Radiation Hard Memory

Radiation testing of candidate memory devices for Laplace mission

ESTEC Contract No.: 4000101358/10/NL/AF

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CNES/ESA Radiation Effects Final Presentation Days
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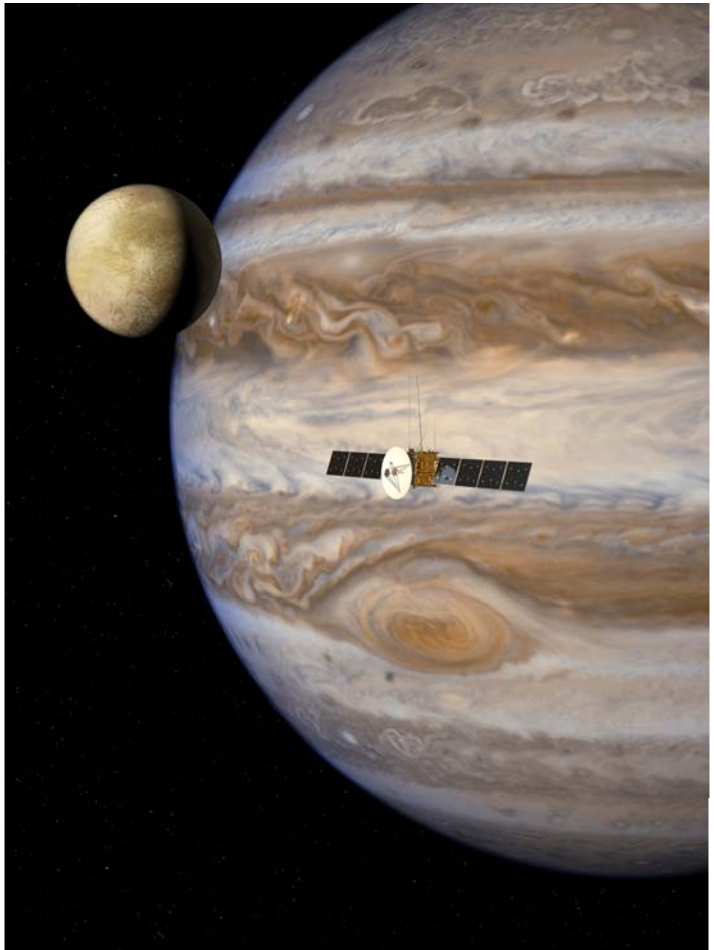
Context

Context
RHM Overview

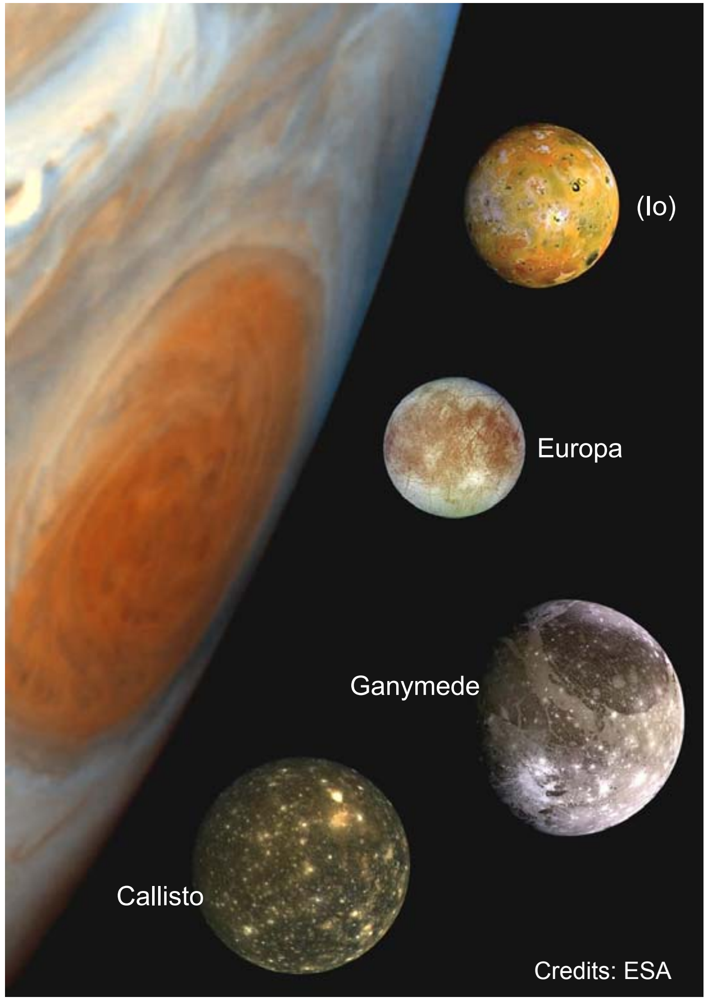
- Radiation test program for commercial DRAM and NV memories for application in harsh radiation environment (EJSM Laplace / JUICE mission), focus on TID behaviour and severe SEE (SEFI, destructive failure, etc.)
- Collaboration between Airbus DS GmbH (former Astrium GmbH) as prime and IDA (Institut für Datentechnik und Kommunikationsnetze), TU Braunschweig
- Technical Officer (ESA): Véronique Ferlet-Cavrois
- ESTEC Contract No.: 4000101358/10/NL/AF


JUICE. Credits: ESA/AOES

Context

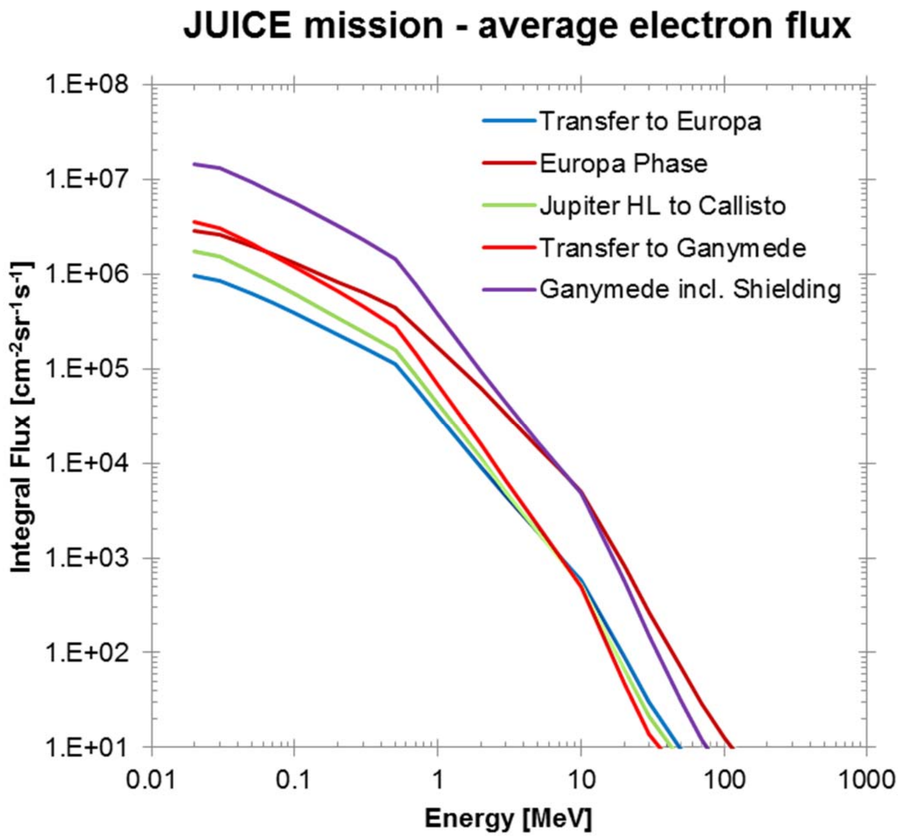
EJSM Laplace / JUICE Mission

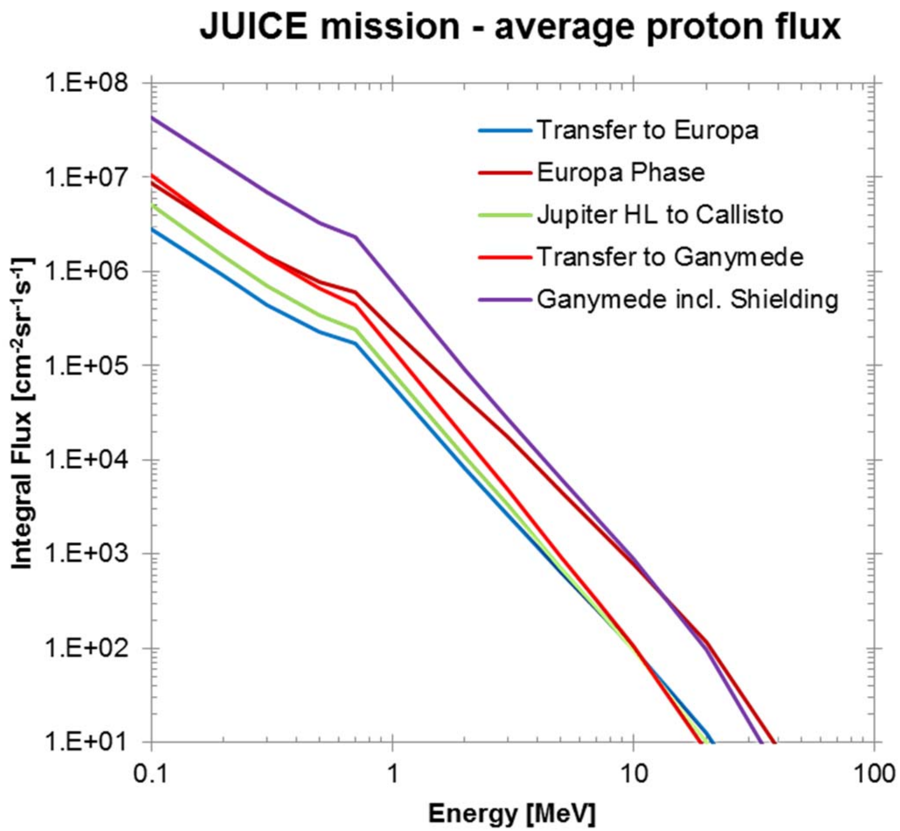
- ESA's Cosmic Vision 2015-2025 plan
- 2012: Selection of JUICE (Jupiter Icy Moon Explorer) for L1 launch slot of ESA Cosmic Vision science programme
  - Launch planned for 2022 with Ariane 5
  - Mission until > 2033 (>4000 days)
  - 7.5 years cruise towards Jupiter
  - Jupiter orbit insertion in 01/2030
  - Tour in the Jupiter system including several flybys of Callisto and two flybys of Europa
  - Callisto gravity assist sequence to raise orbit inclination to observe Jupiter polar regions and to transfer to Ganymede
  - Polar orbit insertion around Ganymede in 9/2032



Context

JUICE Radiation Environment – Trapped Particles





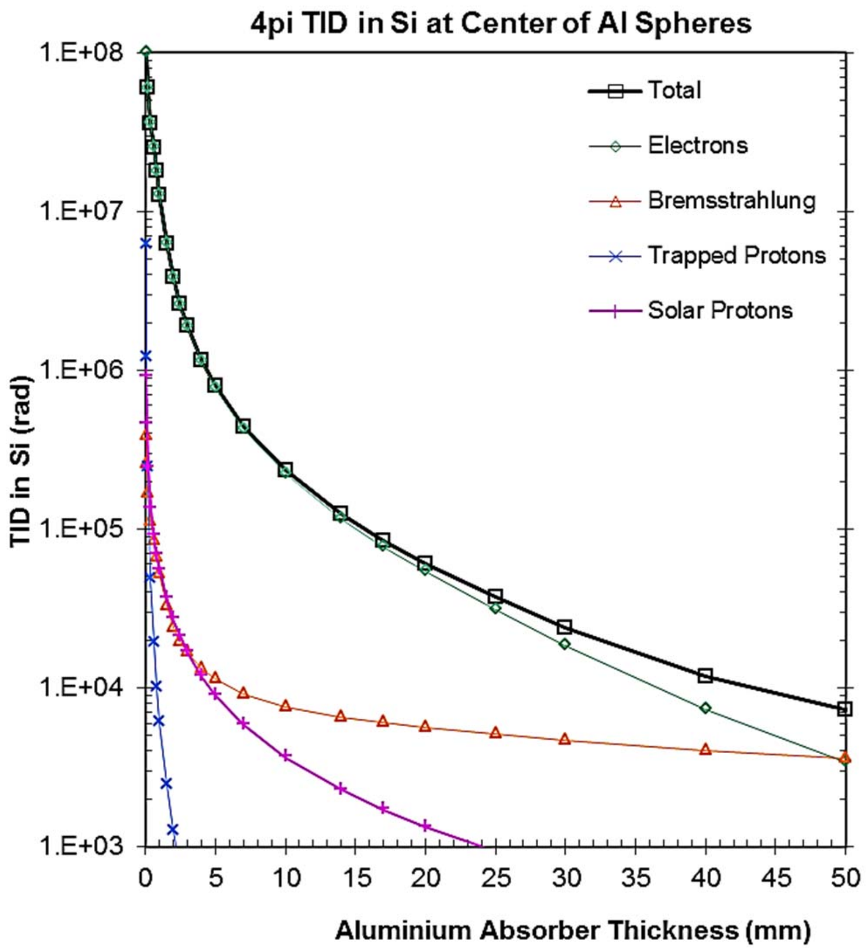
Very high fluxes and high energies of electrons.

Very high fluxes of lower energy protons, low fluxes of higher energy protons.

Context

JUICE Radiation Environment - TID

Shielding Thickness [mm]	Total ionising dose in Si for Spherical Al Shielding [rad] Total	Electrons	Brems-strahlung	Trapped Protons	Solar Protons
0.05	1.75E+08	1.67E+08	3.90E+05	6.15E+06	9.14E+05
0.1	1.02E+08	1.00E+08	2.56E+05	1.21E+06	4.60E+05
0.2	6.03E+07	5.96E+07	1.68E+05	2.43E+05	2.45E+05
0.4	3.60E+07	3.57E+07	1.12E+05	4.87E+04	1.35E+05
0.6	2.53E+07	2.51E+07	8.53E+04	1.93E+04	9.11E+04
0.8	1.81E+07	1.79E+07	6.63E+04	1.00E+04	6.88E+04
1	1.28E+07	1.28E+07	5.21E+04	6.04E+03	5.54E+04
1.5	6.33E+06	6.25E+06	3.27E+04	2.44E+03	3.69E+04
2	3.84E+06	3.78E+06	2.41E+04	1.25E+03	2.72E+04
2.5	2.63E+06	2.58E+06	1.96E+04	7.59E+02	2.11E+04
3	1.92E+06	1.88E+06	1.67E+04	5.04E+02	1.69E+04
4	1.17E+06	1.14E+06	1.32E+04	2.62E+02	1.19E+04
5	7.96E+05	7.75E+05	1.13E+04	1.59E+02	9.02E+03
7	4.44E+05	4.28E+05	9.19E+03	7.50E+01	5.85E+03
10	2.35E+05	2.23E+05	7.62E+03	3.39E+01	3.65E+03
14	1.25E+05	1.16E+05	6.52E+03	1.58E+01	2.28E+03
17	8.50E+04	7.73E+04	6.02E+03	1.03E+01	1.71E+03
20	6.06E+04	5.37E+04	5.64E+03	7.12E+00	1.33E+03
25	3.71E+04	3.10E+04	5.14E+03	4.33E+00	9.44E+02
30	2.41E+04	1.86E+04	4.71E+03	2.88E+00	7.05E+02
40	1.18E+04	7.35E+03	4.05E+03	1.50E+00	4.37E+02
50	7.29E+03	3.41E+03	3.57E+03	9.10E-01	3.03E+02
60	5.32E+03	1.88E+03	3.22E+03	6.03E-01	2.22E+02
80	3.62E+03	8.06E+02	2.68E+03	3.13E-01	1.33E+02
100	2.64E+03	4.30E+02	2.14E+03	1.86E-01	8.78E+01



Context

JUICE Radiation Environment - TID

TID Mission Profile:

Phase	Duration [days]	1mm [krad]	2mm [krad]	4mm [krad]	7mm [krad]	10mm [krad]	14mm [krad]	20mm [krad]	40mm [krad]
Cruise	2711	55	27	12	6	4	2	1	-
To Europa	458	1040	338	113	46	25	14	7	2
Europa Phase	38	383	160	65	29	17	10	5	1
Jupiter HL to Callisto	248	767	236	72	26	14	7	3	1
To Ganymede	311	1660	465	127	41	20	10	4	1
Ganymede science	318	8957	2613	782	296	156	82	39	7
Total	4084	12863	3839	1171	443	234	125	61	12
1 Europa Flyby	14	189	78	32	14	8	5	2	1

TID Level of interest: > 400 krad

Parts Selection

Parts Selection

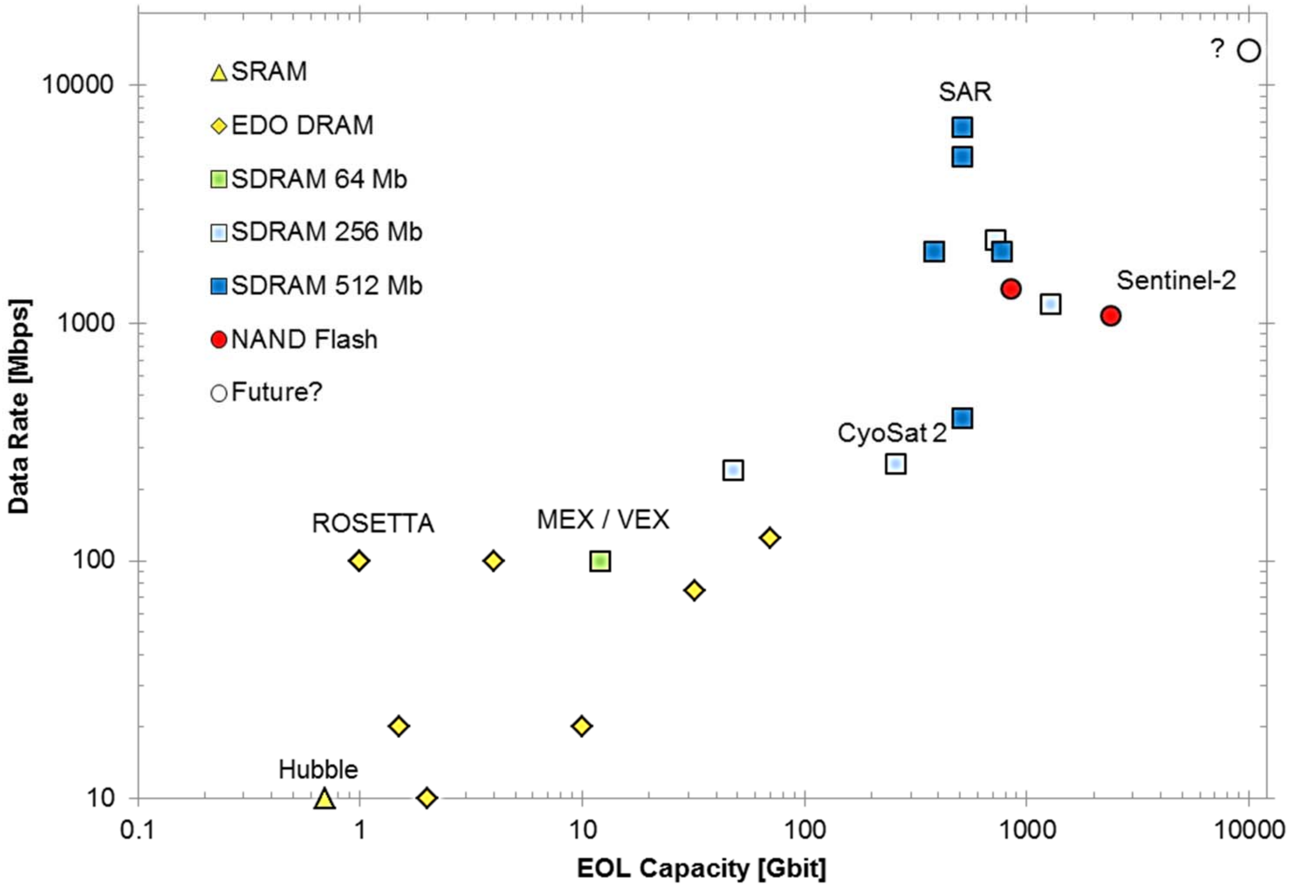
Selection Criteria - Radiation

- Radiation performance – to be investigated
  - TID: level of interest > 400 krad, minimum >> 50 krad
  - SEL LET threshold > 60 $MeV \cdot cm^2 \cdot mg^{-1}$
  - Good SEFI behaviour

Parts Selection

Selection Criteria - Mission Demands (SSR/SSMM)

- **Exponential increase of demands on storage size & data rate**
  - **→ 10 Tbit**
  - **→ 14 Gbps**
- **SDRAM (8 x 512 Mb) "State-of-the-art" but storage size limited to < 2 Tb**
- **First flight heritage with NAND Flash**



Parts Selection
Selection Criteria - Performance

- Radiation performance – to be investigated
  - TID: level of interest > 400 krad, minimum >> 50 krad
  - SEL LET threshold > 60 MeV·cm^2·mg^{-1}
  - Good SEFI behaviour
- Density ≥ 4 Gb (MCM of 8 x 512 Mb “state-of-the-art”)
- High speed, low power
- Easy I/F

Parts Selection

DRAM

- Computing DRAM
  - PM, EDO DRAM
  - SDR SDRAM (“state-of-the-art”)
  - DDR, DDR2, DDR3, DDR4 SDRAM
- Mobile DRAM
- Graphic DRAM

Non-volatile Memory

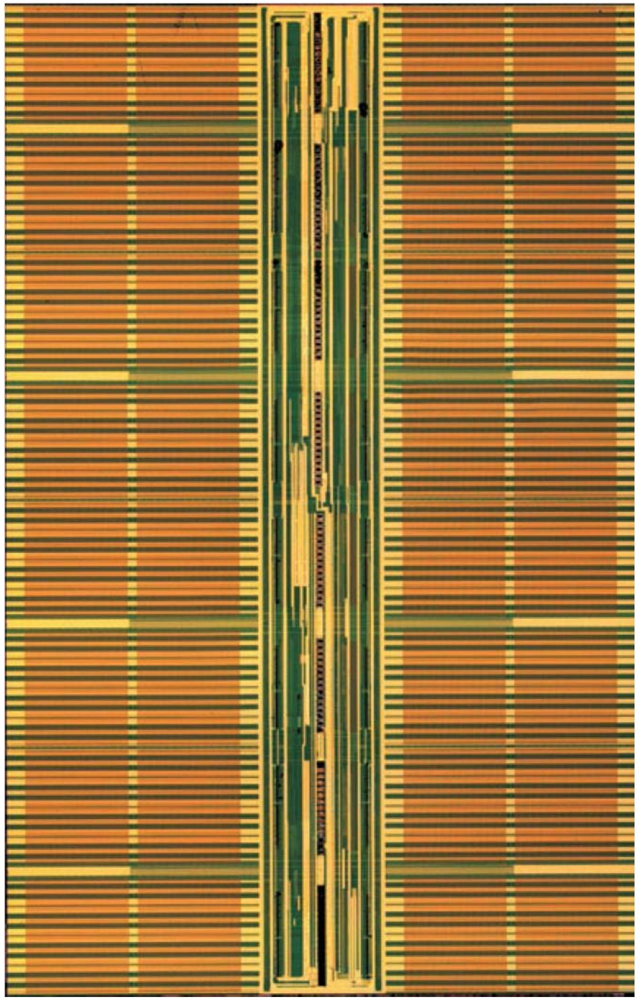
- Flash
  - NOR (1 bit, 2 bits)
  - NAND (SLC, MLC, TLC, 3-D)
- MRAM
  - MTJ
  - STT
- PCRAM
- FeRAM
- ReRAM, …

Parts Selection
DDR3 SDRAM

- Focus on latest DDR3 SDRAM technology with monolithic densities up to 4 Gb. Additional tests with 2 Gb DDR3 parts.

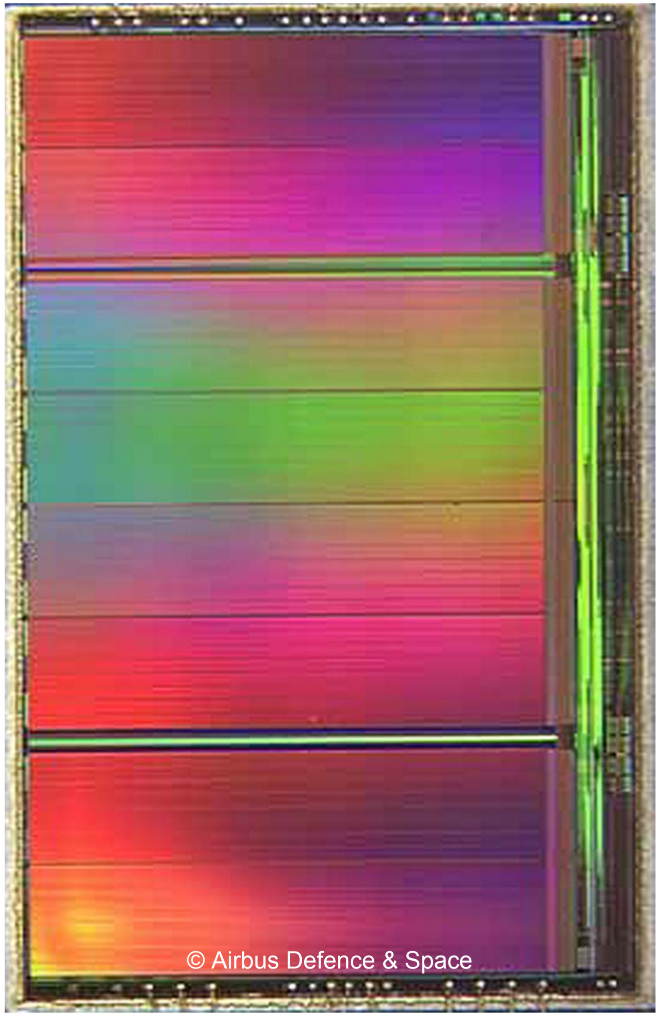
4 Gb DDR3:
- Elpida EDJ4208BASE-DJ-F (obsolete)
- SK Hynix H5TQ4G83MFR-H9C
- Micron MT41J512M8RH-093:E
- Samsung K4B4G0846B-HCH9
- Nanya NT5CB512M8CN-EK

2 Gb DDR3:
- SK Hynix H5TQ2G83BFR-H9C
- Nanya N5CB256M8BN-CG
- Micron MT41J256M8HX-15E:D
- Samsung K4B2G0846B
- Samsung K4B2G0846D



Parts Selection
NAND Flash

- Only SLC NAND flash technology provides sufficient endurance (50k…100k EPC), data retention, and speed. Test of heritage SLC parts as reference + latest SLC technology available.



Reference:

- ❑ Samsung K9WBG08U1M (SLC, 4 x 8 Gb, 51 nm)
- ❑ Micron MT29F8G08AAAWP-ET:A (SLC, 8 Gb, 50 nm)

Focus on state-of-the-art technology:

- ❑ Micron MT29F16G08ABACAWP-IT:C (SLC, 16 Gb, 25 nm)
- ❑ Micron MT29F32G08ABAAAWP-IT:A (SLC, 32 Gb, 25 nm)

Performed Test Campaigns

TID:

- October 2012: 1st in-situ TID testing of 4 Gb DDR3
- March 2013: Unbiased pre-selecting TID tests on DDR3
- October 2013: Unbiased pre-selecting TID tests on DDR3
- January 2014: In-situ TID testing of NAND flash and DDR3

SEE / Heavy Ions:

- May 2011: 1st SEE tests of 2 Gb DDR3 and angular tests on NAND flash, RADEF
- January 2012: SEE characterisations of Micron 16/32 Gb NAND flash & 2/4 Gb DDR3, RADEF
- April 2012: Further SEE characterisations of NAND flash and DDR3, RADEF
- December 2012: High range SEE testing on DDR3 (including SEL) and angular characterisation of Micron 16 Gb NAND flash, TAMU

SEE / Protons

- March 2014: SEE characterisations of 4 Gb DDR3, PSI
- April 2014: SEE characterisations of 16/32 Gb NAND flash

Detailed Radiation Test Results

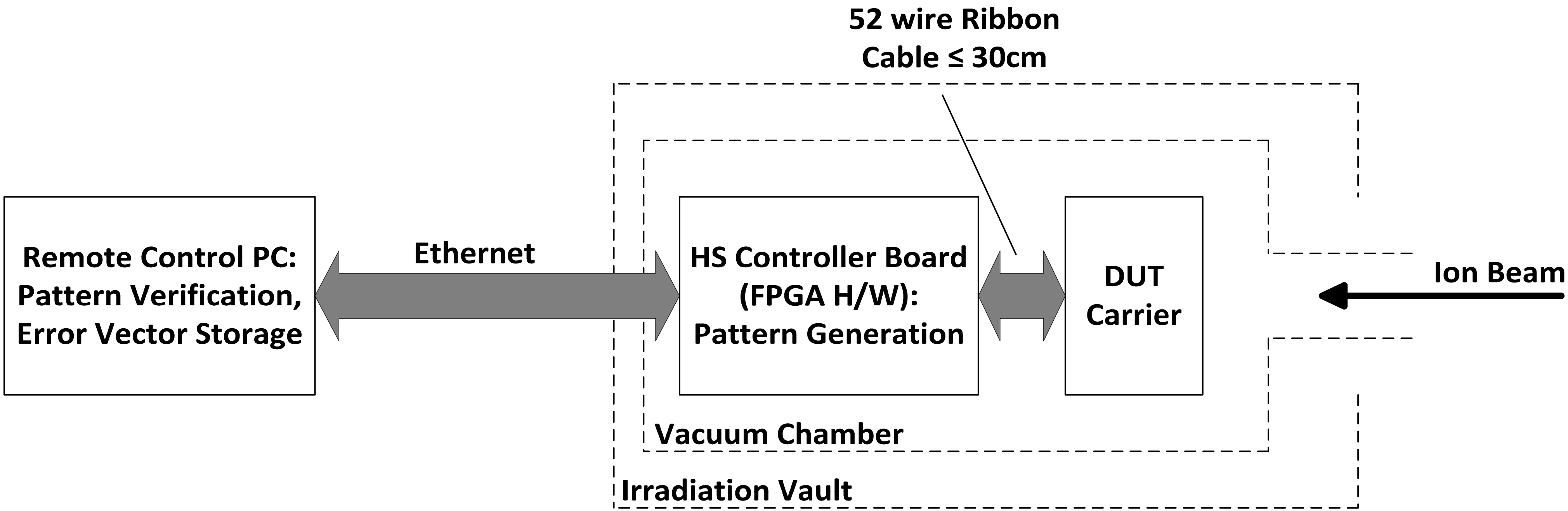
Main results

- Tolerance dose:
  - State-of-the-art NAND Flash: ≈ 30 krad
  - State-of-the-art DDR3 SDRAM: ≈ 400 krad (Hynix)
- Both types suffer from SEE error mechanisms with data loss:
  - NAND Flash: destructive failure (DF)
  - DDR3 SDRAM: device SEFI
- Both types are latch-up free
- Parts with good test coverage:
  - NAND Flash: 16/32-Gbit Micron, no other parts procurable
  - DDR3 SDRAM: 4-Gbit Hynix, other parts have substantial errors

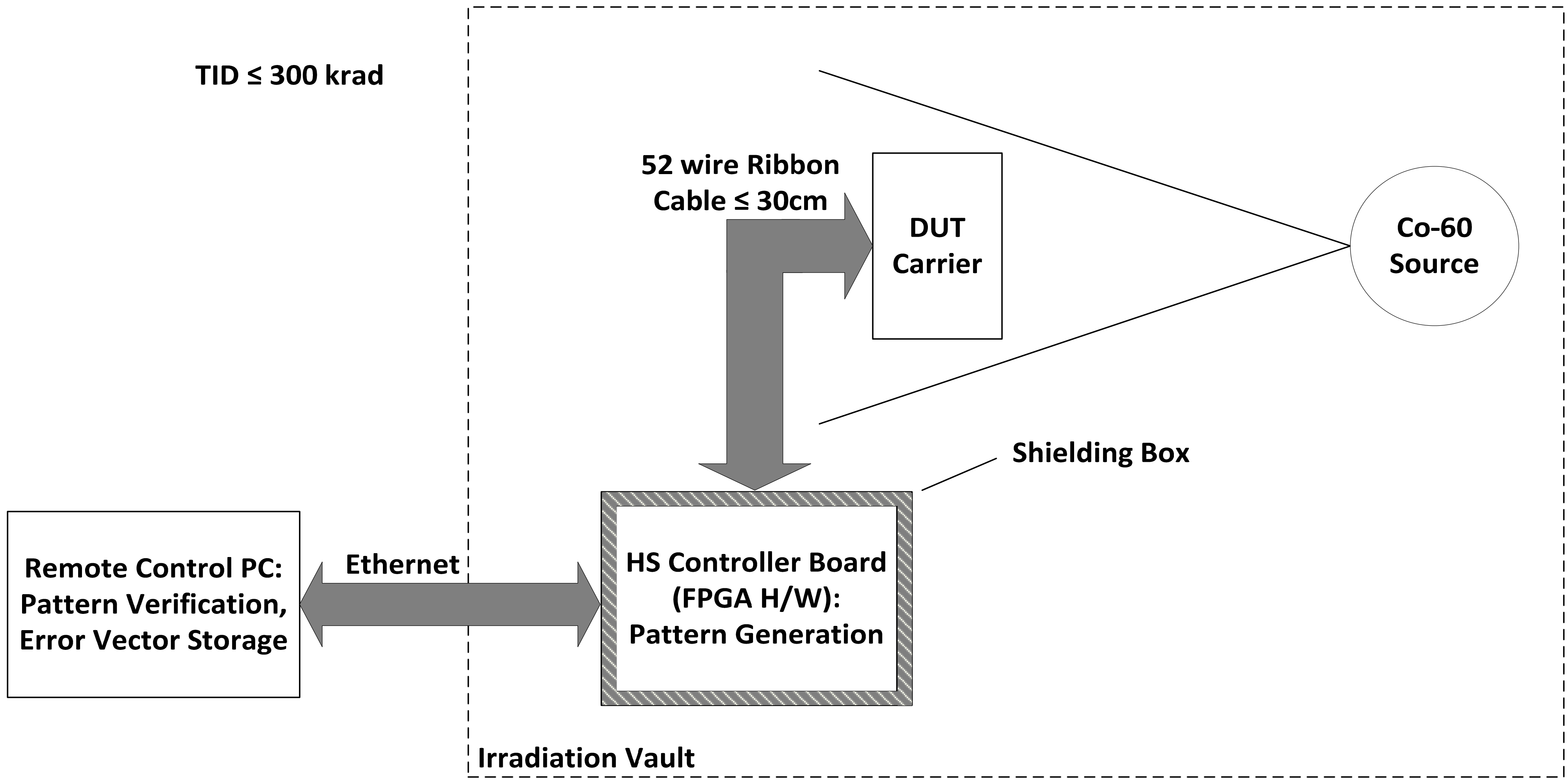
Outline

- NAND-Flash
  - Test equipment, error classification
  - Test Results
    - Heavy-ion SEE
    - Proton SEE
    - ^{60}Co TID
- DDR3 SDRAM
  - Test equipment
  - DUT preparation
  - Test Results
    - Heavy-ion SEE
    - Proton SEE
    - ^{60}Co TID
- Comparison

NAND-Flash: SEE HI

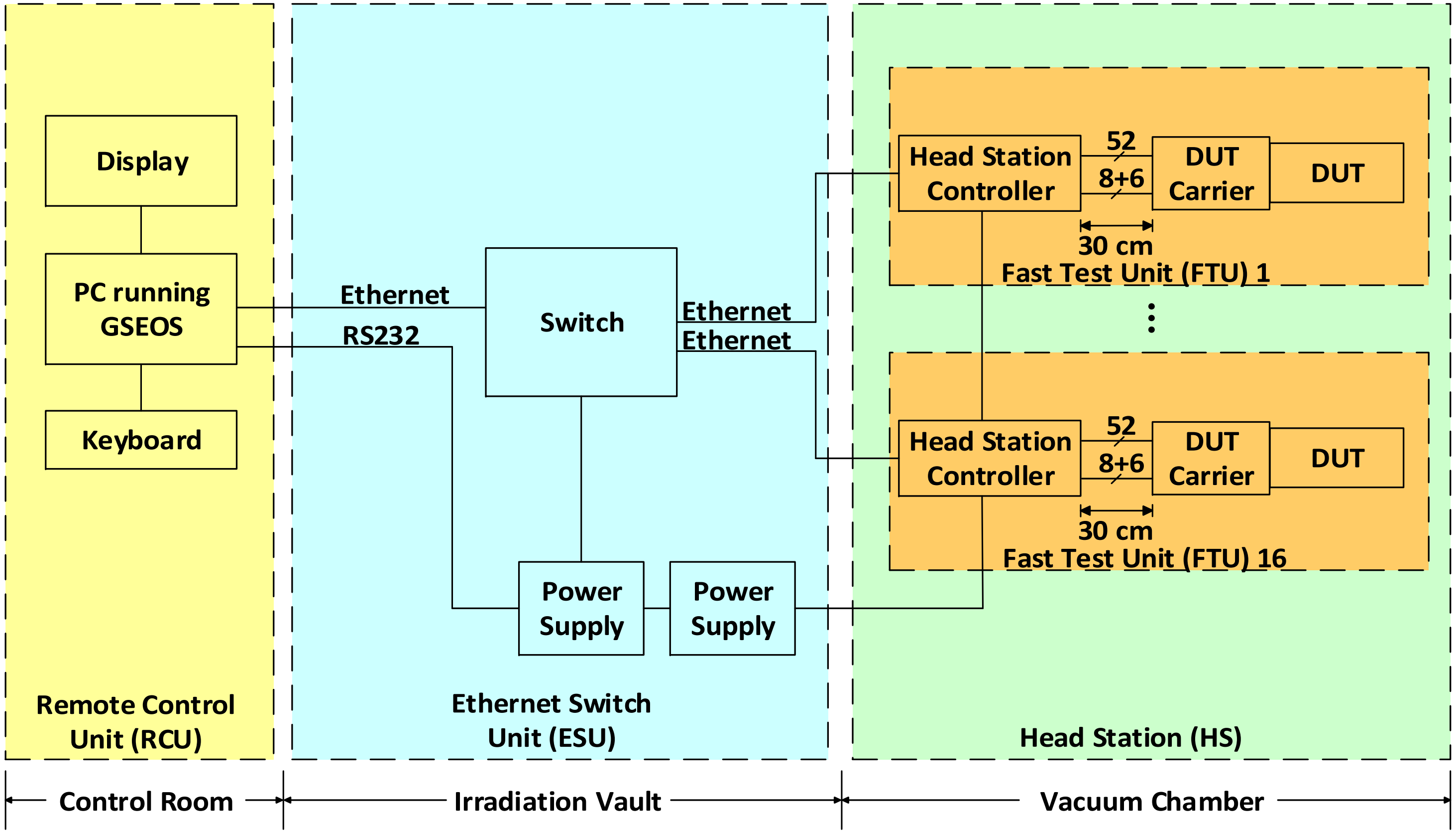


NAND-Flash: TID (+ SEE Protons)



