Astrium Space Transportation
Competence Centre

MEMSRAD

Technical Note – TN4
Part 3
PROTON TEST REPORT
MEMS Type 1
Colibrys Accelerometers

ESA_QEC1010TS_C

DIFFUSION

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TA413

- De la page documentaire, du résumé de synthèse et de la présente liste de diffusion :

TE6	M. ABOUT
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Internal reference : TE612 n° 152 415	Issue	Rev.	Date : 02/07/09
Structured reference :	1		Page

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TITLE MEMSRAD: MEMS Sensitivity to Space Radiation

MEMS Type 1: Radiation test Results on Colibrys Accelerometers

ABSTRACT

This document constitutes the detailed report of the Proton Radiation testing on MEMS Type 1: Colibrys Accelerometers. This report covers the tasks of different WPs: 4000.1, 4000.2, 5000.1& 5000.21 related to Accelerometers. These works are done by following Consortium members: Infoduc and Astrium ST.

KEYWORDS

MEMS, Sensors, Radiation, Space, Guidelines

File ref. : Software : WORD 97		Configuration management		Distribution category		
Language code : ENG Taking precedence : FR		None	☐	Interest	Short term	☐
		Internal	☐		Medium or long term	☐
figures	appendices	Customer	☐	Sup. distribution	Authorized ☐	Checked ☐

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ISSUE / REVISION STATUS RECORD		
Issue and revision n°	**Date**	**Main reasons for document change (+ paragraphs nb concerned in case of revision) Document validity status (reference and date)**
1	02-07-09	Original document

ABSTRACT

SECTION: TE612 **NUMBER**: 152 415 **DATE**: 02/07/09

AUTHOR(S): TE612 : C. OUDEA
Infoduc : R. GAILLARD & P. POIROT

TITLE: MEMSRAD

MEMS Type 1: Proton Radiation test Results on Colibrys Accelerometers

This document constitutes the detailed report of the Proton Radiation testing on MEMS Type1: Colibrys Accelerometers.

This report covers the tasks of different WPs: 4000.1, 4000.2, 5000.1& 5000.21 related to Proton testing:

- Radiation testing preparations & Campaigns
- Exploitation of results
- Results analysis

Section Manager TE612

V. FORMOND

SUMMARY

1. INTRODUCTION

This document gives the result of the proton tests performed on MS8002 accelerometers manufactured by Colibrys. The aim of this test was to verify that test guidelines that are applied to prepare the radiation test plan and the test procedure are well adapted to MEMS devices.

During proton tests on this accelerometer different effects are expected:

- Total dose effects due to direct ionisation by protons
- Single event transient (SET) due to nuclear reactions of protons with Silicon or SiO2 nucleus. Transients can be observed at the outputs and on the power supply.
- Eventually single Event Latch-up. SEL is seen as a permanent increase of the power supply current and need shut-down of the power supply.
- SEFI (Single event functional Interrupt) is an other possible failure mode where output voltage and power supply current are modified for a long time duration.
- Displacement Damage is mainly induced in the crystalline lattice by nuclear recoils

In the first chapter a brief description of the Device Under Test (DUT) is given and the main aspects of the test plan are recalled.

In the second Chapter the different effects observed during the experiment are detailed: SET (Single Event Transients) and total dose effects observed at the outputs (Temperature output and acceleration output).

Finally results are discussed and the need to enhance test procedures and complementary experiments is presented.

2. APPLICABLE DOCUMENTS

[1] Statement of Work – MEMSRAD: MEMS sensitivity to space radiation, appendix to AO/1-5056/06/NL/CP, ref: TEC-QCT/2005SSOW09/LM/NS, issue 1, rev.5, 17th January 2006.

[2] Technical Proposal by Astrium ST – ref TE 060 195 Issue 1, rev 0, 02/05/2006

[3] Test Plan for MEMS type 1 by Astrium ST – ref TE624 n° 149152, 3rd December 2007

3. DUT DESCRIPTION AND RADIATION TEST PLAN

3.1 DUT DESCRIPTION

The MS-Accelerometer MS8000 is based on MEMS capacitive technology.

The sensor is independent from the electronics. Three electronic chips are used:

a temperature sensor, an analog ASIC called Interface Circuit in the block diagram, a microcontroller.

The accelerometer output signal “Vout” is a ratiometric analogue voltage as described hereafter:

Vout= Bias +(Scale factor*Acceleration)

Where the parameters are defined as follows:

Bias(V) is the output voltage at 0g acceleration

Scale factor (V/g) is the sensor sensitivity

Acceleration (g) is the applied acceleration in the sensitive axis Z.

Calibration registers:
The microcontroller loads calibration registers at RESET when the power supply is applied.

3.1.1 Block Diagram

The block diagram of the accelerometer is given in figure 1

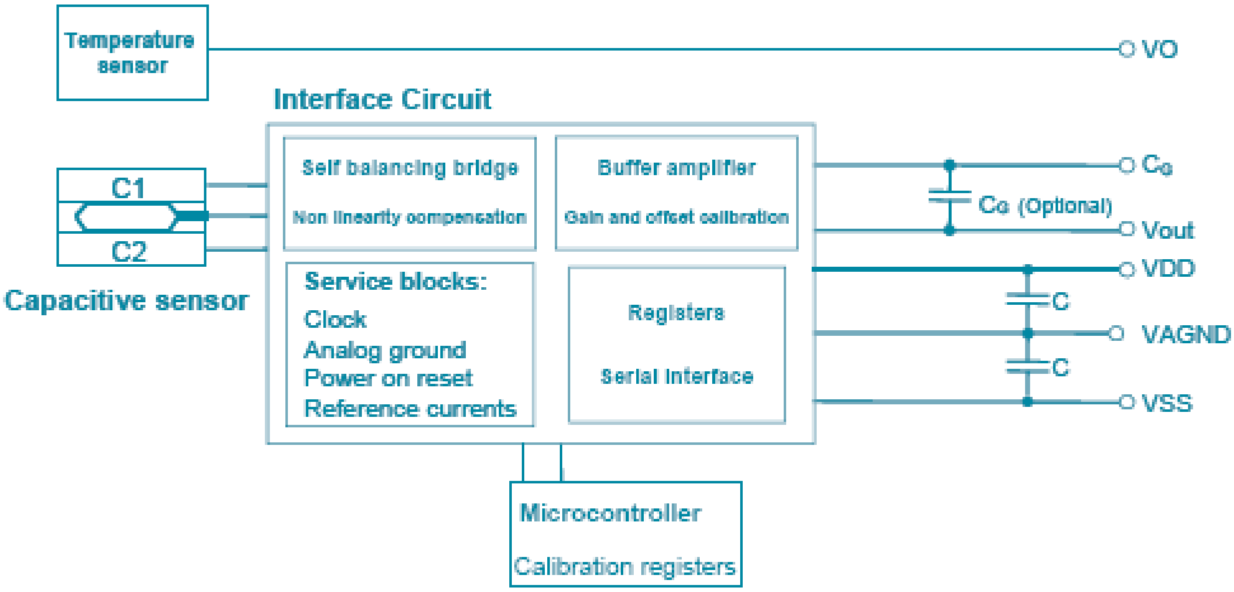


Figure 1: Block Diagram of MS8002 Accelerometer from Colibrys

3.1.2 Packages

The packages remained closed because proton range is great enough to cross the package thickness.

