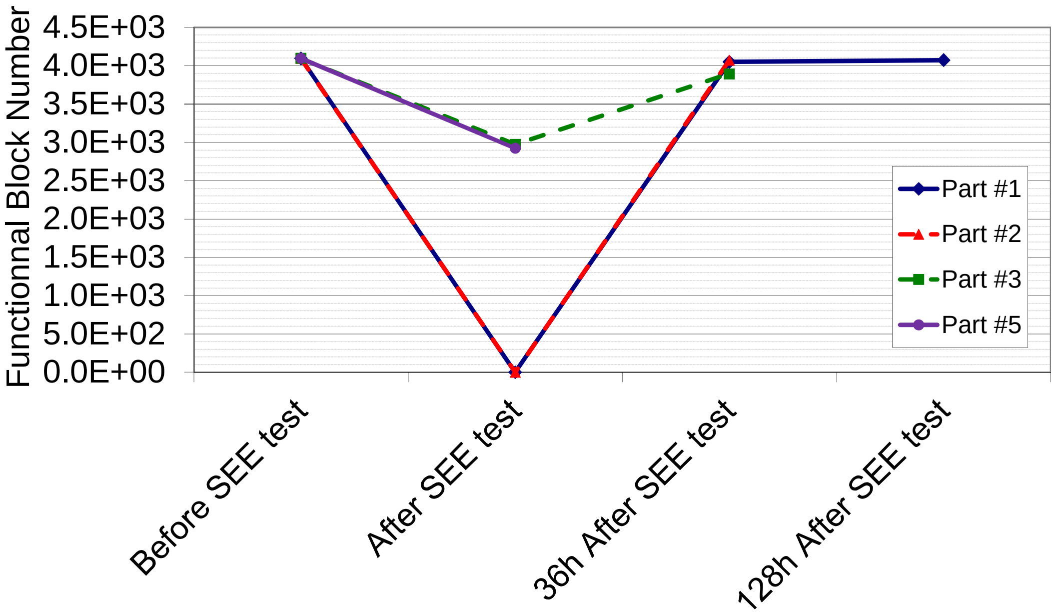


Figure 76 : MT29F4G08AAC Number of functional blocks before and after SEE test using the Xenon ion

The next table resumes the number of functional Block at each step of test.

TABLE 18 : MT29F4G08AAC Number of functionnal block before and after SEE test using the Xenon ion

	Part#1	Part#2	Part#3	Part#4
Before SEE test	4095	4095	4095	4095
After SEE test	0	0	2972	2924
36h After SEE test	4050	4073	3893	Not mesured
128h After SEE test	4071	Not mesured	Not mesured	Not mesured

Component 1 and 2 were tested without the guard system, in order to measure the complete High Current Event (HCE) signature. After heavy ion test, both of them show the entire block in error.
Component 3 and 5 were tested using the guard system with a threshold at 50mA. As shown in previous figure, many blocks are detected as bad blocks after heavy ion test.
Therefore components irradiated without the guard system, so subject to HCE with high current, show a more important degradation compared to part protected against SEL.
Moreover, it appears that this effect is not permanent.
After 36 hours of annealing at room temperature, the measured devices are almost totally functional. Only some Blocks are always “not functional” and this number decreases again after 128 hours.

This observation has not been detected using other ions. For example, all devices remain functional after runs using the Krypton ion (LET = 32.6 MeV.cm²/mg) up to a dose level of 6.77 krad(Si) (corresponding to a total fluence of 6.12E4 p/cm²). The dose level is then probably not the origin of non-functionality.

This effect could potentially be induced by High Current Event (HCE), detected as SEL in TABLE 17.
The next figure presents the cross section curve of High Current Event detected with a current threshold at 50 mA.

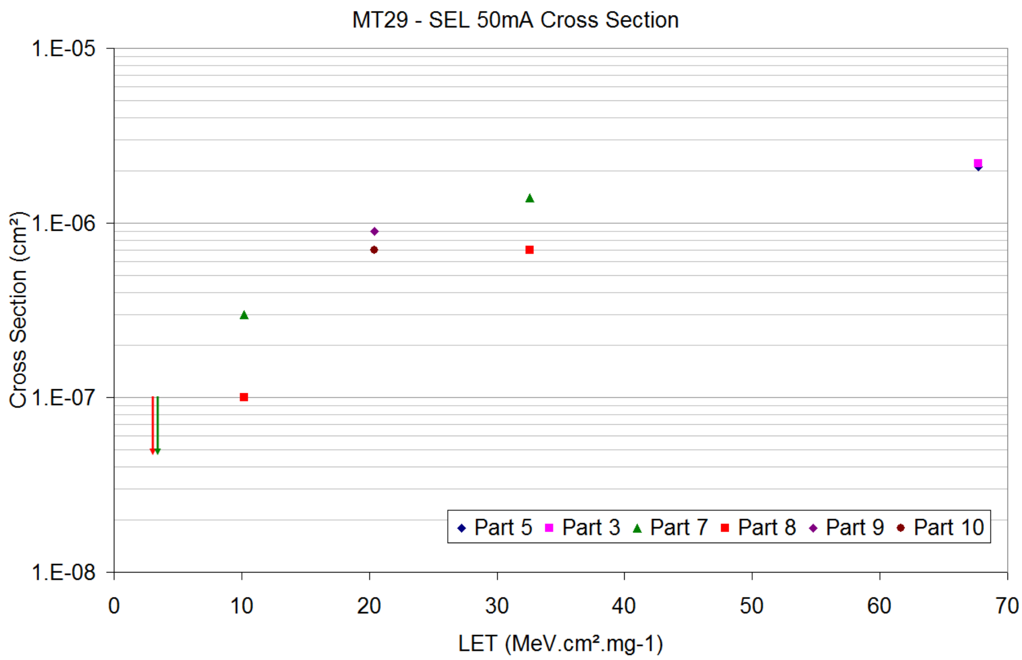


Figure 77: MT29F4G08AAC High Current Event (higher than 50mA) cross section curve

High Current Event LET threshold is lower than 10.2 MeV.cm²/mg. Moreover this effect seems to induce a temporary functional failure at LET of 67.7 MeV.cm²/mg but not at lower LETs.

The following figures present current spectrum measured during a run using the Xenon ion and the Krypton ion. Current spectrum are almost identical: three thresholds are observed at 5 mA, 30 mA and at 50 mA.

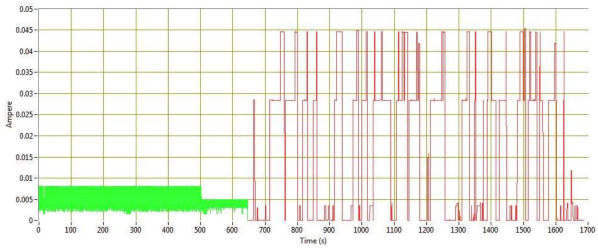


Figure 78: Current spectrum for MT29F4G08AAC. Data is taken with ^{124}Xe ion at LET 67.7 MeV.cm²/mg at the UCL facility

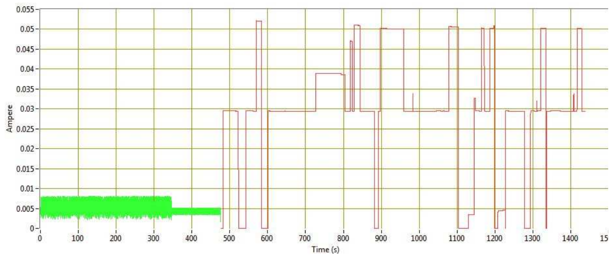


Figure 79: Current spectrum for MT29F4G08AAC. Data is taken with ^{83}Kr ion at LET 32.6 MeV.cm²/mg at the UCL facility

This hypothesis can be supported by literature.
Indeed as explained in [RD4], this phenomenon was destructive for all the NAND flash memories under the presented study except for the Micron Technology 2 Gb and 4 Gb. This coincides with the temporary device non-functionality.
Moreover, in [RD3] it is explained that the high currents started at an LET around 8.3 MeV-cm²/mg; however, high current spikes lead to a catastrophic failure at a higher LET around 19.6 MeV.cm²/mg for 32 Gb MLC Micron Technology NAND flash memories. This observation shows that HCE have different impacts according to the LET, which correspond to the effect observed during this study.

Considering these observations, the Xenon ion (LET = 67.7 MeV.cm²/mg) has not been used for SEE tests during the Synergy study. Indeed only five parts were available for SEE tests. It appears not acceptable to damage most of TID exposed devices after the first high LET SEE cocktail.

7.3.2.2. *Impact of long time opened condition on SEE sensitivity*

The next figures present the SEU cross section curve comparison between all devices not tested against TID irradiation. One non-irradiated device was tested at each TID step and is then named LOTI, LOTB, LOTC and LOTD.

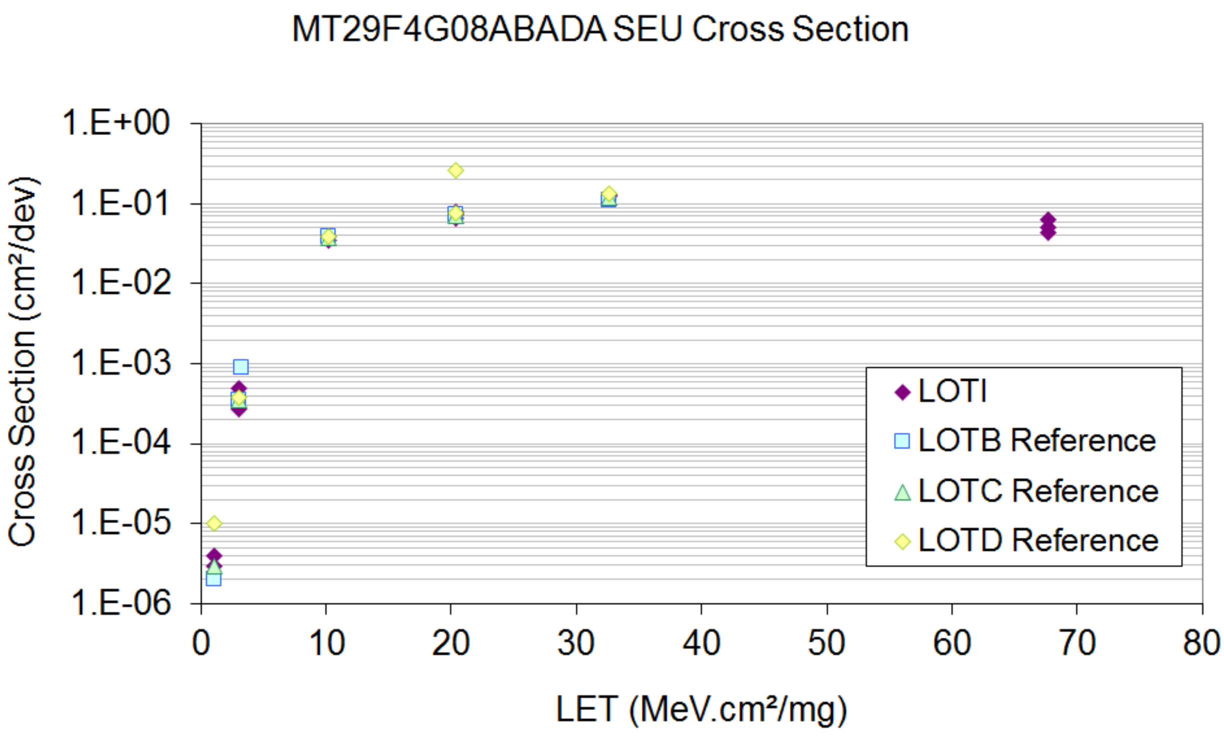


Figure 80 : MT29F4G08AAC SEU cross section curve comparison between non ^{60}Co irradiated devices

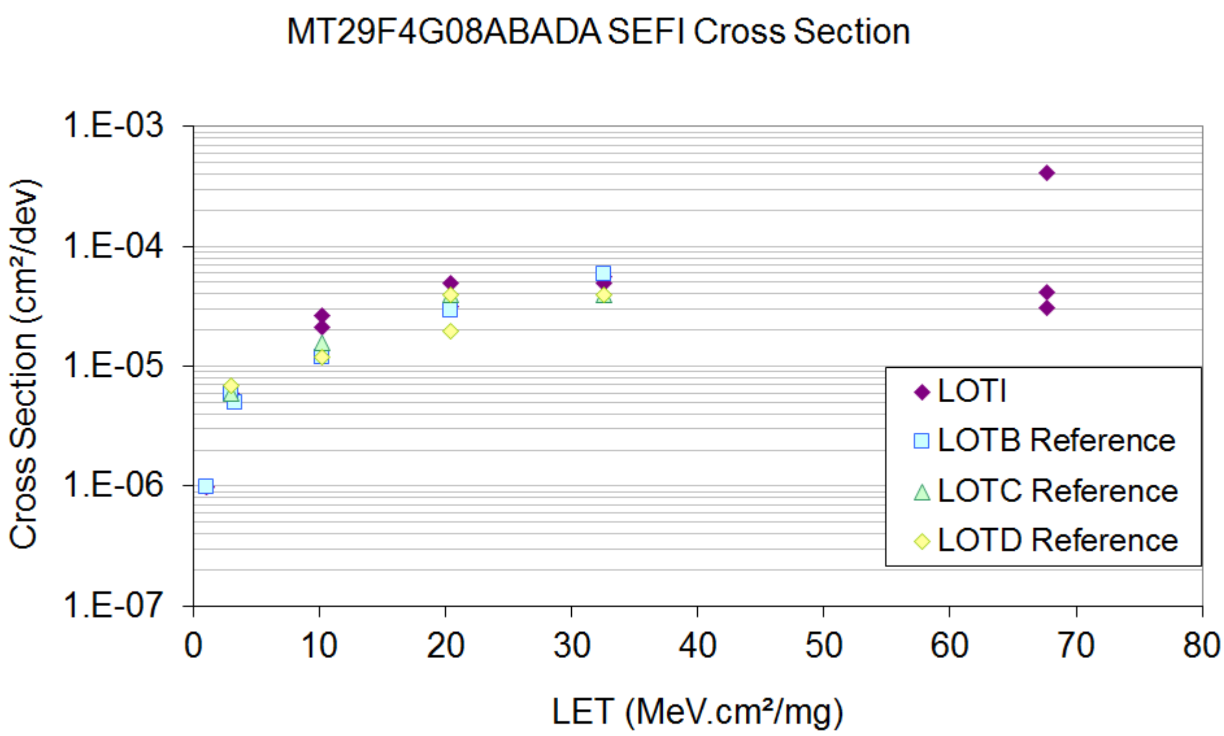


Figure 81 : MT29F4G08AAC SEFI cross section curve comparison between non ^{60}Co irradiated devices

As shown in previous graphs, the cross section curve shapes of LOTI are the same as for the others LOTs. We conclude that the delidded condition in a non-controlled atmosphere has no impact on the SEU and SEFI cross section curve.

