Radiation-induced SEL in a COTS SRAM memory - test and flight data

Investigation on intra-die variability and radiation-induced SEL in a COTS SRAM memory flying on Proba-V + Flight data analysis of SEL in a COTS Samsung SRAM and comparison with SEE test results

Douglas A. Santos, Lucas M. Luza, André M. P. Mattos, Thomas Borel, Viyas Gupta, Luigi Dilillo

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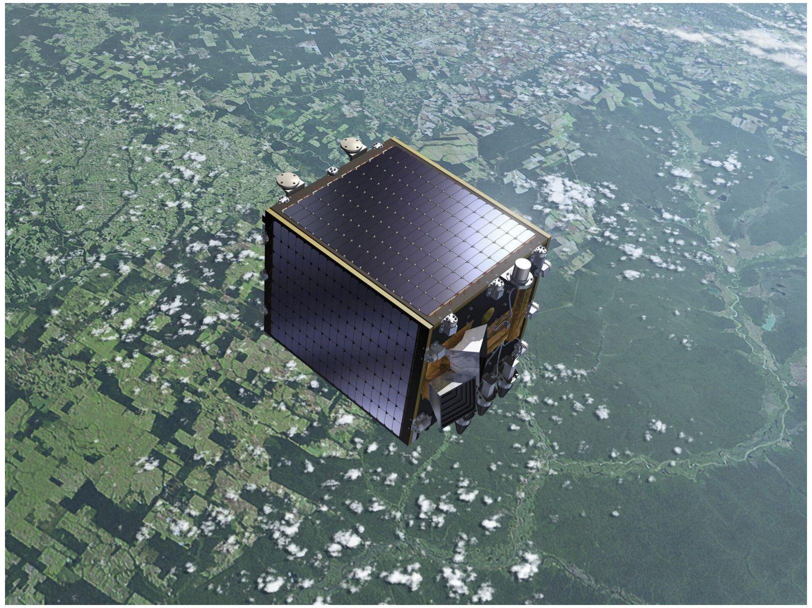
Outline

- PROBA-V Context
- Motivation
- Experimental Setup
- Accelerator Experiments
- SEFI Analysis
- Conclusion

PROBA-V Mission

Project for **On**-**B**oard **A**utonomy - **V**egetation

- Miniaturized version of the VEGETATION instruments
  - Tracks the vegetation's evolution and its links to climate changes from the SPOT 4 and 5 satellites
- Launched on May 2013
  - Low Earth heliocentric orbit at an altitude of 820 km
  - Main mission ended in June 2020
  - Still in operation



PROBA-V Representation
ESA - P.Carril, 2012

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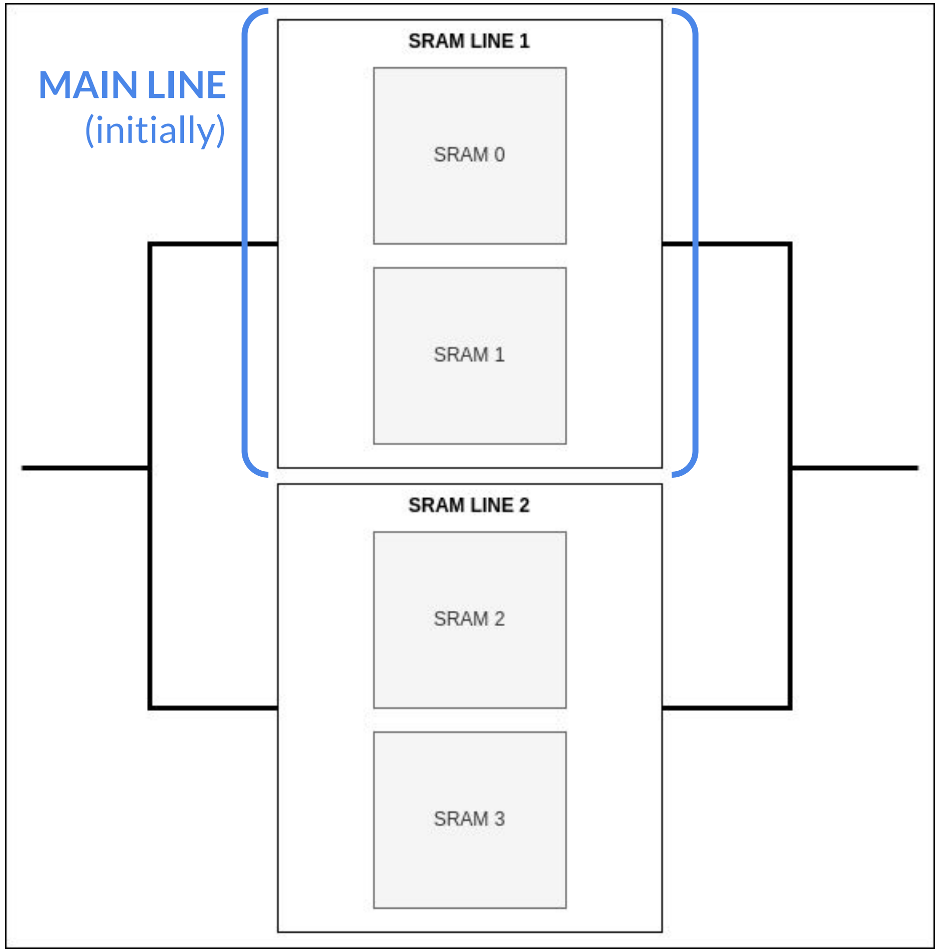
PROBA-V Dual Memory Redundancy



Main and redundant memory lines

- Both memory lines implement ECC with single-error correction and double-error detection
- Main operates most of the time
- Redundant takes over temporarily when the ECC fails (error 406)

Switching from main to redundant lines takes between **3-4** minutes

Memory: Samsung K6R4016V1D

PROBA-V Flight Error Reporting

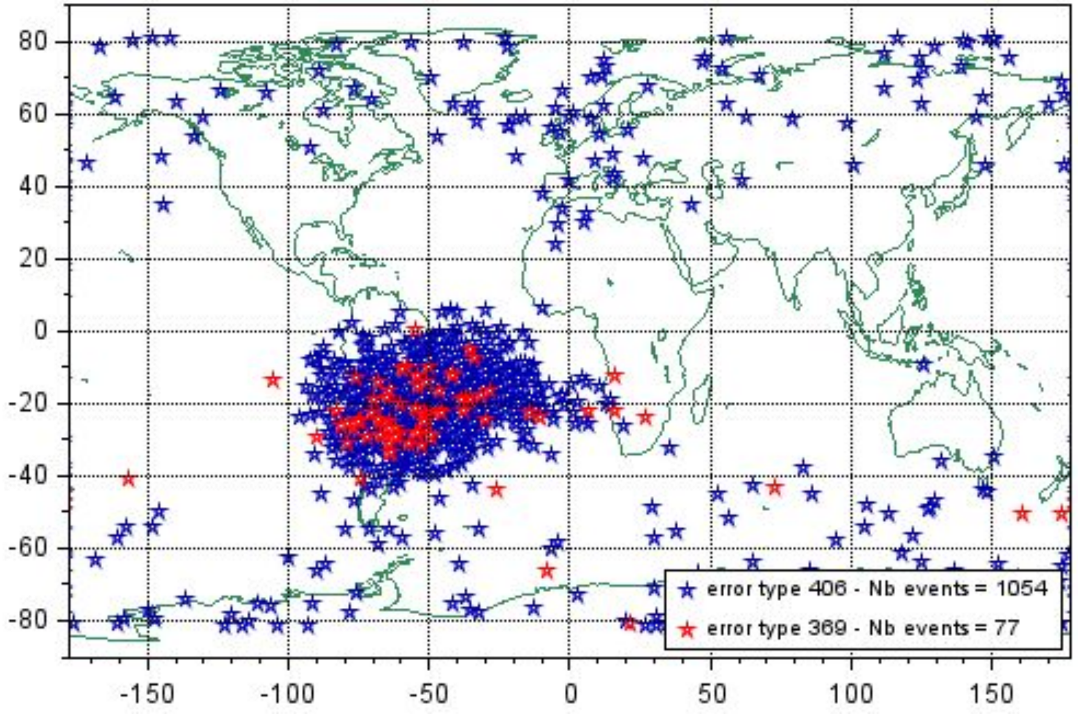
Monitored SRAM errors through error type flags

- Flag 406 - Uncorrectable
  - ECC failure
  - This flag is logged when the SRAM memory undergoes a Single Event Latch-Up (SEL)
- Flag 369 - Correctable
  - 1000 accumulated single errors
  - This flag was defined during the course of the PROBA-V mission, they were not initially recorded. The flag is raised when the SRAM memory remains functioning but at least 1000 single errors are detected during the EDAC checks

PROBA-V: Observed Effect

Error flags appeared frequently during the flight, mostly in SAA area and polar regions

- 07/05/2013 to 03/03/2020
- 1054 errors with type flag 406
- 77 errors with type flag 369



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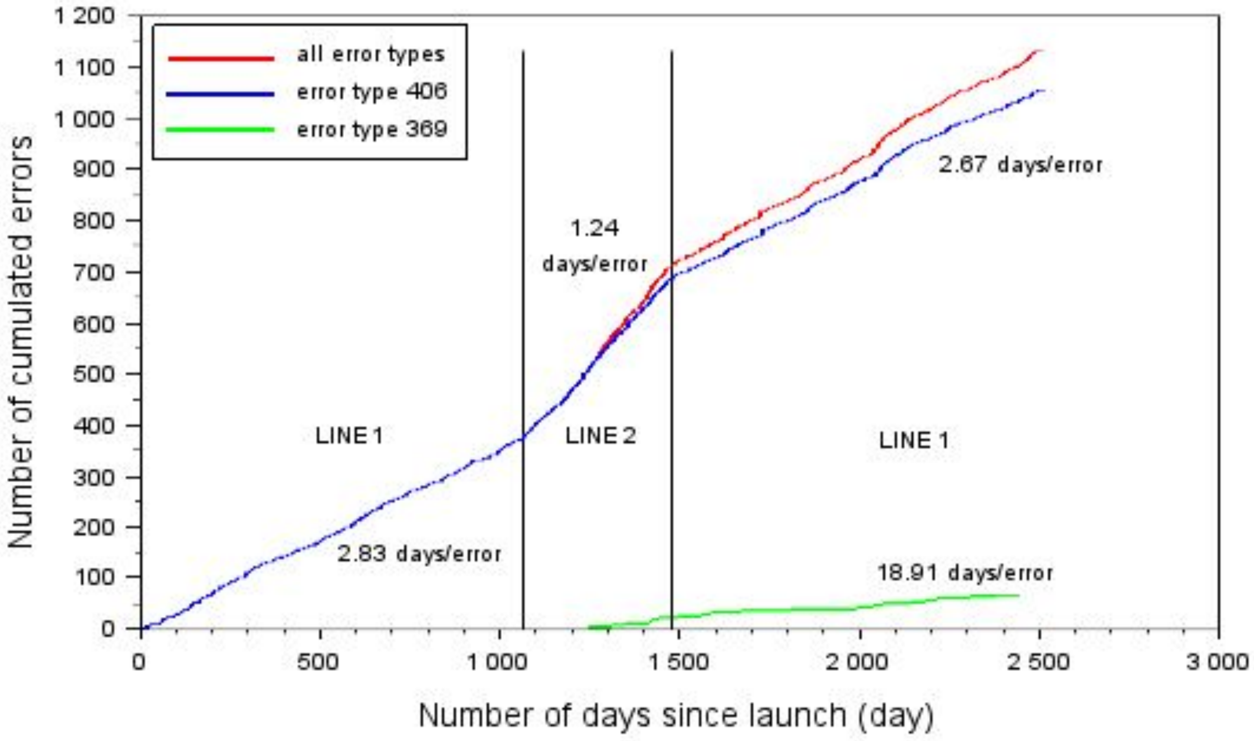
PROBA-V: Error types in time (in flight)



LINE 2 was manually defined as main line at around day 1000

Increased error rate (2.3x)

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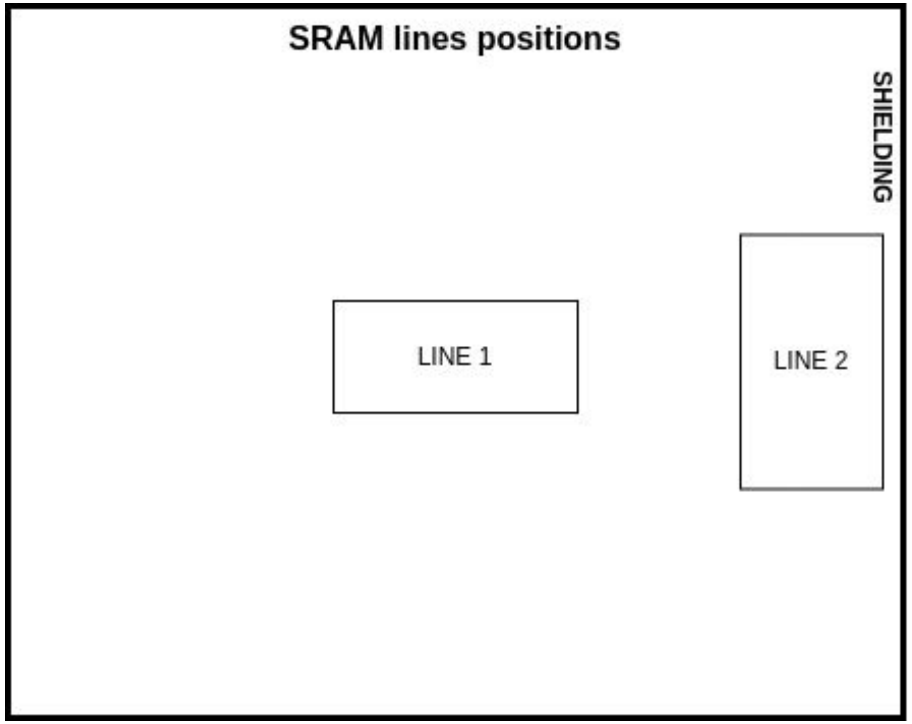
Hypothesis

Two hypothesis could explain these effects:

