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CONTRACT REPORT

ESA/ESTEC Contract No. 11755/95/NL/NB-WO1/CO1

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Title

LUNA ES/3, 16 MBIT DRAM (IBM)

HEAVY ION & PROTON SEE CHARACTERIZATION TEST REPORT

Summary :

Low Voltage memories were tested under heavy ion and proton irradiation, in order to study the effect of supply voltage on the SEE sensitivity. Additional results including study of operating and temperature effects is also addressed. This report presents the results obtained on 16 Mbit IBM DRAMs.

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SUMMARY

Test sample characteristics :

Part Name :	LUNA-ES/3	**Function :**	4 x 4M DRAM
Technology :	CMOS, 0.5 µm	**Package :**	MMS plugging package
Manufacturer :	IBM	**Location :**	Montpellier, France
Sample size :	3 (H.I), 3 (P)	**Date Code :**	9609, 20.12.12

Heavy ion results

The following table summarizes the Heavy ion SEU test results:

	LET Threshold (MeV.cm^2/mg)	**Cross-section (cm^2/dev.) at LET=34 MeV.cm^2/mg**	**Cross-section (cm^2/bit) at LET=34 MeV.cm^2/mg**
Vcc=3.3V	1.7<LETth<5.85	6.2e-2	3.7e-9
Vcc=4.5V	≈5.85	5.3e-2	3e-9

Summary of SEU heavy ion results

	LET Threshold (MeV.cm^2/mg)	**Saturation Cross-section (cm^2/dev.)**
Vcc=3.3V	5.85<LETth<10 (block, row)	<2e-4 (block, row)
Vcc=4.5V	5.85 (block), >34 (row)	not evaluated

Summary of multiple error heavy ion results

Heavy ion test conclusion :

The results of these experiments demonstrate that 16 Mbit DRAM Luna ES/3 from IBM are highly sensitive to heavy ion induced SEU : for parts biased at 3.3V, the cross section at LET=34 MeV.cm^2/mg is 4e-9 cm^2/bit and the threshold LET is between 1.7 and 5.85 MeV.cm^2/mg. Parts biased at 4.5V are moderately less sensitive : the saturated cross section is comparable, and the threshold LET is slightly higher. The main difference is observed on multiple errors : row errors were only observed during the tests at Vcc=3.3V. Multiple error cross sections are order of magnitude lower than SEU cross sections.

Additional heavy ion results:

These devices exhibit no Latch-up sensitivity, up to a LET of 34 MeV.cm^2/mg

No effect of frequency (fmax→fmax/4) can be evidenced on heavy ion cross section values at saturation.

The initial memory content does not influence the cross section.

The devices exhibited no heavy ion single hard error sensitivity.

Proton results

The following table summarizes the proton SEE test results:

	Proton Energy Threshold (MeV)	Saturated Cross-section (cm^2/bit)
Vcc=3.3V	<20	≈2.5e-16
Vcc=4.5V	20<Ep<40	≈5e-17

Proton conclusion :

The results of these experiments demonstrate that 16 Mbit DRAM LUNA-ES/3 from IBM are sensitive to proton induced SEU. The cross section, at the maximum proton energy of 60 MeV, is approximately 2.5e-16 cm^2/bit for parts biased at 3.3V. When biased at Vcc=4.5V, these devices exhibit a lower sensitivity to proton induced SEU : cross sections are reduced by a factor from 5 to 10, and the threshold Ep is between 20 and 40 MeV.

Additional proton results:

These devices exhibit no Latch-up sensitivity, up to a proton energy of 60 MeV

No effect of frequency (fmax→fmax/4) can be evidenced on proton cross section values at saturation.

No effect of temperature (T room→T 65°C) can be evidenced on proton cross section values at saturation.

The "1" initial memory content is more sensitive than "0" initial memory content.

These device exhibited no proton single hard error sensitivity.

No multiple errors (row or column errors) were recorded during the proton irradiations. Other multiple error types could not be identified in absence of a bit map.

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1. INTRODUCTION

The aim of this work is to investigate radiation effects in low and standard voltage technologies. The study is focused on memory devices, which require lower voltage to achieve higher integration. Parts selected concern SRAM (1 Mbit, 2 types), DRAM (16 Mbit, 2 types), and FLASH memories (8 Mbit, 1 type).

The object of this document is to describe the irradiation of 16 Mbit DRAM Luna-ES/3 from IBM, in order to measure their sensitivity to heavy ion and proton induced SEU.

Irradiation were performed in November/December 1996 (30th-1st) according to the procedures referenced in the following paragraph.

This work was performed in the frame of the WO1/CO1 for ESA/ESTEC Contract n°11755/95/NL/NB.

2. REFERENCE DOCUMENTS

[1] ESA/SCC Basic Specification 25100

[2] IBM Manufacturer Data Sheet

[3] "Radiation Prescreening Programme On Low Voltage Memories For ESA/ESTEC Contract N°11755/95/NL/NB" MMS Contract WP1 Report Ref. DOF/DEC/TP6.577.

[4] "The Heavy Ion Irradiation Facility at CYCLONE-a dedicated SEE beam line", G. Berger, G. Ryckewaert, R. Harboe-Sorensen, L. Adams, 1996 IEEE Radiation Effects Data Workshop

[5] "Testeur de mémoire haute densité", D. Winkel, TSEU-MAV-PE-000 (MMS report)

[6]Radiation data trends on high integrated memories for ESTEC Contract N°11755/95/NL/NB, Bruno Doucin (MMS report, ref DOF/GER/NT6.612)

[7]"Space Radiation Evaluation of 16 Mbit DRAMs for Mass Memory Applications", P. Calvel, P. Lamothe, C. Barillot, R. Ecoffet, S. Duzellier, E. G. Stassinopouloss, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL 41, N0 6, Dec. 94

[8]"Heavy Ion test report on 16 Mbit DRAM from Texas Instruments, IBM, Hitachi", C.Poivey, P. Garnier, DOF/SIC/CP/RP4.442

[9] Statement of work- QCA/RHS-CDS1.WP-MAR.'95, Issue 1, "Call-Off Order 1, Study and Radiation testing of Low Voltage Technologies".

[10] R. Harboe-Sorensen, " Heavy Ion, Proton and Co60 Radiation Evaluation of 16 Mbit DRAM Memories for Space Application" 1995 IEEE Radiation Effects Data Workshop.

3. PART DETAILS

3.1. DEVICE IDENTIFICATION

3.1.1. References

Type : Luna-ES/3
Manufacturer : IBM
Place : Montpellier, France
Packaging : Dice packaged at MMS (square plugging package)

3.1.2. Function

16 Mbit DRAM

3.1.3. Technology

CMOS, 0.5 µm

3.1.4. Part Procurement

Origin : Montpellier Technologies, IBM France (dice provided by IBM, Corbeil, Fr)
Level : No
Temperature range : not evaluated
Date code : 9609, 20.12.12
Screening : No screening
Sample size : 3 (H.I), 3 (P)
Manufacturer Marking : No Marking
Detailed specifications : Manufacturer Data sheet

3.1.5. Previous SEE details/history

No radiation data is published on this particular device type but tests have been performed on similar devices, from other manufacturers [6] (see page 4).

During this campaign, proton tests were performed prior to heavy ion tests; samples irradiated with heavy ions are different from samples irradiated with protons.

The following table summarizes previous SEE results on IBM LUNA E/C. ECC stands for Error Correction code : a built-in ECC provide spare bits, which automatically reduces the sensitivity of the DRAMs.

