Risk assessment of SEE events due to high energy electrons during the JUICE mission

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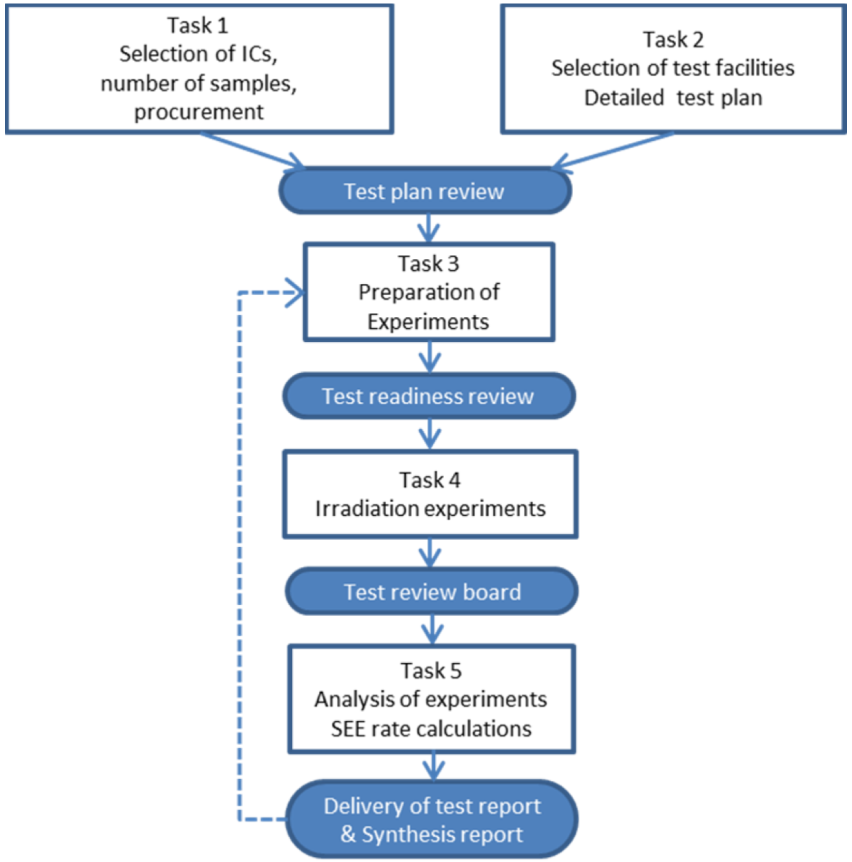
Outline

- Project Overview
- Part Selection
- Radiation Test Summary
- JUICE, GEO and LEO Environment Description
- Error Rate Calculations Methodology
- Mission Error Rates Estimations
- Conclusions

Project Overview

- **Risk assessment of SEE events due to high energy electrons during the JUICE mission**
- Comparison to
  - Other sources of SEE
    - Jupiter's protons (low and high energies)
    - Heavy-ions near Jupiter
    - SEP and GCR protons and heavy-ions
  - Typical Earth orbit missions:
    - GEO
    - LEO, 800 km, 98° inclination
- Project tasks
  - T1: Selection of the ICs
  - T2: Selection of the test facilities
  - T3: Experiment preparation
  - T4: Test under radiation
  - T5: SEE rate calculations



Selected SRAMs

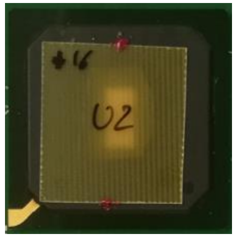
Manufacturer	Reference	Size	Process	Comment
RENESAS	R1RW0416DSB	4 Mbit	180nm	Hardened, with specific transient MBU effects
ISSI	IS61WV20488BLL-10TLI	16 Mbit	65nm	Technology node reported by CERN
CYPRESS	CY7C2562XV18-450BZXC-ND	72 Mbit	65nm	QDR-II+ high speed SRAM
ONSEMI	N01S830HAT22I	1 Mbit	unknown	SPI Serial SRAM
-	28nm SRAM	64 Mbit	28nm	Provided by IROC commercial partner

RENESAS

ISSI

CYPRESS

ONSEMI

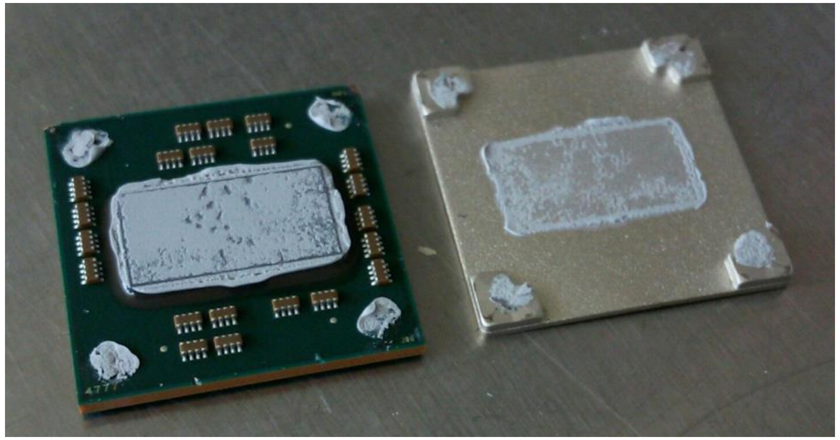

28nm SRAM

Complex Components

- MCU: ATMEL SAM V71Q21RT Space Version
  - 32 bit ARM Cortex M7 based Micro-Controller
  - Technology: 65 nm
- XILINX ZU3EG MP-SOC
  - Ultrascale+ architecture FPGA
  - ARM based Processing System
  - Technology: TSMC 16nm FinFET

ATMEL SAM V71Q21RT

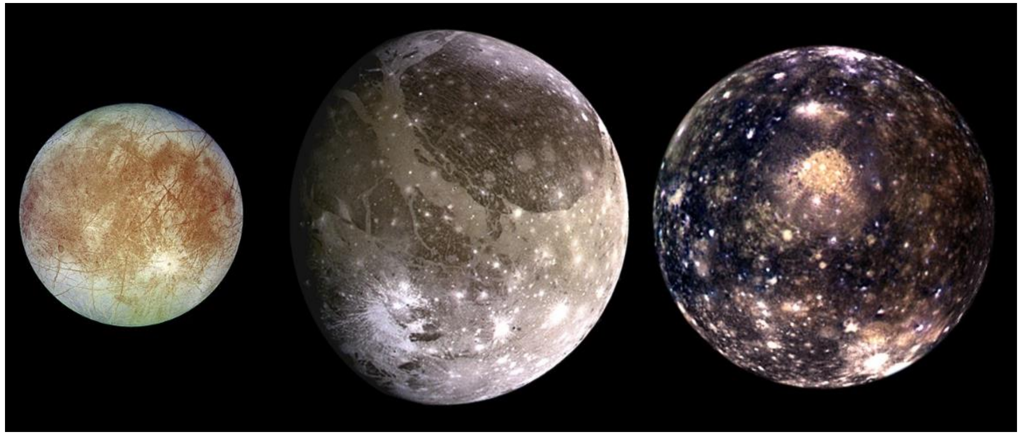
- Test Goals
  - SEL on all power domains
  - SEU Characterization
    - Memories (SRAM/FLASH)
    - FPGA Fabric (CRAM/BRAM/DistRAM/FF/TMR)
  - Functional CPU test
    - Integer: COREMARK
    - Floating point: PiFFT
  - Peripheral testing