7.3.2.3. Impact of Total Ionizing Dose on SEE sensitivity

The next figures present SEU and SEFI cross section curve comparisons between all devices subject to synergetic effect. LOTI (0 krad(Si)), LOTB (36 krad(Si)), LOTC(72 krad(Si)) and LOTD(100 krad(Si)) are shown.

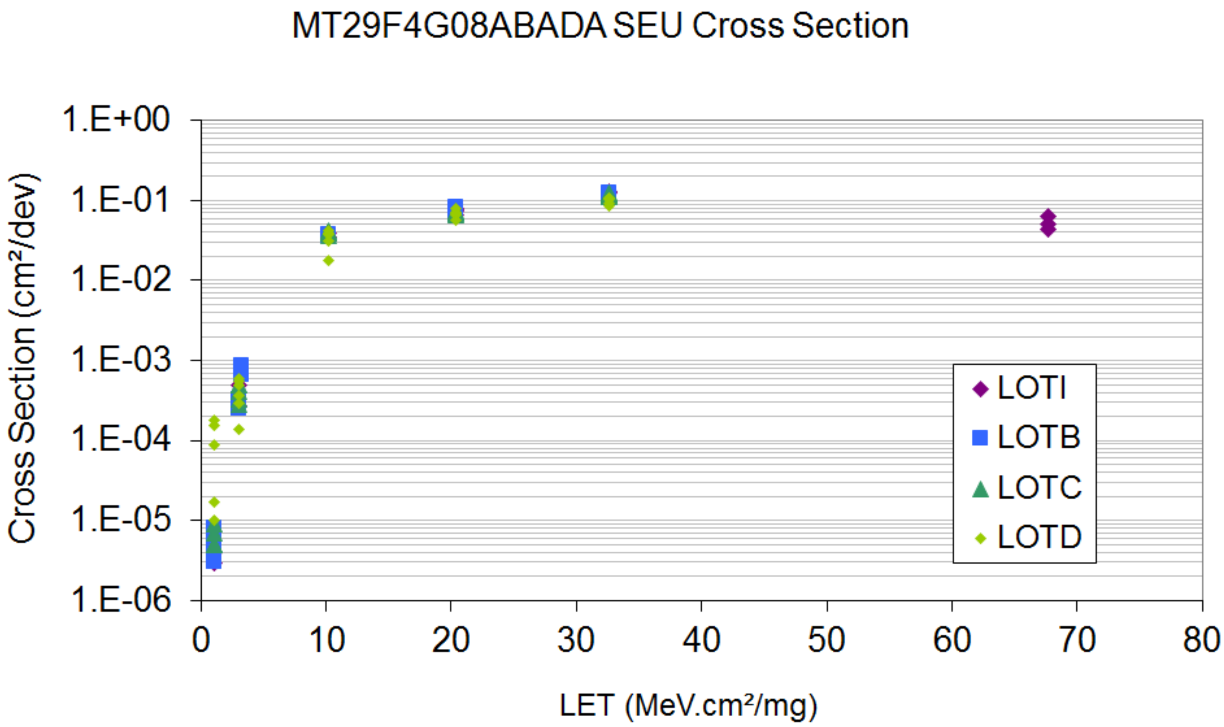


Figure 82 : MT29F4G08AAC SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (36 krad(Si)), LOTC(72 krad(Si)) and LOTD(100 krad(Si))

As presented in Figure 82, SEU cross section curves are equivalent no matter which the received dose is except at low LET. Indeed at 1.1 MeV.cm²/mg, it seems that sensitivity increase with the dose level. This tendency is not observed for other ions. SEU test has been performed at 67 MeV.cm²/mg only for LOTI. However, considering the sensitivity at 32.6 MeV.cm²/mg no difference between LOTs is expected at higher LET.

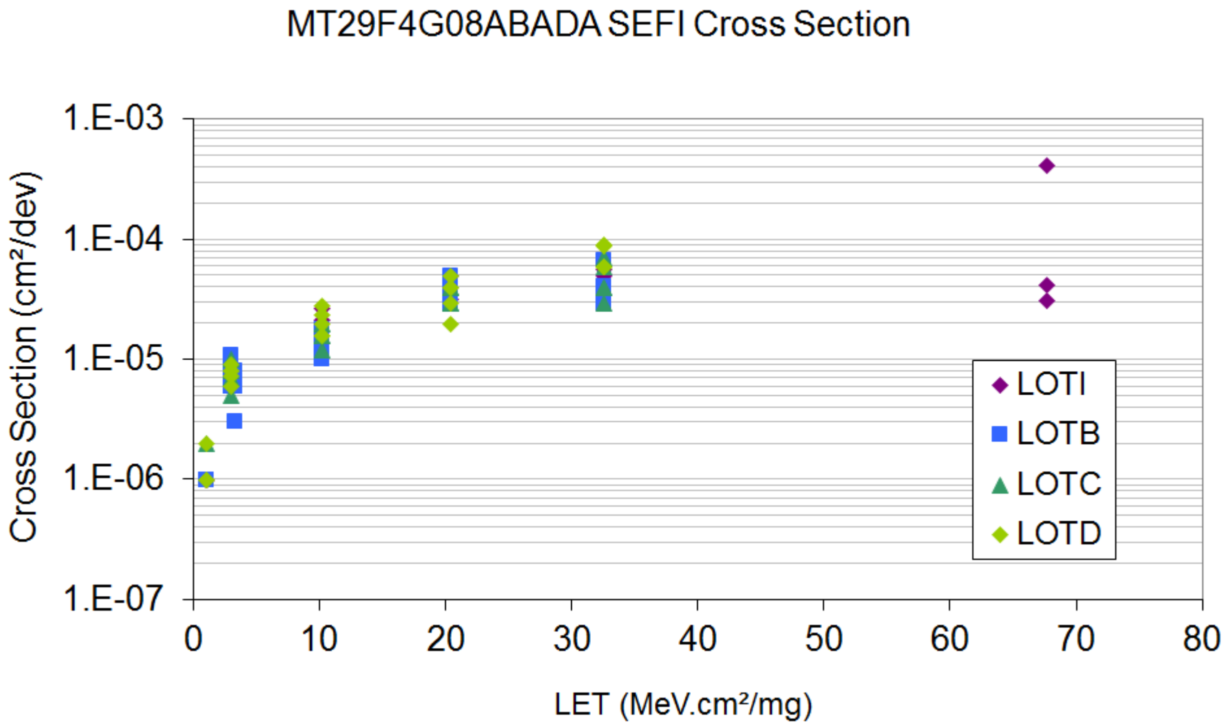


Figure 83 : MT29F4G08AAC SEFI cross section curve comparison between LOTI (0 krad(Si)), LOTB (36 krad(Si)), LOTC(72 krad(Si)) and LOTD(100 krad(Si))

As shown in the previous figure, cross section curves after TID exposure are equivalent to the reference tested at each TID step (Figure 80 and Figure 81). Moreover SEFI sensitivity is equivalent no matter the received dose.

7.3.2.4. *Impact of Total Ionizing Dose on SEFI and SEU error bars*

Error bars are calculated as described in the ESCC25100, using 95% confidence level and 10% fluence uncertainty.
As explained before, the impact of total ionizing Dose on error bars is evaluated for the lower LET where events are detected at each test.
The following figures show the total ionizing dose impact on error bars for

- 1.1MeV.cm²/mg for SEU
- 3 MeV.cm²/mg for SEFI

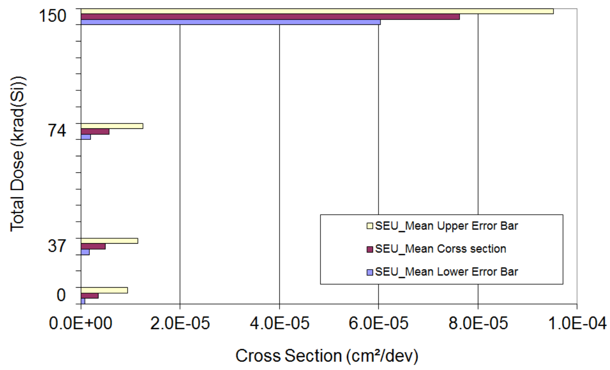


Figure 84 : AD558 SEU error bars for 95% confidence level and 10% fluence uncertainty at 1.1MeV function of Total Dose

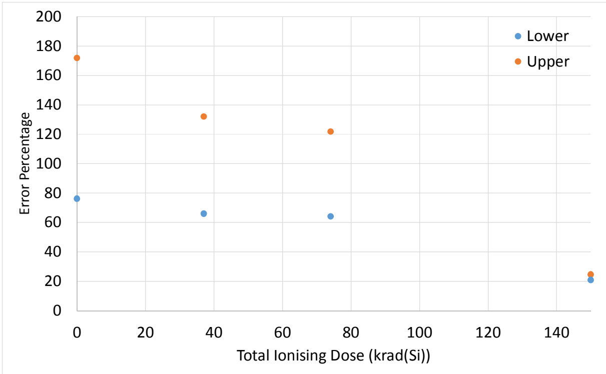


Figure 85 : AD558 SEU percentage of error at 1.1 MeV.cm²/mg function of Total Dose

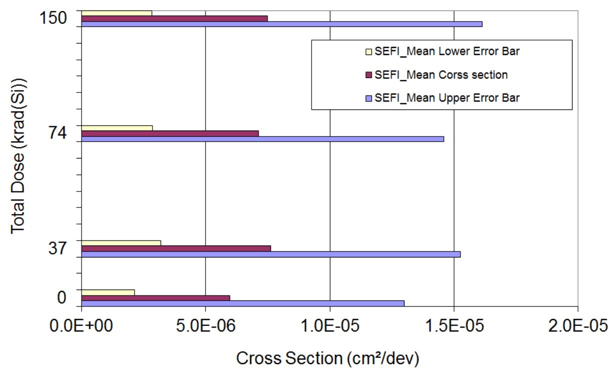


Figure 86 : AD558 SEFI error bars for 95% confidence level and 10% fluence uncertainty at 3MeV function of Total Dose

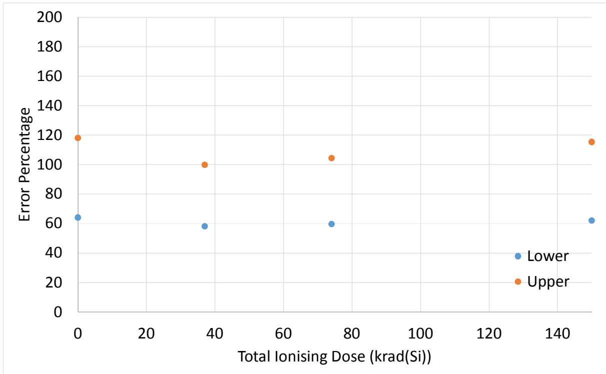


Figure 87 : AD558 SEFI percentage of error at 3 MeV.cm²/mg function of Total Dose

As shown in the previous figures, the measured SEU cross section increases at final total dose as the percentage error decreases.
However the TID level does not have any impact on the SEFI cross section and error bar.

7.3.2.5. Impact of bias condition during TID irradiation on SEE sensitivity

Figure 88 and Figure 89 show SEU cross section curves according to the received dose and the bias condition used during ^{60}Co irradiation.
Figure 90 and Figure 91 show the corresponding Weibull cross section parameter evolution with Total Ionizing Dose. The Weibull parameters are determined using the automatic fit available in the OMERE software.

