CORHA:
Non-volatile Memories

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Outline

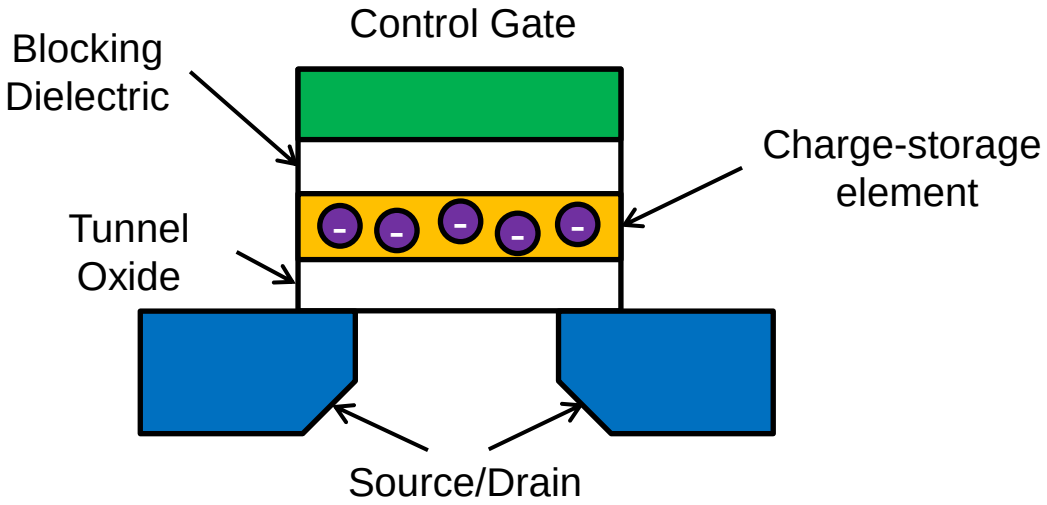
- Introduction
  - Non-volatile Memories for Small Satellites
  - Devices and Storage Concepts
- Experimental Results
  - Total Ionizing Dose
    - Lot-to-lot Variability Study
  - Single Event Effects:
    - Heavy Ions
    - Protons
- Conclusions

- Microcontrollers and FPGAs used in small satellites require low-footprint non-volatile memories (NVM) for configuration, code, and data storage purposes
  - The **Serial Peripheral Interface** (SPI) is low-pin count: simplified routing and small board area occupation
  - The **Flash NOR** interface has a larger pin-count and footprint, but provides faster random access

Devices

	MB85RS256TY	CY15B102QN	CY14V101PS	MT28EW128ABA
Part Type	SPI Ferroelectric RAM	SPI Ferroelectric RAM	SPI Non-volatile SRAM (SONOS)	Parallel NOR Flash Memory (Floating Gate)
Manufacturer	Fujitsu Semiconductor	Cypress	Cypress	Micron Technology
Size	256 kbit	2 Mbit	1 Mbit	128 Mbit
Operating Voltage	1.8 to 3.6 V	1.8 to 3.6 V	Core 2.7 to 3.6 V; I/O 1.71 to 2.0 V	Core 2.7 to 3.6 V; I/O 1.65 to 3.6 V
Operating Temperature	-40°C to 125°C	-40°C to 125°C	-40°C to 85°C	-40°C to 85°C
Package	SOP8	SOIC8	SOIC16	TSOP56

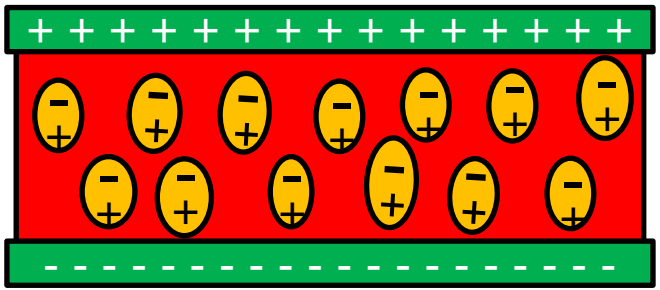
Charge-based Cells



- Storage concept: Inject or remove **charge** between the control gate and the channel
- Charge storage element: **floating polysilicon gate (FG)**, **charge-trap layer** (e.g. Semiconductor Oxide Nitride Oxide Semiconductor - SONOS)
- Radiation can remove stored charge

Ferroelectricity

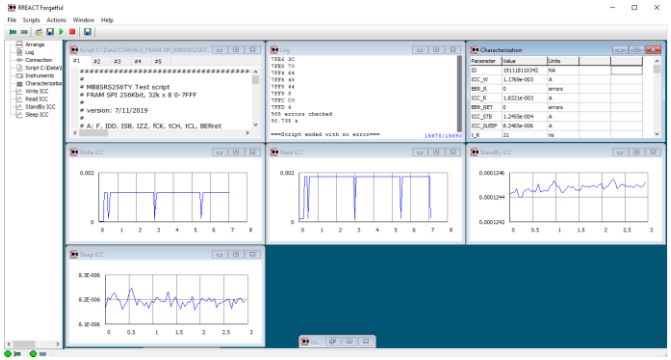
Polarized by an electric field



$$D=\varepsilon_0 E+P$$

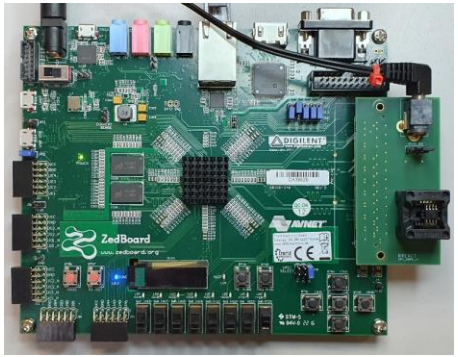
- When an electric field is applied across a dielectric materials, **polarization** of the dipoles occurs.
- When the field is removed, the polarization disappears unless **ferroelectric materials** are used
- Cells are not very sensitive to **radiation**, peripheral circuitry can be, but voltages are low

TID Irradiation and Annealing



Custom SoC-based system for parametric characterization and power analyser

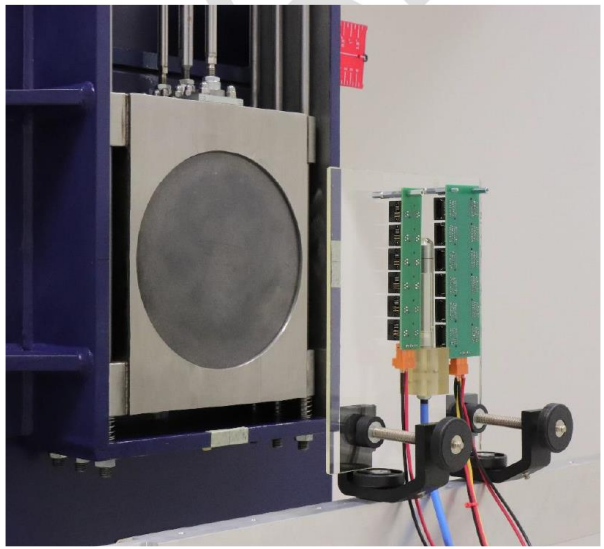
- Functionality
- Power: operating, standby, etc.
- Timing: read, program, setup and hold time, etc.