Xilinx ZU3EG

JUICE Environment Overview

- Type of particles
  - Trapped Electrons
  - Trapped Protons
  - Trapped Ions
  - Solar Protons
  - Heavy-Ions



Jupiter Galilean Moons: Europa, Ganymede, Callisto

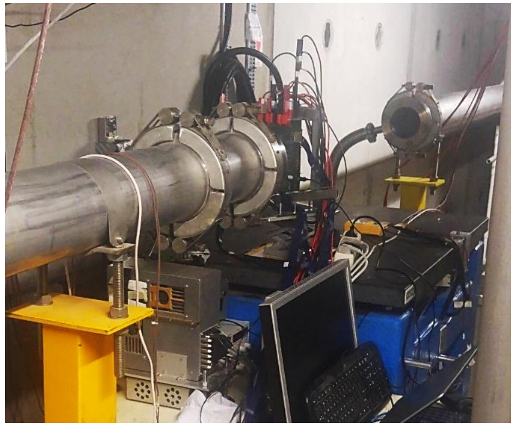
- Spacecraft shielding scenario
  - Standard: 3.7 mm Aluminum
  - Electronic vault: 17 mm Aluminum

- Comparison with Earth orbits
  - GEO
  - LEO, 800km, 98°
  - Launch date: 2024/01/01
  - Duration: 15 years

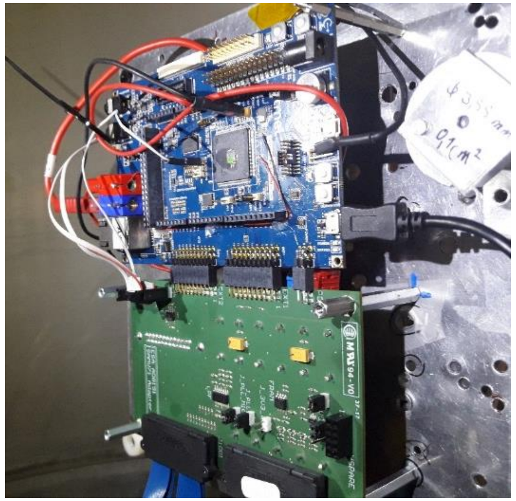
JUICE Spacecraft

Test Campaign Overview

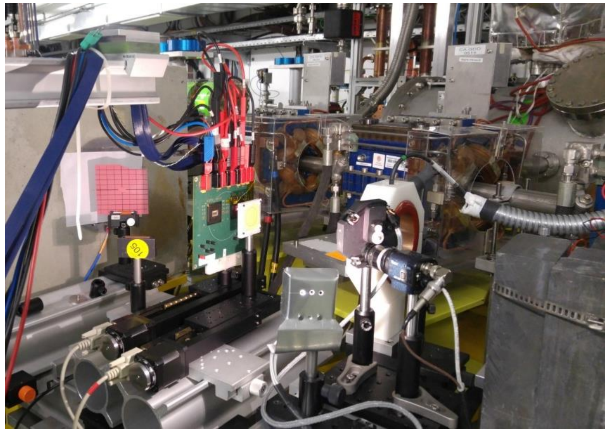
- 4 Heavy-Ion test Campaigns
  - 3 @UCL: Standard 10 MeV/amu cocktail
  - 1 @CERN H8: Ultra-high energy Xe ion bean (30 GeV/amu)
    - LET≈3.7MeV/cm²/mg
- High-Energy Electron: CERN VESPER (60, 120 and 150 MeV)
- High-Energy proton: PSI PIF (230 MeV)
- Low-Energy proton: RADEF (500 keV to 6 MeV)