- Different temperatures affect the SRAM's SEL susceptibility

- The difference in environments affect the SEL susceptibility



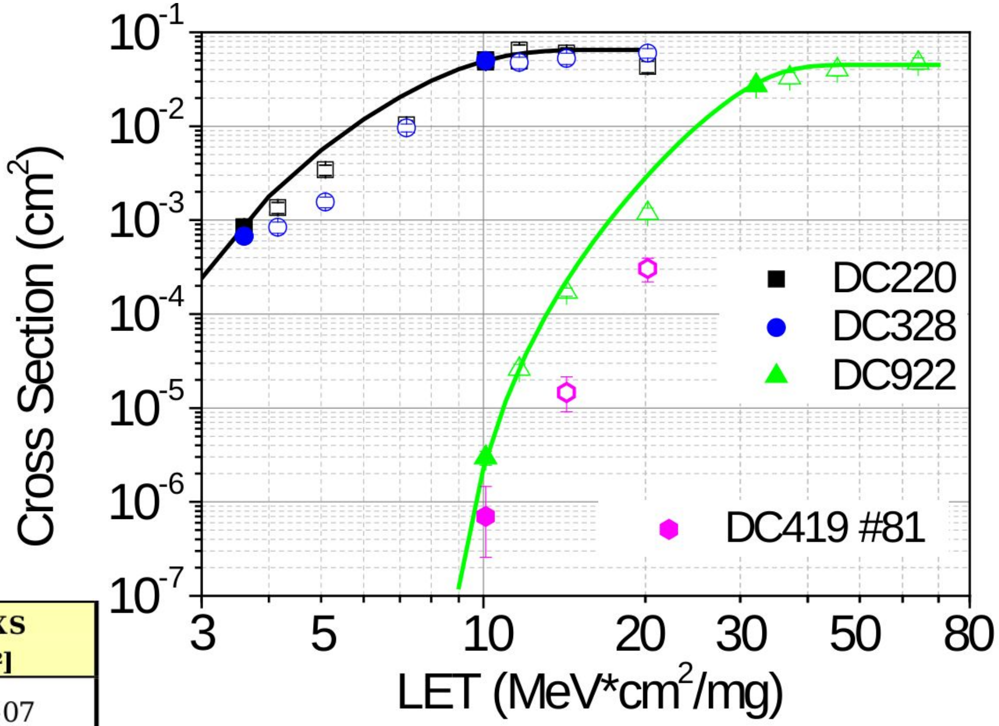
Pre-flight test report

Characterized the SRAM memories for SELs with heavy-ions

Did not report number of errors

- Test performed only in static mode

Lower tested LET of 10.1 MeV/cm²/mg



Run #	Angle [deg.]	Eff. LET [MeVcm²/mg]	Fluence [cm⁻²]	Time [s]	Corrected Fluence [cm⁻²]	SEL #	SEL XS [cm²]
52	0	10.1	1.00E+07	1154	9.98E+06	7	7.01E-07
53	60	20.2	3.81E+05	220	3.36E+05	103	3.06E-04
54	45	14.3	2.18E+06	259	2.11E+06	31	1.47E-05

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Motivation

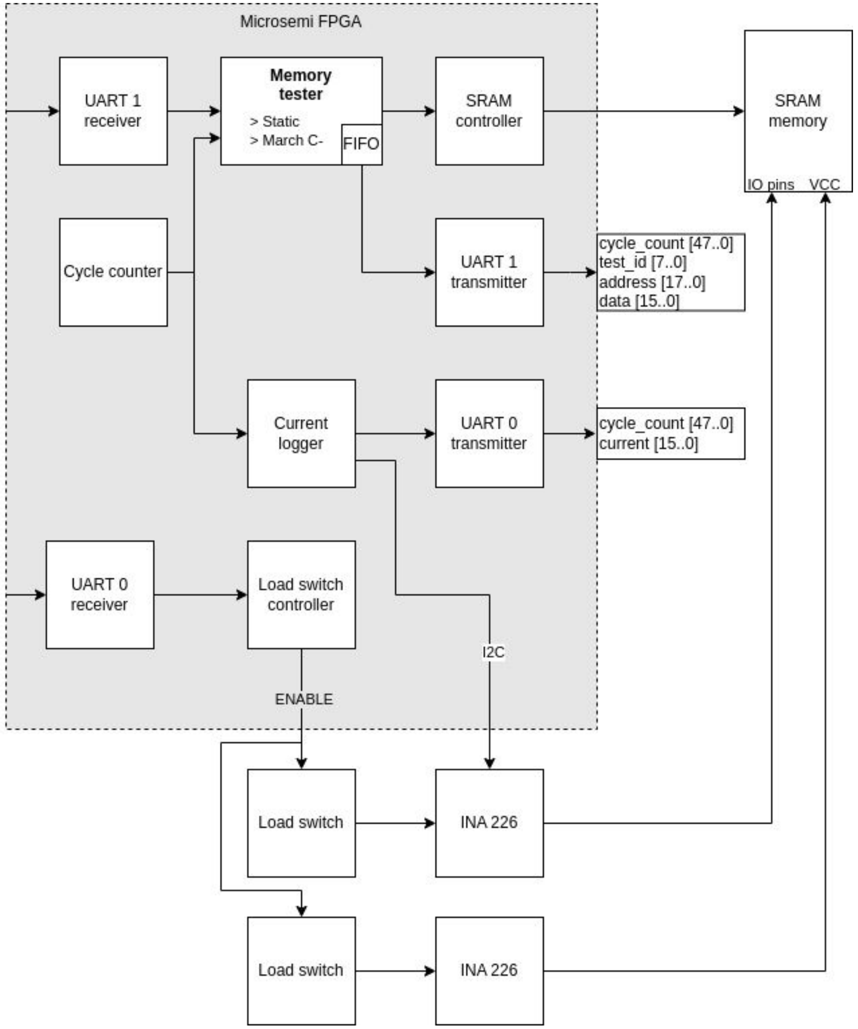
Identify the effects of the SEL in the memory

- Pre-flight experiments could not predict the observed outcome
- Identify the ECC failures during flight

Prove that ECC failures happened because of SEFIs caused by SELs

Experiment Setup

Experiment Setup



Setup with precise timestamping

- Current measured with 25 uA precision
- Timestamp based on internal clock
- Errors and current reported with Timestamps

Enables Real-time comparison between errors and current

Experiment Setup: Test Modes

Static 0xAA

- Write 0xAAAA in all addresses
- Irradiate the DUT
- If SEL, power cycle the memory

Do not read the memory to check for errors latch-up occurs

March C-

- Mimics actual operation with the memory
- If SEL, power cycle and restart test

```
  ↑ {w0}
{↑ {r0,w1}; 0x11 / 0x12
  ↑ {r1,w0}; 0x19 / 0x1A
  ↓ {r0,w1}; 0x21 / 0x22
  ↓ {r1,w0}; 0x29 / 0x2A
  ↑ {r0}} 0x31
```

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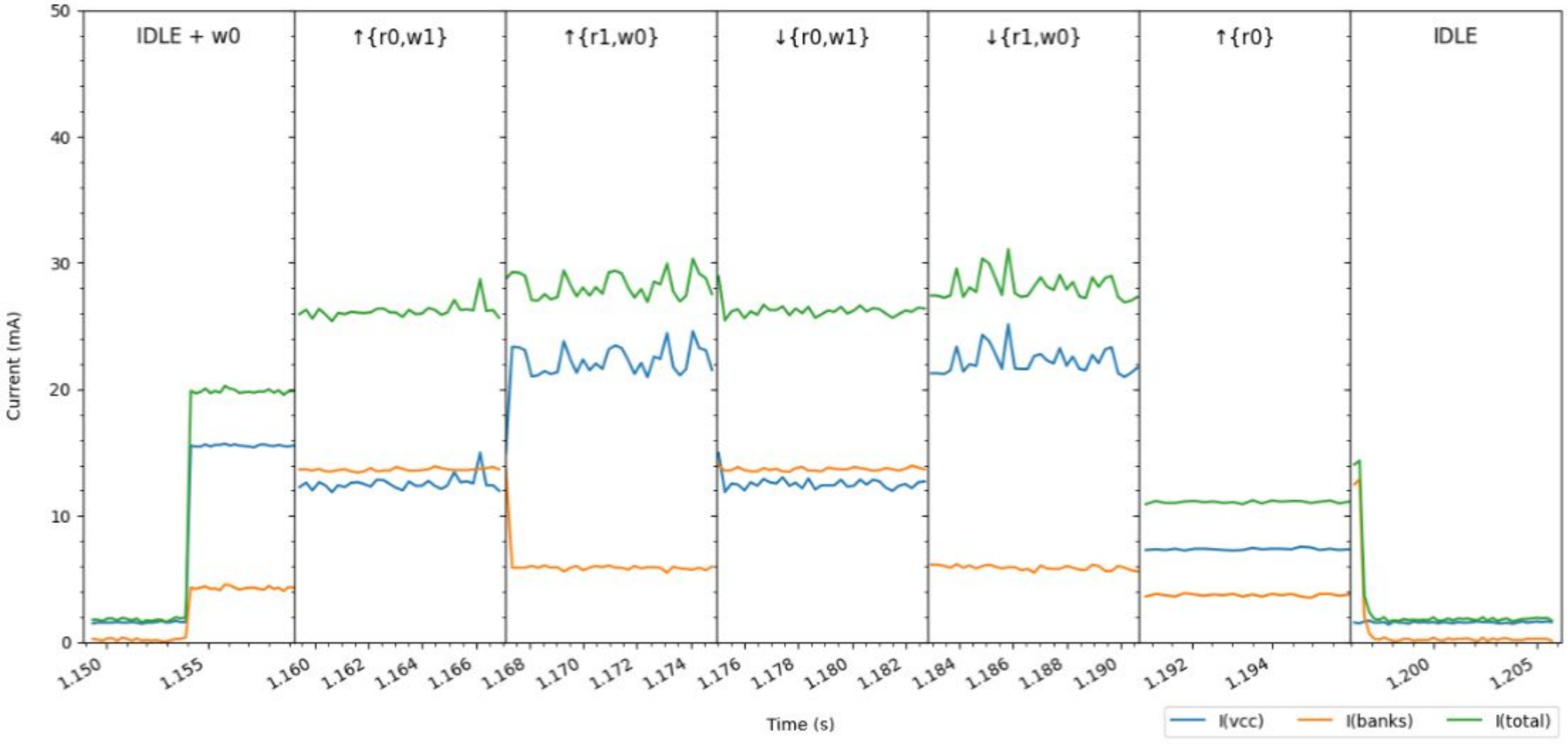
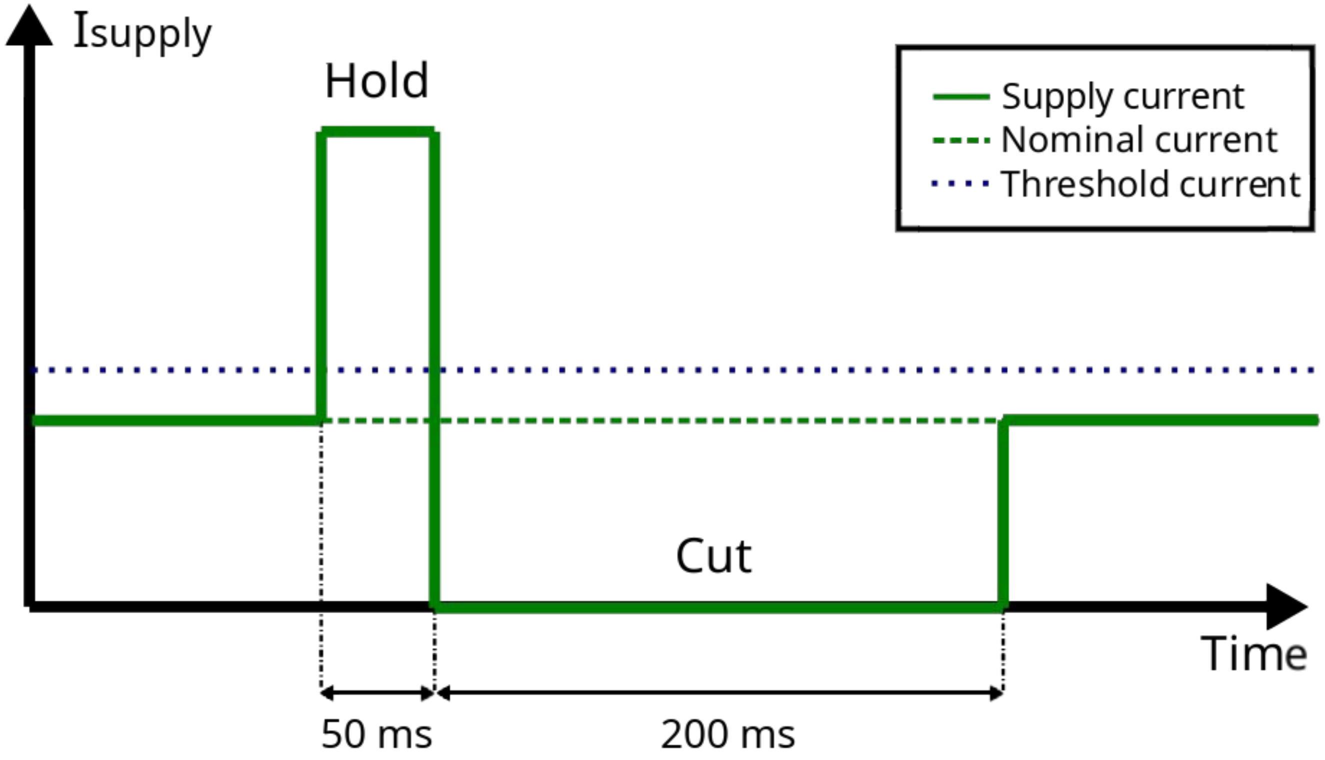
Experiment Setup: Current Monitoring