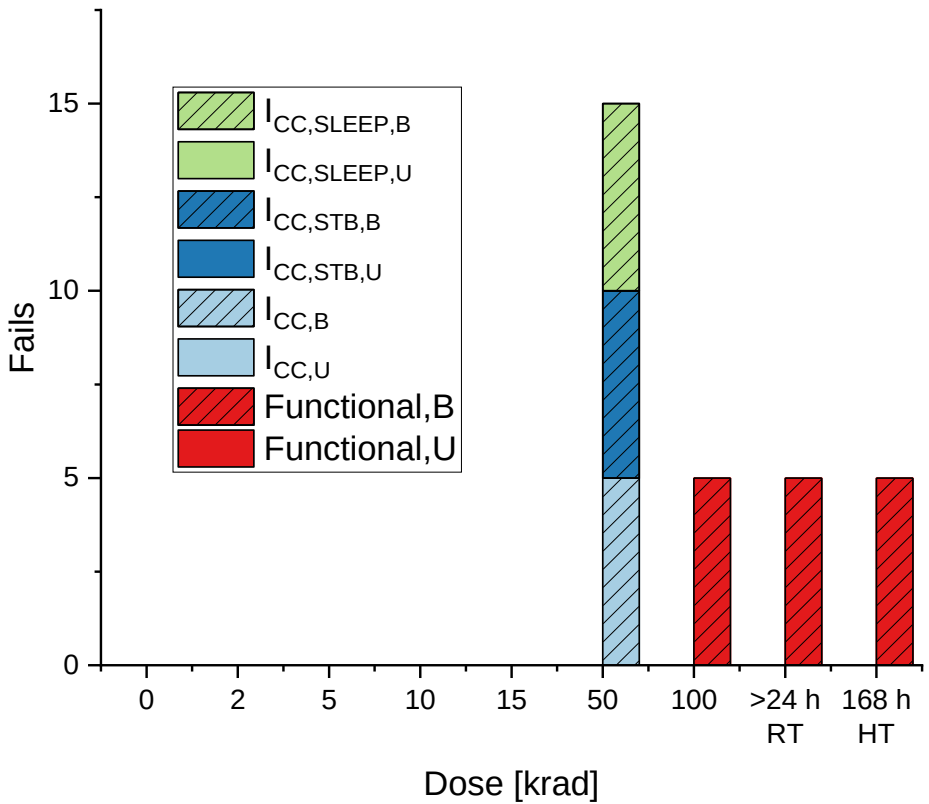
Facility and Experiments

- Co^{60} source at Seibersdorf Laboratories
- Dose rate: 2.4 krad(Si)/hour
- Steps: 2, 5, 10, 15, 50, 100 krad(Si)
- 24+ hours annealing at room temperature + 1 week at 100°C
- Devices
  - 5 samples under static bias **(**memories were idle, but selected, ready to operate)
  - 5 unbiased samples (grounded pins)
  - References for each experimental conditions
- Parametric degradation measured and failure modes identified up to 100 krad(Si)

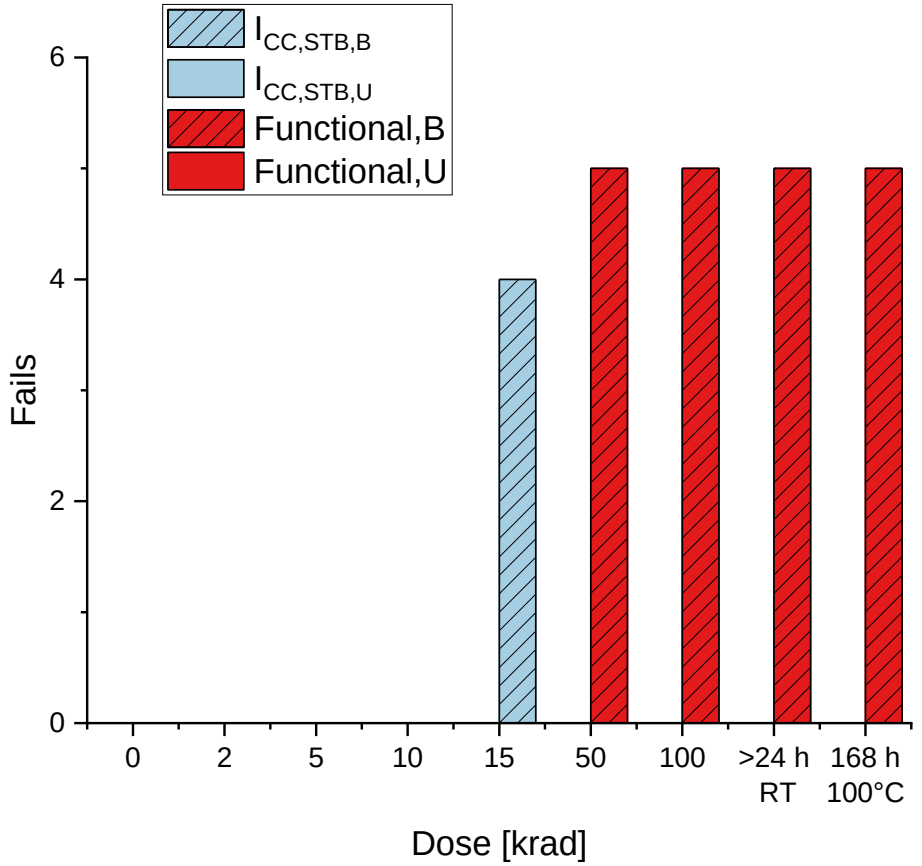
SEIBERSDORF LABORATORIES



- Ferroelectric memory from Fujitsu
- No issues with cells (FRAM)
- Minor parametric (power consumption) between 15 and 50 krad(Si) in all the biased samples
- Functional failures between 50 and 100 krad(Si) in all the biased samples

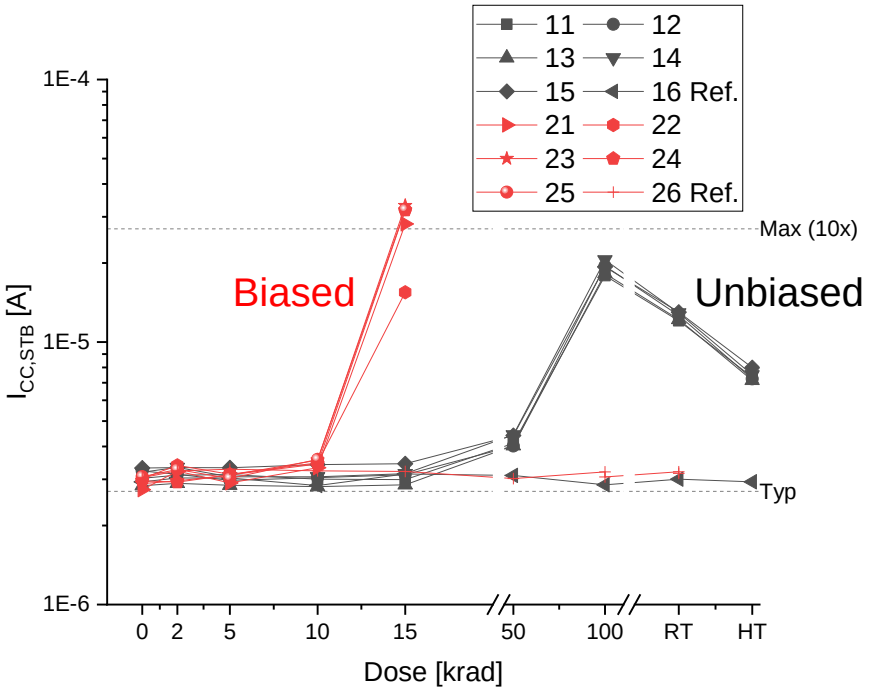


- Ferroelectric memory from Cypress
- No issues with cells (FRAM)
- Minor parametric (standby power consumption) between 15 and 50 krad(Si) in 4 out 5 biased samples
- Functional failures between 50 and 100 krad(Si) in biased samples

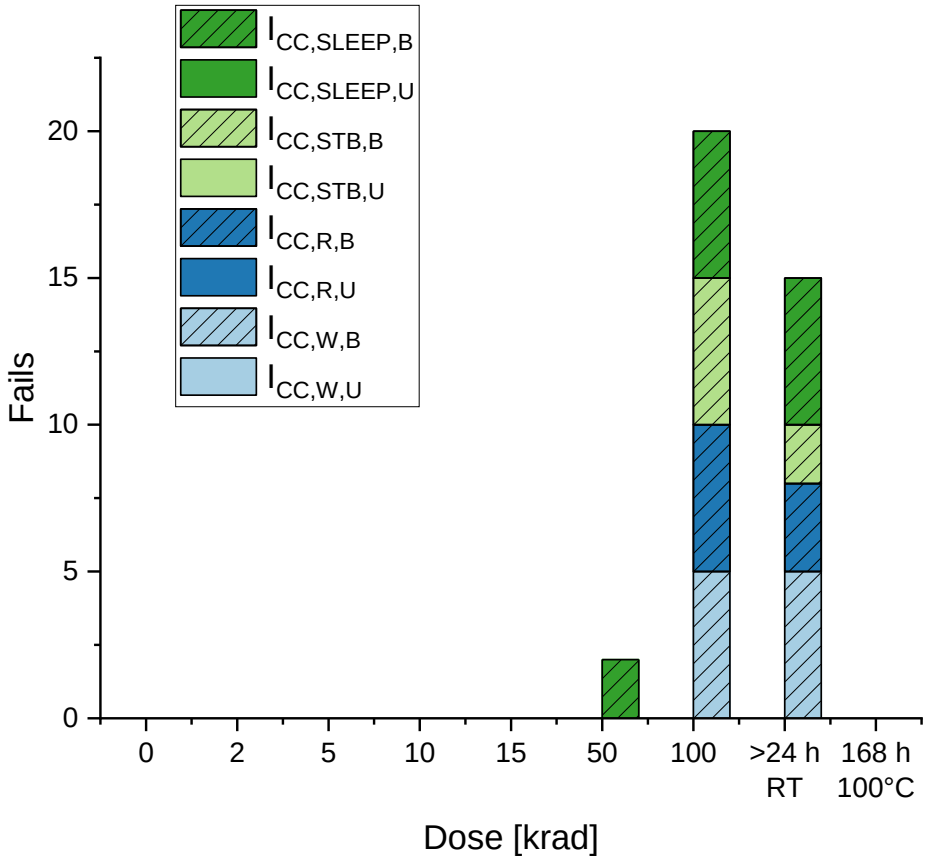


CY15B102QN (2)