Type	**Size**	**Voltage**	**LETth**	**σ(cm^2/dev)**	**ref**
Heavy ion Results					
IBM Luna E	16 Mbit	5(Ext)	SEU : 2 MeV.cm^2/mg	0.5e-1	[7]
			Row Er. 5 MeV.cm^2/mg	1e-4	
			Col. Er. 4 MeV.cm^2/mg	1e-4	
IBM Luna C	16 Mbit	3.6(Ext)	SEU (ECC Off) : 3 MeV.cm^2/mg	2e-1 (ECC Off)	[7]
			SEU (ECC On): 4 MeV.cm^2/mg	3e-3 (ECC On)	
			Row Er. 6 MeV.cm^2/mg	2e-5	
			Col. Er. 4 MeV.cm^2/mg	1e-4	
IBM Luna E	16 Mbit	5(Ext)	SEU : 2 MeV.cm^2/mg	2.3e-1	[8]
(5116400)			Row Er. <7 MeV.cm^2/mg	6e-4	
			Col. Er. 3 MeV.cm^2/mg	2e-3	
			SEFI* <4.9 MeV.cm^2/mg	>2e-4	
Proton Results					
Type	**Size**	**Voltage**	**Epth (MeV)**	**σ(cm^2/bit) at 300 MeV**	**ref**
IBM Luna C	16 Mbit	3.6(Ext)	Not evaluated	≈1 e-15 (only multiple errors)	[10]
IBM Luna E	16 Mbit	5(Ext)	≈ 29	≈1 e-16 (mult. Err. at 200MeV)	[10]

Summary of parametric/functional failures on 16 Mbit IBM DRAMs

*** SEFI : device cannot be rewritten. The statistic on these events is very low.**

3.2. TECHNICAL INFORMATION

This device is a 3.3 V low voltage device which was tested both at 3.3 V and 4.5 V. The internal voltage regulator is not connected. Therefore, when these devices are biased at 4.5V, the internal voltage is equal to the supply voltage.

General informations

Name	IBM Luna ES/3
Die Mark	No
Access time/ns	Not measured
Temperature range/°C	Not measured
Organization	4Mx4Bit
Supply Voltage/V	3.0-5.5

Technology

Name	IBM Luna ES/3
CMOS	advanced CMOS
Design rules	0.5 µm
Epitaxial layer	2.1 µm
Die size	6 mm x 14.6 mm
Cell size	1 µm x 2.4 µm

A photography of the die is given in the annex.

4. TEST DESCRIPTION

4.1. IRRADIATION FACILITY

Name : Louvain-La-Neuve Cyclotron

Location : Université Catholique de Louvain
Centre de Recherches du Cyclotron
Chemin du Cyclotron, 2, 1348,
Louvain-La-Neuve, Belgium

4.1.1. Beams currently available

A cocktail of heavy ions can be provided, allowing quick (in a few minutes) changes of ion species. The characteristics of the associated LET are reported in table 1 (**X** in the last column refers to the type of ions used during this campaign) :

Ion	Ion Energy (MeV)	Range [µm Si]	LET (MeV.cm²/mg)	Beam used
^{84}Kr	316	43	34	X
^{40}Ar	150	42	14.1	X
^{20}Ne	78	45	5.85	X
^{15}N	62	64	2.97	
^{10}B	41	80	1.7	X
^{132}Xe	459	43	55.9	

Table 1 Cocktail 1 that can be provided by LLN cyclotron.

- By varying the ion species, ion energy and angle of incidence, the error Cross-section (σ) can be determined as a function of LET. A controlled flux between 10 and 10^5 (part./cm²)/s is used for heavy ion tests. A complete presentation of the Cyclotron Facility SEE beam line is presented in ref [4].

4.1.2. Proton energies available

- Proton energies available at the LLN cyclotron are ranging from 10 to 60 MeV. Low energies are obtained by degrading the 60 MeV beam. For these tests, 2e+07 to 1e+08 part/cm²/s proton fluxes were used.

4.2. TEST SET UP DESCRIPTION

4.2.1. Heavy ion test set-up

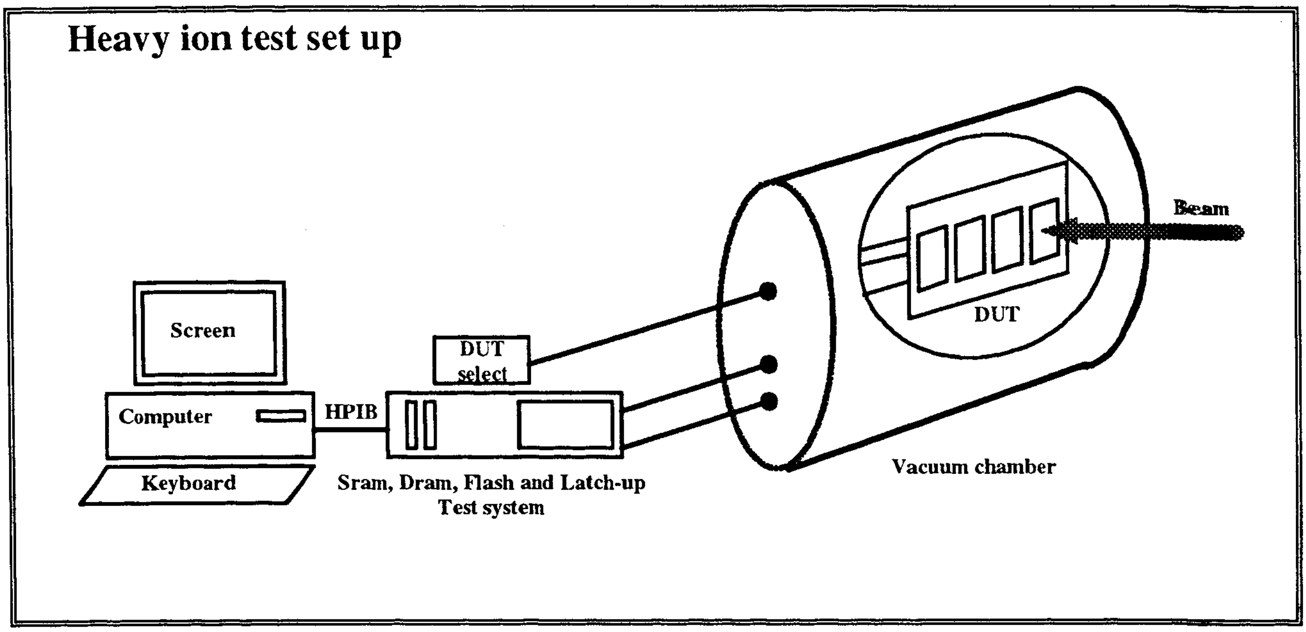


Fig. 1 Description of the heavy ion test set-up.

Comments :

The DUT are mounted on 4 zero-insertion-force sockets. Due to the low heavy ion penetration, parts were delidded for the heavy ion tests.

The tested device is selected by a switching commuter, located outside of the vacuum chamber.

The supply voltage is provided by the memory tester. The memory tester is also located outside of the vacuum chamber. The maximum frequency (Fmax) for tests is 0.77 MHz for DRAMs. This frequency can be divided by 2, 4, or 8. The maximum SEU rate is 335000 SEU/s (errors are systematically counted and recorded with the corresponding address).

The tester also includes a delatcher. The Latch-up detection threshold is programmable (set at 40 mA for the DRAM). The cut-off time is of 10 ms.

A complete description of the memory tester is given in [5].

4.2.2. Proton test set-up

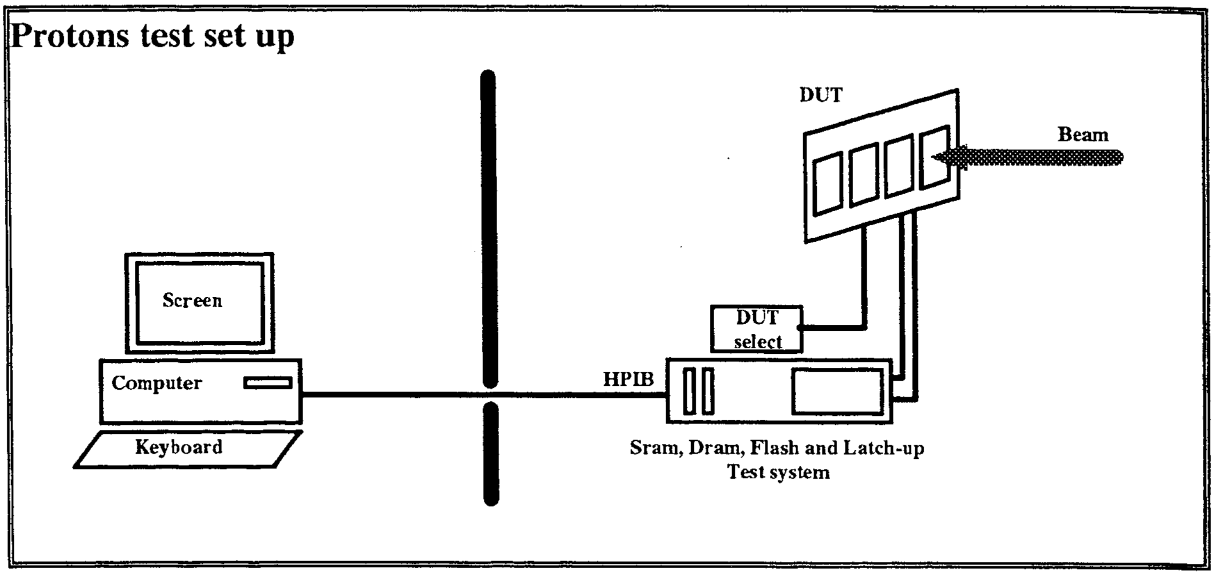
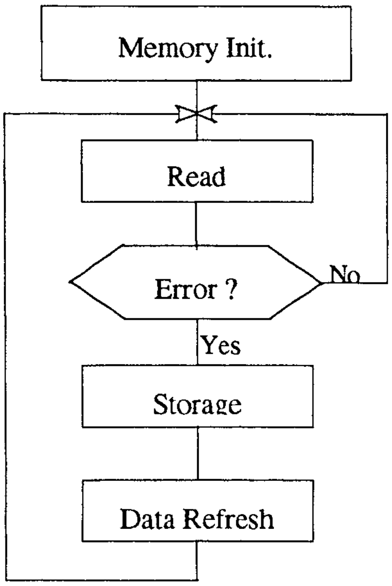