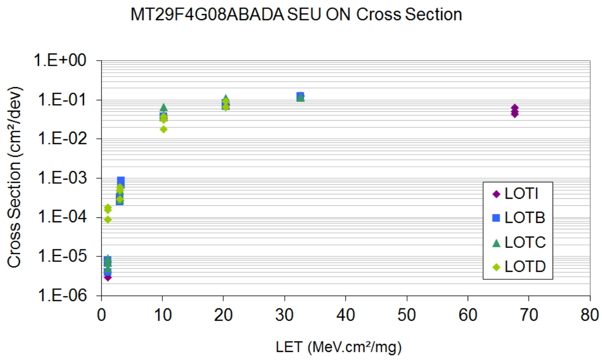


Figure 88 : MT29F4G08AAC SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (36 krad(Si)), LOTC(72 krad(Si)) and LOTD(100 krad(Si)) biased during TID irradiation

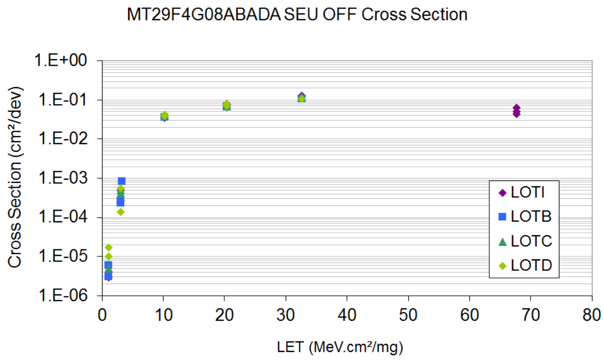


Figure 89 : MT29F4G08AAC SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (36 krad(Si)), LOTC(72 krad(Si)) and LOTD(100 krad(Si)) unbiased during TID irradiation

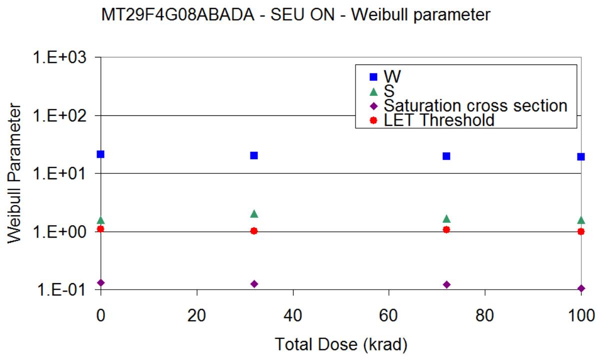


Figure 90 : MT29F4G08AAC Weibull SEU cross section curve parameter as a function of dose level for the biased parts during TID irradiation

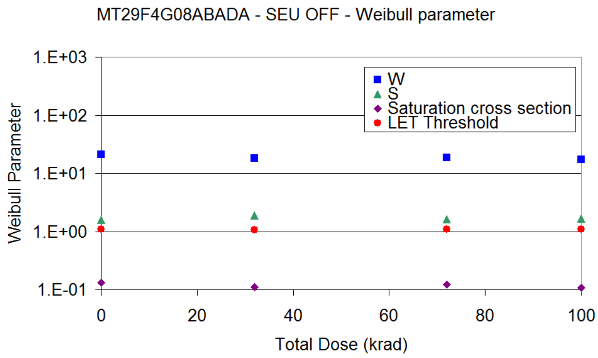


Figure 91 : MT29F4G08AAC Weibull SEU cross section curve parameter as a function of dose level for the unbiased parts during TID irradiation

These results show that SEU cross section curves and Weibull parameters are equivalent no matter the received dose, in OFF bias condition used during TID exposure. However, the SEU sensitivity is higher at 100 krad for the lower LET (1.1 MeV.cm²/mg). This result is not observed on the Weibull parameter evolution due to the high sensitivity of this reference.

The next figures show the SEFI cross section curves according to the received dose and the bias condition and corresponding Weibull cross section parameter evolution with Total Ionizing Dose.

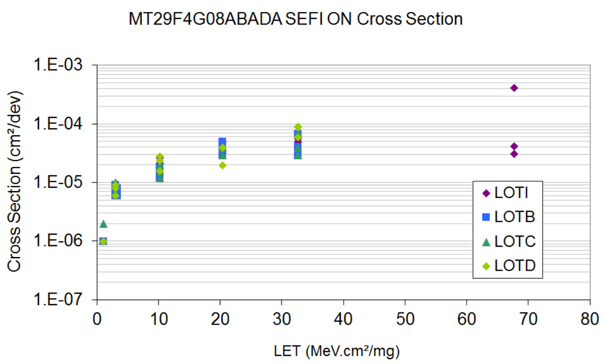


Figure 92 : MT29F4G08AAC SEFI cross section curve comparison between LOTI (0 krad(Si)), LOTB (36 krad(Si)), LOTC(72 krad(Si)) and LOTD(100 krad(Si)) biased during TID irradiation

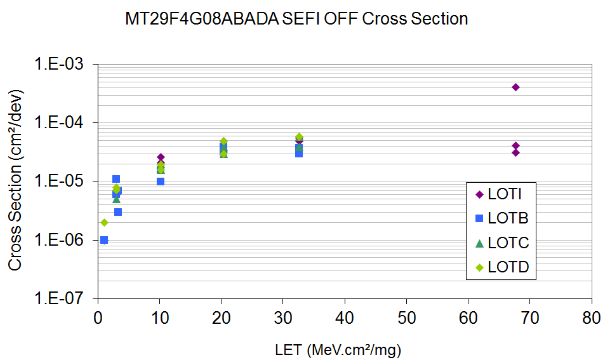


Figure 93 : MT29F4G08AAC SEFI cross section curve comparison between LOTI (0 krad(Si)), LOTB (36 krad(Si)), LOTC(72 krad(Si)) and LOTD(100 krad(Si)) unbiased during TID irradiation

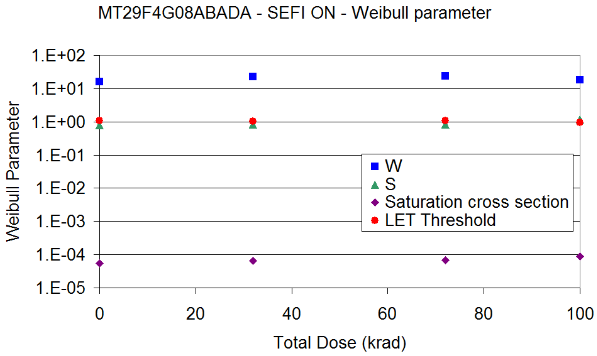


Figure 94 : MT29F4G08AAC Weibull SEFI cross section curve parameter as a function of dose level for the biased parts during TID irradiation

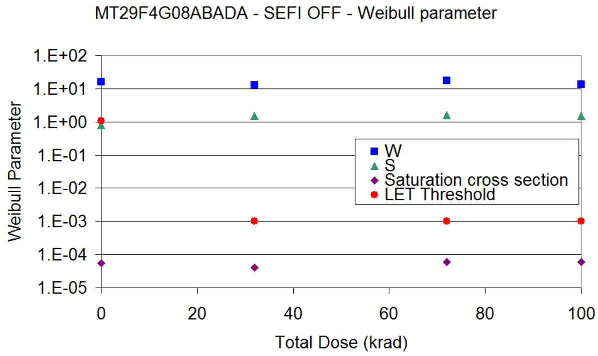


Figure 95 : MT29F4G08AAC Weibull SEFI cross section curve parameter as a function of dose level for the unbiased parts during TID irradiation

These results show that SEFI cross section curves and Weibull parameters are equivalent no matter the received dose.
As shown in Figure 95, the SEFI LET threshold seems to be higher at 0 krad(Si) for unbiased parts.
Weibull parameters are constant with the dose level no matter what event or bias condition, except for the LET threshold. Indeed the LET threshold varies from 1E-3 MeV.cm²/mg to 1 MeV.cm²/mg. These variations are not induced by the dose level but by the automatic fit. SEE test results indicated that the LET threshold is lower than 1.1 MeV.cm²/mg whatever the dose applied.

7.3.2.6. *Impact of Total Ionizing Dose on NAND Flash Functionality*

Before each SEE test, a functional test is performed on the NAND Flash memories.
All the 4096 blocks are written with the pattern AA55 and read again. If an error is detected the block is defined as a Bad Block and is not used during the following SEE test.
The next figure presents the mean number of Bad Blocks measured at TID steps before SEE test.

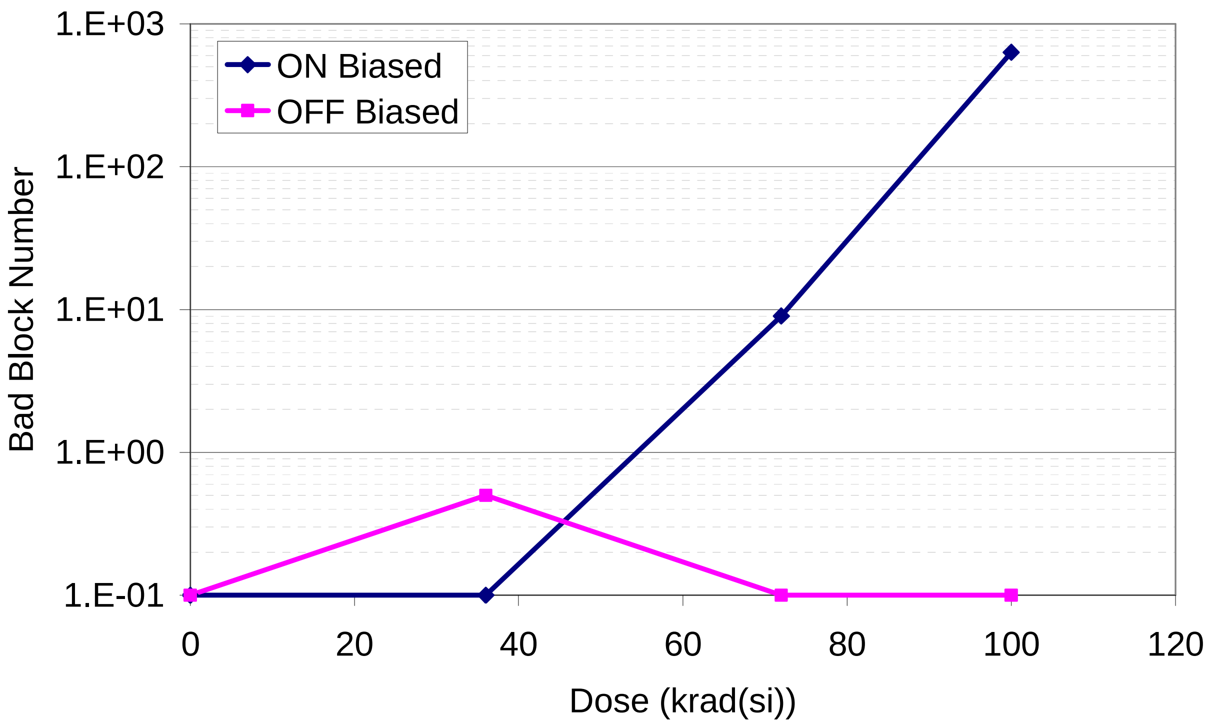


Figure 96 : Mean Number of Bad Blocks as a function of total ionizing dose

TABLE 19 : Number of Functional Blocks at each TID step for each device tested under heavy ions

		Dose (krad(Si))			
		0	36	72	100
Functional Block Number	Part Bias ON 1	4095	4095	4069	3769
	Part Bias ON 2	4095	4095	4094	3613
	Part Bias ON 3	4095	4095	4095	3007
	Part Bias OFF 1	4095	4095	4095	4095
	Part Bias OFF 2	4095	4094	4095	4095

As shown in the previous figure, the number of Bad Blocks increases with Total Ionizing Dose level for ON biased parts during the Cobalt 60 irradiation.

This means that one or more memory cells are not writable anymore in the bad block after TID exposure. The number of bit errors in each block is unknown. However as the number of bad blocks increases, the number of cell error increases probably with the same tendency.

7.3.2.7. *Impact of Total Ionizing Dose on SEL sensitivity*

During the first SEE test campaign, several runs were performed using the highest LET without SEL protection. As no permanent damage was observed, this reference can be considered as not sensitive to SEL.

However as described in literature, NAND Flash are subject to High Current Event (HCE). The SEL protection circuit was then used to evaluate the number of HCE with a current higher than a given value. The current threshold was fixed at 50 mA during all the study, which is sufficiently high to measure an HCE cross section without a high power cycling frequency.

The SEL sensitivity presented in the next figure corresponds to High Current Event (HCE) observed during SEE tests with a current higher than 50 mA.
As explained in §7.3.2.1, the Xenon ion (67.7 MeV.cm²/mg) was used only during the SEE pre-characterization, because this ion induces temporary device non-functionality. Due to beam time availability, HCE tests have only been performed at one LET: the higher available after the Xenon ion, the Krypton ion (32.6 MeV.cm²/mg). No HCE events were detected at lower LET due to the lower fluence used. The corresponding cross section is then lower than 10E-06 cm²/dev.
The next figure presents the cross section curves obtained for each SEE test campaign.

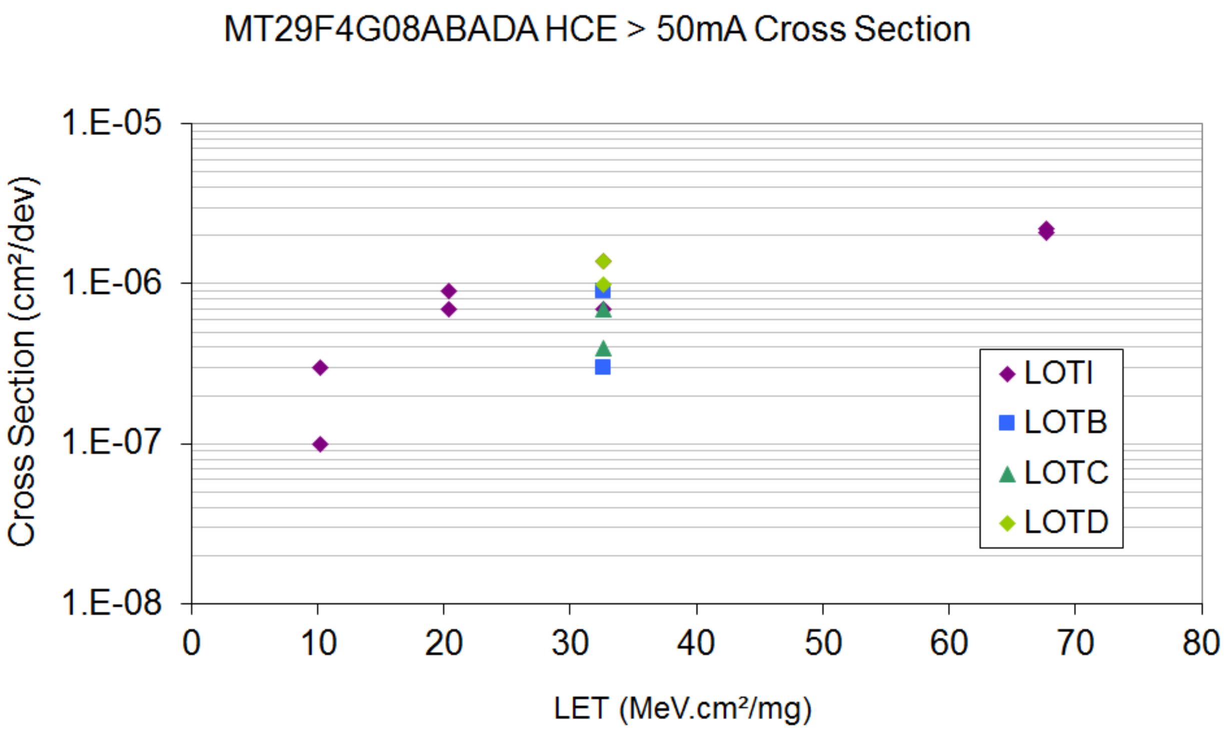


Figure 97 : MT29F4G08AAC HCE > 50mA cross section curve comparison between LOTI (0 krad(Si)), LOTB (36 krad(Si)), LOTC(72 krad(Si)) and LOTD(100 krad(Si)) with current threshold = 50 mA

As shown here above, Total Ionizing Dose does not have an impact on HCE number.