- Limited sample-to-sample variability within tested lot
  - One device marginally better and below the set limit
- Current increases also in unbiased devices, but stays below max spec

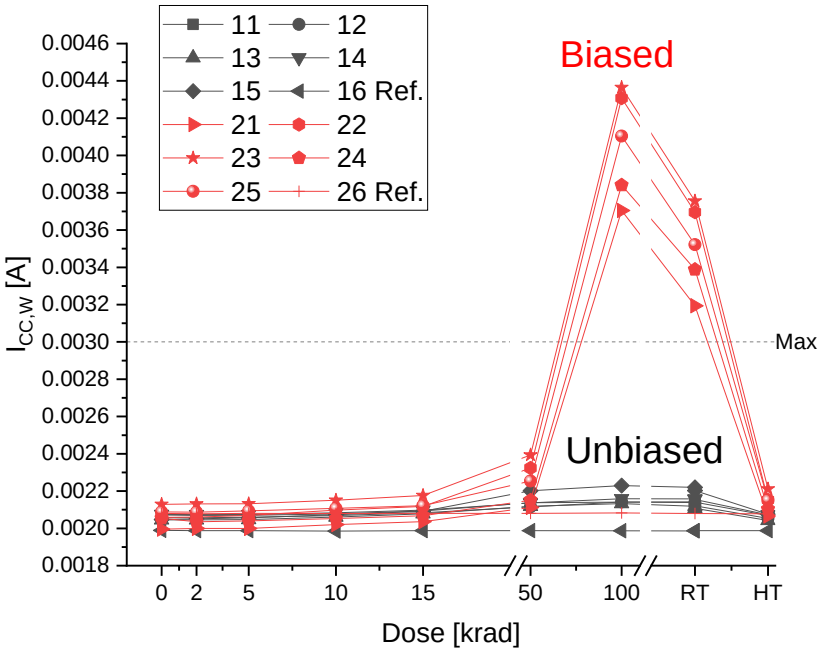


- Non-volatile SRAM memory
- No issues with functionality of volatile (SRAM) or non-volatile (SONOS) storage
- Tolerable power consumption degradation in the peripheral circuitry above 50 krad(Si)
- No functional failures

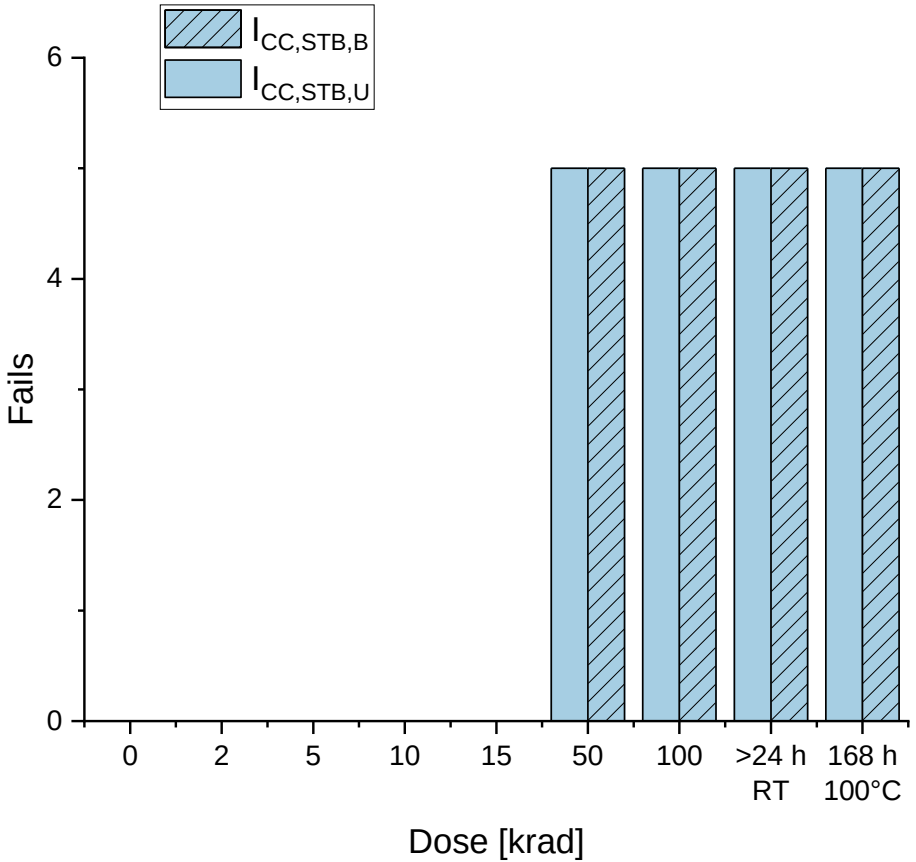


CY14V101PS (2)

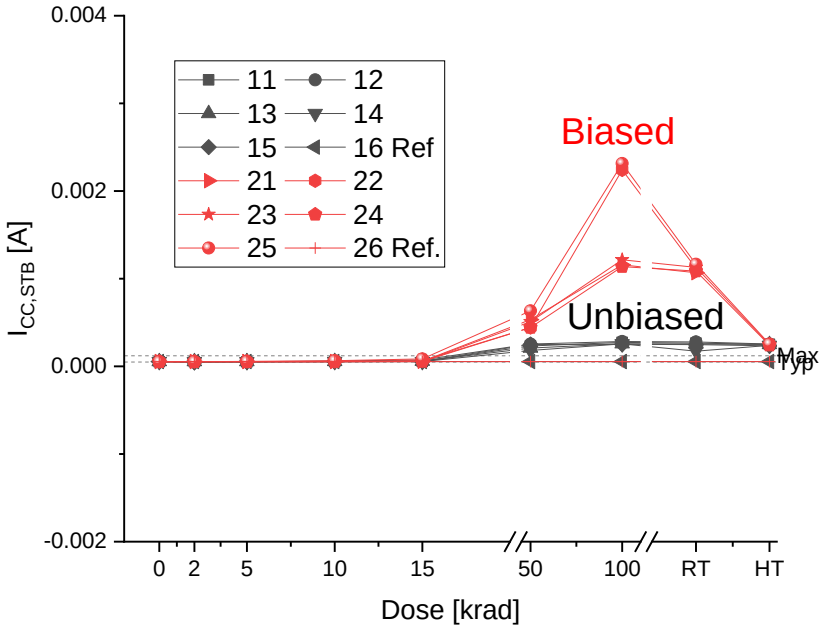
- Supply current during write
- Some sample-to-sample variability
- Current marginally increases also in unbiased devices, but stays well below max spec



- NOR Flash memory
- No issues with functionality of cells (Floating Gate)
- Increase in standby current, both in biased and unbiased components
- No functional failures

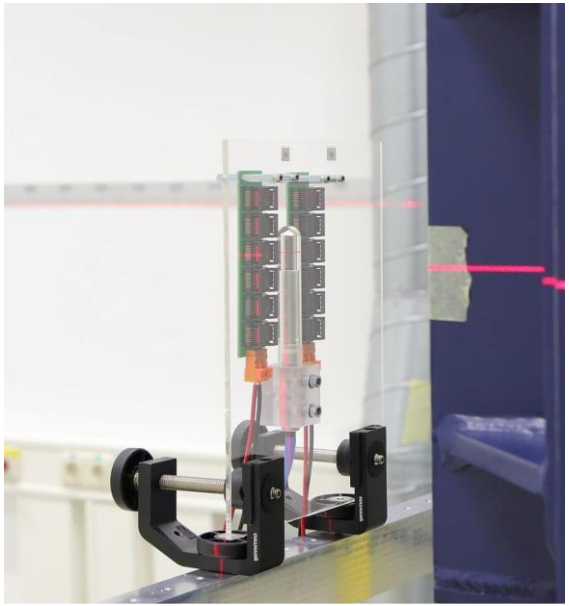


- Some sample-to-sample variability
- Current increases also in unbiased devices over Max limit, but much less than in biased devices