Fig. 2 Description of the proton test set-up

The proton test set-up is the same as the heavy ion test set-up. (see previous page for details). The main difference is that no vacuum chamber is needed for proton tests.

4.2.3. Test sequence



Test sequence flow chart

5. HEAVY ION EXPERIMENTAL RESULTS

5.1. HEAVY ION IRRADIATION TEST SEQUENCE

The heavy ion irradiation test sequence is reported in the following tables. Fluences in column 9 are corrected fluences, according to the tilt (corrected fluences = real fluences x cosθ). The LET=10 is an effective LET which is obtained by using the ^{20}Ne ion at an incidence of 54°. The run number refers to the total irradiation test sequence, including all the memories tested during this campaign.

All the devices were tested with a Cb (checkerboard) pattern during irradiations. Since they were also tested with All to 0, All to 1, and /Cb patterns between runs, it was also checked that they were not sensitive to Single Hard Errors (SHE), up to a LET of 34 MeV.cm²/mg (a SHE is a stuck bit, due to deposited dose in the oxyde of the cell transistors. It is generally detected when testing a device under a pattern and its complementary pattern : the stuck bit remains in its initial configuration).

ICC+ is the consumption current for 4 memories biased together.

Run	Dev.	Vcc/f	LET (Si) [MeV.cm²/mg]	Tilt [°]	Eff. LET (Si) [MeV.cm²/mg]	Flux [p/cm²/s]	Time (s)	Fluence [p/cm²]	ICC+ [mA]
15	SN3	3.3V/fmax	34	0	34	150	173	23575	+22.9
16	SN3	3.3V/fmax	34	0	34	150	71	14297	+22.9
17	SN4	3.3V/fmax	34	0	34	150	125	17502	+23.9
18	SN4	3.3V/fmax	34	0	34	150	158	25096	+23.9
19	SN4	3.3V/(fmax/4)	34	0	34	150	146	15592	+16.1
20	SN4	3.3V/(fmax/4)	34	0	34	150	100	8014	+16.1
21	SN3	3.3V/(fmax/4)	34	0	34	150	158	7801	+15.6
22	SN3	3.3V/(fmax/4)	34	0	34	150	107	9502	+16.1
38	SN5	3.3V/(fmax)	14.1	0	14.1	270	217	58131	+23.9
39	SN4	3.3V/(fmax)	14.1	0	14.1	270	71	21224	+22.9
52	SN5	3.3V/fmax	5.85	0	5.85	410	596	245770	+23.5
53	SN4	3.3V/fmax	5.85	0	5.85	950	381	363820	+23.5
54	SN4	3.3V/fmax	5.85	54	10	1000	180	85060	+23.5
55	SN5	3.3V/fmax	5.85	54	10	1000	236	221441	+23.5

Table 2: Heavy Ion Irradiation Test Sequence

Run	Dev.	Vcc/f	LET (Si) [MeV.cm²/mg]	Tilt [°]	Eff. LET (Si) [MeV.cm²/mg]	Flux [p/cm²/s]	Time (s)	Fluence [p/cm²]	ICC+ [mA]
66	SN5	3.3V/fmax	1.7	0	1.7	10000	103	1.0e+06	~23
67	SN4	3.3V/fmax	1.7	0	1.7	10000	113	1.0e+06	~23
70	SN5	4.5V/fmax	1.7	0	1.7	9000	116	1.0e+06	+35.7
71	SN4	4.5V/fmax	1.7	0	1.7	9000	158	1.5e+06	+35.7
82	SN5	4.5V/fmax	5.85	0	5.85	1000	/	266386	+36.6
83	SN5	4.5V/fmax	5.85	0	5.85	2000	/	497728	+36.6
84	SN4	4.5V/fmax	5.85	0	5.85	2000	/	400000	+36.6
88	SN4	4.5V/fmax	34	0	34	1200	/	**OVL***	+35.7
89	SN4	4.5V/fmax	34	0	34	800	/	**OVL***	~38
90	SN4	4.5V/fmax	34	0	34	250	/	5516	~38
91	SN5	4.5V/fmax	34	0	34	250	/	8546	~35

Table 2 (end) : Heavy Ion Irradiation Test Sequence

* These runs were not taken into account due to overload of the tester FIFO.

5.2. ANALYSIS OF HEAVY ION RESULTS: METHOD

5.2.1. Calculation of SEE cross-sections

The cross-sections were calculated as follows :

$$\sigma(\mathrm{LET}) = \mathrm{N/F}$$

where :

σ is the SEE Cross-section (cm²/device), expressed as a function of the Heavy Ion LET

LET is the Linear Energy Transfer $\left(\frac{1}{\rho}\frac{dE}{dx}\right)$, in MeV.cm²/mg

N is the total Number of SEE

F = Fluence (part./cm²) (corrected according to the incident angle).

The cross section per bit is obtained by dividing the cross section for the device by the total number of bits of the memory.

For multiple error treatment, see detailed explanation in 5.3.3 page 13.

The minimum of fluence required is 1e+6 ions/cm², if no event is detected. By default, a value of 1 for N is used to calculate the cross-section when no event is observed (Cf. statistical treatment).

The LET threshold is defined as the minimum LET value at which no event occurs at a fluence of 10^6 particles/cm².

When multiple upsets are observed during a run due to row or column errors, this errors minus one are substracted from the total number of errors.

5.2.2. Statistical treatment

The confidence limits shown in the following tables represent the values of the cross section between which the true value of cross section lies within a 90% probability.

The calculation of the confidence limits is made on the basis of a Poisson distribution for the events. Note that when large numbers of errors are observed, the statistical errors become insignificant. The assumptions made therefore are :

- only one event possible per incident ion

- small probability of event

For an event number> 600, no confidence limit is calculated.

5.3. HEAVY ION CROSS SECTION MEASUREMENTS

5.3.1. Tables of heavy ion results

Results in tables 3, 4 and 5 are obtained after correction of multiple errors (row or column errors).

Test Sample	Test n°	SEU	Fluence (part/cm^2)	**Effective LET [MeV.cm^2/mg]**	**X-Section [cm^2/bit]**	90% Conf. Limits [cm^2]
SN4	67	0	1.0 e+06	**1.7**	**5.9 e-14**	5.96e-18/1.37e-13
SN5	66	0	1.0 e+06	**1.7**	**5.9 e-14**	5.96e-18/1.37e-13
SN4	53	23	3.6 e+5	**5.85**	**3.8 e-12**	2.60e-12/5.40e-12
SN5	52	46	2.5 e+05	**5.85**	**1.1 e-11**	1.42e-11/8.59e-12
SN5	55	6*	2.2 e+05	**10**	*	*
SN4	54	3*	8.5 e+04	**10**	*	*
SN4	39	783	2.1 e+04	**14.1**	**2.2 e-09**	/
SN5	38	2191	5.8 e+04	**14.1**	**2.2 e-09**	/
SN4	18	1347	2.5 e+04	**34**	**3.2 e-09**	/
SN4	17	850	1.7 e+04	**34**	**2.9 e-09**	/
SN3	16	880	1.4 e+04	**34**	**3.6 e-09**	/
SN3	15	1375	2.4 e+04	**34**	**3.5 e-09**	/

Table 3 : Cross section measurements for Vcc=3.3V (*) : see § 5.3.2.