7.4. SRAM R1RW0416 FROM Renesas

7.4.1. SRAM R1RW0416 TID tests results

Six R1RW0416 Lots have been irradiated under ^{60}Co:

- LOTP : 10 non delidded parts (5 ON + 5 OFF) up to 250 krad (Si) at 310 rad(Si)/h at GAMRAY
- LOTA: 10 non delidded parts (5 ON + 5 OFF) up to 150 krad (Si) at 74 rad(Si)/h at UCL
- LOTB: 10 delidded parts (5 ON + 5 OFF) up to 42 krad (Si) at 74 rad(Si)/h at UCL
- LOTC: 10 delidded parts (5 ON + 5 OFF) up to 78 krad (Si) at 74 rad(Si)/h at UCL
- LOTD: 10 delidded parts (5 ON + 5 OFF) up to 114 krad (Si) at 74 rad(Si)/h at UCL
- LOTE: 10 delidded parts (5 ON + 5 OFF) up to 150 krad (Si) at 74 rad(Si)/h at UCL

No intermediary TID step have been performed for LOT B, C, D and E. Results for these lots are summarized on the same graph where each represents a TID step LOT.
The next figure presents the comparison between LOTA and the compilation of LOT B, C, D, E (named LOTBCDE).

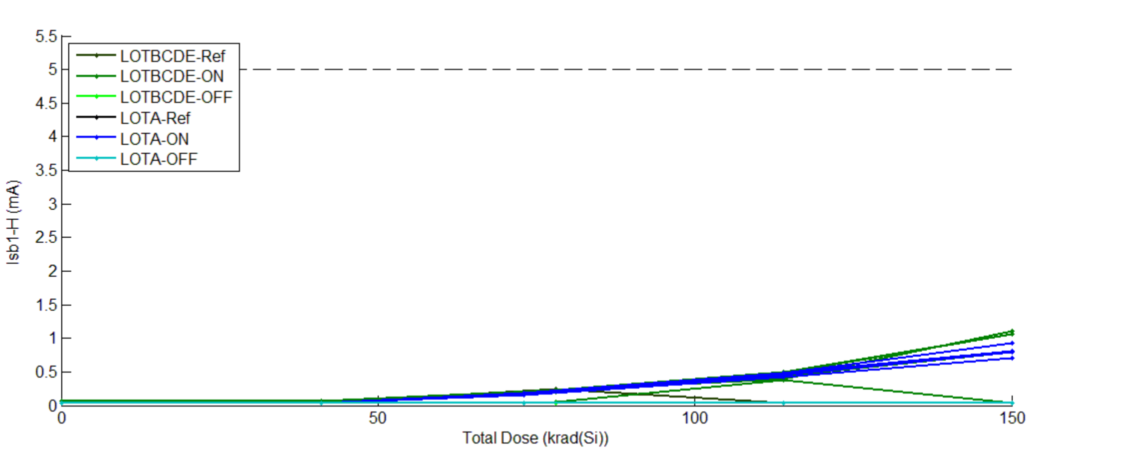


Figure 98 : R1RW0416 Isb1-H function TID LOTA compare to LOT BCDE

As it can be seen, two atypical parts are identified in the LOT BCDE biased ON. Nevertheless, in most cases no difference is observed between LOTA (non-delidded parts) and LOTBCDE (delidded parts): the long time opened condition in a non-controlled atmosphere has no impact on the degradation for this reference.

The next figure presents the comparison between LOTA and LOTP.

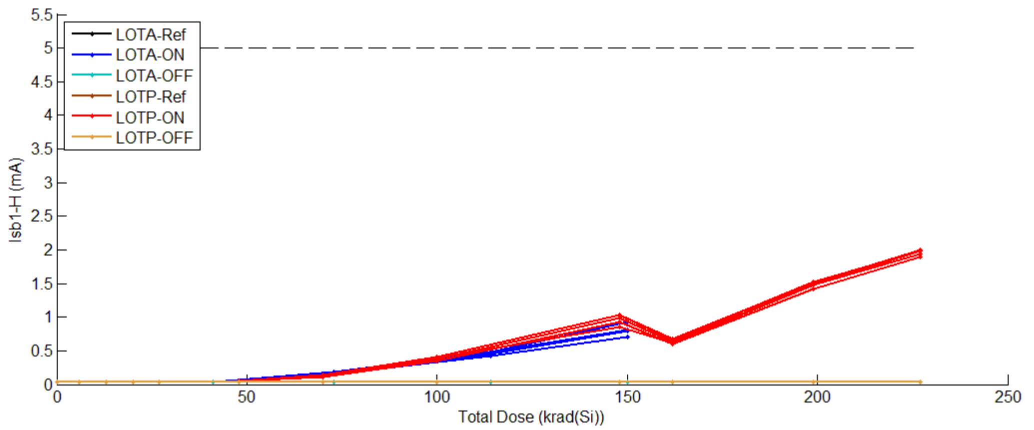


Figure 99: R1RW0416 Isb1-H function TID, LOTA compare to LOT P

As shown here above, no difference is observed between LOTA (74 rad/h) and LOTP (310 rad/h) up to 150 krad(Si): the ^{60}Co dose rate has no impact on the degradation for this reference.

Between 150 krad(Si) and 168 krad(Si), a degradation recovery is observed on LOTP ON biased components. This behavior is induced by a power cut-off during the irradiation. Parts which were biased at the beginning of irradiation are then unbiased during this time laps. As SRAM are CMOS processed, ON parts are more impacted by TID irradiation than OFF parts. An annealing is then observed between 150 krad(Si) and 168 krad(Si). After 168 krad(Si), power was re-established, and a positive degradation can be observed again with the same trend as before the power cut-off.

7.4.2. SRAM R1RW0416 SEE tests results

Five R1RW0416 Lots have been irradiated under heavy ions:

- LOTI : 3 parts
- LOTB: 5 parts following TID irradiation up to 42 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTC: 5 parts following TID irradiation up to 78 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTD: 5 parts following TID irradiation up to 114 krad (Si) (3 ON + 2 OFF) and 1 reference
- LOTE: 5 parts following TID irradiation up to 150 krad (Si) (3 ON + 2 OFF) and 1 reference

7.4.2.1. Impact of long time opened condition on SEU sensitivity

The next figures present the SEU cross section curve comparison between all devices not tested against TID irradiation. One non-irradiated device was tested at each TID step and is named LOTI, LOTB, LOTC, LOTD and LOTE.

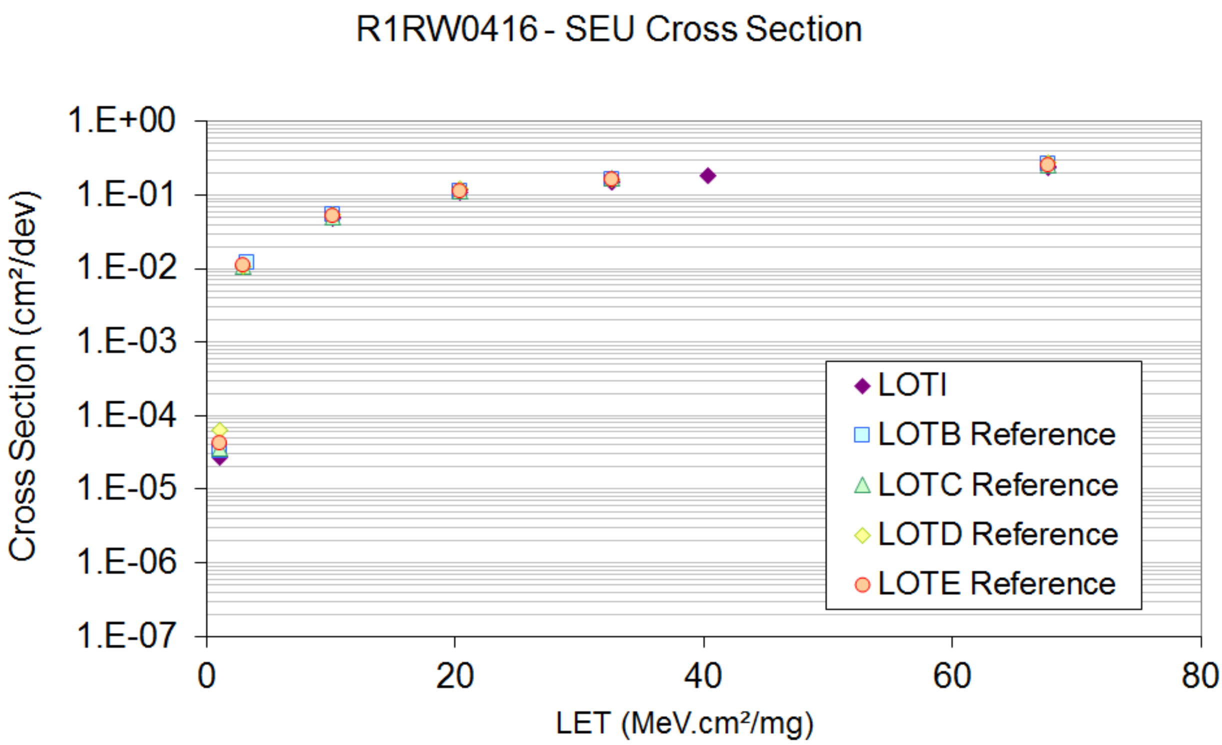


Figure 100 : R1RW0416 SEU cross section curve comparison between non ^{60}Co irradiated devices

As it can be seen, the cross section curve shape for LOTI is the same as for the others LOTs. We conclude that the delidded condition in a non-controlled atmosphere has then no impact on the SEU cross section curve.

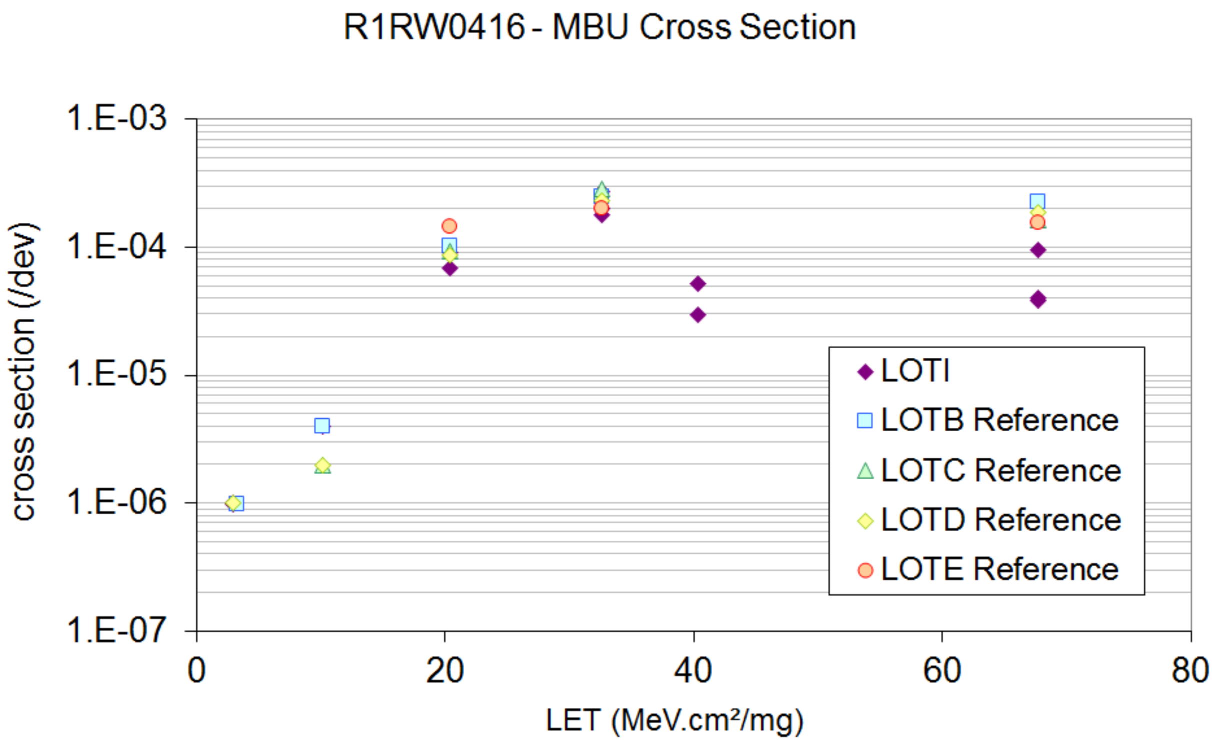


Figure 101 : R1RW0416 MBU cross section curve comparison between non ^{60}Co irradiated devices

Unlike the SEU results, a difference is observed between the MBU LOTI cross section curve and the others MBU cross section curves.
This result is described in more detail in § 7.4.2.8.

7.4.2.2. *Impact of Total Ionizing Dose on SEU sensitivity*

The next figure presents the SEU and MBU cross section curves comparison between all devices subject to synergetic effect. LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) are shown.

