Self-adaptive Single-Event Upset Resilience in Reconfigurable Systems for Space Applications

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innovations for high performance microelectronics

Leibniz Association

17nd Nov, 2021

Outline

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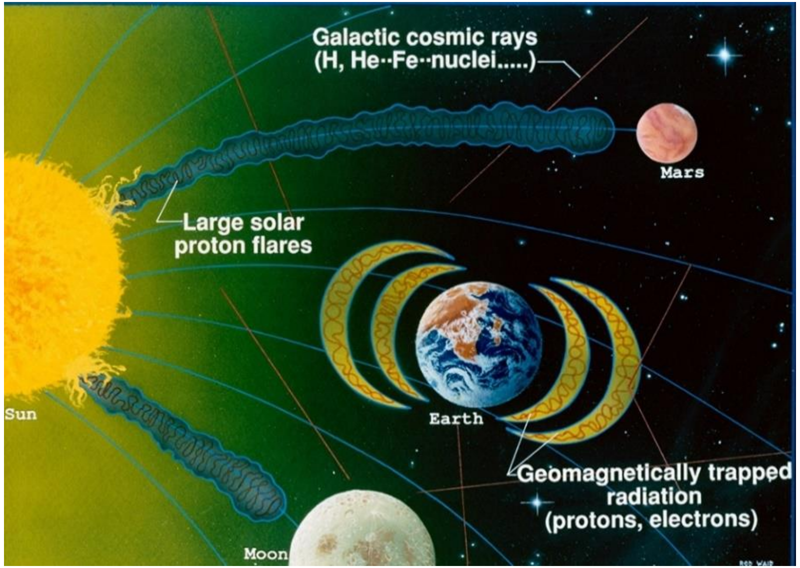
Background

❖ Space radiation environment

- Complex (wide range of sources and energies)
- Dynamic (variable radiation intensity)

❖ Radiation sources in space

- Trapped in planetary magnetospheres
  - Van Allen belts for Earth
- Galactic Cosmic Rays (GCRs)
  - *From deep space*
- Solar Particle Events (SPEs)
  - *Solar flares and coronal mass ejections from the Sun*



[Illustration from https://www.nasa.gov]

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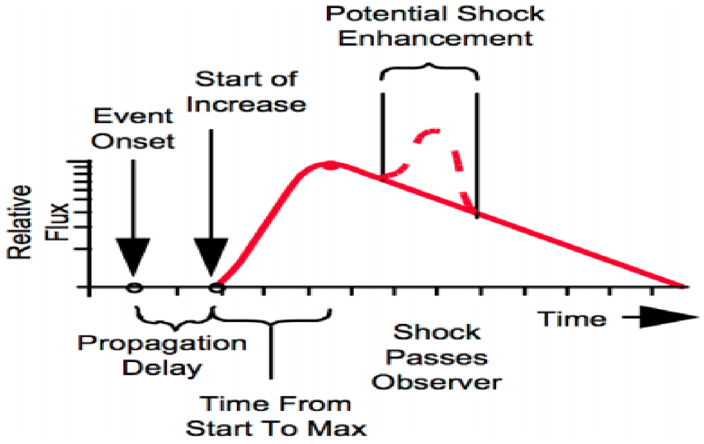
➡ **Dominate the radiation environment**



During SPEs, the particle flux in space may increase by 2 – 6 orders of magnitude during a period of several hours or days

Background

❖ Single Event Effects (SEEs)

- Major reliability threat for Integrated Circuits (ICs) used in space applications
- Caused by a single energetic particle (e.g. proton, neutron, heavy ion)
- *Soft SEEs*: temporary impact (data loss)
- *Hard SEEs*: permanent physical damage
- Soft SEEs are critical for nano-scale ICs:
  - **Single Event Transients (SETs)** – voltage glitches in combinational logic
  - **Single Event Upsets (SEUs)** – bit flips in memory and sequential logic

Radiation environment

↓

Particle-matter interaction

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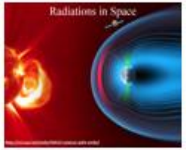
Charge collection and current pulse formation

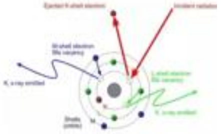
↓

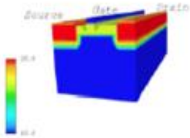
Soft or hard SEE on cell level

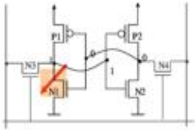
↓

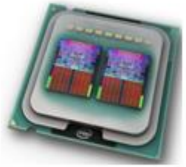
Erroneous response of the system











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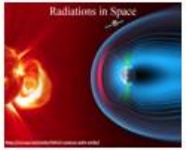
➡ Main concern here

Radiation environment



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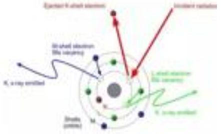

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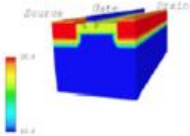
Charge collection and current pulse formation



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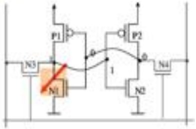

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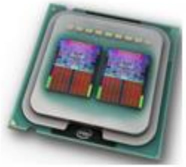


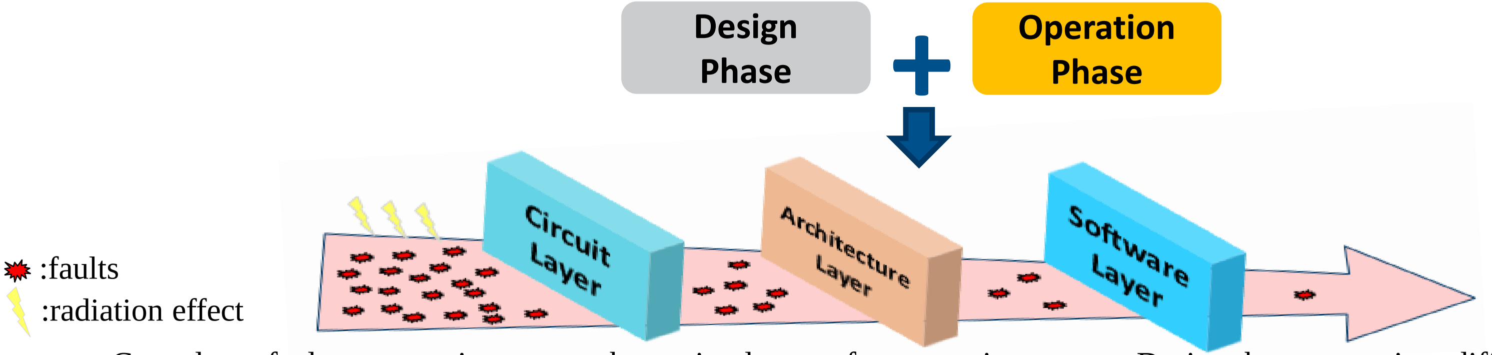
Background

❖ Design phase: Design Space Exploration (DSE)

- ➢ Technology selection
- ➢ Hardware, software, system domain

❖ Operation phase: run-time reconfiguration

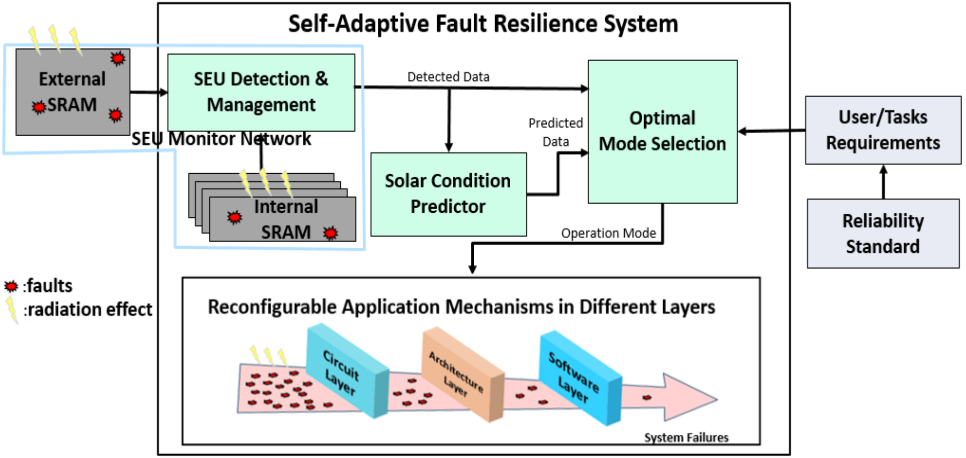
- ➢ Sensor network: radiation, aging, temperature, etc.
- ➢ Reconfigurable operation modes



Cross-layer faults propagation across abstraction layers of a computing system. During the propagation, different masking effects may block the propagation of the fault, thus reducing the impact on the system's reliability.