Experiment Setup: SEL Analysis

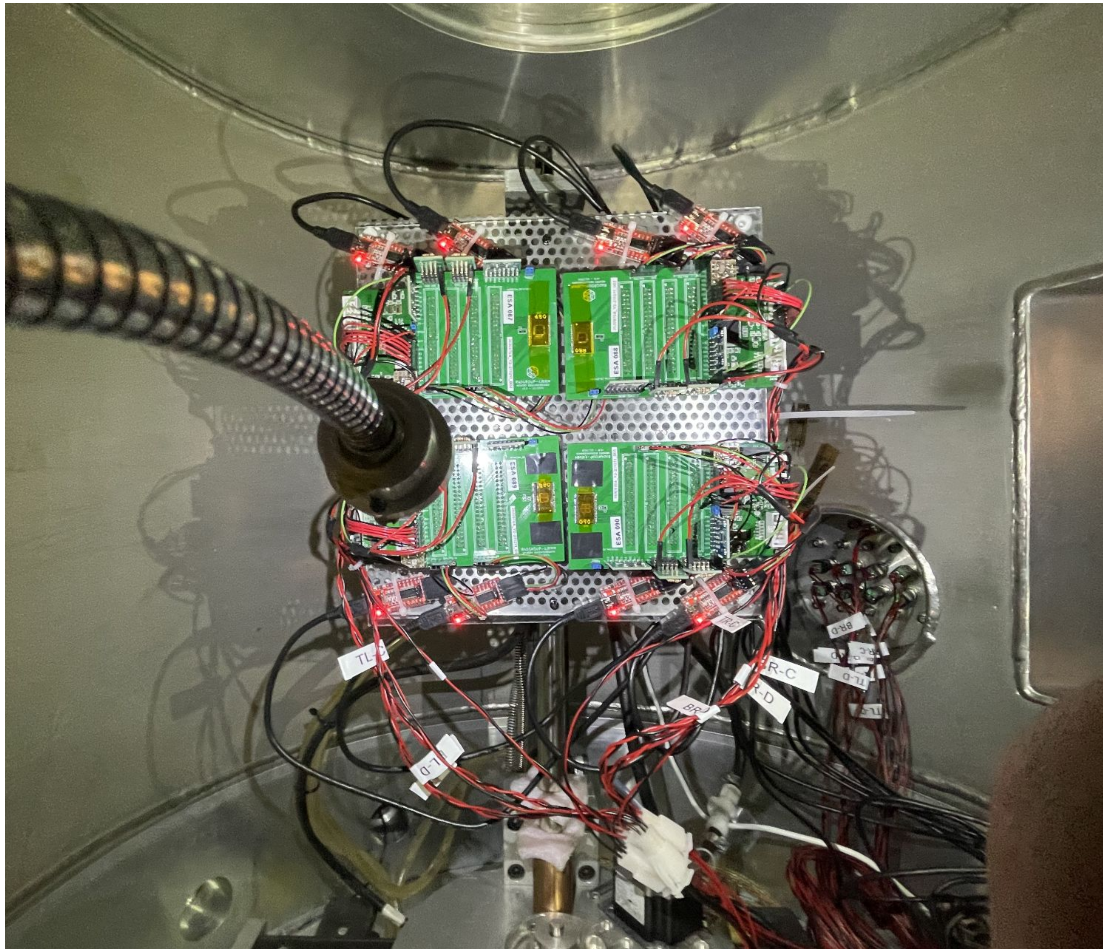
Test Parameters

- Hold time:
  - 50 ms
- Cut time:
  - 200 ms
- Threshold:
  - 10 mA
  - 80 mA
  - 120 mA
  - Max



Accelerator tests

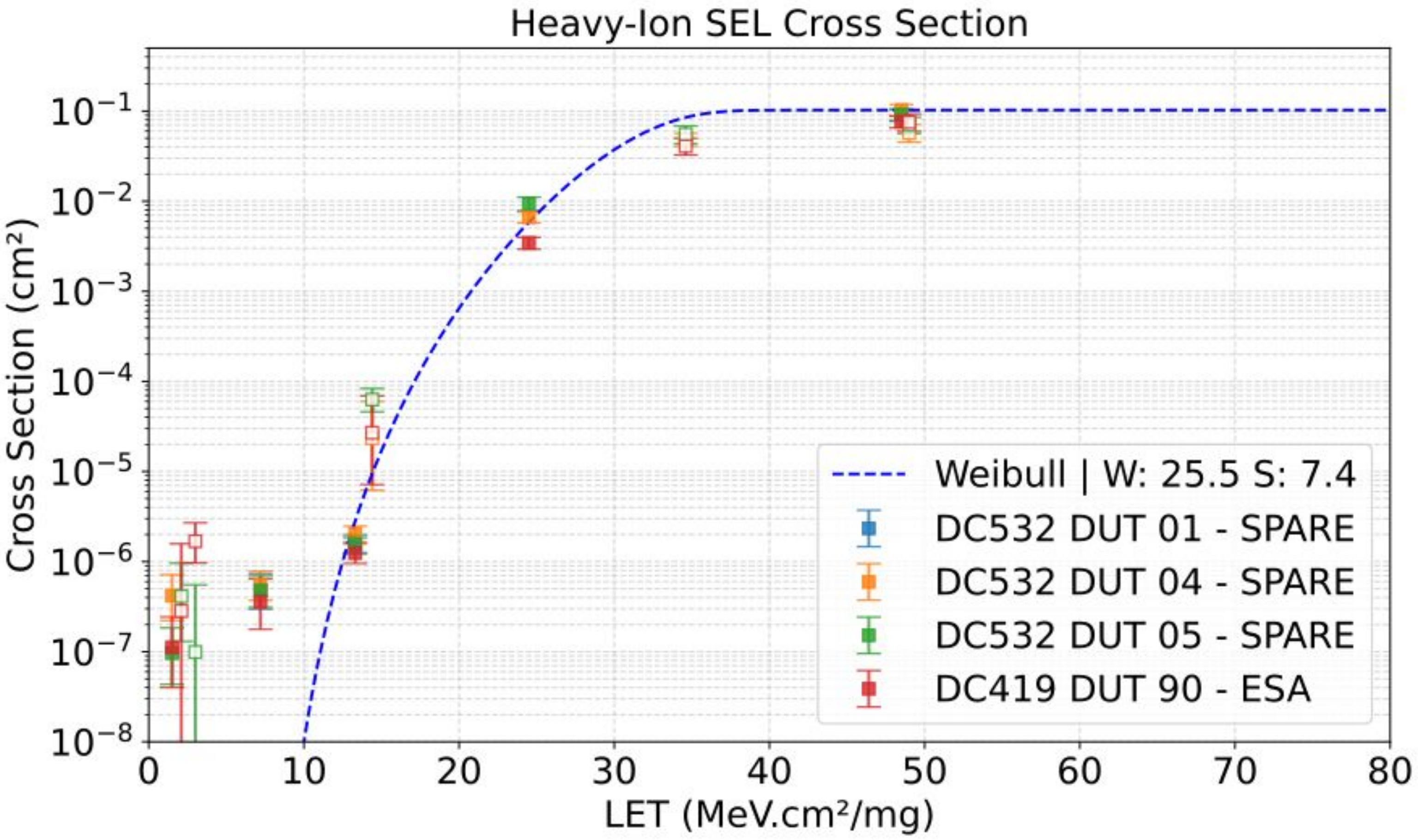
Accelerator tests: Heavy-Ions



Heavy-Ions Experiment

- RADEF Facility
- February 2022
- Tested LETs:
  - 7.2 MeV/cm²/mg
  - 13.3 MeV/cm²/mg
  - 14.4 MeV/cm²/mg
  - 24.5 MeV/cm²/mg
  - 34.6 MeV/cm²/mg
  - 48.5 MeV/cm²/mg
  - 49.0 MeV/cm²/mg
- Some of the LETs were achieved by testing the DUTs in different angles

Heavy-Ion SEL Cross Section



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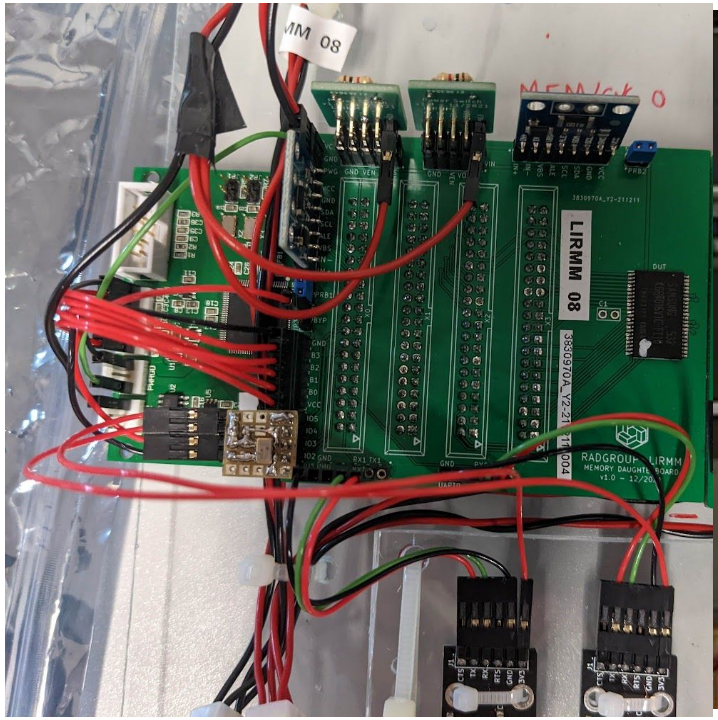
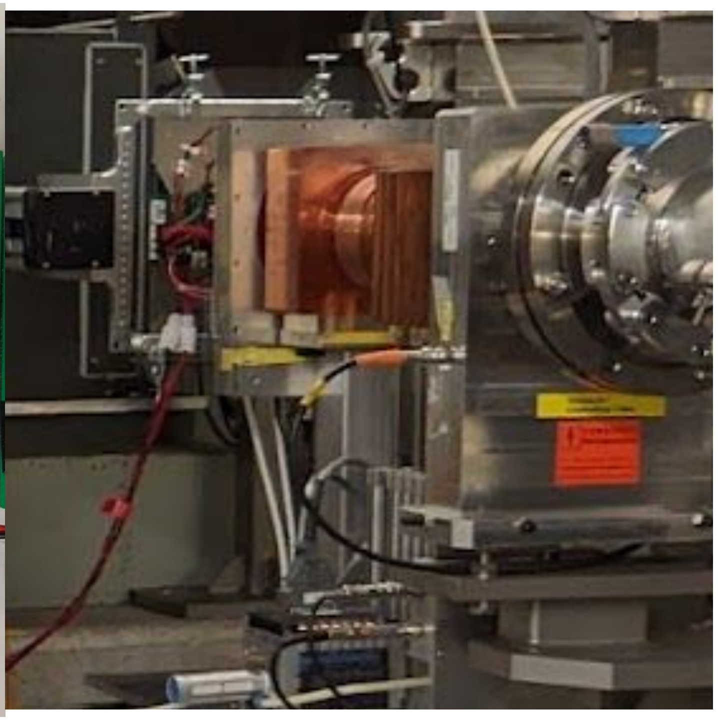
Accelerator tests: Protons





Proton Experiment

- PSI facility
- December 2022
- Tested energies
  - 51 MeV
  - 70 MeV
  - 101 MeV
  - 151 MeV
  - 200 MeV
- DUTs were tested separately to have a smaller and homogeneous beam

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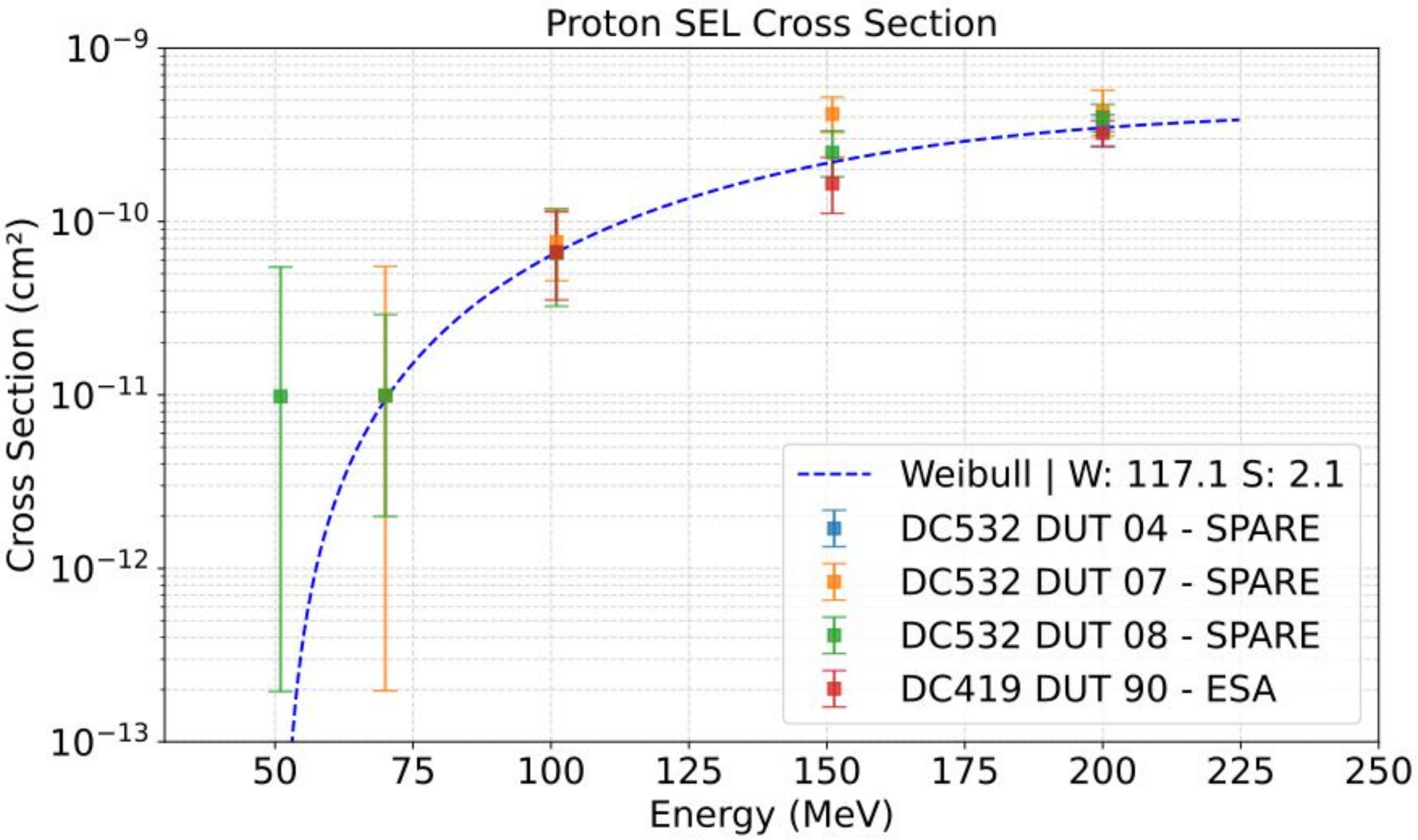
Proton SEL Cross Section