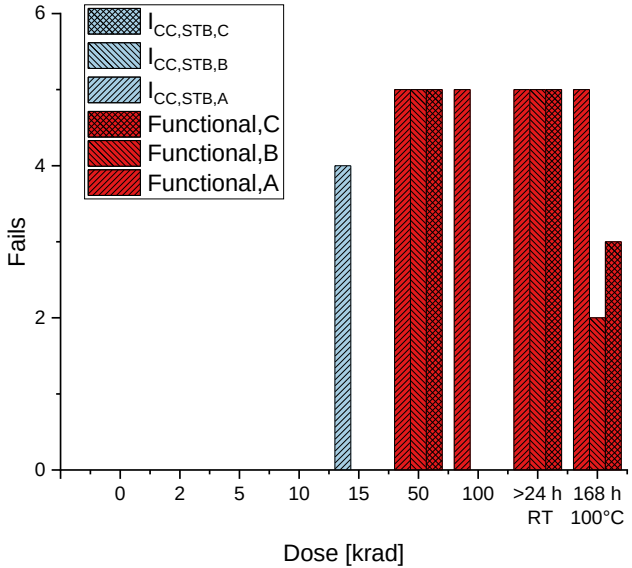
CY15 – TID Lot-to-lot Results

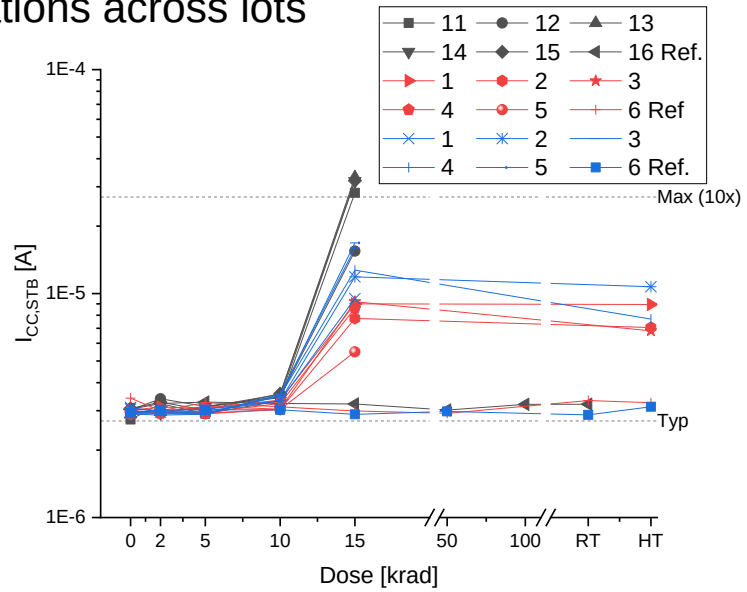
- TID variability study
  - Same steps and measurements as during the first campaign
  - CY15 FRAM ferroelectric memory



CY15 – TID Lot-to-lot results, biased components

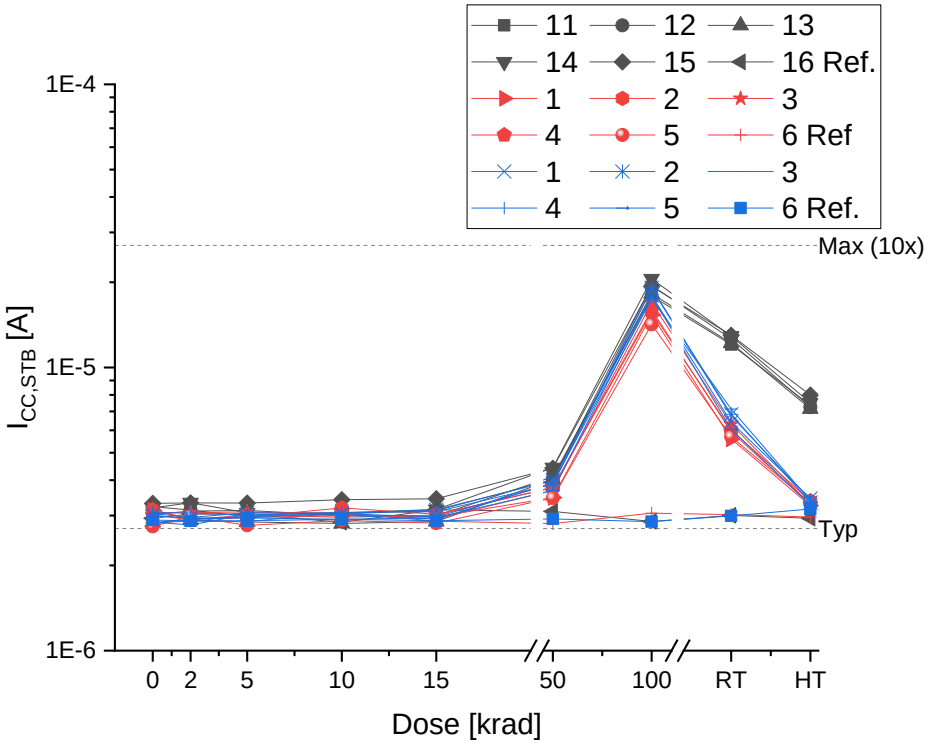
- Functional failures after 50 krad(Si) in all three lots
- Lot-to-lot Variability is visible in stand-by current evolution with TID
- Recovery of some samples after 100°C annealing. N.B. Lot A (black) irradiated to 100 krad(Si), lot B and lot C (red and blue) to 50 krad(Si)
- All other parameters do not show significant variations across lots



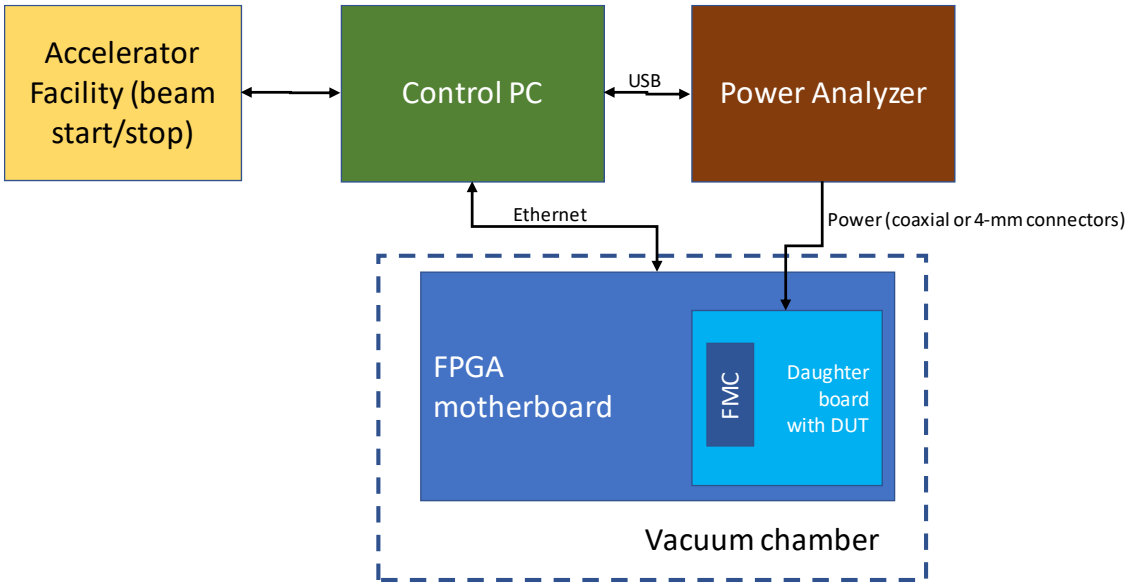


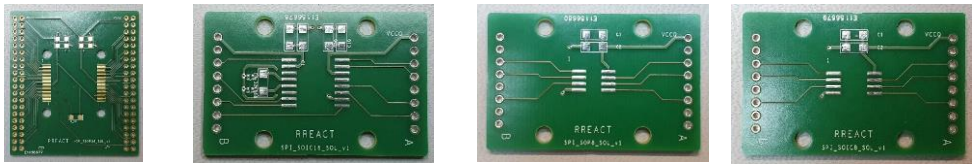
CY15 – TID Lot-to-lot results, grounded components

- No failure observed
- Increase in stand-by current (not so different from biased components)
- N.B. Lot A (black) irradiated to 100 krad(Si), lot B and lot C (red and blue) to 50 krad(Si)