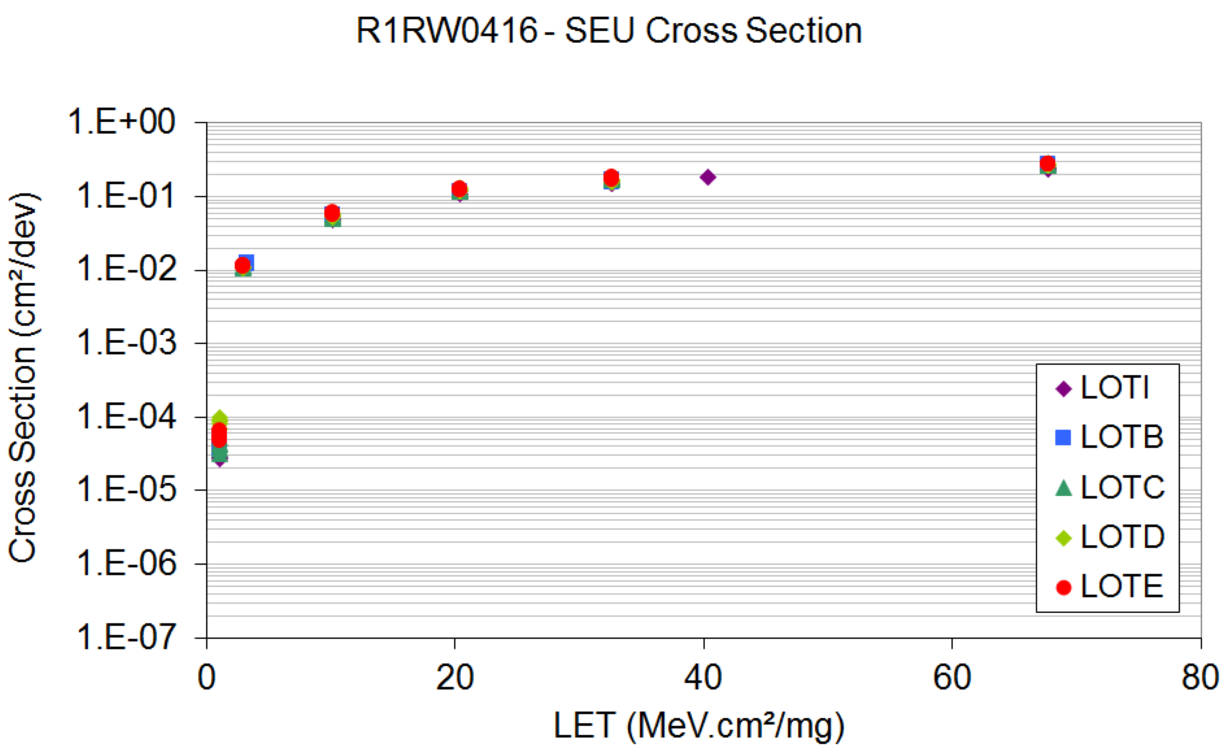


Figure 102 : R1RW0416 SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si))

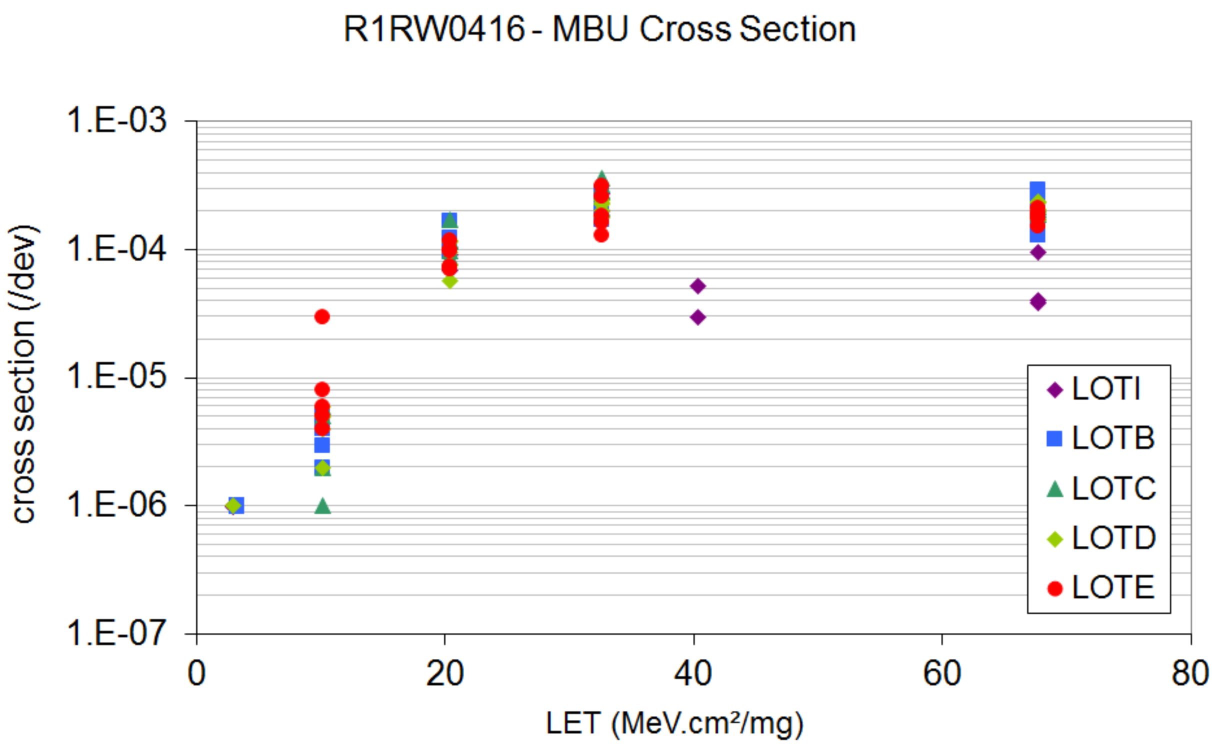


Figure 103 : R1RW0416 MBU cross section curve comparison between LOTI (0krad(Si)), LOTB (42krad(Si)), LOTC(78krad(Si)), LOTD(114krad(Si)) and LOTE (150krad(Si))

As shown in the previous figure, cross section curves after TID exposure are equivalent to the reference tested at each TID step (Figure 100 and Figure 101).
As for the non-irradiated parts, a difference is observed between LOTI and the following LOTs on MBU cross section. This result is described in more detailed in § 7.4.2.8.

7.4.2.3. Impact of Total Ionizing Dose on SEU and MBU error bars

Error bars are calculated as described in the ESCC25100, using 95% confidence level and 10% fluence uncertainty.
As explained before, the impact of total ionizing Dose on error bars is evaluated for the lower LET where events are detected at each test.
Following figures represent then, total ionizing impact on error bars for

- 1.1MeV.cm²/mg for SEU
- 10.2 MeV.cm²/mg for MBU

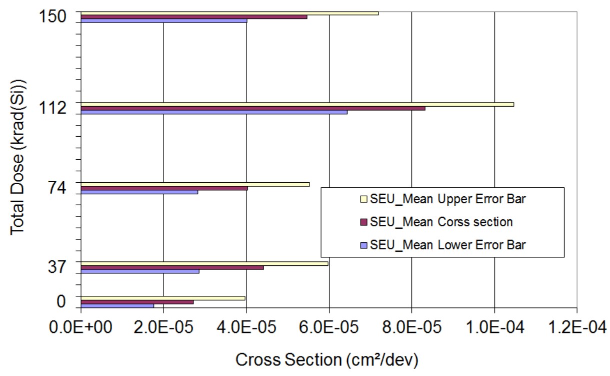


Figure 104 : R1RW0416 SEU error bars for 95% confidence level and 10% fluence uncertainty at 1.1 MeV.cm²/mg function of Total Dose

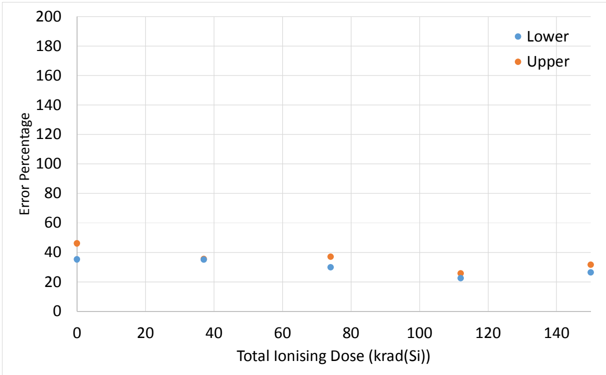


Figure 105 : R1RW0416 SEU percentage of error at 1.1 MeV.cm²/mg function of Total Dose

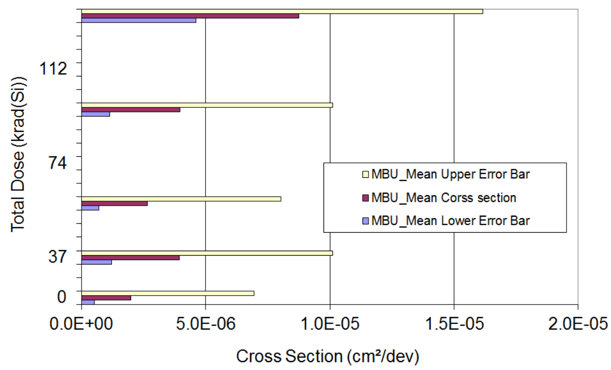


Figure 106 : R1RW0416 MBU error bars for 95% confidence level and 10% fluence uncertainty at 10.2 MeV.cm²/mg function of Total Dose

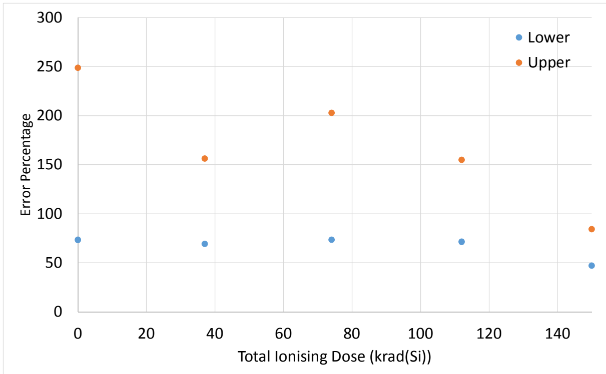


Figure 107 : R1RW0416 MBU percentage of error at 10.2 MeV.cm²/mg function of Total Dose

As shown in previous figure, the measured MBU cross section increases at the final total dose as the percentage error decreases. However the TID level does not have any impact on the SEU cross section and error bar.

7.4.2.4. Impact of bias condition during TID irradiation on SEE sensitivity

Figure 108 and Figure 109 represent the SEU cross section curves according to the received dose and the bias condition used during ^{60}Co irradiation.
Figure 110 and Figure 111 show the corresponding Weibull cross section parameter evolution with Total Ionizing Dose. The Weibull parameters are determined using the automatic fit available in the OMERE software.

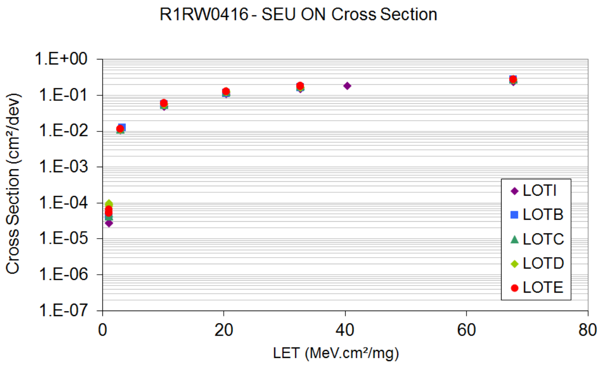


Figure 108 : R1RW0416 SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) biased during TID irradiation

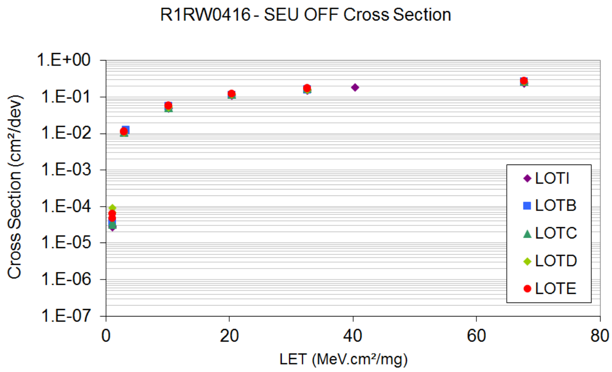


Figure 109 : R1RW0416 SEU cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) unbiased during TID irradiation

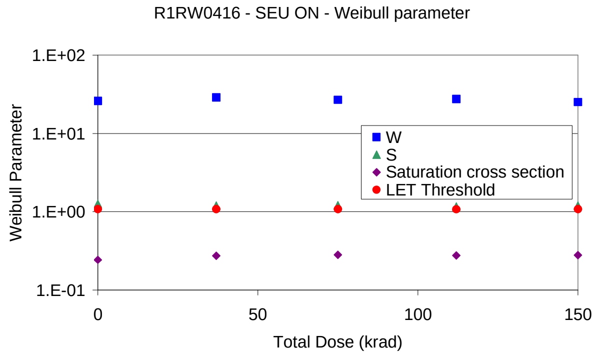


Figure 110 : R1RW0416 Weibull SEU cross section curve parameter as a function of dose level for the biased parts during TID irradiation

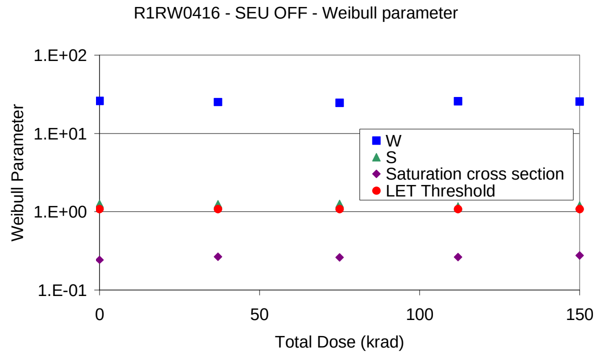


Figure 111 : R1RW0416 Weibull SEU cross section curve parameter as a function of dose level for the unbiased parts during TID irradiation

These results show that SEU cross section curves and Weibull parameters are equivalent no matter the received dose and the bias condition used during TID exposure.
The same representation is used for the MBU test results. As for SEU, cross section curves and Weibull parameters are equivalent no matter the received dose and the bias condition used during TID exposure.