NAND-Flash: Standard SEE Tests

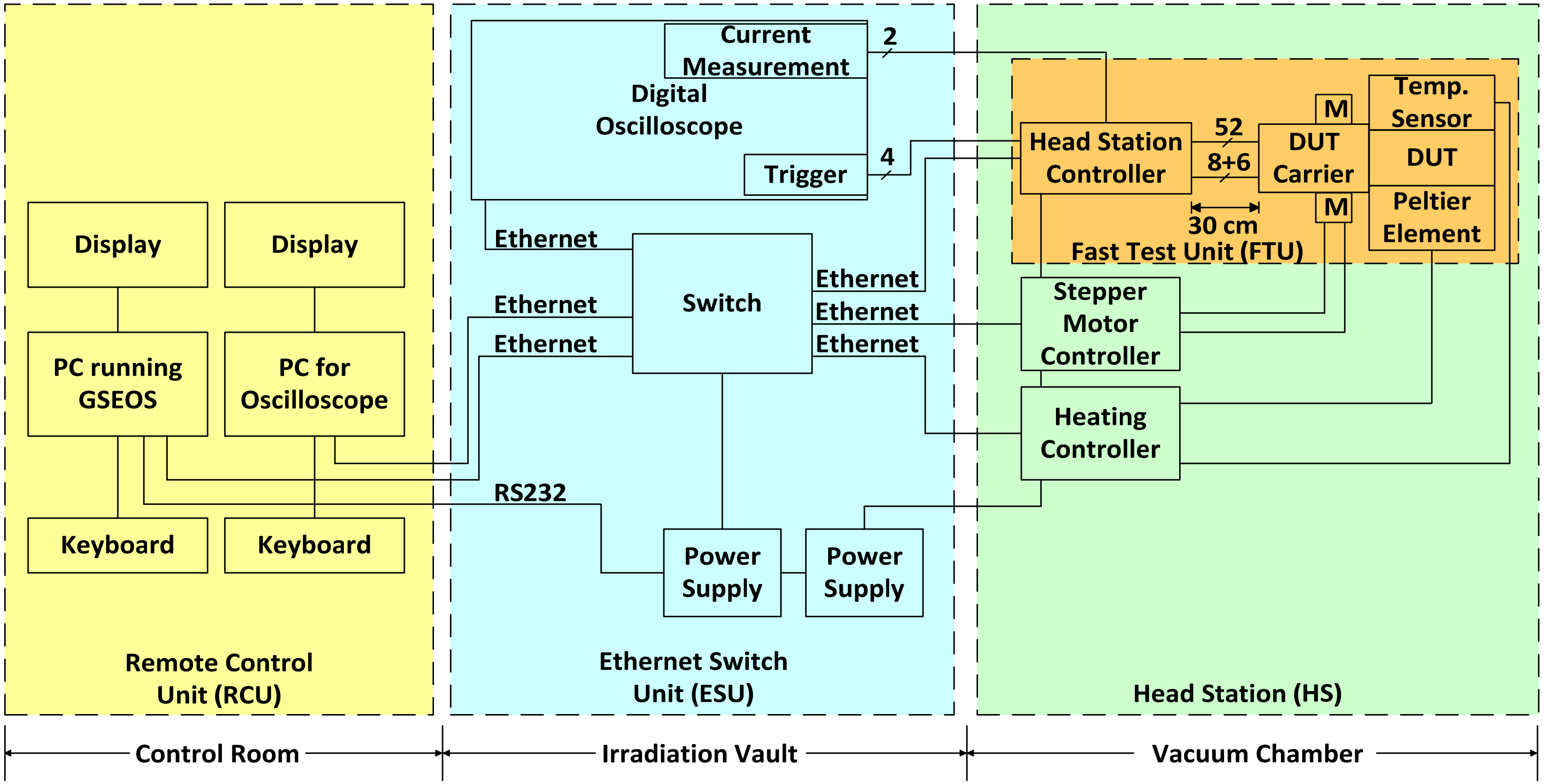
Functional Block Diagram



- Capability to operate up to 16 DUTs

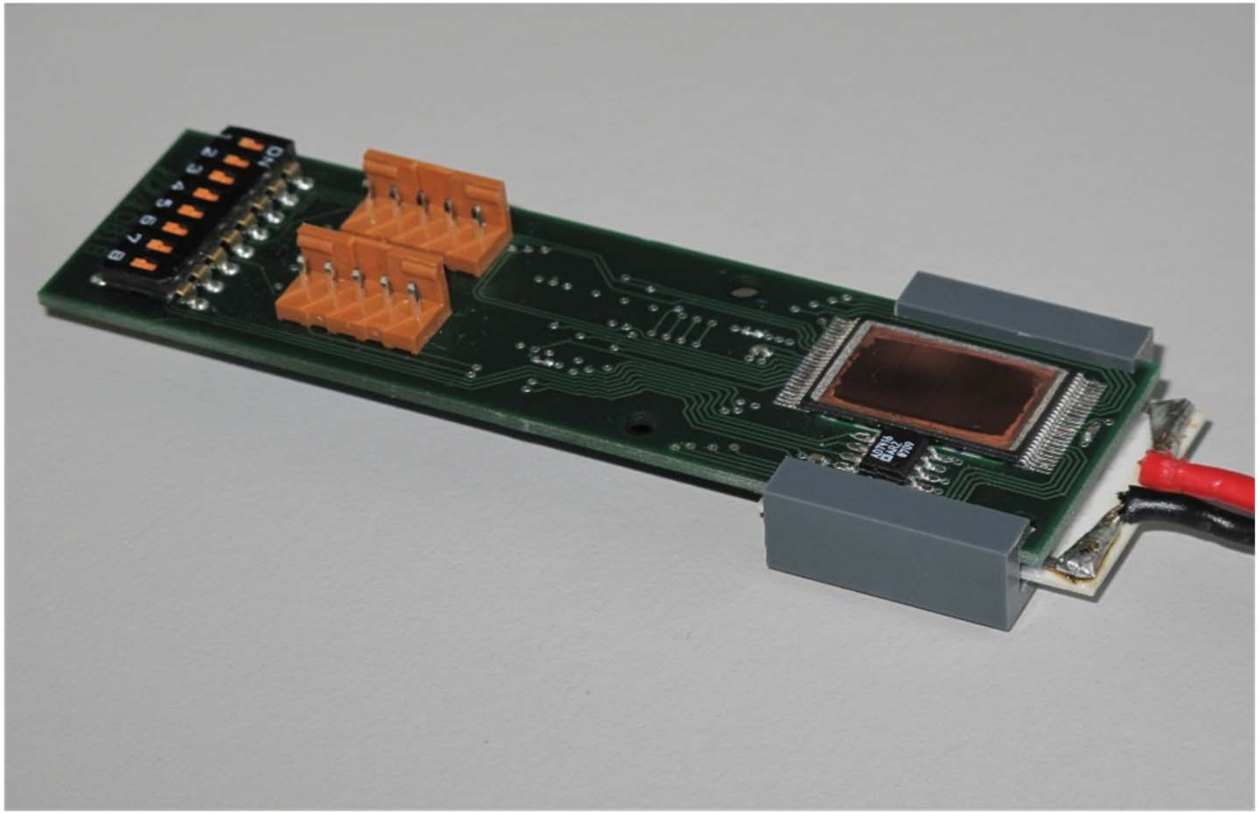
NAND-Flash: Enhanced SEE Tests

Functional Block Diagram



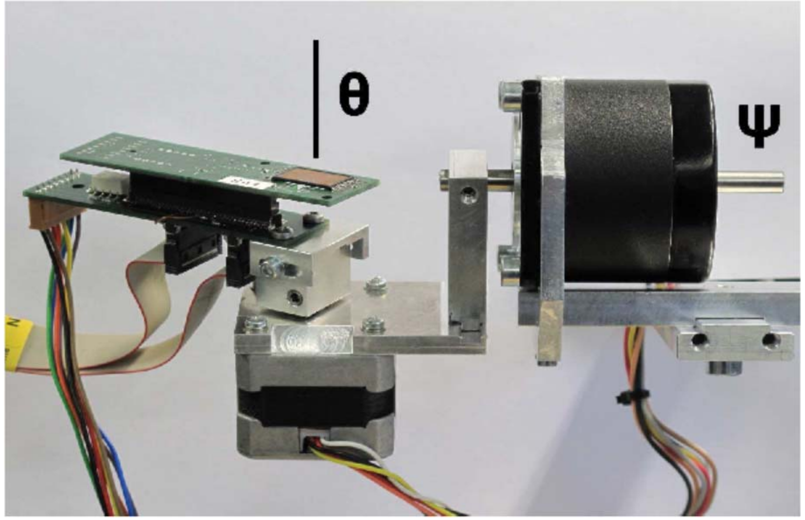
- Heating and cooling
- Tilting
- Current Measurement (Remote controlled Digital Oscilloscope)

NAND-Flash: Heating of the DUT

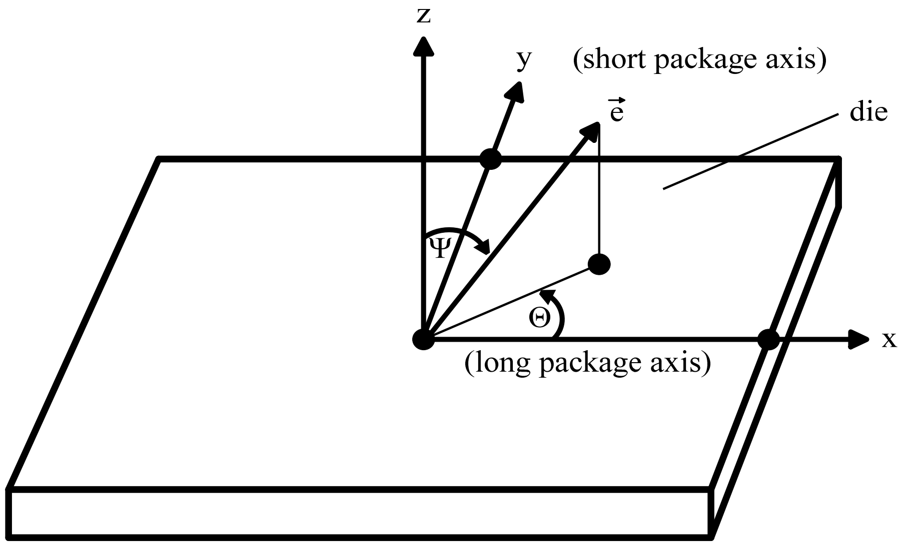


- PCB with DUT, Peltier element and temperature sensor

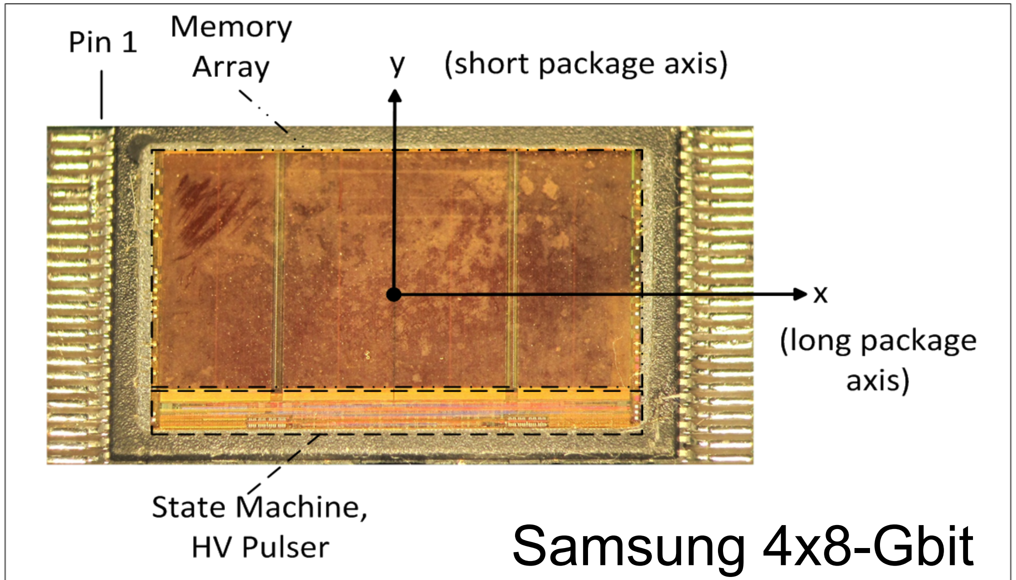
NAND-Flash: Tilting of the DUT



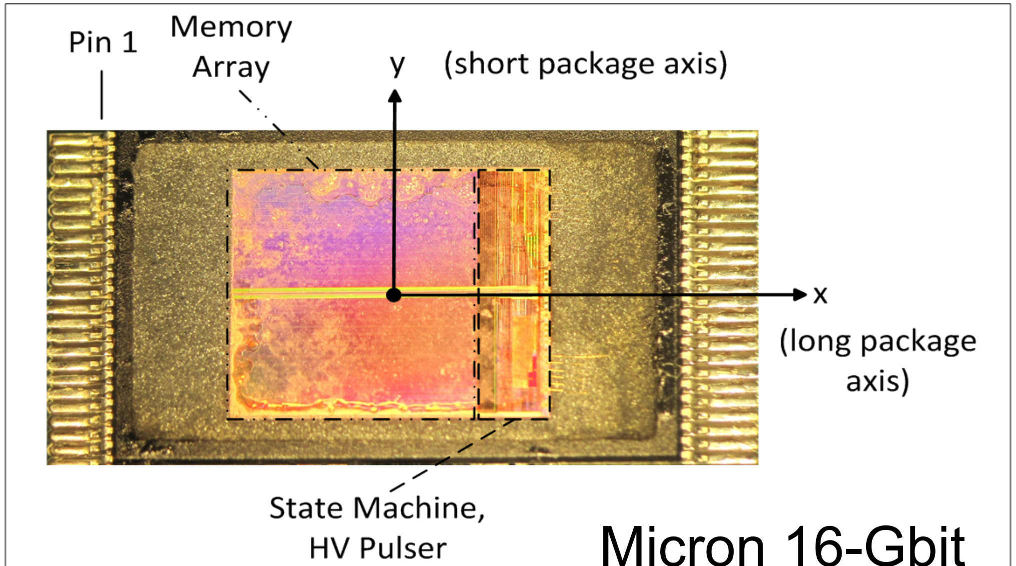
Tilting setup



Definition of Azimuth and Elevation Angle



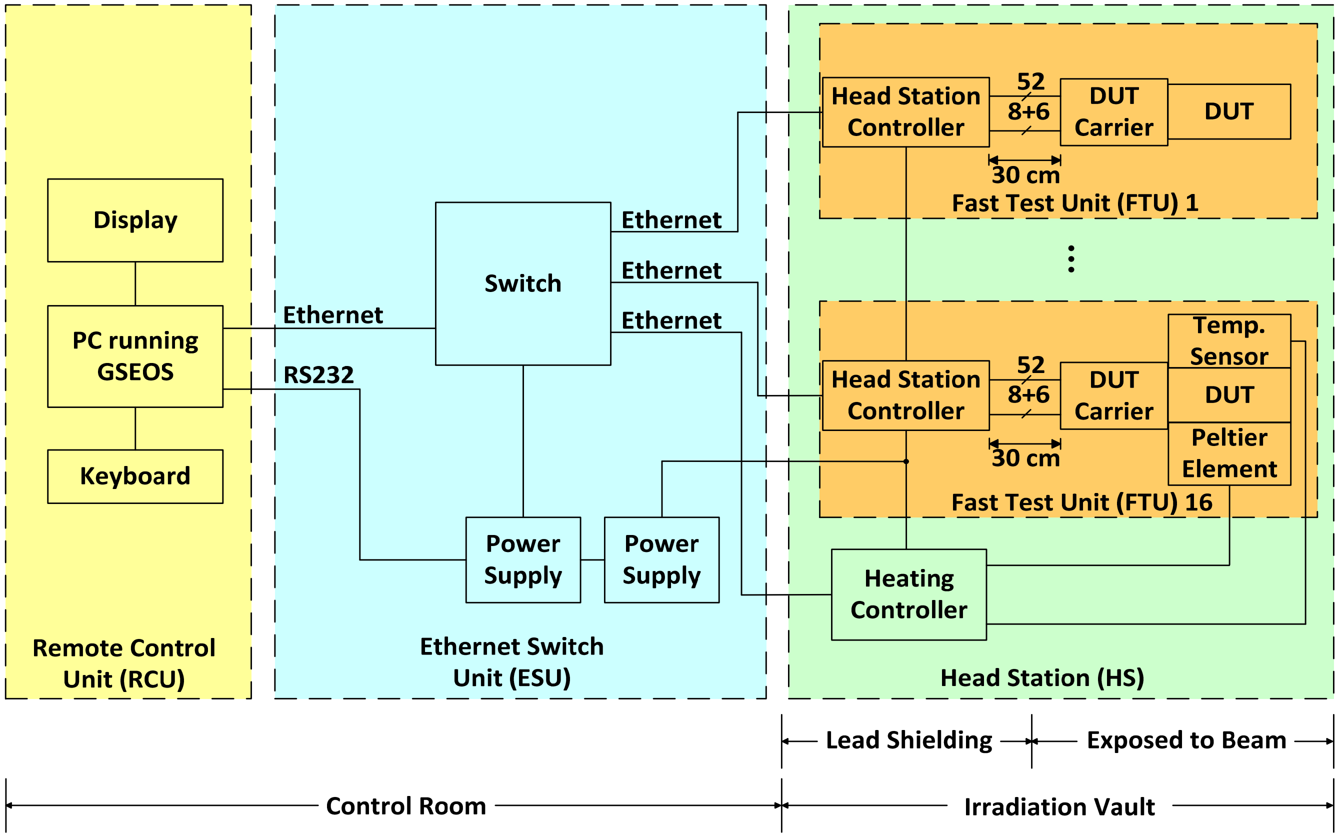
Samsung 4x8-Gbit



Micron 16-Gbit

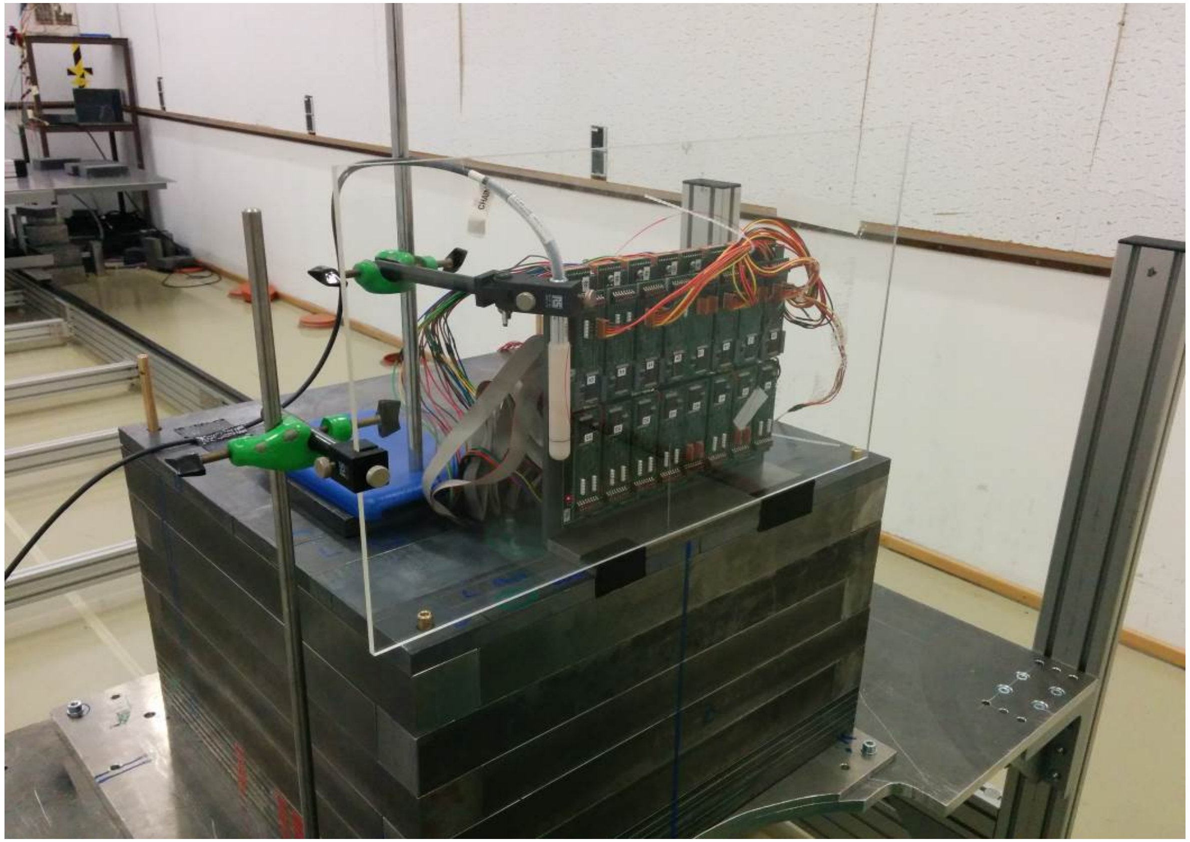
NAND-Flash: TID and Proton Tests

Functional Block Diagram



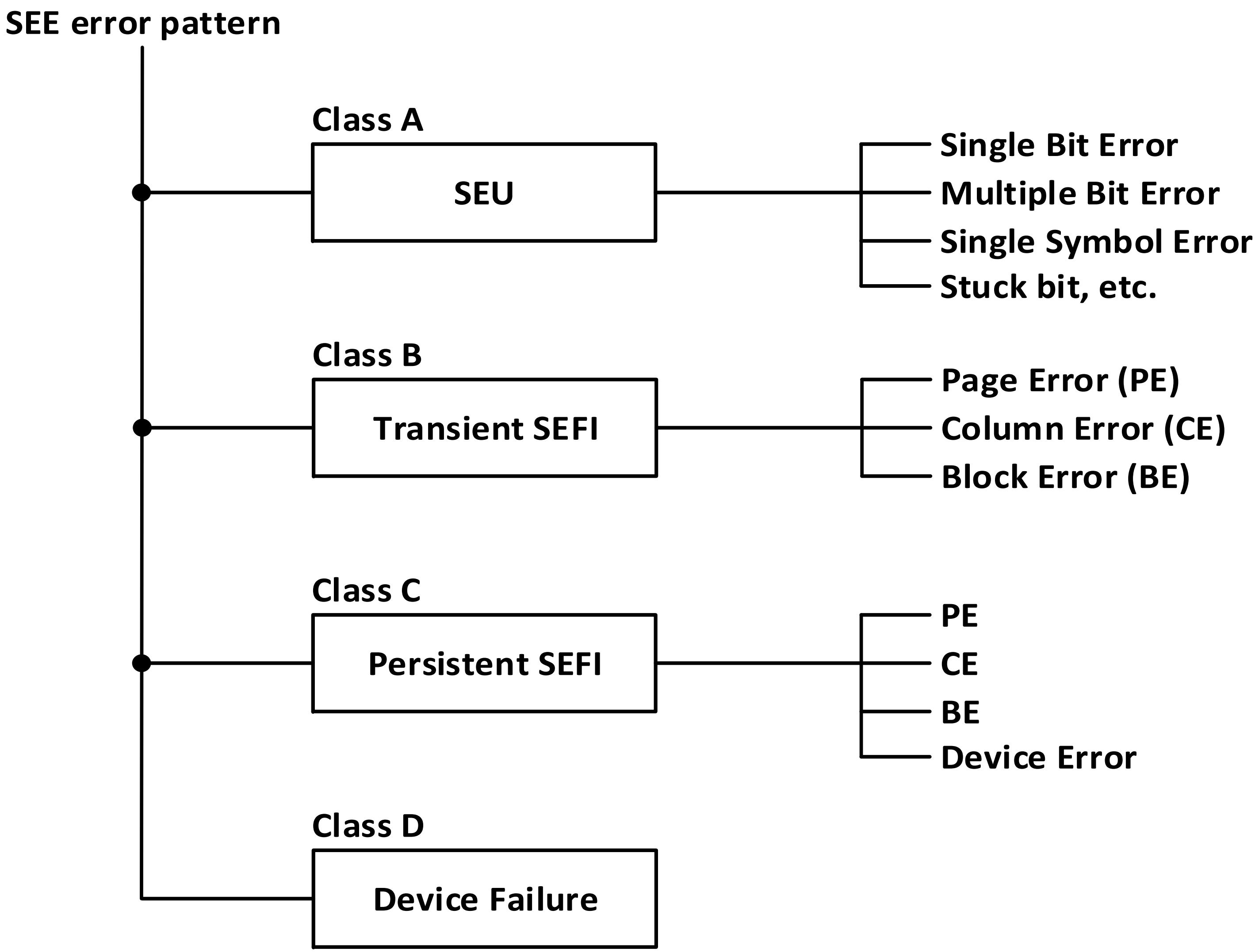
- Capability to operate up to 16 DUTs

NAND-Flash: TID shielding box

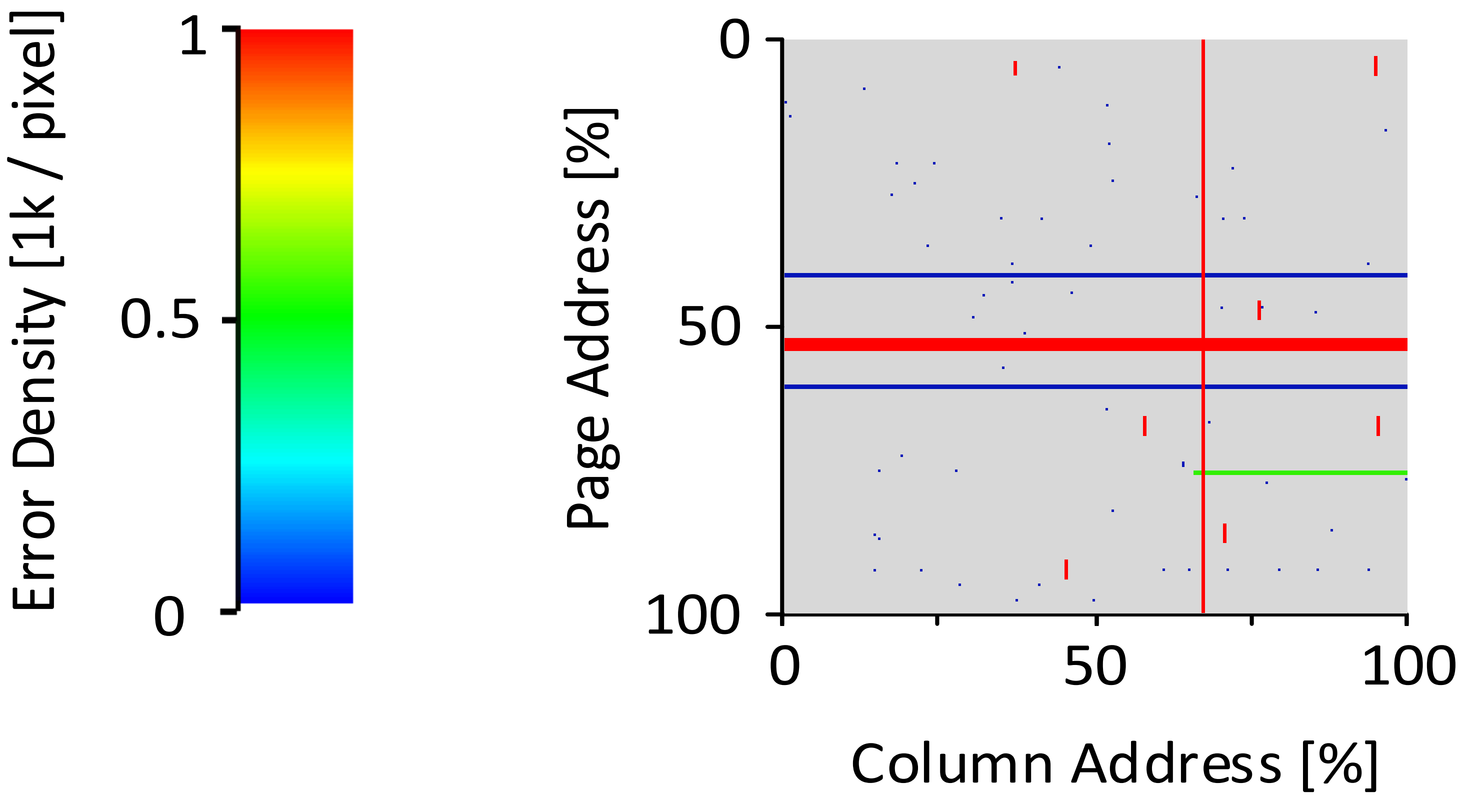


- 16 DUTs mounted above the shielding box

NAND-Flash: Error Classification



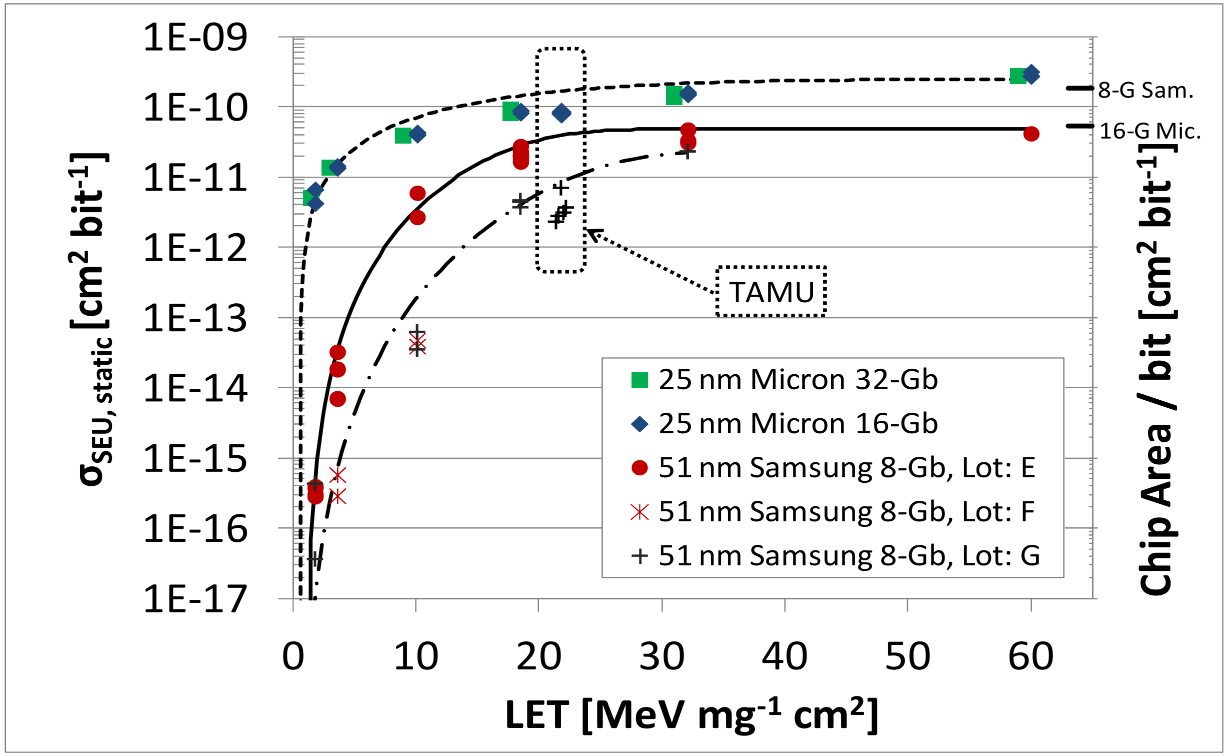
NAND-Flash: Error Image



NAND-Flash results

Heavy Ion SEE

NAND-Flash SEE HI: SEU cross section



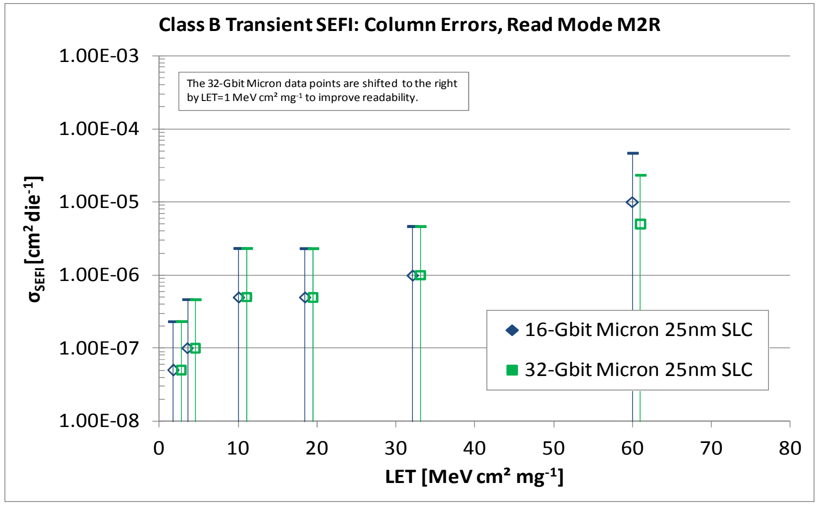
- TAMU cross section points are a bit below the RADEF measurement
- Effect of temperature?