Setup for SEE Tests

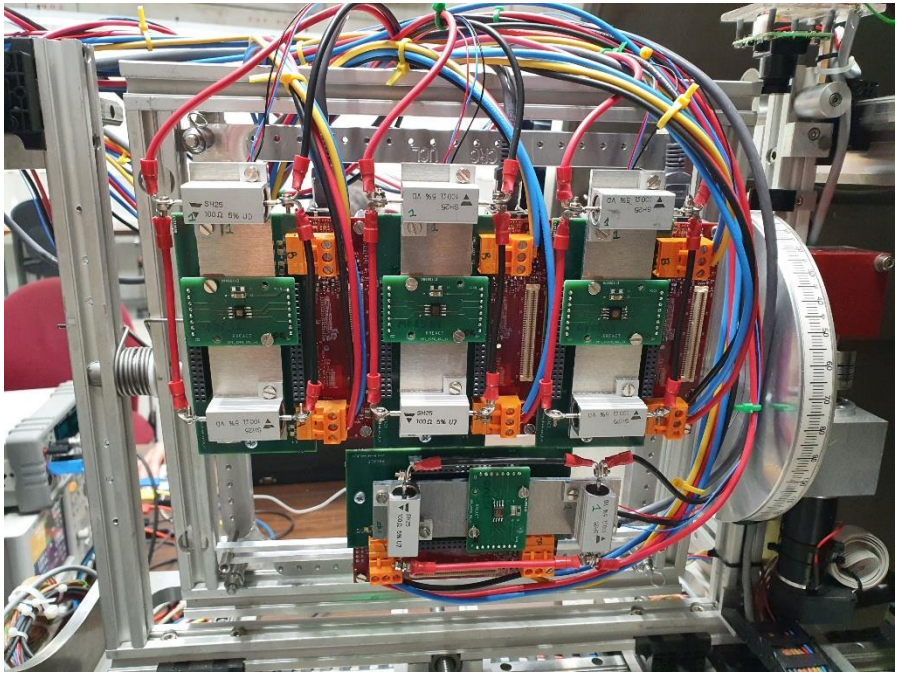


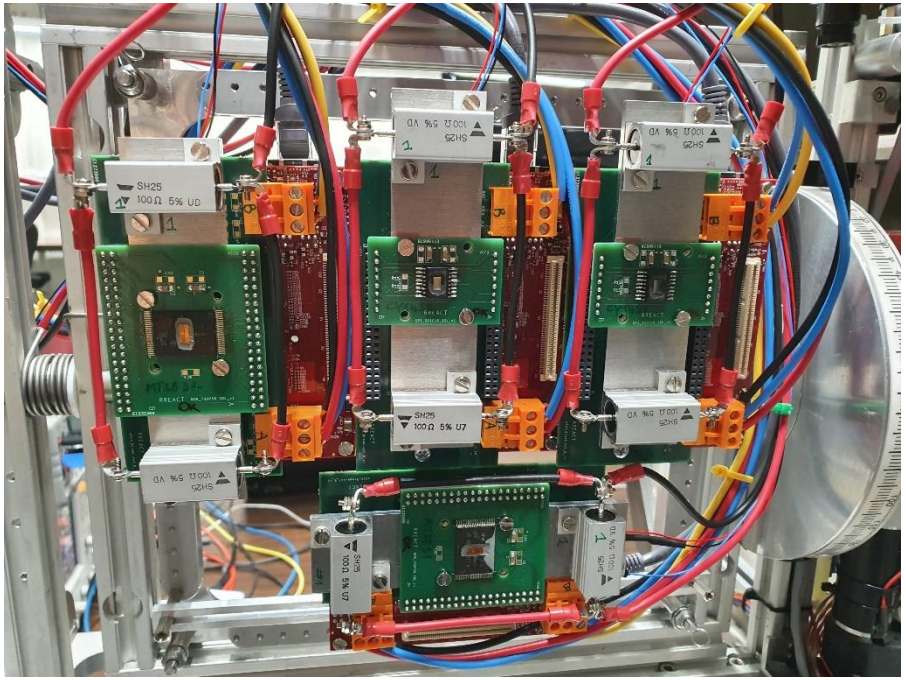


SEE test setup

- SoC-based motherboard and Power Analyzer (similar to TID setup) + adapter boards
- Start/stop beam commands with dedicated interface
- Delidded components soldered on one side of the adapter board, with heater on the other side
- A sensor is used to monitor the temperature of the board
- Calibration in vacuum to measure die temperature

Heavy-ion Measurements





- Experimental setup in HIF vacuum chamber

Detection of SEU and SEFI

SEU test sequence:

- The memory is **written**
- **Powered off** for non-volatile cells, standby for volatile
- Exposure to a given fluence of particles,
- Power on
- **Read**
- The number of SEU is logged and used to calculate the cross section

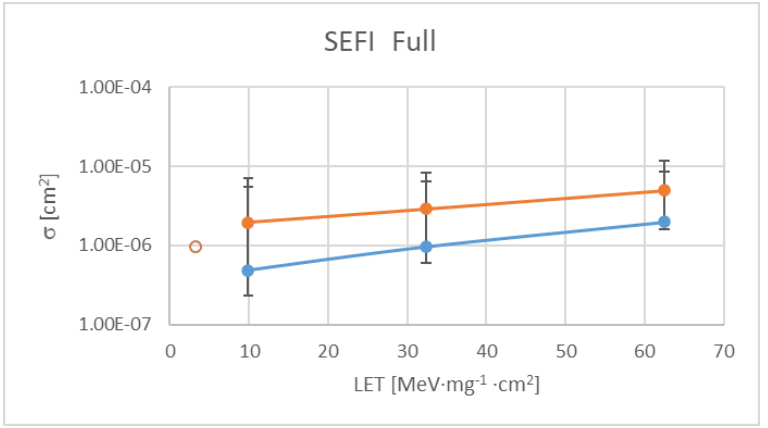
SEFI test sequence:

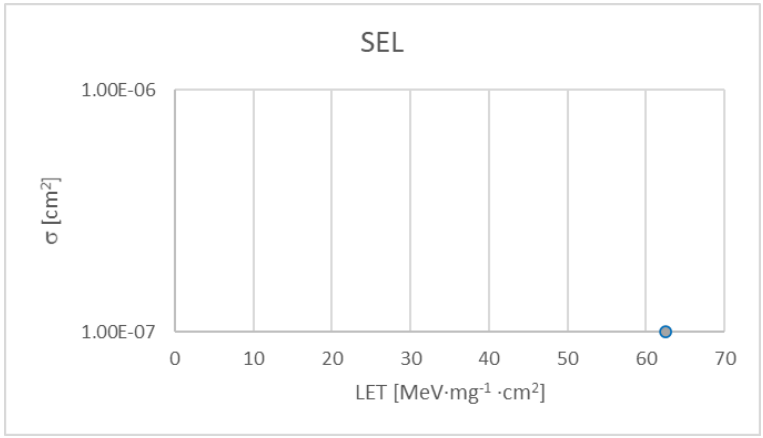
- The memory is continuously exercised through a **loop of (erase)/program/read (SEFI full) or read (SEFI read)** operations
- When a **large number of events** is detected or some other **exceptional conditions** occur, the control PC stops the beam and power-cycle the memory
- When and if the device becomes operational again, the test is resumed
- The number of SEFI is logged and used to calculate the cross section

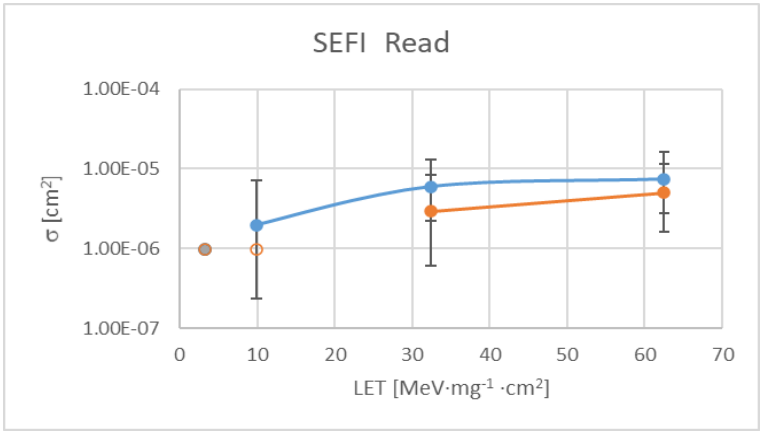
SEL test sequence:

- The memory is **biased and heated** to the target temperature (RT for the most sensitive devices)
- Exposure in **idle ready-to-operate** conditions (to maximize the visibility of SEL)
- The **supply current** is monitored and when a **sudden increase** is detected, the power and beam are cut
- Brief test to see if memory is operational and if so, then exposure is resumed.
- The number of SEL is logged and used to calculate the cross section

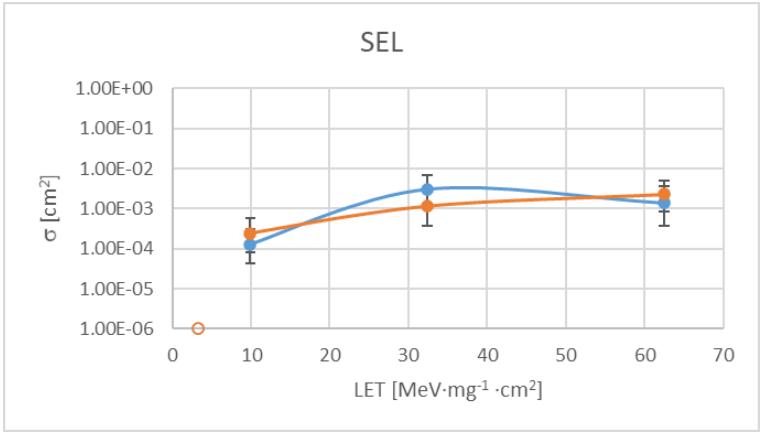
- FRAM technology
- Cells are immune up to > 60 MeV·mg^{-1}·cm^2
- SEFI σ considerably lower than in the Cypress devices
- No SEL @ 85°C