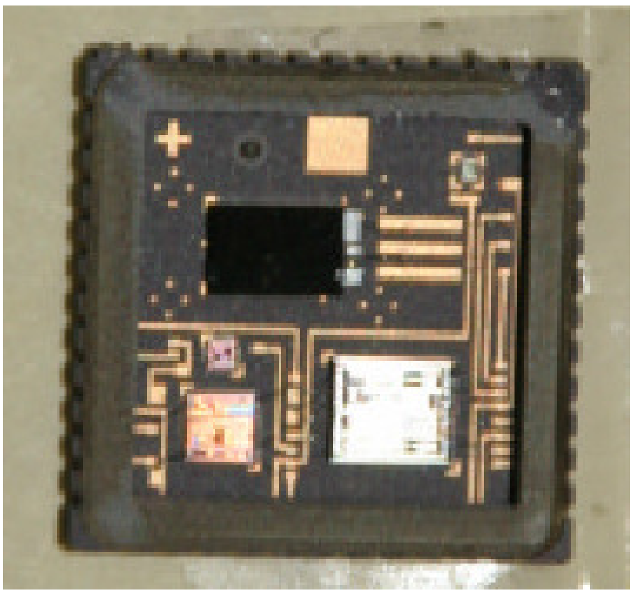


Fig 2 Position of sensor and electronic chips

The opened package is shown in Fig2. The different parts of the accelerometer are clearly seen:
The sensor is a black rectangular in the upper left part.

At this time, the other dies are not surely identified. Some Investigations with a microscope have been performed, but more information from Colibrys is waited for.
The actual hypothesis is that the microcontroller is at the lower part on the left and the interface circuit on the lower part on the right.
The temperature sensor is located in the upper part right side.

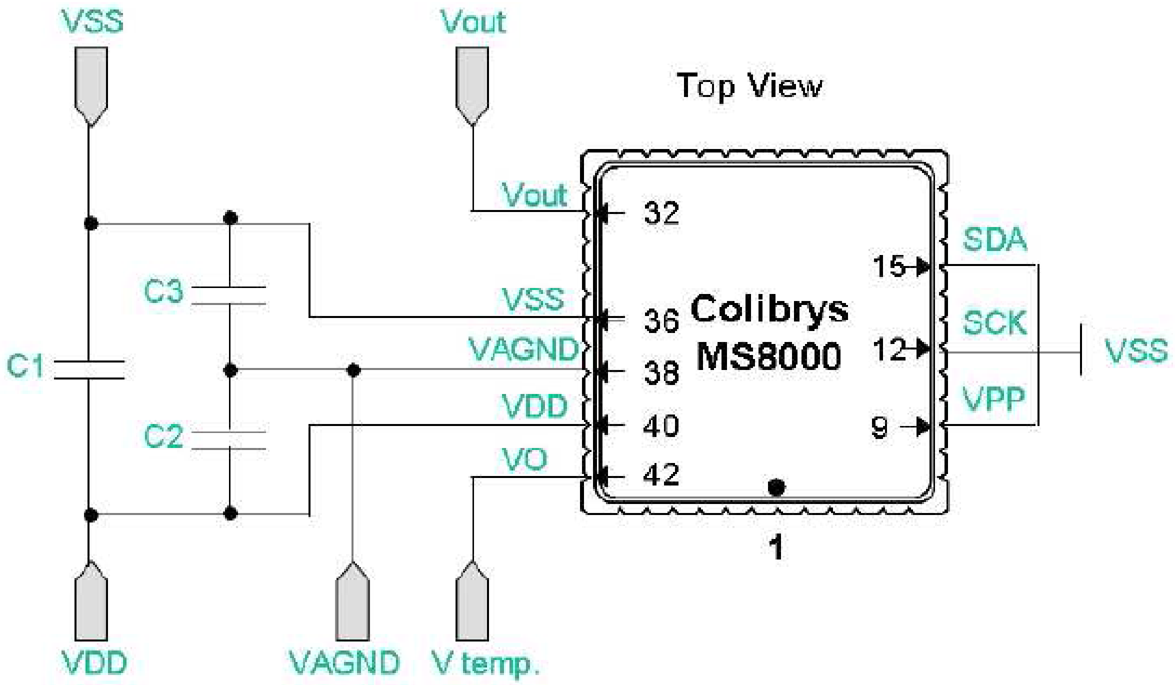


Fig3: Evaluation board schematic C1=C2=C3=1µF

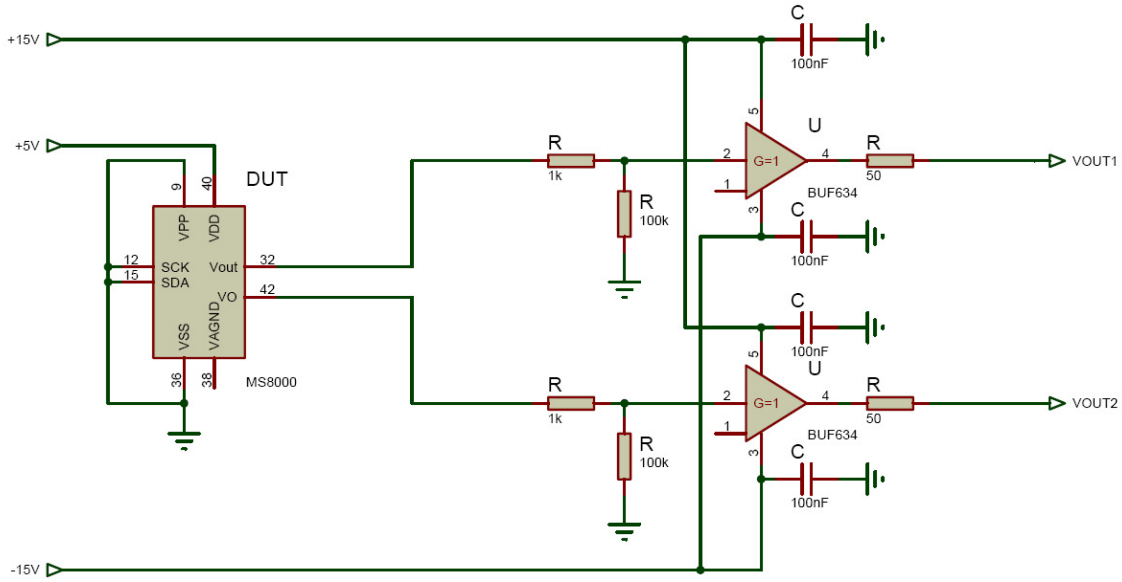
Output Voltage Vout and the output of the Temperature sensor are monitored during irradiation with Digital Storage Oscilloscopes.

An external buffer is used on each output. This buffer allows the driving of a coaxial cable terminated at the DSO input by its characteristic impedance 50 Ohm.