Goal: Self-adaptive platform

❖ Dynamically select the optimal operation modes under variable environments & user requirements during run-time, achieve the dynamic trade-off between reliability, performance and power consumption in real-time



Overview of the proposed self-adaptive platform

1. **When** to optimize the system?
   - ➢ Radiation Monitor
   - ➢ Solar Condition Prediction
2. **How** to optimize the system?
   - ➢ Optimal mode selection of existing reconfigurable mechanisms

Outline

Motivation of SEU Monitor

- **Limitations of state-of-the-art SEU monitors (e.g. memory-based, pixel detectors)**
  - Stand-alone monitors increases the overall cost, area and power consumption
    - *Size of the monitors are* limited
  - Stand-alone monitors could not be realized in the same technology as target system
    - *Data processing more challenging*

- **Focus of this work**
  - **Non-standalone SEU monitor, integrating the SRAM-based SEU monitor and data storage functions in the same SRAM chip**
  - **Permanent faults detection in memory**
  - **Easy to implement in embedded systems**

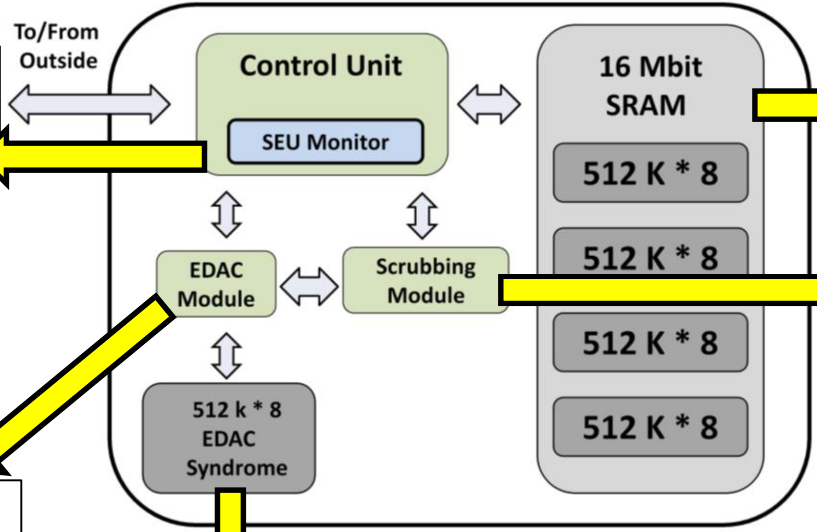
Implementation of the SEU monitor

- **On-chip data storage (SRAM) is used also as a particle detector**
  - Negligible area and power overhead compared to stand-alone SRAM detectors
- **Same operating principles as standalone SRAM detectors**
  - Number of SEUs in a given time interval (once per hour) is measured
  - Standard scrubbing and EDAC procedures used to correct single errors
- **Additional function**
  - Detection of permanent errors in SRAM
  - Avoid faults over-counting

Implementation of the SEU monitor

- 20 Mbit embedded SRAM as a particle detector

- **Control Unit:** dedicated faults detection control flow



- 16 Mbit SRAM: store normal data

- **Scrubbing:** scrub memory words during fault checking

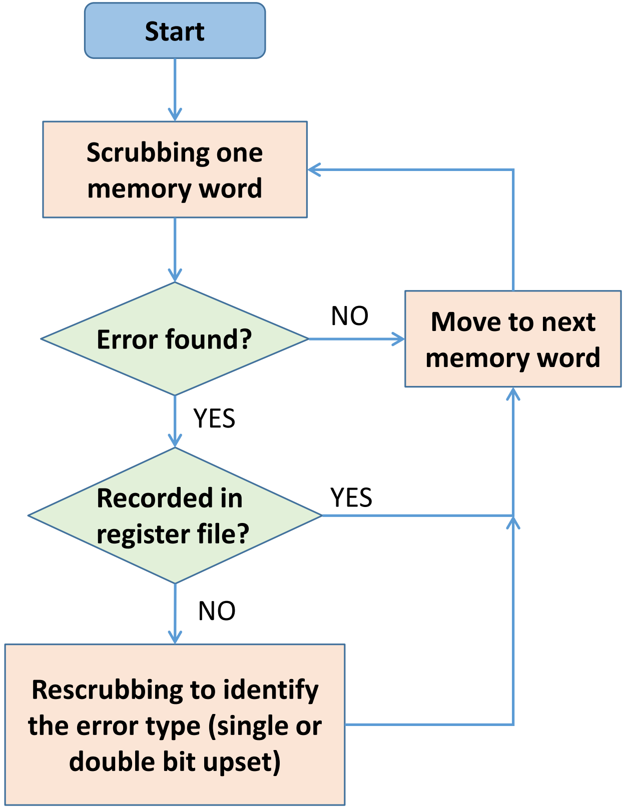
- **Error Detection And Correction (EDAC):** Coding approaches to protect memory contents, such as (39,32) HSIAO SEC-DED

- 4 Mbit SRAM: store the 7-bit EDAC check bits of each memory word

Implementation of the SEU monitor

❖ Error detection and correction flow

- Scrubbing procedure reads all memory words to detect errors
- Re-scrubbing the memory word when a new error is detected
- Single bit error is corrected in the 1st scrubbing round
- **Error type is determined in the 2nd scrubbing round: single, double or permanent faults**
- Error address is logged in register file
- One scrubbing cycles takes around 50 ms



Analysis and results of SEU Monitor

Synthesis results for 20Mbit SRAM

Parameter	Value
Technology (*µm*)	0.13
Supply Voltage (*V*)	1.2
Frequency (*MHz*)	50
Total area (mm^2)	14
Total power dissipation (*mW*)	384
'Non-SRAM' part* area (mm^2)	0.0957
'Non-SRAM' part power (*mW*)	0.211

Area and power dissipation comparison between 20Mbit SRAM and 'Non-SRAM' part

	20 Mbit SRAM	Non-SRAM part
Area (mm^2)	13.9 (99.3 %)	0.0957 (0.7%)
Power consumption (*mW*)	383 (99.9%)	0.211 (0.1%)

Area and power dissipation comparison in the 'Non-SRAM' part

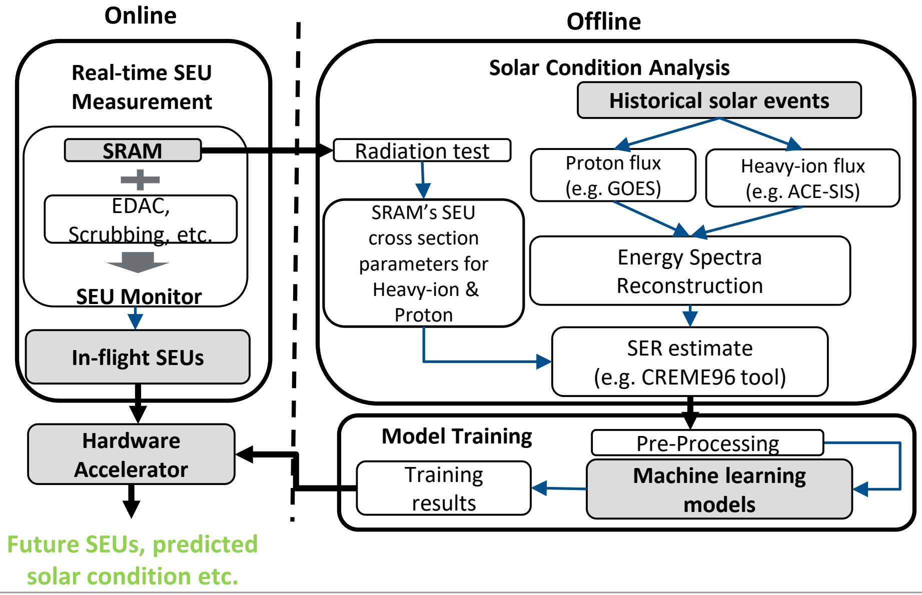
	SEU Monitor	EDAC + Scrubbing + Control Unit
Area (um^2)	95739 (84 %)	18706 (16%)
Power consumption (*mW*)	0.211 (80%)	0.054 (20%)