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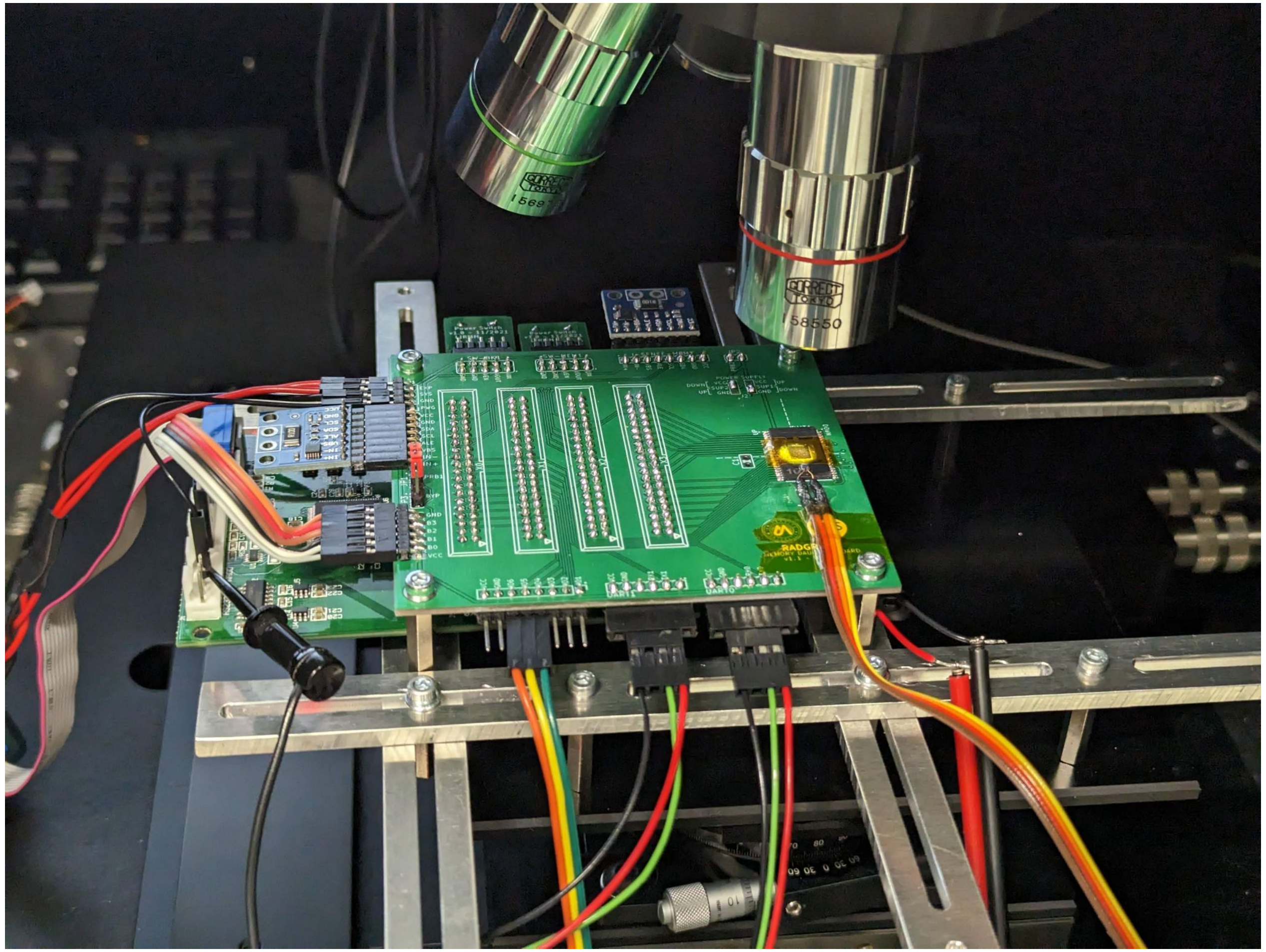
Accelerator tests: Laser



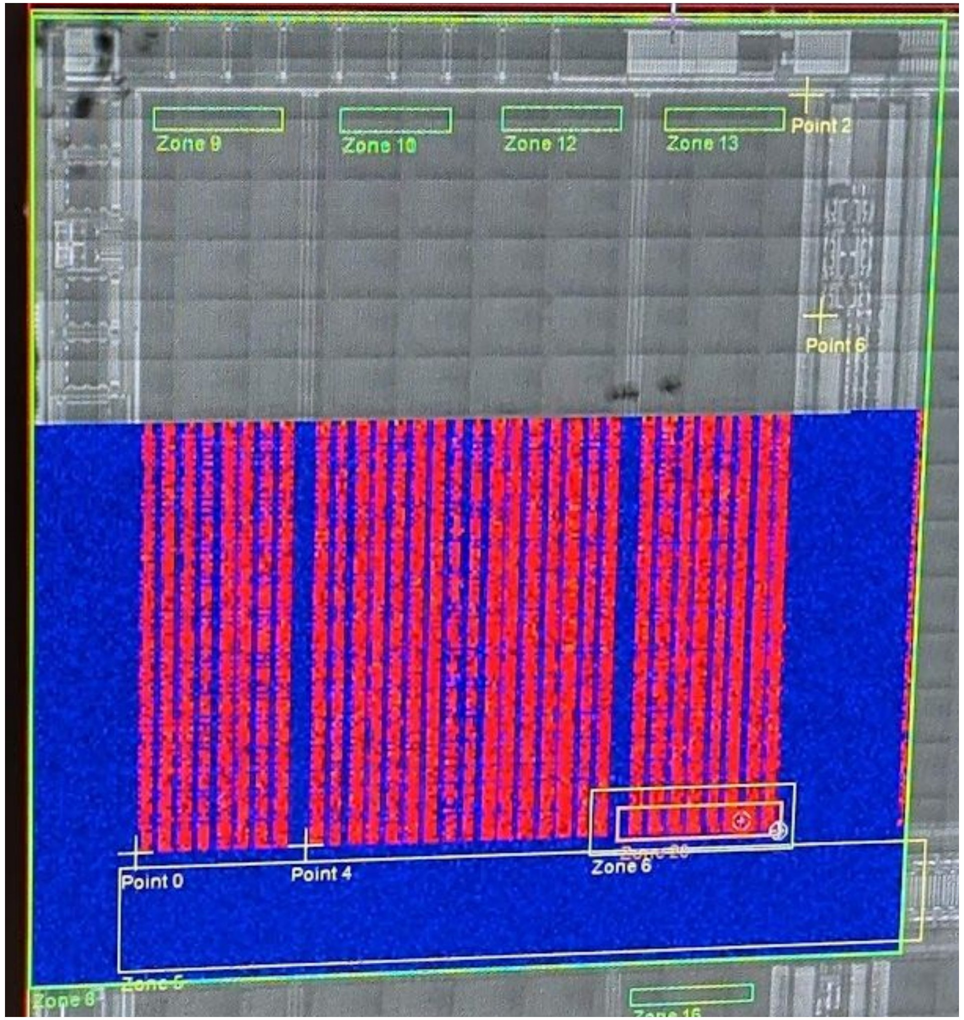
Laser Experiment

- ESTEC
- May 2023
- Tested energies up to 550 pJ
- Tested with different temperatures
    - 25°C (room temperature)
    - 40°C
    - 60°C

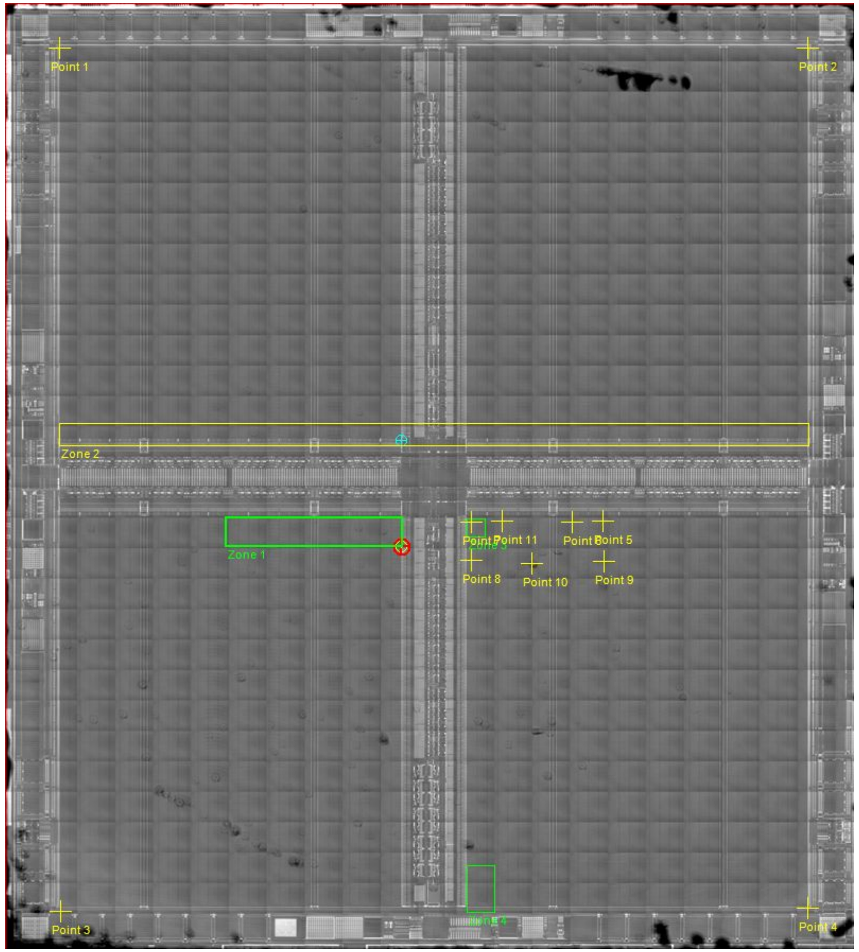
Laser Characterization

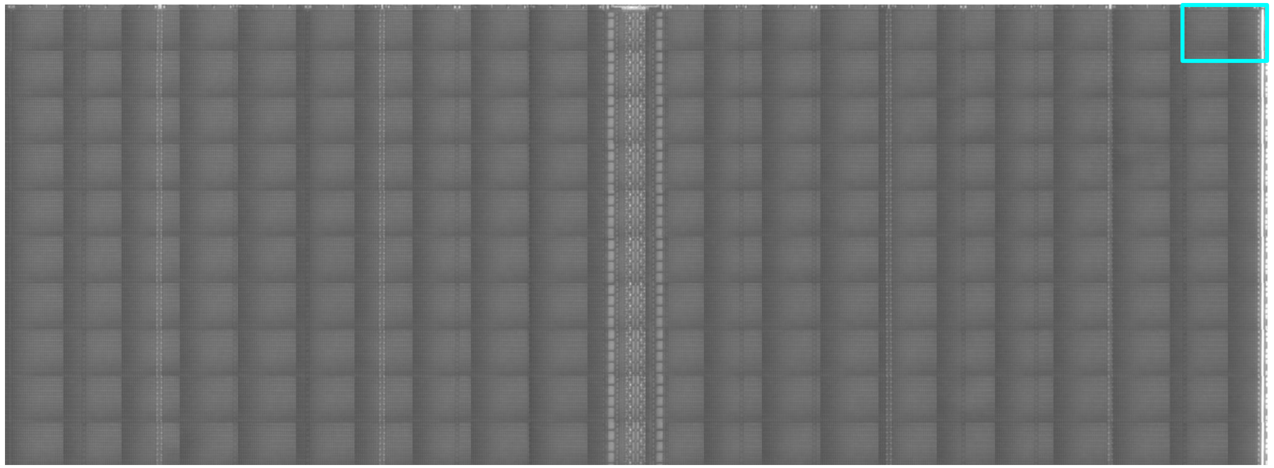
Preliminary test

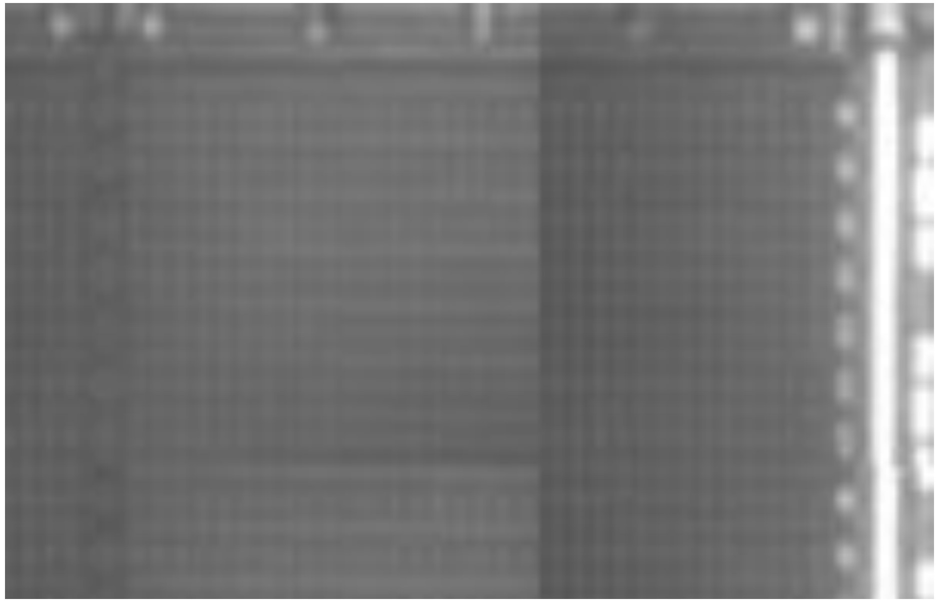
- Zone 8
- Laser energy: 210 pJ
- Includes different areas of the die
  - Periphery
  - Memory cells