The serial resistor of 50 Ohm at the output of the buffer, and the 50 Ohm input resistor provide a voltage divider by a factor 2.

During the second part of the experiment (global irradiation), the 50 Ohm resistor at the input of the DSO was not present so output voltage is not divided.

With a coaxial cable length of 20m and a capacitance of 100pF/m, the equivalent cable capacitor is 2nF. So the rise time of the pulse will be greater than $50*2\ 10^{-9}$= 100ns.



The power supply current and voltage are continuously measured during irradiation with a high resolution voltmeter and ammeter.
The measurement rate is about 3 measurements per second.

3.2 RADIATION TEST:

In the radiation test plan the following steps are required:
Obtaining accelerometers with uniform characteristics and traceability of the electronic components
Initial detailed parameter measurements

3.2.1 List of irradiated devices

Ten different devices have been tested during this experiment:
The references are:
6015-070, 6018-041, 6018-168, 6025-214,6025-237, 6026-014, 6026-024, 6026-052, 6026-115, 6026-153

3.2.2 Position of the accelerometer

The accelerometer is perpendicular to the ion beam with the sensitive axis of the sensor horizontal. So the accelerometer is in 0g position.

3.2.3 Proton Energy

Several Proton energies were used during the experiment: 200MeV, 150 MeV, 100MeV, 60 MeV.

The following list gives the name and conditions of the different Runs and the flux and energy of the proton beam
The ionizing dose deposited at each run is also given.

3.2.4 Positions of irradiation

The accelerometer is a system with different components. with two main parts: the acceleration sensor and the electronic parts.
In the first part of the experiment, a collimator is used to irradiate only the sensor. Then the full system is irradiated at the different proton energies.

4. SET MEASUREMENTS RESULTS:

SET measurements are performed with Digital Storage Oscilloscopes at the two available outputs namely the Acceleration output at Vout and Temperature Output at the output of the temperature sensor.
Only transients with an amplitude greater than 250mV are recorded (This is obtained with a trigger threshold value of 250mV). For a given run a positive or negative trigger is chosen.

4.1 POSITION 1: SENSOR

The capacitive sensor position is described in fig1

The sensor was tested during the following runs on device 6025-237 at energy of 150 and 200 MeV

Run	tilt	flux	fluence	dose	cum dose	SEU/SET	SET temp
45	0	1,47E+08	1,00E+10	702	702	0	
46	0	1,30E+08	1,00E+10	704	1406	0	
47	0	1,30E+08	1,00E+10	705,7	2111,7	0	
48	0	1,15E+08	1,00E+10	589	2700,7	5	
49	0	1,15E+08	1,00E+10	588	3288,7	1	
50	0	1,15E+08	1,00E+10	585	3873,7	2	1
51	0	1,15E+08	1,00E+10	585	4458,7	1	
52	0	1,15E+08	1,00E+10	587	5045,7	3	
53	0	1,15E+08	1,00E+10	587	5632,7	1	
54	0	1,15E+08	1,00E+10	585	6217,7	1	1

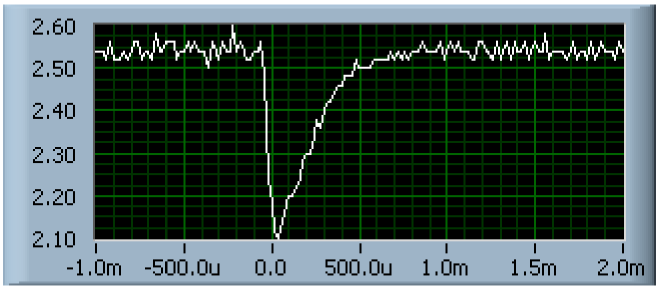
4.1.1 Power supply current:

No events were observed on the power supply Icc records during these runs.

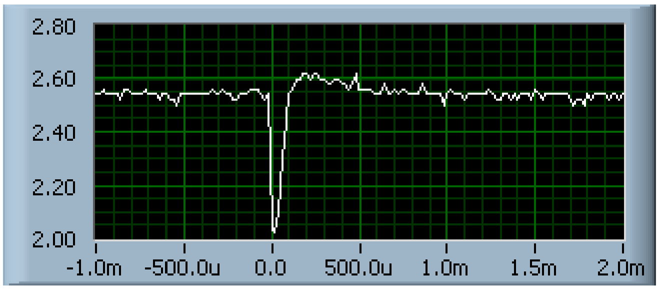
4.1.2 Output voltage transients:

A few Small transients on output voltage were observed during run 48 to 54.

Different shapes are observed.
When the trigger slope is negative, Bipolar Transients (negative transient followed by a slower positive recovery) and Negative Transient are observed.
The total duration of the transients is less than1ms.



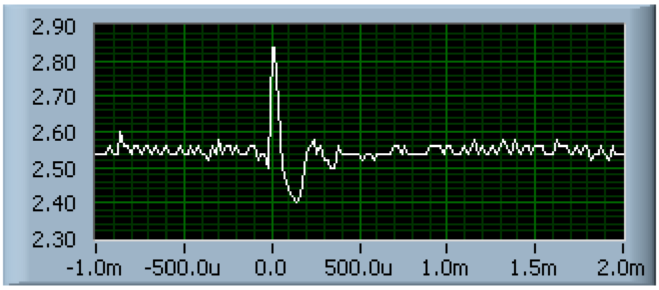
Negative transient with recovery in t<1ms.



Bipolar transient with fast negative (<100µs) followed by small positive recovery.

The maximum negative transient is about -0.2g

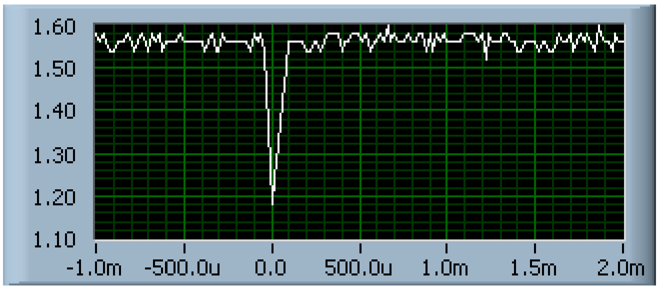
The positive transients have also a bipolar shape (short positive duration followed by a smaller negative one)

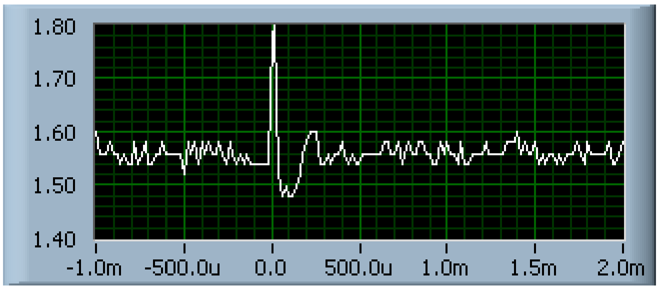


4.1.3 Temperature sensor voltage transients:

Only a few SET were observed: negative pulses during Run47, Run48 and Run 50 and a positive one during run 54.
The duration of the pulse is less than 100µs. The negative pulse amplitude is between 0,3 and 0.4V.
The positive amplitude is 0.3V.