*: 'Non-SRAM' part contains **control unit**, **SEU monitor**, **EDAC** and **scrubbing module**

Outline

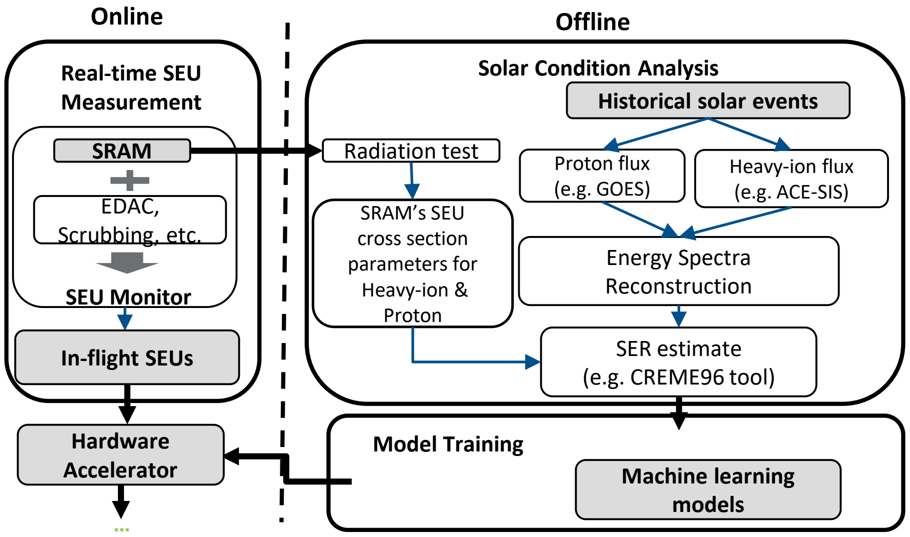
Solar Condition Prediction

- Proposed SEU monitor can provide the in-flight real-time SEU rate
- Available public historical space particle flux databases from previous space missions
- Numerous machine learning models
- Target: Prediction of in-flight SRAM SEUs and SPEs from an on-board SEU monitor
- Two phases with four main blocks:



Historical Events Analysis

- Target: obtain the historical in-flight target SRAM SEU rates from real historical SPE flux data
- Output: Hourly Soft Error Rate (SEU rate) data of the target SRAM during the selected SPEs
- Four main steps:



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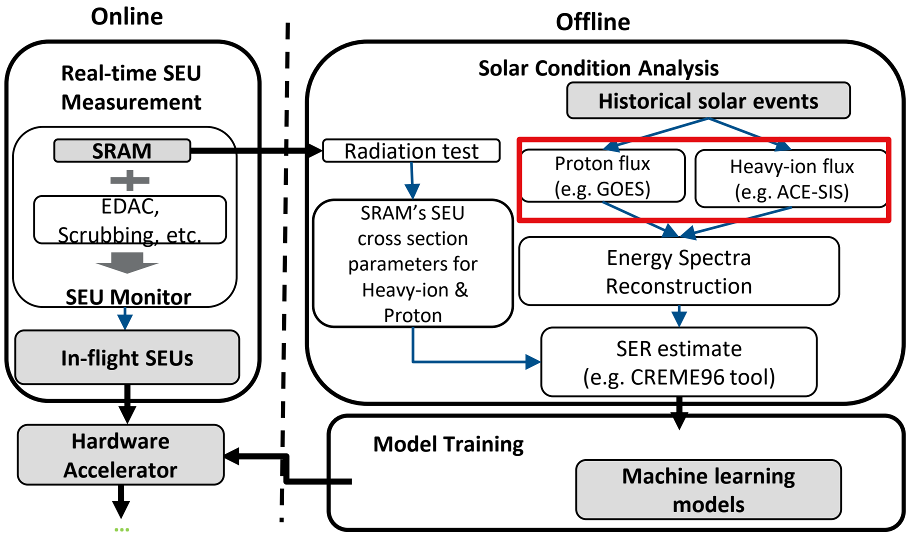
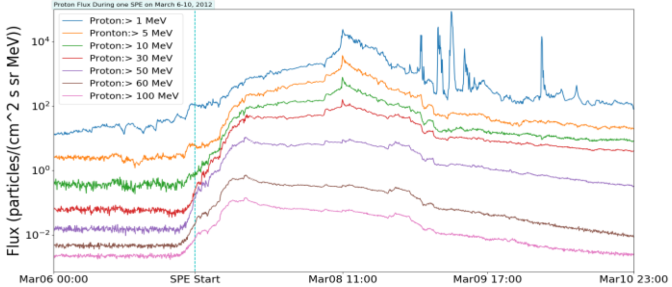
- Output: Hourly Soft Error Rate (SEU rate) data of the target SRAM during the selected SPEs
- Four main steps:
  1) Collection of historical solar events flux data;

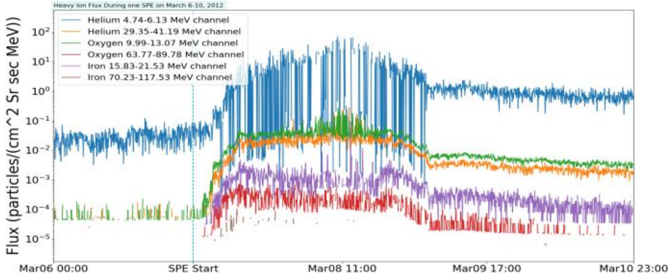
: Proton data

: [He, C, N, O, Ne, Na, Ma, Al, Si, S, Ar, Ca, Fe, Ni] ion data

Collected all 36 SPEs flux data (over 5000 hours) occurred in Solar Cycle 24 (2008-2019)