NAND-Flash SEE HI: SEFI

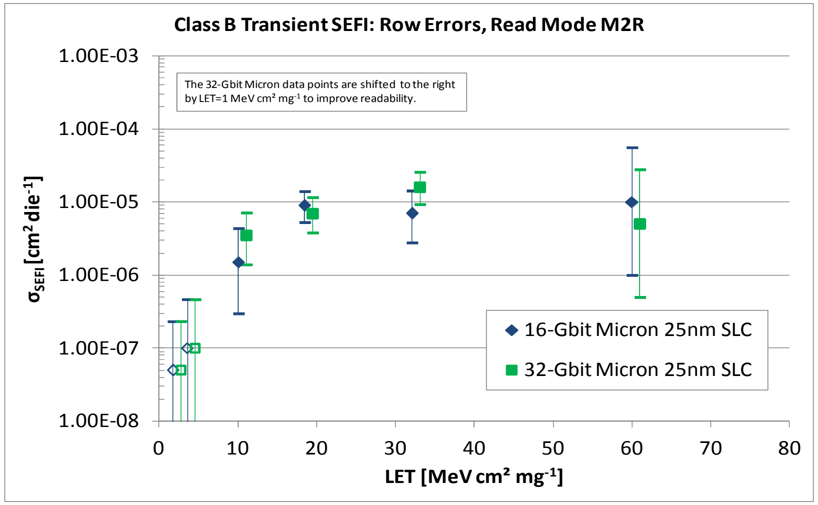
- classified into Column Errors, Row Errors and Block Errors
- measured individually for each mode
- the influence of the respective mode is rather minor
- Marching Mode 5 (without PC) delivers nearly the same cross section than Marching Mode 1 (with PC) in contrast to early NAND-Flash generations
- all row errors are transient
- all column errors are persistent
- one out of 2000 xenon ions generates a Class C Persistent SEFI (resolvable by PC)

NAND-Flash SEE HI: Class B Transient SEFI

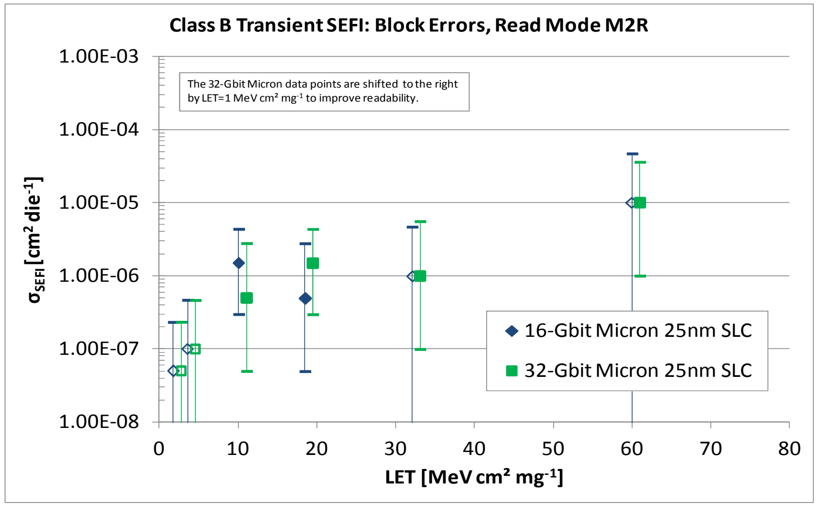
Column Errors



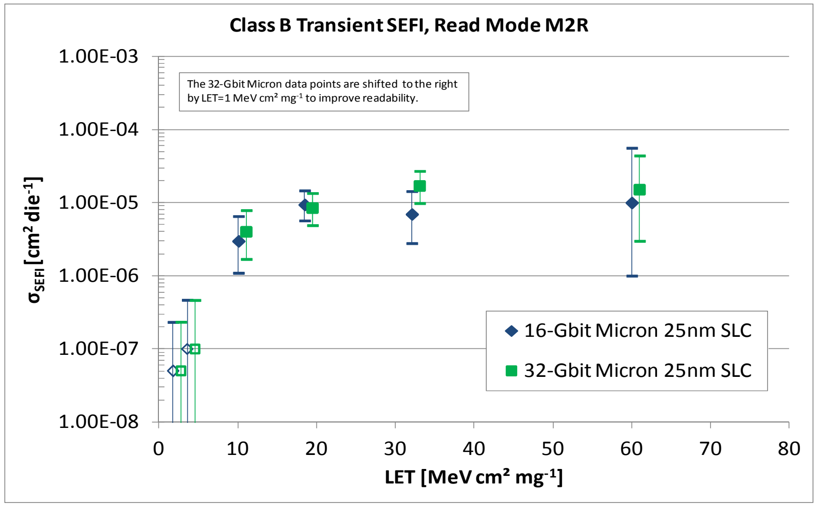
Row Errors



Block Errors

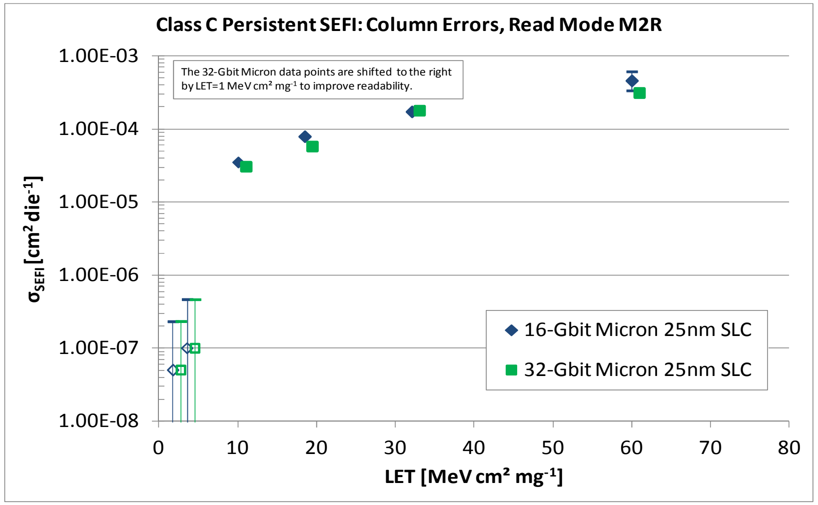


All Errors

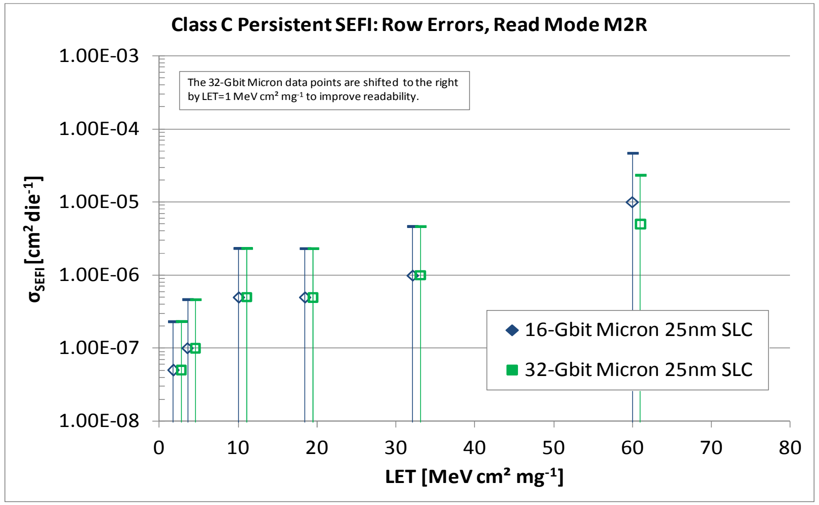


NAND-Flash SEE HI: Class C Persistent SEFI

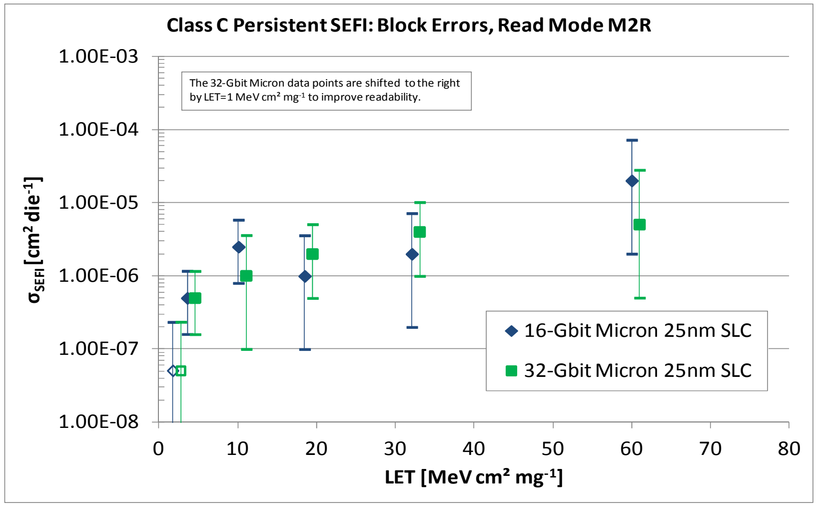
Column Errors



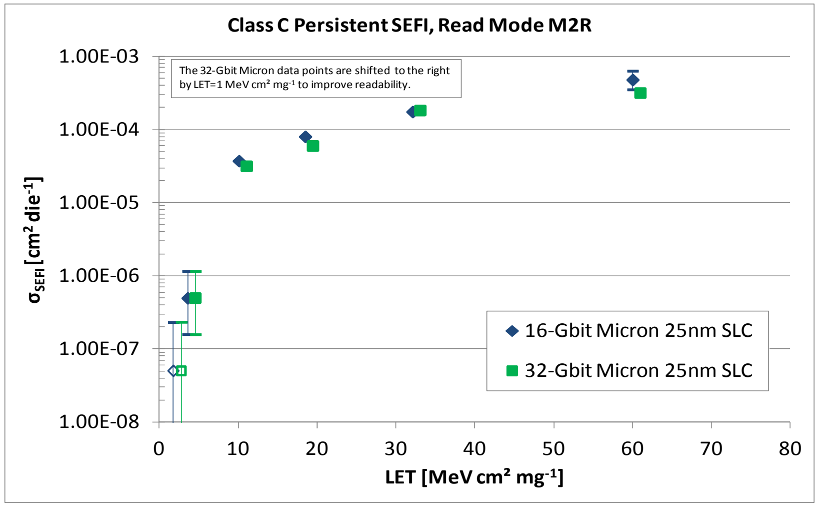
Row Errors



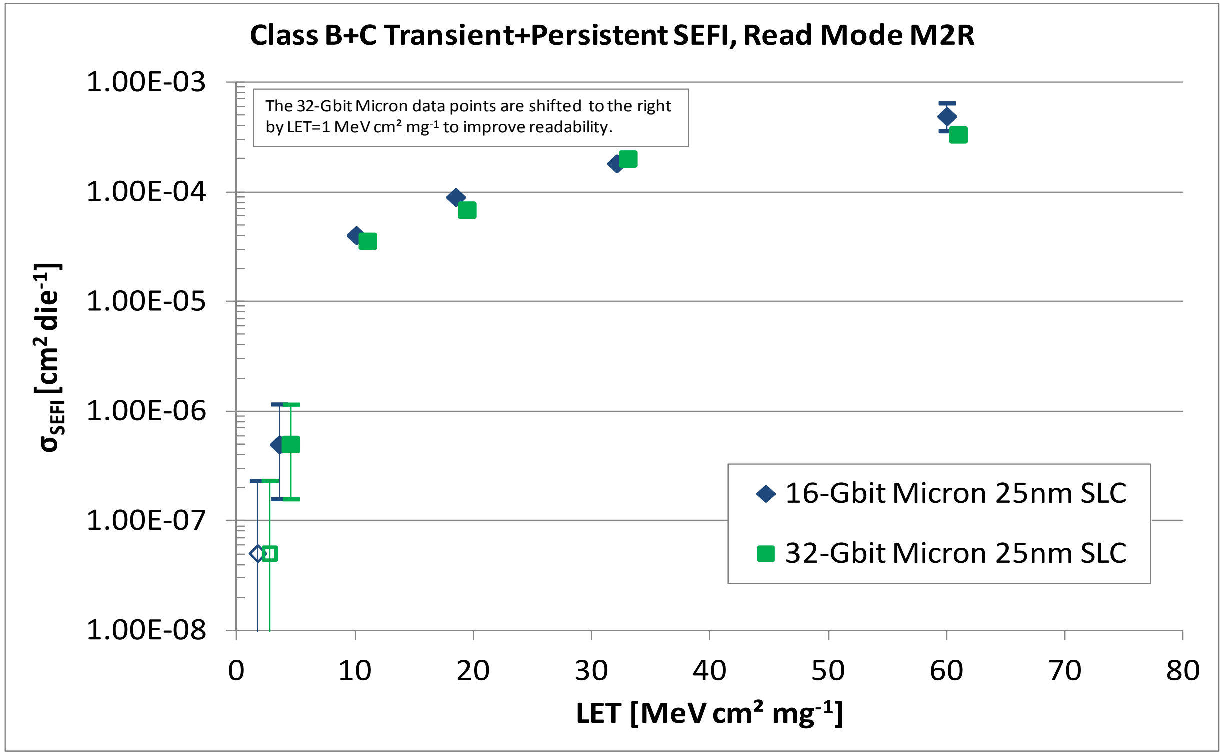
Block Errors



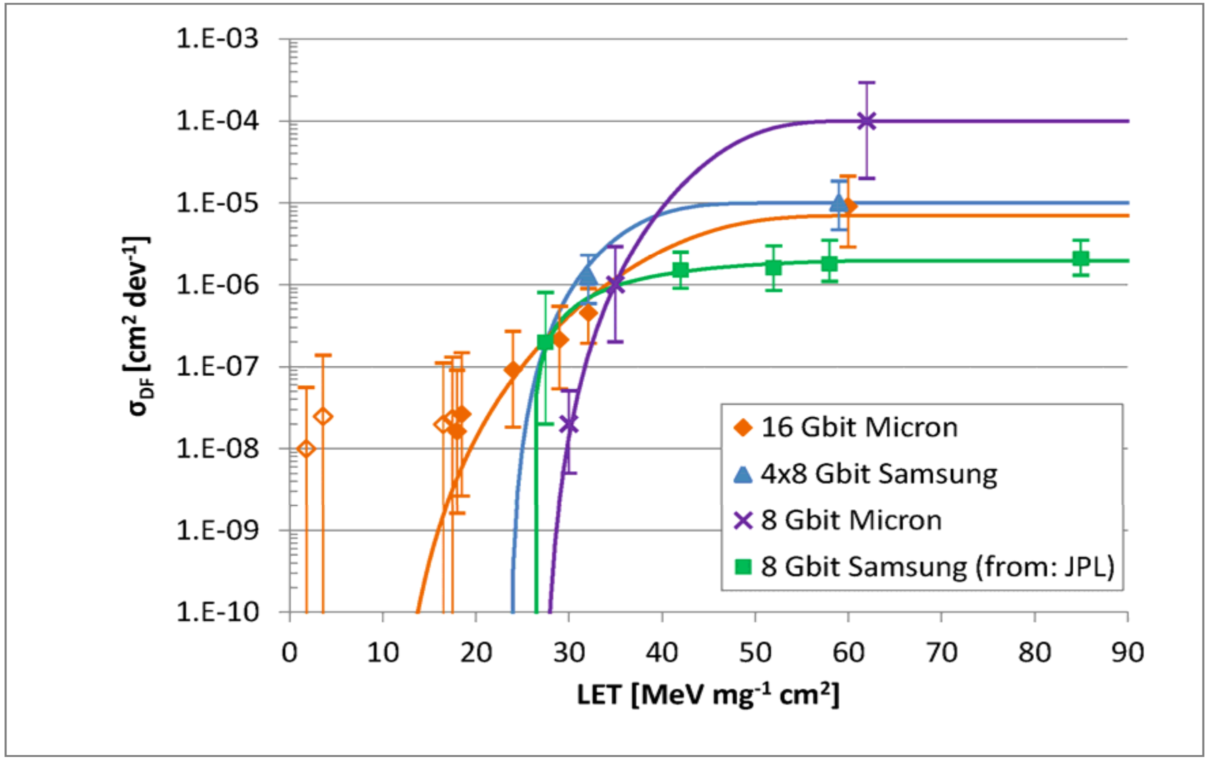
All Errors



NAND-Flash SEE HI: All SEFI

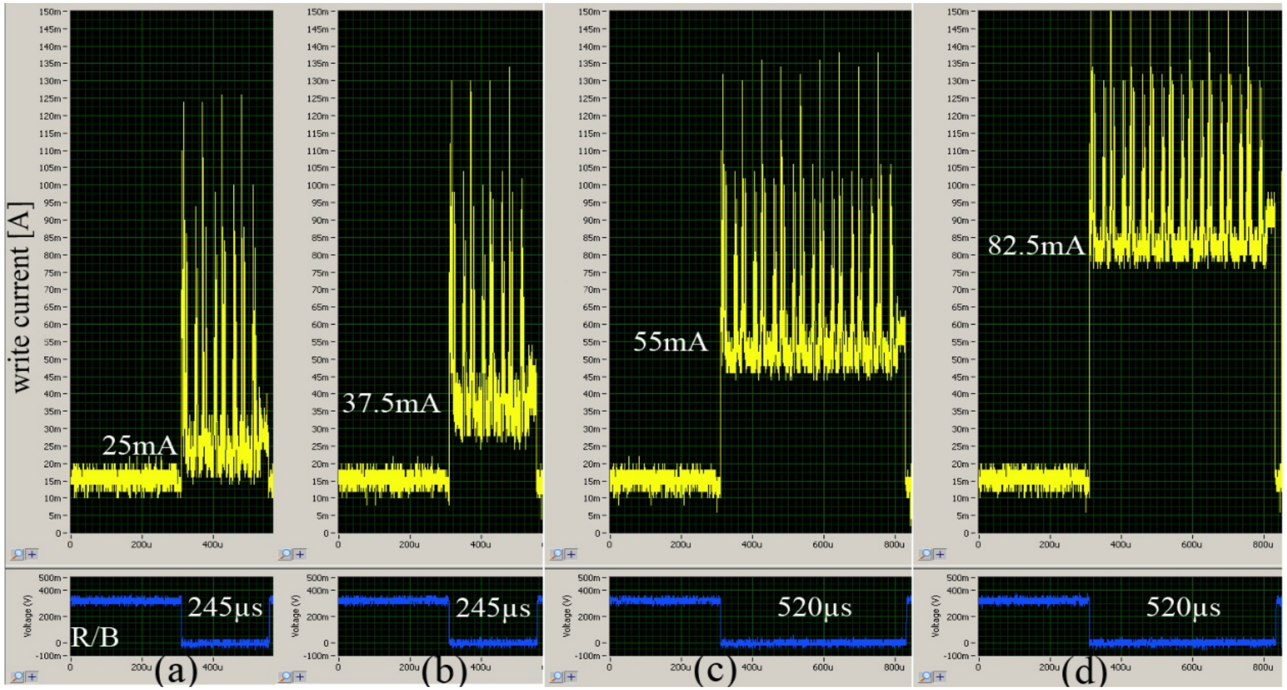


NAND-Flash SEE HI: Destructive Failure



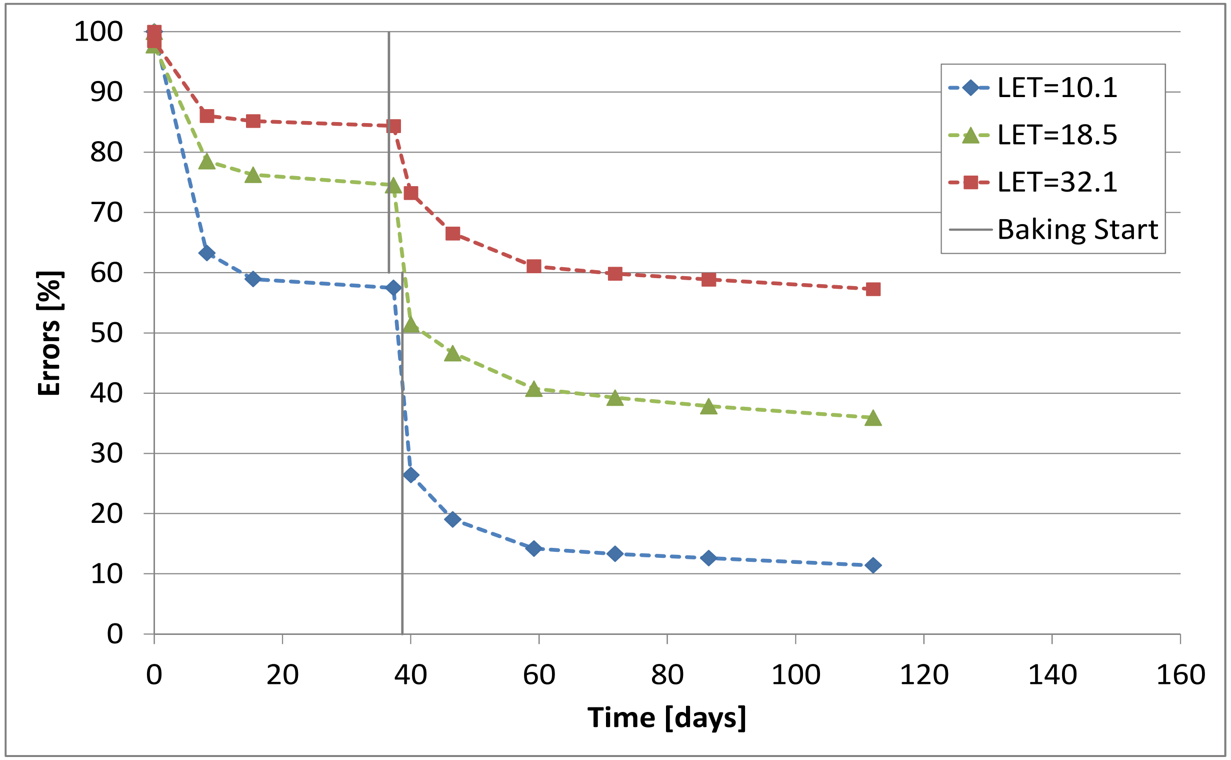
- permanent damage with definite data loss
- no flux dependence found (flux between 30 and 8000 cm^{-2} s^{-1})
- therefore we conclude that the DF is triggered by a single hit and not by the coincidence of several hits
- 16 Gbit Micron shows also other DF types affecting the on-chip microcontroller

NAND-Flash SEE HI: Destructive Failure



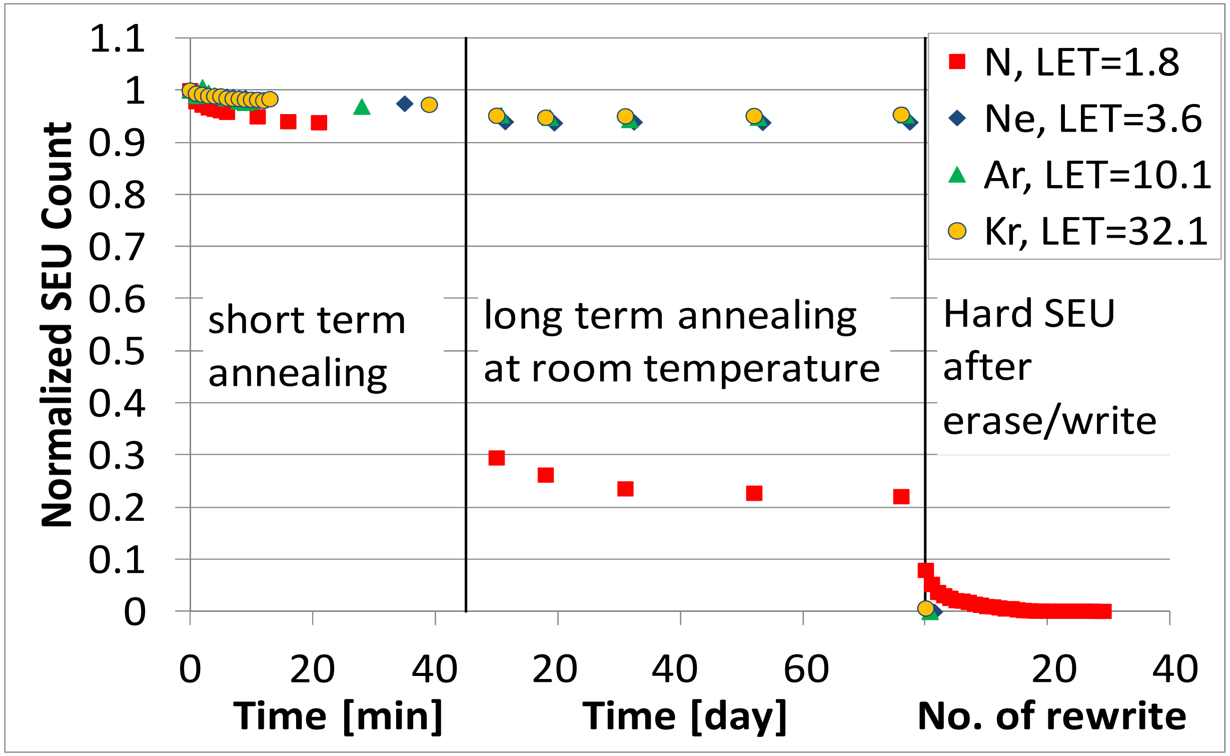
- Increase of write and erase current but
- No SEL found

NAND-Flash SEE HI: Soft Error Annealing



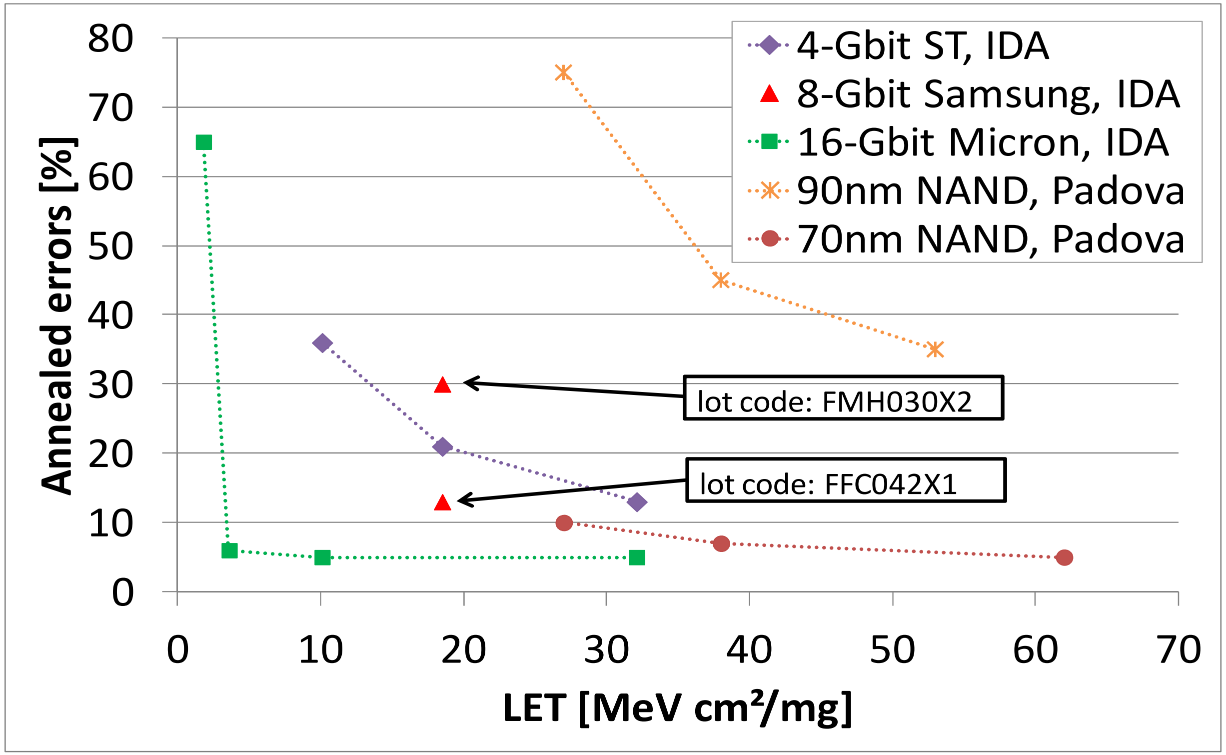
- Short term and long term SEU annealing, 4 Gbit ST Microelectronics

NAND-Flash SEE HI: Soft Error Annealing



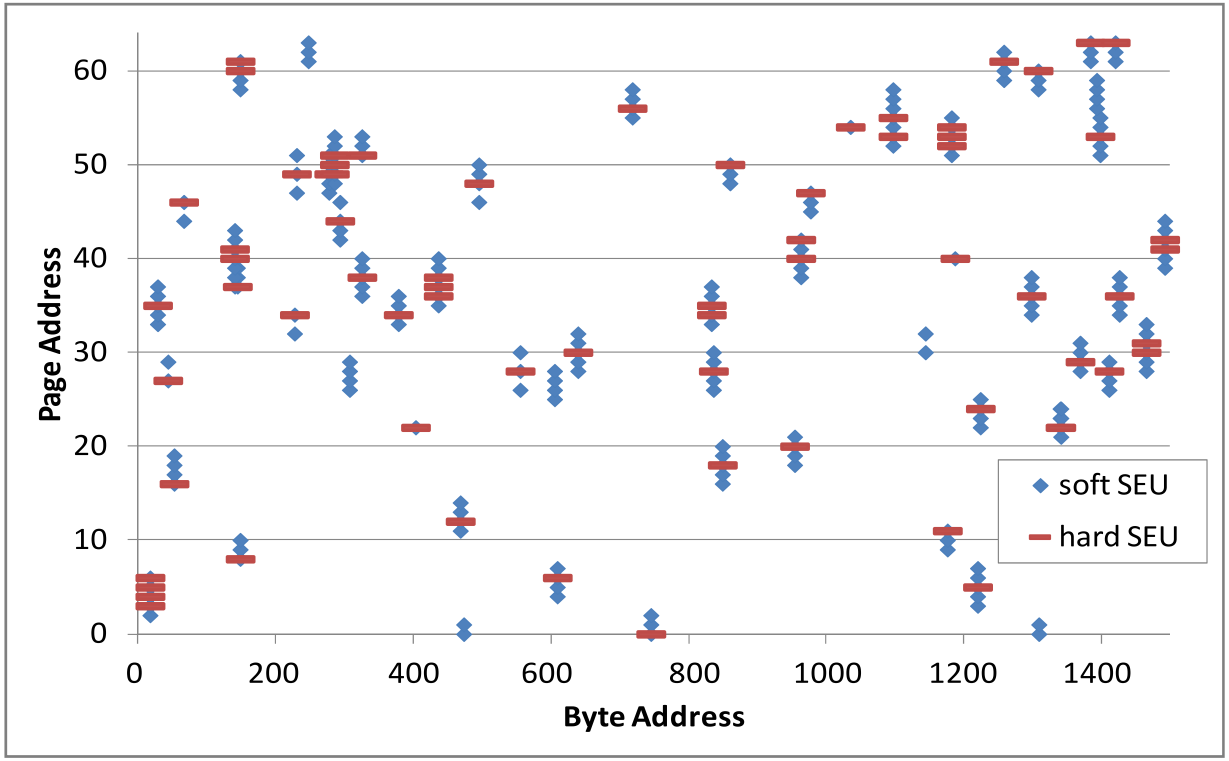
- Short term and long term SEU annealing, Micron 16/32-Gbit NAND-Flash **feature size 25 nm**

NAND-Flash SEE HI: Annealing Comparison



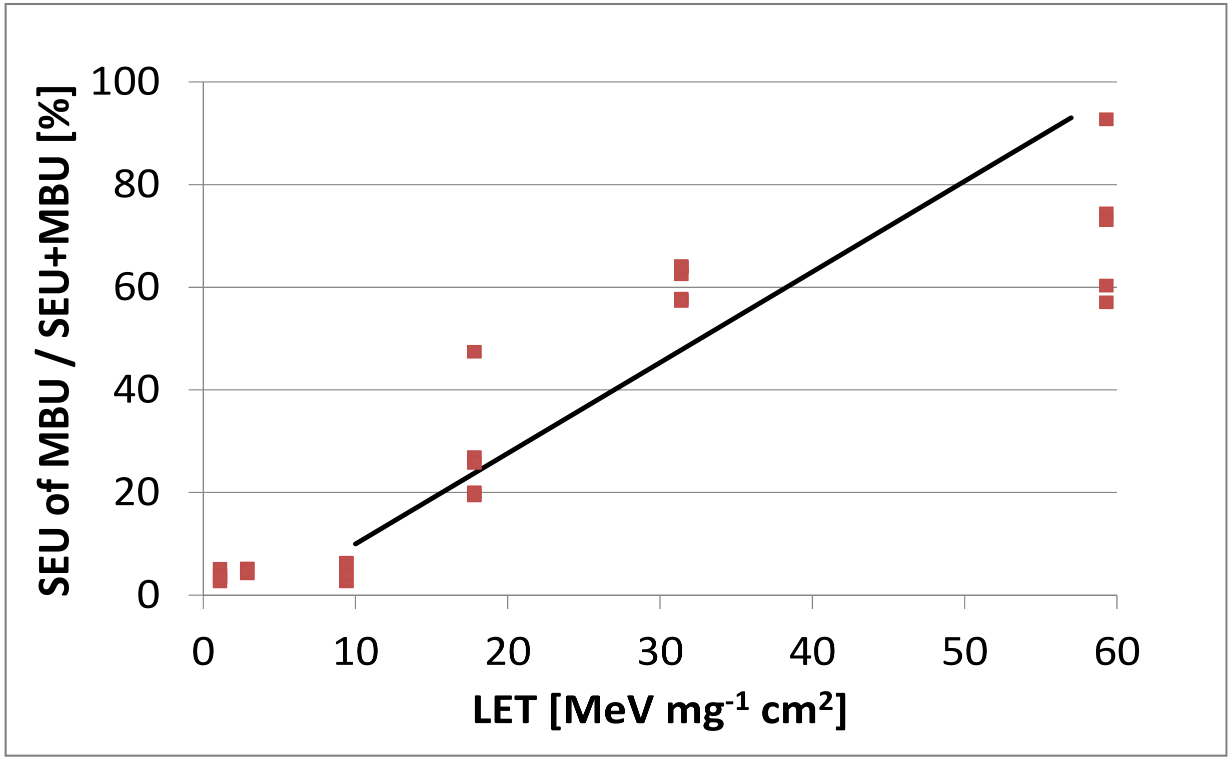
- Annealing depends strongly on the feature size

NAND-Flash SEE HI: Hard SEUs within MBUs



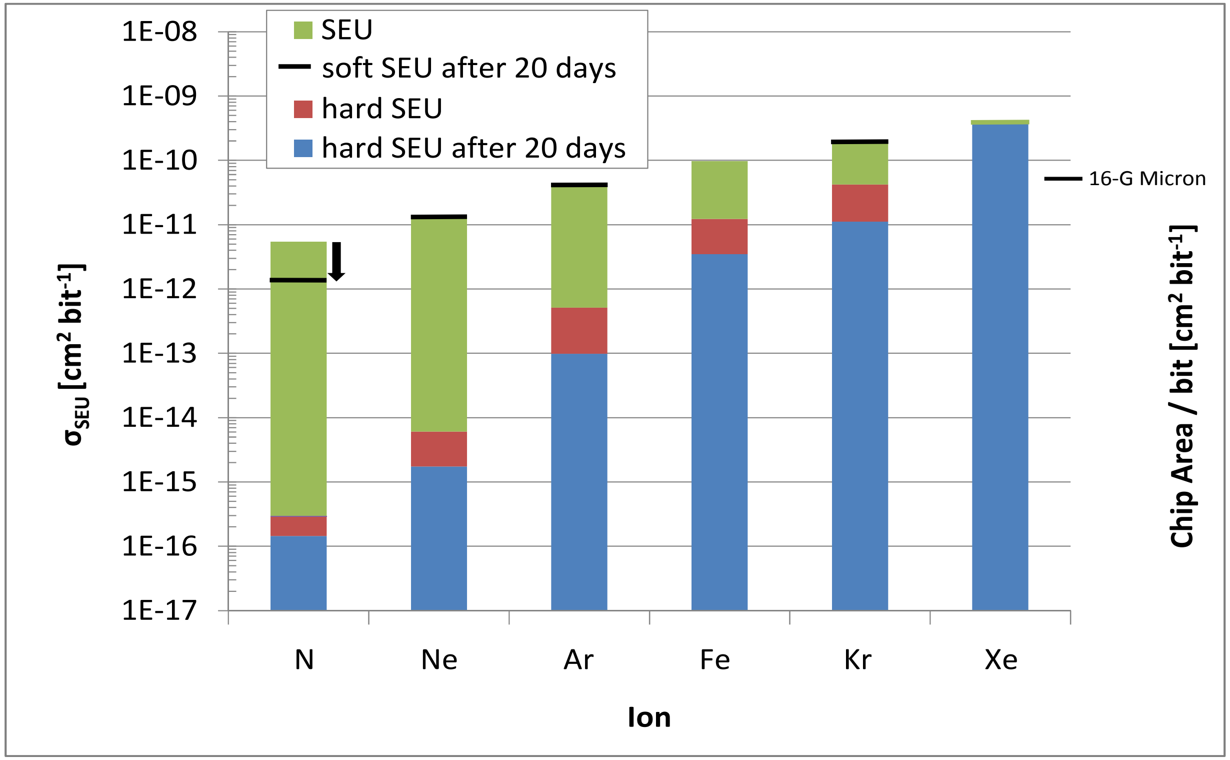
- Micron 16-Gbit SLC NAND-Flash, MBUs at normal incidence, Xe, LET=60
- hard SEUs accumulate over the mission time
- soft SEUs accumulate only over the data storage time, which is only of some days
- hard SEUs survive scrubbing and can therefore be more harmful

NAND-Flash SEE HI: Hard SEUs within MBUs



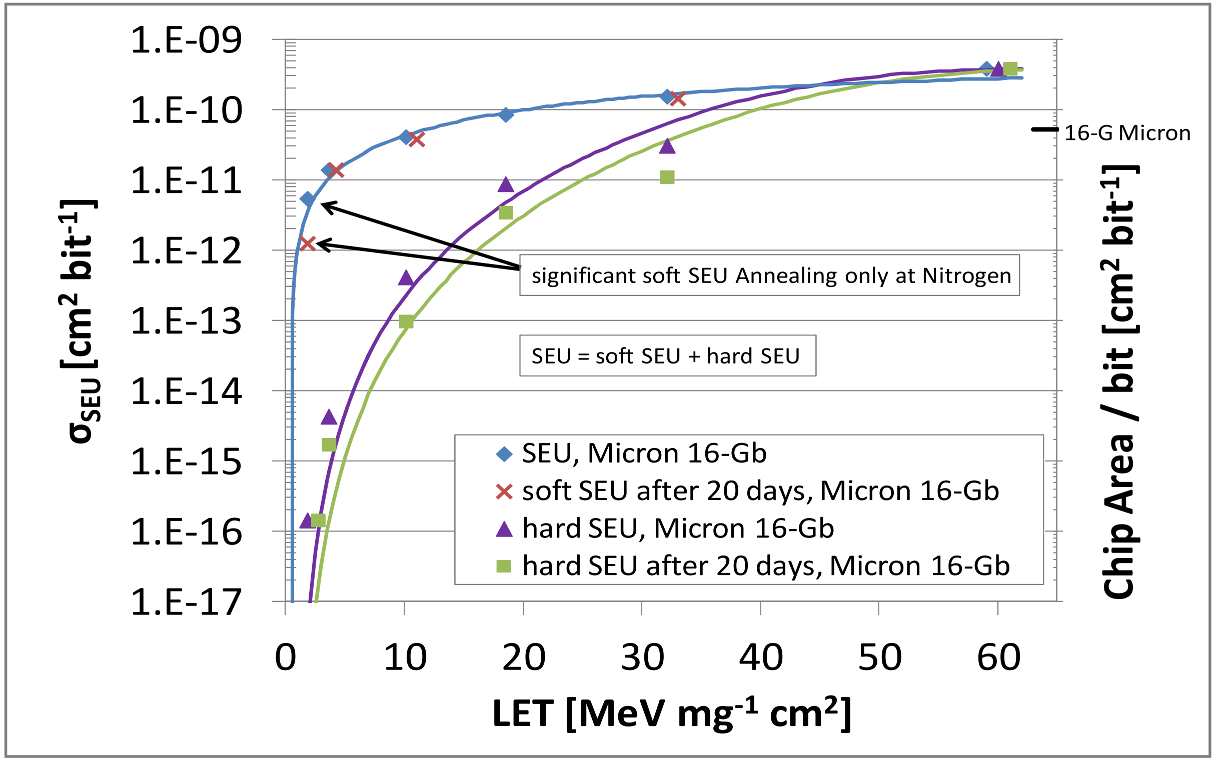
- With increasing LET the number of SEUs related to MBUs increases