Test Sample	Test n°	SEU	Fluence (part/cm^2)	**Effective LET [MeV.cm^2/mg]**	**X-Section [cm^2/bit]**	90% Conf. Limits [cm^2]
SN4	71	0	1.5 e+06	**1.7**	**3.9e-14**	5.96e-18/9.15e-14
SN5	70	0	1.0 e+06	**1.7**	**5.9e-14**	5.96e-18/1.37e-13
SN4	84	2	4.0 e+05	**5.85**	**2.9 e-13**	9.38e-13/5.29e-14
SN5	91	465	8.6 e+03	**34**	**3.2 e-09**	3.09e-09/3.50e-09
SN4	90	273	5.5 e+03	**34**	**2.9 e-09**	2.66e-09/3.26e-09

Table 4 : Cross section measurements for Vcc=4.5V

Test Sample	Test n°	SEU	Fluence (part/cm^2)	**Effective LET [MeV.cm^2/mg]**	**X-Section [cm^2/bit]**	90% Conf. Limits [cm^2]
SN4	19	851	1.6 e+04	**34**	**3.2 e-09**	/
SN4	20	451	8.0 e+03	**34**	**3.3 e-09**	3.09e-09/3.62e-09
SN3	22	561	9.5 e+03	**34**	**3.5 e-09**	3.27e-09/3.77e-09

Table 5 : Cross section measurements for Vcc=3.3V, fmax/4

5.3.2. Heavy ion result analysis

The figure 4.a) exhibits the heavy ion induced cross sections for IBM DRAM 16 Mbit Luna ES/3.

A complete characterization was performed at Vcc = 3.3V

Effect of supply voltage (Vcc = 4.5V) was addressed at 1.7, 5.85, and 34 MeV.cm²/mg.

Effect of operating frequency was addressed at a LET value of 34 MeV.cm²/mg.

LET=10 MeV.cm²/mg is an effective value. The small amount of recorded SEU (6 for run 55, and 3 for run 54) at this LET may be due to the vertical geometry of the DRAM sensitive volume (a smaller amount of charge can be collected in the sensitive volume with a tilt. Therefore, the corresponding data are not plotted in Fig.4.a).

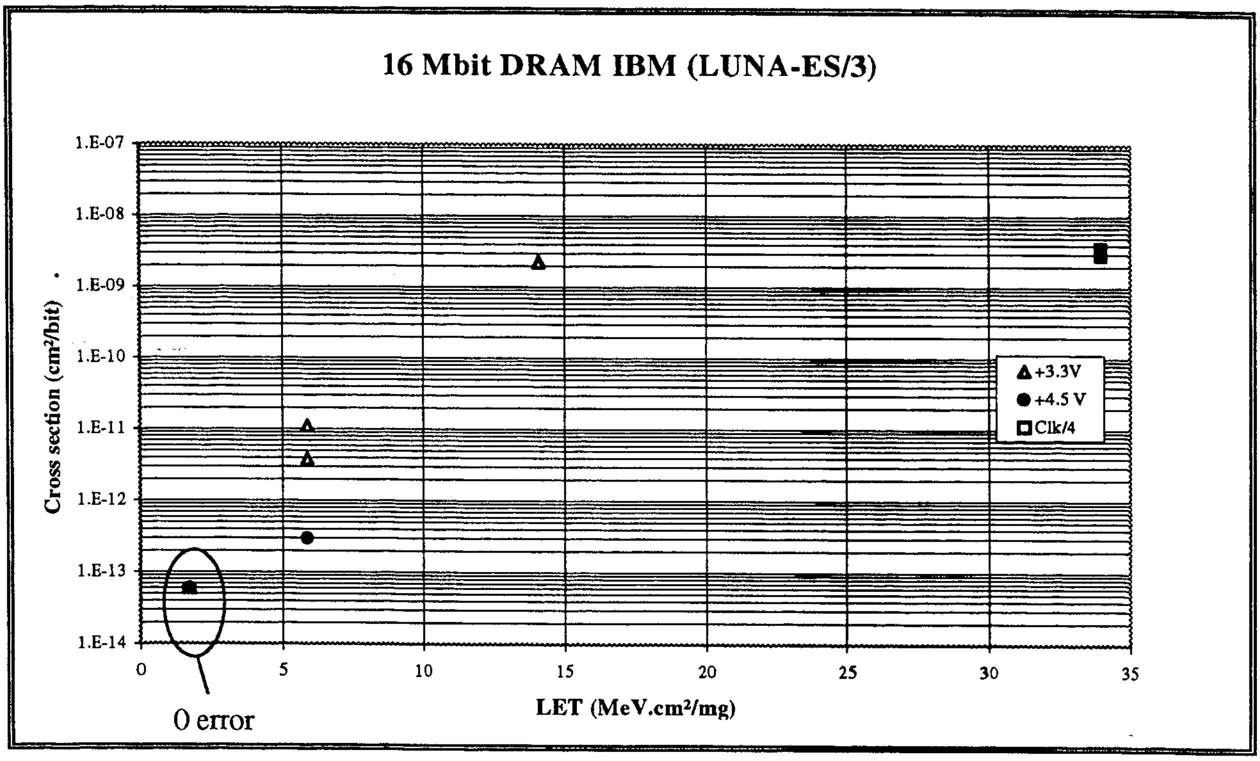


Fig. 4. a) Heavy ion cross section measurements for IBM DRAM 16 Mbit

Effect of supply voltage :

The effect of supply voltage is not very important for this device. At the maximum tested LET (34 MeV.cm²/mg), the cross sections are comparable. The main difference is near the threshold LET region, for which parts biased at 4.5V exhibit a lower sensitivity. Both supply voltage lead to no sensitivity at LET=1.7 MeV.cm²/mg. A stronger effect was expected, since no internal regulator was connected to the memory cells.

Effect of the operating frequency (fmax→fmax/4) :

No operating frequency effect was evidenced at the LET of 34 MeV.cm²/mg (the only tested LET for frequency effect study).

Effect of the initial memory content:

As shown in Annex, the cross section does not vary with the initial content of the memory (0-1, or 1-0 transitions).

Multiple errors :

Multiple errors were observed during heavy ion irradiation. These errors can be classified in row errors, or column errors according to their address. Column errors are generally coupled (i.e col. adress 200 and 201, or 1f4 and 1f5) and contain either 256 or 512 errors. Further analysis showed that the column errors were most of the time located at the same row address range (i.e between row adress b05 and bff, or 301 and 3ff). This is particularly true for runs 38, 52, and 54, which include 8 column errors which could in fact be considered as 1 block error each time. Row errors generally contain 1024 errors. Details on the multiple error results are given in the annex.

Figure 4. b) gives the comparison between block error cross-sections, row errors and SEU cross sections at 3.3V : at high LET, the sensitivity of SEU is several orders of magnitude higher than the multiple error sensitivity, whereas, in the threshold LET region, the difference is less important.