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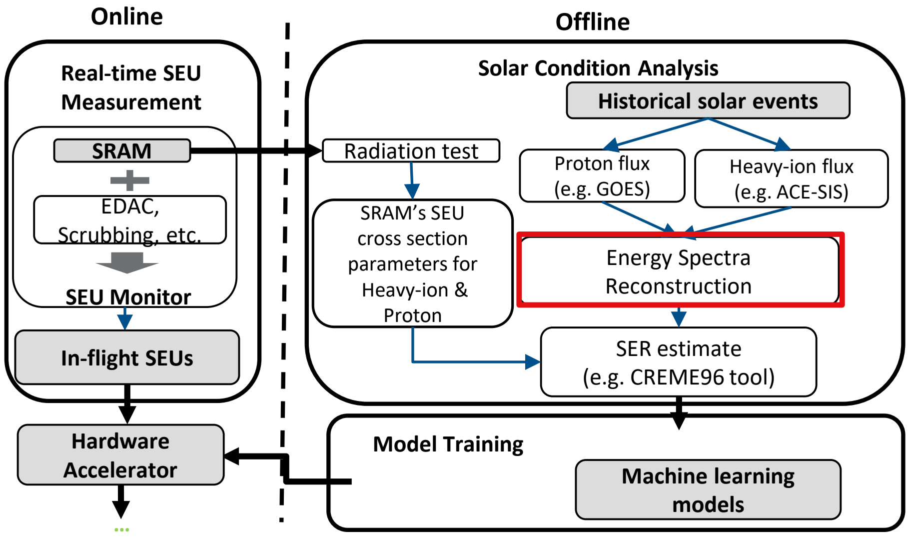
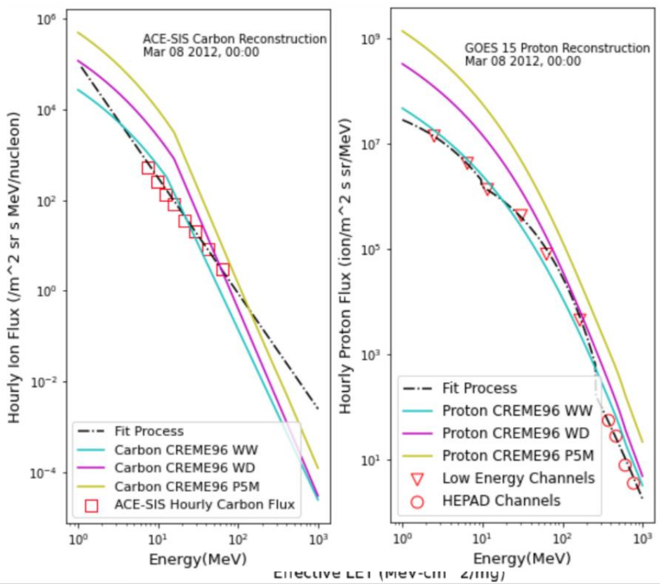
- Output: Hourly Soft Error Rate (SEU rate) data of the target SRAM during the selected SPEs
- Four main steps:
  1) Collection of historical solar events flux data;
  2) SPE energy spectra reconstruction;

- Issues of flux data obtained from online databases:
  - Data gaps
  - Low energy range
  - Incomplete ion type measurements





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- Four main steps:
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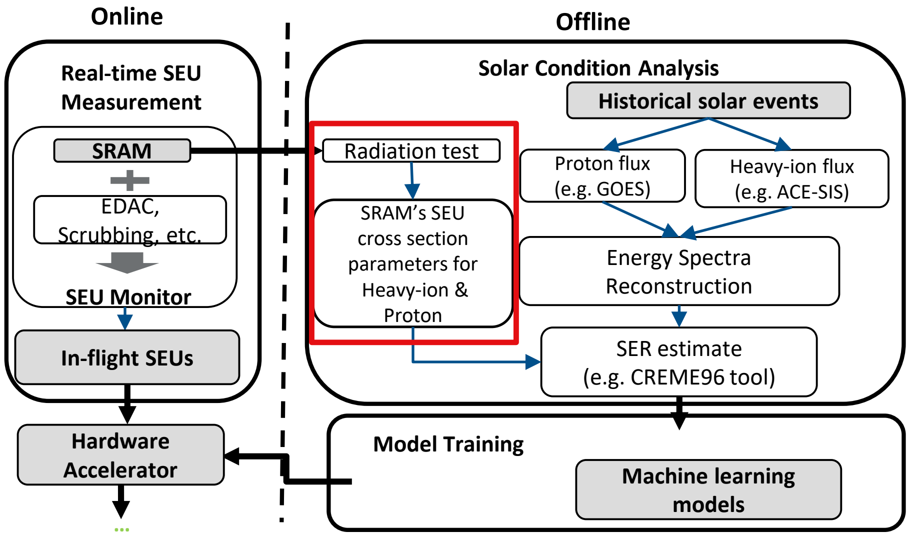
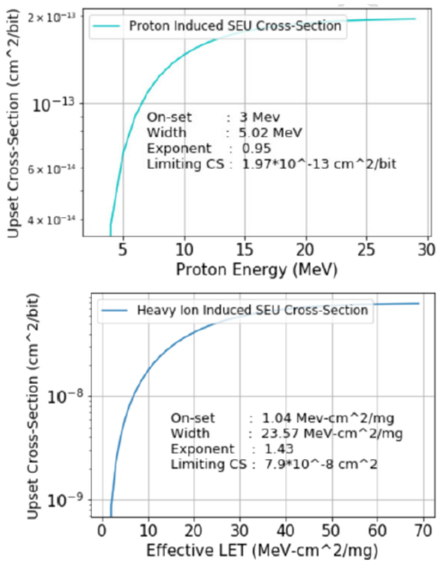
  2) SPE energy spectra reconstruction;
  3) Target SRAM cross-section parameters;

- SRAM: 65 nm COTS SRAM in bulk technology from Cypress
- Weibull fit for heavy-ion and proton cross-section for the target SRAM from radiation tests





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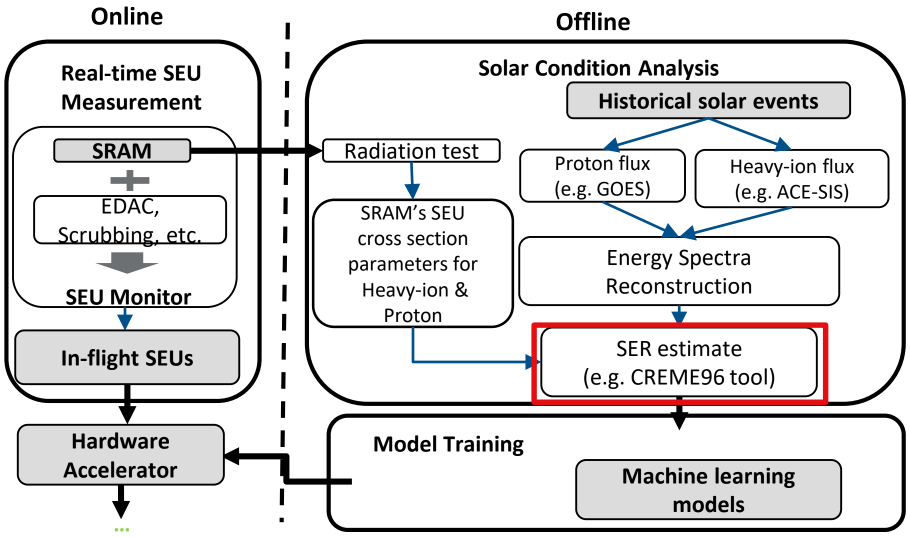
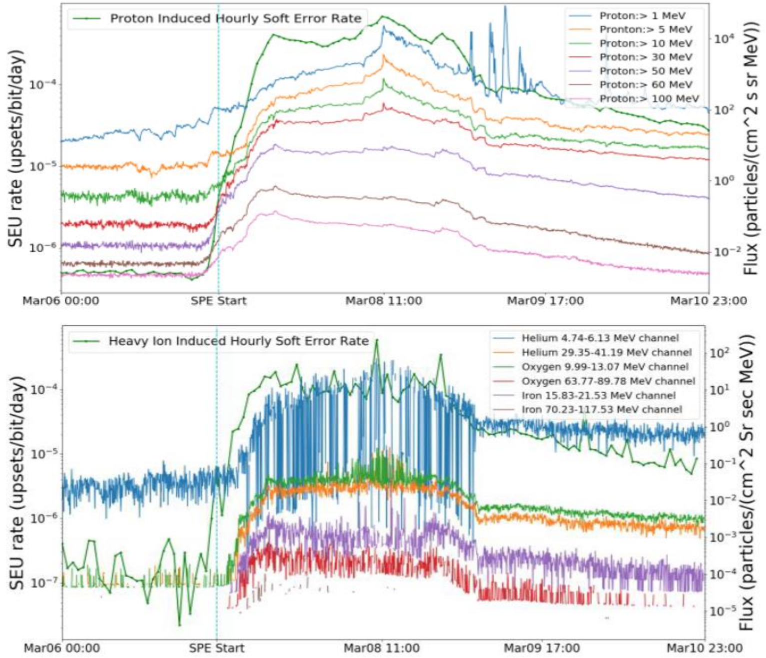
  3) Target SRAM cross-section parameters;
  4) Hourly SRAM SER estimation.