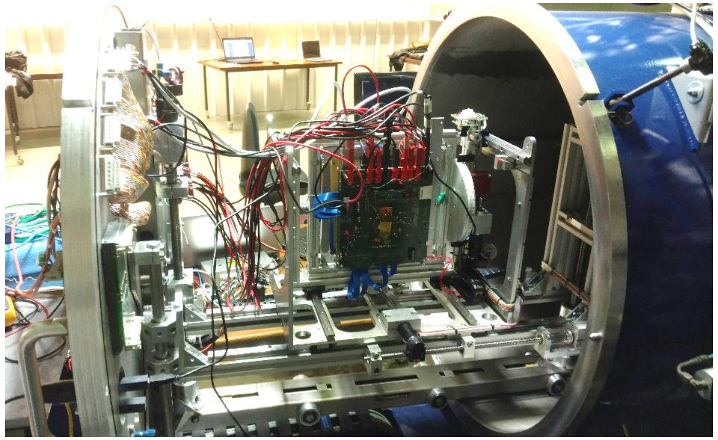
CERN H8



SAM V71Q21RT - RADEF



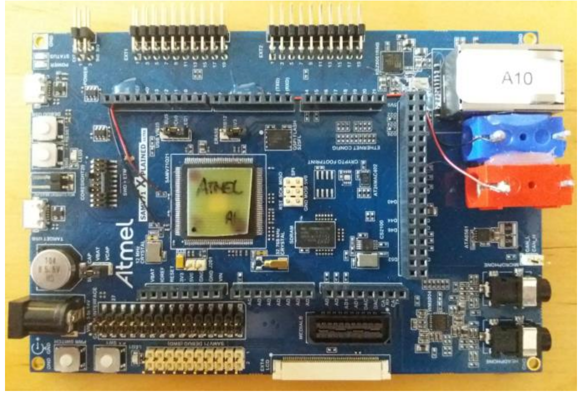
28nm SRAM - VESPER

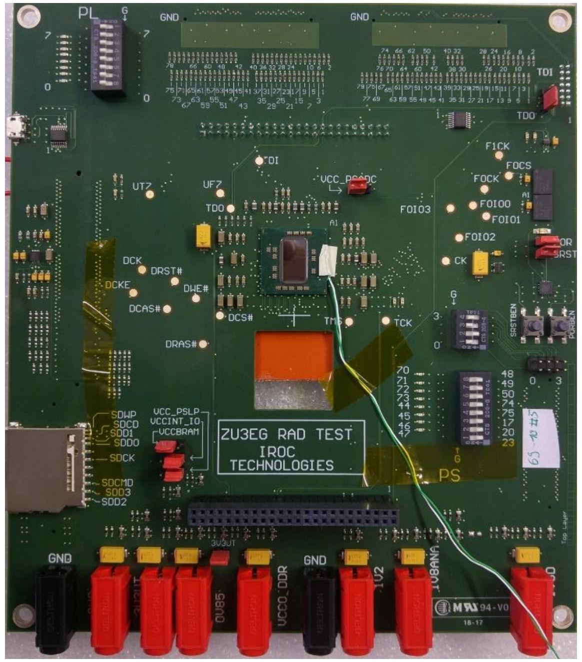


ZU3EG - UCL

Test Methodology Description

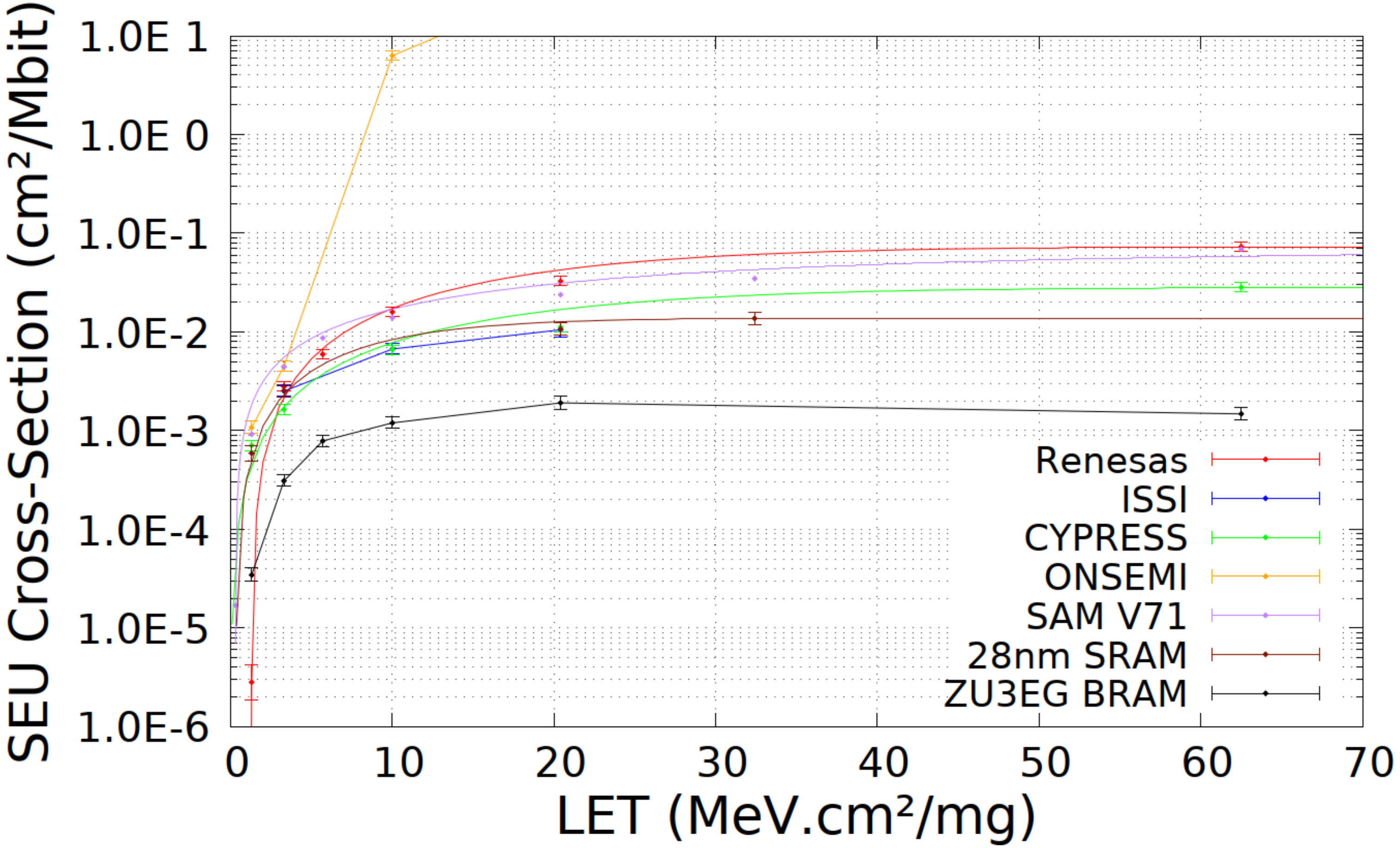
- SRAM Test platform: FPGA based tester
  - Current monitoring
  - Dynamic algorithms
  - MBU/MCU and SEFI analysis
- Atmel SAM V71Q21RT
  - Tests implemented in Software on the DUT
  - Re-use of evaluation board
- Xilinx ZU3EG MPSoC
  - Dedicated test board designed by IROC
  - SEL detection based on current and temperature
  - CRAM monitored with Xilinx SEM-IP
  - FPGA resources tested from external interface
  - Functional benchmarks running on R5 CPUs





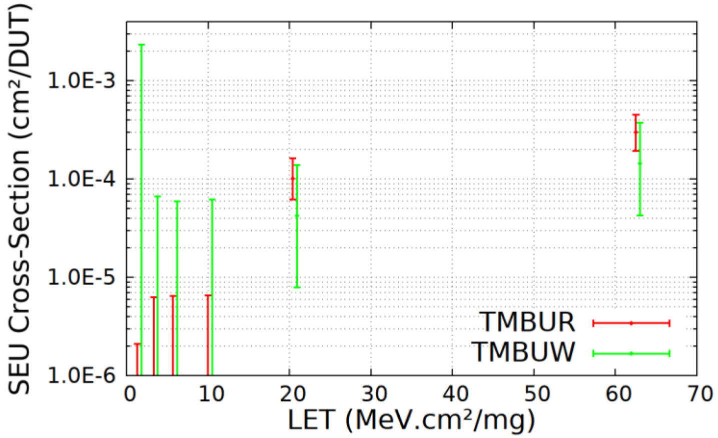
Test Results Overview

- Direct Ionization
  - ONSEMI: SEFI Mechanism
  - ISSI: High SEL sensitivity
  - Renesas: Higher LET threshold => not sensitive to PDI
  - ZU3EG: Lower SEU sensitivity

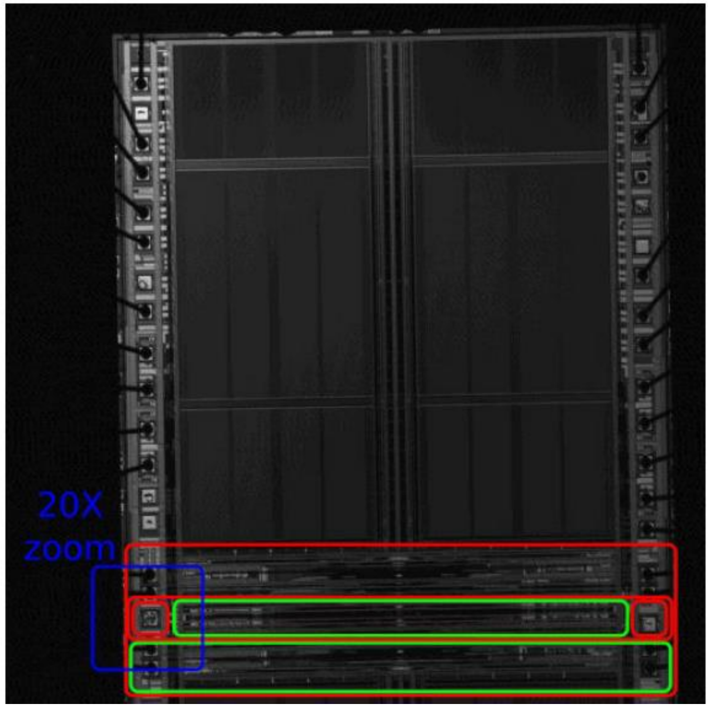


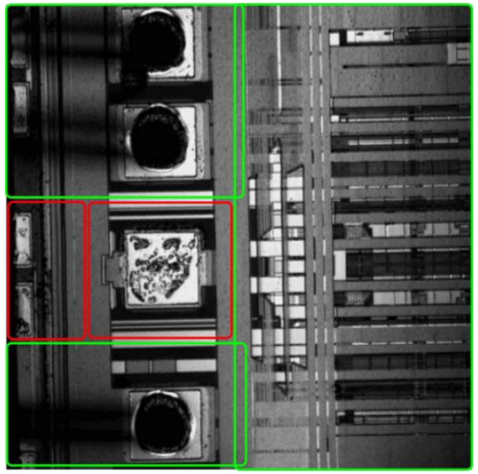
Radiation Test Results Summary RENESAS - R1RW0416DSB