NAND-Flash SEE HI: Annealing of Soft and Hard SEUs



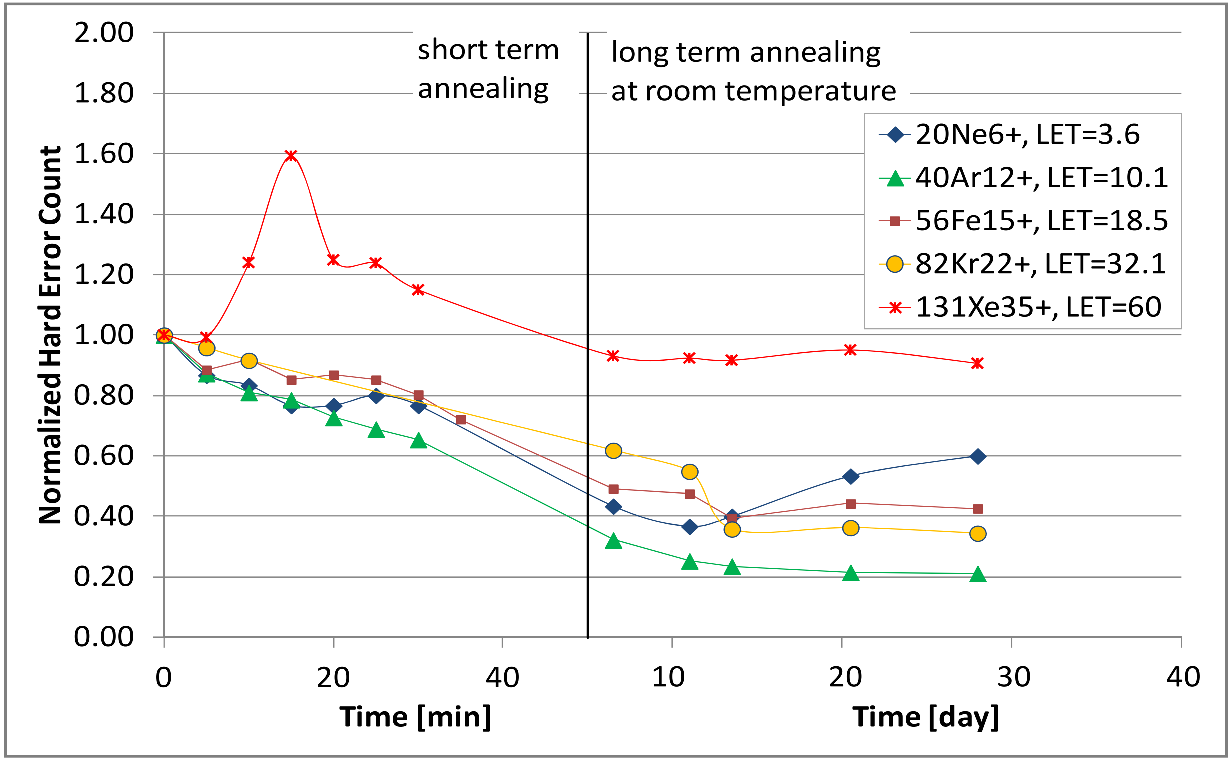
- Cross section of soft and hard SEUs,
  directly after exposure and 20 days later, 16-Gbit Micron SLC NAND-Flash

NAND-Flash SEE HI: Annealing of Soft and Hard SEUs



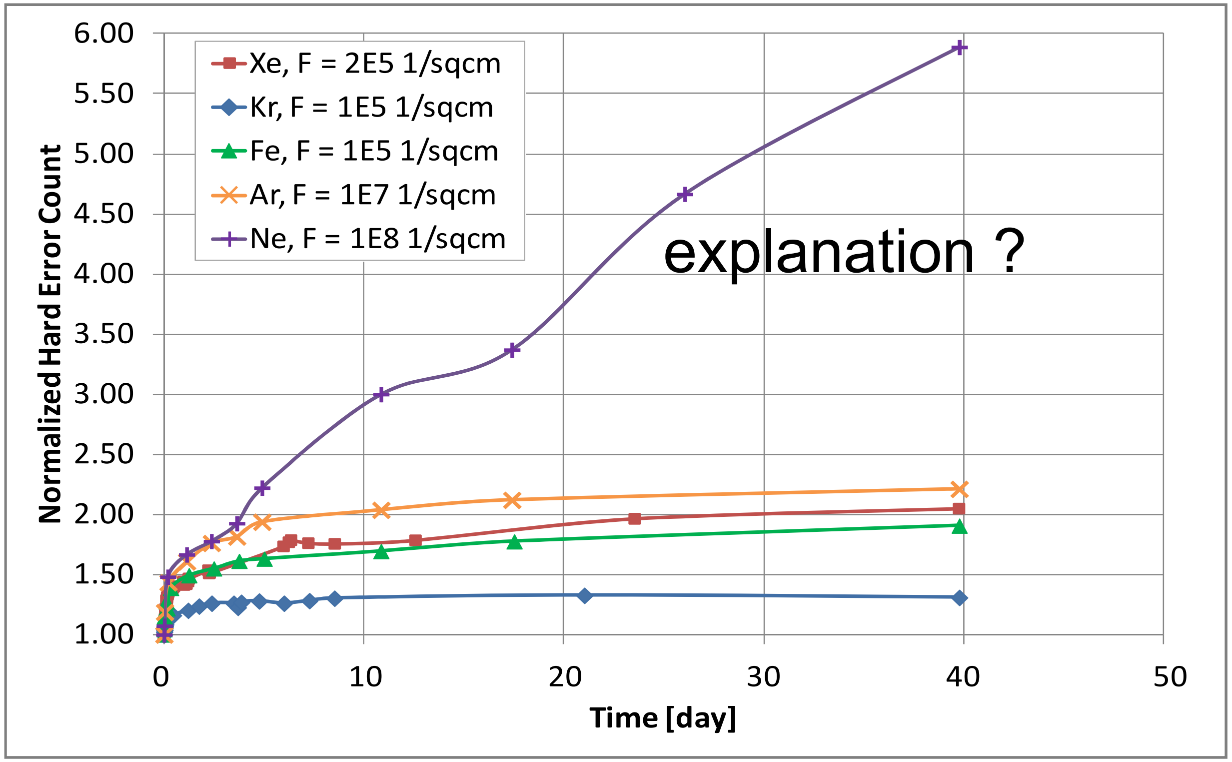
- Cross section of soft and hard SEUs,
  directly after exposure and 20 days later, 16-Gbit Micron SLC NAND-Flash

NAND-Flash SEE HI: Annealing of Hard SEUs



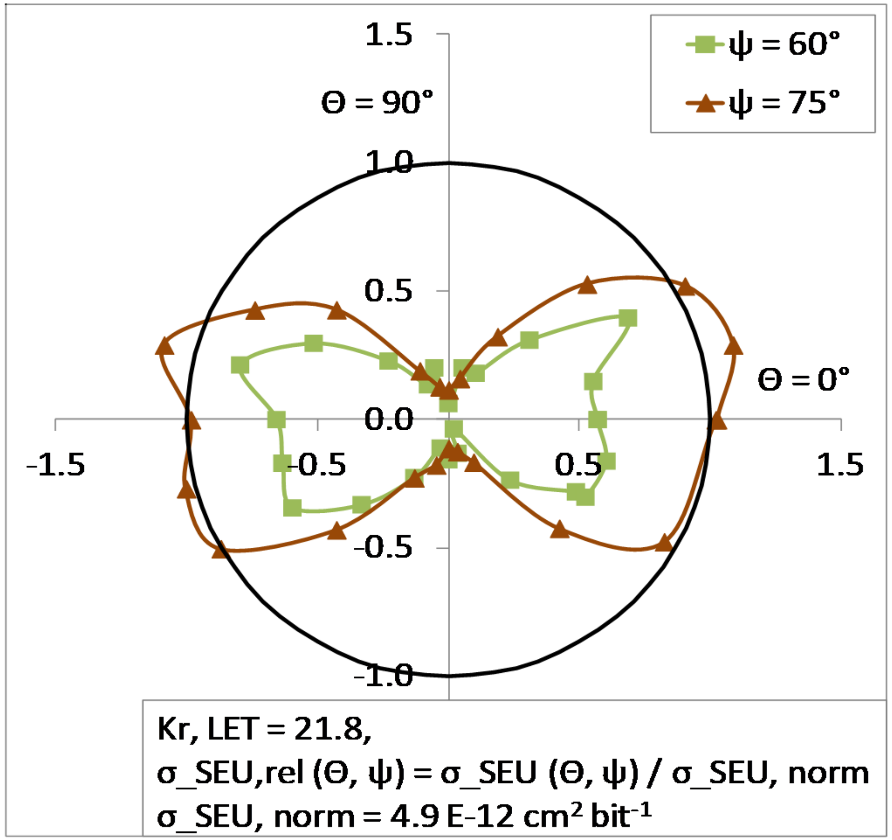
- Short term / long term Hard Error annealing, Micron 16/32Gbit NAND-Flash DUTs unbiased

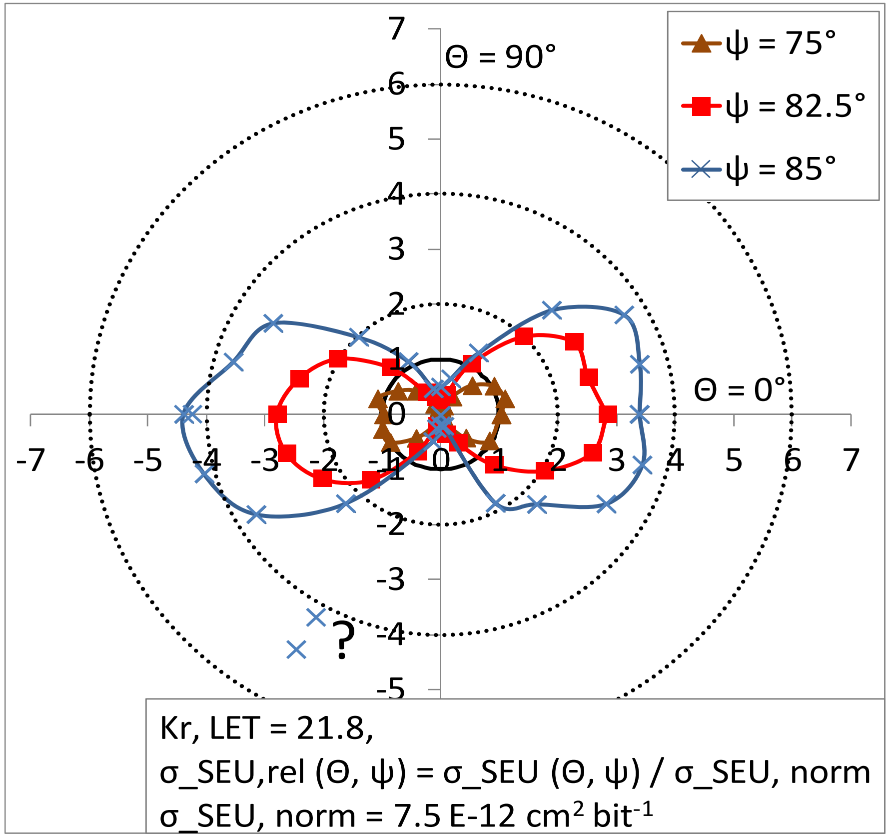
NAND-Flash SEE HI: Annealing of Hard SEUs



- Development of the hard SEU count after repeated erase-write-read cycles

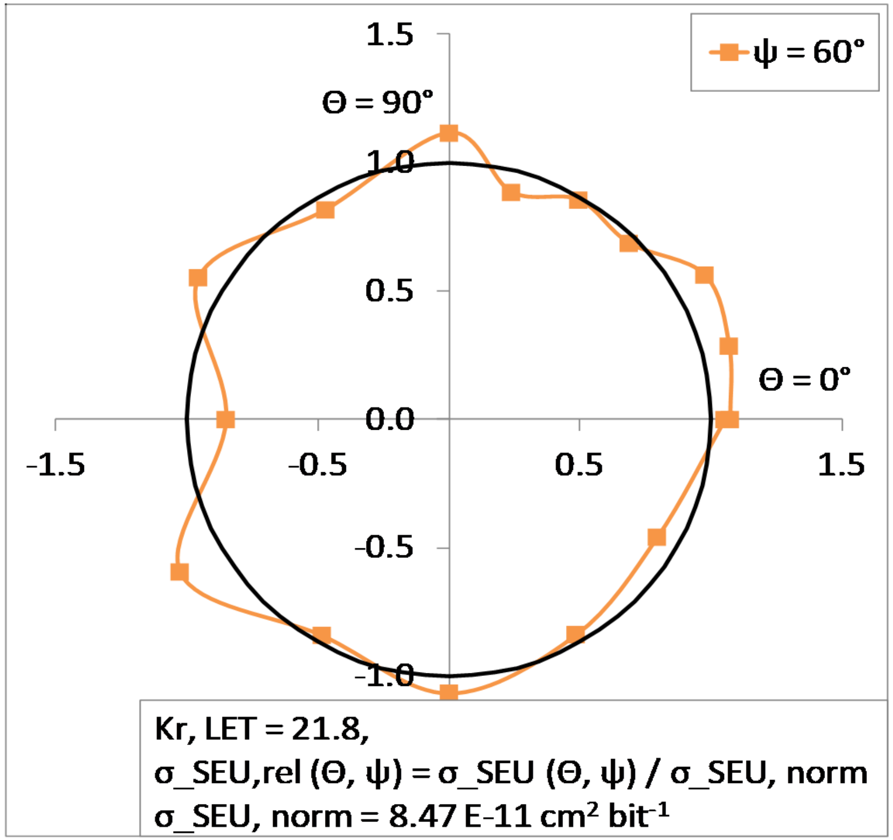
NAND-Flash SEE HI: Omni directional ion incidence

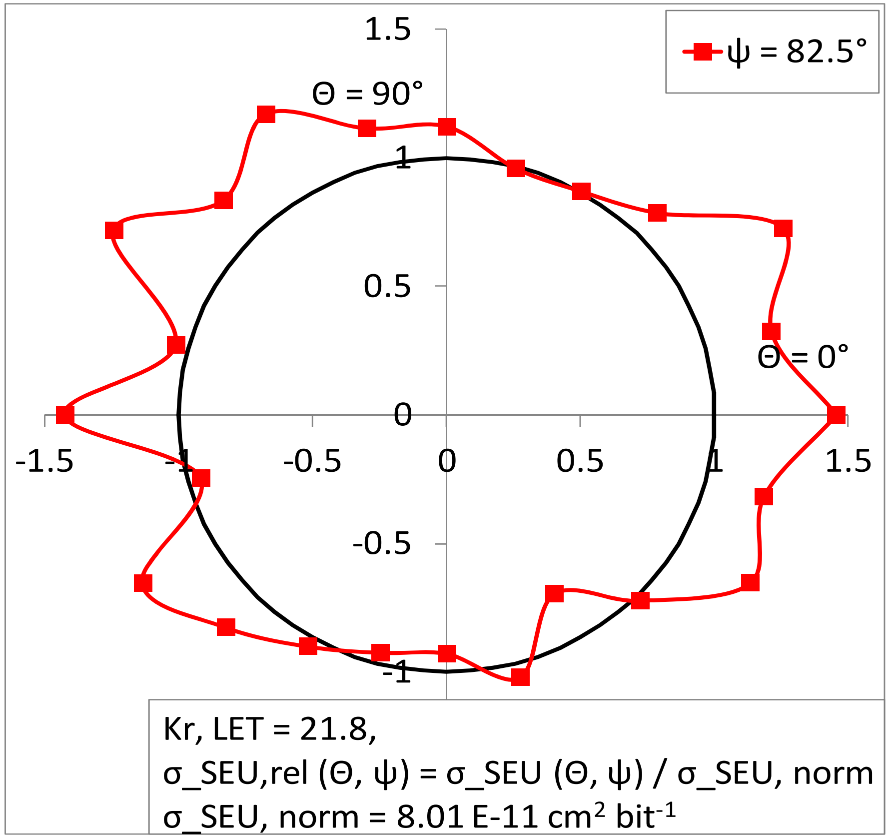




- Samsung 4x8-Gbit, Kr, TAMU, Texas
- strong angular dependence

NAND-Flash SEE HI: Omni directional ion incidence



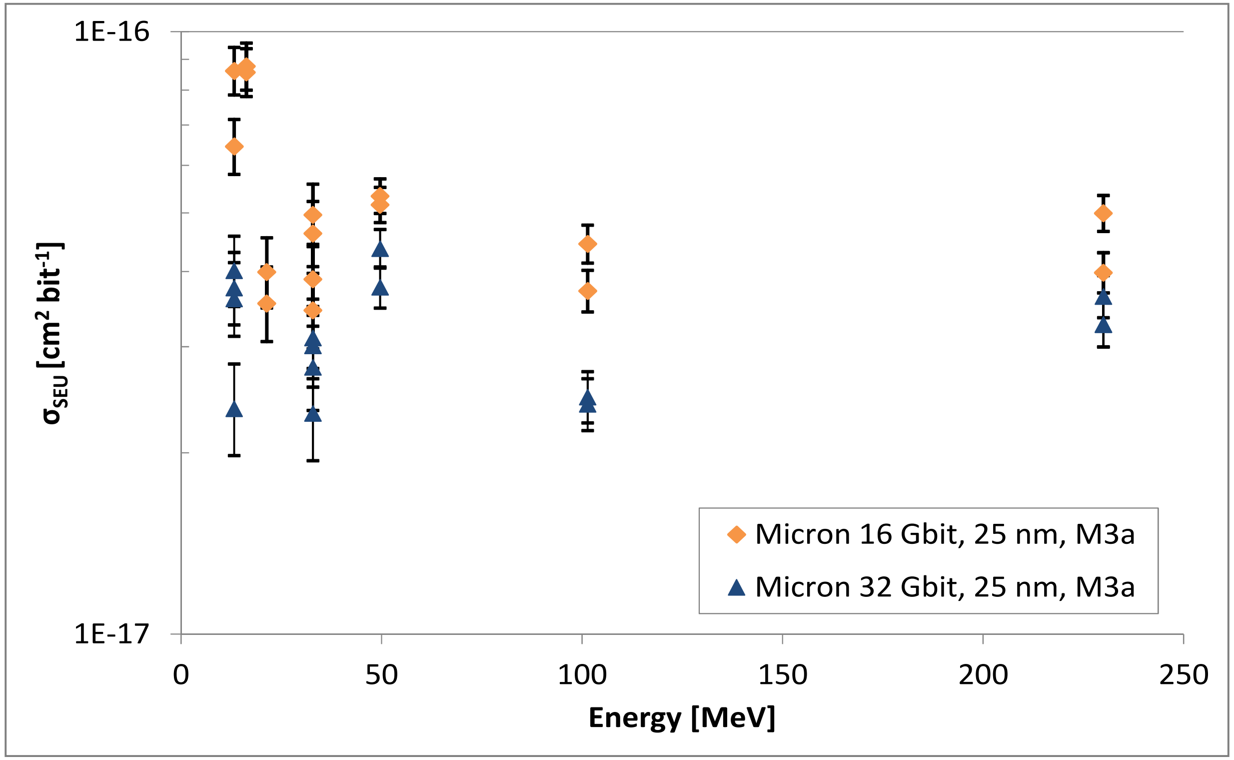


- Micron 16-Gbit, Kr, TAMU, Texas
- weak angular dependence

NAND-Flash results

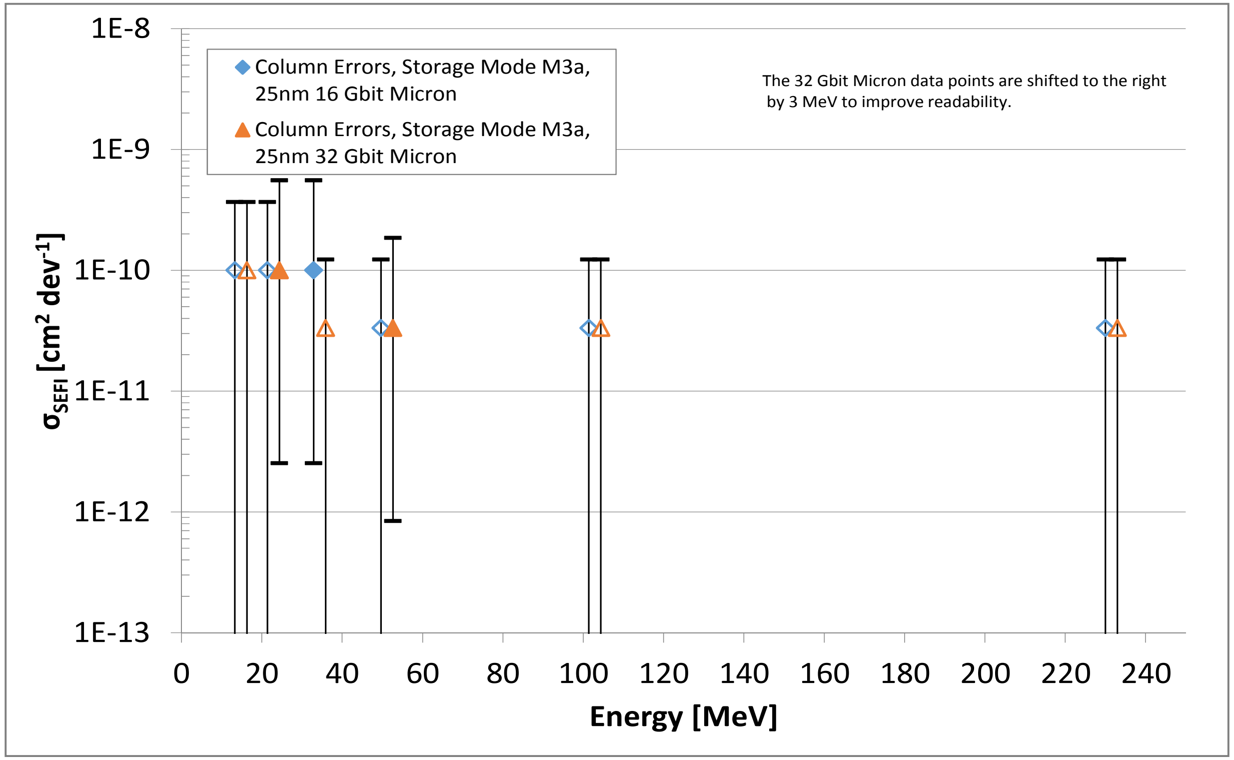
Proton SEE

NAND-Flash SEE Proton: SEU



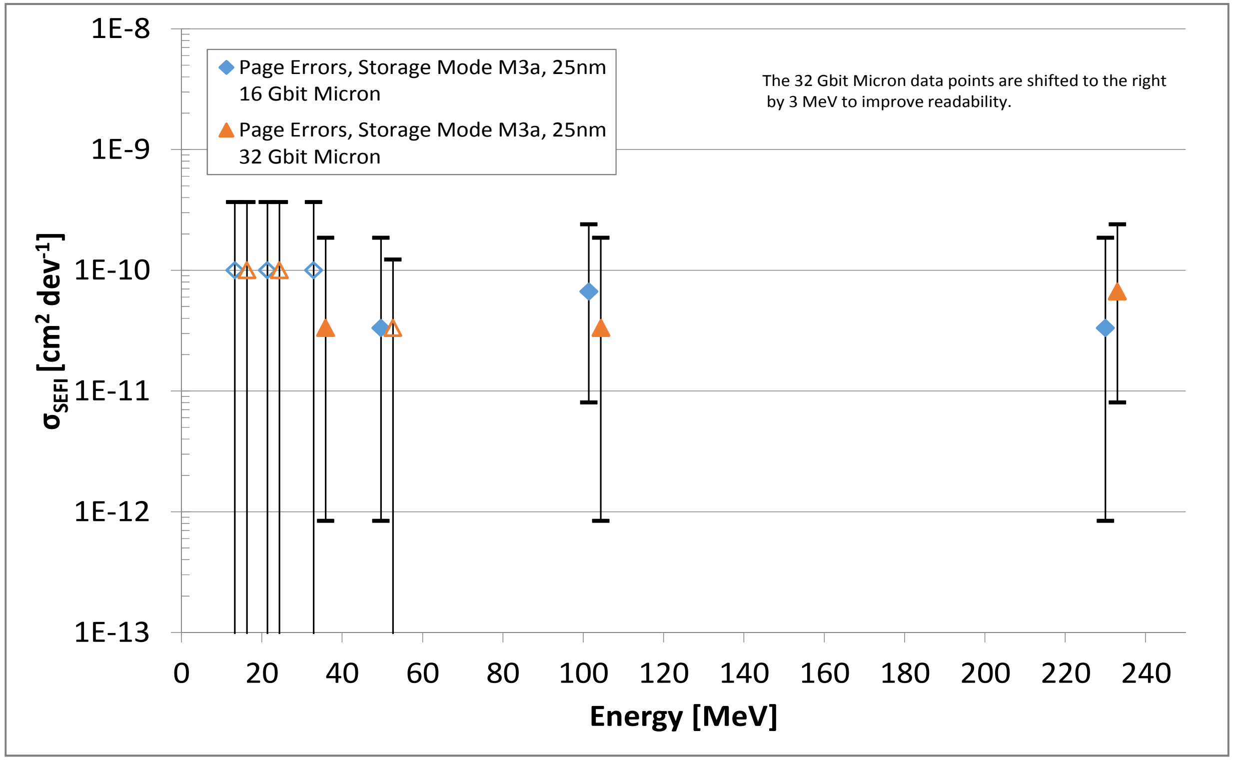
- 25 nm NAND-Flash is by three orders of magnitude more sensitive to proton SEUs than 51 nm NAND-Flash
- increase of SEUs towards low energies
- should be investigated further to exclude peculiarities of the source

NAND-Flash SEE Proton: SEFI, Column Errors



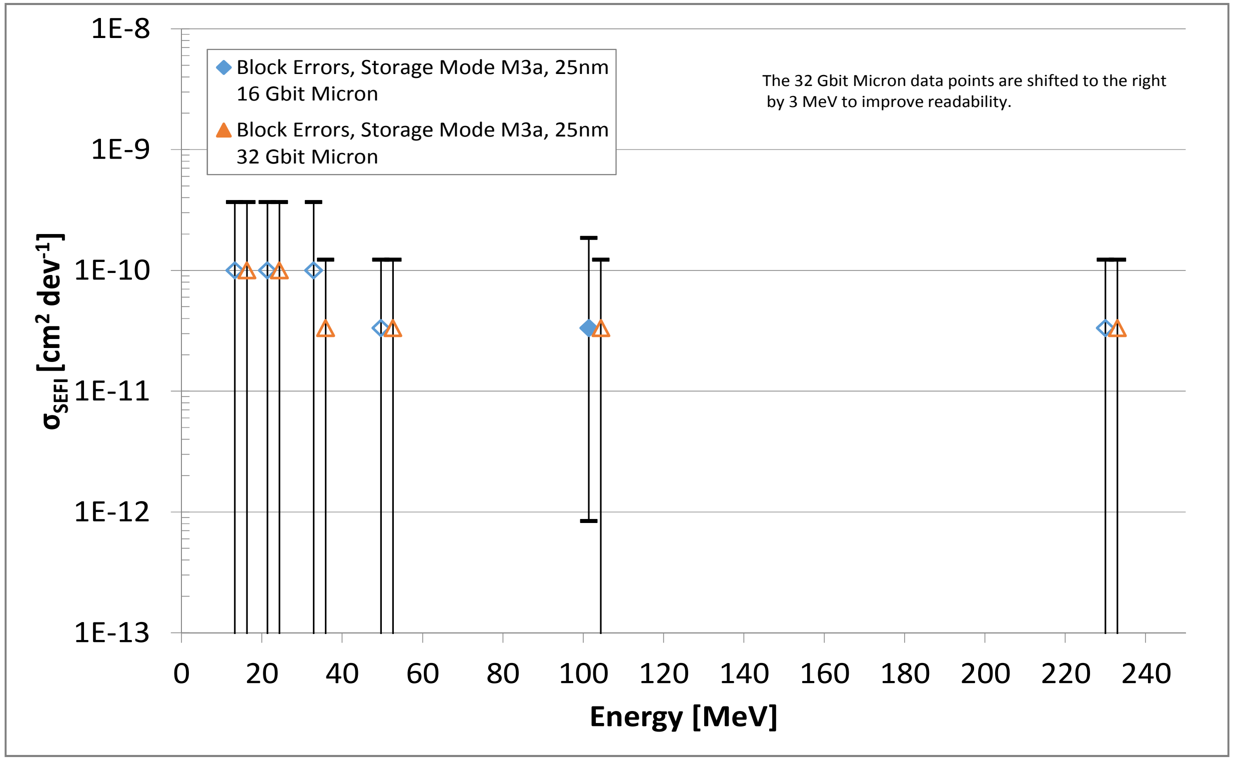
- the SEFI count is very low
- to get more SEFI events a higher fluence is needed
- limited beam time
- limited total dose

NAND-Flash SEE Proton: SEFI, Row Errors



- the SEFI count is very low
- to get more SEFI events a higher fluence is needed
- limited beam time
- limited total dose

NAND-Flash SEE Proton: SEFI, Block Errors

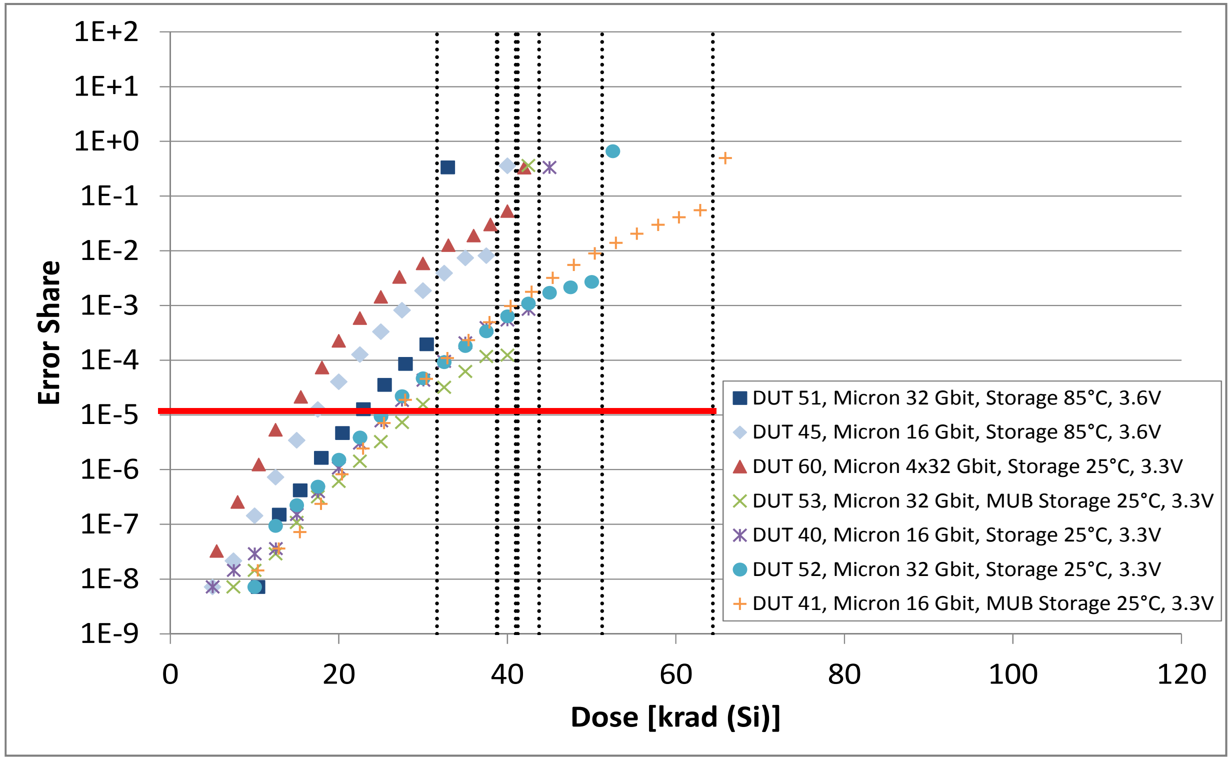


- the SEFI count is very low
- to get more SEFI events a higher fluence is needed
- limited beam time
- limited total dose
- **No Destructive Failure or SEL observed**

NAND-Flash results

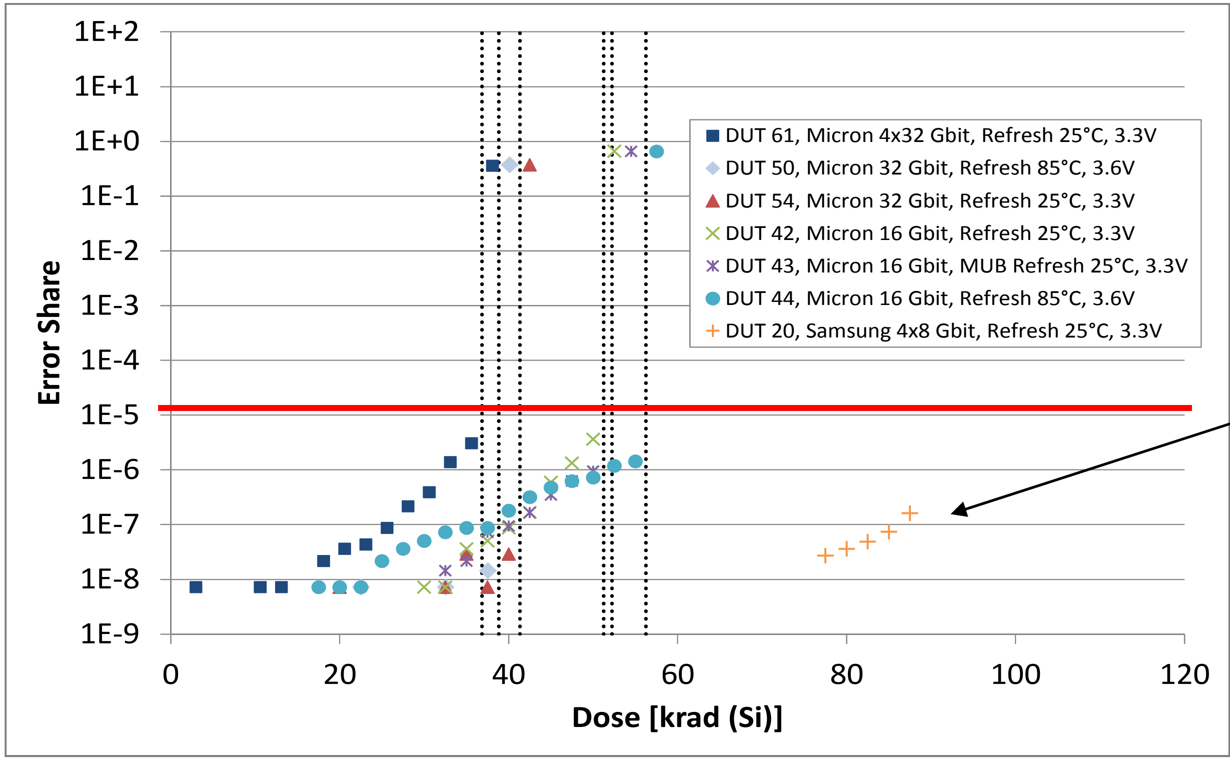
^{60}Co TID

NAND-Flash TID: Error Share in Storage Mode



- Class A SEUs and Class D Destructive Failures were observed
- no Class B or C SEFIs
- functional breakdown of each DUT is marked with dotted line
- first random data errors already between 5 and 10 krad(Si)
- Destructive Failure between 32 and 64 krad (Si)

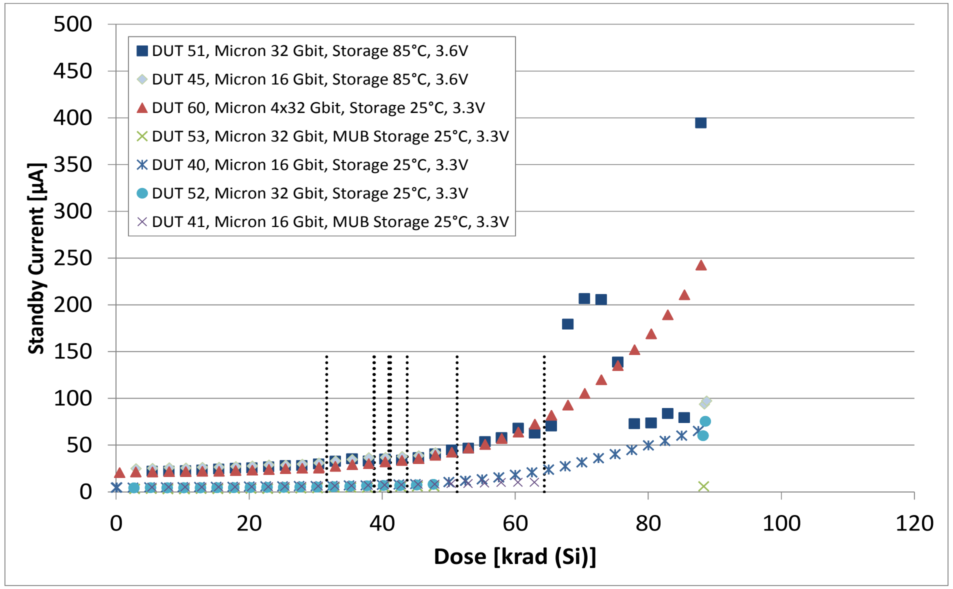
NAND-Flash TID: Error Share in Refresh Mode



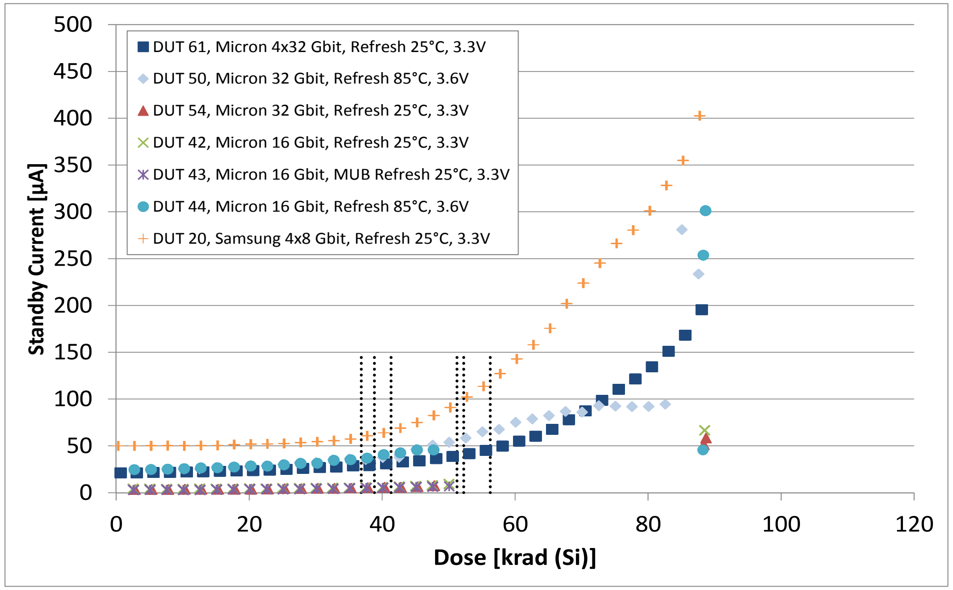
- Samsung 51nm: first SEUs after 70 krad(Si), no functional breakdown until end of test at 90 krad(Si)