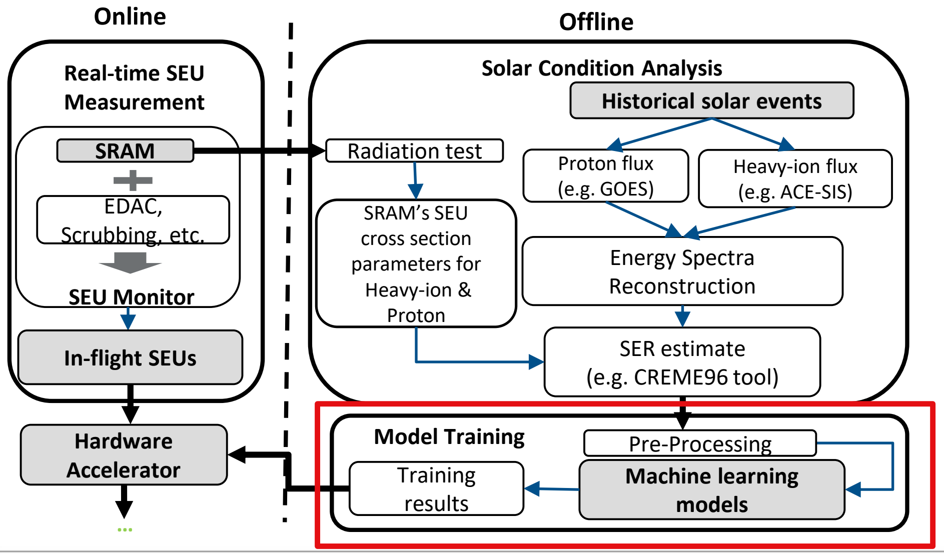


- CREME96: widely used suites for evaluating the in-orbit soft error rate for space applications



Model Training

- Target: obtain a machine learning model which is able to predict SEUs 1 h in advance
- Using several consecutive past hourly SEU data to predict the following hour SEU
- Three main steps:



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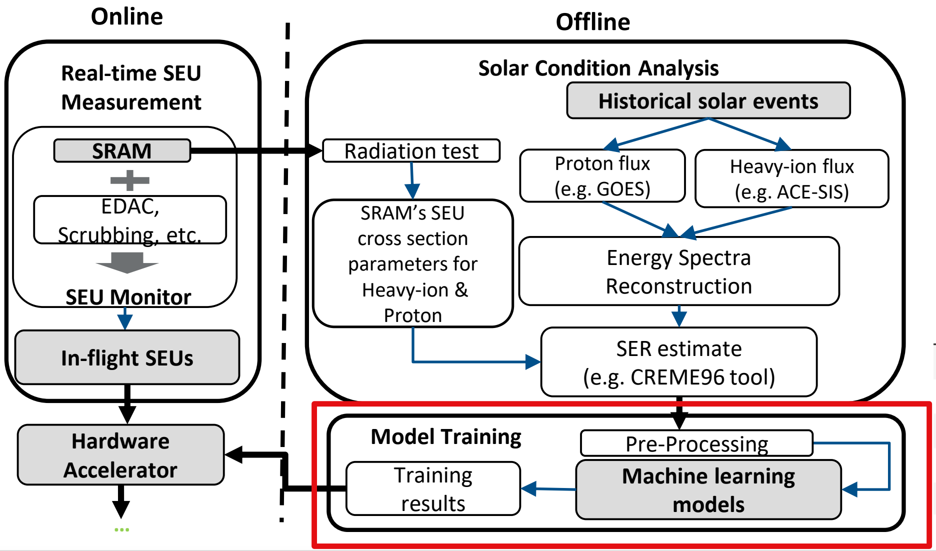
  1) Pre-processing of the Test and Training Data Set

- Convert the SER data (SEU/bit/day) from CREME96 tool to SEUs in one hour (SEU/hour), **depends on the size of target SRAM**
- Normalize the input data to the range of (0, 1)



CREME96

Convert Normalize

Event	Datetime	SER	Upsets	Normalized Upsets	-4h	-3h	-2h	-1h	0h
2010aug14	2010-08-14 05:00:00	6.570279e-07	60.0	0.000458	0.000481	0.000465	0.000450	0.000450	0.000458
2010aug14	2010-08-14 06:00:00	6.777285e-07	61.0	0.000465	0.000465	0.000450	0.000450	0.000458	0.000465
2010aug14	2010-08-14 07:00:00	7.164588e-07	58.0	0.000443	0.000450	0.000450	0.000458	0.000465	0.000443
2010aug14	2010-08-14 08:00:00	5.650890e-07	59.0	0.000450	0.000450	0.000458	0.000465	0.000443	0.000450
2010aug14	2010-08-14 09:00:00	6.858362e-07	57.0	0.000435	0.000458	0.000465	0.000443	0.000450	0.000435

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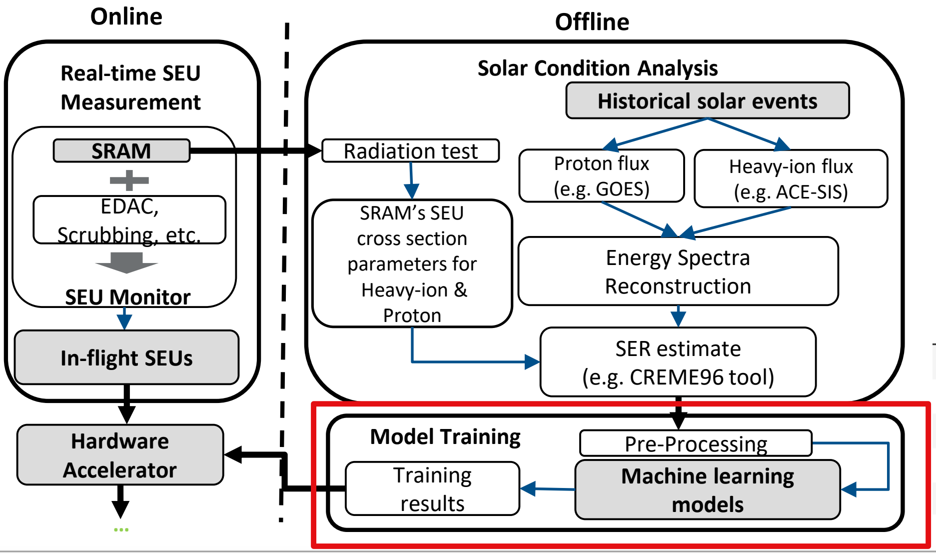
  3) Model evailation and comparison