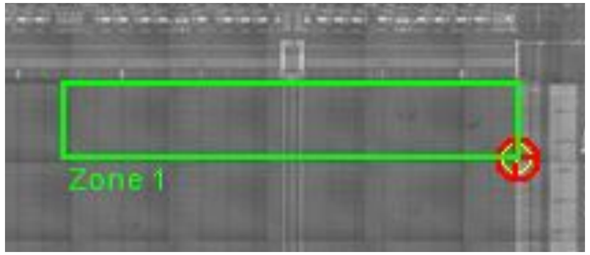
Laser Characterization: Zone Selection

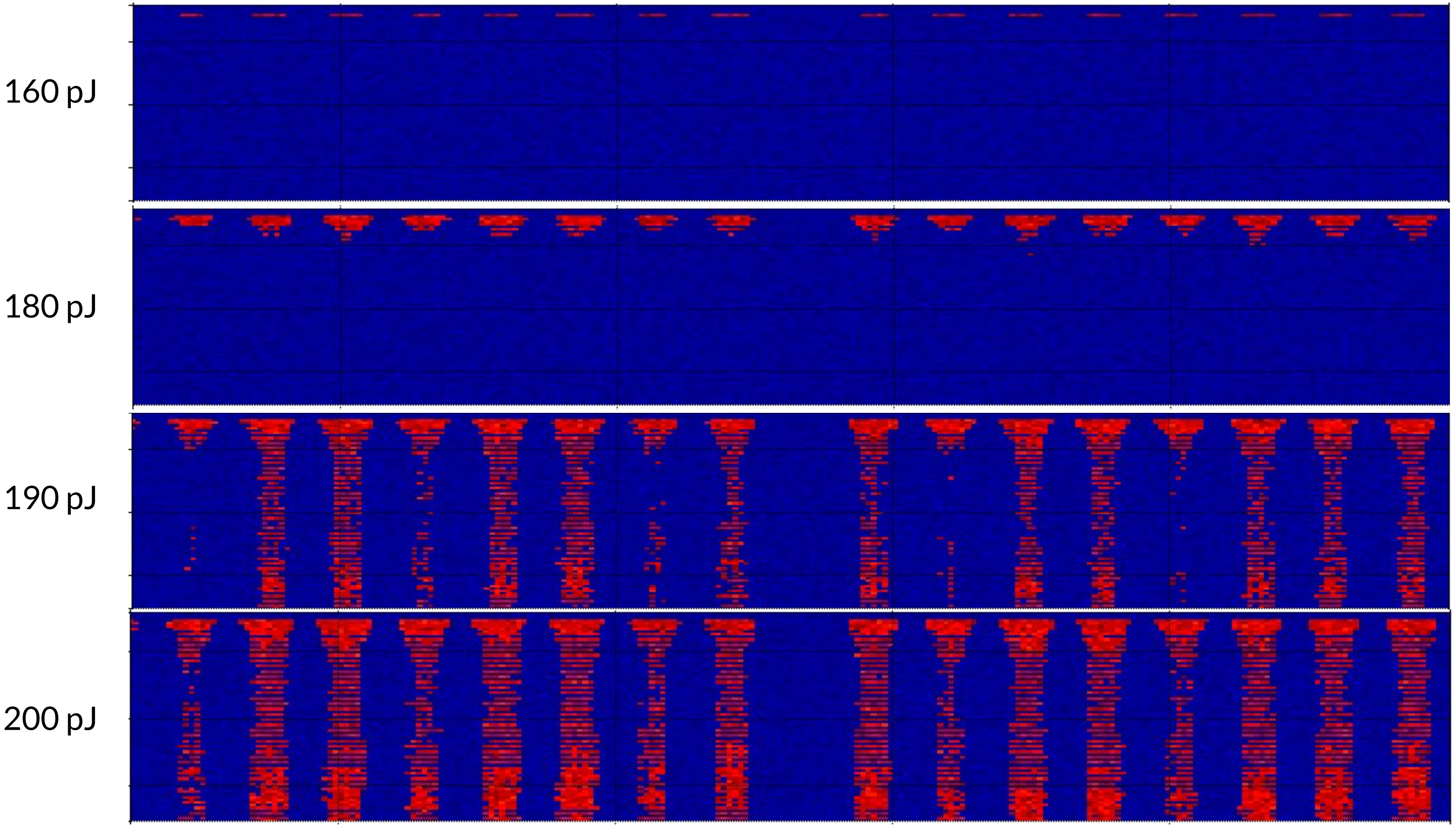




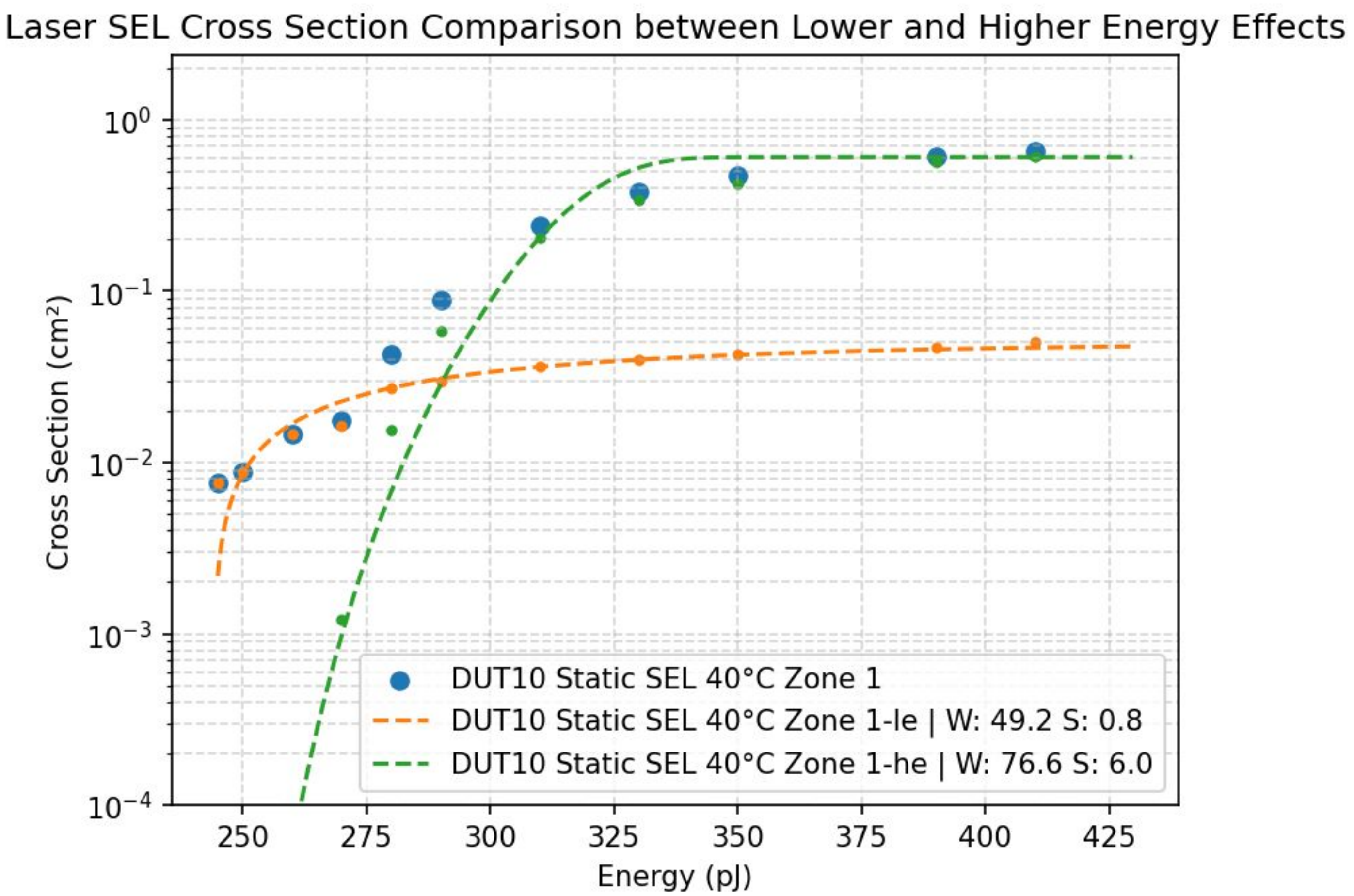


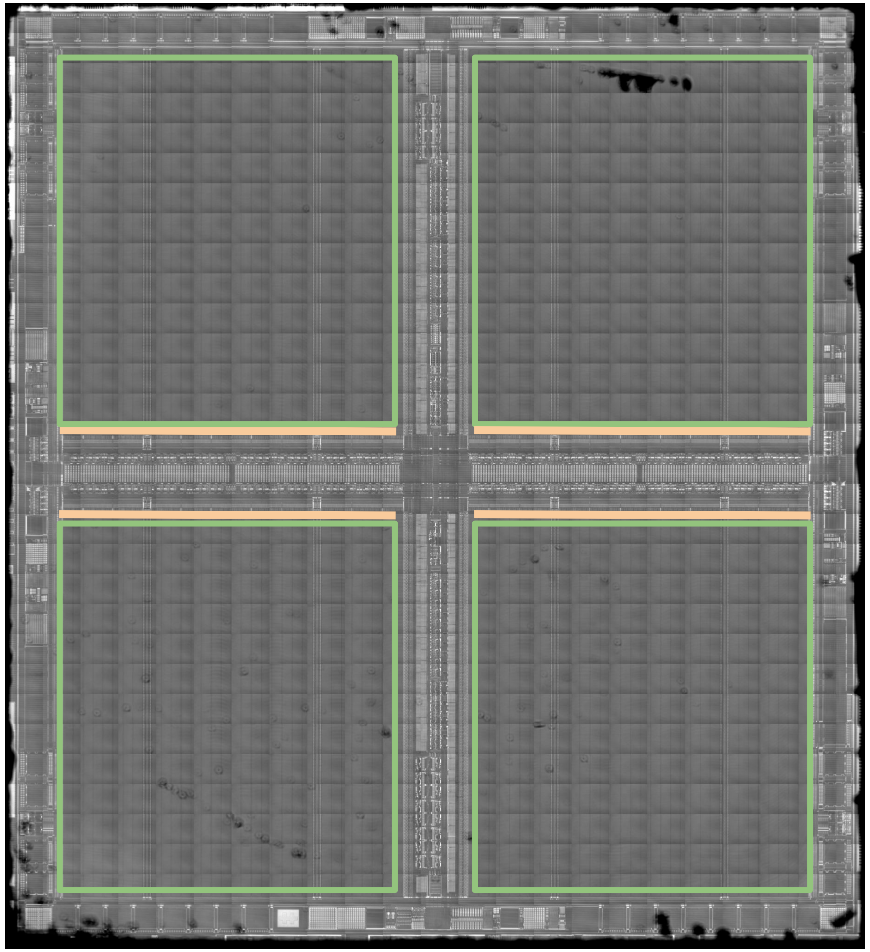
Laser Characterization





Laser Characterization: Lower energy effect





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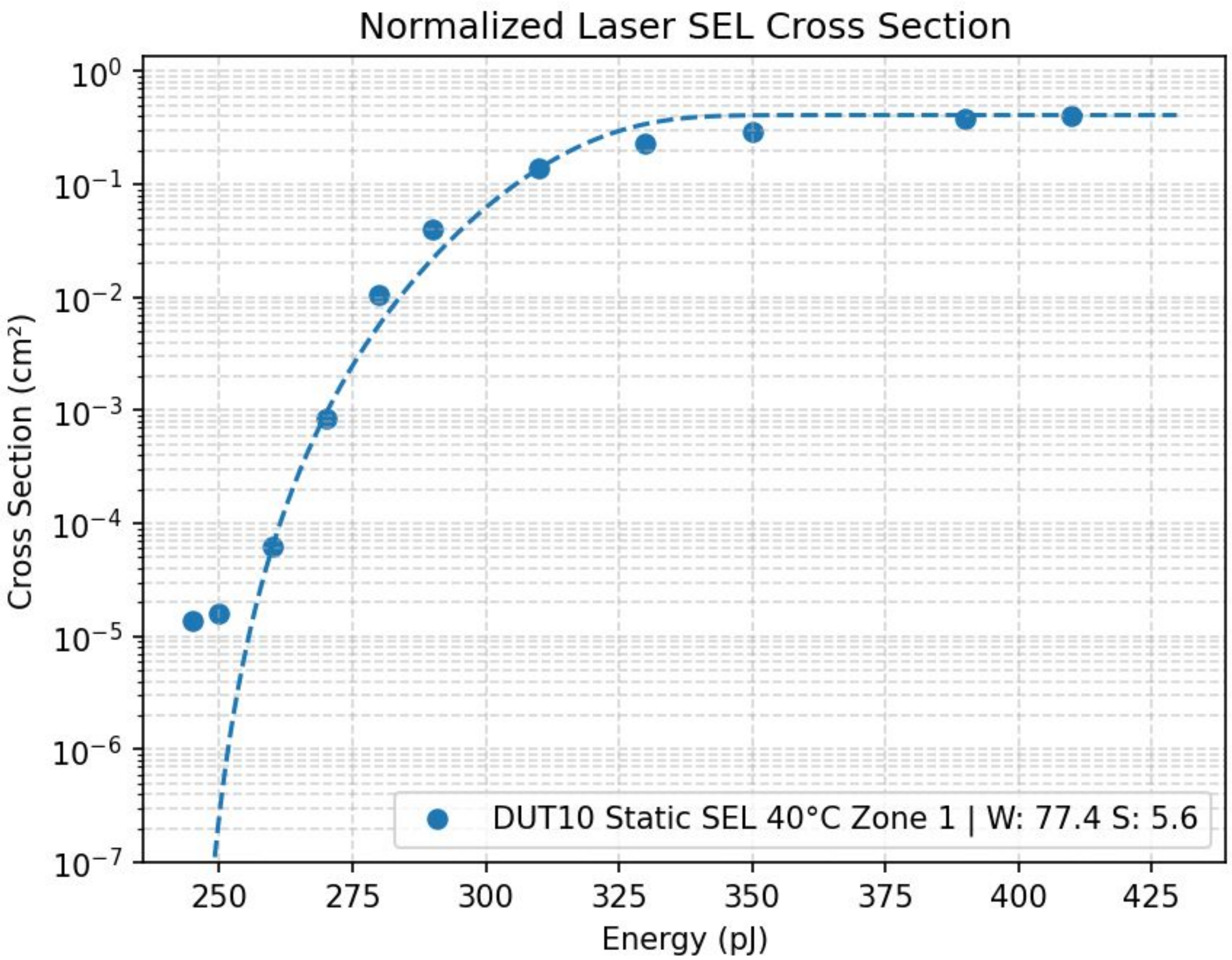
Normalized Laser SEL Cross Section