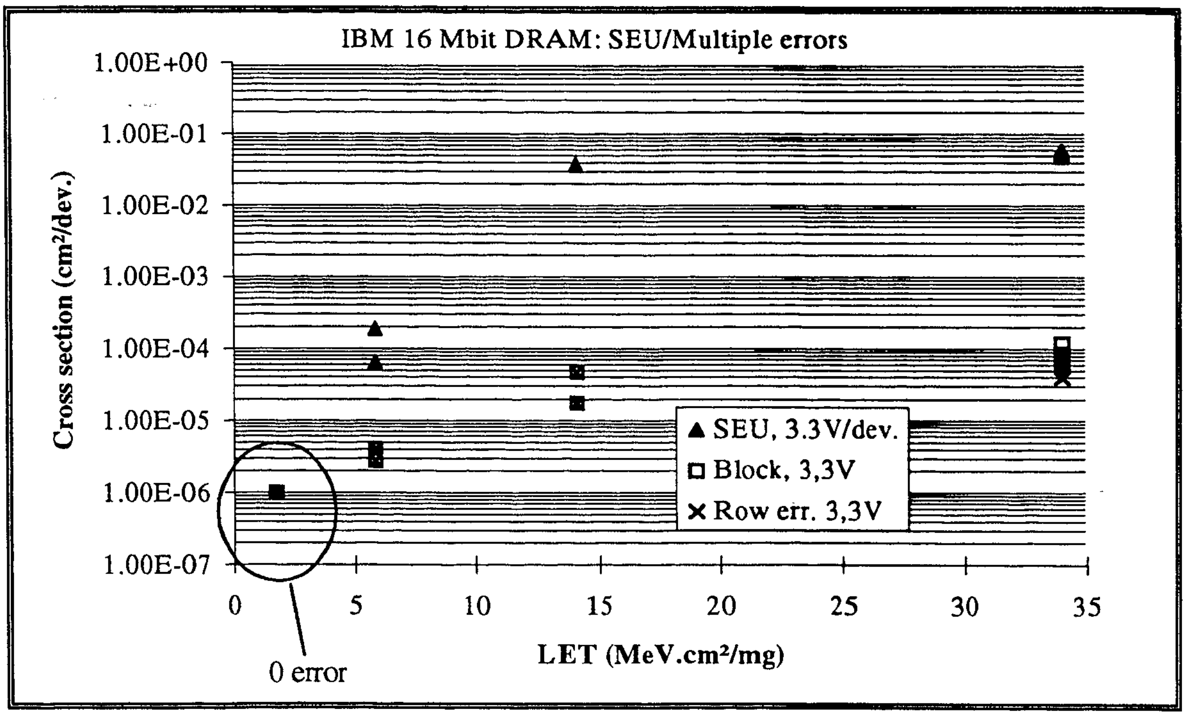


Fig. 4. b) Heavy ion cross section measurements for IBM DRAM 16 Mbit at 3.3V : comparison between multiple error and SEU error cross sections. Results (*) give overestimated value due to very low statistic.

No clear influence of either the Vcc voltage or the test frequency on multiple error rate was observed, due to the low occurrence rate.

5.3.3. Problems encountered/Discussion

Test 53 on SN4 was not correctly recorded by the memory tester, but the number of SEU was read from the front panel of the PC, at the end of the run.

5.4. HEAVY ION TEST CONCLUSIONS

The results of these experiments demonstrate that 16 Mbit DRAM Luna ES/3 from IBM are highly sensitive to heavy ion induced SEU : for parts biased at 3.3V, the cross section at LET=34 MeV.cm²/mg is 4e-9 cm²/bit, and the threshold LET is between 1.7 and 5.85 MeV.cm²/mg. Comparison between 4.5V and 3.3V biased show a comparable saturated cross section, and lower sensitivity (at 4.5V) near the threshold LET. Multiple error sensitivity is also lower at 4.5V : no row error were found in this biasing condition.

Additional heavy ion results:

These devices exhibit no Latch-up sensitivity, up to a LET of 34 MeV.cm²/mg

No effect of frequency (fmax→fmax/4) can be evidenced on heavy ion cross section values at saturation.

The initial memory content does not influence the cross section.

Multiple errors (column and row errors) were observed during the tests. Cross sections are order of magnitude lower than SEU cross-sections.

The devices exhibited no single hard error sensitivity.

6. PROTON EXPERIMENTAL RESULTS

6.1. PROTON IRRADIATION TEST SEQUENCE

The proton irradiation test sequence is given in the following tables.

The run number refers to the total irradiation test sequence, including all the memories tested during this campaign.

ICC+ is the consumption current for 4 memories biased together.

Run	Device	Vcc/f	Energy (p) [MeV]	Flux [p/cm^2/s]	Fluence [p/cm^2]	Depos./cumul. dose (kRad[Si])	ICC+ [mA]
20	SN1	4.5V/fmax	60	9.26e+07	1e+10	1.5/1.5	37
21	SN2	4.5V/fmax	60	8.47e+07	1e+10	1.5/1.5	37
22	SN1	4.5V/fmax	40	9.01e+07	1e+10	2/3.5	36
23	SN3	4.5V/fmax	40	9.35e+07	1e+10	2/2	36
24	SN3	4.5V/fmax	60	9.17e+07	1e+10	1.5/3.5	36
48	SN1	3.3V/fmax	60	1.0e+08	1e+10	1.5/5	23
49	SN3	3.3V/fmax	60	1.19e+08	1e+10	1.5/5	23
50	SN2	3.3V/(fmax)	40	9.62e+07	1e+10	2/3.5	23
51	SN1	3.3V/(fmax)	40	9.62e+07	1e+10	2/7	23
56	SN1	3.3V/(fmax)	20	1.15e+08	1e+10	3.5/10.5	22.5
57	SN2	3.3V/(fmax)	20	1.11e+08	1e+10	3.5/7	22.5
58	SN3	3.3V/(fmax/4)	60	1.05e+08	1e+10	1.5/6.5	22.5
59	SN1	3.3V/(fmax/4)	60	1.05e+08	1e+10	1.5/8.5	22.5
64	SN1	3.3V/fmax/65°C	60	1.19e+08	1e+10	1.5/10	/
65	SN3	3.3V/fmax/65°C	60	1.23e+08	1e+10	1.5/8	/

Table 6: Proton Irradiation Test Sequence

6.2. ANALYSIS OF PROTON RESULTS : METHOD

6.2.1. Calculation of SEP cross-sections

The cross-sections were calculated as follows :

$$\sigma(Ep) = N/F$$

where :

σ is the SEP Cross-section (cm^2/device), expressed as a function of the Proton Energy

N is the total Number of SEP

F = Fluence (part./cm^2) (corrected according to the incident angle).

The cross section per bit is obtained by dividing the cross section for the device by the total number of bits of the memory.

The fluence is set at 1e+10 p/cm^2 for all the runs. By default, a value of 1 for N is used to calculate the cross-section when no event is observed (Cf. statistical treatment).

6.2.2. Statistical treatment

The confidence limits shown in the following tables represent the values of the cross section between which the true value of cross section lies within a 90% probability.

The calculation of the confidence limits is made on the basis of a Poisson distribution for the events. Note that when large numbers of errors are observed, the statistical errors become insignificant. The assumptions made therefore are :

- only one event possible per incident proton
- small probability of events

For an error rate > 600, no confidence limit is calculated

6.3. PROTON CROSS SECTION MEASUREMENTS

6.3.1. Tables of proton results

Test Sample	Test n°	SEU	Fluence (part/cm²)	**P. Energy [MeV]**	**X-Section [cm²/bit]**	90% Conf. Limits [cm²]
SN1	48	37	1.0 e+10	**60**	**2.2 e-16**	1.64e-16/2.90e-16
SN3	49	25	1.0 e+10	**60**	**1.5 e-16**	1.03e-16/2.09e-16
SN3	50	17	1.0 e+10	**40**	**1.0 e-16**	6.45e-17/1.52e-16
SN1	51	14	1.0 e+10	**40**	**8.3 e-17**	5.04e-17/1.30e-16
SN1	56	0	1.0 e+10	**20**	**6.0 e-18**	5.96e-17/1.37e-17
SN3	57	1	1.0 e+10	**20**	**6.0 e-18**	3.05e-19/2.82e-17

Table 7 : Cross section measurements for Vcc=3.3V, Fmax, T=25°C

Test Sample	Test n°	SEU	Fluence (part/cm²)	**P. Energy [MeV]**	**X-Section [cm²/bit]**	90% Conf. Limits [cm²]
SN1	20	8	1.0 e+10	**60**	**4.8 e-17**	2.37e-17/8.60e-17
SN2	21	2	1.0 e+10	**60**	**1.2 e-17**	2.12e-18/3.75e-17
SN3	22	2	1.0 e+10	**40**	**1.2 e-17**	2.12e-18/3.75e-17
SN3	23	0	1.0 e+10	**40**	**6.0 e-18**	5.96e-18/1.37e-17

Table 8 : Cross section measurements for Vcc=4.5V, Fmax, T=25°C

Test Sample	Test n°	SEU	Fluence (part/cm²)	**P. Energy [MeV]**	**X-Section [cm²/bit]**	90% Conf. Limits [cm²]
SN3	58	25	1.0 e+10	**60**	**1.5 e-16**	1.035e-16/2.08e-16
SN1	59	38	1.0 e+10	**60**	**2.26 e-16**	1.69e-16/2.96e-16

Table 9 : Cross section measurements for Vcc=3.3V, Fmax/4, T=25°C

Test Sample	Test n°	SEU	Fluence (part/cm²)	**P. Energy [MeV]**	**X-Section [cm²/bit]**	90% Conf. Limits [cm²]
SN1	64	17	1.0 e+10	**60**	**1.3 e-16**	6.45e-17/1.52e-16
SN3	65	26	1.0 e+10	**60**	**1.6 e-16**	1.08e-16/2.15e-16

Table 10 : Cross section measurements for Vcc=3.3V, Fmax, T=65°C

6.3.2. Proton result analysis

The figure 5 exhibits the proton induced cross sections for IBM DRAM 16 Mbit Luna ES/3.