- Five regression model:
  1) **Linear regression (Linear Least Squares)**
  2) Decision Tree
  3) K-Nearest Neighbors
  4) Multi-Layer Perceptron Neural Network
  5) **Recurrent Neural Network (RNN) with Long Short-Term Memory (LSTM)**
- Hyperparameters : A random search method combined with a grid search
- Model evaluation: MAE, MAX, RMSE, R^2

$$y = M(x) \Rightarrow M?$$

CREME96 Convert Normalize X y

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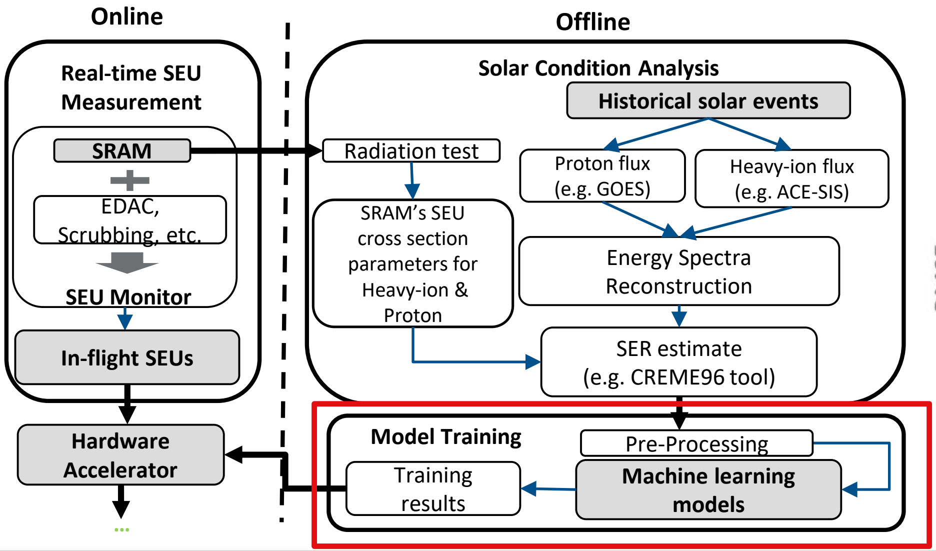

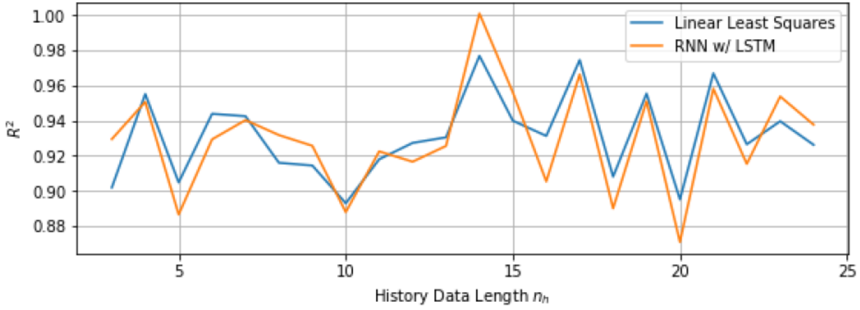

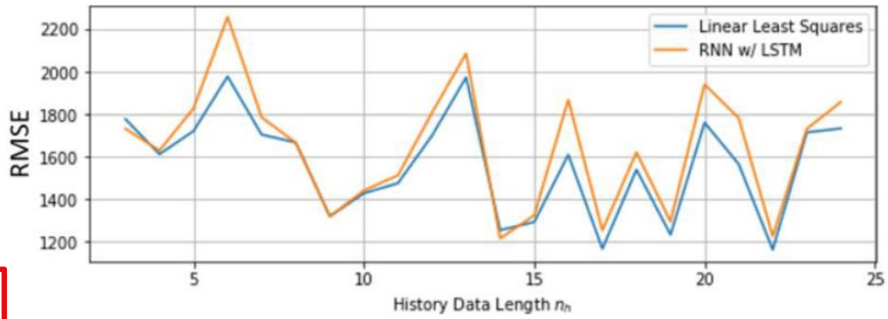

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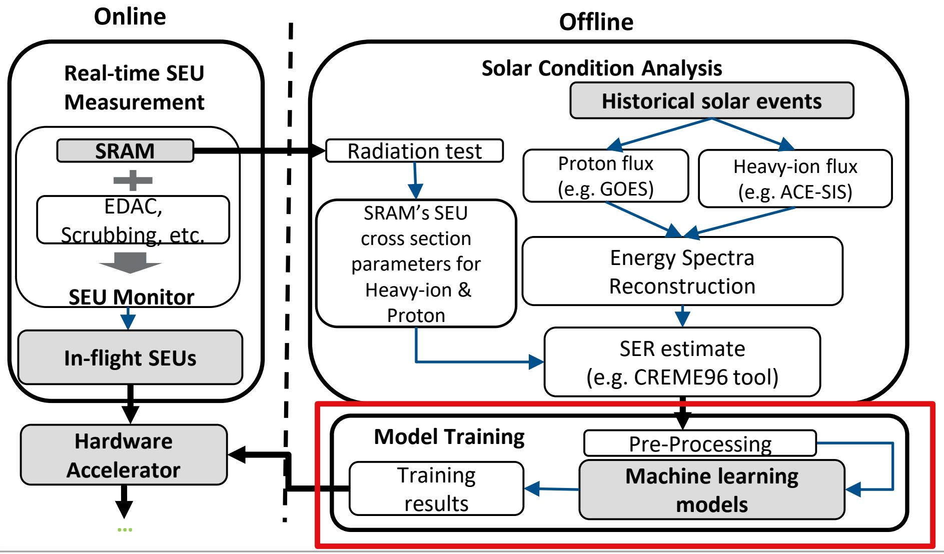
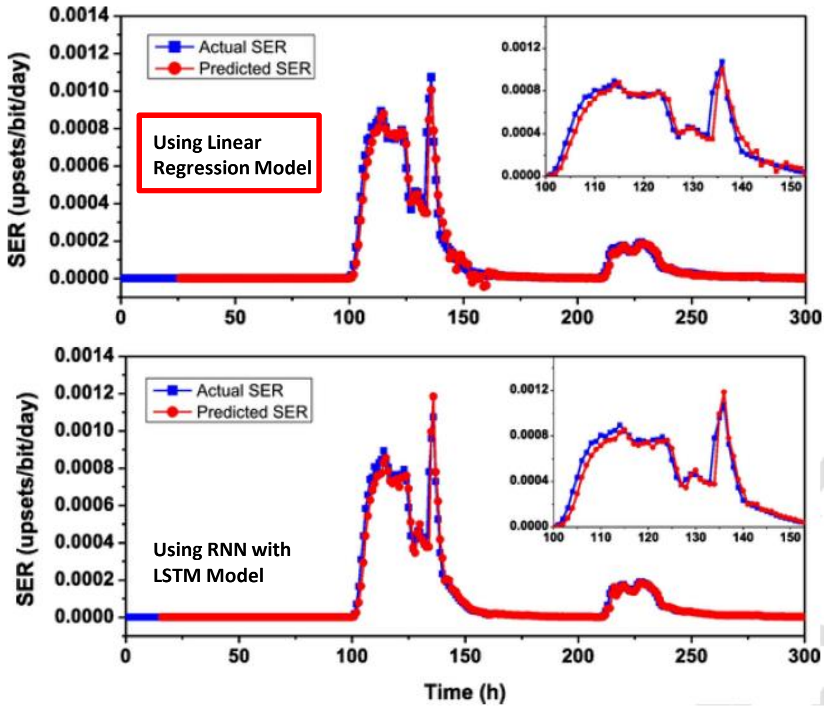
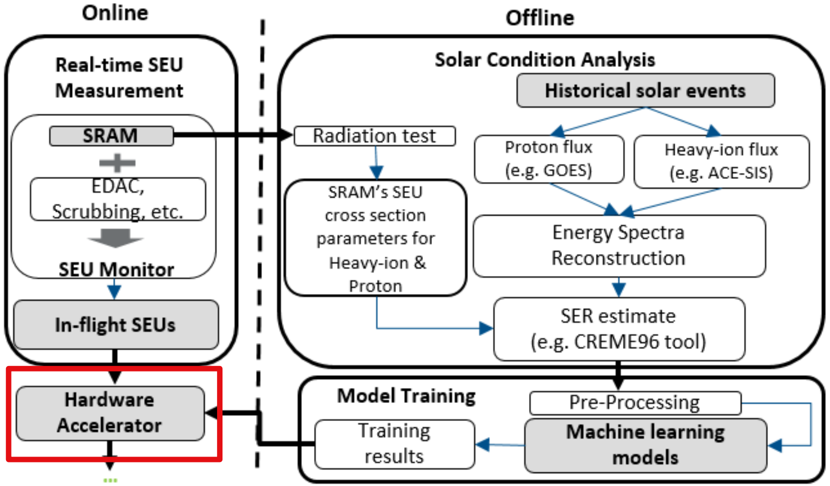