- Direct ionization
  - Transient MBU effect observed
    - $LET_{TH} \approx 20$ MeV.cm²/mg
    - Can occur during read and write operations
  - Additional LASER test @CNES
    - TMBU comes from unbounded IOs pads



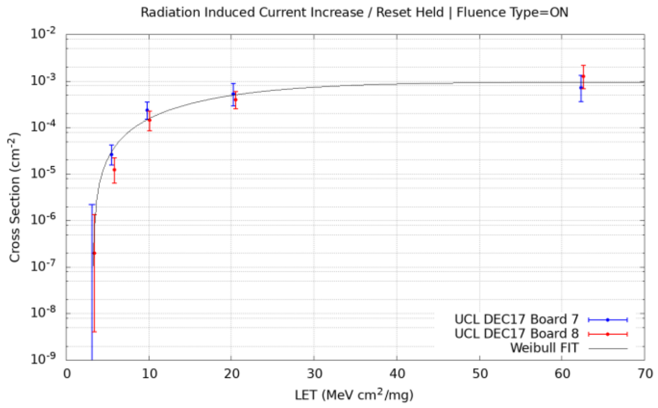
Heavy-ions

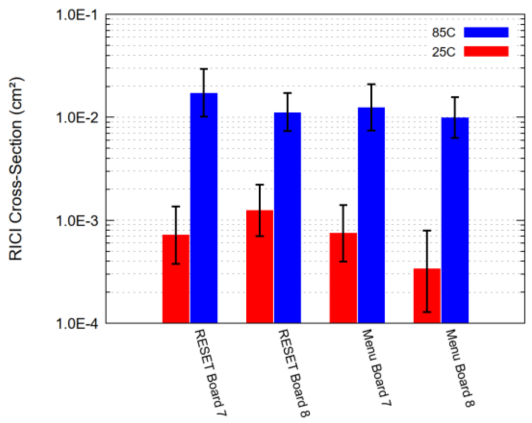


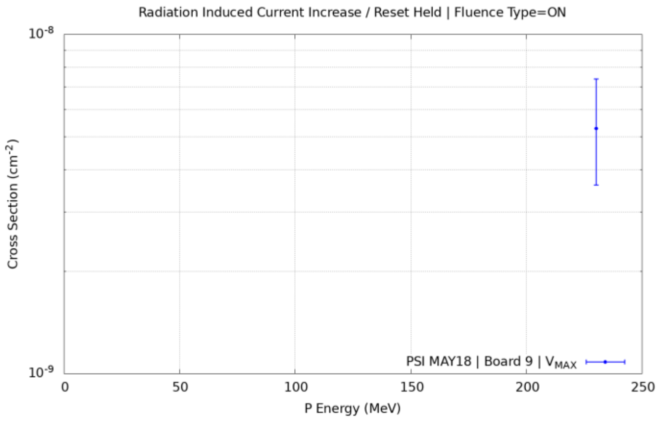


Radiation Test Results Summary
ATMEL - SAM V71Q21RT (Space version) - SEL

- Heavy-Ions: large number of current increase observed ($XS_{SAT} \approx$ 1E-3 cm²/DUT)
  - Power-cycle needed to recover
  - Sensitivity increase with temperature
  - Behavior observed under normal and reset conditions
- High-energy protons: only observed at high-temperature
  - XS_{SAT} = 5e-9 cm²/DUT