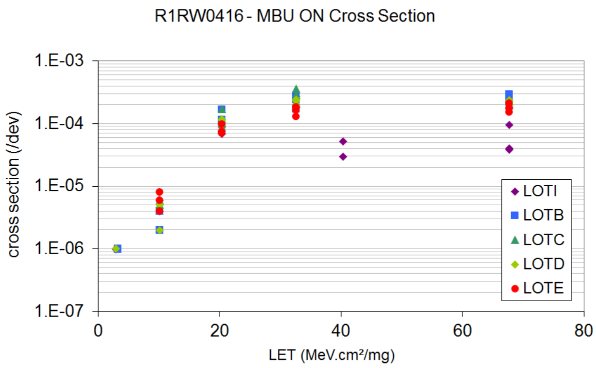


Figure 112 : R1RW0416 MBU cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) biased during TID irradiation

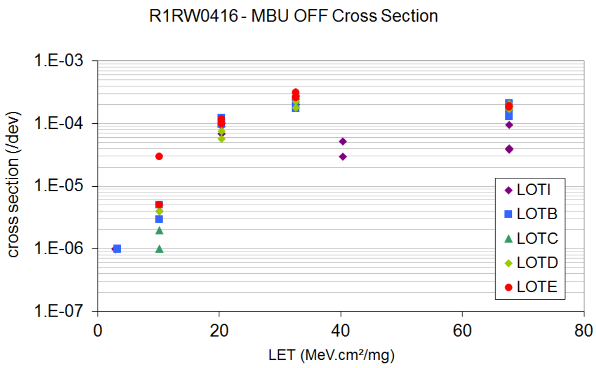


Figure 113 : R1RW0416 MBU cross section curve comparison between LOTI (0 krad(Si)), LOTB (42 krad(Si)), LOTC(78 krad(Si)), LOTD(114 krad(Si)) and LOTE (150 krad(Si)) unbiased during TID irradiation

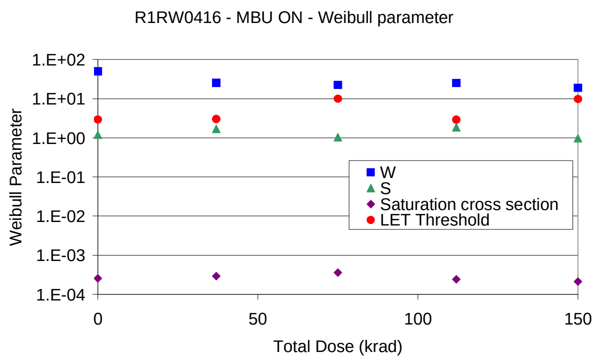


Figure 114 : R1RW0416 Weibull MBU cross section curve parameter as a function of dose level for the biased parts during TID irradiation

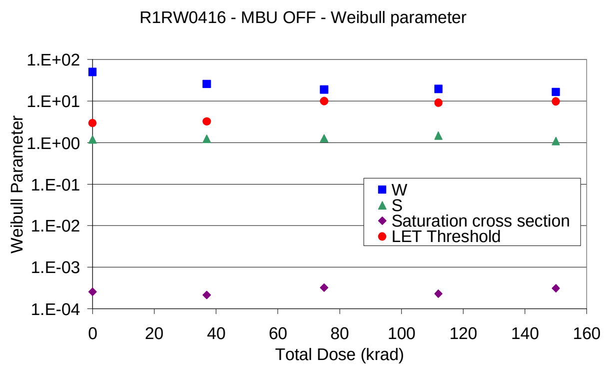


Figure 115 : R1RW0416 Weibull MBU cross section curve parameter as a function of dose level for the unbiased parts during TID irradiation

7.4.2.5. *Impact of Total Ionizing Dose on SEU signature: imprint effect*

During the TID test, all devices were written using the pattern AAAA. To evaluate if the TID exposure could have an impact on the reading data, all components were tested under heavy ions using the pattern AAAA on half of the memory and using 5555 on the other half. By comparison between cross section curves where SEU are detected on AAAA pattern or 5555 pattern, the imprint effect can be evaluated.
Figure 116 and Figure 117 represent cross section curves where SEU are detected on AAAA pattern and on 5555 pattern.

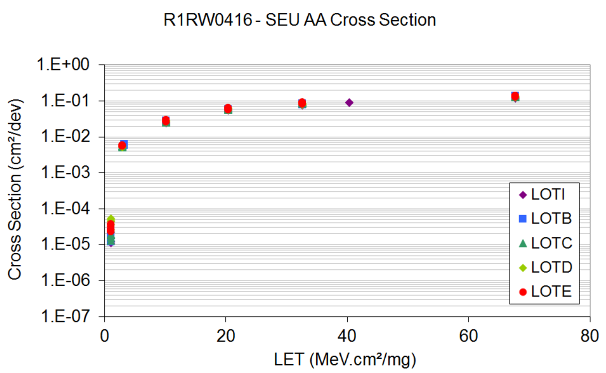


Figure 116: : R1RW0416 AAAA SEU cross section curve comparison between LOTI, LOTB, LOTC, LOTD and LOTE

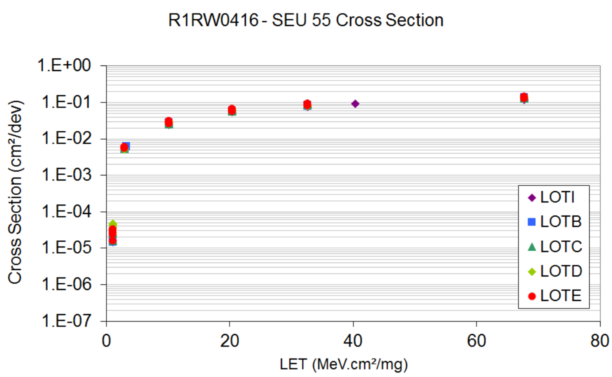


Figure 117: : R1RW0416 5555 SEU cross section curve comparison between LOTI, LOTB, LOTC, LOTD and LOTE

No difference, as a consequence no imprint effect, is observed between these two results.

Figure 118 and Figure 119 show the percentage of SEU error occurring on each data bit. This percentage is almost constant on all of the 16 data bits, no matter the dose applied. We conclude that Total Ionizing Dose has no impact on SEU localization in the tested word.

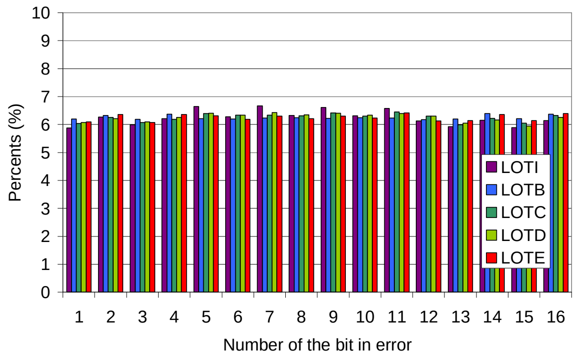


Figure 118: : R1RW0416 percentage of bit in error on AA pattern for LOTI, LOTB, LOTC, LOTD and LOTE

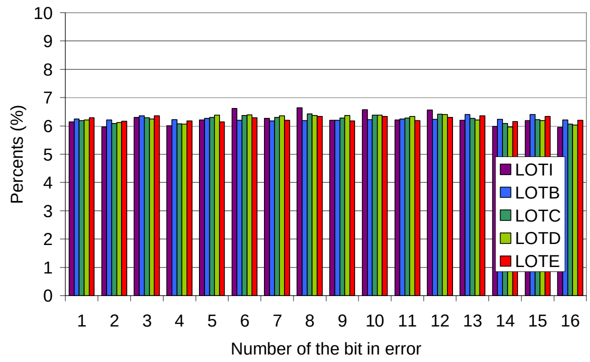


Figure 119: : R1RW0416 percentage of bit in error on 55 pattern for LOTI, LOTB, LOTC, LOTD and LOTE

7.4.2.6. Impact of Total Ionizing Dose on MBU multiplicity

As for SEU, cross section curves where MBU are detected on AAAA pattern and on 5555 pattern are represented in the following figures. No sensitivity difference is observed no matter the pattern used. An imprint effect is not observed on MBU effect.

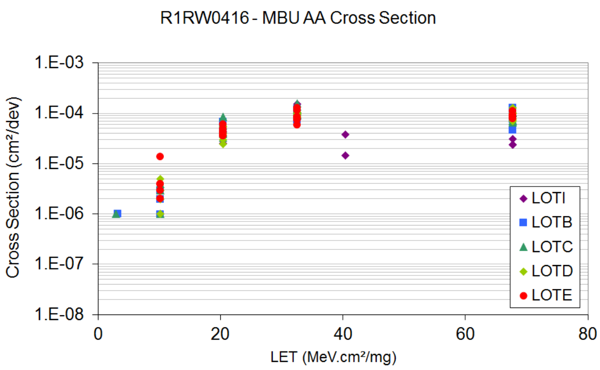


Figure 120: R1RW0416 AA MBU cross section curve comparison between LOTI, LOTB, LOTC, LOTD and LOTE

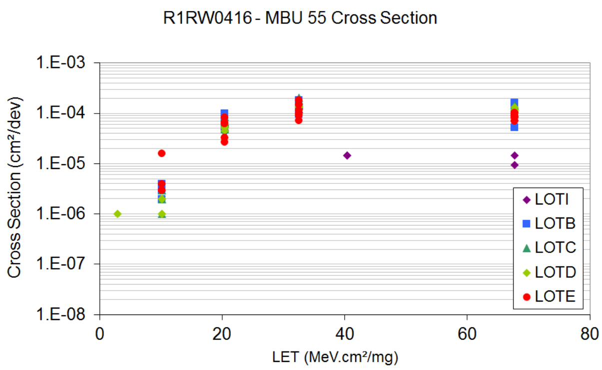


Figure 121: R1RW0416 55 MBU cross section curve comparison between LOTI, LOTB, LOTC, LOTD and LOTE

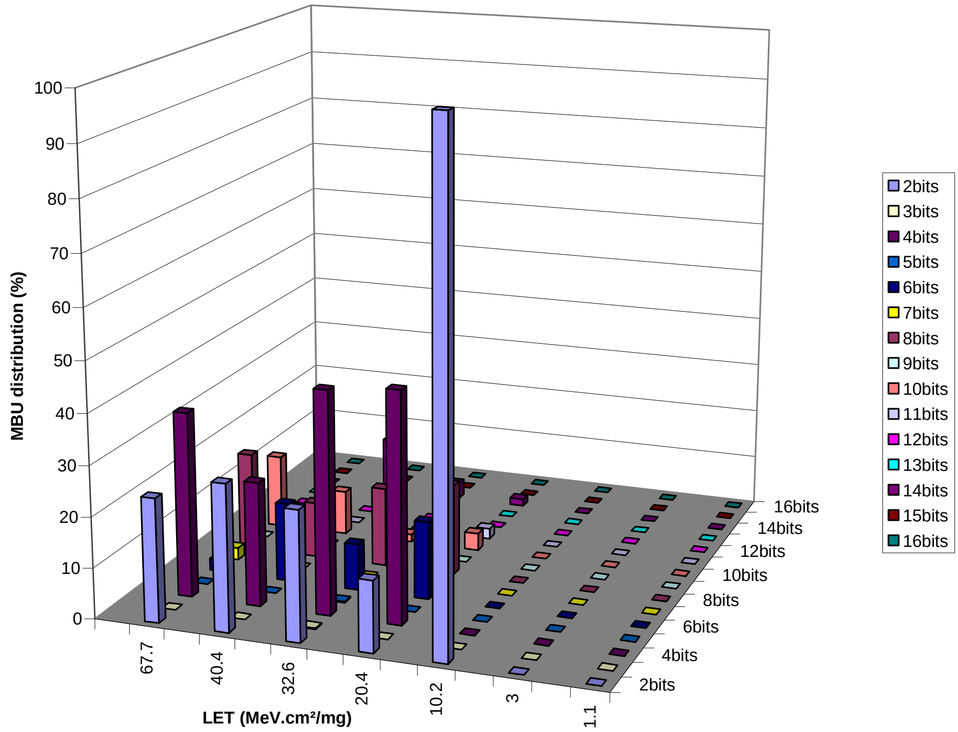


Figure 122: R1RW0416 Mean MBU distribution percentage function multiplicity for LOTI

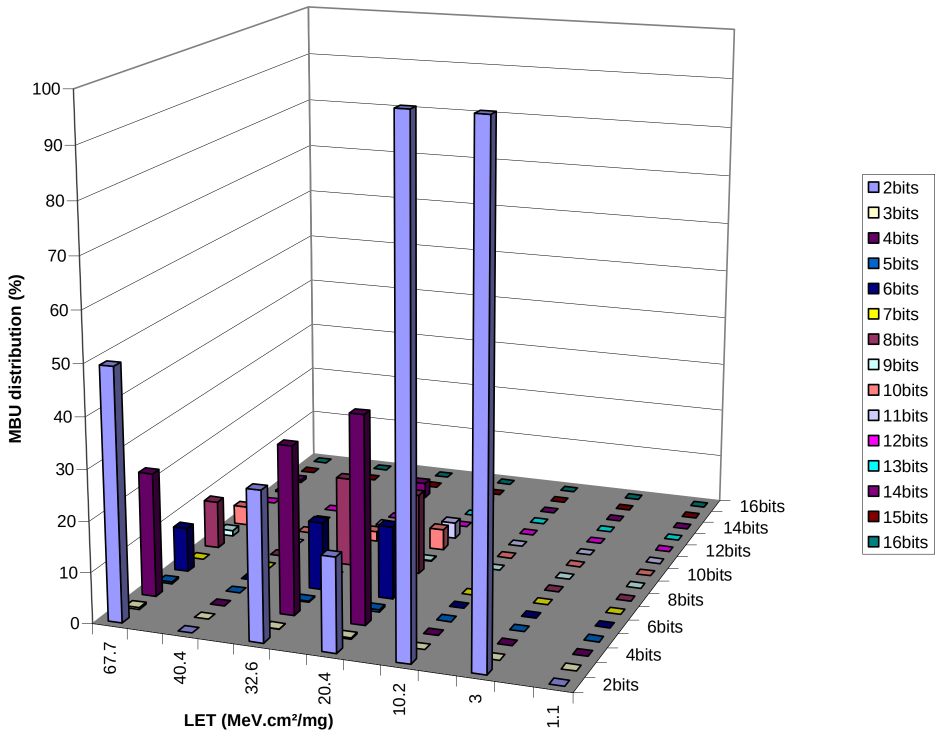


Figure 123: R1RW0416 Mean MBU distribution percentage function multiplicity for LOTB