Prediction over a SPE from 2011-01-19 to 2011-02-01

Hardware Accelerator

- Target: implement the linear regression model with an ultra-low cost
- Hourly SEU data from monitor, coefs from training model
- Accumulator: multiplication operation through successive additions
- Improves area usage and power consumption by slowing down the calculation process



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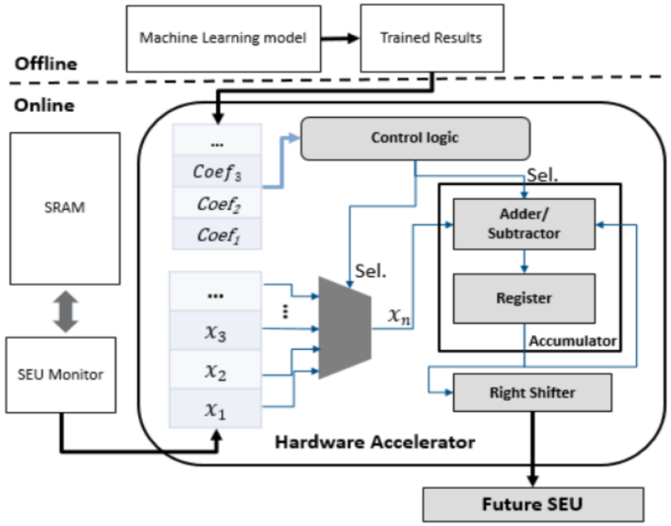


Example: $\mathrm{SEU}_{\mathrm{Pred}} = 41x1 + 3x2 + (-38)x3 + 33x4 + 3x5 + (-29)x6 + 26x7 + (-1)x8 + (-22)x9 + 21x10 + (-1)x11 + (-15)x12 + 13x13 + (-1)x14 + (-7)x15 + 6x16 + (-2)x17$

- A total of 262 clock cycles is needed for one calculation
- 5.24 us when working frequency is 50 MHz

Synthesis Results of Hardware Accelerator

- Proposed design is general and can be implemented in different technologies
- In IHP´s 130 nm bulk CMOS library with 1.2 V supply voltage, and 50 MHz

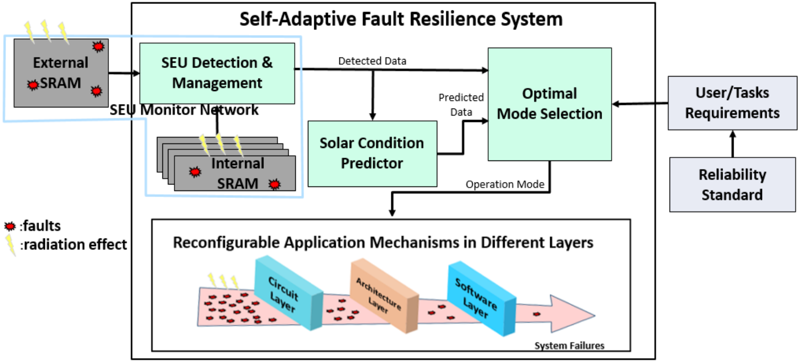
	Area (mm^2)	Power (mW)
20 Mbit SRAM	14	384
SEU Monitor	0.0957	0.211
Hardware Accelerator	0.642	3.23

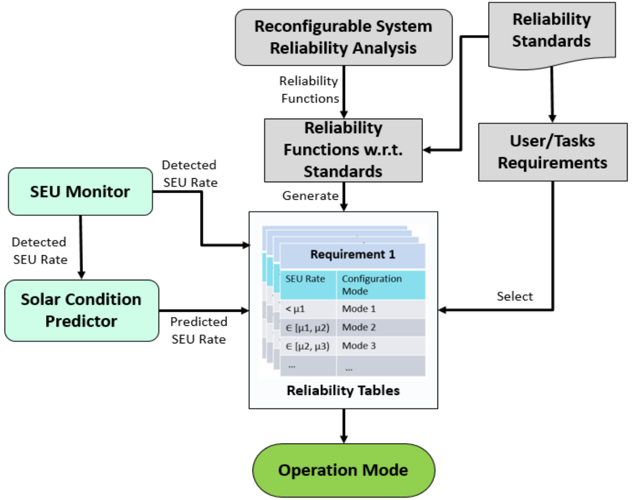
Compared with 20 Mbit SRAM, the induced power and area consumption of proposed hardware accelerator are only 0.8% & 4.5%, respectively

Outline

Self-adaptive Platform

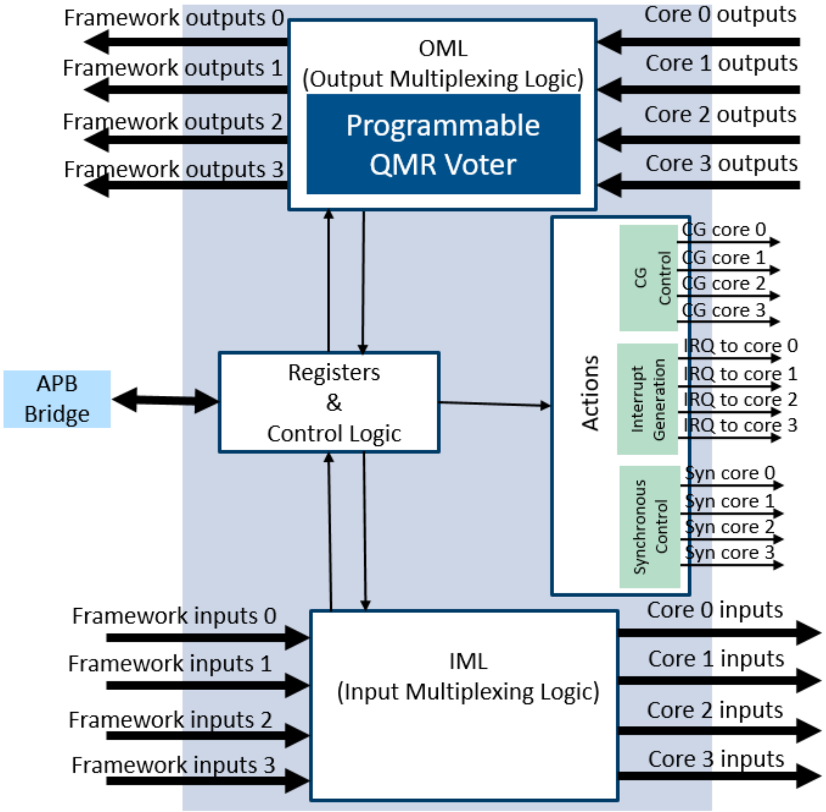
- **Proposed designs are intended to be used in multiprocessing systems:**
  - Multiprocessing system:
    - Inherent hardware redundancy
    - Available reconfigurable mechanisms:
      - Core-level N-Module Redundancy (NMR)
      - Adaptive Voltage Frequency Scaling
      - Dynamic task scheduling
      - ……
  - Reliability requirements:
    - Safety Integrity Level (SIL) standard
  - Pre-defined reliability tables:
    - Collect from reliability functions of modes





Application with Core-level NMR

- **Case study: Self-adaptive quad-core system**
  - De-stress (low power) mode
    - One or more cores operate, while others are switched off
  - Core-level fault tolerant mode
    - *Dual Modular Redundancy (DMR)*
    - *Triple Modular Redundancy (TMR)*
    - *Quad Modular Redundancy (QMR)*
  - High performance mode
    - All cores operate in parallel, i.e. execute different tasks