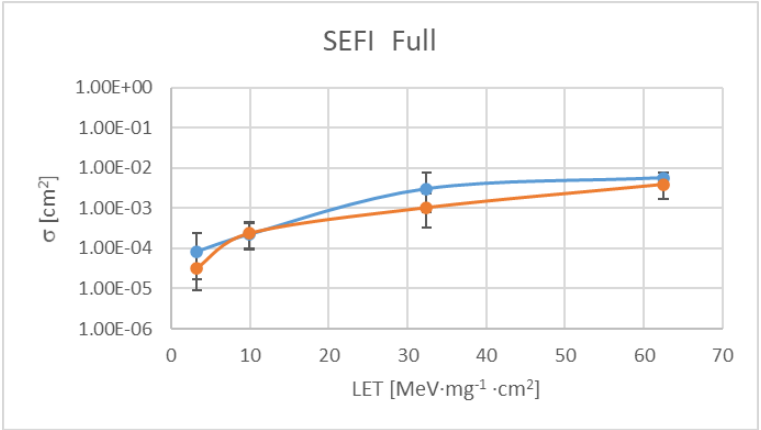


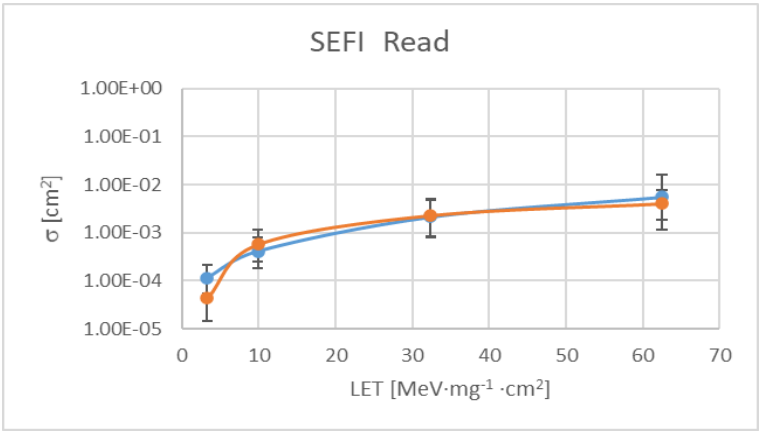




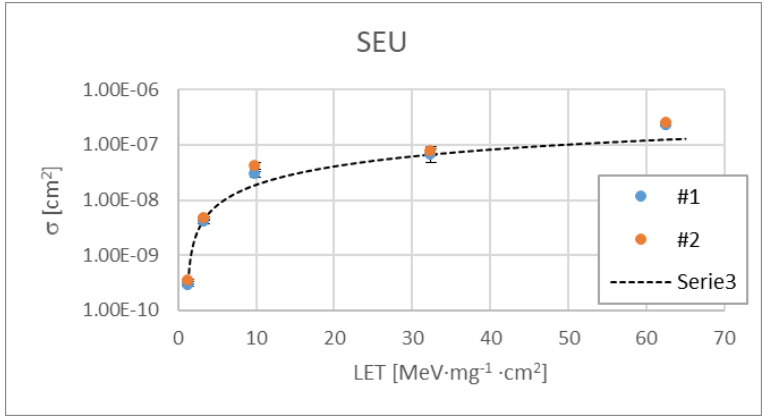
- FRAM technology
- Cells are immune up to > 60 MeV·mg^{-1}·cm^2
- Cross sections for SEFIs and SEL (at room temperature) are very close
- Hard to tell if there is a spike in the current, when the device is operating and dynamic current dominates, but it is likely

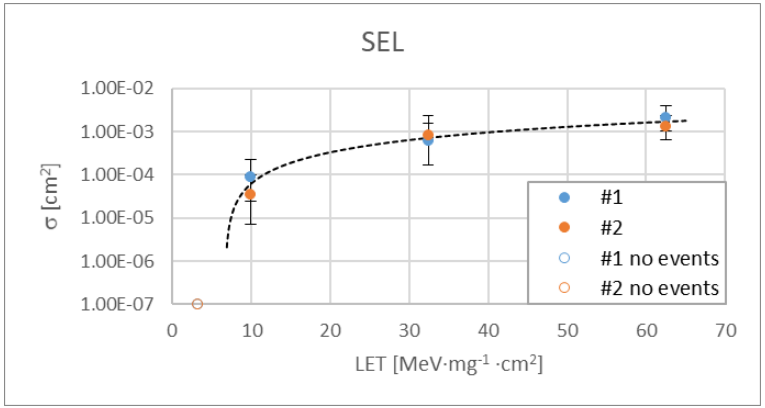


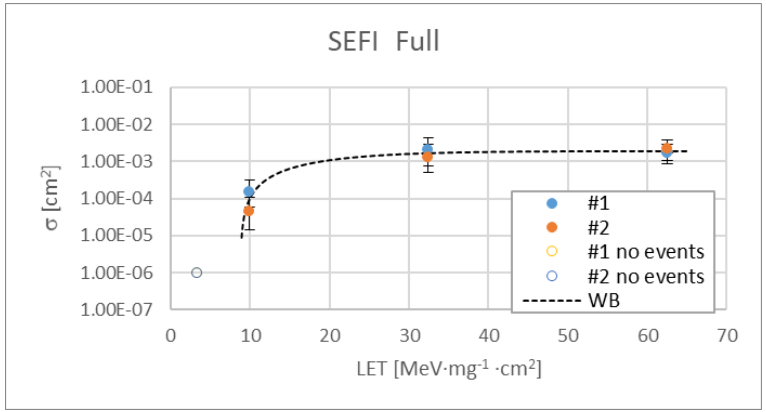




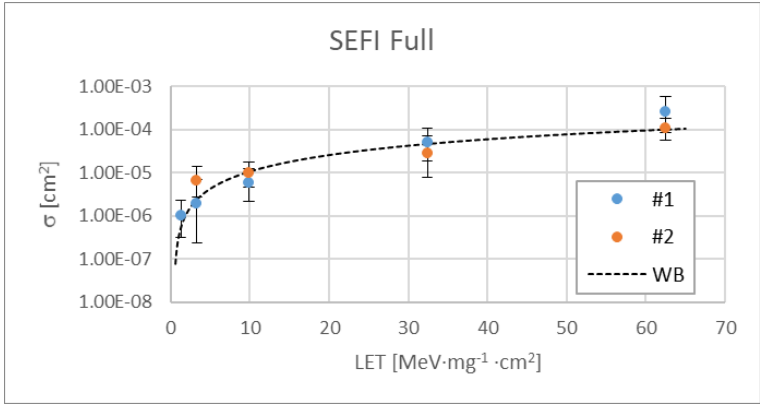
- nvSRAM (SRAM+SONOS)
- NV cells are immune up to 62.5 MeV·mg^{-1}·cm^2 (higher LET will be tested)
- SRAM cells are sensitive
- SEL (RT), SEFI σ are similar (again, hard to tell if there is a spike in SEFI events, but it is likely)