A complete characterization was performed at Vcc = 3.3V, considering the proton energies : 20, 40, 60 MeV

Effect of supply voltage (Vcc = 4.5V) was studied at a 60 MeV proton energy.

Effect of operating temperature was studied at 60 MeV.

The cross section per bit is obtained by dividing the cross section for the device by the total number of bits of the memory.

All the results given above represent a mean value obtained by dividing the total number of errors divided by the total number of bits of the memory.

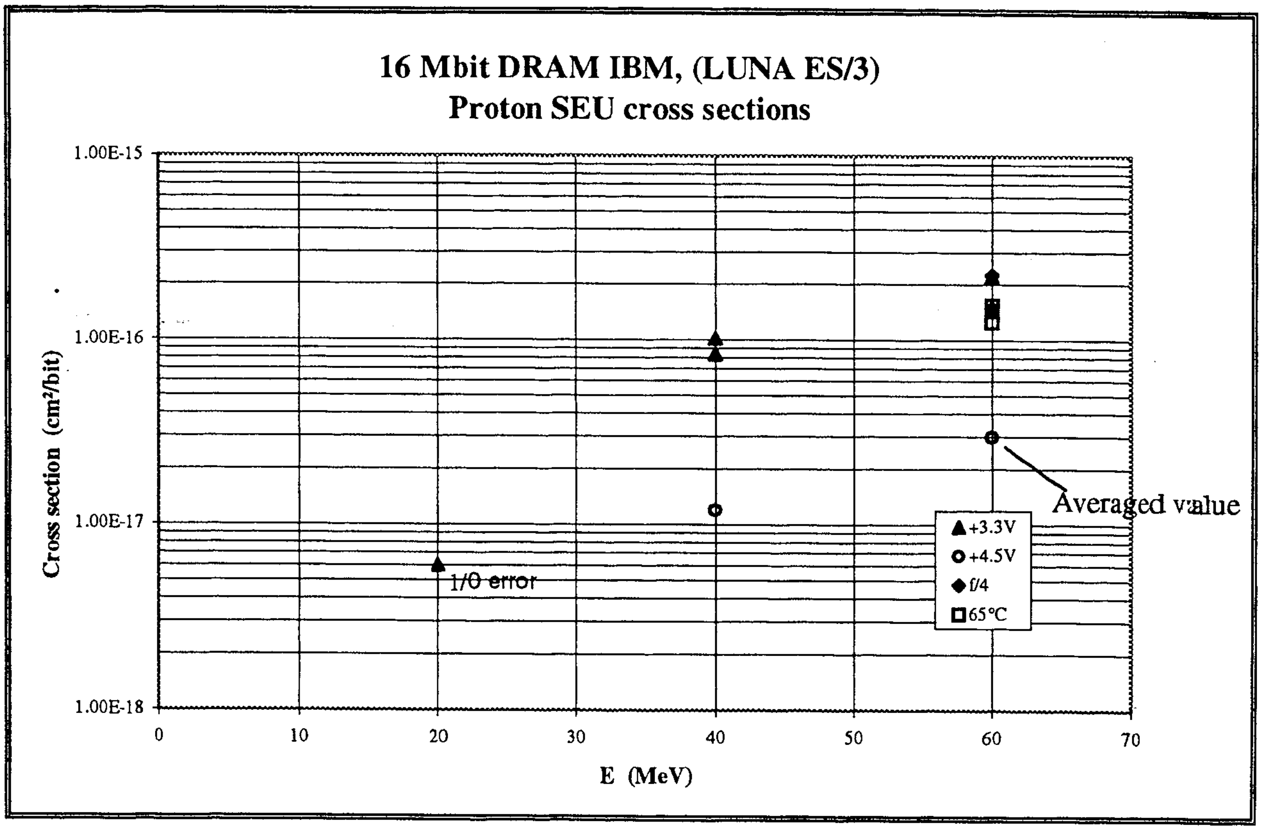


Fig. 5 Proton cross section measurements for IBM 16 Mbit DRAM

Effect of supply voltage :

When the devices are biased at 4.5V the SEU sensitivity is lowered : the average saturated cross-section is divided by a factor of 6 and the proton energy threshold is higher.

Effect of the operating frequency (fmax→fmax/4) :

No specific effect was evidenced at the proton energy of 60 MeV.

Effect of the operating temperature (T room →T 65°C) :

No specific effect was evidenced at the proton energy of 60 MeV.

Effect of memory content

As shown in Annex 2, the sensitivity is higher for an initial content of 1 and the energy threshold is lower.

Multiple errors

No multiple errors (row or column) were found during the proton irradiations

6.3.3. Problems encountered/Discussion

No specific problem was encountered during irradiations.

6.4. PROTON TEST CONCLUSIONS

The results of these experiments demonstrate that 16 Mbit DRAM LUNA-ES/3 from IBM, biased at 3.3V, are sensitive to proton induced SEU. The cross section, at the maximum proton energy of 60 MeV, is approximately 2.5e-16 cm²/bit. When biased at Vcc=4.5V, these devices exhibit a lower sensitivity to proton induced SEU : cross section are reduced by a factor from 5 to 10, and the threshold Ep is between 20 and 40 MeV.

Additional proton results:

These devices exhibit no Latch-up sensitivity, up to a proton energy of 60 MeV

No effect of frequency (fmax→fmax/4) can be evidenced on proton cross section values at saturation.

No effect of temperature (T room→T 65°C) can be evidenced on proton cross section values at saturation. The 1 initial memory content is more sensitive than 0.

These device exhibited no proton single hard error sensitivity.

No multiple errors (row or column errors) were recorded during the proton irradiations. Other multiple error types could not be identified in absence of a bit map.

7. CONCLUSION

Heavy ion and proton characterizations were performed on IBM 16 Mbit DRAM Luna-ES/3, at 3.3V. Additional runs at 4.5V and at a lower operating frequency were studied. Results are summarized in the following tables.

A comparison with SEE results on other IBM 16 Mbit LUNA-E/C DRAMs shows that the sensitivity of this version is consistent with previous results, summed up in paragraph 3.1.5 [7,8] for ions and [10] for protons.

	LET Threshold (MeV.cm²/mg)	Cross-section (cm²/dev.) at LET=34 MeV.cm²/mg	Cross-section (cm²/bit) at LET=34 MeV.cm²/mg
Vcc=3.3V	1.7<LETth<5.85	6.2e-2	3.7e-9
Vcc=4.5V	≈5.85	5.3e-2	3e-9

Summary of SEU heavy ion results

	LET Threshold (MeV.cm²/mg)	Saturation Cross-section (cm²/dev.)
Vcc=3.3V	5.85<LETth<10 (block, row)	<2e-4 (block, row)
Vcc=4.5V	5.85 (block), >34 (row)	not evaluated

Summary of multiple error heavy ion results

	Proton Energy Threshold (MeV)	Saturated Cross-section (cm²/bit)
Vcc=3.3V	<20	≈2.5e-16
Vcc=4.5V	20<Ep<40	≈5e-17