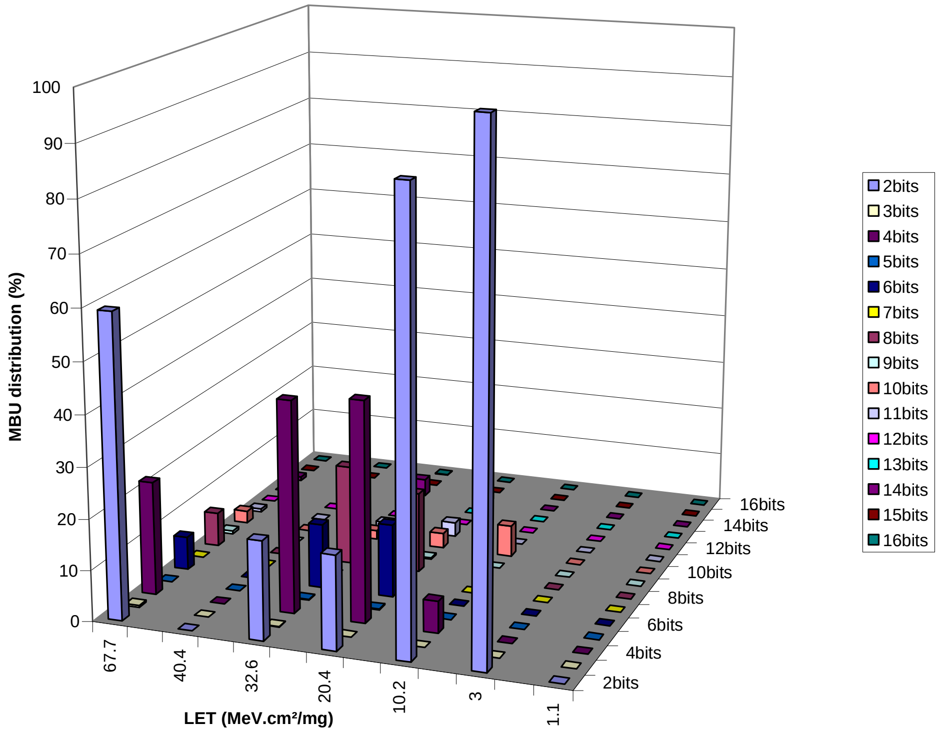


Figure 124: R1RW0416 Mean MBU distribution percentage function multiplicity for LOTC

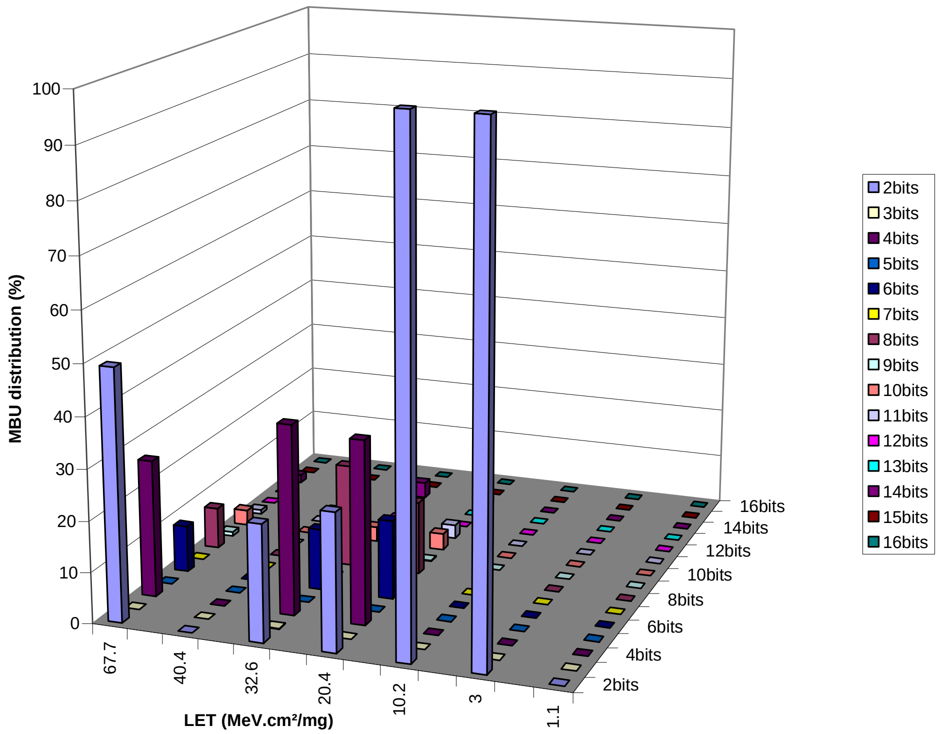


Figure 125: R1RW0416 Mean MBU distribution percentage function multiplicity for LOTD

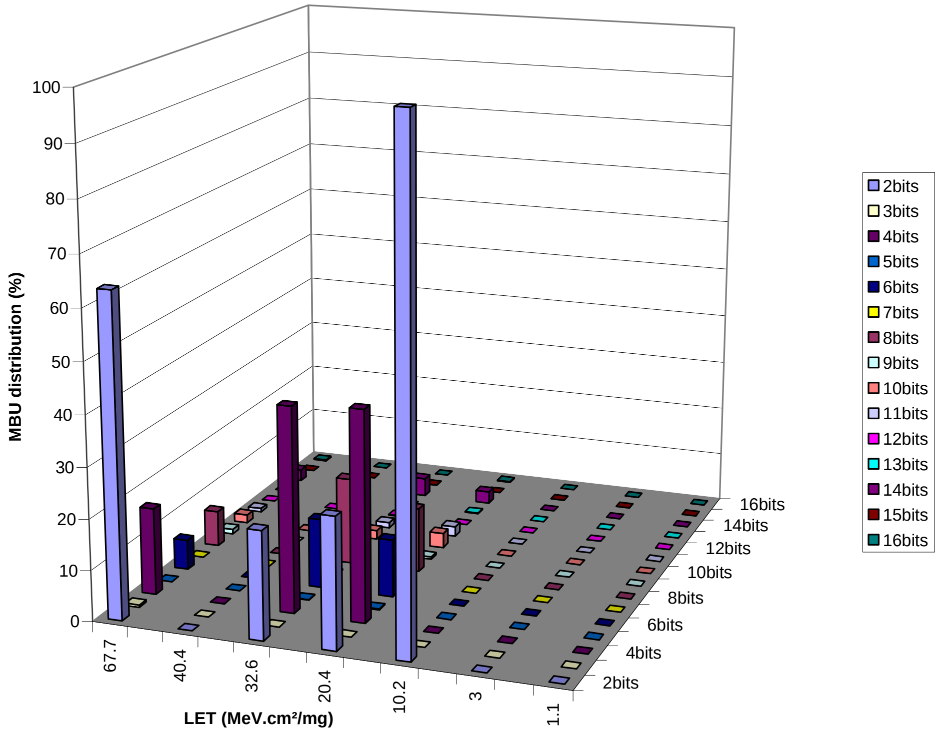


Figure 126: R1RW0416 Mean MBU distribution percentage function multiplicity for LOTE

7.4.2.7. *Impact of Total Ionizing Dose on SEL sensitivity*

No SEL has been observed on this reference.

7.4.2.8. *MBU test Results*

As shown in §7.4.2.1 and in §7.4.2.2, MBU cross section curves are different between LOTI and other LOTs. This difference is observed especially for high LETs: Xenon (67.7 MeV.cm²/mg) and Krypton (32.6 MeV.cm²/mg).

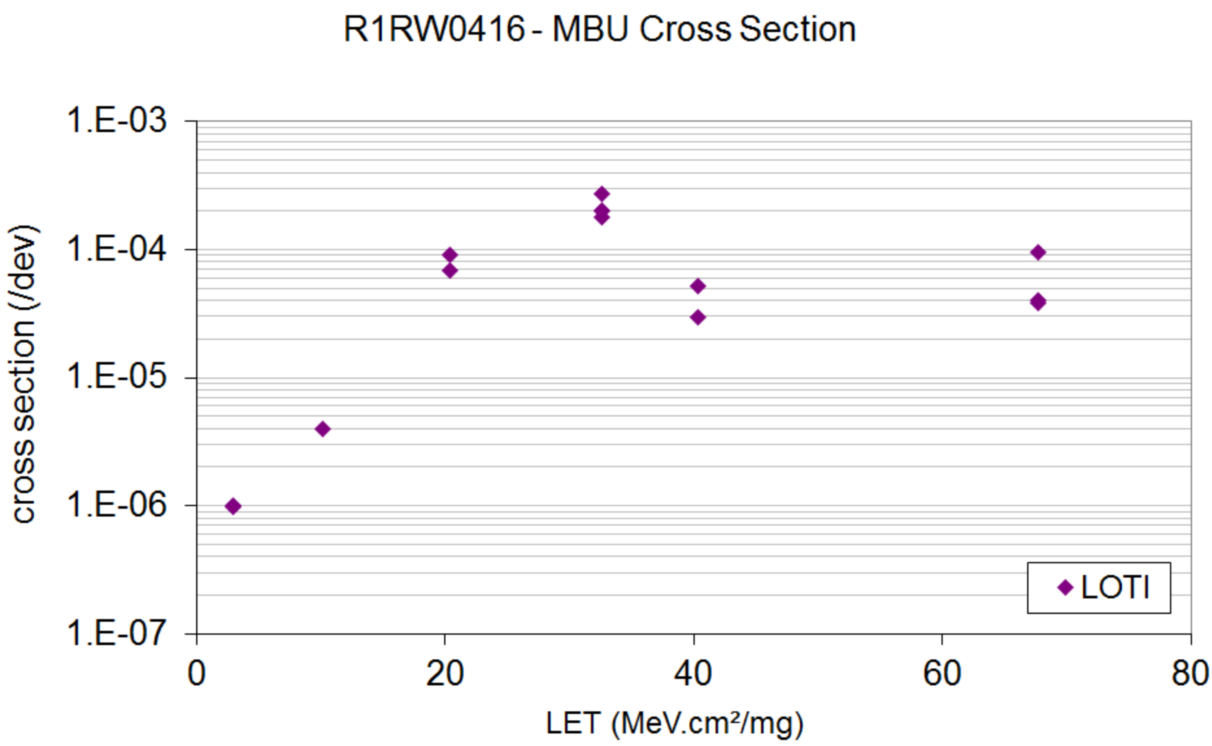


Figure 127 : R1RW0416 AA MBU cross section curve comparison LOTI

Moreover the MBU signature, as described in §7.4.2.7, is unusual: MBU multiplicity are even multiplicity.
The next table presents some of MBU detected during run #3 on part 3 using the Xenon ion (67.7 MeV.cm²/mg) on LOTD.

TABLE 20 : example of erroneous pattern detected during MBU test on R1RW0416

Erroneous word	Attended word	Multiplicity
5445	5555	2
BAAB	AAAA	2
455D	5555	2
D55D	5555	2
5595	5555	2
28AA	AAAA	2
D455	5555	2
AAA0	AAAA	2
1455	5555	2
AEBA	AAAA	2
8AAE	AAAA	2
D551	5555	2
4557	5555	2
22AA	AAAA	2
ABEA	AAAA	2
5555	0505	4
8E8E	AAAA	4
4554	0404	4
A0A0	AAAA	4
AAAA	A0FA	4

A0A0	AAAA	4
AAAA	A0A0	4
5555	0505	4
2020	AAAA	6
0404	5555	6
0	AAAA	8
BAAB	2020	8

Some of these errors are very symmetric; E.g. 5445 and 8E8E, which lead one to indicate that the detected MBU are potentially not real MBU.
Moreover, some of these errors show an exepted pattern different from AAAA or 5555. These errors are induced by a previous error as shown in the following table:

TABLE 21 : Transient error detected as MBU on R1RW0416

DUT data	Reference Data	Address	Error Type	Address cycle	Timestamp
0505	5555	2152D	4	8	20.878111
0505	5555	2152D	4	8	20.878111
5555	0505	2152D	2	9	20.993462

During the 8th read cycle memory, one error has been detected at the address 2152D with the pattern 0505. The test bench tries to write 5555 on this address and read the data again. The same erroneous pattern is read again. This data could not be rewritten, and is considered as stuck (type 4 errors). In order to not detect this error at the following read cycle, the erroneous pattern has been written in the reference memory.
During the next read cycle, at same address, the pattern 5555 has been read instead of 0505.
This error is probably induced by the impact of heavy ion on the peripheral circuitry of the SRAM detected as transient MBU on the memory array.

Mean cross section obtained using an LET of 67.7 MeV.cm²/mg and flux used are plotted here under as a function of tested LOT.