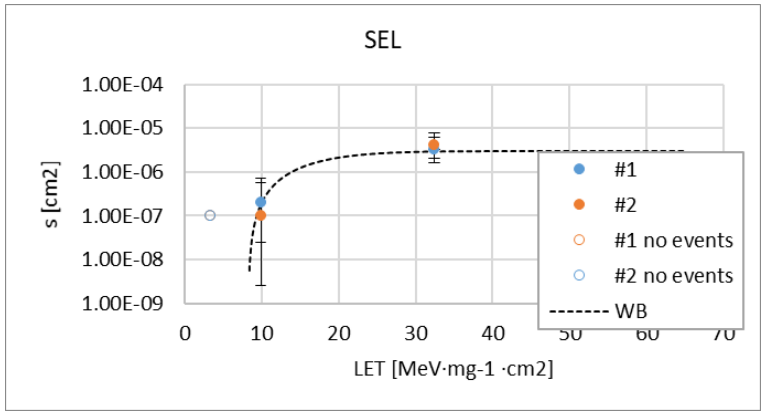


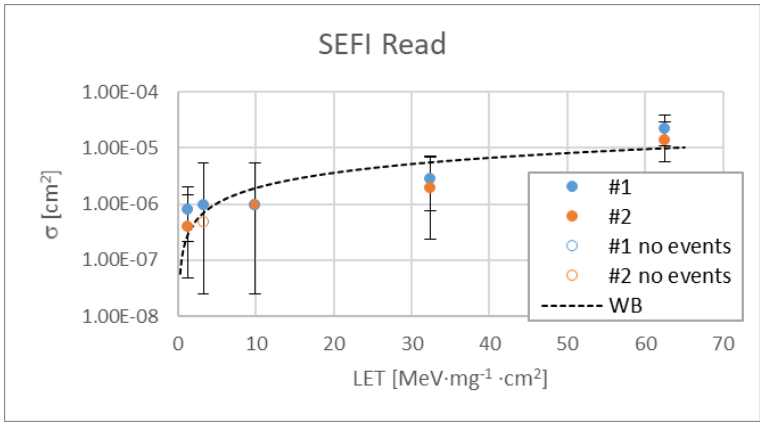




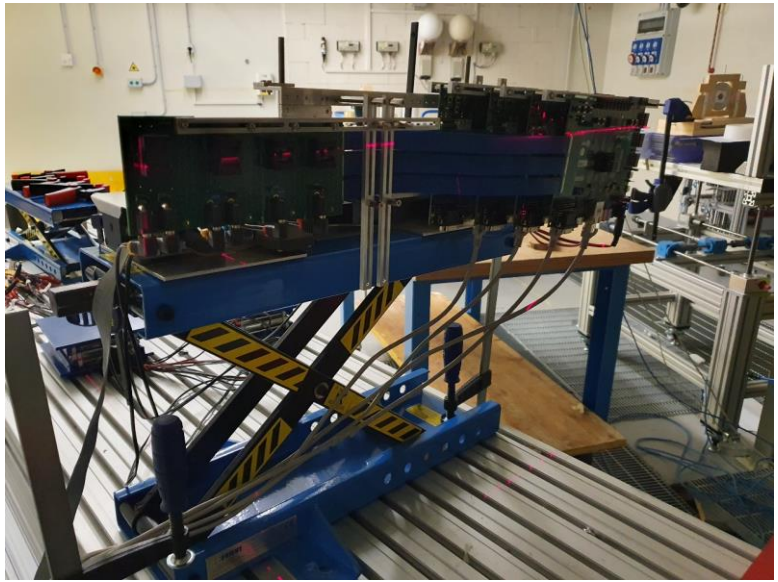
- NOR Flash
- Cells sensitive at 62.50 MeV·mg^{-1}·cm^2, $\sigma < 10^{-10}$ cm^2
- Destructive events with Xe (inability to program and erase). Likely charge pump failure, not related to TID







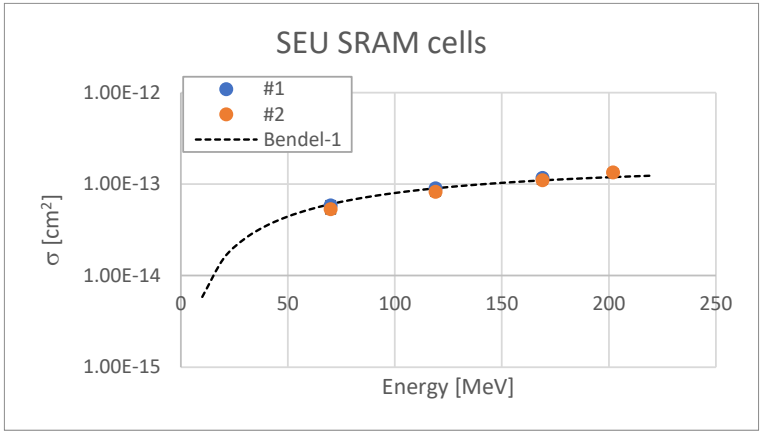
UPD Proton Tests

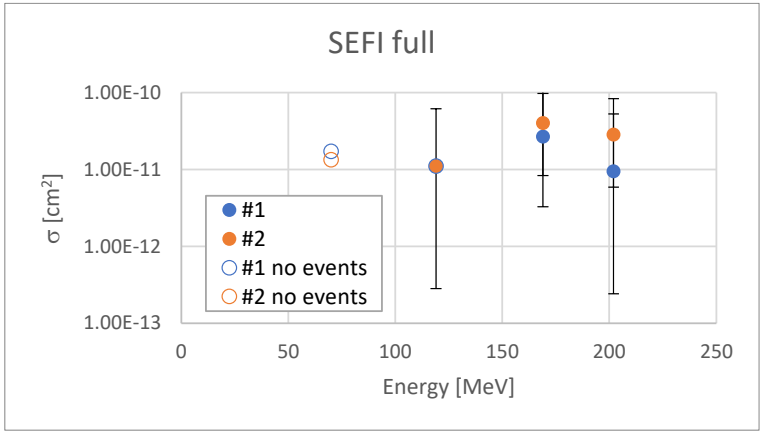


- The two most sensitive devices have been tested with protons
  - CY14 nvSRAM
  - CY15 FeRAM
- TIFPA Trento Facility in Italy
  - Flux ~ 3e8

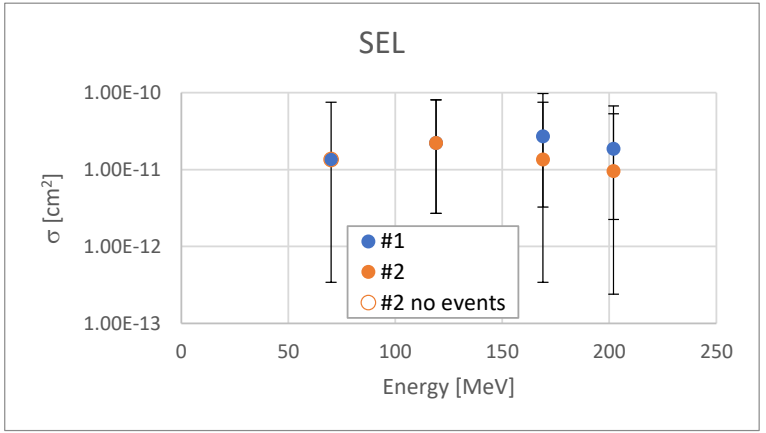
DUT energy [MeV]	Range [mm Si]	LET [MeV/(mg/cm²)]
70	22	$8.016 \cdot 10^{-3}$
119	56	$5.370 \cdot 10^{-3}$
169	104	$4.220 \cdot 10^{-3}$
202	141	$3.617 \cdot 10^{-3}$

CY14: Proton Results

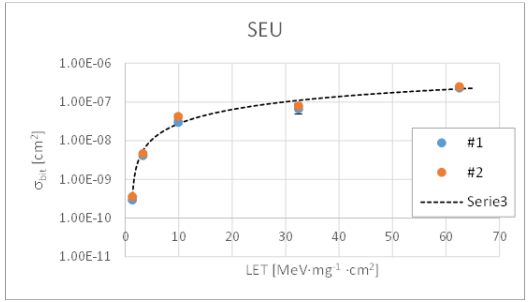


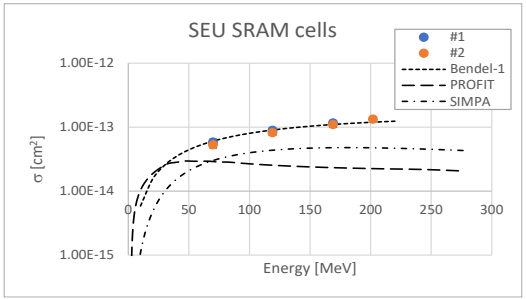


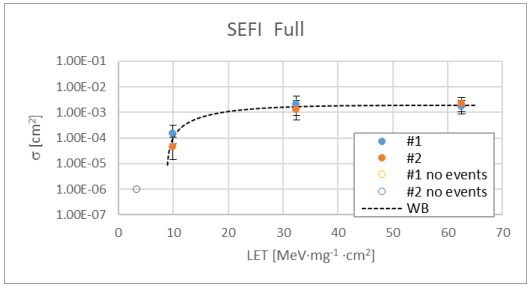
- Events (SEU, SEFI and SEL) with protons consistent with heavy-ion sensitivity
- Large error bars and significant dose for SEFIs