Summary of proton results

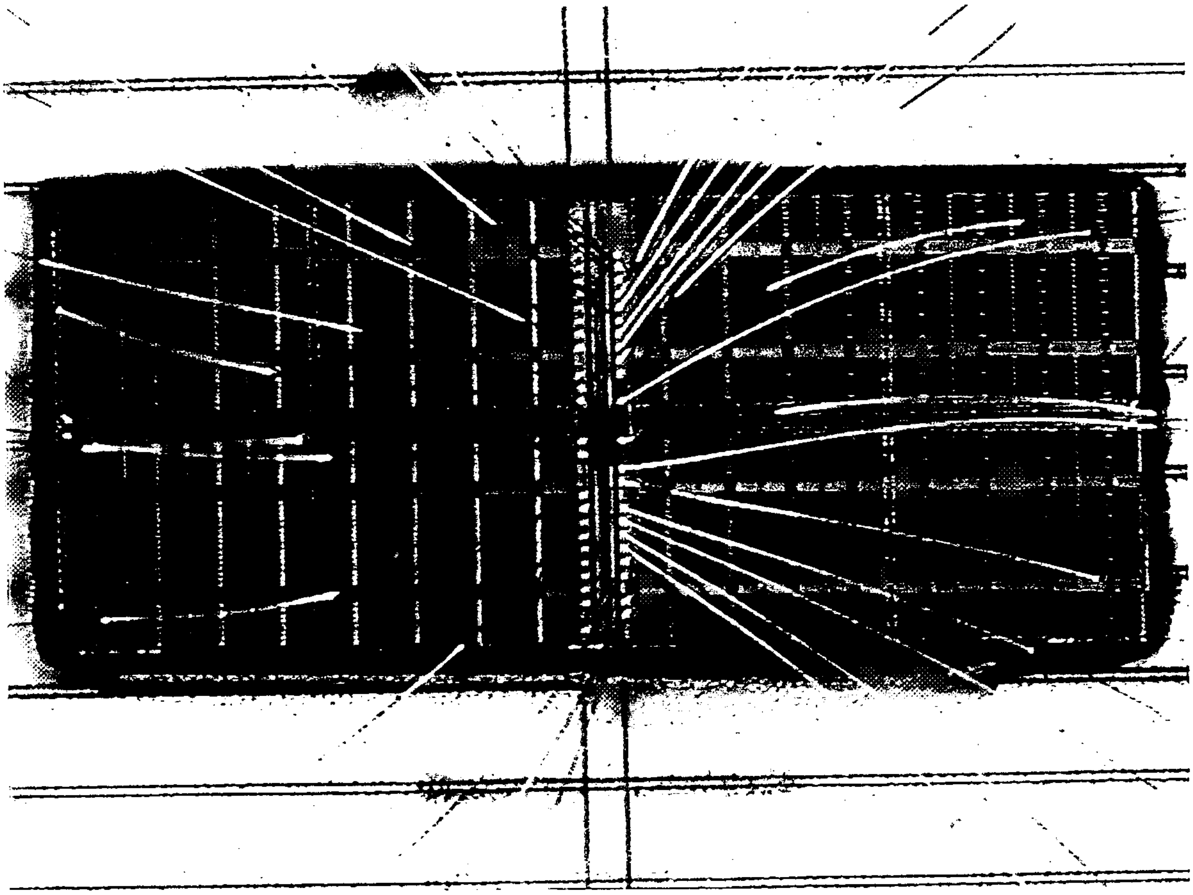
Analysis of the results shows that :

- No effect of operating frequency was evidenced on the heavy ion and proton cross section measurements.

- Increasing supply voltage from 3.3V to 4.5V does not decrease strongly the device SEU susceptibility for heavy ion irradiation. On the contrary, the effect of supply voltage on cross sections is significant for proton irradiation and multiple errors.
- The initial memory content does not affect the device susceptibility for heavy ion irradiation, but 1 content is more sensitive than 0 content for proton irradiation.
- Multiple errors (rows columns and block errors) are observed with heavy ion irradiation but not with proton irradiation. Cross sections are several order of magnitude lower than SEU cross-sections.
- These devices are not sensitive to heavy ion and proton induced LU.

8. ANNEX

8.1. DIE PHOTOGRAPHY



Photography of the die marking

8.2. DETAILS OF RESULT ANALYSIS

Row Errors

The following tables give the number of row errors observed during the different heavy ions tests.

A maximum of 2 row errors per test were observed at LET=10 MeV.cm²/mg or greater for Vcc=3.3V.

For a higher applied bias Vcc-4.5V, no row errors were observed.

IBM		**Vcc=3.3V**				
RUN	**SN**	**Row Err.**	**Size (bits)**	**Fluence (part/cm²)**	**LET (MeV.cm²/mg)**	**Cross. Sec. (cm²/device)**
15	3	3	16777216	23575	34	1.27E-04
16	3	0	16777216	14297	34	<6.99E-05
17	4	1	16777216	17502	34	5.71E-05
18	4	1	16777216	25096	34	3.98E-05
38	5	0	16777216	58131	14.1	<1.72E-05
39	4	0	16777216	21224	14.1	<4.71E-05
54	4	0	16777216	85060	10	*
55	5	2	16777216	221442	10	*
52	5	0	16777216	245770	5.85	<4.06E-06
53	4	*	16777216	363820	5.85	<2.74E-06
66	5	0	16777216	1000000	1.7	<1.00E-06
67	4	0	16777216	1000000	1.7	<1.00E-06

Table a-1 Row errors at Vcc=3.3V (*see § 5.3.3)

IBM		**Vcc=4.5V**				
RUN	**SN**	**Row Err.**	**Size (bits)**	**Fluence (part/cm²)**	**LET (MeV.cm²/mg)**	**Cross. Sec. (cm²/device)**
90	4	0	16777216	5520	34	<1.81E-04
91	5	0	16777216	8550	34	<1.17E-04
84	4	0	16777216	400000	5.85	<2.5E-06
70	5	0	16777216	1000000	1.7	<1E-06
71	4	0	16777216	1500000	1.7	<6E-07

Table a-2 Row errors at Vcc=4.5V

IBM	**3.3V**	**fmax/4**				
RUN	**SN**	**Row Err.**	**Size (bits)**	**Fluence (part/cm²)**	**LET (MeV.cm²/mg)**	**Cross. Sec. (cm²/device)**
19	4	1	16777216	15592	34	6.41E-05
20	4	0	16777216	8014	34	< 1.25E-04
22	3	0	16777216	9502	34	< 1.05E-04

Table a-3 Row errors at Vcc=3.3V, f/4

Column/Block Errors:

IBM						
RUN	**SN**	**Block Err.**	**Size**	**Fluence**	**LET**	**Cross. Sec. (cm^2/device)**
15	3	3	16777216	23575	34	1,27E-04
16	3	0	16777216	14297	34	<6,99E-05
17	4	2	16777216	17502	34	1,14E-04
18	4	3	16777216	25096	34	3,98E-04
38	5	1	16777216	58131	14,1	1,72E-05
39	4	0	16777216	21224	14,1	<4,71E-05
54	4	1	16777216	85060	10	*
55	5	0	16777216	221442	10	*
52	5	1**	16777216	245770	5,85	<4,07E-06
53	4	0	16777216	363820	5,85	<2,75E-06
66	5	0	16777216	1000000	1,7	<1,00E-06
67	4	0	16777216	1000000	1,7	<1,00E-06

Table a-4 Column/Block error sensitivity at Vcc=3.3V (* see § 5.3.2)

**** not recorded**

IBM		Vcc=4.5V				
RUN	SN	Block. Err.	Size (bits)	Fluence (part/cm^2)	LET (MeV.cm^2/mg)	Cross. Sec. (cm^2/device)
90	4	0	16777216	5520	34	< 1.81E-04
91	5	0	16777216	8550	34	< 1.16E-04
84	4	4	16777216	400000	5.85	1.00E-05
70	5	0	16777216	1000000	1.7	< 1E-06
71	4	0	16777216	1500000	1.7	< 6E-07

Table a-5 Column/Block error sensitivity at Vcc=4.5V

IBM		f/4				
RUN	SN	Col. Err.	Size (bits)	Fluence (part/cm^2)	LET (MeV.cm^2/mg)	Cross. Sec. (cm^2/device)
19	4	2	16777216	15592	34	1.3E-04
20	4	1	16777216	8014	34	1.2E-04
22	3	1	16777216	9502	34	1.1E-04

Table a-6 Column/Block error sensitivity at Vcc=3.3V, f/4

Proton additional test results

The following tables exhibit the IBM 16 Mbit DRAM proton sensitivity in details, separating the 1 → 0 from the 0 → 1 transition results, and comparing with the "total" results. These tables show that the sensitivity of the device is dependent on the bit transition type. Figures a-3 and a-4 also exhibit these results.