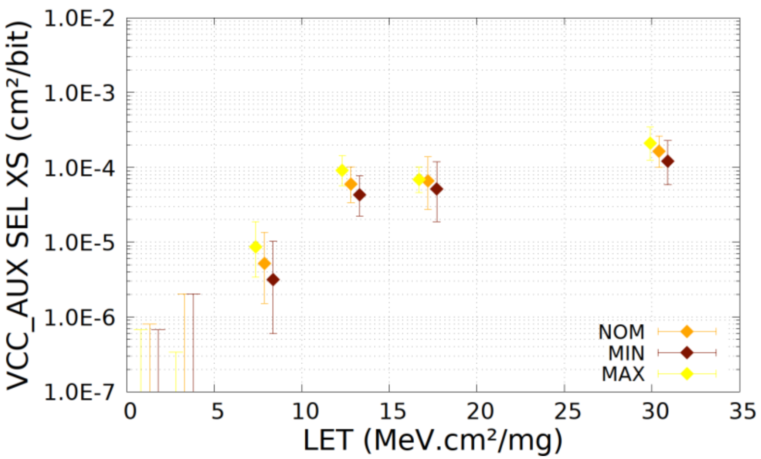


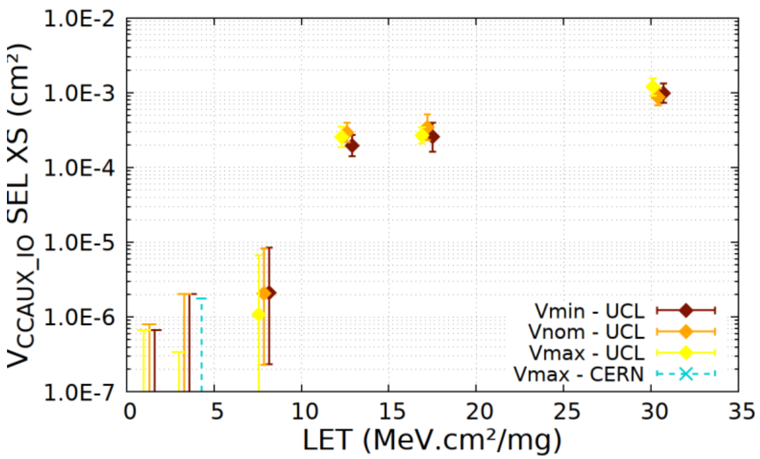


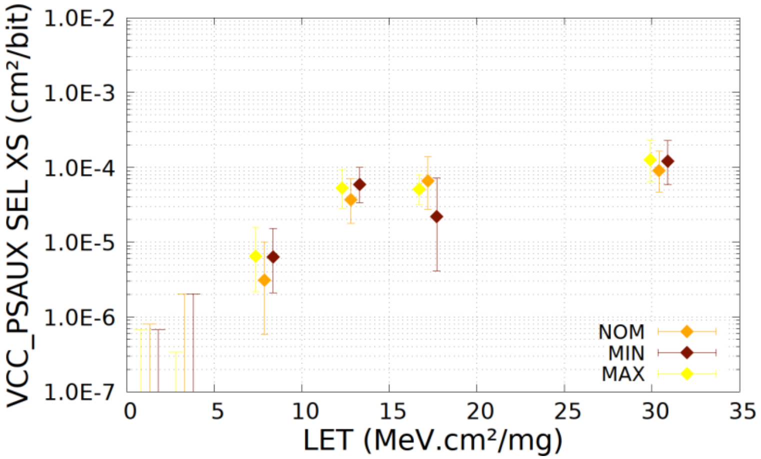


Radiation Test Results Summary
XILINX ZU3EG - SEL

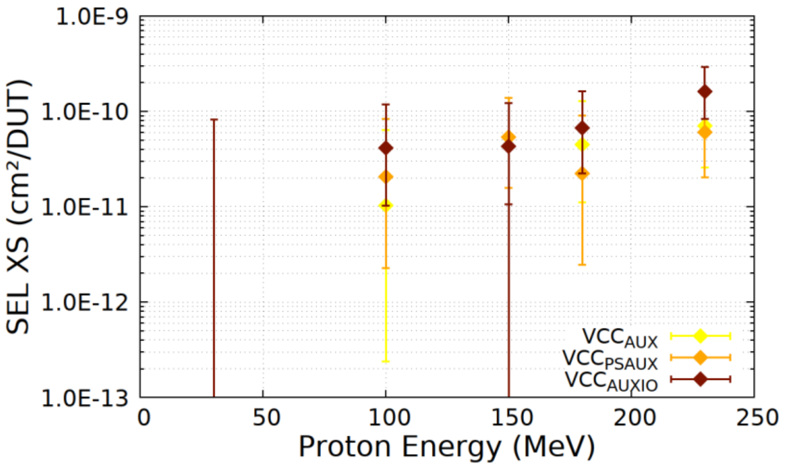
- Direct Ionization





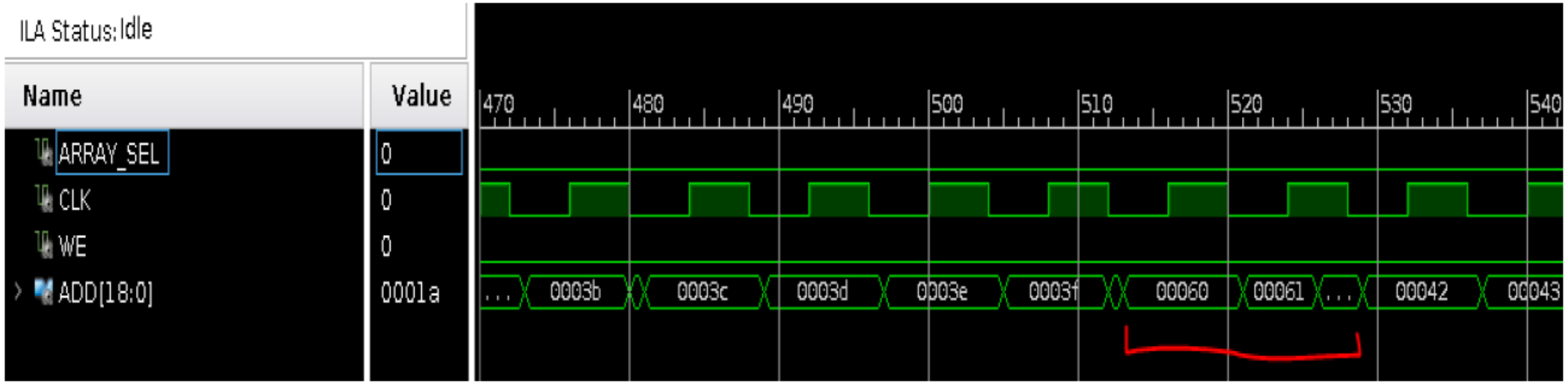


- Indirect Ionization:
  - Also dominated by VCC_AUXIO
  - Not sensitive to high-energy electrons



Hard damage on HDIO input paths

- During radiation test, HDIO were biased at Vmax (3.3V)
- Following to SEL events at high LET (Xe and Ni ions), some functional issue was observed on HDIO input paths
  - During exploratory HI test campaign, HDIO were used as SRAM address bus



  - During next test campaign, a specific HDIO monitoring was set-up
    - 3 additional damages observed

Error Rate Calculation Methodologies

- Heavy-Ions: Standard IRPP Approach
  - Sensitive volume thickness = 2 µm
- High-energy protons / electrons:
  - For electron, 15 MeV energy threshold was considered *
  - Convolutional Product of cross-section and mission flux

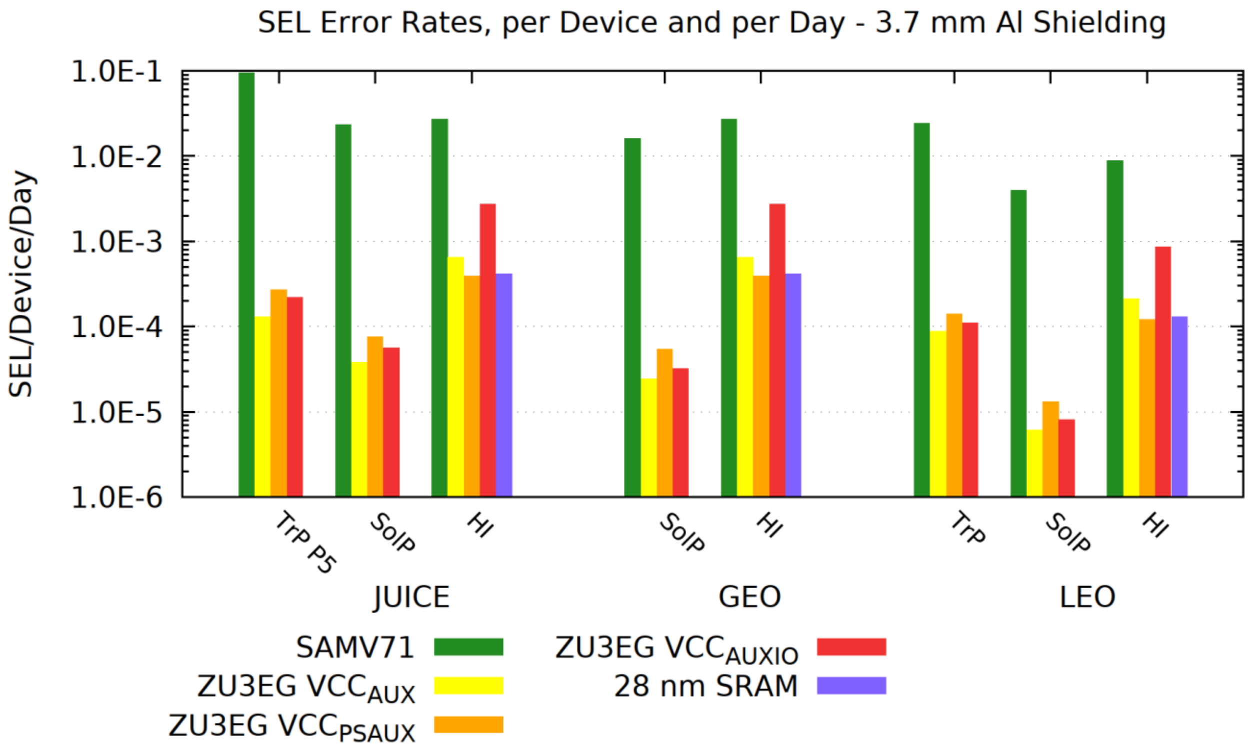
$$SEE_{RATE} = \int_E XS_{SEE}(E) \times \Phi(E)\, dE$$

- Proton Direct ionization:
  - Fit of low-energy cross-section to 2nd order polynomial
  - Convolutional Product of cross-section and mission flux

* : M. Tali *et al.*, "Mechanisms of Electron-Induced Single-Event Upsets in Medical and Experimental Linacs," in *IEEE TNS*, 2018.
A. Samaras *et al.*, "Experimental Characterization and Simulation of Electron-Induced SEU in 45-nm CMOS Technology," in *IEEE TNS*, 2014.
C. Inguimbert *et al* "Electron Induced SEUs: Microdosimetry in Nanometric Volumes," in *IEEE TNS*, 2015.