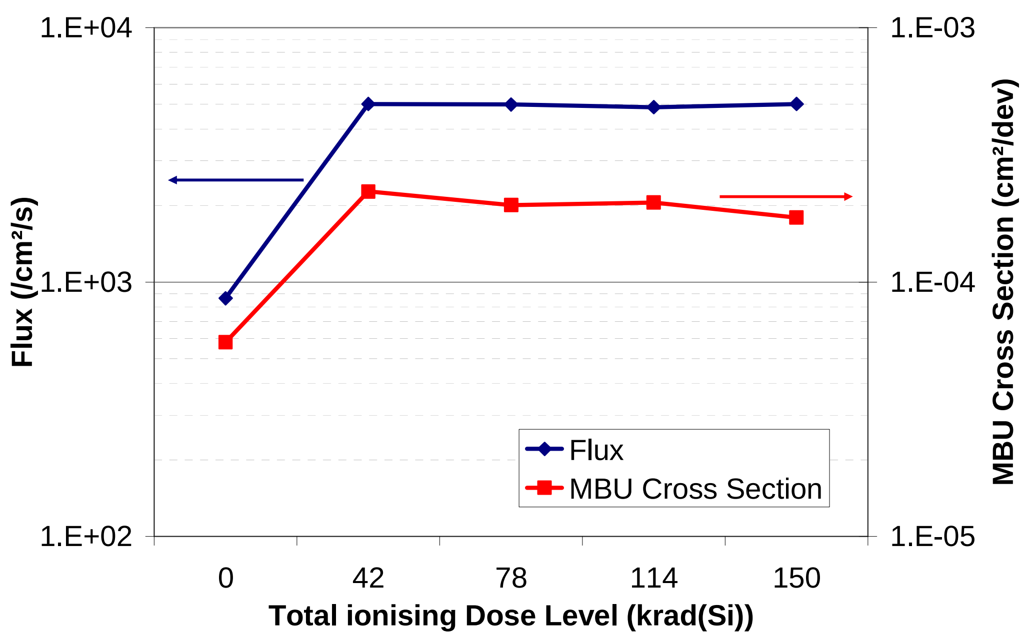


Figure 128 : Mean cross section obtained at 67.7 MeV.cm²/mg and flux used as a function of the LOT tested

TABLE 22 : Mean cross section obtained at 67.7 MeV.cm²/mg and flux used as a function of tested LOT

	Mean Flux used with xenon ion #/cm²/s	Mean Cross section obtained with Xenon ion cm²/device
LOTI 0krad	8.63E+02	5.80E-05
LOTB 42krad	5.01E+03	2.27E-04
LOTC 78krad	4.99E+03	2.01E-04
LOTD 114krad	4.87E+03	2.06E-04
LOTE 150krad	5.01E+03	1.79E-04

A shown in Figure 128, lower fluxes were used during the first campaign compared to SEE test performed during the synergy study. This corresponds also to a lower measured MBU cross section.
The flux used has an impact on the measured MBU cross section.
As MBU events also include SEE on peripheral circuitry, MBU post-treatment has been performed in order to suppress these errors from MBUs.
The next figures present detected MBU before and after treatment for LOTI.

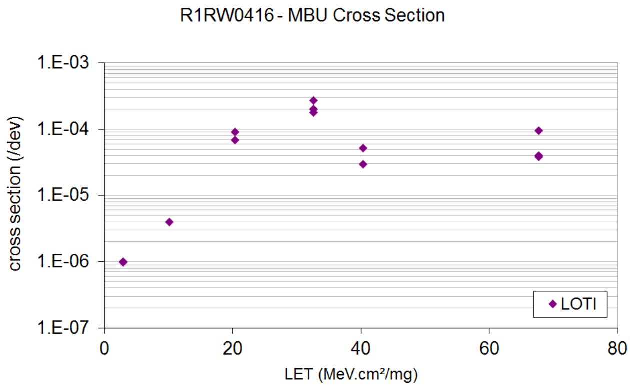


Figure 129 : detected MBU before treatment - LOTI

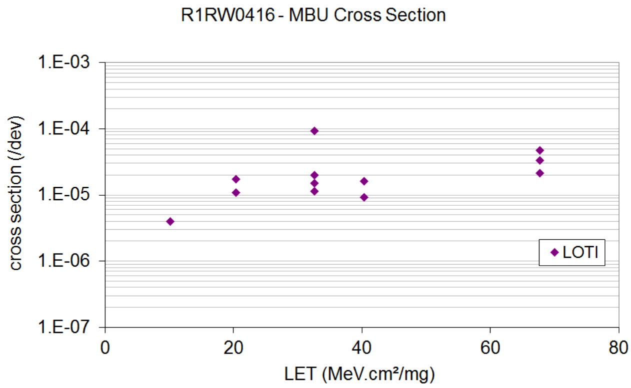


Figure 130 : detected MBU after treatment - LOTI

These results show that the MBU cross section is more coherent after treatment. This results show that SEE on peripheral circuitry, detected as transient MBU on the memory array, are sensitive to the flux used.
However, as shown in the following figure and table, one cross section point performed at 32.6 MeV.cm²/mg is still higher compared to other measurements performed on the same LET. This point has been evaluated using a higher flux than those used for the following characterizations.

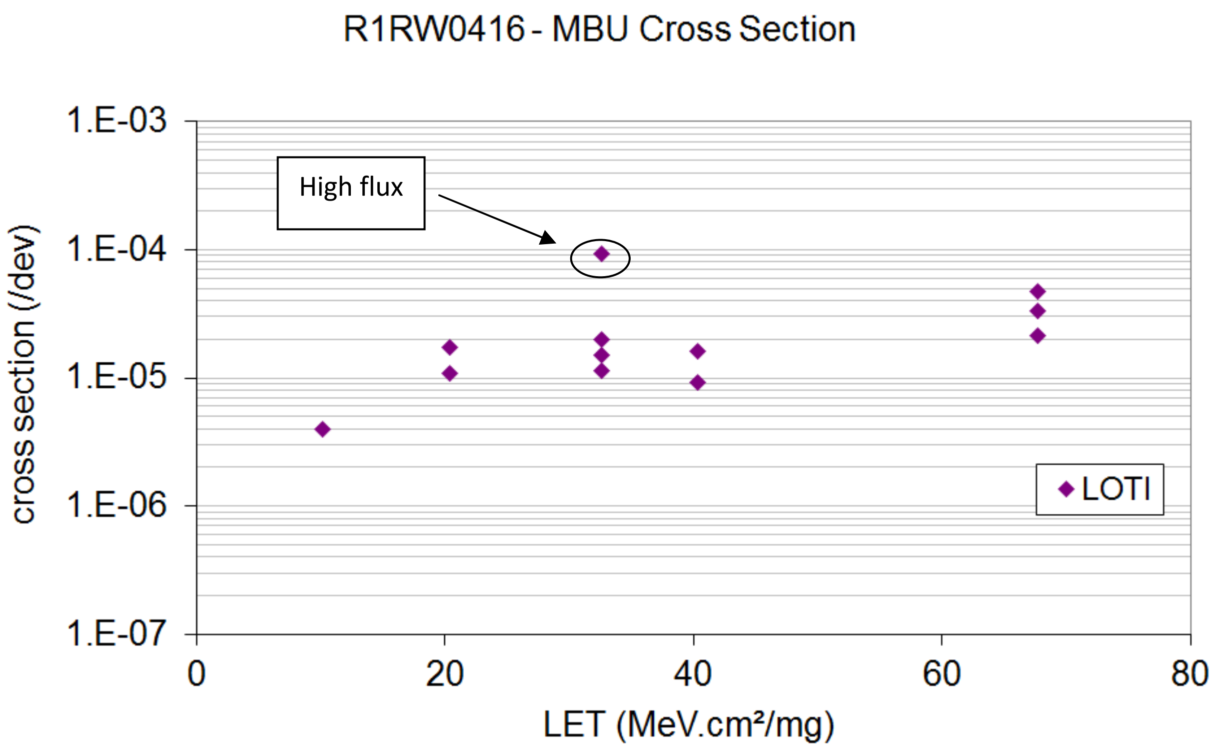


Figure 131 : high flux point on detected MBU after treatment - LOTI

TABLE 23 : MBU test results obtained after treatment on LOTI using Krypton ion (LET = 32.6 MeV.cm²/mg)

Run	Part	T°	Ion	Energy (MeV)	Range (µm)	LET (MeV.cm²/mg)	Tilt (°)	Flux ($cm^{-2}.s^{-1}$)	Time (s)	Run Fluence (cm^{-2})	MBU	Cross Section
8	3	25	$^{83}Kr^{25+}$	756	92	32.6	0	1.58E+03	417	6.58E+05	13	1.98E-05
9	4	25	$^{83}Kr^{25+}$	756	92	32.6	0	1.51E+03	411	6.20E+05	7	1.13E-05
19	4	25	$^{83}Kr^{25+}$	756	92	32.6	0	9.99E+03	102	1.02E+06	94	9.22E-05
20	3	25	$^{83}Kr^{25+}$	756	92	32.6	0	5.17E+01	1275	6.59E+04	1	1.52E-05

These results show that all SEE on peripheral circuitry are not suppressed during treatment. No sufficient information on recorded errors is available to perform a more complete treatment.

8. CONCLUSION

Combined TID and SEE tests have been performed on four references:

- ADC AD9042 from Analog Device
- DAC AD558 from Analog Device
- Flash NAND MT29F4G08AAC from Micron
- SRAM R1RW0416 from Renesas

All these references have been irradiated up to a high total dose level to evaluate a potential impact of TID on SEE sensitivity for standard missions (LEO, MEO or GEO) and for the high dose JUICE mission. SEE tests have been performed at several TID steps in order to evaluate if the SEE sensitivity evolves with the TID level.

The main objective of this study was to evaluate the impact of total dose on SEE sensitivity. In order to control external parameters that may have an impact on the SEE sensitivity or on the TID degradation, several parameters have been monitored during this study:

<u>Impact of delidding on TID degradation</u>

Delidded and undelidded devices were placed under Cobalt 60 irradiation. At each TID steps parametric measurements have been performed on delidded and undelidded devices. As TID irradiations took place during 12 weeks, this test evaluates the impact of non-controlled atmosphere storage. For all studied references, no difference was observed between delidded and undelidded devices on parametric measurements. We conclude that the long time storage in non-controlled atmosphere had no impact on the device degradation.

<u>Impact of dose rate on TID degradation</u>

TID results have also been compared for delidded parts using two different dose rates. A first pre-characterization has been performed at GAMRAY (TRAD) using a dose rate of 310 rad/h in order to evaluate the TID sensitivity for each reference. These sensitivities have been used to determine the final dose level, and therefore the dose rate, usable for the synergy study. A dose rate of 74 rad/h was been used at UCL (Belgium) during the synergy study. No impact of dose rate has been observed for the ADC, the SRAM and the Flash NAND. For the DAC device, the lot used for the synergy study is subject to the worst degradation observed during Cobalt 60 irradiation.

<u>Impact of traceability on TID degradation</u>

TID results are not equivalent for the DAC AD558 from Analog Device. To evaluate the origin of this discrepancy, a new TID irradiation was performed on ten delidded parts at GAMRAY (TRAD) using the same dose rate as the one used at UCL (74 rad/h). These results indicate that different diffusion lots were used during this study. This traceability difference does not impact the SEE sensibility.

<u>Control Reference Used for SEE testing</u>

The first campaign for each reference was performed to determine an SEE cross section curve.

At each TID step, a reference part not subject to irradiation was tested to control that SEE testing conditions are exactly the same as during the first campaign.

Impact of TID on SEE sensitivity (saturated cross section, LET threshold)

Finally, SEE test results have been compared for each reference according to the TID level. No TID impact on SEE sensitivity has been observed no matter the received dose is and no matter the reference. Moreover the biasing used during Cobalt 60 irradiation does not have any impact on the SEE sensitivity no matter what the reference is.

Impact of TID on SEE signature

SEE signatures were also studied according to the TID exposure.

- AD9042 SET signature, defined as consecutive false conversions, is identical no matter what the TID dose level is.
- AD558 SET signature, defined by voltage amplitude and duration, is identical no matter what the TID dose level is.
- During R1RW0416 TID test, all devices were written using the pattern AAAA. In order to evaluate if the TID exposure could have an impact on the reading data, all components were tested under heavy ions using the pattern AAAA on half of the memory and using 5555 on the other half. The imprint effect can be evaluated by comparing cross section curves where SEU were detected on AAAA pattern or 5555 pattern. No difference, and no imprint effect, was been observed.
- R1RW0416 MBU multiplicity cross sections are equivalent no matter what the received dose is. We conclude that TID irradiation has no impact on MBU multiplicity.
- MT29F4G08AAC High Current Event number with current higher than 50 mA is identical no matter what the TID dose level it is.

MT29F4G08AAC SEE and TID impact on Reliability

Functional testing shows that the number of Bad Blocks increases with Total Ionizing Dose level for biased devices during ^{60}Co irradiation. This means that one or more memory cells are not writable in the bad block after TID exposure.
TID irradiation has an impact on reliability, as errors are detected after TID exposure.
Heavy ions produced also errors in the flash memory.
No synergetic effect has been observed as the number of errors produced by heavy ions is the same no matter what the TID dose level is.
The number of errors will increase during the mission due to both contributions of TID and heavy ions. This effect is observed for high dose level, up to 40 krad(Si). Therefore, this combined effect will be more important during the JUICE mission, especially for biased components. This effect need to be taken into account for the reliability of the device.

9. PERSPECTIVES

Various perspectives can be proposed following this study.

- NAND Flash memories show functional degradation following SEE test and TID test. Indeed Bad Blocks are detected after Xenon irradiation and after Cobalt 60 irradiation. Further investigation on the radiation effects on NAND Flash can be performed to understand the origin of this degradation as a function of the irradiation source.
- The synergy effect has been studied for four different devices. However this study could be completed by the analysis of a TID-SEE synergetic effect on other kind of components like MOSFETs. The impact of TID on SEB and SEGR could be evaluated.
- The synergy effect considered during this study was the effect of TID on SEE sensitivity. It would also be interesting to investigate the effect of TNID on the SEE sensitivity.
- Finally the effect of SEE on the parametric degradation could also be interesting to investigate. Indeed an SEL run is performed up to a fluence of 10E7 ions/cm². Using the Xenon ion of UCL, a total ionizing dose level of 10.8 krad(Si) is deposed during this test. A parametric measurement could be performed after a Xenon run and be compared to the degradation obtained under Cobalt 60 at the same dose.