- Refresh every 2.5 krad(Si)
- first random data errors already between 3 and 30 krad(Si)
- periodic refresh keeps the error share below $1 \cdot 10^{-5}$, tolerable before ECC
- Refresh has no influence on the Destructive Failure
- with periodic refresh the Destructive Failure occurrence determines the total dose

NAND-Flash TID: Standby Current



Storage Mode



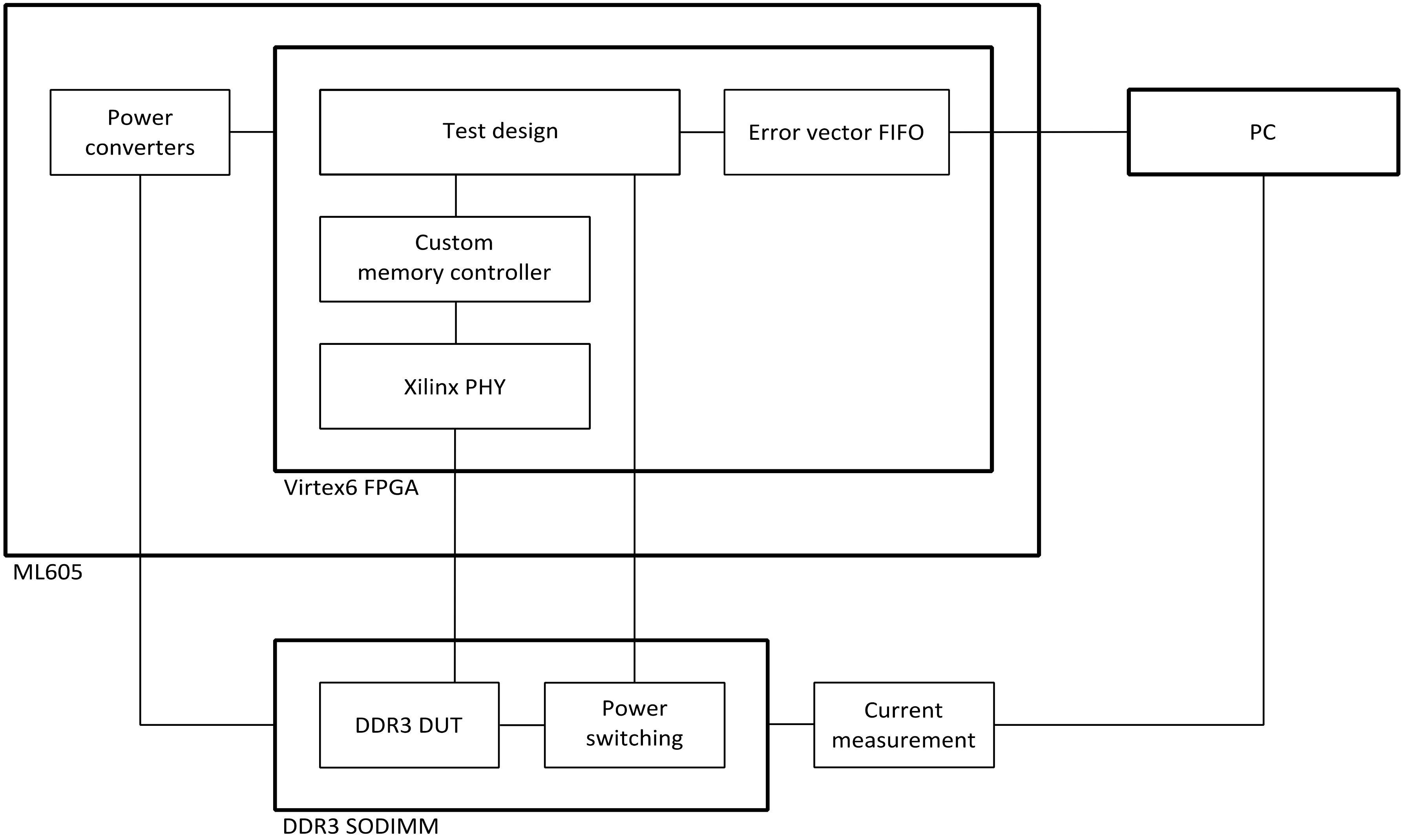
Refresh Mode

- no correlation between standby current increase and Destructive Failure
- standby current remains below the specified datasheet value at DF
- After DF the standby current increases further or drops again in some cases
- Standby current of DUTs operated at 3.6V is by a factor of 5 higher compared to the 3.3V DUTs

DDR3 – Overview

- Test equipment
- DUT preparation
- Test procedures
- Test results
  - Heavy-ion SEE
  - Proton SEE
  - ^{60}Co TID

DDR3 – Test equipment

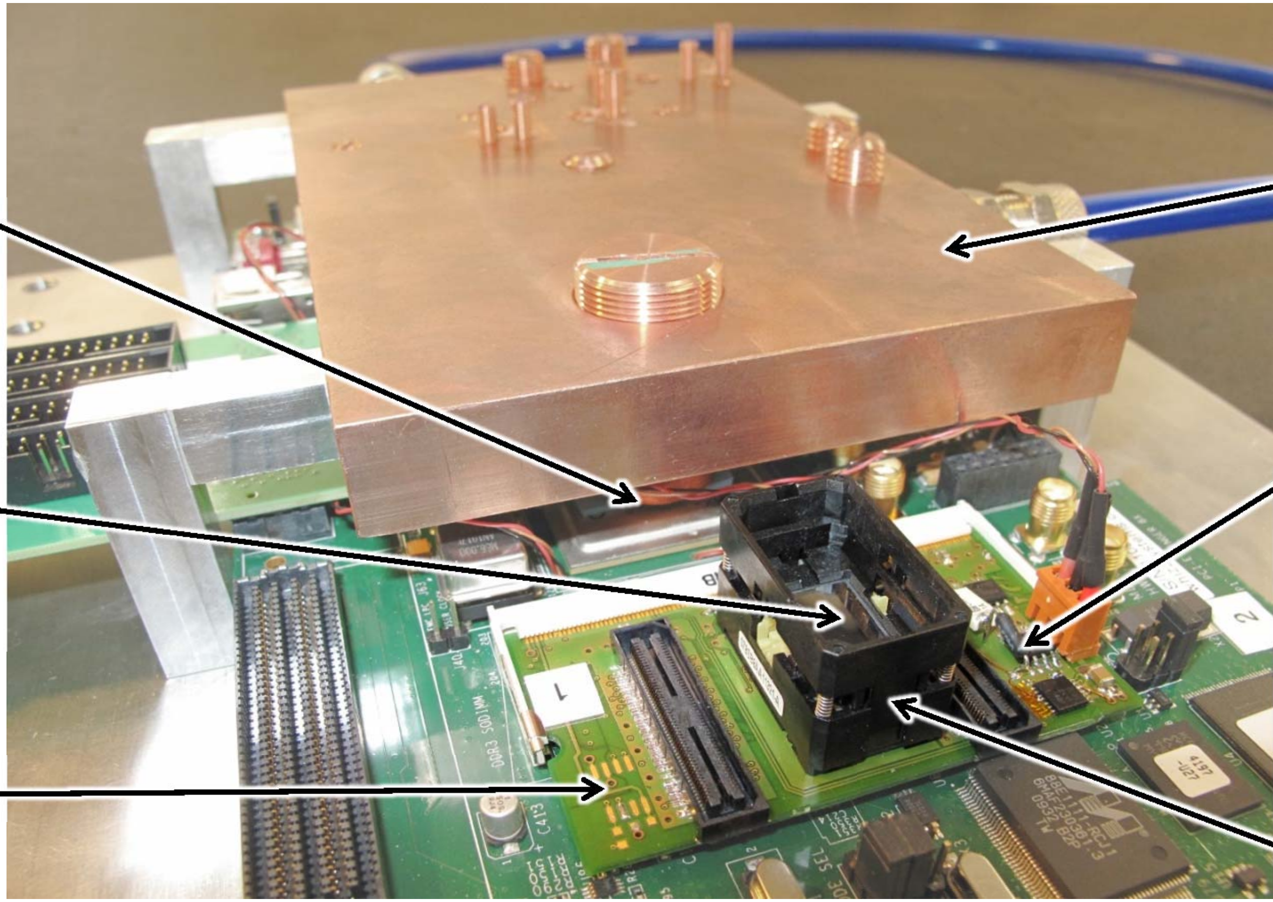


DDR3 – Test equipment

FPGA
(Xilinx Virtex6)

DDR3 device
(opened)

Custom
SODIMM



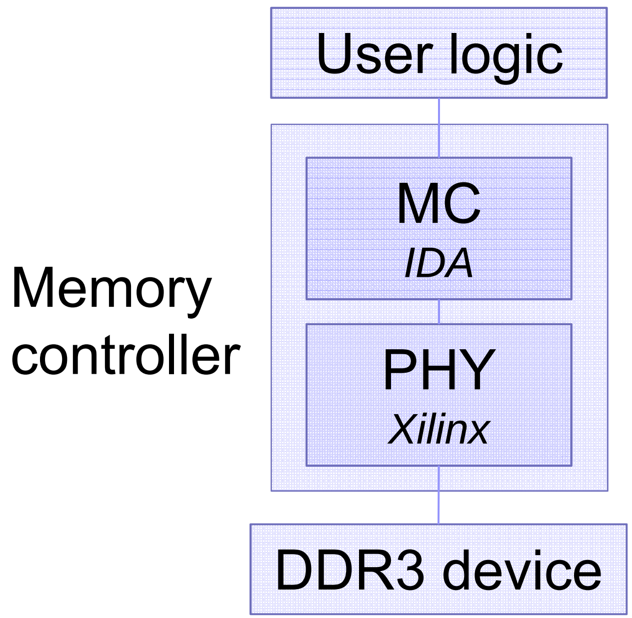
Water cooler

Power switching

ZIF socket

DDR3 – Test equipment – SDRAM controller

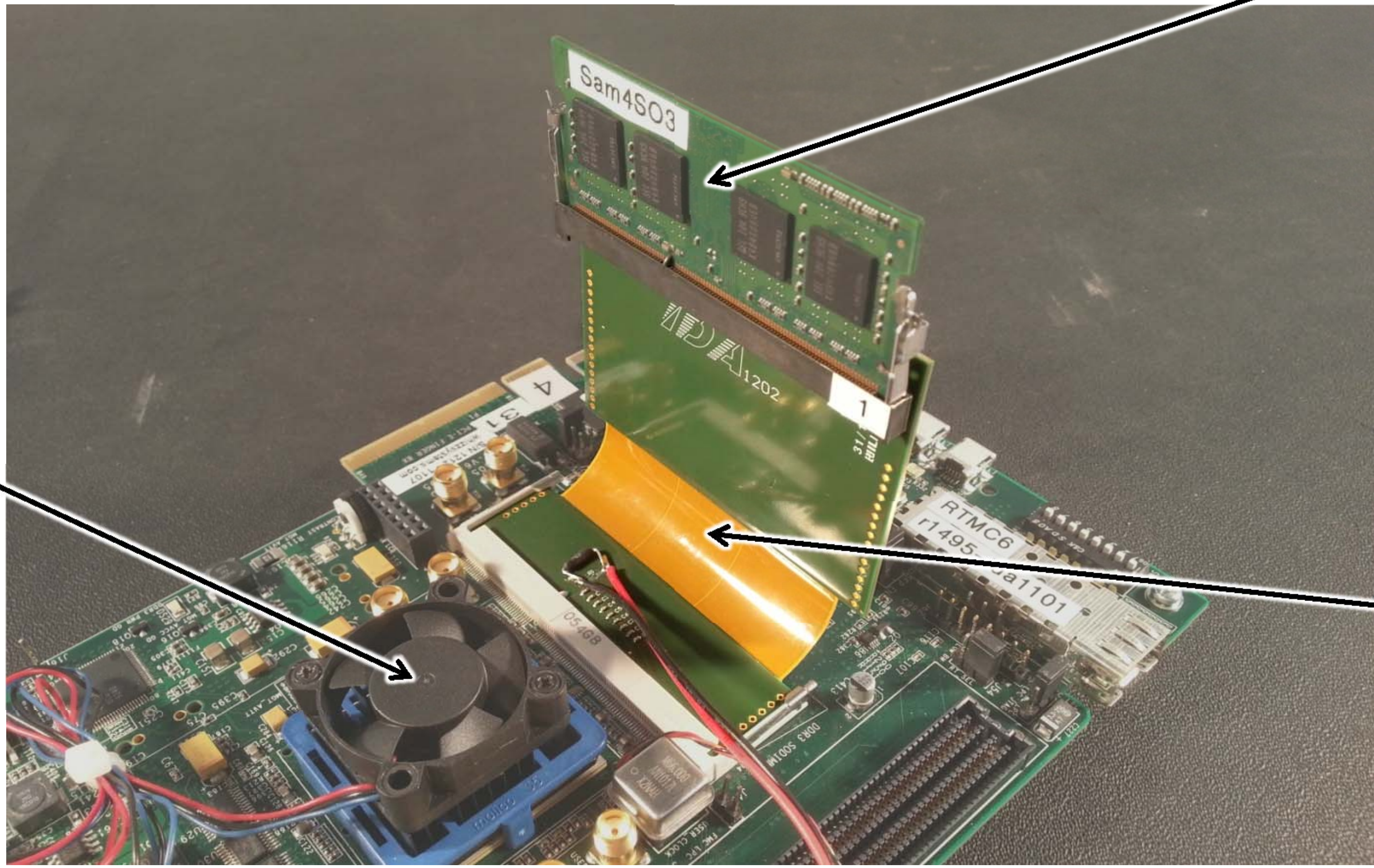
- Custom DDR3 SDRAM controller
- Special feature: software conditioning
  - Rewrite mode registers
  - Reset DLL
  - Calibrate ZQ
- Interfaces with Xilinx' PHY



DDR3 – Test equipment

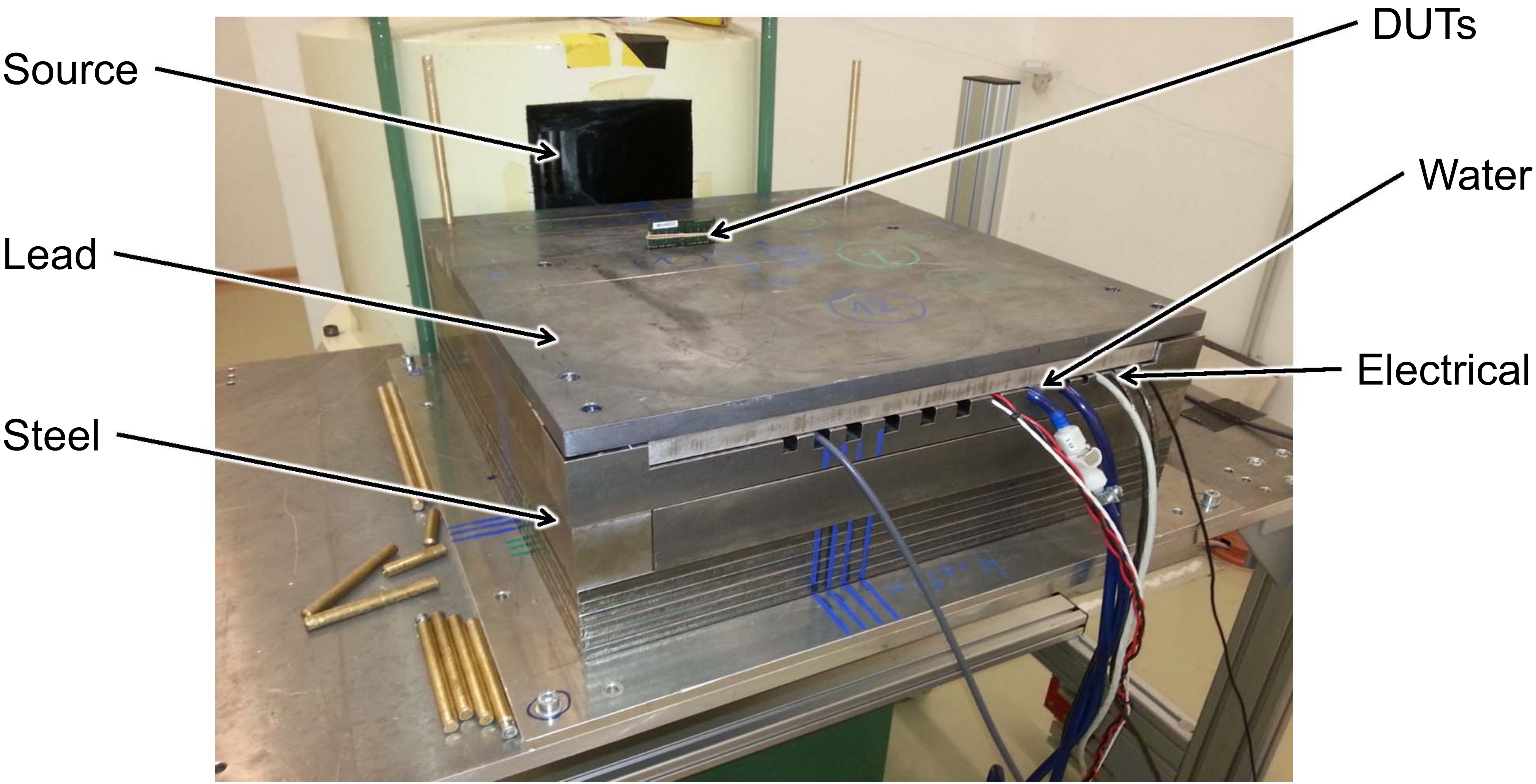
SODIMM

FPGA
(Xilinx Virtex6)

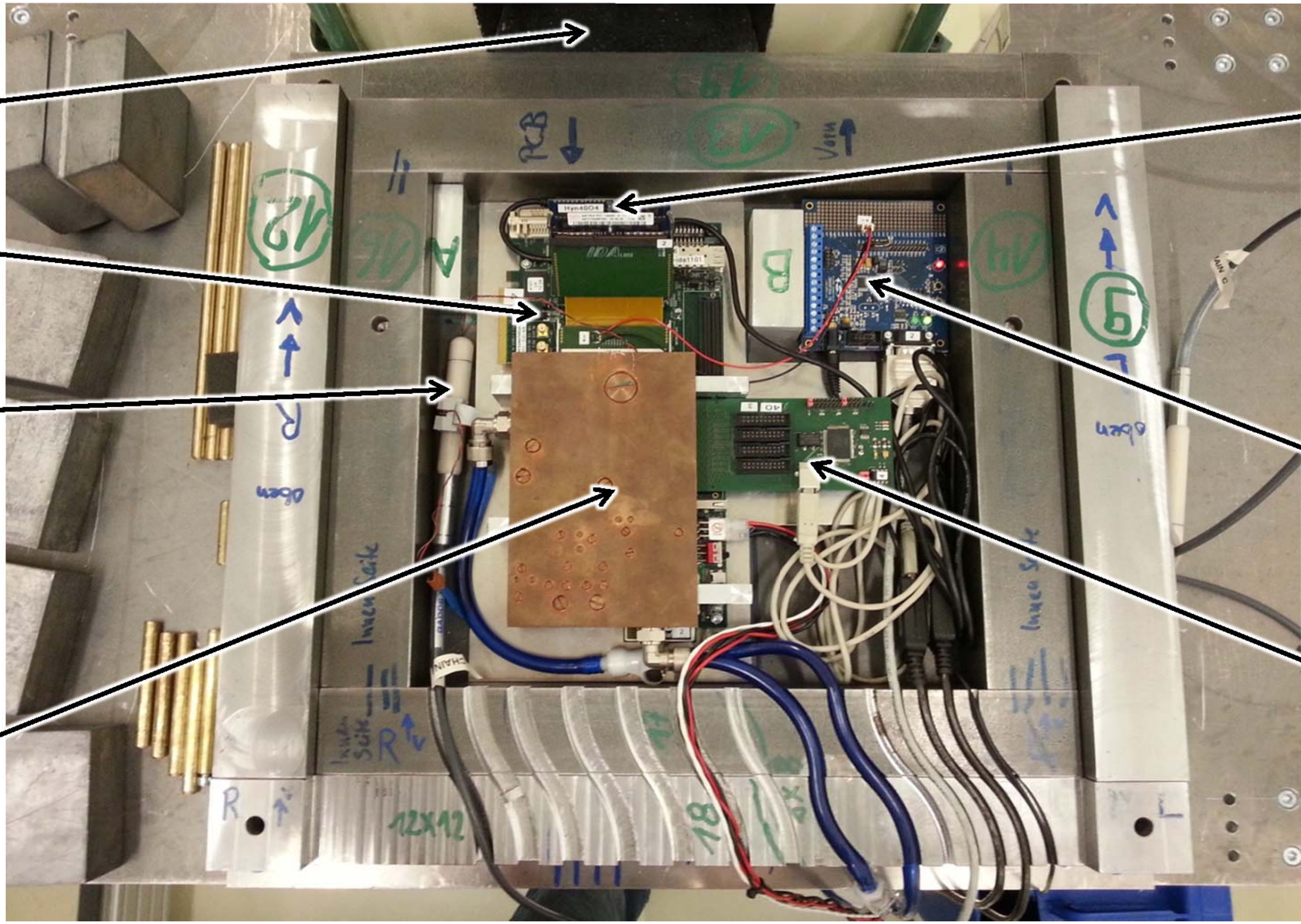


Flexible
extension

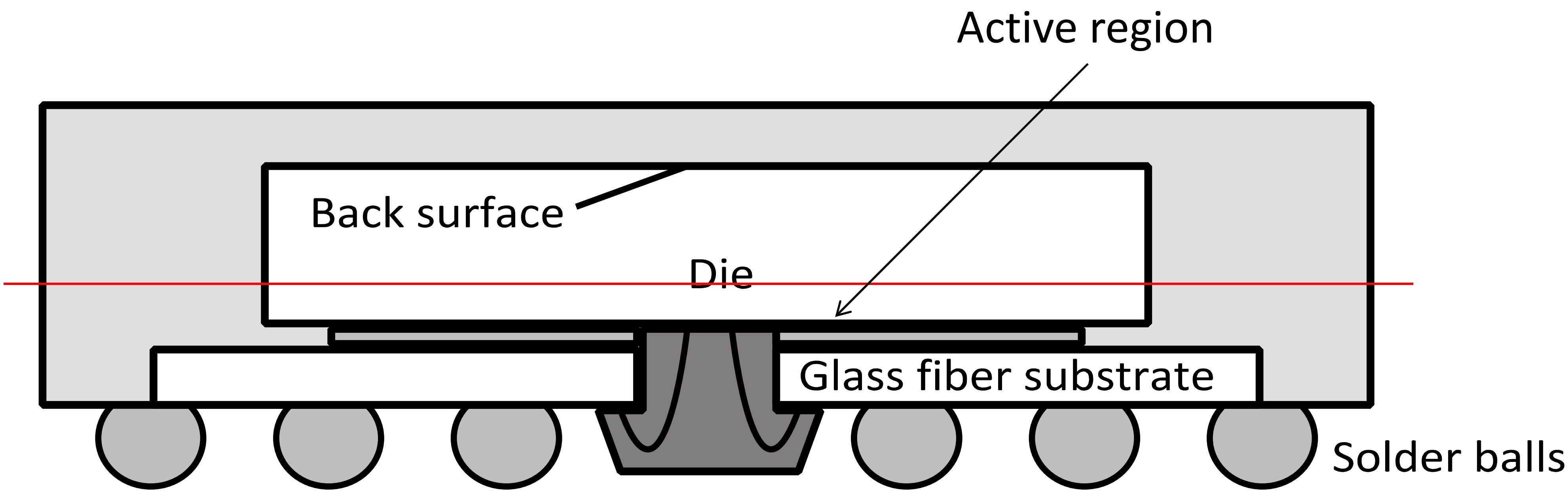
Test equipment – shielding



Test equipment – shielding



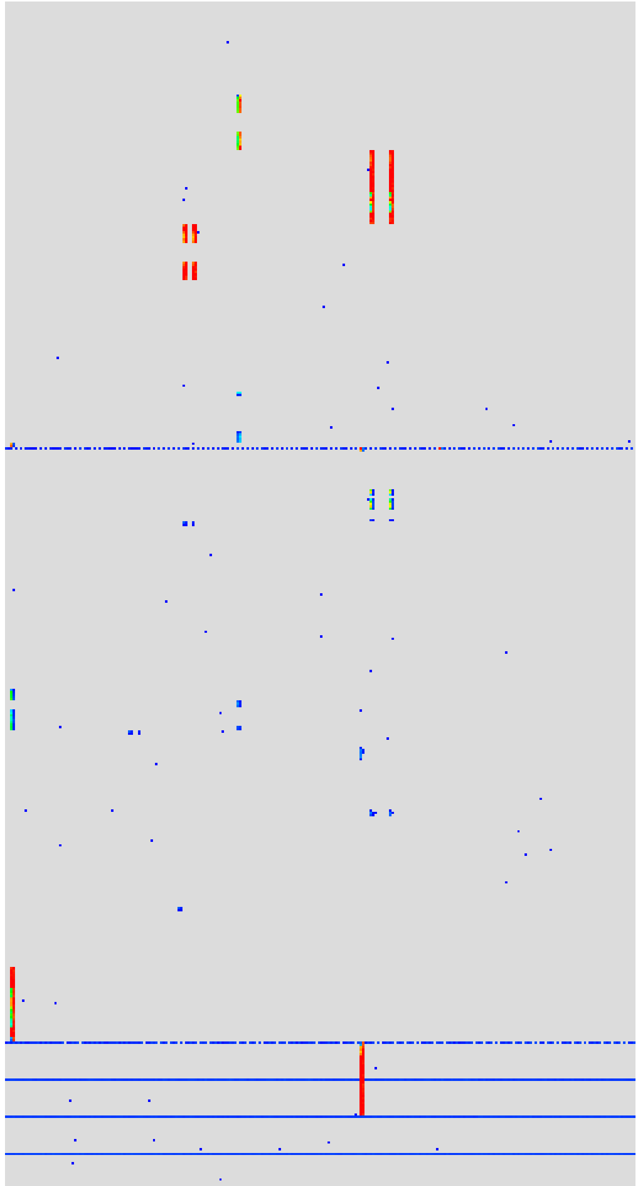
DDR3 – DUT preparation



Thinning was performed by Fraunhofer Institute for Applied Optics and Precision Engineering, Jena

DDR3 – SEE error classification

- SEUs
  - Stuck bits
- Row SEFis
- Column SEFIs
- Device SEFIs



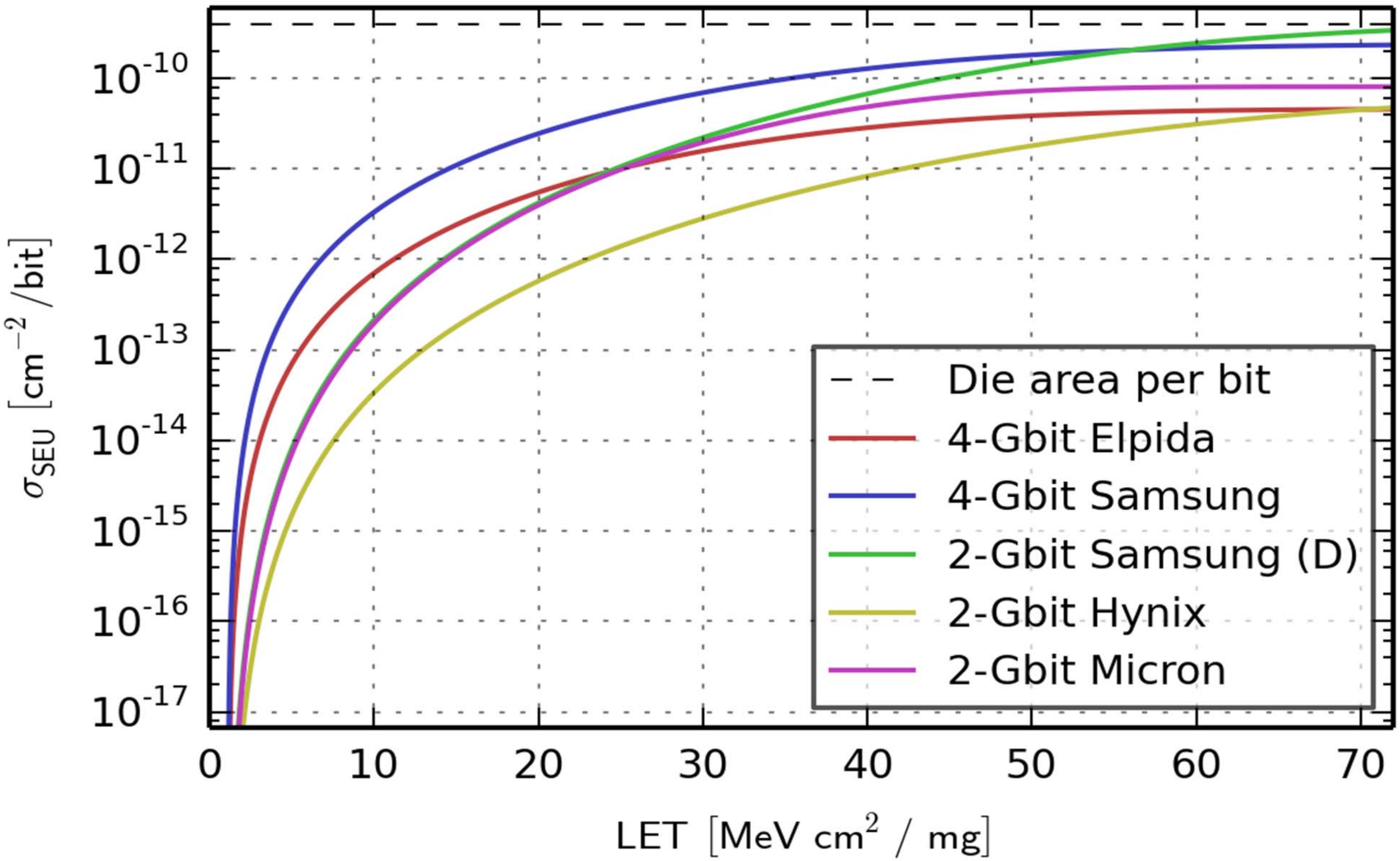
DDR3 SDRAM results

Heavy ion SEE

DDR3 results – heavy ion SEE - Overview

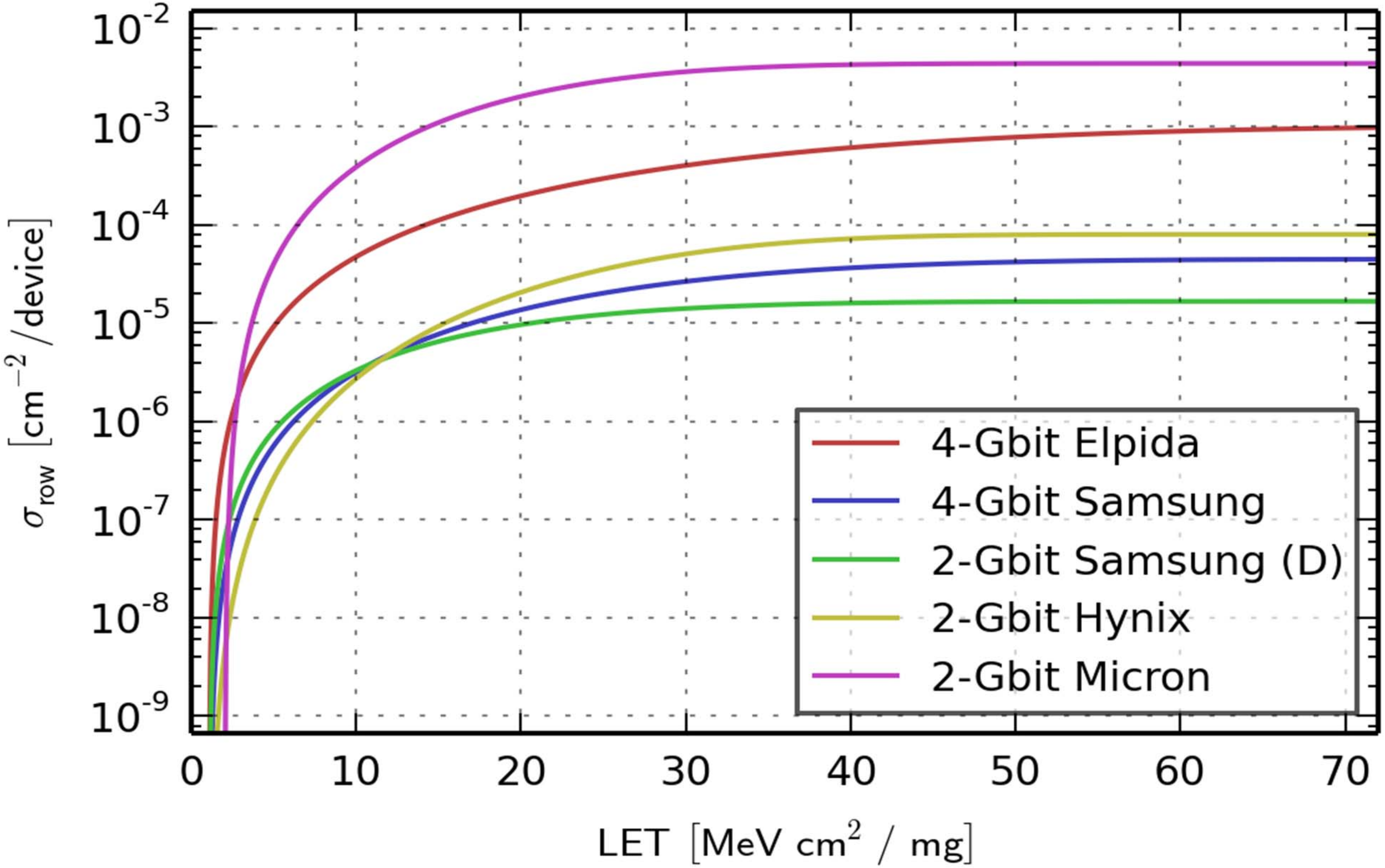
- 4 tests:
  - 3 × RADEF, Jyväskylä
  - 1 × TAMU, College Station
- 7 tested parts:
  - 2 Gbit: Samsung, Hynix, Micron, Nanya
  - 4 Gbit: Samsung, Hynix, Elpida