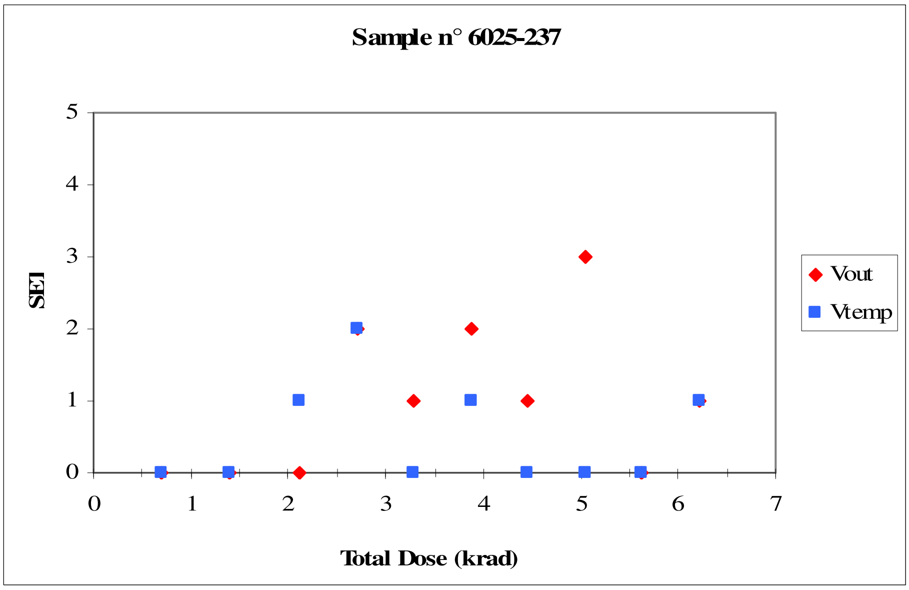
The waveforms are given below for the negative and positive SET.



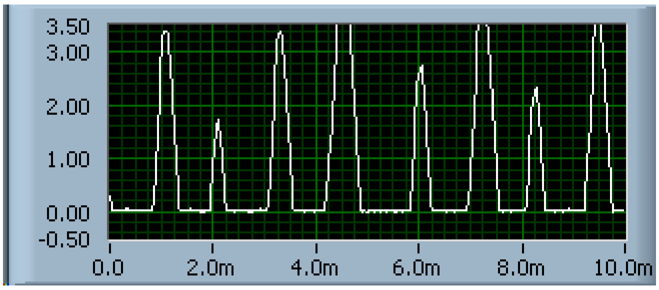


This SET at the output of the temperature sensor can be related to protons that reach directly the temperature sensor, due to the non perfect collimation of the proton beam.

The number of transients is given below for the different runs. The abscissa is the total dose received by the sensor during Runs 45 to 54.



At the end of this experiment the device was non functional: After switching the power supply Off and On again the output is oscillating as shown here after



Discussion:
The observed loss of functionality of the device at the end of the test can be interpreted following two hypotheses:

1) the sensor alone is irradiated: The loss of functionality would indicate that the sensor is sensitive to a total dose of 6 krad because the electronic parts are supposed not to be irradiated

2) the collimator does not fully protect the electronic parts and what is observed is a degradation of the electronic parts with behaviour identical to the total irradiation.

As some transients were observed on temperature sensor, the second hypothesis seems to be preferred.

4.2 GLOBAL IRRADIATION

During these runs all the elementary parts of the hybrid are irradiated at the same time. All the effects of the protons can be observed simultaneously: Total dose effects, displacement damage and single event effects. The different runs are detailed below with the Run number, the initial Icc value, the final Icc value at each step and the flux and energy of the protons. The number of SET observed and the general observations will be presented in a following paragraph.
Tilt angle of 0° and 90° were used during the test.

Run	Device	Initial Icc	Final Icc	Energy	Tilt	Flux	Fluence	Dose	Total Dose
55	6018-168	0,349		150	0	7,60E+07	1,00E+10	705	705
56	6018-168	0,35		150	0	6,92E+07	1,00E+10	704	1409
57	6018-168		0,35	150	0	7,46E+07	1,00E+10	707	2116
58	6018-168		0,35	150	0	9,41E+07	1,00E+10	707	2823
59	6018-168		0,349	200	0	1,36E+08	1,00E+10	588	3411
60	6018-168		0,352	200	0	1,36E+08	1,00E+10	588	3999
61	6018-168		1,2	200	0	1,36E+08	1,00E+10	588	4587
62	6018-168		1,02	200	0	1,35E+08	1,00E+10	588	5175
63	6018-168		3,2	200	0	1,36E+08	1,00E+10	588	5763