IBM		Vcc=3.3V								
RUN	**SN**	**Upsets**			**Size**	**Fluence**	**E**	**Cross. Section**		**(cm^2/bit)**
		0	**1**	**Total**	**(bits)**	**(p/cm^2)**	**(MeV)**	**0**	**1**	**Total**
48	1	10	27	37	16777216	1.00E+10	60	1.19E-16	3.22E-16	2.21E-16
49	3	7	18	25	16777216	1.00E+10	60	8.34E-17	2.15E-16	1.49E-16
50	3			17	16777216	1.00E+10	40			1.01E-16
51	1	1	13	14	16777216	1.00E+10	40	1.19E-17	1.55E-16	8.34E-17
56	1	0	0	0	16777216	1.00E+10	20	6.00E-18	6.00E-18	6.00E-18
57	3	0	1	1	16777216	1.00E+10	20	6.00E-18	1.19E-17	5.96E-18

Table a-10 Separation of 1 → 0 from the 0 → 1 transitions,
and comparison with total error results, at Vcc=3.3V

IBM		Vcc=4.5V								
RUN	**SN**	**Upsets**			**Bits**	**Fluence**	**E**	**Cross. Section**		**(cm^2/bit)**
		0	**1**	**Total**	**(bits)**	**(p/cm^2)**	**(MeV)**	**0**	**1**	**Total**
20	1	1	7	8	16777216	1.00E+10	60	1.19E-17	8.34E-17	4.77E-17
21	2	0	2	2	16777216	1.00E+10	60	6.00E-18	2.38E-17	1.19E-17
24	3	0	0	0	16777216	1.00E+10	60			
22	3	0	0	2	16777216	1.00E+10	40	6.00E-18	6.00E-18	1.19E-17
23	3	0	0	0	16777216	1.00E+10	40	6.00E-18	6.00E-18	6.00E-18

Table a-11 Separation of 1 → 0 from the 0 → 1 transitions,
and comparison with total error results, at Vcc=4.5V

IBM		**Vcc=3.3V**		**f/4**						
RUN	**SN**	**Upsets**			**Bits**	**Fluence**	**E**	**Cross. Section**		**(cm^2/bit)**
		0	**1**	**Total**	**(bits)**	**(p/cm^2)**	**(MeV)**	**0**	**1**	**Total**
58	3	11	14	25	16777216	1.00E+10	60	1.31E-16	1.67E-16	1.49E-16
59	1	12	26	38	16777216	1.00E+10	60	1.43E-16	3.10E-16	2.26E-16

Table a-13 Separation of 1 → 0 from the 0 → 1 transitions, and comparison with total error results, at Vcc=3.3V, f/4

IBM		**Vcc=3.3V**		**t=65°C**						
RUN	**SN**	**Upsets**			**Size**	**Fluence**	**E**	**Cross. Section**		**(cm^2/bit)**
		0	**1**	**Total**	**(bits)**	**(p/cm^2)**	**(MeV)**	**0**	**1**	**Total**
64	1	4	17	21	16777216	1.00E+10	60	4.77E-17	2.03E-16	1.25E-16
65	3	4	22	26	16777216	1.00E+10	60	4.77E-17	2.62E-16	1.55E-16

Table a-14 Separation of 1 → 0 from the 0 → 1 transitions, and comparison with total error results, at Vcc=3.3V, t=65°C

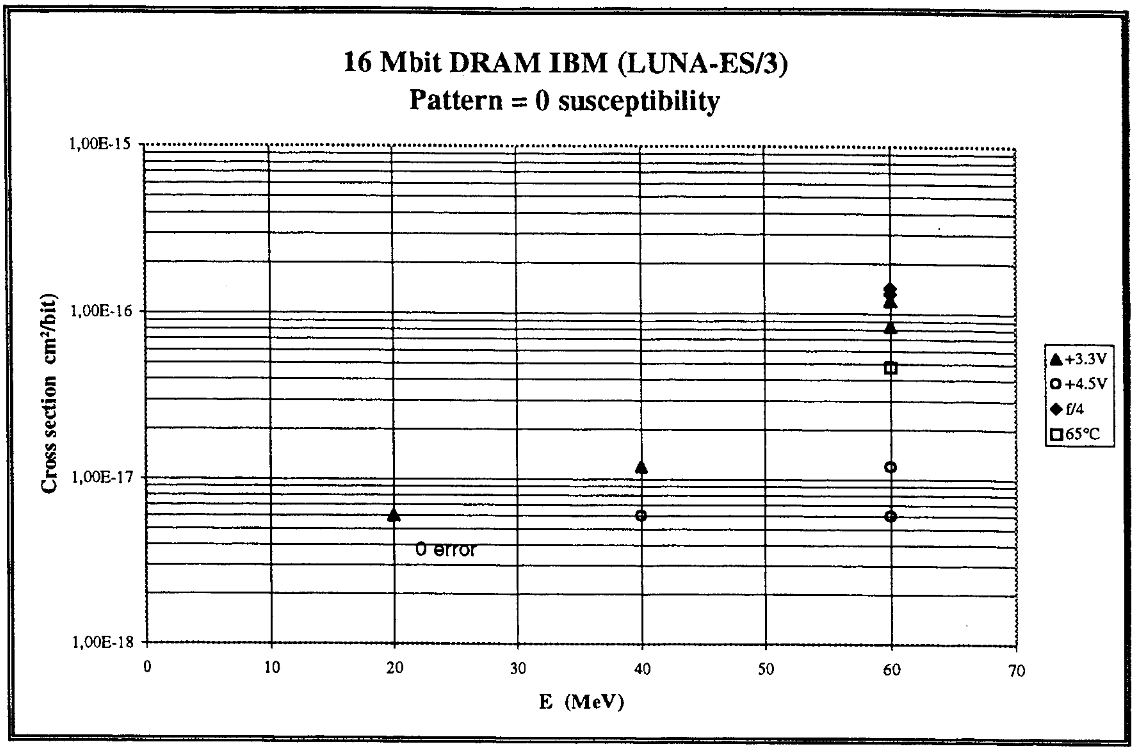


Fig. a-3 Proton SEU Cross section measurements for 1→0 transitions

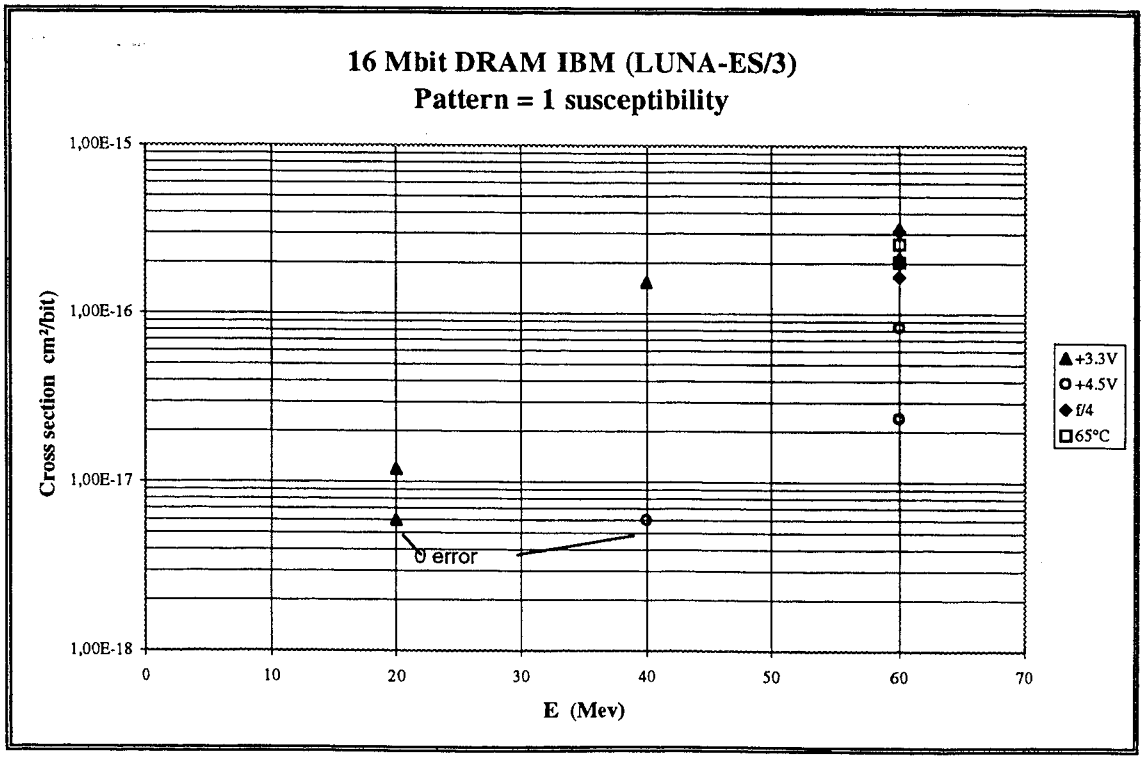


Fig. a-4 Proton SEU Cross section measurements for 1→0 transitions