DDR3 results – heavy ion SEUs

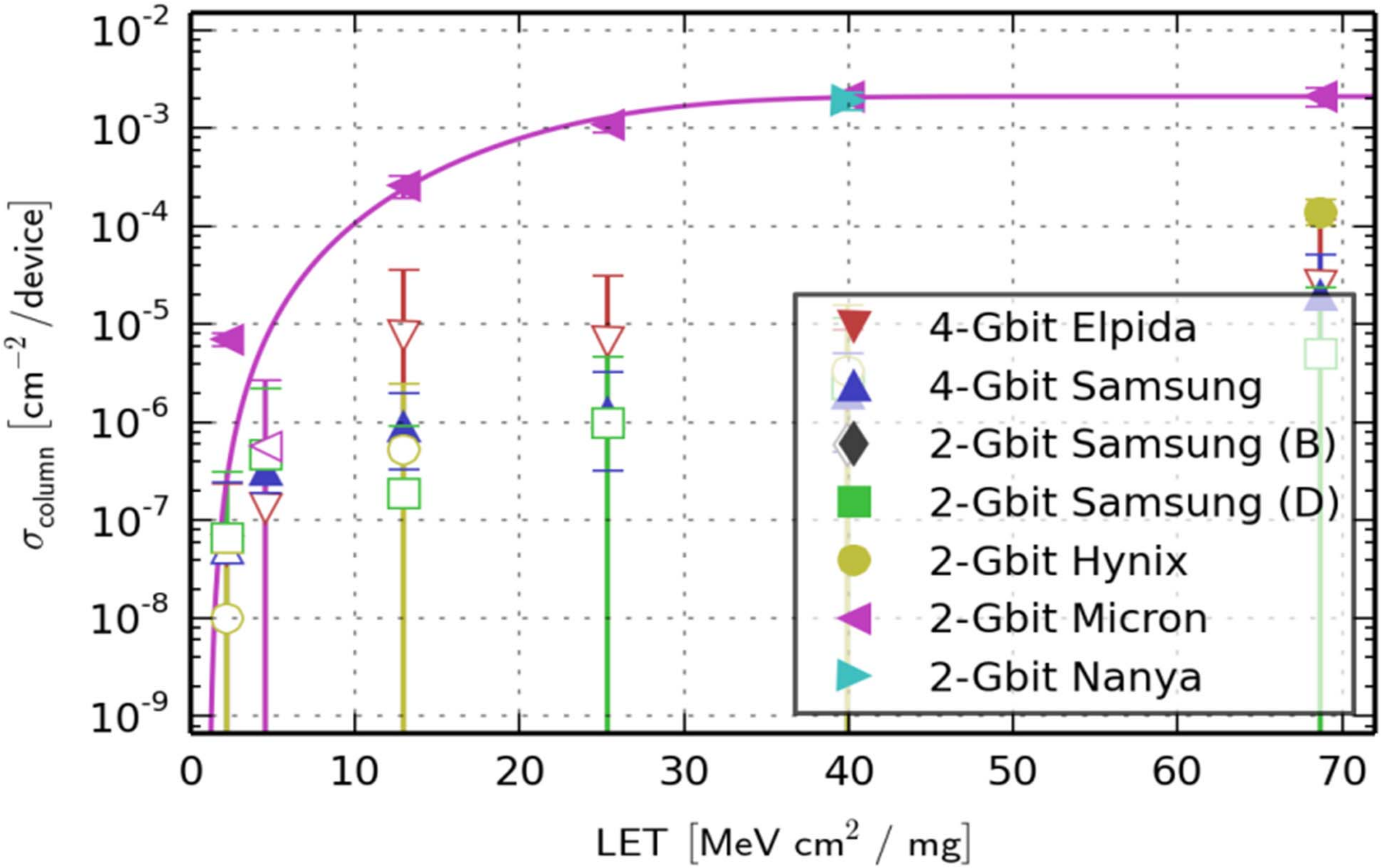


Few MBUs

DDR3 results – heavy ion row SEFIs

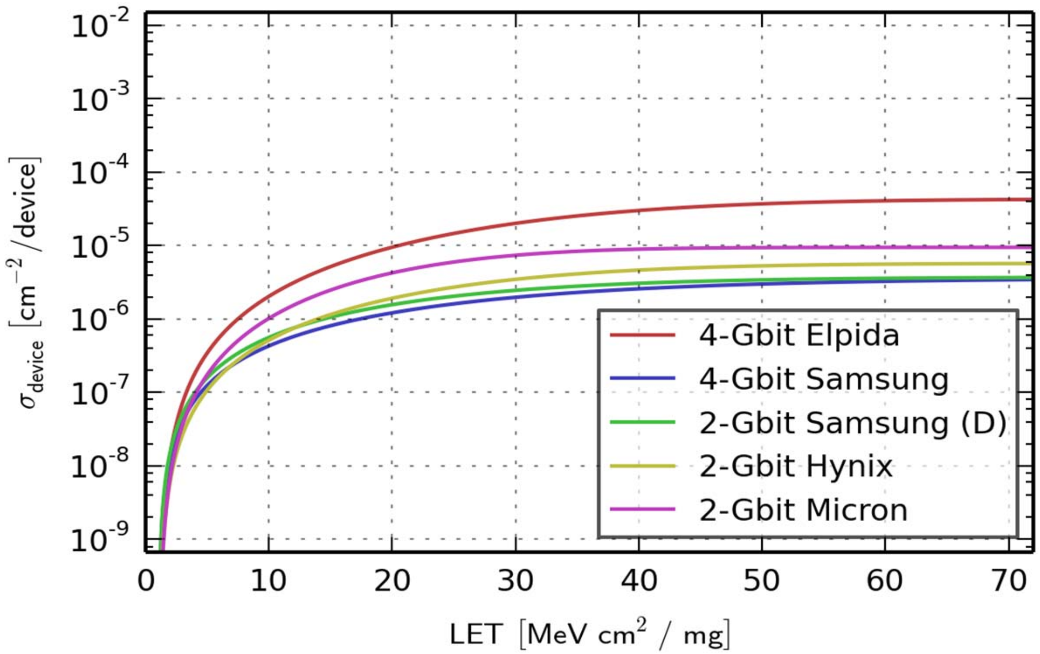


DDR3 results – heavy ion column SEFIs

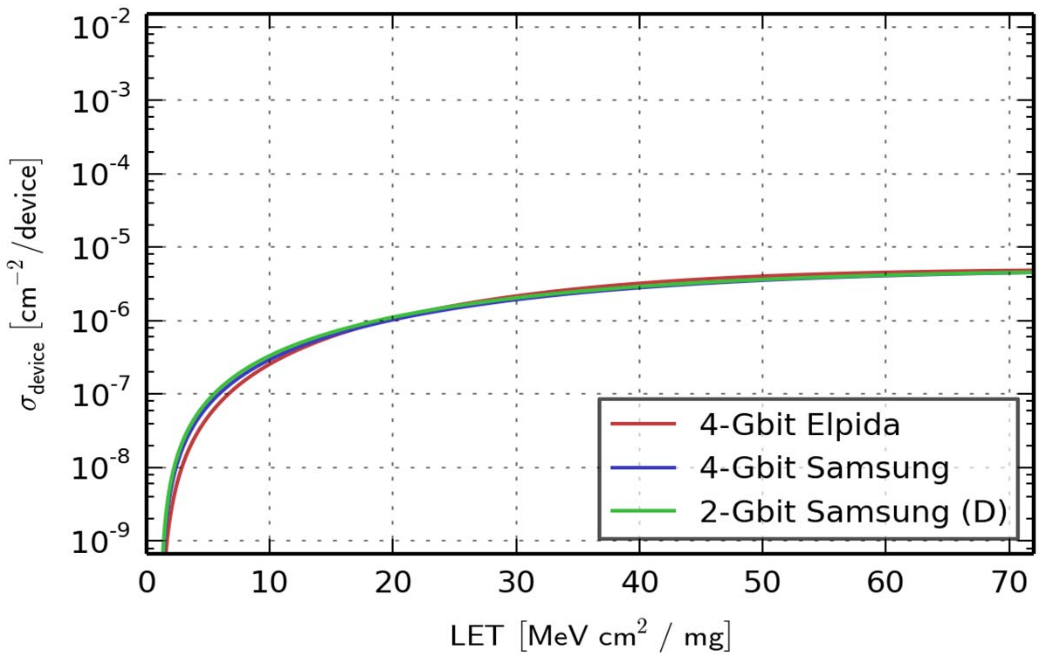


DDR3 results – heavy ion device SEFIs

Without software conditioning



With software conditioning

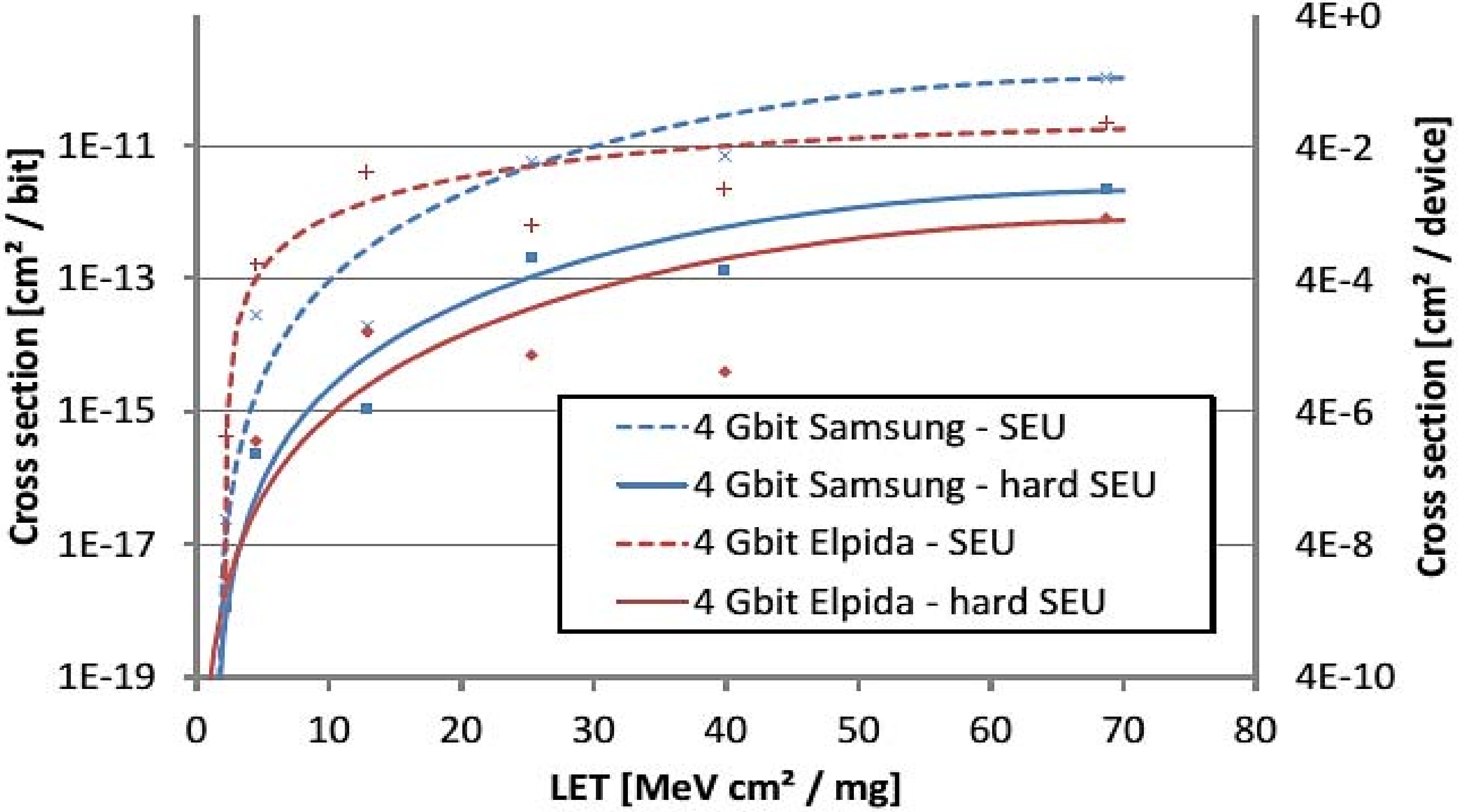


DDR3 results – SEL

- Setup:
  - 4 Gbit, Samsung and Hynix
  - 80 °C
  - 10^7 cm^{-2} Xenon, 61.1 MeV cm^2 / mg
  - Write/read mode
- Result:
  - No SEL
  - Current returns to original value after irradiation

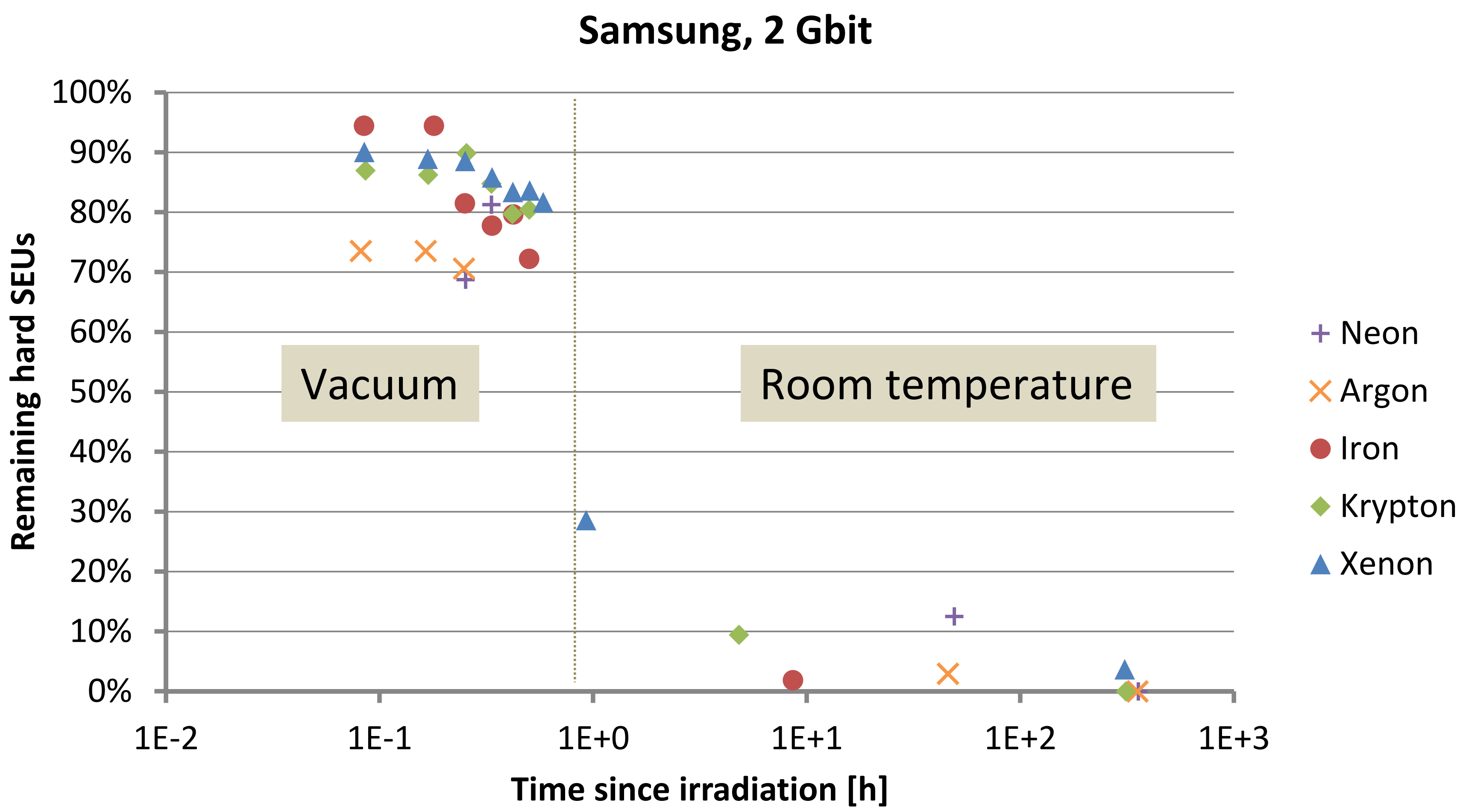
DDR3 results – hard SEUs

- Hard SEUs: can not be removed by rewriting



DDR3 results – hard SEU annealing

No soft SEU annealing for DRAM due to refresh



DDR3 results – heavy ion SEE – SEFI mitigation

- C1
  - Rewrite mode registers
  - DLL reset
  - ZQ calibration

No data loss

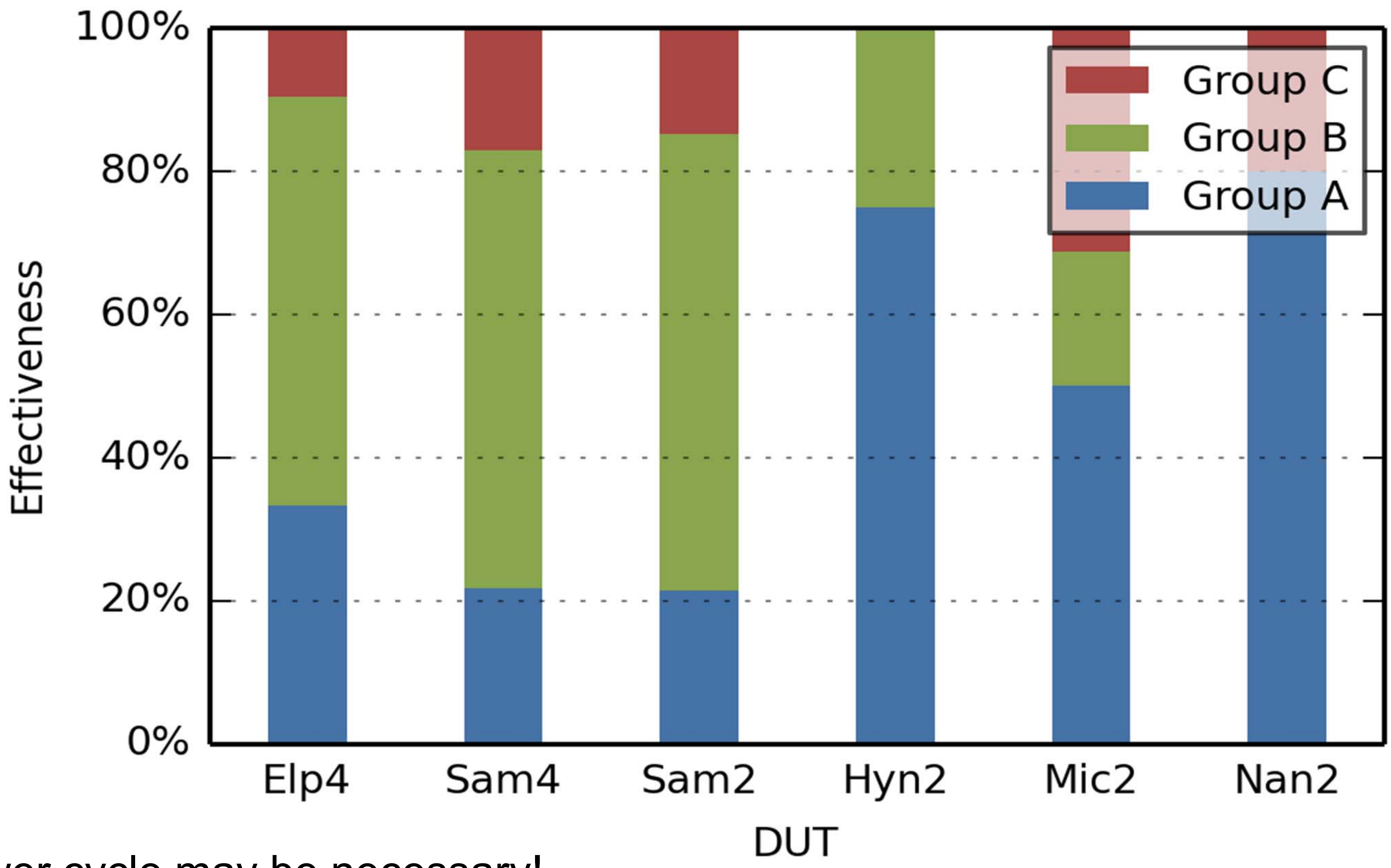
- C2
  - Reset DDR3 device
  - Reset memory controller (recalibrates line delays)

Data retention not guaranteed

- C3
  - Power cycle

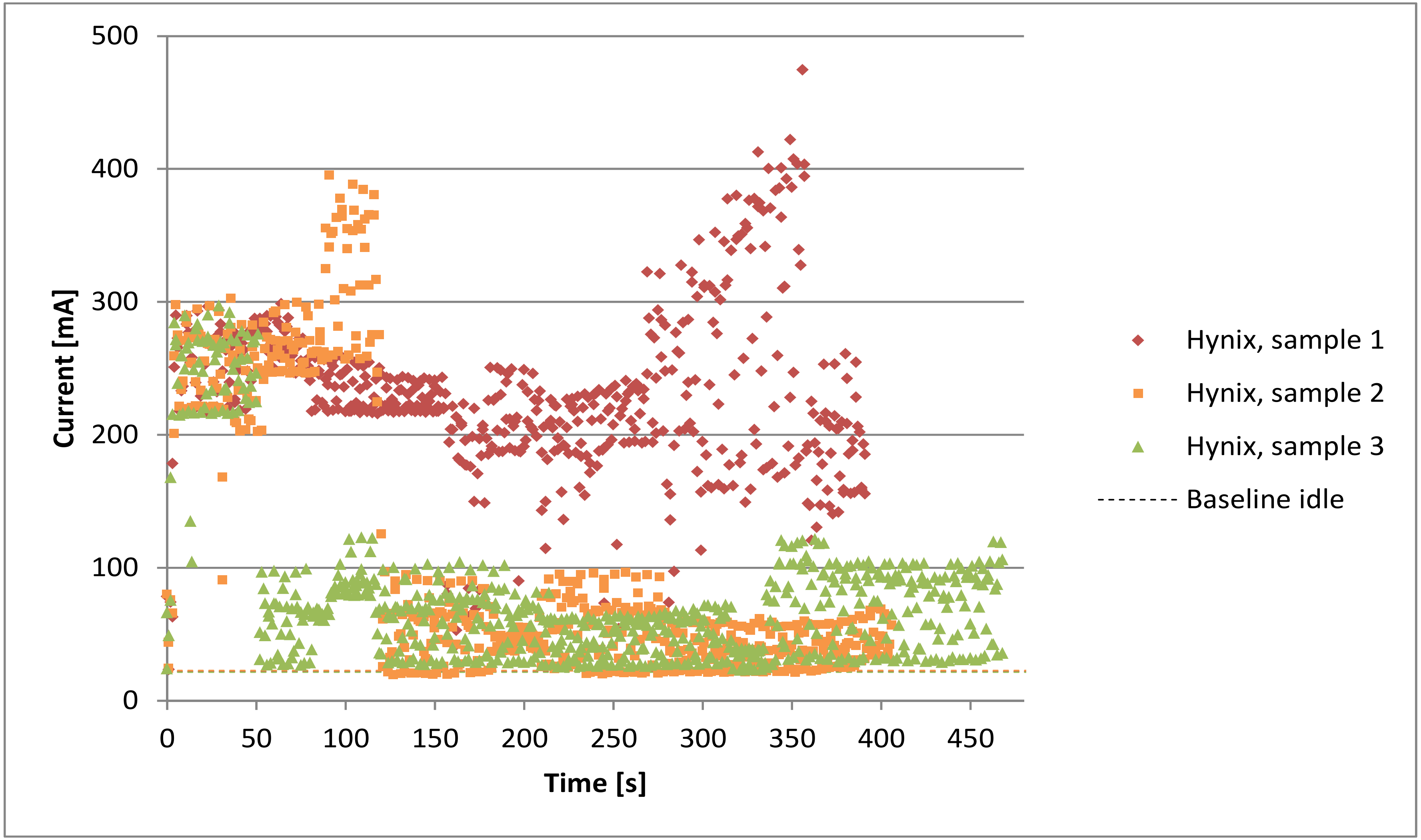
Data loss

DDR3 results – heavy ion SEE – SEFI mitigation



Power cycle may be necessary!