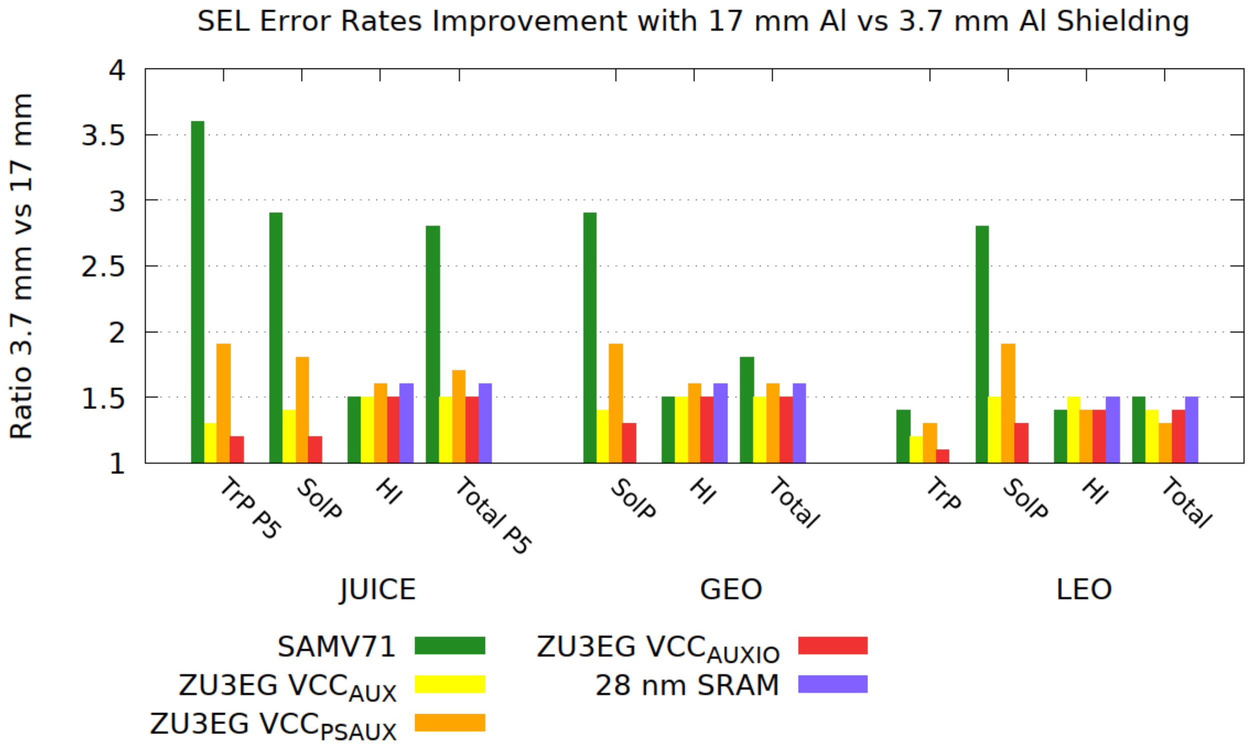
Mission Average SEL Rates

- Per particle type
  - HI dominates for ZU3EG and 28 nm SRAM
  - Trapped protons dominates for SAM V71Q21RT



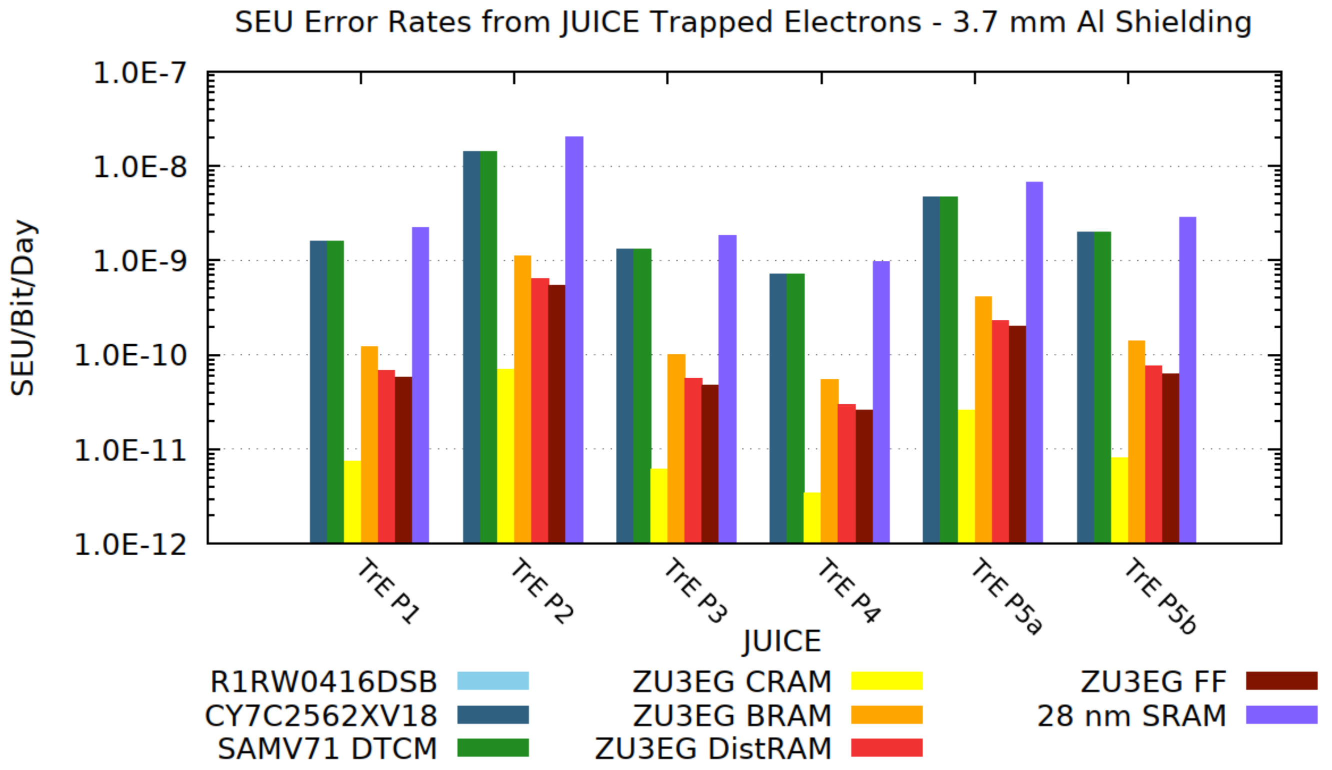
Mission Average SEL Rates
Impact of Shielding

- Increasing shielding has limited impact on SEL rates
  - ≈ 1.5X for ZU3EG and 28 nm SRAM
  - ≈ 3X for SAM V71Q21RT