Optimal Mode Selection with Core-level NMR

❖ **Reliability functions of quad-core system:**

$$R_{de-stress}(t) = R_{high-performance}(t) = e^{-\lambda_c t}$$

$$R_{DMR}(t) = e^{-2\lambda_c t}$$

$$R_{TMR}(t) = 3e^{-2\lambda_c t} - 2e^{-3\lambda_c t}$$

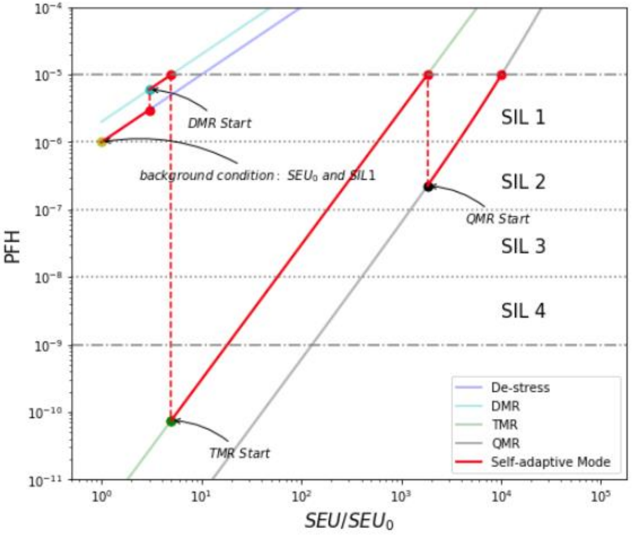
$$R_{QMR}(t) = P * 6e^{-2\lambda_c t}\left(1 - 2e^{-\lambda_c t} + e^{-2\lambda_c t}\right) + 4e^{-3\lambda_c t} - 3e^{-4\lambda_c t}$$

❖ **Reliability standard:** *SIL level is based on the "Probability of dangerous failure per hour (PFH)"*

Low — Reliability — High

$$SIL\ 1 : PFH \in (10^{-5}, 10^{-6})$$
$$SIL\ 2 : PFH \in (10^{-6}, 10^{-7})$$
$$SIL\ 3 : PFH \in (10^{-7}, 10^{-8})$$
$$SIL\ 4 : PFH \in (10^{-8}, 10^{-9})$$

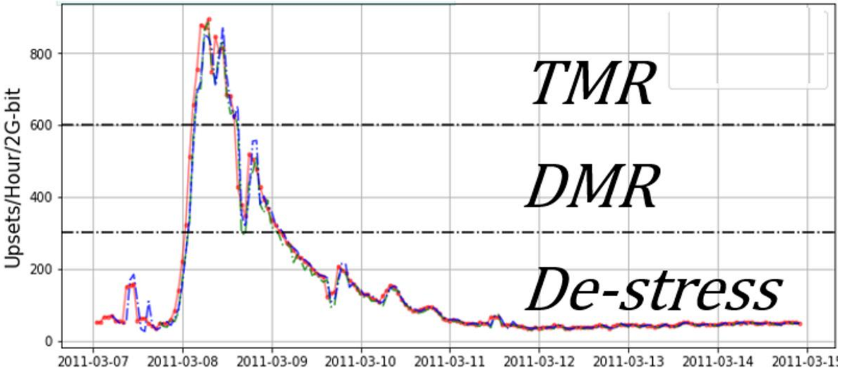
$$PFH = 1 - R_{mode}$$

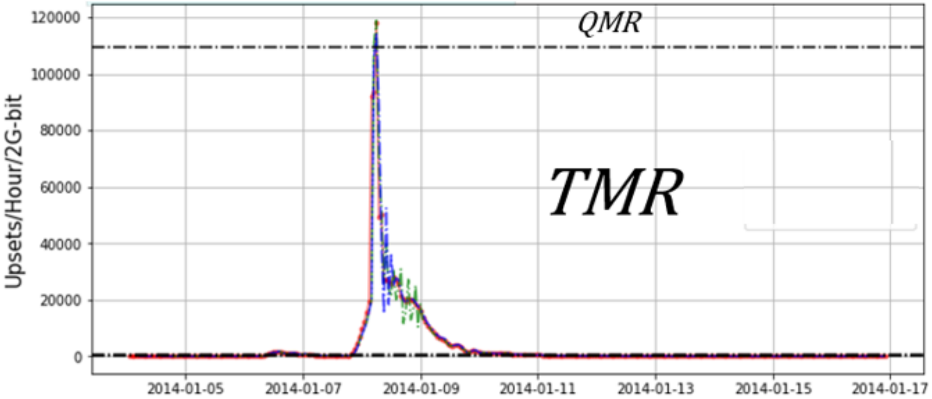


Example: Require SIL 1 level reliability. Assume during background condition, SEU_0 , the system can be guaranteed to maintain at least SIL 1 level of reliability.

Results with Core-level NMR

❖ During small and large SPEs for a 2G bit SRAM (background SEU_0 is around 40) :





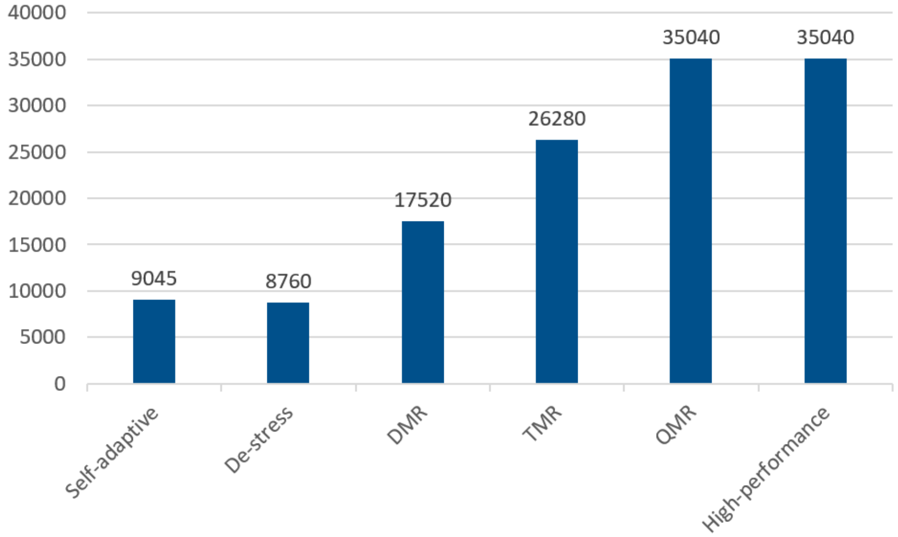
❖ For solar cycle 24, TMR is suitable for most SPEs. Only during the peak period of the large SPEs, TMR could not meet the SIL 1 requirements.

Analysis of Results

- **Case study: all SPEs during Solar Cycle 23 with target SRAM-based SEU monitor**
  - SPEs accounts for around 2.4% of the annual average time
  - Self-adaptive mode switching: configuring the DVFS or Core-level NMR
  - Power consumption in a year is lower than individual DMR, TMR and QMR configurations

SER (*upsets/(bit*day)*)	Operating Mode	Duration Time/Year* (hours)
$< 10^{-6}$	High-Performance De-stress	8556
$10^{-6} \sim 10^{-5}$	DVFS	143
$10^{-5} \sim 10^{-4}$	TMR	43
$> 10^{-4}$	QMR	19

*: merge of SEU rate under different solar conditions into a one-year average



Outline

1. Background
2. Single Event Upset (SEU) Monitor
3. Solar Condition Prediction
4. Optimal Mode Selection in Reconfigurable System
6. Summary

Summary

- An on-chip low-cost non-standalone SEU monitor for space applications has been presented

- An approach for predicting the in-flight SEU variation of the on-board SEU monitor system in space applications is proposed

  - A dedicated ultra-low cost hardware accelerator has been proposed

- Application for self-adaptive multiprocessing systems:

  - Optimal operating mode can be dynamically determined based on the SEU rates

  - Realize the trade-off between reliability, performance and power consumption during run-time

Thank you for your attention!

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