DDR3 results – heavy ion SEE – current

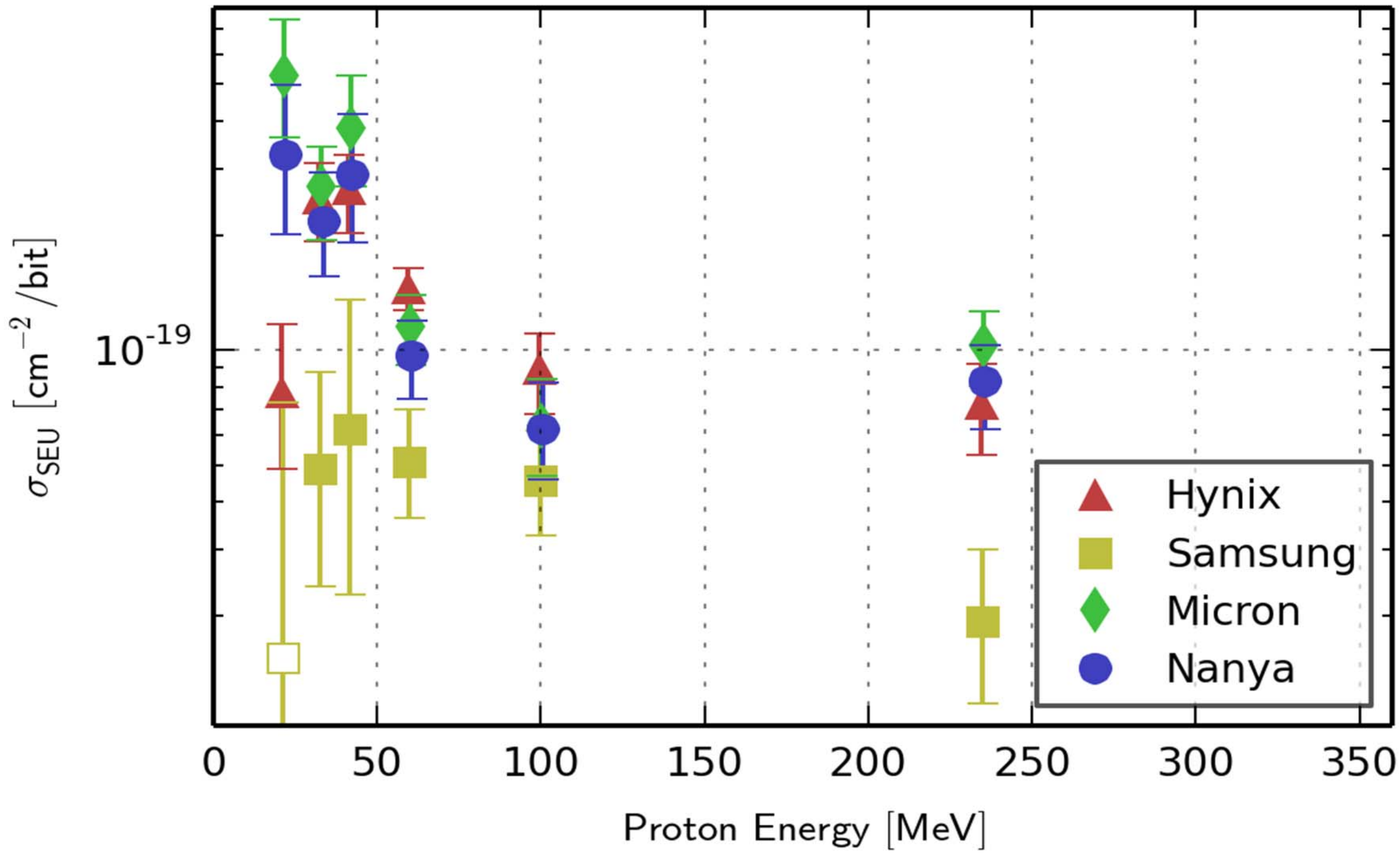


4-Gbit Hynix devices, LET 60 MeV cm^2 / mg, 80 °C

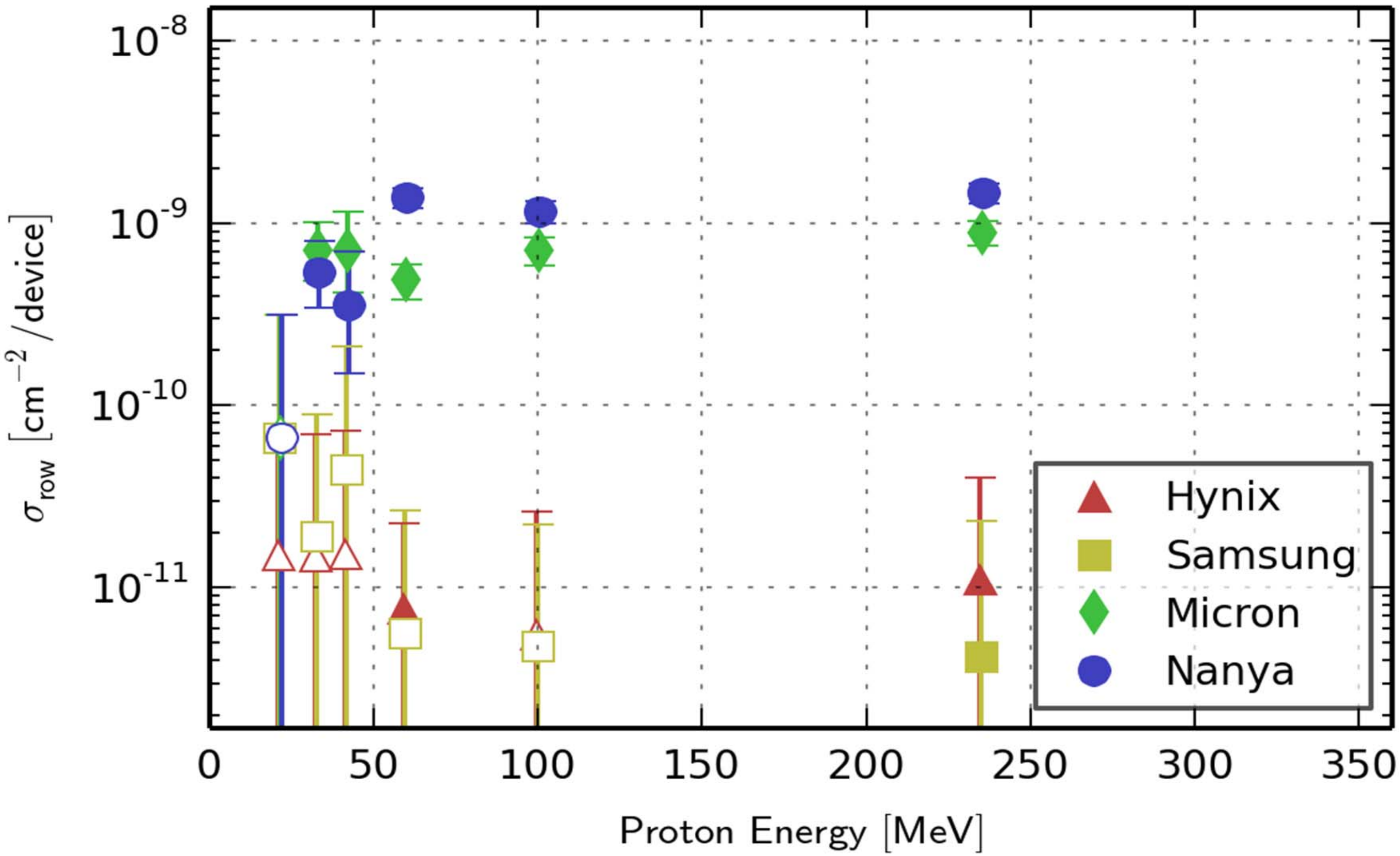
DDR3 SDRAM results

Proton SEE

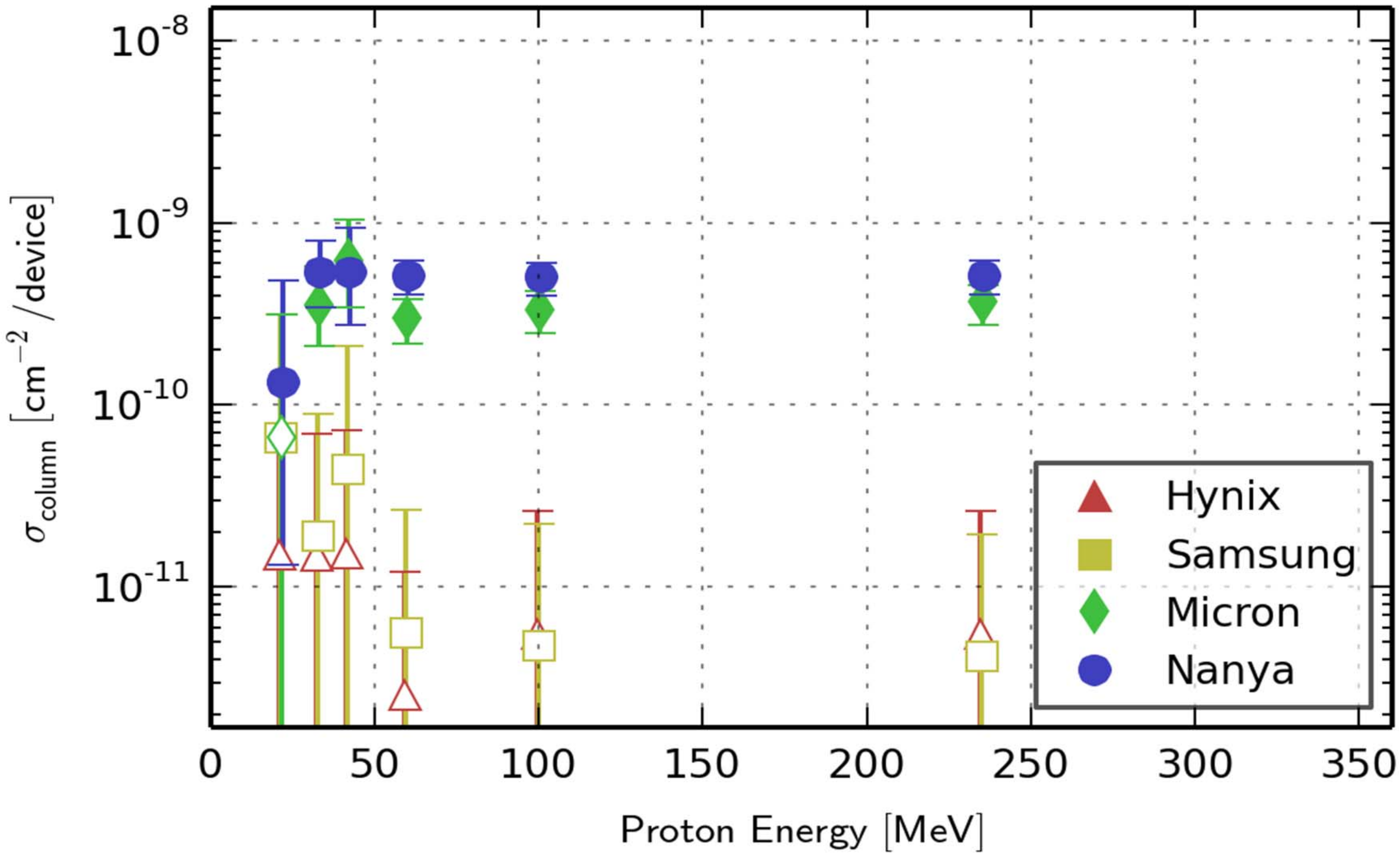
DDR3 results – proton SEUs



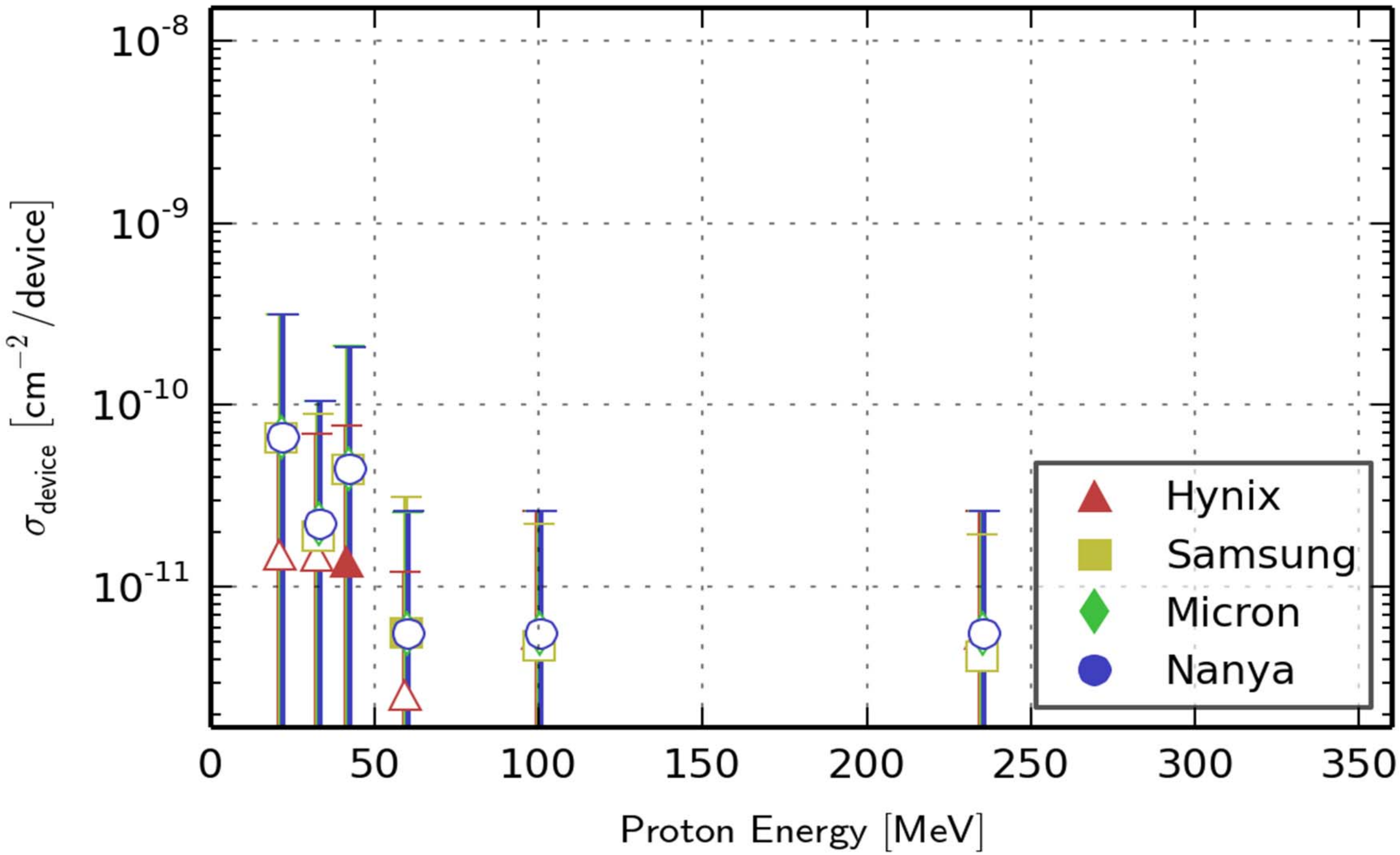
DDR3 results – proton row SEFIs



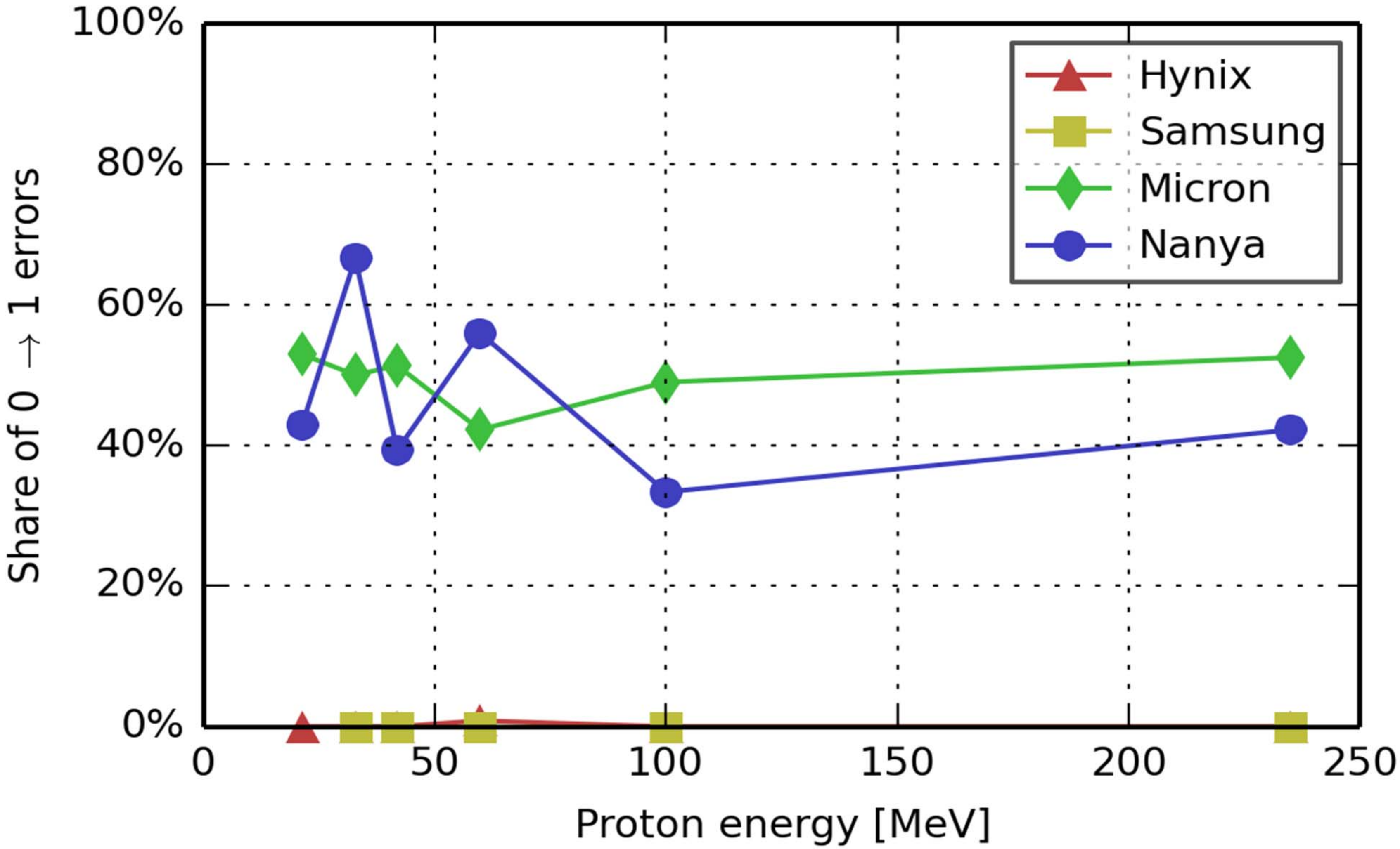
DDR3 results – proton column SEFIs



DDR3 results – proton device SEFIs



DDR3 results – proton SEU polarity



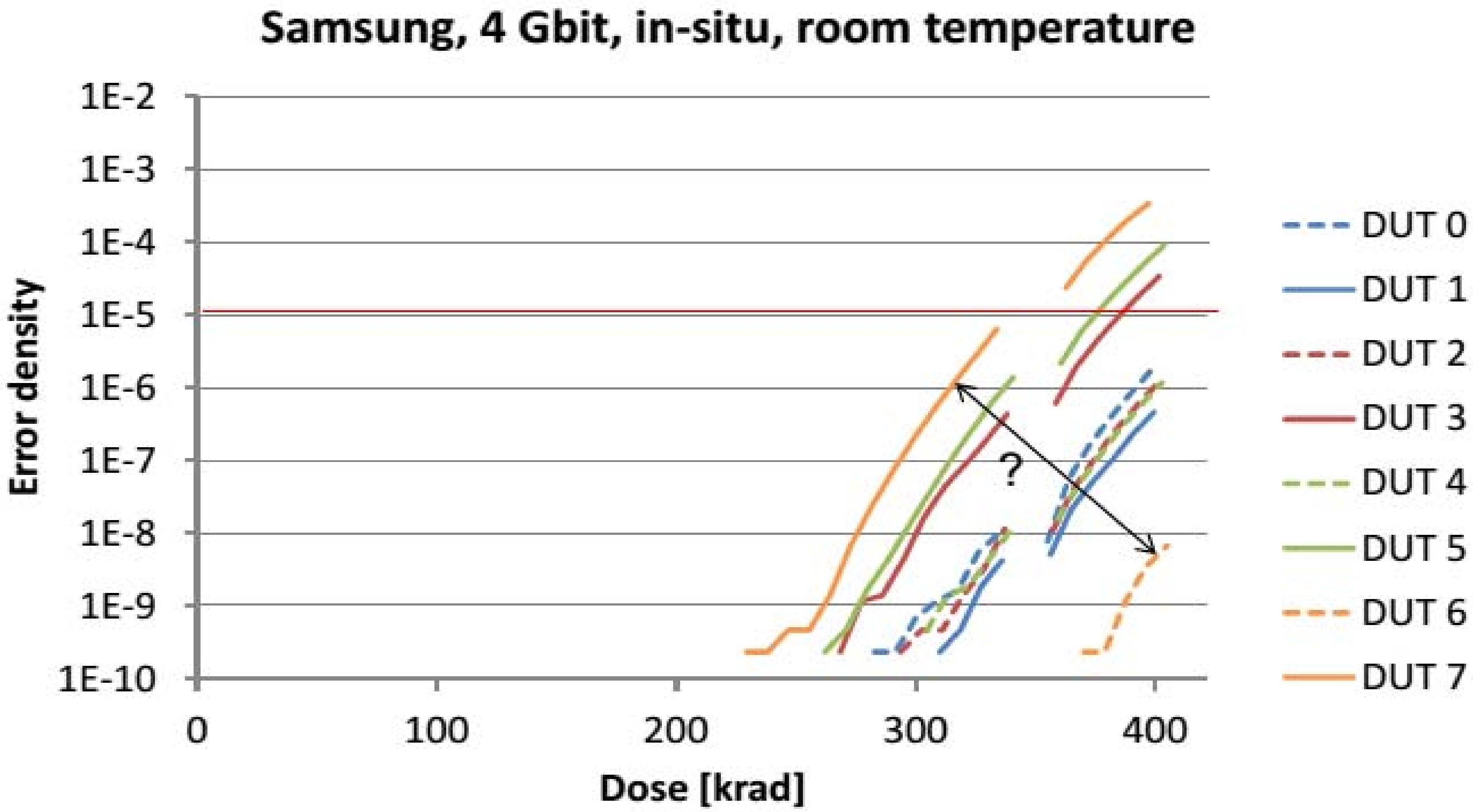
DDR3 SDRAM results

^{60}Co TID

DDR3 results – TID - Overview

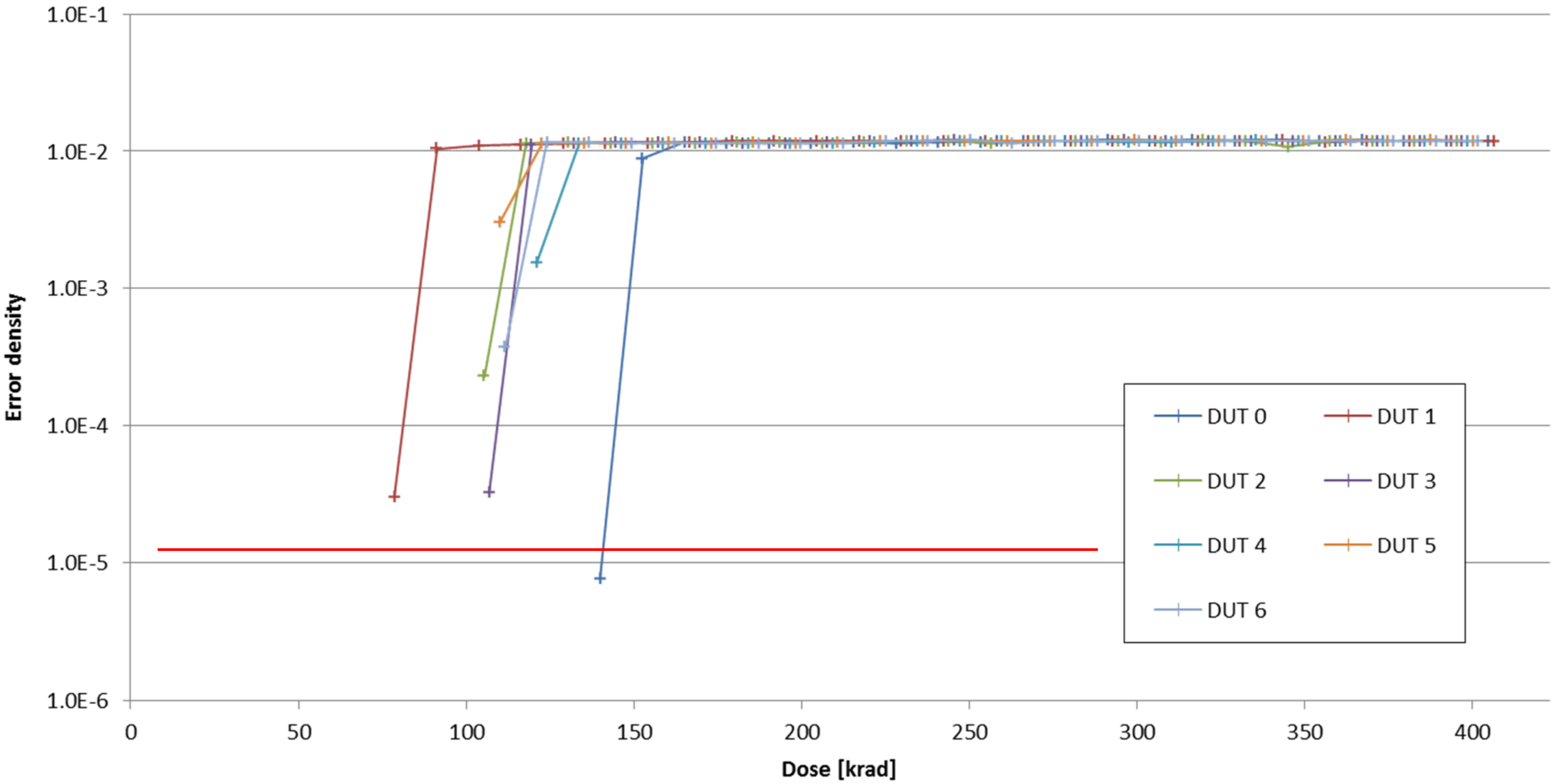
- 4 tests:
  - 2 × In-Situ
  - 2 × Unbiased
- 3 + 7 parts tested:
  - In-Situ, 4 Gbit: Samsung, Hynix, Micron
  - Unbiased, 4 Gbit: Samsung, Hynix, Micron, Nanya, Elpida
  - Unbiased, 2 Gbit: Samsung, Hynix, Micron, Nanya

DDR3 results – TID – error density



DDR3 results – TID – error density

Micron, 4 Gbit, in-situ, room temperature

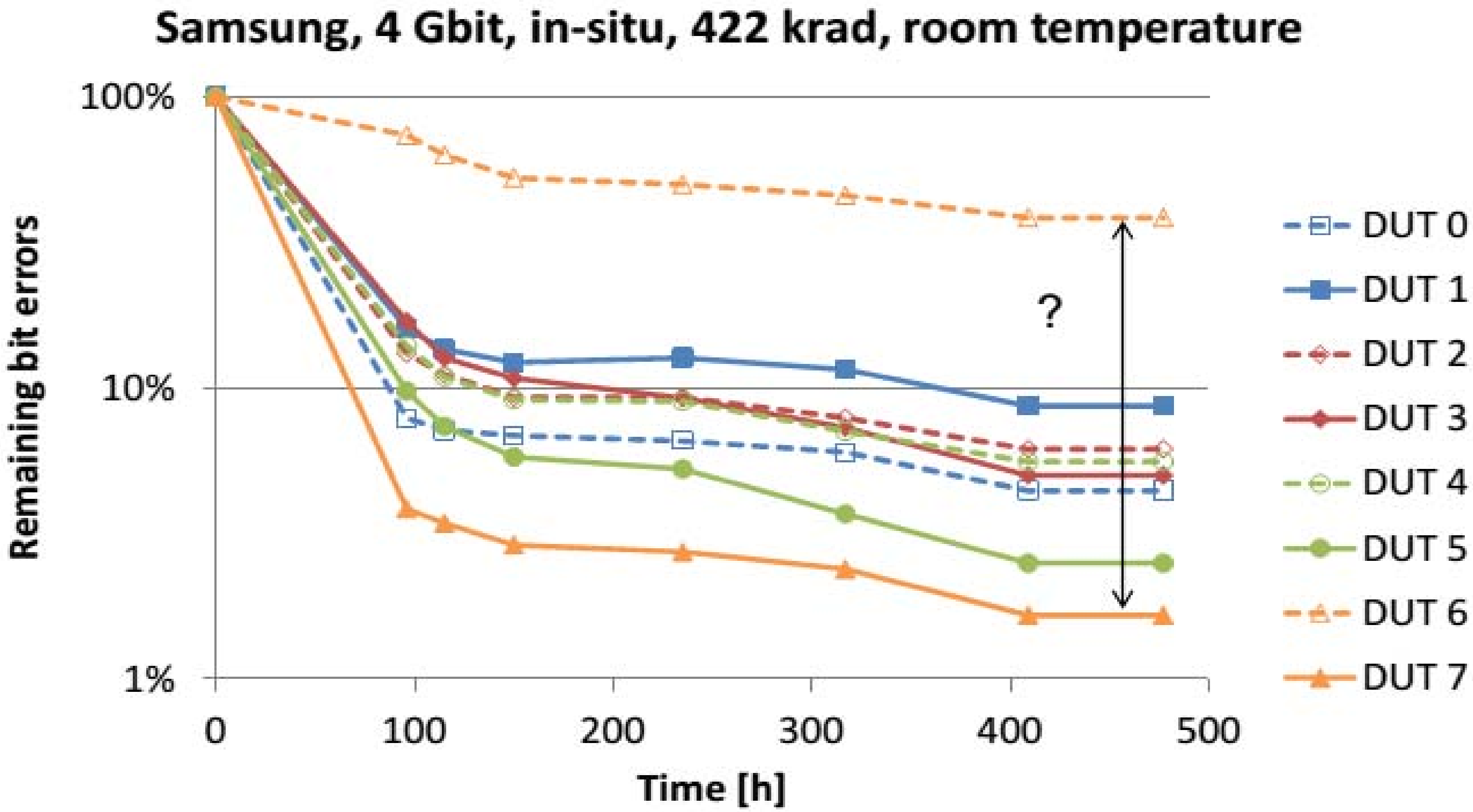


This part looked good in an unbiased test, but bad in an in-situ test!

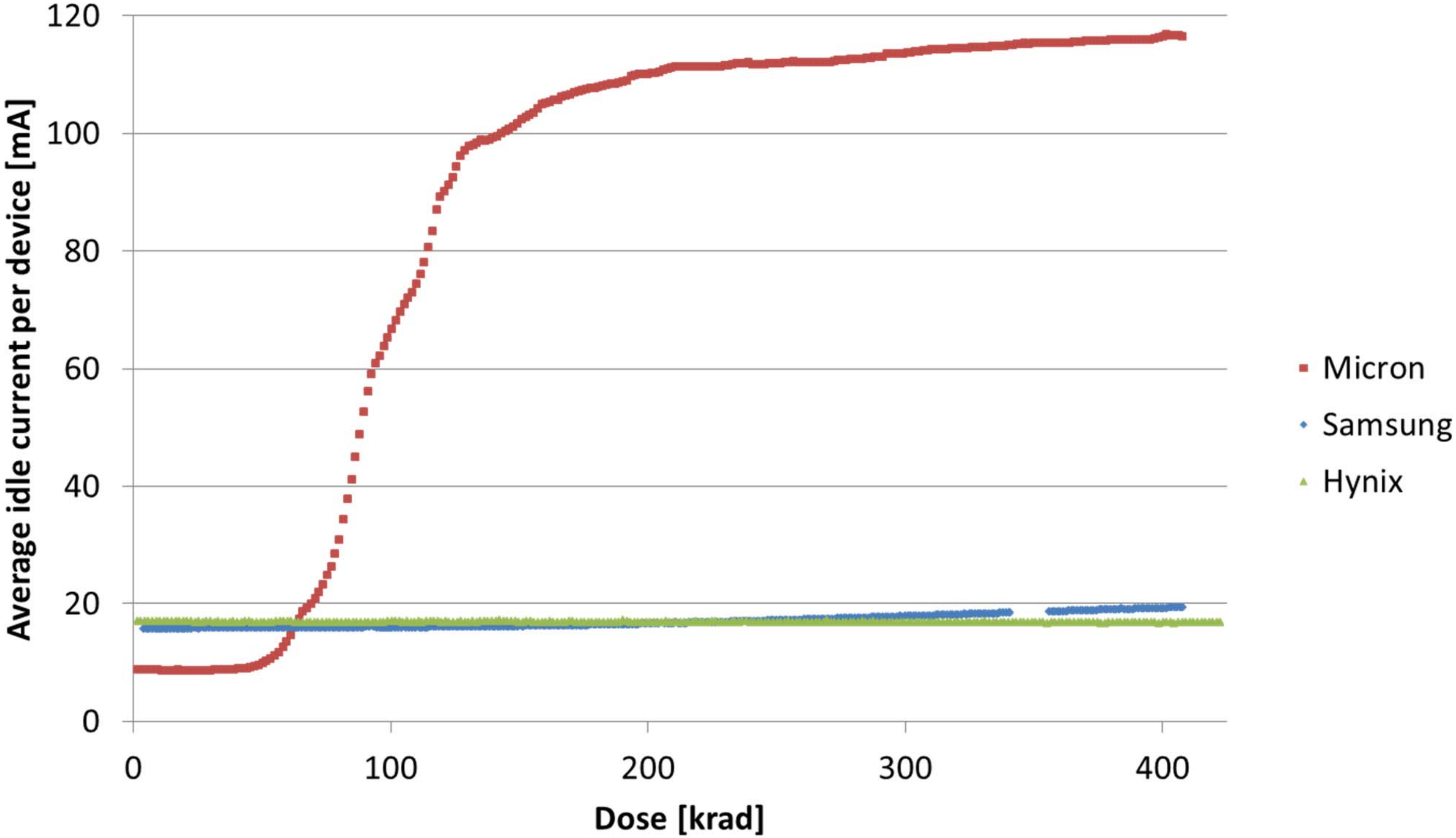
DDR3 results – TID – error density

- 4-Gbit Hynix device: no errors up to >400 krad at room temperature

DDR3 results – TID – error annealing

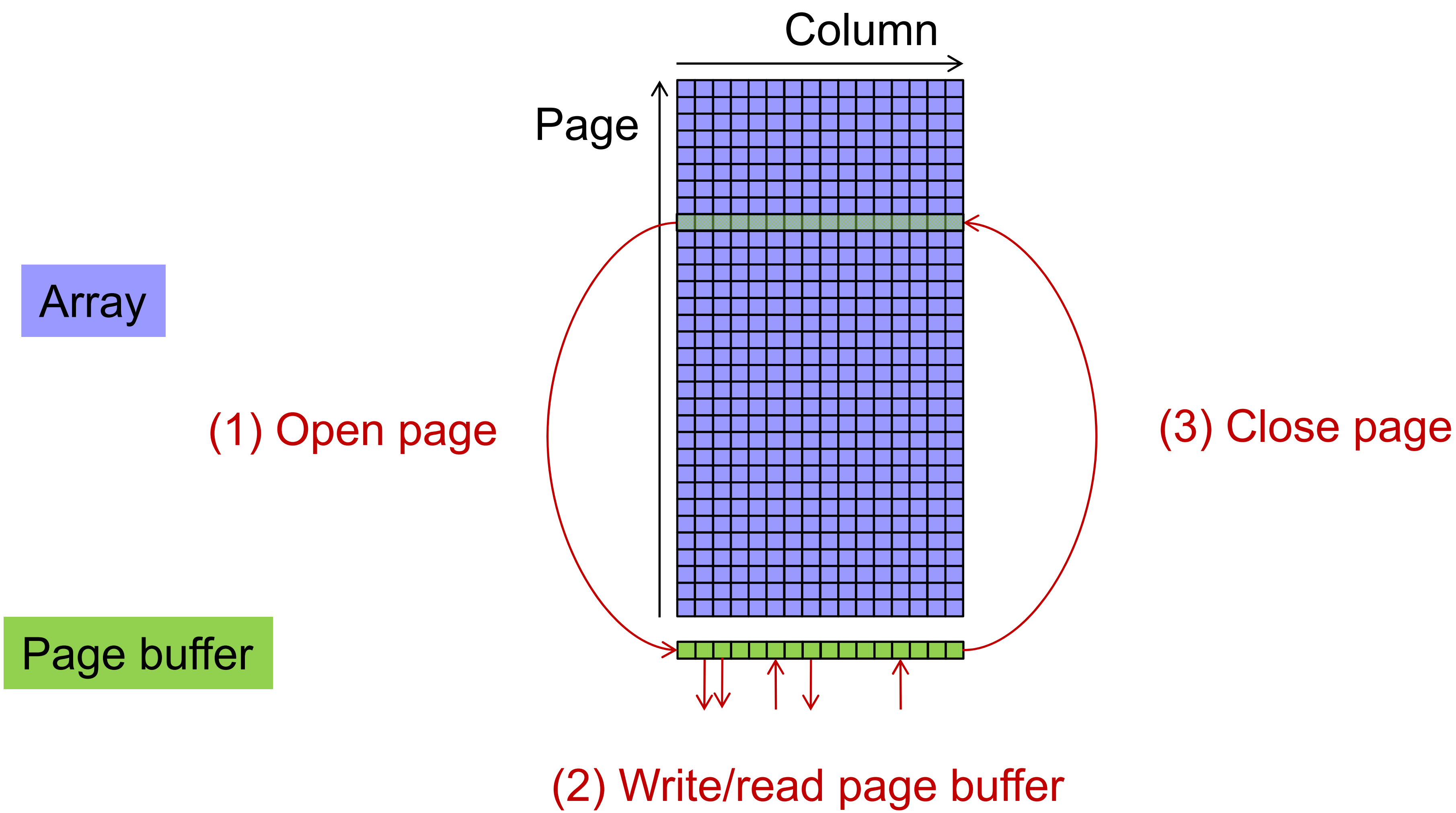


DDR3 results – TID – current

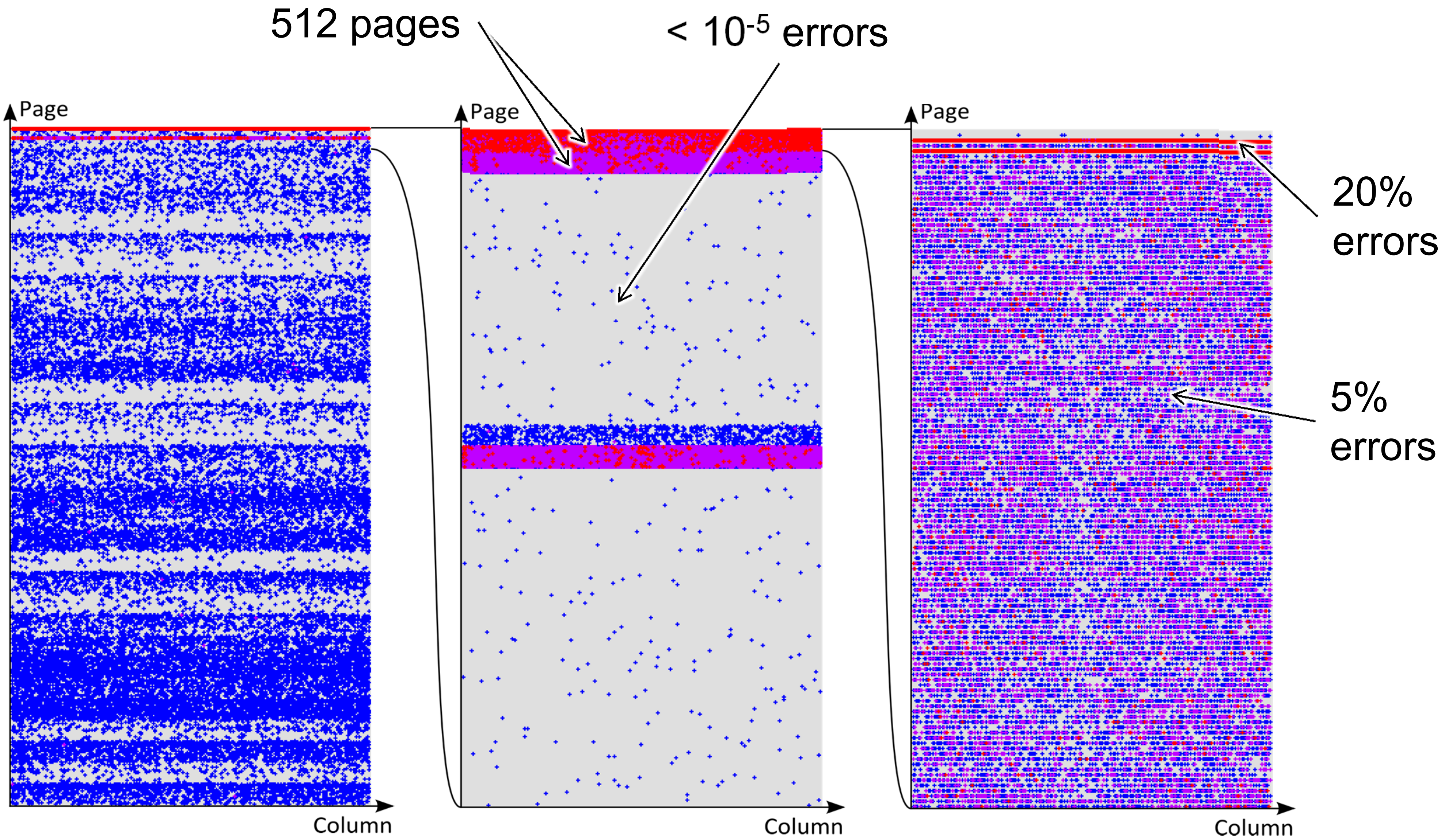


DDR3 results – TID – Band error pattern – background

SDRAM operation:



DDR3 results – TID – Band error pattern (4-Gbit Samsung)



DDR3 results – TID – Band error pattern – background

- Last accessed page is repeatedly opened after the test
- Errors appear on the last page *and other pages*
- Observed for:
  - 4-Gbit Samsung (in-situ)
  - 2-Gbit Samsung (revision D, unbiased)
  - 2-Gbit Micron (unbiased)
  - 2-Gbit Hynix (unbiased)
- Not observed for:
  - **4-Gbit Hynix (in-situ/unbiased)**
  - 4-Gbit Elpida (unbiased)
  - 2-Gbit Samsung (revision B, unbiased)
  - 2-Gbit Nanya (unbiased)
- Mechanism not understood so far
- Can be mitigated by appropriate controller design

DDR3 results – summary

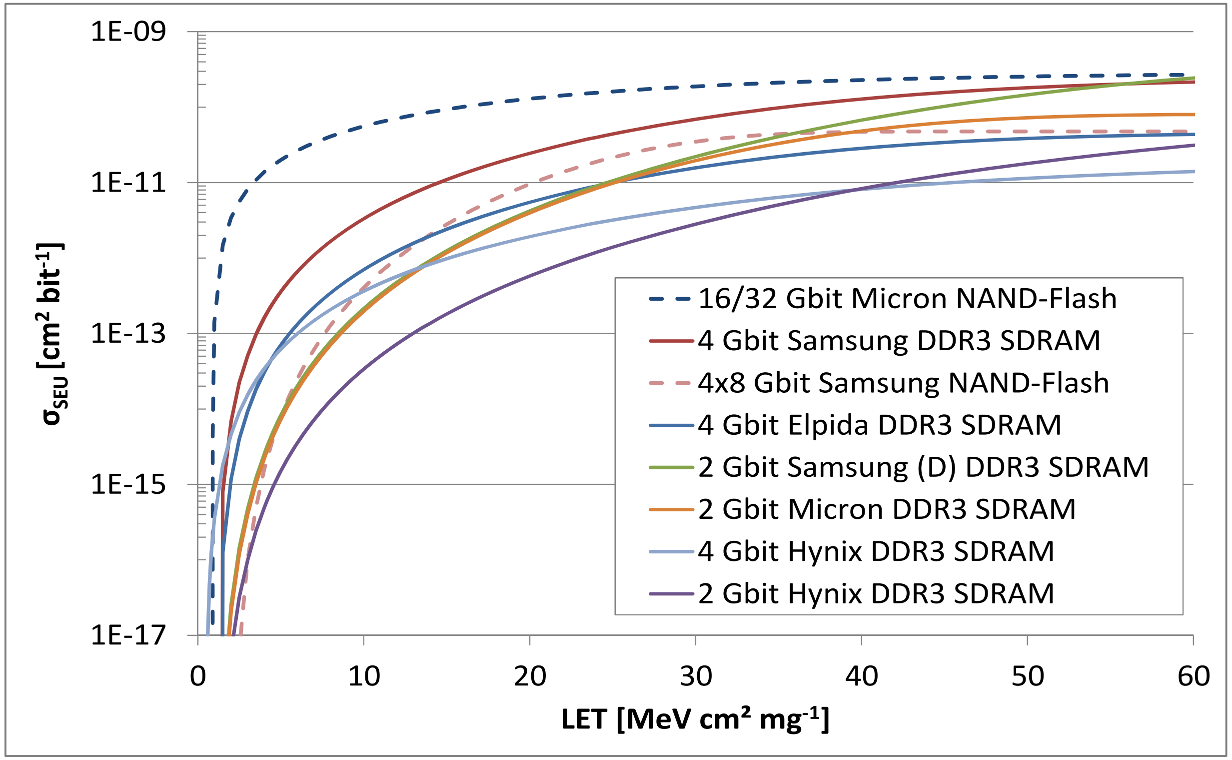
- **SEE:**
  - **No SEL** (LET=60, normal incidence)
  - Software conditioning reduces SEFI sensitivity for some part types
  - ≈10% hard SEUs
  - Significant hard SEU annealing
- **TID**:
  - DDR3 SDRAM is useful for ≥ 400 krad (Hynix)
  - Other parts: band error pattern – triggered by mode of operation
  - Significant annealing
  - Idle current increase: none (Hynix) to extreme (Micron)
  - In-situ results can be worse than unbiased results (example: 4-Gbit Micron)
    - In-situ tests are required
    - Unbiased preselection tests may be useful

Comparison between

NAND-Flash and DDR3 SDRAM

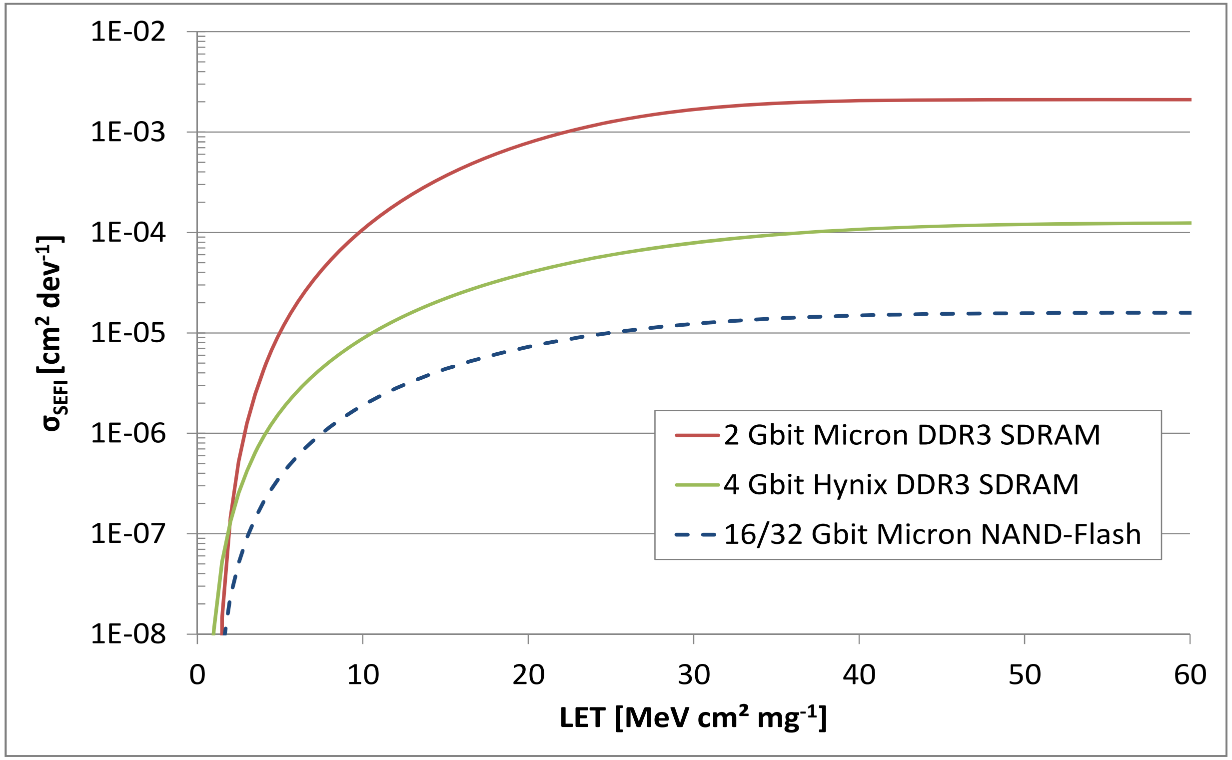
Test Results

Comparison SEE HI: SEU



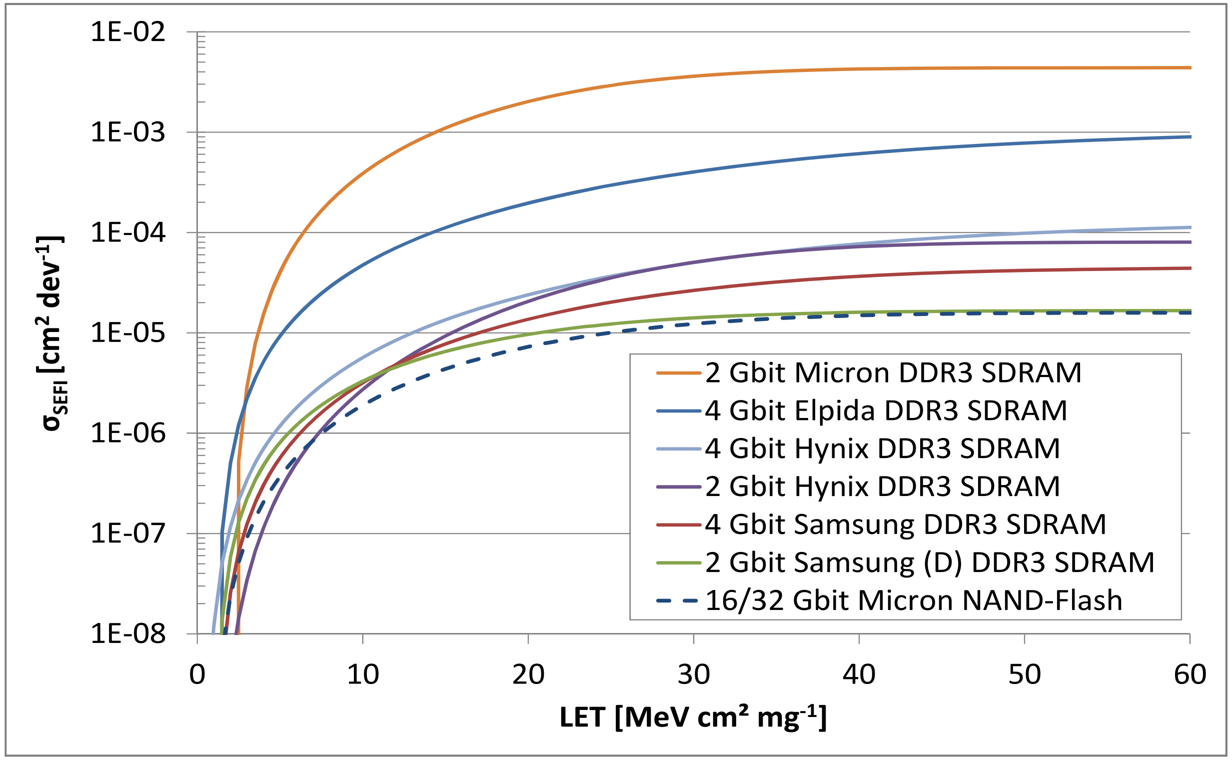
- The 25 nm NAND-Flash cross section at low LET is about two orders of magnitude higher compared to the DDR3 SDRAM cross section and the 4x8 Gbit NAND-Flash cross section.

Comparison SEE HI: Column SEFI



- The column SEFI cross section of the 2 Gbit Micron DDR3 SDRAM is two orders of magnitude higher compared to the respective 16/32 Gbit NAND-Flash cross section.