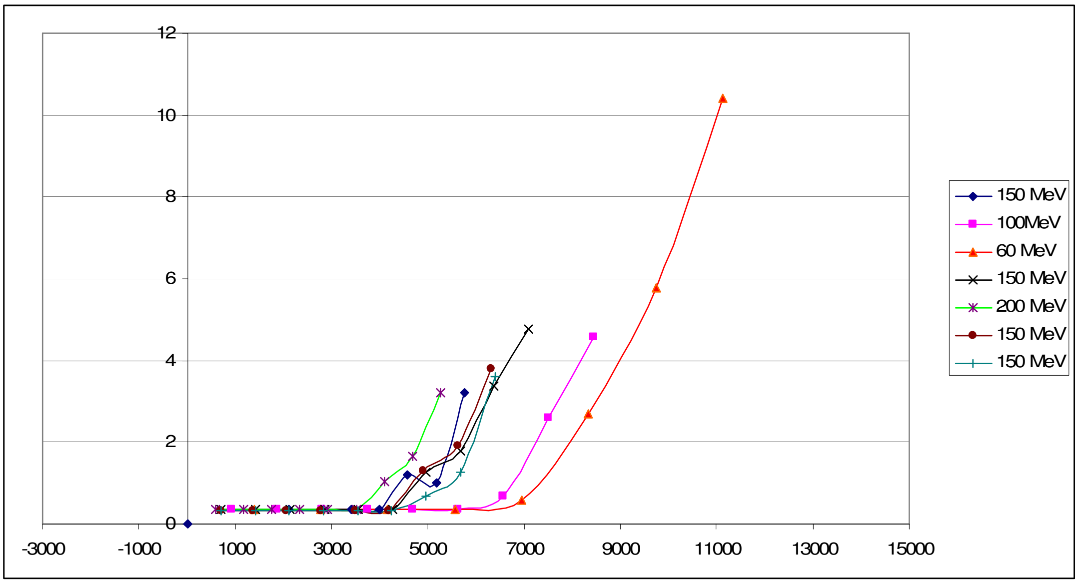
64	6026-052	0,348	0,349	100	0	7,72E+07	1,00E+10	938	938
65	6026-052		0,349	100	0	9,80E+07	1,00E+10	941,8	1879,8
66	6026-052		0,349	100	0	9,76E+07	1,00E+10	939	2818,8
67	6026-052		0,349	100	0	9,76E+07	1,00E+10	938,5	3757,3
68	6026-052		0,35	100	0	9,71E+07	1,00E+10	934,2	4691,5
69	6026-052		0,36	100	0	9,71E+07	1,00E+10	934,1	5625,6
70	6026-052		0,694	100	0	9,73E+07	1,00E+10	936	6561,6
71	6026-052		2,6	100	0	9,71E+07	1,00E+10	934,8	7496,4
72	6026-052		4,56	100	0	9,78E+07	1,00E+10	941,3	8437,7
73	6018-041	0,346	0,346	60	0	1,02E+08	1,00E+10	1388	1388
74	6018-041		0,346	60	0	1,04E+08	1,00E+10	1395	2783
75	6018-041		0,347	60	0	1,03E+08	1,00E+10	1391	4174
76	6018-041		0,349	60	0	1,04E+08	1,00E+10	1391	5565
77	6018-041		0,596	60	0	1,04E+08	1,00E+10	1388	6953
78	6018-041		2,7	60	0	1,04E+08	1,00E+10	1387	8340
79	6018-041		5,77	60	0	1,04E+08	1,00E+10	1401	9741
80	6018-041		10,4	60	0	1,04E+08	1,00E+10	1399	11140
81	6026-14	0,349	0,349	150	0	1,75E+08	1,00E+10	713,4	713,4
82	6026-14		0,349	150	0	2,15E+08	1,00E+10	709,3	1422,7
83	6026-14		0,349	150	0	2,13E+08	1,00E+10	716,3	2139
84	6026-14		0,349	150	0	2,12E+08	1,00E+10	715,3	2854,3
85	6026-14		0,35	150	0	2,14E+08	1,00E+10	704,1	3558,4
86	6026-14		0,354	150	0	2,15E+08	1,00E+10	708,1	4266,5
87	6026-14		1,28	150	0	2,14E+08	1,00E+10	705,1	4971,6
88	6026-14		1,78	150	0	2,16E+08	1,00E+10	710,7	5682,3
89	6026-14		3,38	150	0	2,13E+08	1,00E+10	703,4	6385,7
90	6026-14		4,76	150	0	2,14E+08	1,00E+10	706,4	7092,1
91	6026-153	0,349	0,35	200	0	3,31E+08	1,00E+10	584	584
92	6026-153		0,35	200	0	1,90E+08	1,00E+10	587	1171
93	6026-153		0,35	200	0	1,90E+08	1,00E+10	588	1759
94	6026-153		0,349	200	0	1,89E+08	1,00E+10	583,4	2342,4
95	6026-153		0,35	200	0	1,88E+08	1,00E+10	583,2	2925,6
96	6026-153		0,353	200	0	1,90E+08	1,00E+10	587,6	3513,2
97	6026-153		1,03	200	0	1,91E+08	1,00E+10	591,6	4104,8
98	6026-		1,65	200	0	1,90E+08	1,00E+10	587,4	4692,2

	153								
99	6026-153		3,2	200	0	1,89E+08	1,00E+10	584,7	5276,9
100	6015-070		~30	150	0		1,00E+10		0
101	6025-214			150	0		3,00E+11	21070	21070
102	6026-115	0,336	0,336	150	90	2,04E+08	1,00E+10	715	715
103	6026-115		0,336	150	90	2,03E+08	9,14E+09	641,7	1356,7
104	6026-115		0,336	150	90	2,04E+08	1,00E+10	715,7	2072,4
105	6026-115		0,336	150	90	2,01E+08	1,00E+10	708,2	2780,6
106	6026-115		0,336	150	90	2,02E+08	1,00E+10	708,6	3489,2
107	6026-115		0,34	150	90	2,02E+08	1,00E+10	710,7	4199,9
108	6026-115		1,3	150	90	2,03E+08	1,00E+10	714,4	4914,3
109	6026-115		1,9	150	90	2,00E+08	1,00E+10	704,9	5619,2
110	6026-115		3,8	150	90	2,02E+08	1,00E+10	709	6328,2
111	6026-024	0,33	0,33	150	90	2,02E+08	1,00E+10	710	710
112	6026-024		0,331	150	90	2,06E+08	1,00E+10	707,4	1417,4
113	6026-024		0,331	150	90	2,01E+08	1,00E+10	706,8	2124,2
114	6026-024		0,331	150	90	2,02E+08	1,00E+10	711,8	2836
115	6026-024		0,331	150	90	2,03E+08	1,00E+10	713,1	3549,1
116	6026-024		0,337	150	90	2,01E+08	1,00E+10	707,4	4256,5
117	6026-024		0,69	150	90	2,04E+08	1,00E+10	714,8	4971,3
118	6026-024		1,25	150	90	2,03E+08	1,00E+10	713,2	5684,5
119	6026-024		3,6	150	90	2,03E+08	1,00E+10	712,3	6396,8

4.2.1 Power supply current:

After each step of 1 E10 p/cm2 fluence, the power supply is switched Off and On again to verify the functionality of the device. The power supply current is monitored continuously during irradiation.

The values of Icc at the end of each run are given below.



The power supply current Icc increases rapidly with total dose after a dose ranging from 4 krad to 7krad depending upon proton energy and variation of sensitivity between devices.

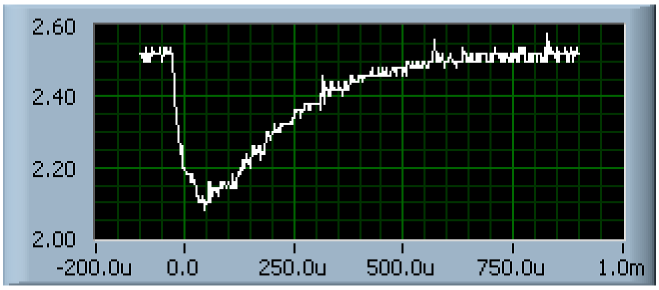
The doses have been calculated from the proton fluence by using LET values as a function of proton energy.
This show that for some runs the device presents some degradation (as indicated by the power supply current) but this degradation may affect only the microcontroller and not the analog part of the system that measures the acceleration.
A degradation of this analog part (interface circuit) results in the variation of the output voltage (at 0g or at +-1g). Only 0g values were measured during this experiment.

4.2.2 Output voltage transients:

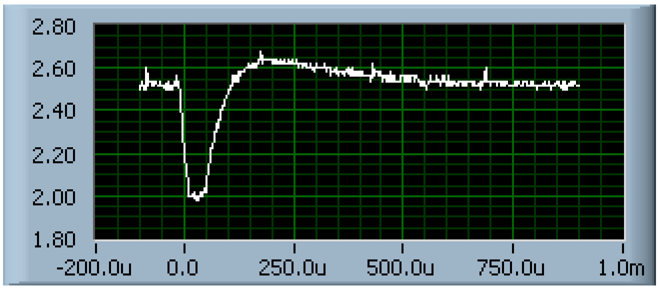
The output voltage is measured with a digital storage oscilloscope. During a given run, trigger slope is either positive or negative with a level of 250mV (10% of the output at 0g), and the sweep rate is set to 1ms/cm, 500µs/cm or 250µs/cm. During previous heavy ions experiment, it was shown that mostly negative transients are observed so in this proton experiment most of the runs were performed with negative trigger.