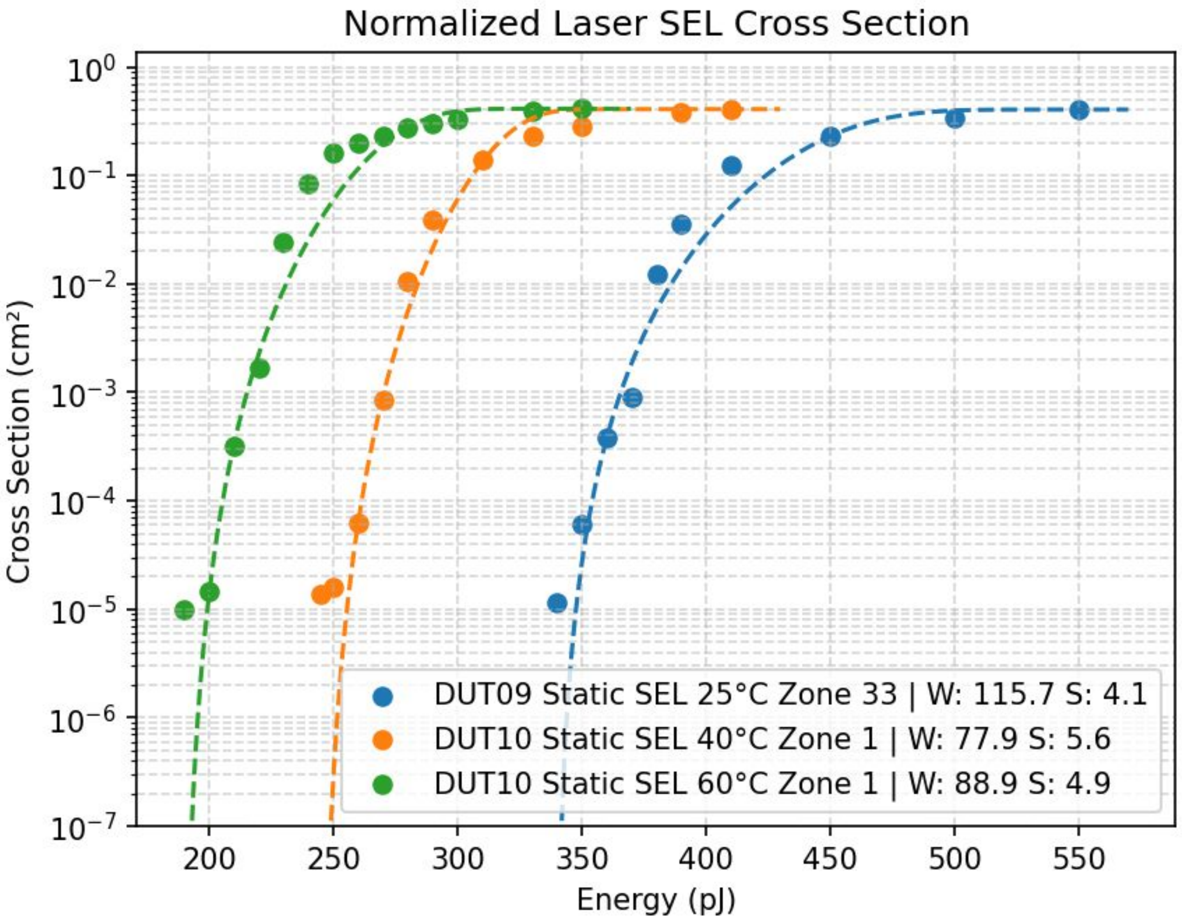
Laser Cross Section for different temperatures

Normalized laser SEL cross section

Energies ranging from 190 to 550 pJ

Characterized with different temperatures

- 25 °C
- 40 °C
- 60 °C

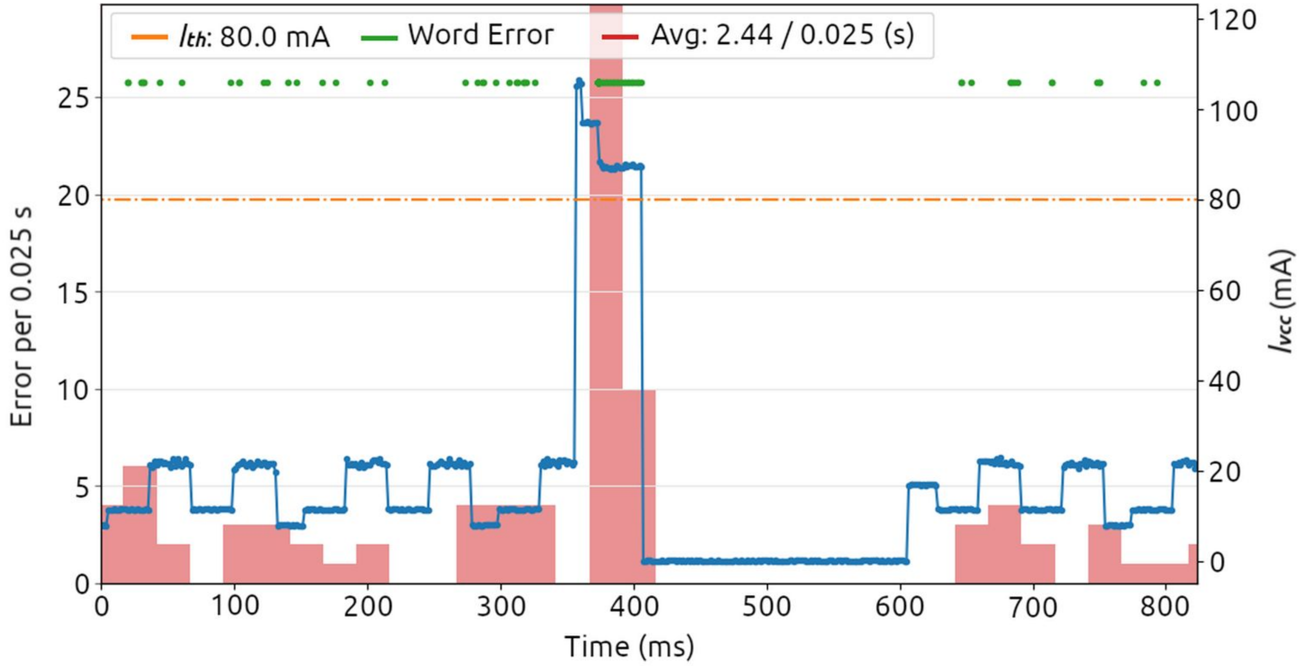


SEFI analysis

SEFIs analysis

HEAVY-IONs - Timeline analysis

Error timestamp x Ivcc



- Example: run 53, March C-, LET 48.5 MeV.cm²/mg, ESA 090

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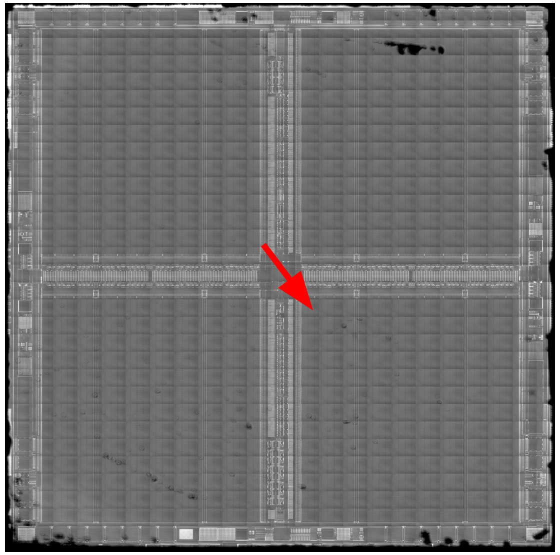
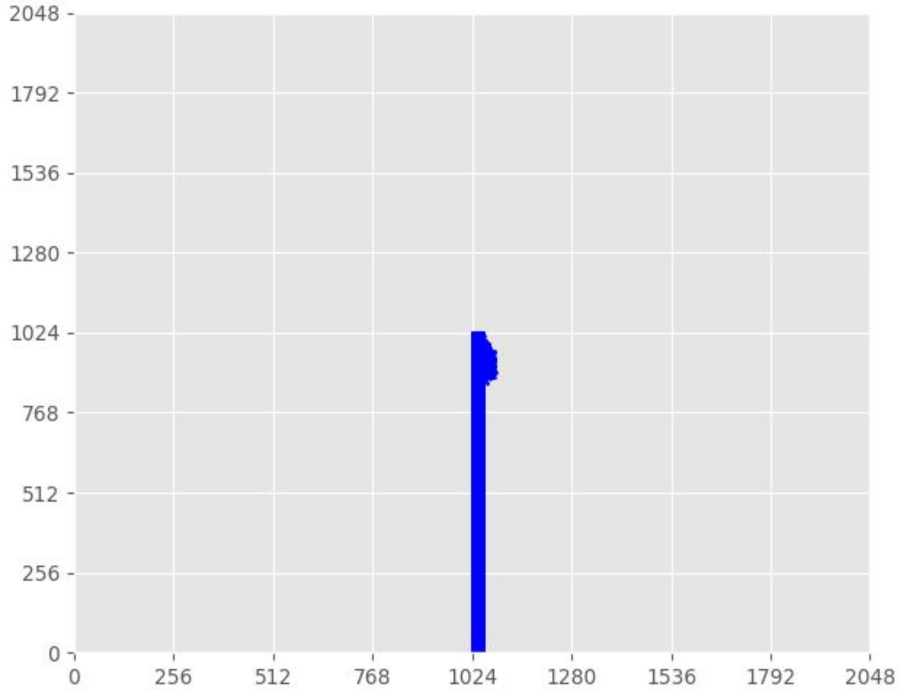
SEFI in SEL

Point-by-point experiment

- Physical bitmap showed SEFI spreading along the bit block column
- Latchup impacts the entire block (vertical) because of the charge sharing

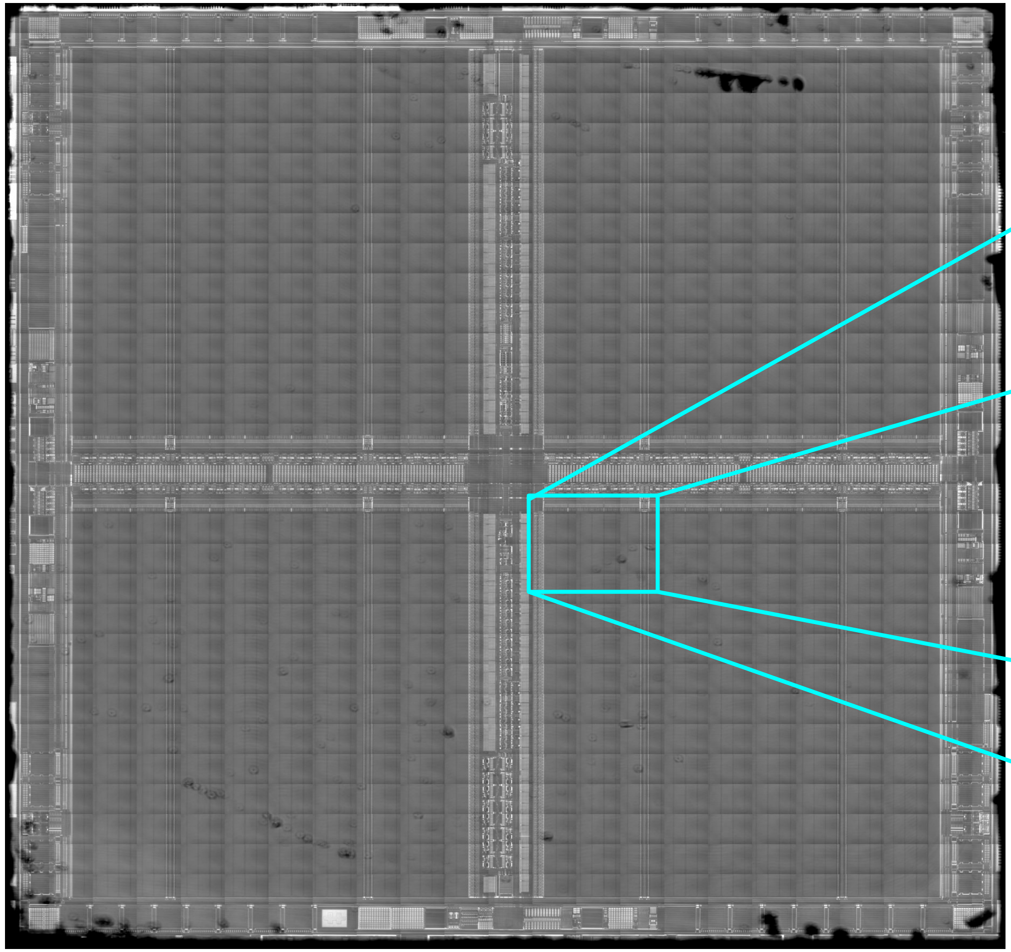


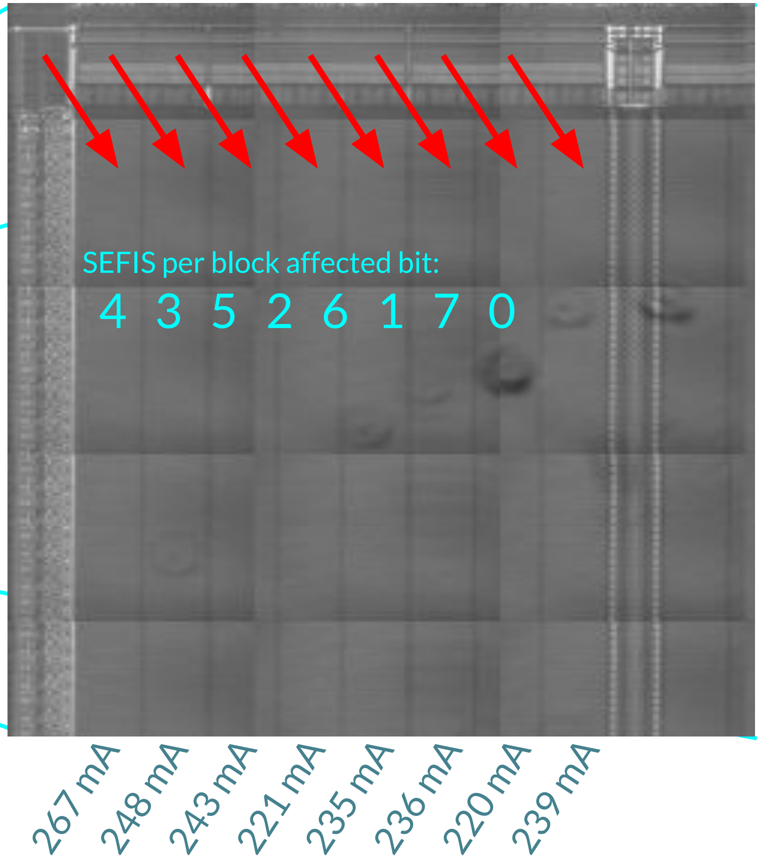
DUT 10 @ 25°C



SEUs in SEFI: Preliminary Physical bitmap

SEFI in SEL




SEFIS per block affected bit:
4 3 5 2 6 1 7 0
267 mA
248 mA
243 mA
221 mA
235 mA
236 mA
220 mA
239 mA

Conclusion

Performed characterization of the SRAM memory

- Heavy-Ions
- Protons
- Laser

SEFIs were proven to be caused by SELs

- Error flag type 406 probably detected most of the SELs

Memories should be characterized also in **dynamic mode**

- Further insight on the errors in the memory can be obtained

The temperature is impacts significantly the susceptibility to SELs

Telemetry data should be carefully selected

Work Status

- Paper accepted in RADECS
  - Heavy-ions and protons characterization
- Paper in the submission process to JINST journal
  - Experimental setup
- New submission to the journal extension
  - Laser characterization and direct comparison with flight data