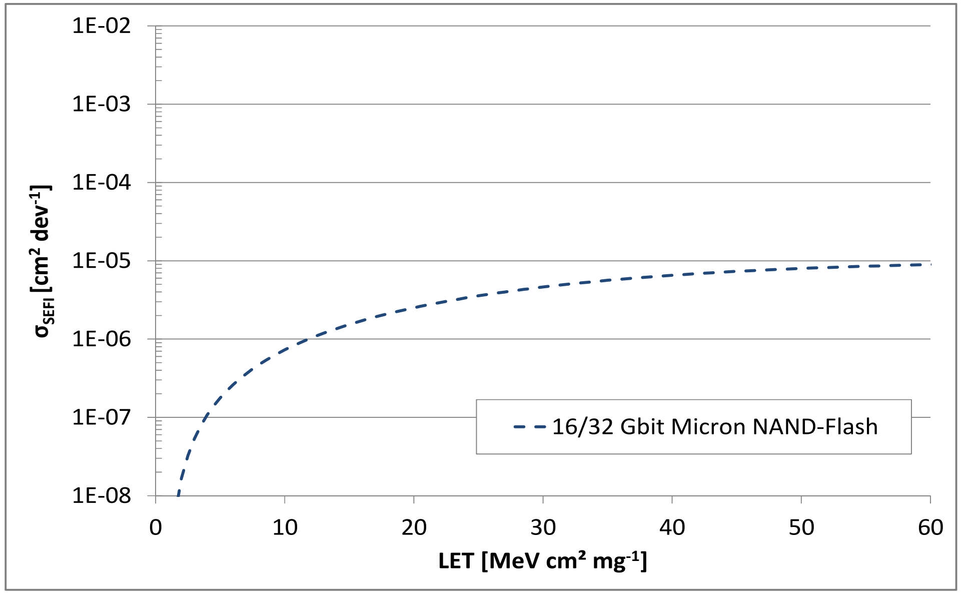
Comparison SEE HI: Row SEFI



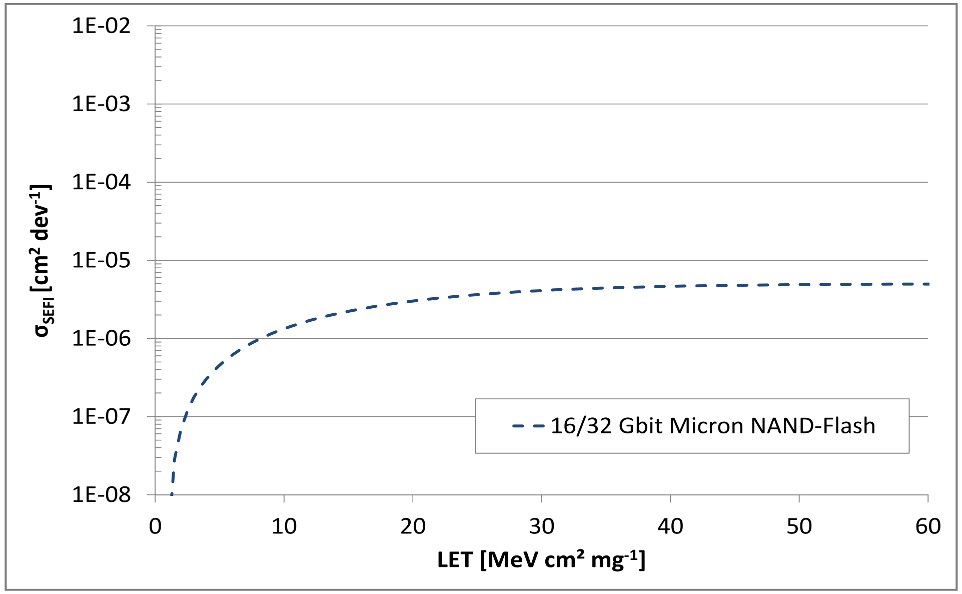
- There are big differences among the DDR3 SDRAM Row SEFI cross sections.
- The 2 Gbit Micron cross section is about two orders of magnitude above the favourable DDR3 parts.
- The 16/32 Gbit NAND-Flash cross section is similar to the favourable DDR3 SDRAM cross sections.

Comparison SEE HI: Block SEFI

Class B: Transient



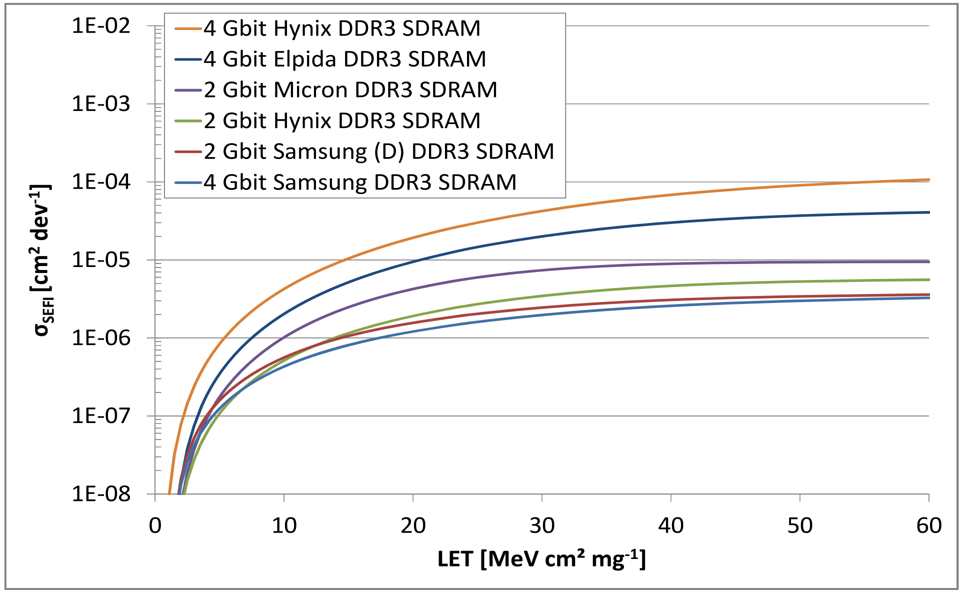
Class C: Persistent



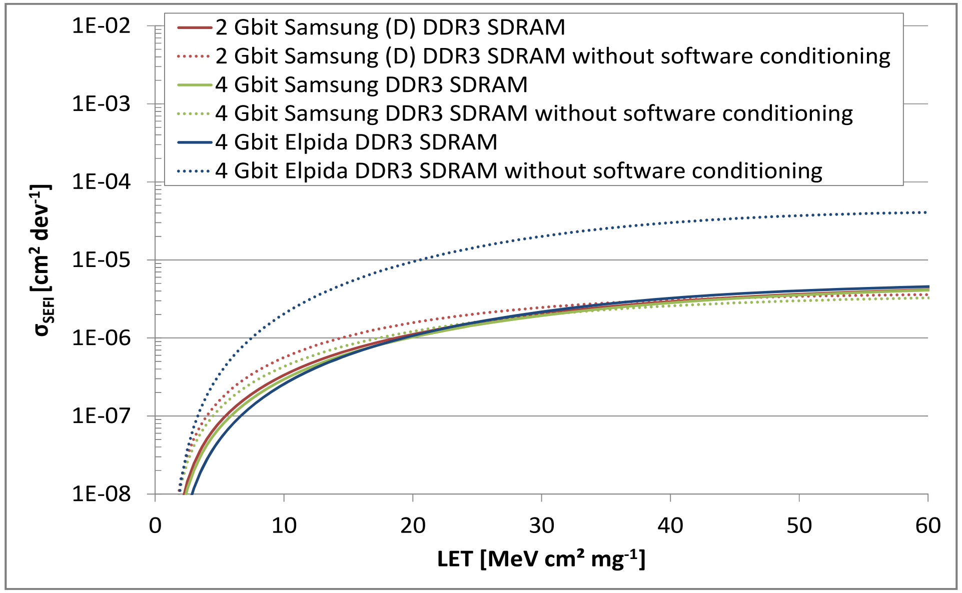
- NAND-Flash only

Comparison SEE HI: Device SEFI

without software conditioning

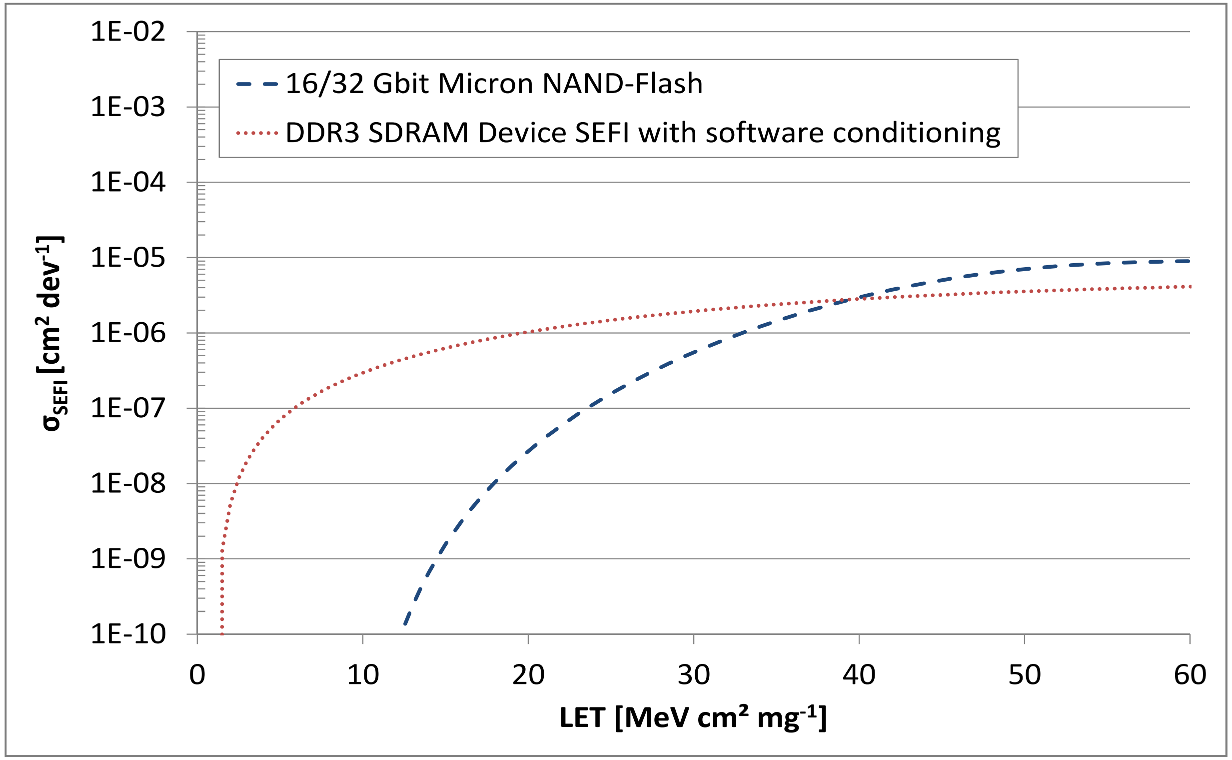


with software conditioning



- DDR3 SDRAM only
- The effectiveness of software conditioning depends on the manufacturer.

Comparison SEE HI: Destructive Failure

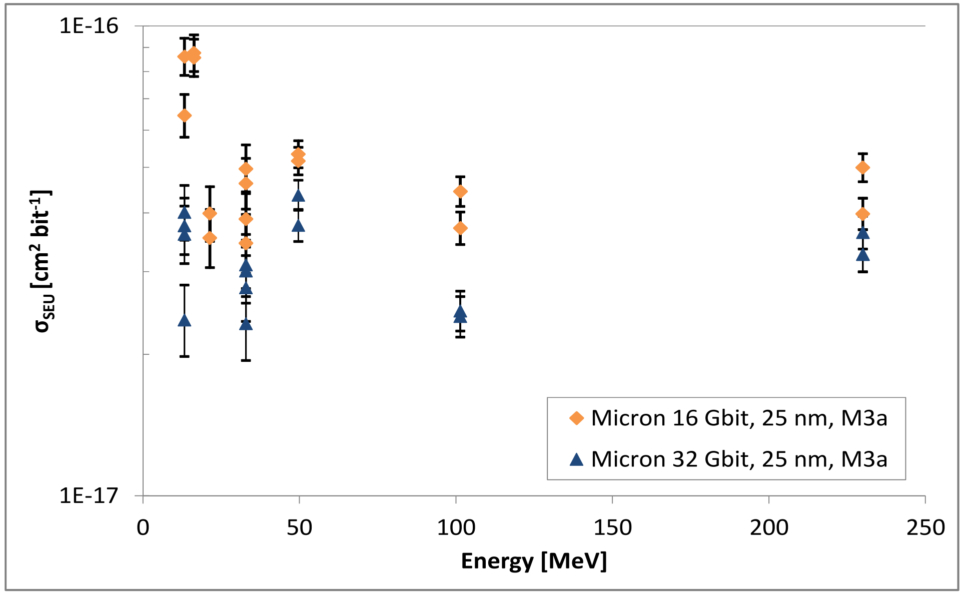


- NAND-Flash only
- The NAND-Flash Destructive Failure is permanent damage with definite data loss.

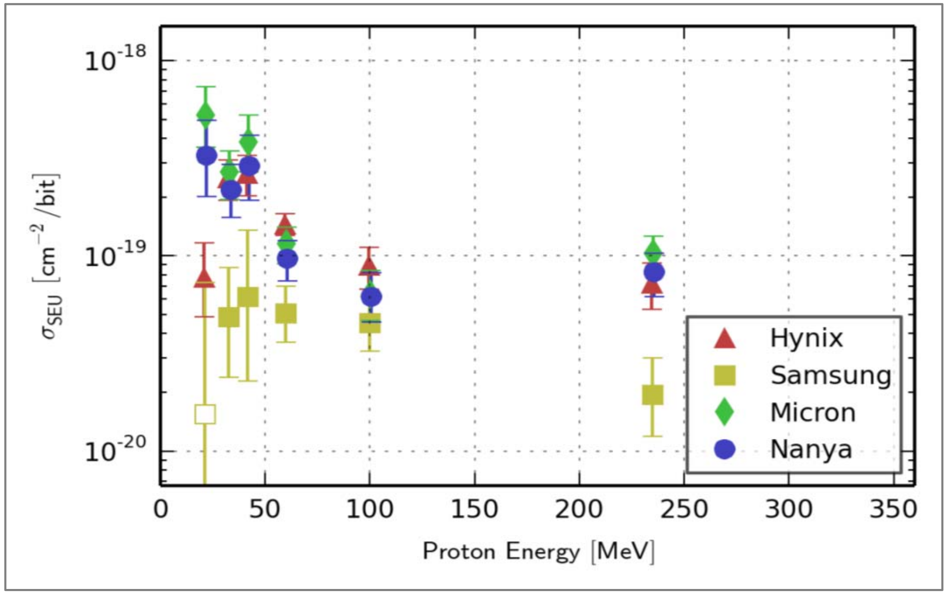
- Neither NAND-Flash nor DDR3 SDRAM suffered from SEL

Comparison SEE Proton: SEU

NAND-Flash



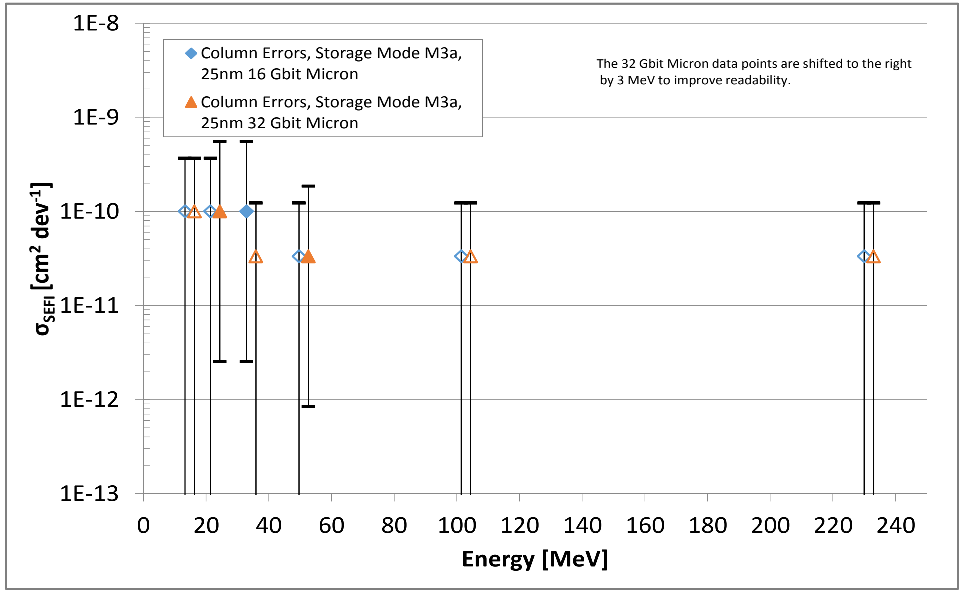
DDR3 SDRAM



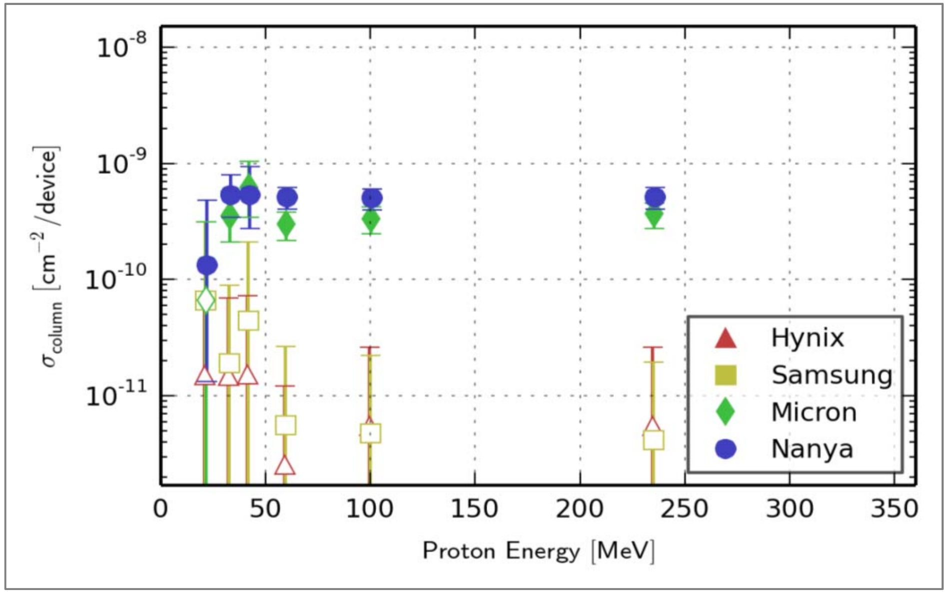
- 25 nm NAND-Flash is by the factor of 400 more sensitive to proton SEUs than DDR3 SDRAM (feature size ≈ 35 nm). NAND-Flash and DDR3 SDRAM show an increase of SEUs towards low energies. This should be investigated further to exclude peculiarities of the source.

Comparison SEE Proton: Column SEFI

NAND-Flash



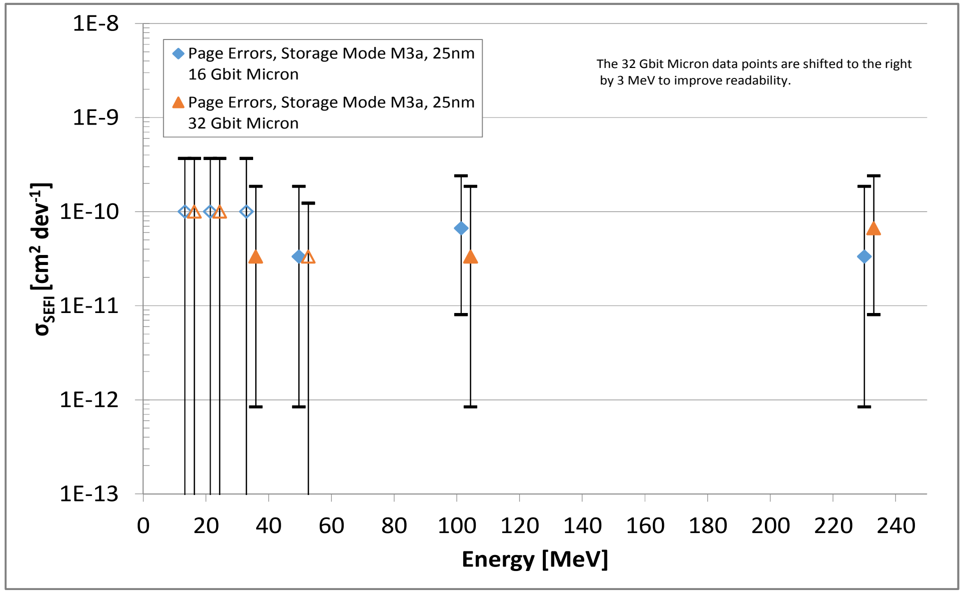
DDR3 SDRAM



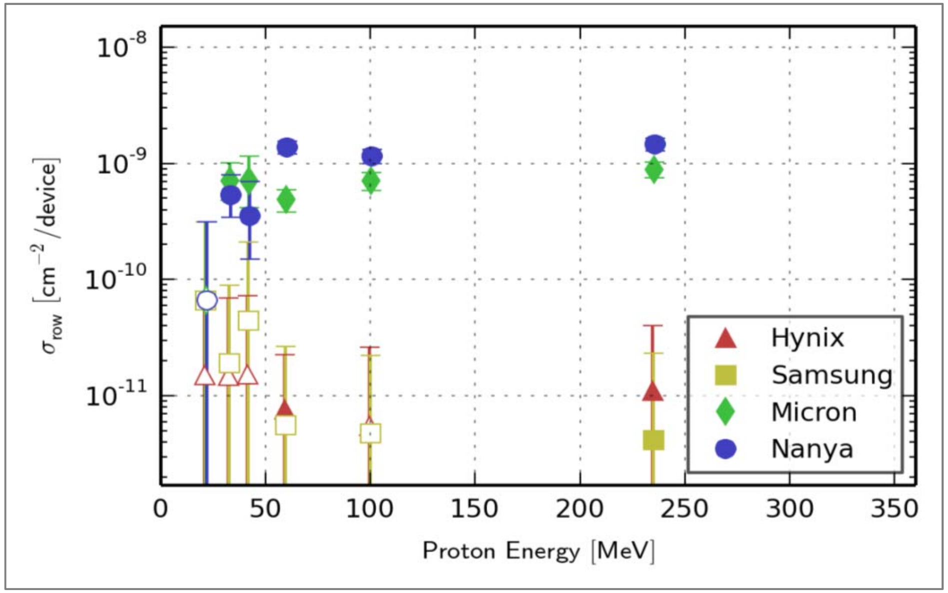
- In most cases the SEFI count is very low. To get more SEFI events the fluence a higher fluence is needed, which is hard to realize because of the limited beam time and in case of NAND-Flash because of the limited total dose.

Comparison SEE Proton: Row SEFI

NAND-Flash

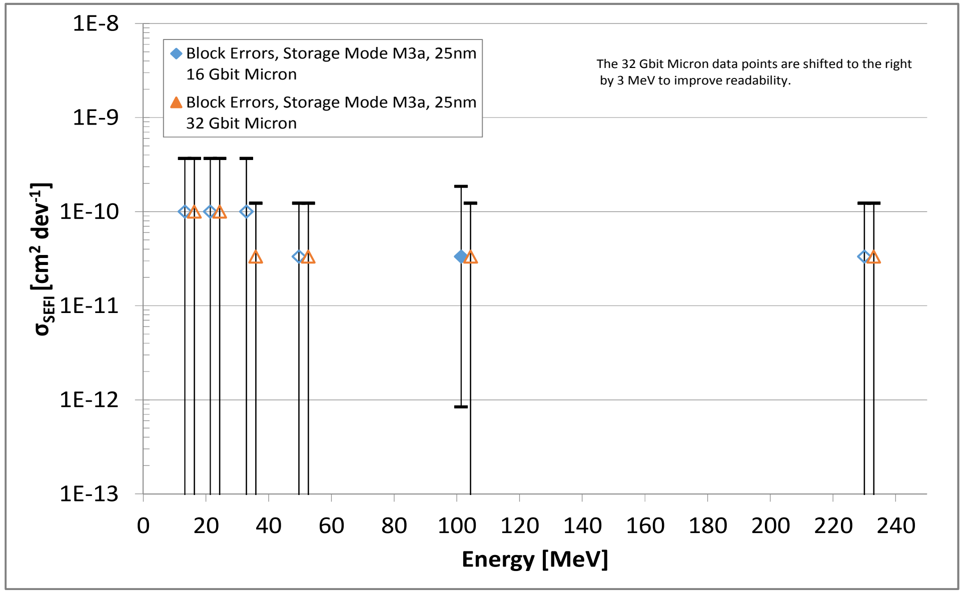


DDR3 SDRAM

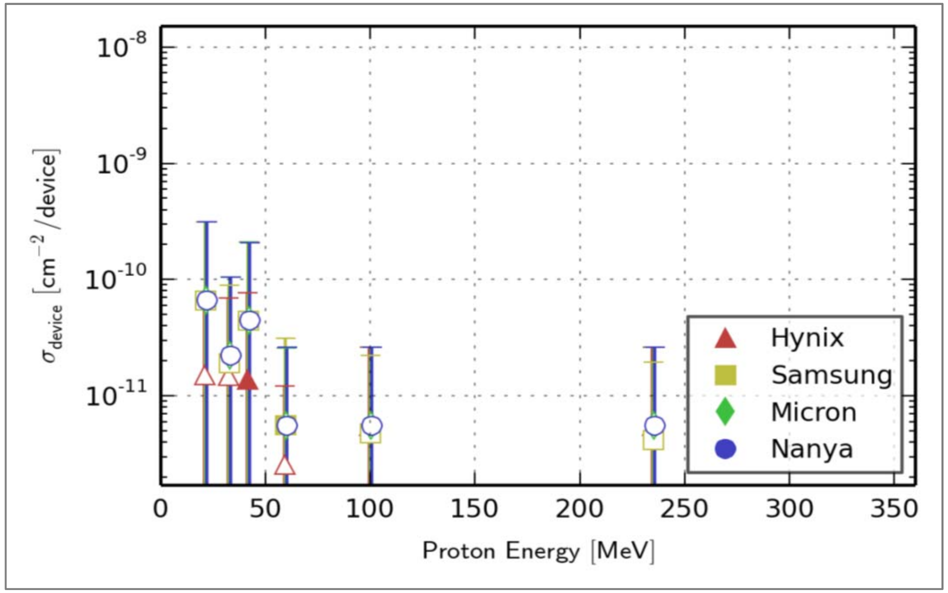


Comparison SEE Proton: Block/Device SEFI

NAND-Flash Block SEFI



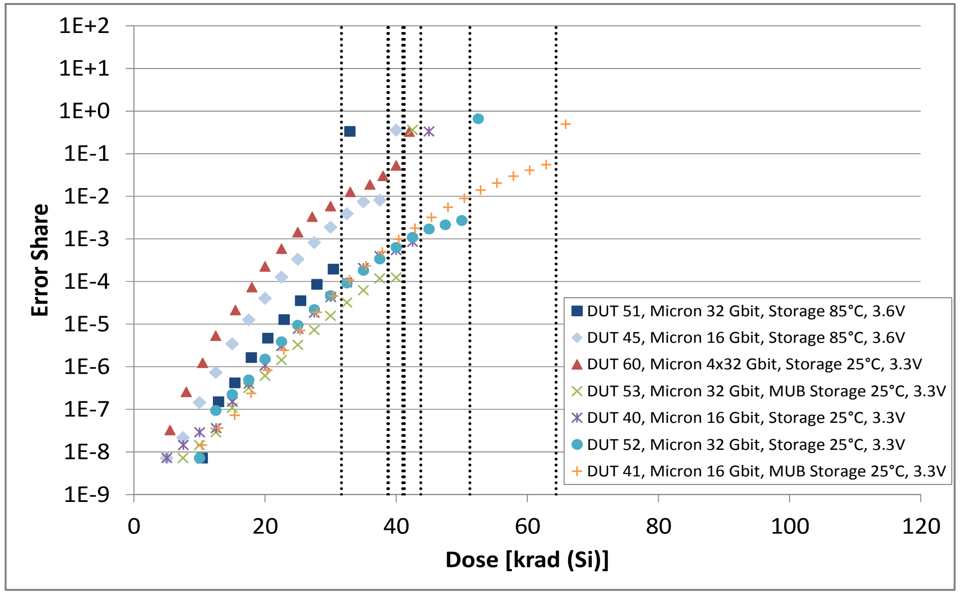
DDR3 SDRAM Device SEFI

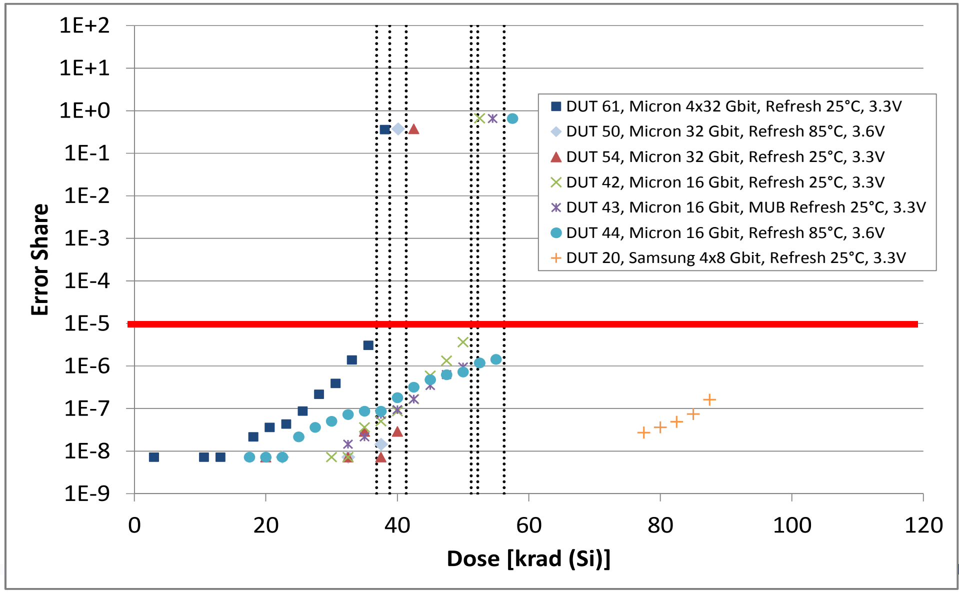


- Neither NAND-Flash nor DDR3 SDRAM suffered from permanent damaging effects like Destructive Failure or SEL

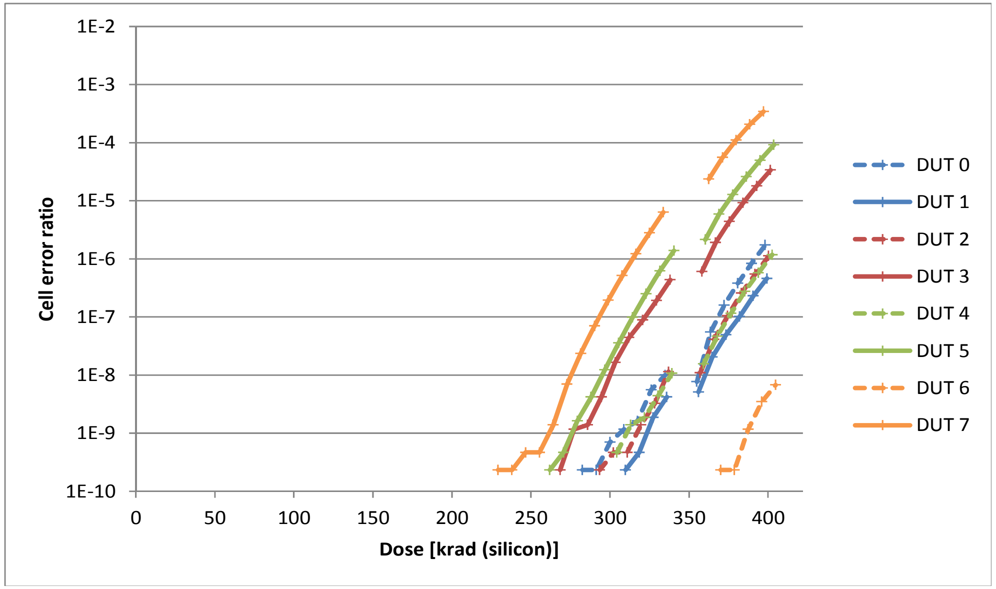
Comparison TID

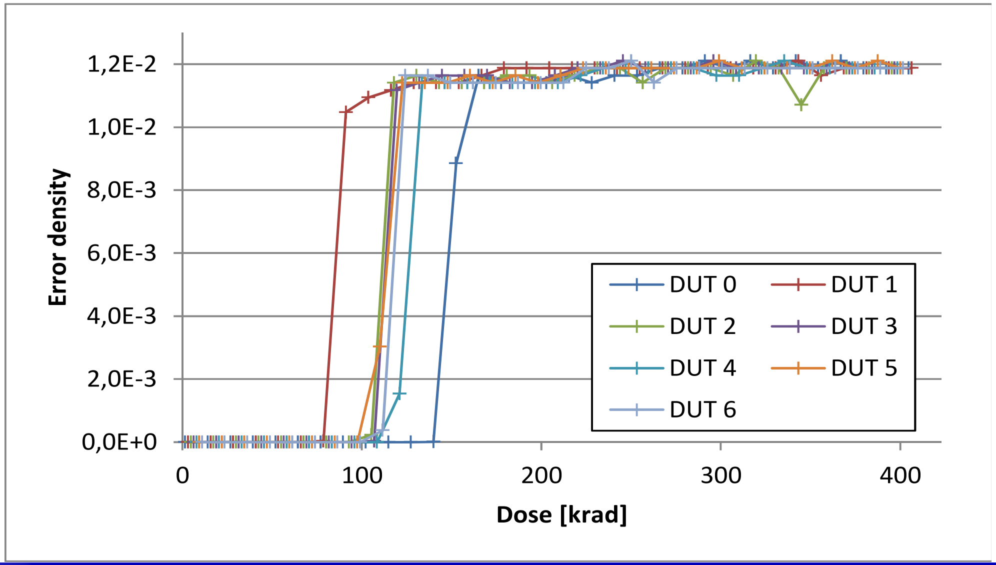
NAND-Flash





DDR3 SDRAM





Recent Publications

[1] M. Herrmann et al., "Heavy ion SEE test of 2 Gbit DDR3 SDRAM", RADECS Data Workshop, DW-28, 2011

[2] K. Grürmann et al., "Heavy Ion sensitivity of 16/32-Gbit NAND-Flash and 4-Gbit DDR3 SDRAM", IEEE NSREC Data Workshop, W-9, 2012

[3] M. Herrmann et al., "New SEE Test Results for 4 Gbit DDR3 SDRAM", RADECS Data Workshop, DW-25L, 2012

[4] K. Grürmann et al., "New SEE Test Results of 16/32-Gbit SLC NAND-Flash", RADECS Data Workshop, DW-23L, 2012

[5] K. Grürmann et al., "Radiation Effects in Flash Memories", IEEE TNS Special Issue, 2013

Conclusions

Results
TID

DDR3 SDRAM

- DDR3 technology in general low sensitive to TID
- Outstanding TID performance of SK Hynix 4 Gb and Samsung 4 Gb devices:
  - H5TQ4G83MFR-H9C: almost insensitive to TID > 400 krad
  - K4B4G0846B-HCH9: 1st data errors at TID > 150 krad
- Very promising candidates for JUICE mission regarding TID

NAND Flash

- Heritage parts with good TID performance > 90 krad, well suitable for JUICE mission
- Scaled technologies show much lower TID tolerance:
  - Functional failures at TID > 30 krad (HDR) independent from applied intermediate refresh
  - Suitable for TID level ≤ 25 krad
  - High amount of shielding mandatory for use in JUICE mission

Results
SEE

DDR3 SDRAM

- Less sensitive to SEU than former technologies and NAND flash
- Increased sensitivity to SEFI leads to the need of further mitigation techniques
- Increase of SEE sensitivity to protons with scaling - direct ionisation?
- No Single Event Latch-up at LET > 60 MeVcm^{2}mg^{-1} and T > 80°C

NAND Flash

- Very good SEU and SEFI performance of heritage parts
- Scaled technologies show increased SEU and SEFI sensitivity compared to heritage parts, but still reasonable
- No data loss in case of SEFI due to non-volatility
- Increase of SEE sensitivity to protons with scaling, 25 nm technology - direct ionisation?
- No Single Event Latch-up at LET > 60 MeVcm^{2}mg^{-1} and T > 80°C
  BUT destructive events at LET < 15 MeVcm^{2}mg^{-1} (LET ≈ 30 MeVcm^{2}mg^{-1} for heritage parts):
  $\lambda_{destructive}$ ≈ 4.3 FIT (< 0.1 FIT for heritage parts)

Results

SEE Rates

SEU [$day^{-1}bit^{-1}$]	Quiet (JUICE) HI	Quiet (JUICE) p^+	Quiet (JUICE) ∑	Solar flare (CREME96, Worst Week) HI	Solar flare (CREME96, Worst Week) p^+	Solar flare (CREME96, Worst Week) ∑
DDR3 SDRAM						
H5TQ4G83MFR	1.0E-14	1.6E-12	**1.6E-12**	9.0E-13	4.1E-09	**4.1E-09**
K4B4G0846B	5.0E-13	4.1E-13	**9.1E-13**	4.4E-11	1.1E-09	**1.1E-09**
NAND Flash						
K9WBG08U1M	8.8E-12	5.2E-14	**8.9E-12**	7.9E-10	4.4E-10	**1.2E-09**
MT29F16G08ABACAWP-IT:C/ MT29F32G08ABAAAWP-IT:A	5.7E-10	8.1E-10	**1.4E-09**	3.6E-08	1.3E-06	**1.3E-06**

SEFI [day^{-1}]	Quiet (JUICE) HI	Quiet (JUICE) p^+	Quiet (JUICE) ∑	Solar flare (CREME96, Worst Week) HI	Solar flare (CREME96, Worst Week) p^+	Solar flare (CREME96, Worst Week) ∑
DDR3 SDRAM						
H5TQ4G83MFR	6.6E-04	6.5E-05	**7.3E-04**	4.8E-01	2.1E-01	**6.9E-01**
K4B4G0846B	7.9E-05	7.2E-07	**8.0E-05**	2.9E-02	3.6E-02	**6.5E-02**
NAND Flash						
K9WBG08U1M	1.3E-05	7.9E-07	**1.4E-05**	1.4E-03	6.1E-03	**7.5E-03**
MT29F16G08ABACAWP-IT:C/ MT29F32G08ABAAAWP-IT:A	4.1E-04	4.5E-04	**8.6E-04**	1.8E-01	1.3	**1.5**

Destructive Failure [day^{-1}]	Quiet (JUICE) HI	Quiet (JUICE) p^+	Quiet (JUICE) ∑	Solar flare (CREME96, Worst Week) HI	Solar flare (CREME96, Worst Week) p^+	Solar flare (CREME96, Worst Week) ∑
NAND Flash						
K9WBG08U1M	2.5E-09	-	**2.5E-09**	2.2E-07	-	**2.2E-07**
MT29F16G08ABACAWP-IT:C	1.0E-07	-	**1.0E-07**	9.6E-06	-	**9.6E-06**

Questions