Observed SET present the same waveforms that were previously observed with the collimator.

Negative SET transients

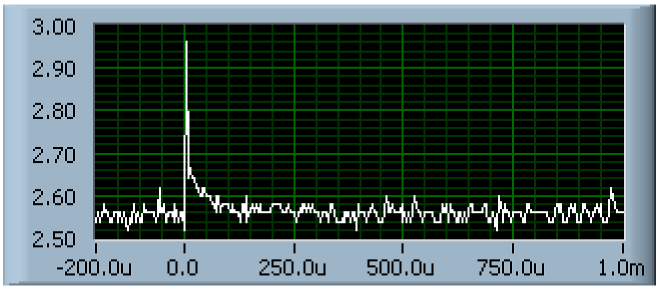


Bipolar transients



The amplitudes vary between 0.3V and 0.5V.

Positive SET has a very short duration with maximum amplitude of 0.5V.

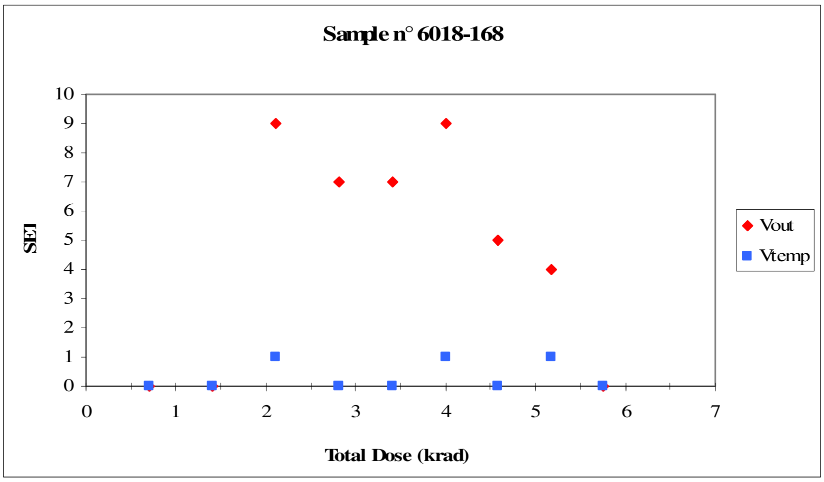


During successive runs the dose increases, and some possible variation of the SET cross-section with total dose may be expected.
The following graphs give the number of SET as a function of total dose

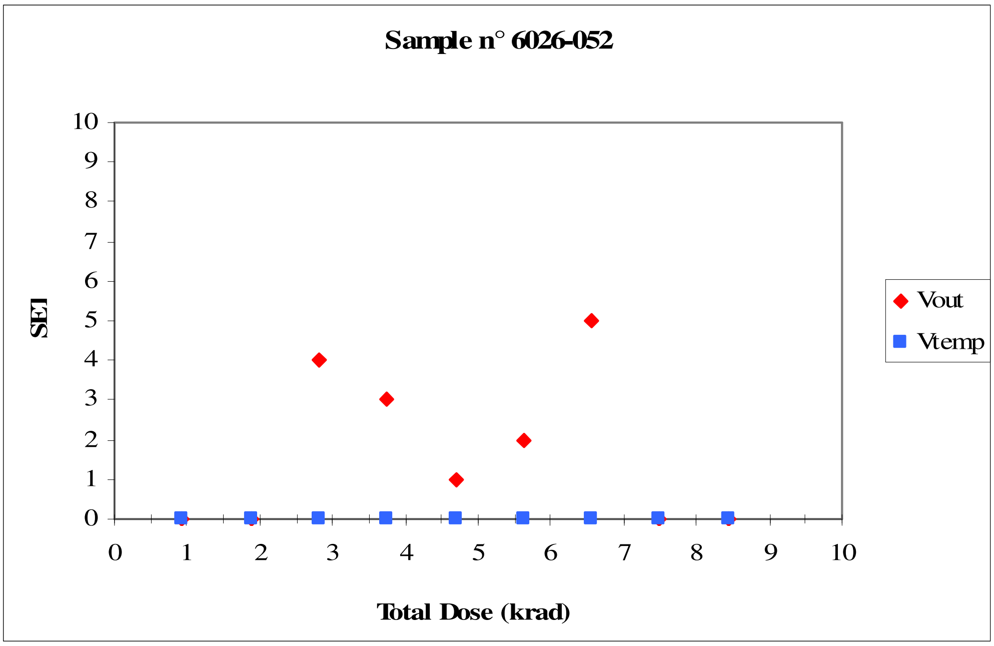
4.2.3 Synthesis of Results

The following curves give the number of SET as a function of dose for the different devices tested during this experiment.

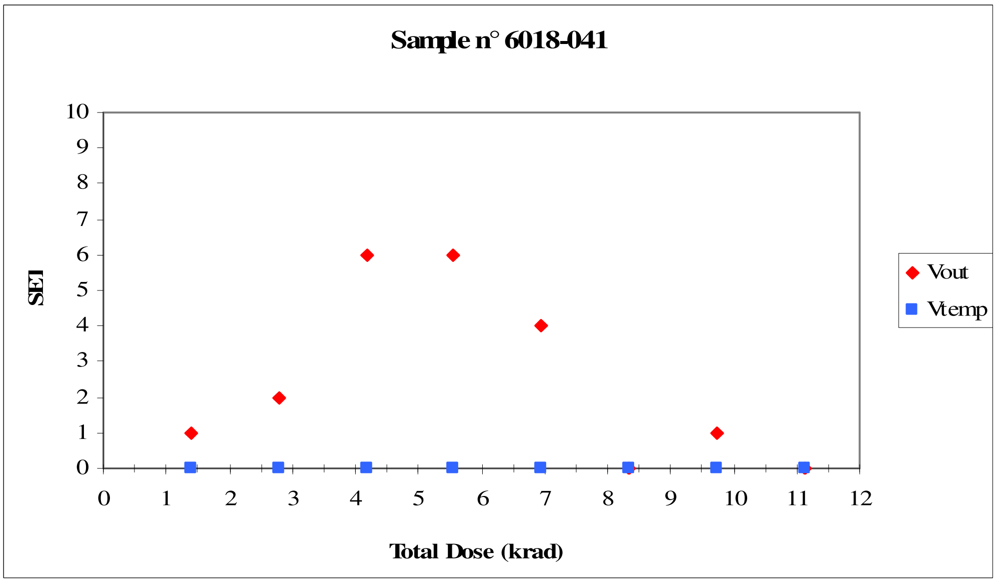
Device 6018-168
Run 55-58: E=150 MeV
Run 59-63: E=200 MeV