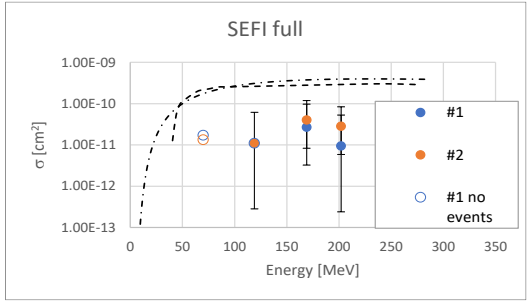


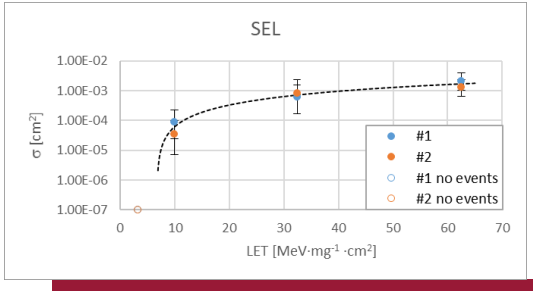
CY14: SIMPA & PROFIT

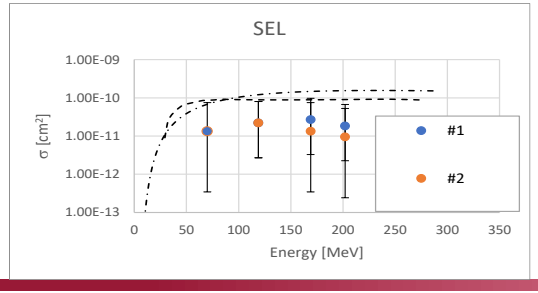










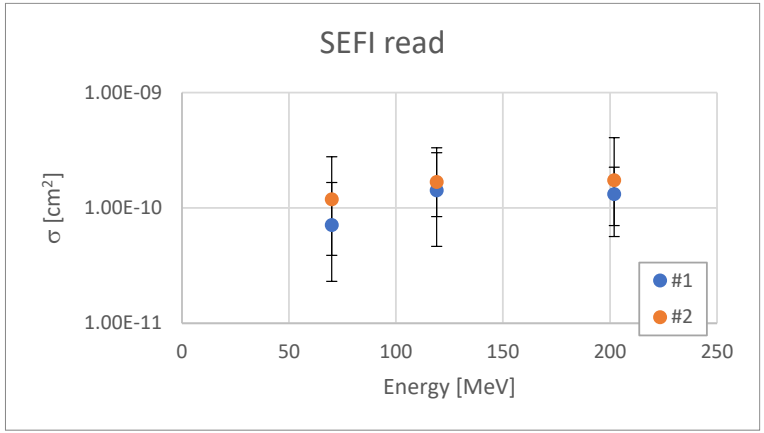


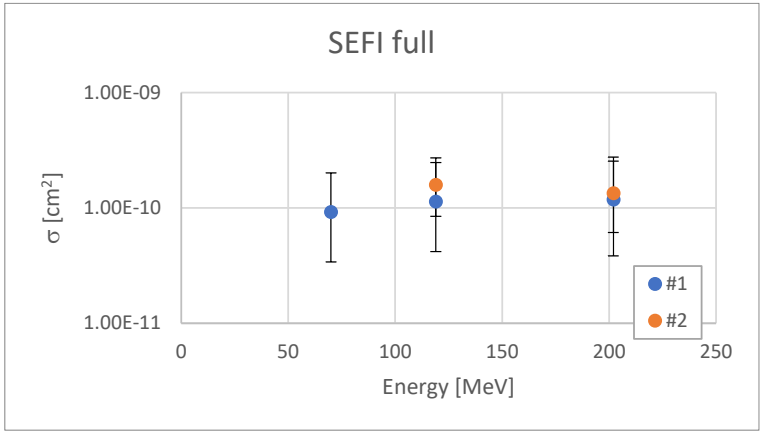
Overestimation of proton effects by PROFIT and SIMPA for SEFIs, underestimation for SEU

Models developed many years ago for SEU:

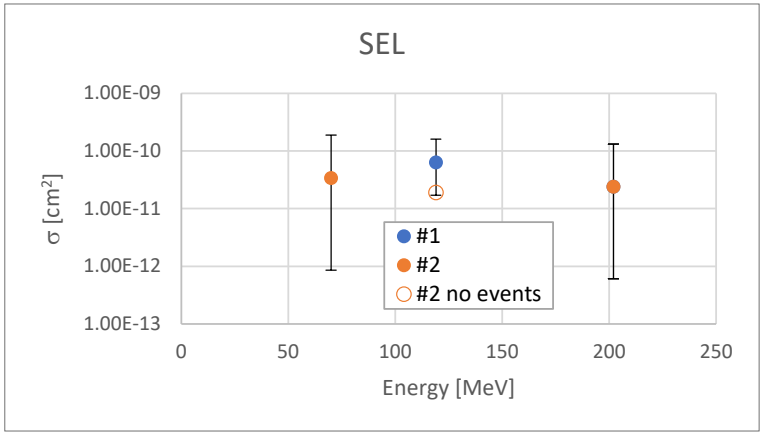
- Fewer materials in the semiconductor industry
- Larger feature size
- Peculiar RAM with associated NV element

CY15: Proton Results

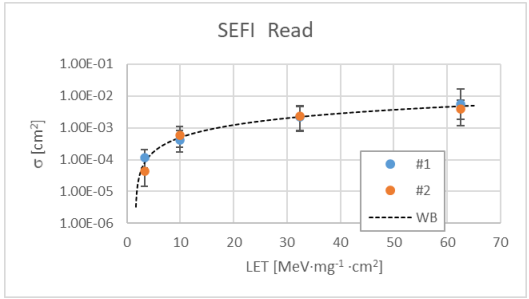


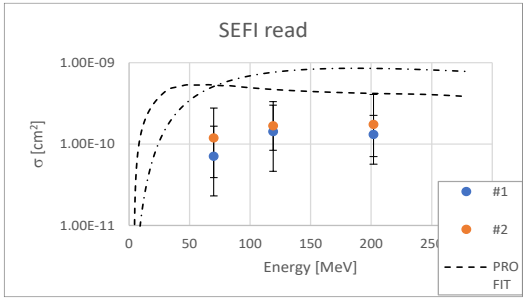


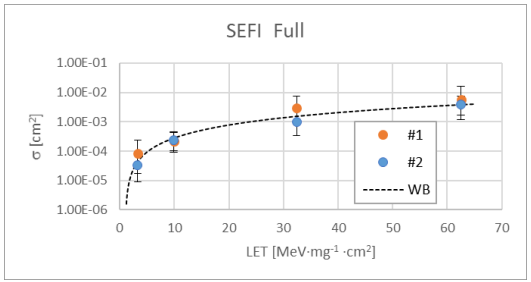
- Events (SEFI and SEL, no SEU) with protons consistent with heavy-ion sensitivity

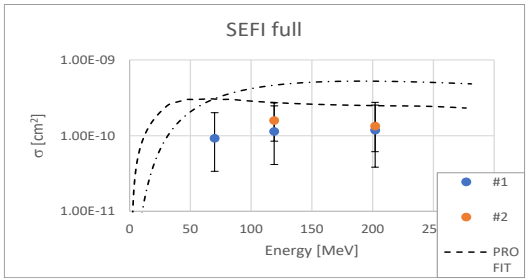


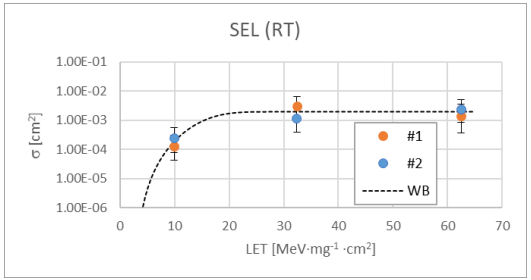
CY15: SIMPA & PROFIT

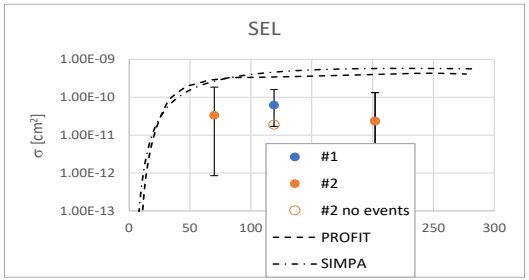












Overestimation of proton effects by PROFIT and SIMPA for SEFI and SEL

Models developed many years ago for SEU:

- Fewer materials in the semiconductor industry
- Larger feature size

Conclusions: TID

- Different SPI memories and a NOR Flash were tested
- Total Ionizing Dose
  - All memory cells, regardless of the storage technology, behave well
  - Increase in the supply current in various conditions and to various extents is the most common issue at doses below 50 krad(Si)
  - Functional failures can appear above 15 krad(Si)
  - In general, the samples show a consistent behavior even between lots in the case of the CY15
  - Small differences are visible in stand-by current for the biased components

Conclusions: SEE

- Single Event Effects
  - All tested NV cells are pretty hard with respect to SEU
    - data loss only with Micron NOR Flash with Heavy Ions (HI) at an LET of 62.5 (small σ)
  - CY14 nvSRAM has expected SEU sensitivity in the SRAM cells (both HI and p)
  - Significant and consistent SEL/SEFI σ in Cypress devices (both HI and p)
  - Destructive events in the Micron NOR Flash with HI at an LET of 62.5 MeV $\cdot$ mg^{-1} $\cdot$ cm^2
- PROFIT & SIMPA
  - Large discrepancies (both overestimation and underestimation) between predicted and measured proton sensitivity