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EXTRA SLIDES

SEU Analysis

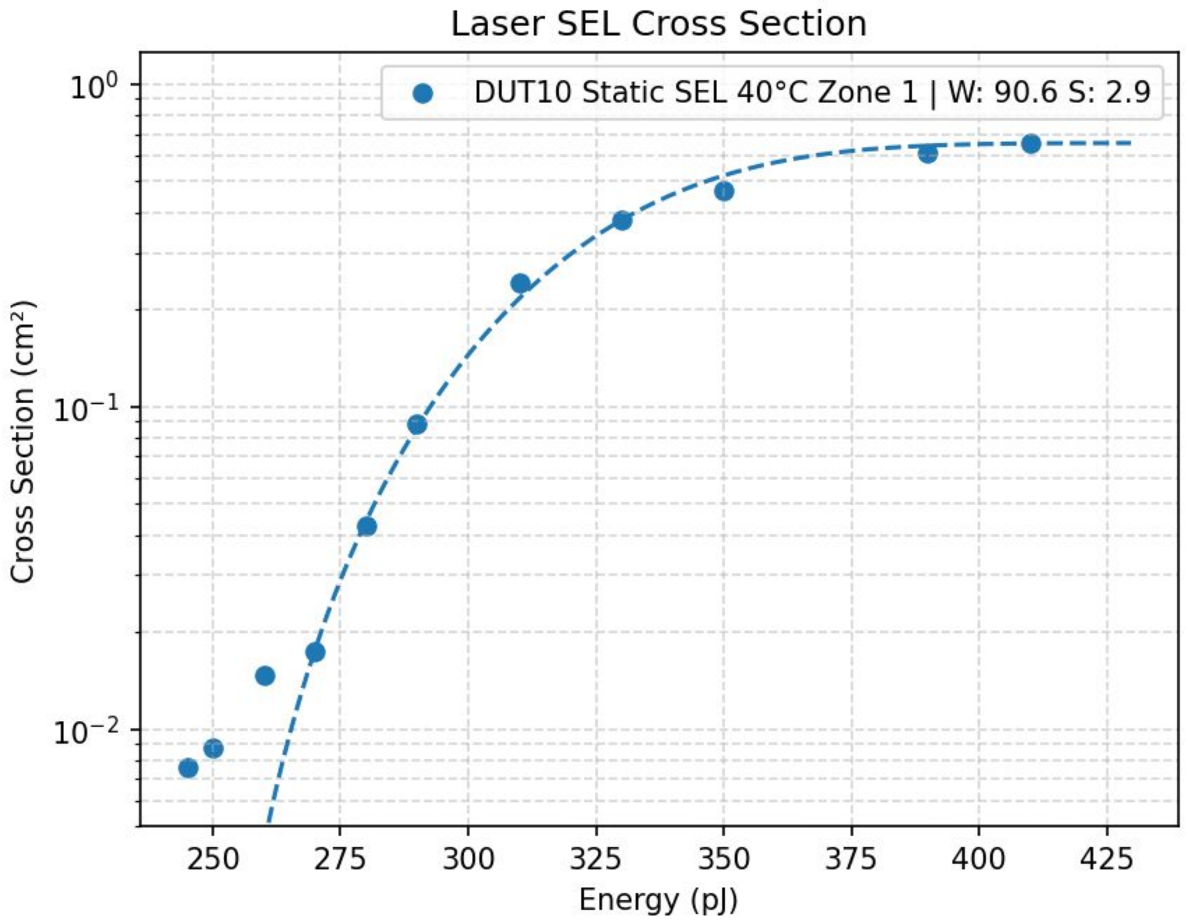
Test Modes

- Dynamic Stress
  - If SEL during run, restart with ↑{w1}

```
 ↑ {w1}
{↑ (r1, w0, r0, r0, r0, r0, r0); 0x11 / 0x12 / 0x13 / 0x14 / 0x15 / 0x16 / 0x17
 ↑ (r0, w1, r1, r1, r1, r1, r1); 0x19 / 0x1A / 0x1B / 0x1C / 0x1D / 0x1E / 0x1F
 ↑ (r1, w0, r0, r0, r0, r0, r0); 0x21 / 0x22 / 0x23 / 0x24 / 0x25 / 0x26 / 0x27
 ↓ (r0, w1, r1, r1, r1, r1, r1); 0x29 / 0x2A / 0x2B / 0x2C / 0x2D / 0x2E / 0x2F
 ↓ (r1, w0, r0, r0, r0, r0, r0); 0x31 / 0x32 / 0x33 / 0x34 / 0x35 / 0x36 / 0x37
 ↑ (r0, w1, r1, r1, r1, r1, r1)} 0x39 / 0x3A / 0x3B / 0x3C / 0x3D / 0x3E / 0x3F
```

Laser SEL Cross Section

> not normalized

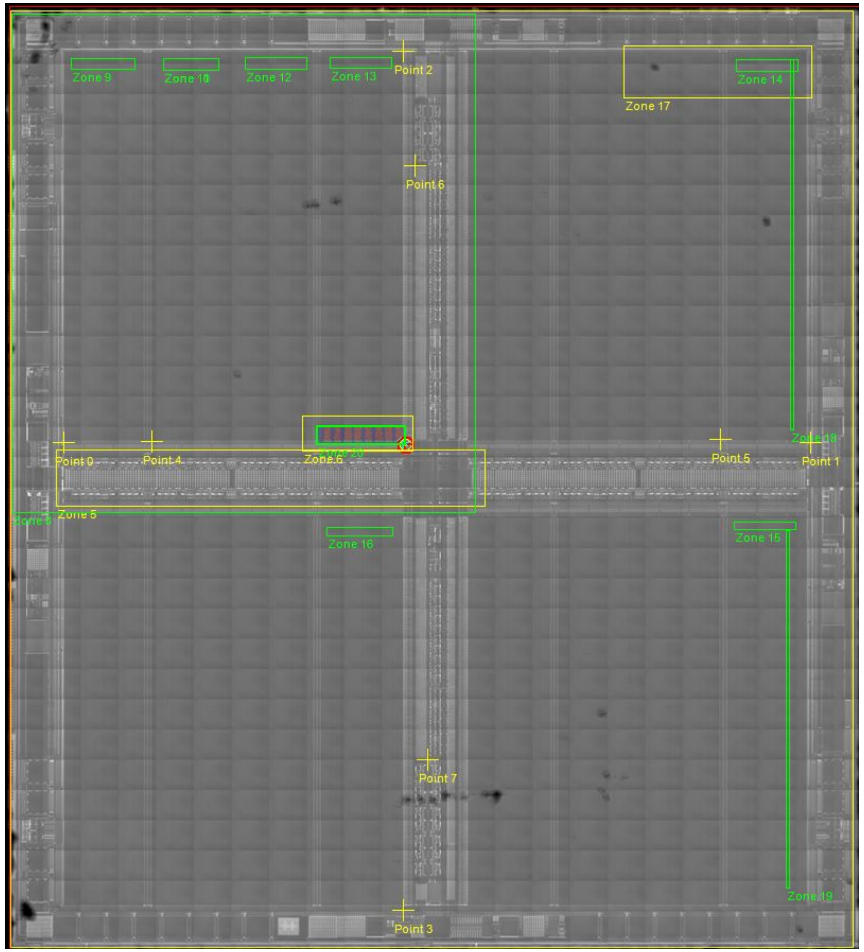


Memory Mapping

LASER experiment

Physical Mapping of the memory cells

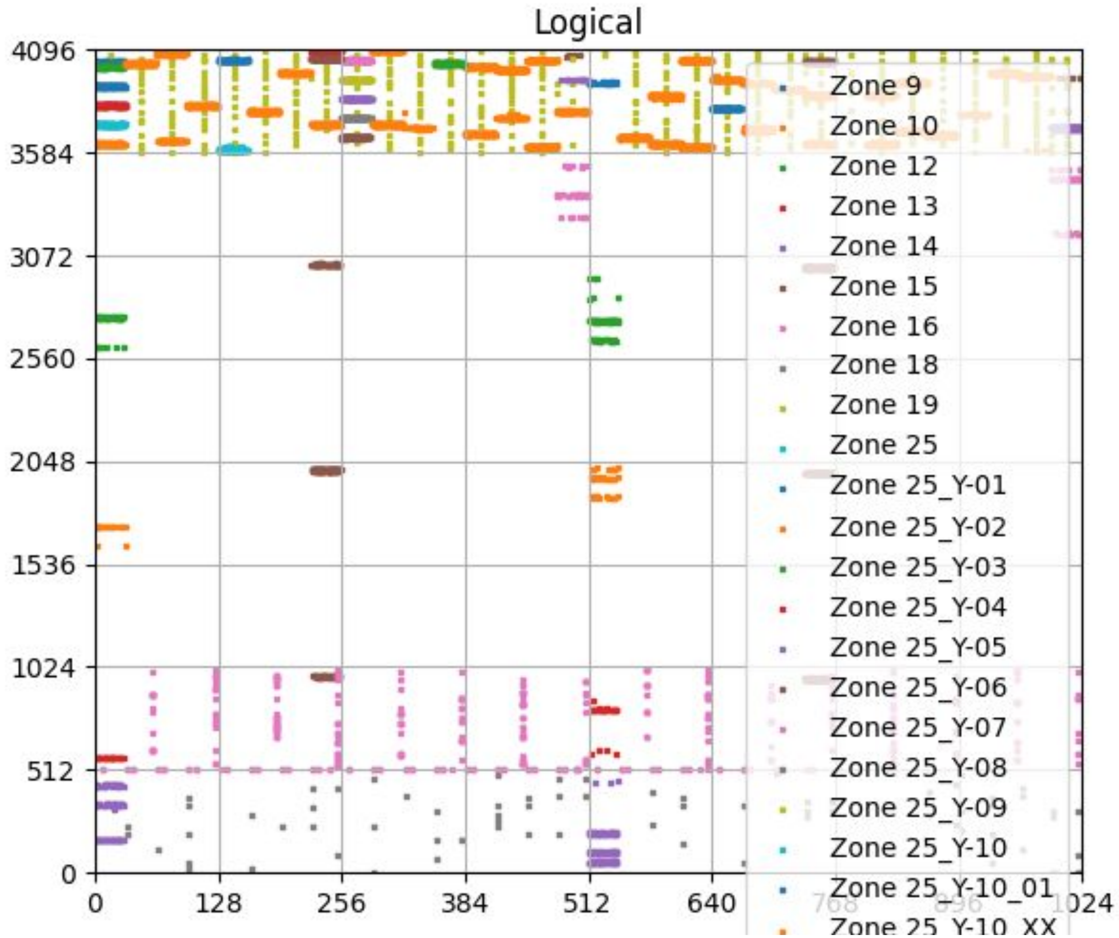
- Selected zones in Laser experiment
- Zones 9, 10, 12, 13, 14, 15, and 16
- Checking with Zones 18 and 19