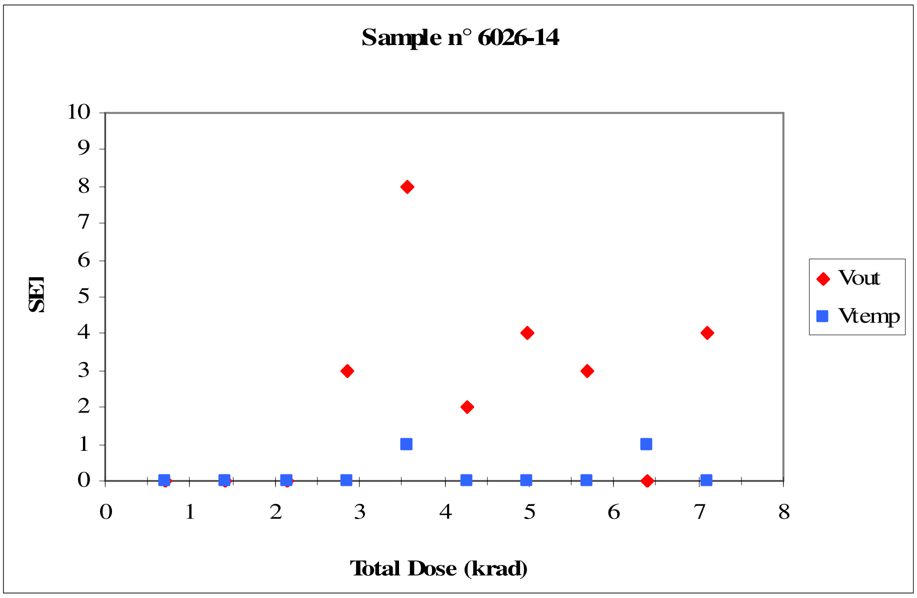
Device 6026-052
Run 64-72 E=100 MeV



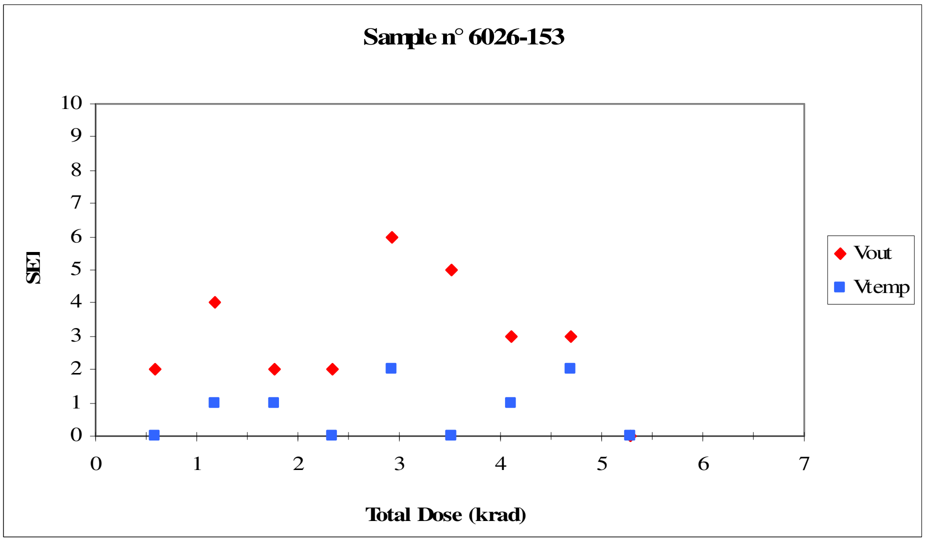
Device 6018-041
Run 73-80 E=60 MeV



Device 6026-14
Run 81-90 E=150 MeV

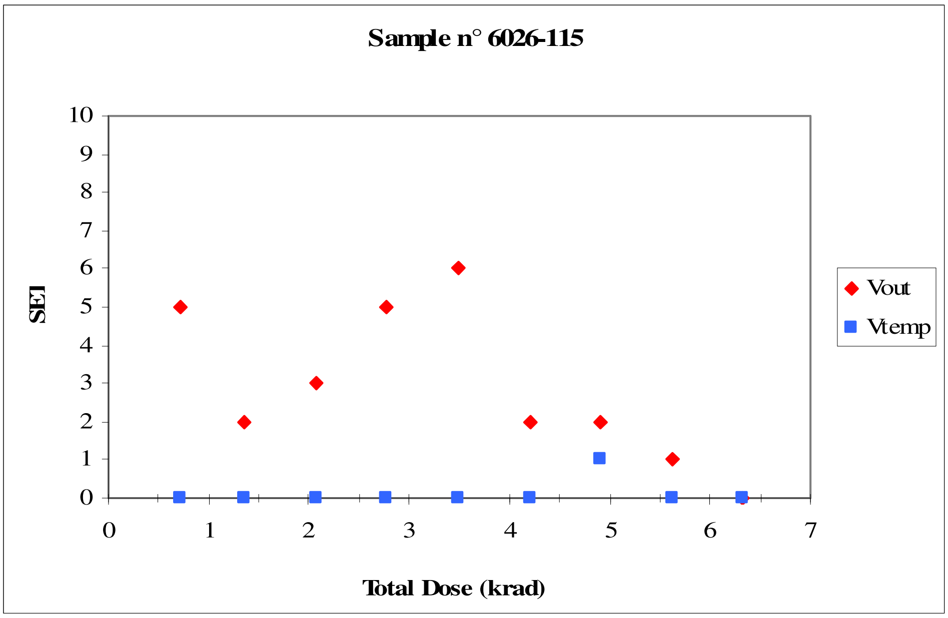


Device 6026-153
Run 91-99 E=200 MeV



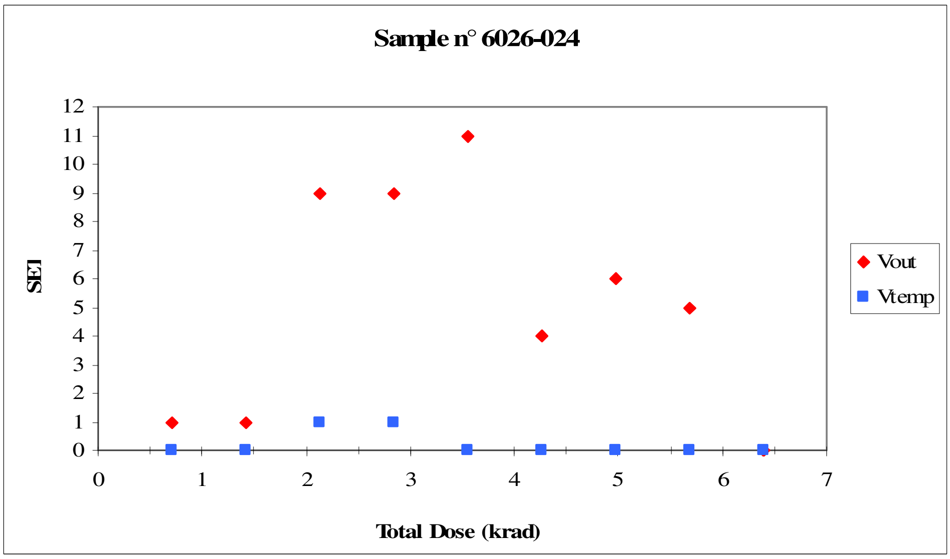
Device 6015-070
Run 100-101 E=150 MeV
The experiment was stopped due to a failure in recording equipment.