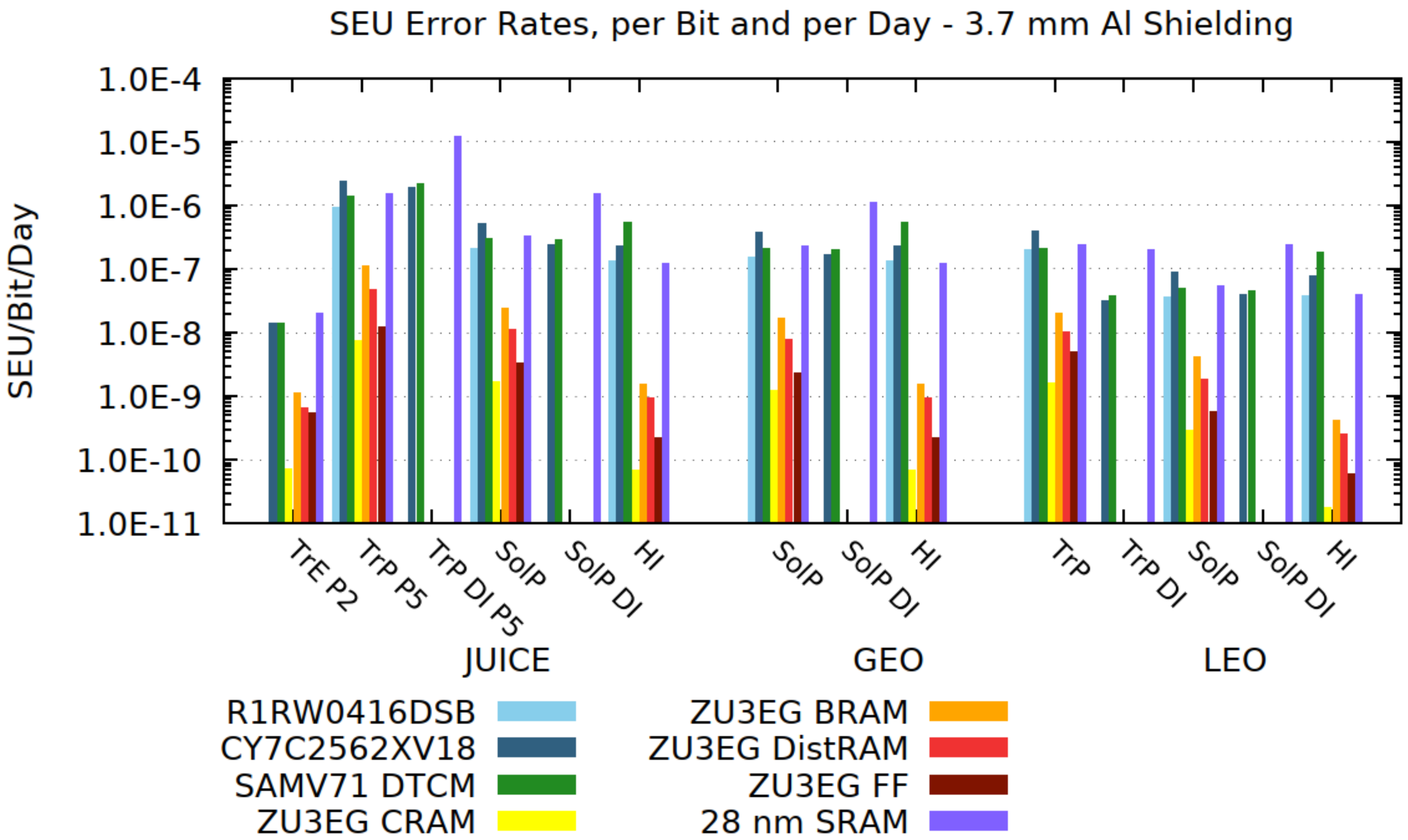
Mission Average SEU Rates
Trapped Electrons

- Phase 2 dominates – consistent with flux comparisons
  - Advanced BULK CMOS device are the most sensitives



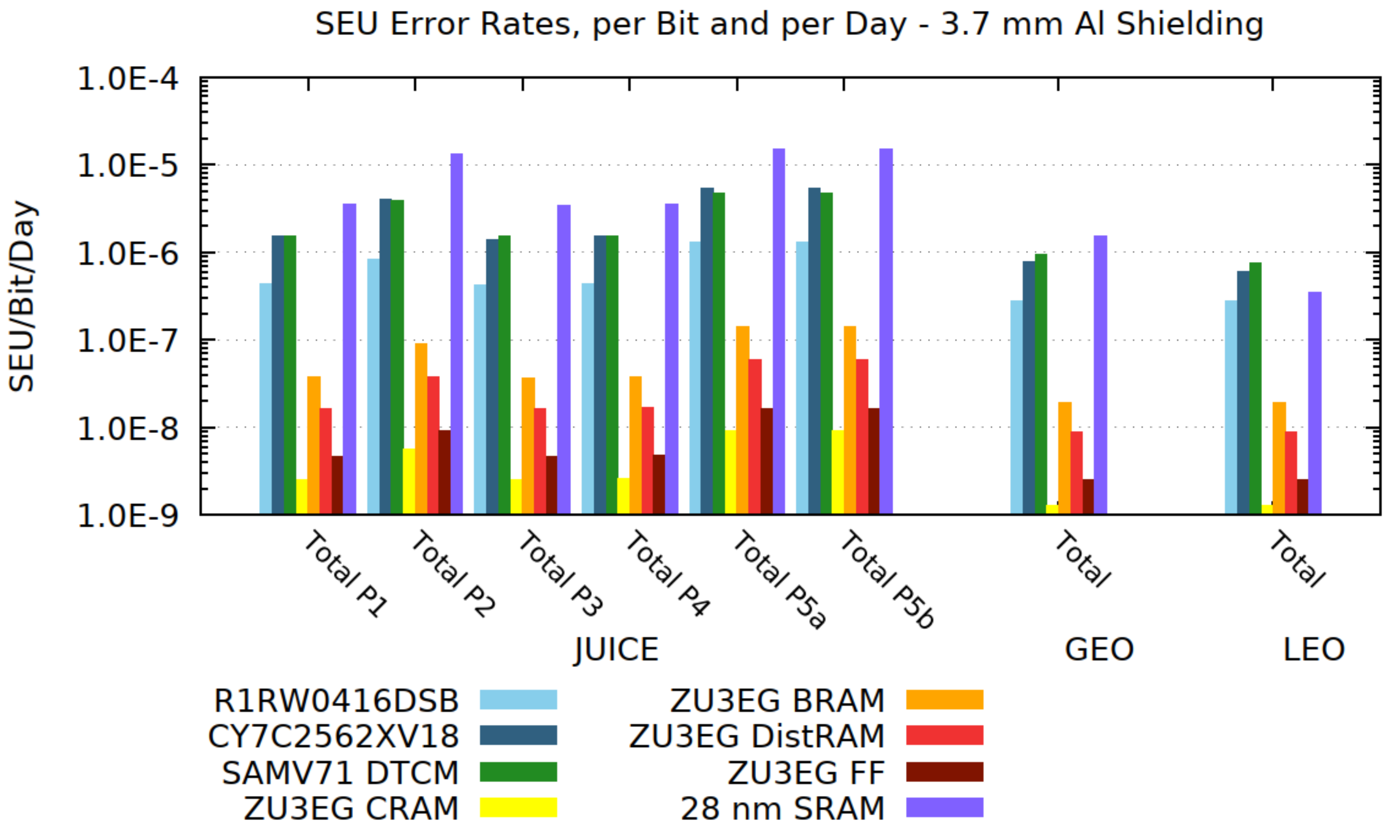
Mission SEU Rate

- Trapped protons dominates
- Electron are not a major SEE risk for JUICE mission