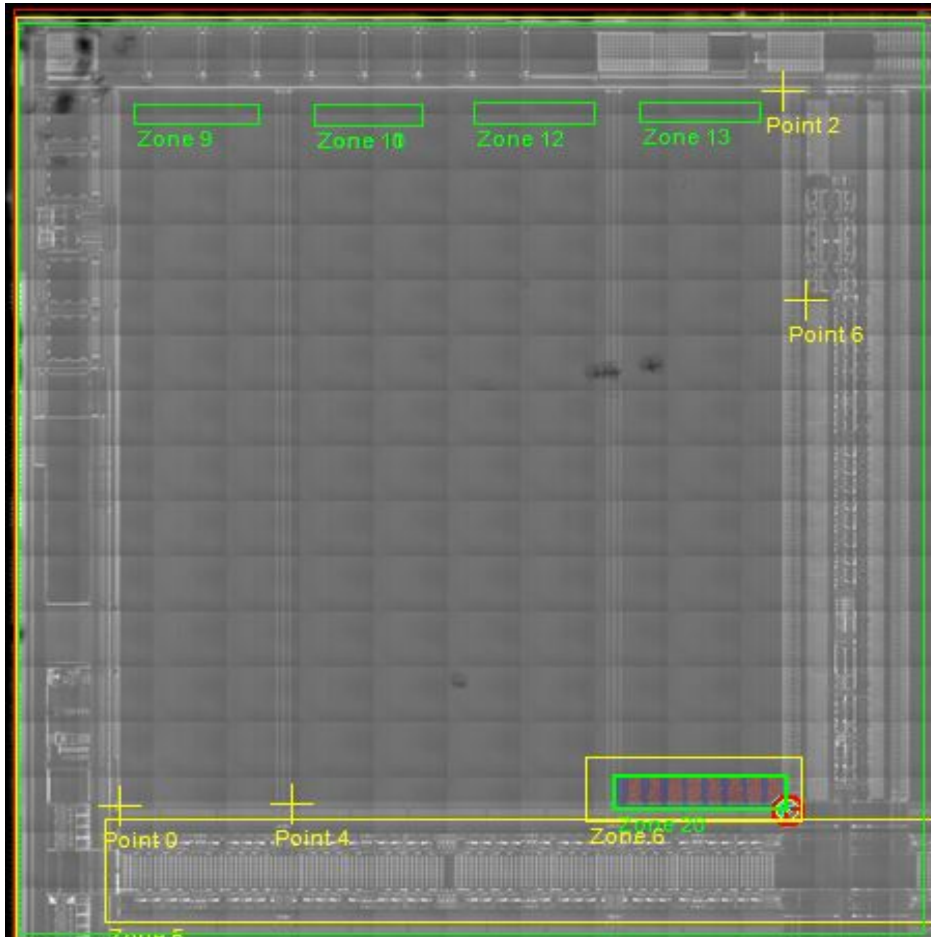
Memory Mapping

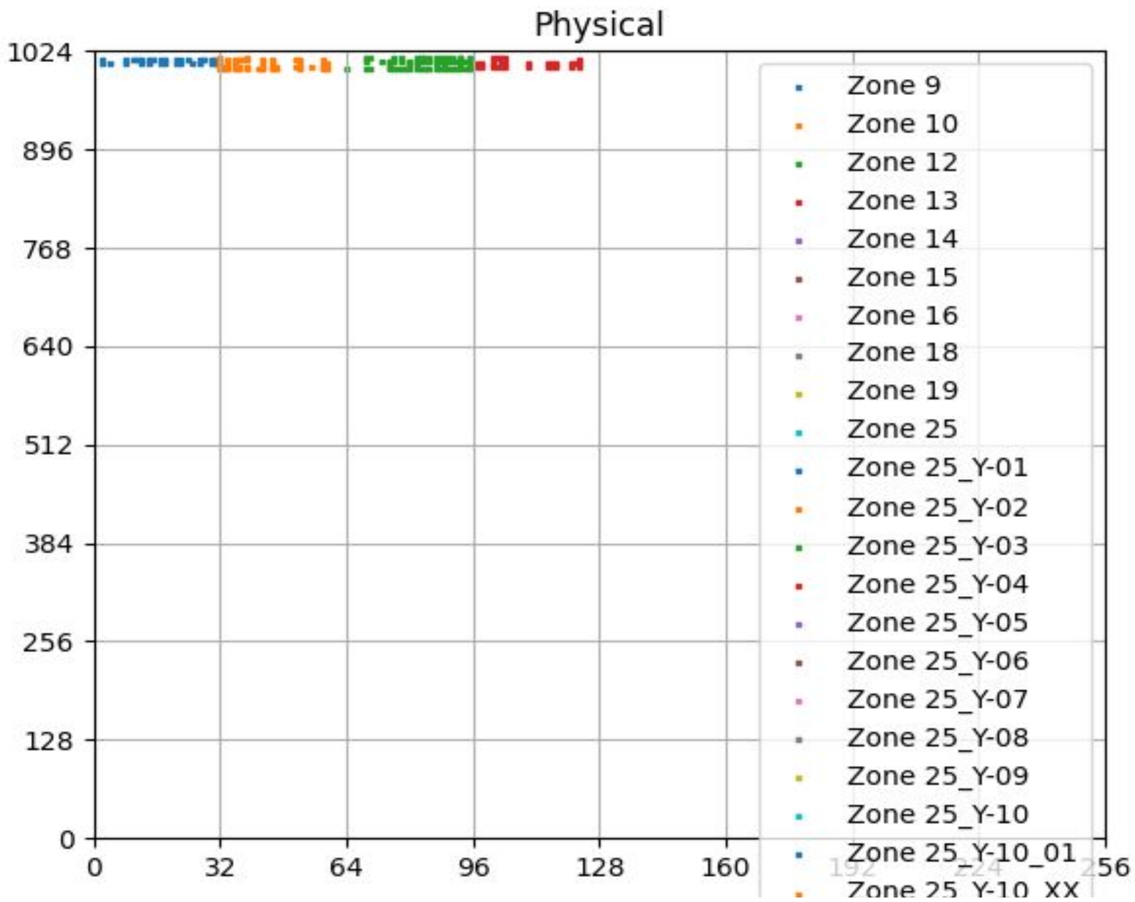
Logical bitmap

- different patterns for tested zones



Memory Mapping





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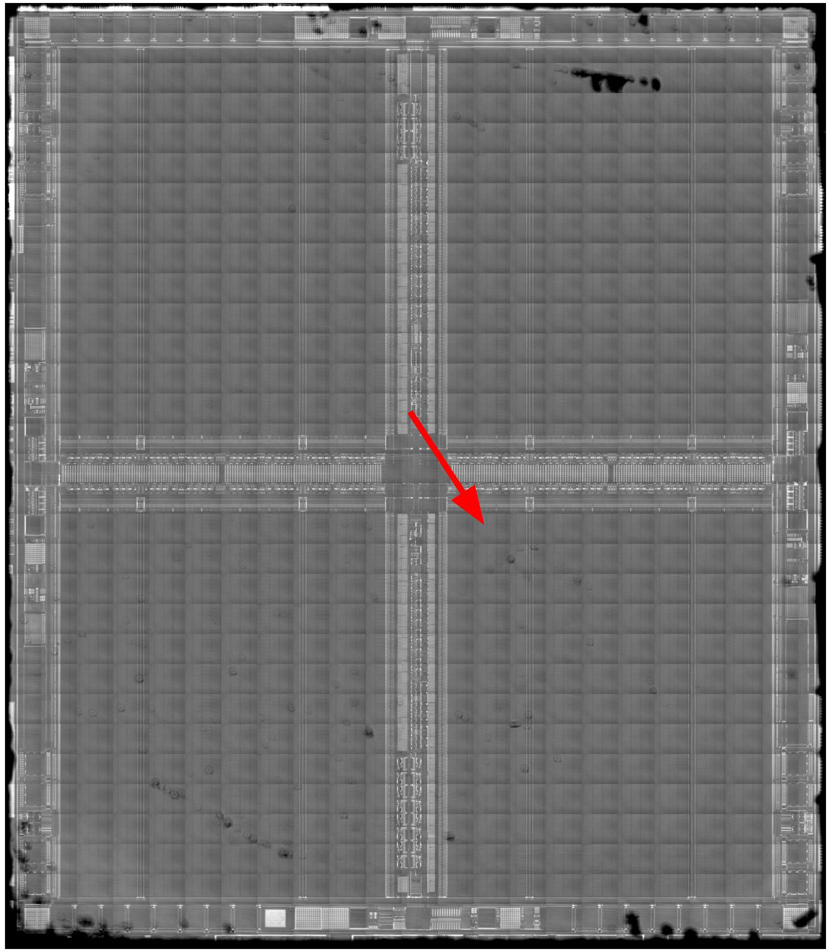
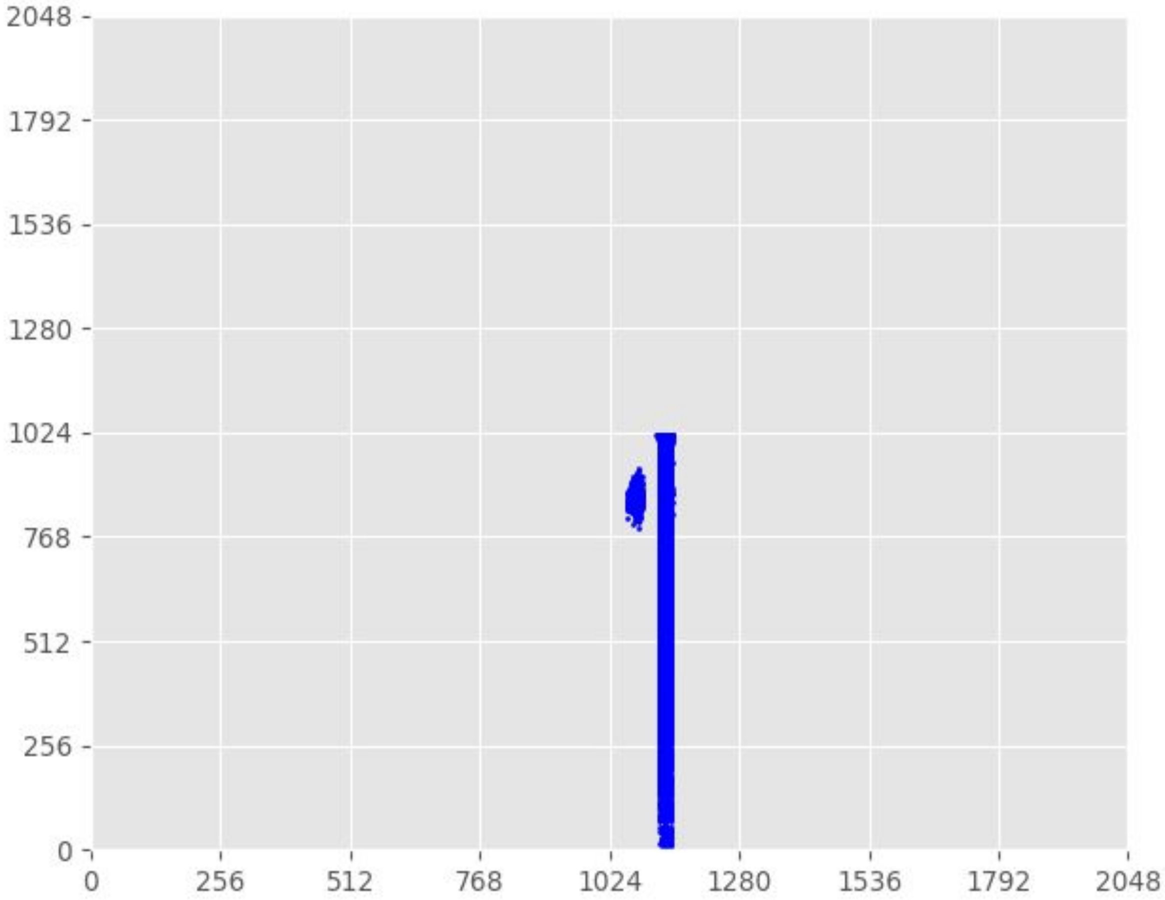
SEFIs in SEL

Followed procedure to read entire memory

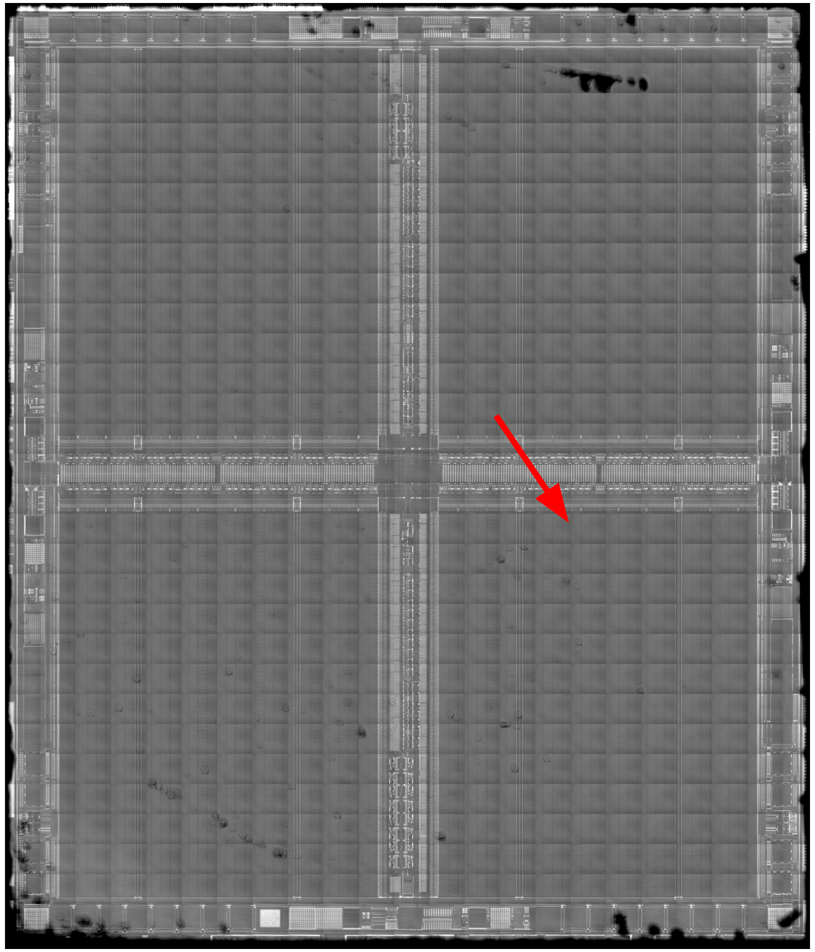
1. Increase memory current threshold to 400 mA
2. Increase banks current threshold to 400 mA
3. Write entire memory with 0xAAAA
4. Position the laser in the top area with SELs at lower energies
5. Trigger SELs with laser pulse in the energies: 340, 350, 360, 390, and 600 pJ.
6. Wait for a few seconds for the current to stabilize
7. Read memory to get complete error bitmap
8. Power cycle memory and go for next energy

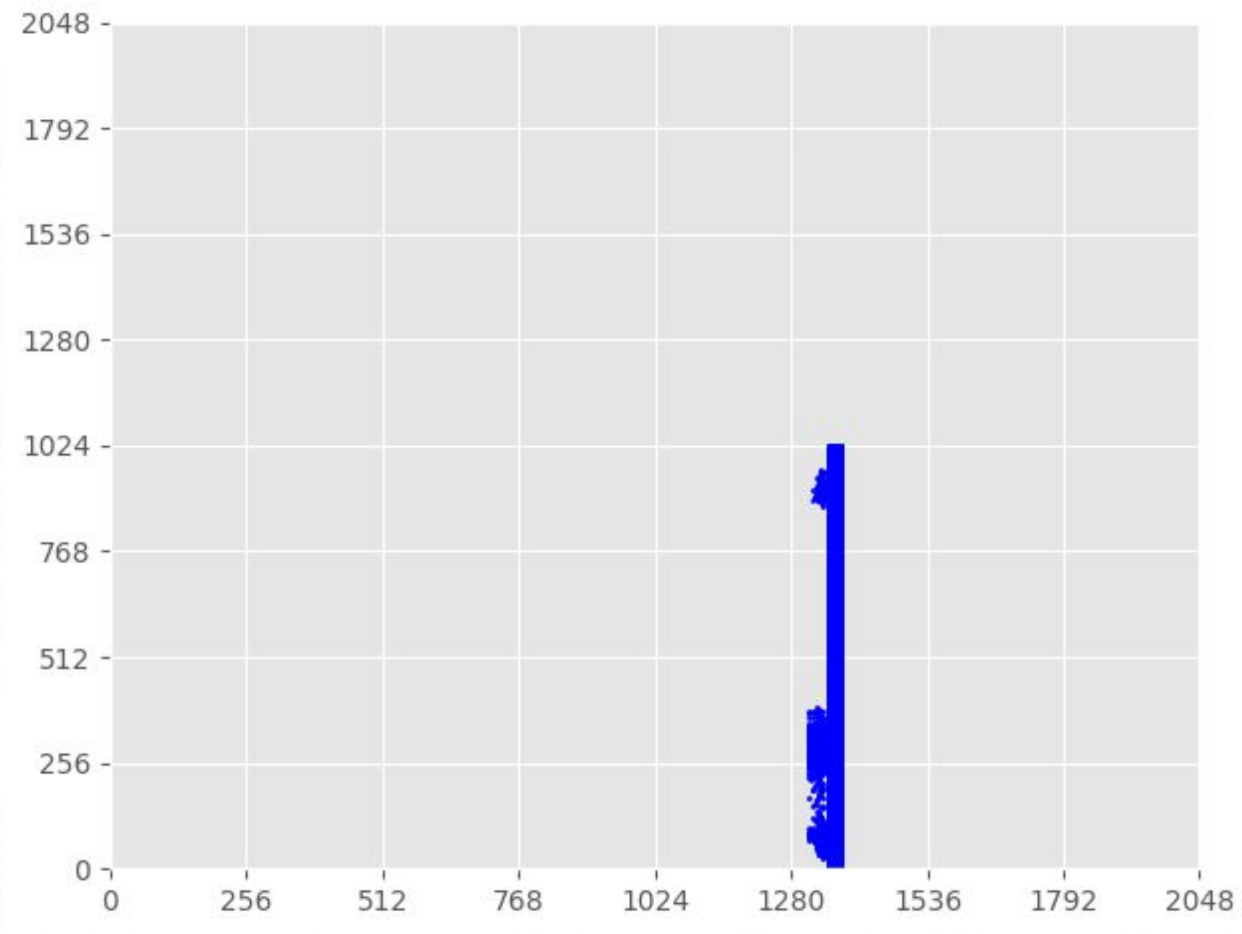
SEFI in SEL: point 4





SEFI in SEL: point 11





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Laser and Heavy-Ion Equivalence

x_hi = (x_ls - 320) * 0.6