Device 6026-115
Runs 102-110 E=150 MeV Tilt=90° 0g position



Device 6026-24

Run 111-119 E=150 MeV Tilt=90° 0g position



4.2.4 Temperature sensor output: shape of the transients

The typical Output Voltage at 20℃ is 1.632 V
The typical Sensitivity is: -11.77 mV/℃
The temperature of the die deduced from the DSO input is about 40℃ (1,42V).
The negative transients have a triangular shape with a rise time of 100µs and a fall time of about 200µs for a voltage amplitude of 0.5V

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4.2.5 Evaluation of the SET cross-section

The SET cross-section can be calculated for each run. But the number of SET is low so the imprecision is rather quite important. So we prefer to perform a mean of the different runs with the same trigger conditions. But we must recall that due to possible variation of the cross-section with total dose, this approach is also a simplification.

Devices	Number of SET	Energy	Fluence	Cross-section
6018-168	16	150-	2E10	8E-10
	21	200	3E10	7E-10
6026-052	15	100	5E10	3E-10
6018-041	19	60	5E10	3.8E-10
6026-14	18	150	5E10	3.6E-10
6026-153	21	200	6E10	3.5E-10
6026-115	25	150-90°	7E10	3.5E-10
6026-24	2	150-90°	4E10	5E-11

No clear variation of the cross-section with the proton energy or tilt angle can be seen. The order of magnitude is 3 E-10 to 8E-10 cm2.

5. DISCUSSION OF RESULTS:

The proton test results of this accelerometer present a great interest and allow us to obtain a lot of information about improvements concerning the testing guidelines of MEMS.

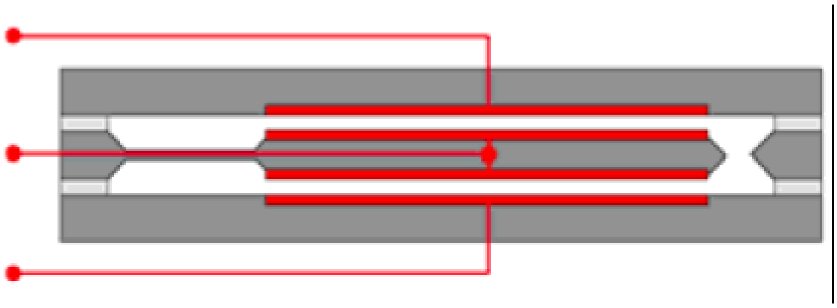
5.1 NEED TO KNOW THE DETAILED STRUCTURE AND TECHNOLOGY OF THE DEVICE

This MEMS device is a full system with a capacitive sensor and associated electronics. To understand the behaviour of this system we need more information than the block diagram given with the data sheet (see 3.1.1)

More technology information is needed on the different parts of the system. This need is presented below.

5.1.1 Sensor information (position 0)

The physical dimensions of the sensor must be known in order to calculate the probability of interaction of protons in this volume and to evaluate the number of possible SET.



Some information can be found in the literature but it is needed to be verified:

The thickness of the suspension beam is 20µm and oxide spacers between wafers have a thickness of 2 µm. Bonding of top and bottom wafer is performed by using silicon fusion bonding (with intermediate oxide)
The residual thickness of the top wafer must be known.

Transients whose origin comes from the sensor were observed during the test with the collimator and probably during the following tests because the amplitudes and waveforms are similar.

A model of the origin of the transient must be developed in order to be able to predict the cross-section and the shape of the transients.

5.1.2 Temperature sensor

The temperature sensor is a COTS. Its reference should be known. Sensitivity to protons has been probably previously studied by the space radiation effects community.

5.1.3 Microcontroller

The microcontroller used is probably a PIC microcontroller (to be confirmed by Colibrys).
Normally the Microcontroller loads information at the power-up of the accelerometer. This activity is related with an increase of power supply current.

When protons have nuclear reactions in the microcontroller, two possibilities exist:
nothing is observed
or a reset would give a reload of calibration registers associated with an increase of power supply current.
Reset was not clearly observed during the proton tests.

5.1.4 ASIC interface circuit

The readout electronic is a Colibrys proprietary solution, self balanced capacitive readout. It is a highly stable low power ASIC with a power consumption lower than 390µA at 5V. The electronic has a power-on reset and a brown out protection to insure a reliable output in the most severe conditions. As previously stated, the sensor contains a PIC microcontroller that is used during the start-up and brown-out reset sequences.

The ASIC is probably developed on a mixed-mode 0.5µm technology from AMI semiconductor.
A more detailed knowledge of the different functions of the ASIC are needed:
Capacitive sensor excitation, demodulation, amplification and filtering
Buffer and registers

This would allow to perform an a priori evaluation of the cross-sections by a simple geometrical evaluation (junction areas, collection length) and with the probability of a nuclear reaction in the sensitive volume.

5.1.5 Total Dose Effects

The MS8002 is very sensitive to total ionizing dose. The failure level is between 4 to 8 krad, depending upon the proton energy and the failure criteria. The failure is observed when the power supply is switched Off and On again after a few minutes.
When the power is applied again, oscillations are observed at the output. These oscillations are not observed if the power supply is not switched off.
The low dose failure level limits strongly the total proton fluence that can be used to study single event effects.
Displacement damage is difficult to separate from total dose effects because not enough information on device technology is available.

5.2 TESTING PROCEDURES

Testing procedures must be detailed in the test plan. In particular the following points should be addressed as basic requirements to be performed during an experiment.

5.2.1 Choosing the flux:

It must be verified that there is no pile-up of successive events. Also it must be verified that the recording performance of the apparatus used during the experiment allow to record a given event rate. This is done by dividing by 5 to 10 the flux and comparing the number of events for a given fluence obtained with the two flux values.

5.2.2 Recording transients

In order to reduce the duration of the experiment, it would be useful to allow to record positive and negative transients on the same run.

5.2.3 Precise knowledge of the time of the events

When several outputs are observed, it would be useful to know if the events recorded are correlated in time or not. This would help to understand the origin of the transient.

5.2.4 Preparing the report:

The output format of the DSO should allow obtaining numerical values of transient voltage-versus time transients in order to allow further analysis of these transients.

6. CONCLUSION

High Energy Protons testing has been performed on the accelerometer MS8002 manufactured by Colibrys.
Single event transients have been recorded during the irradiation of the different parts of the device and total dose degradation has been observed.

The capacitive sensor seems to be sensitive to protons as shown with the experiment with a collimator. But some SET can be generated in the electronic devices even during this experiment.

The interface ASIC which performs many functions and in particular translates the acceleration in a voltage has been shown to be sensitive to heavy ions with LET greater than 20 MeV/cm2/mg.
Here we show that this ASIC must also be sensitive to LET<15 MeV/cm2/mg.

The high sensitivity to total ionizing dose previously observed with Co60 irradiation, is also seen with proton irradiation. The dose effects can not easily be separated from displacement damage.

APPENDICE 1:

Experimental Set-up