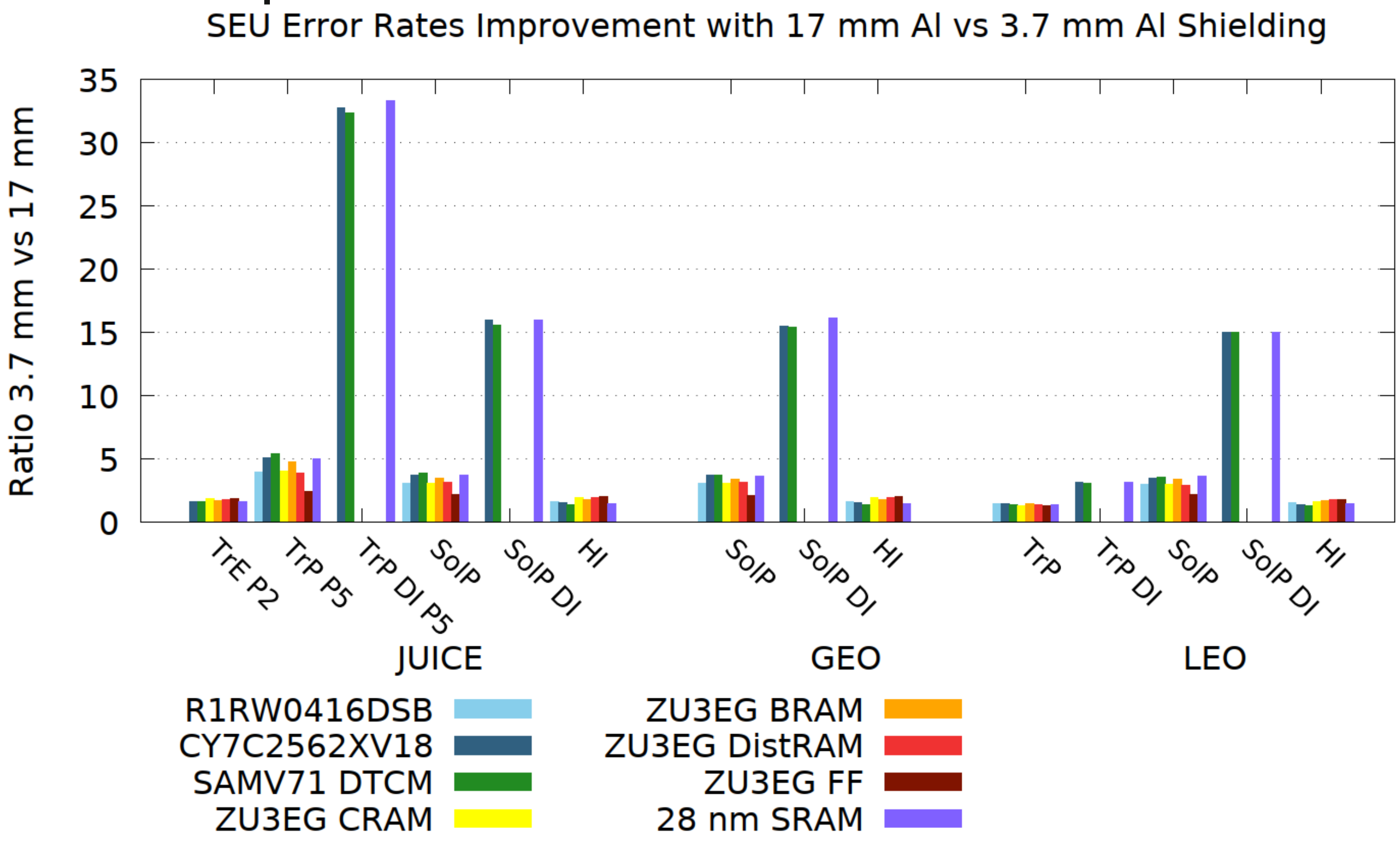
Mission SEU Rate

- JUICE P5 is the strongest constraints for average flux
- SEU rates are 5-10X higher than GEO/LEO



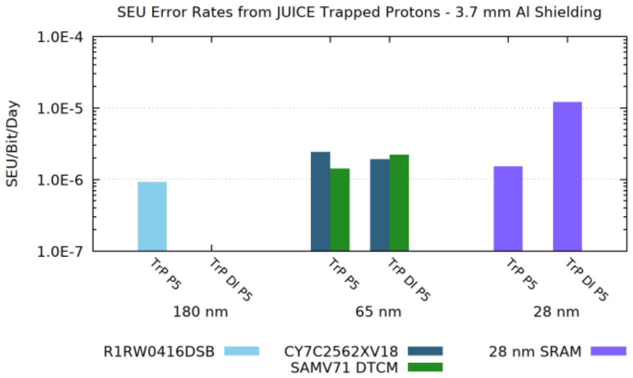
Mission Average SEU Rates Impact of Shielding

- Per particle type
  - Very efficient for proton direct ionization

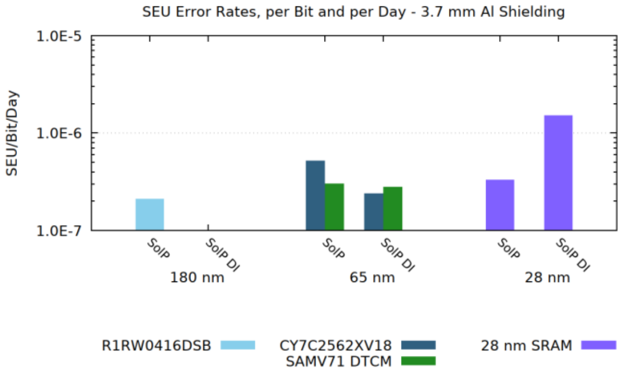


Proton SEU Rates
Direct versus Indirect Ionization

- Direct ionization increases in advanced bulk CMOS technologies
  - JUICE trapped protons / solar protons

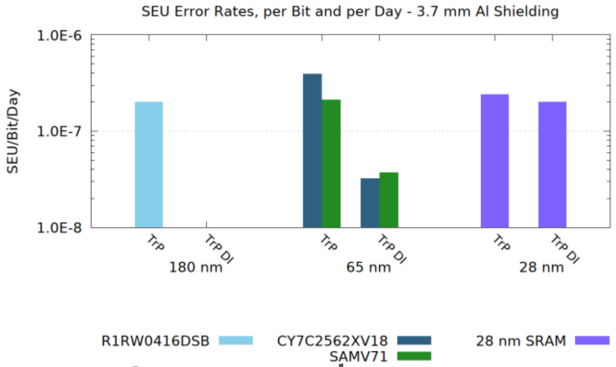


JUICE Trapped Protons P5

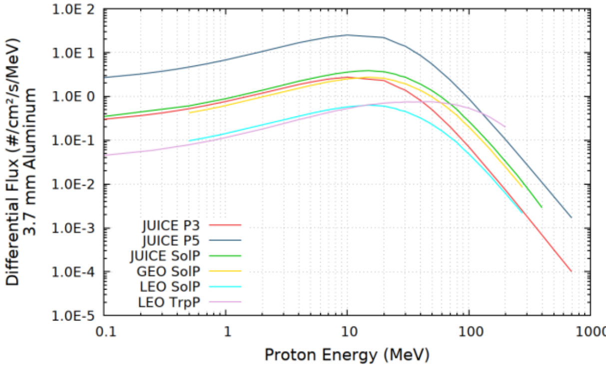


JUICE Solar Protons

  - LEO Trapped Protons: Indirect ionization is more important



LEO Trapped Protons



Proton flux versus JUIC, LEO and GEO Missions

Conclusions

- IC characterization for JUICE mission
  - 7 components considered
  - 8 test campaigns (3 HI, UHE HI, LASER, 2 Protons, electrons)
  - New mechanisms investigated (proton direct ionization, high-energy electrons)
- Main conclusions
  - Main SEL contribution came from heavy-ions or trapped protons
  - Main SEU contribution came from trapped protons
  - Proton Direct ionization contribution increases in advanced bulk CMOS
  - Trapped electron contribution never dominates
  - Increasing shielding thickness is efficient for proton direct ionization
  - For most devices, JUICE error rate are 5-10X higher than Earth orbits
    - Only the 28 nm SRAM JUICE error rate are much higher, due to direct proton ionization (20-40X)

Questions / Discussions