Bridging methodology from component to system-level for the assessment of radiation effects in digital systems

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RADSAGA Final Conference and Industrial event

Israel DA COSTA LOPES, RADSAGA ESR 13, Work Package #3

RADiation and Reliability Challenges for Electronics used in Space, Aviation, Ground and Accelerators (RADSAGA) is a project funded by the European Commission under the Horizon2020 Framework Program under the Grant Agreement 721624. RADSAGA began in Mars 2017 and will run for 5 years.

Presentation outline

- Introduction and motivation
- Case study and instrumentation development
- Radiation experiments
- Bridging methodology development

Radiation environments and applications

Applications

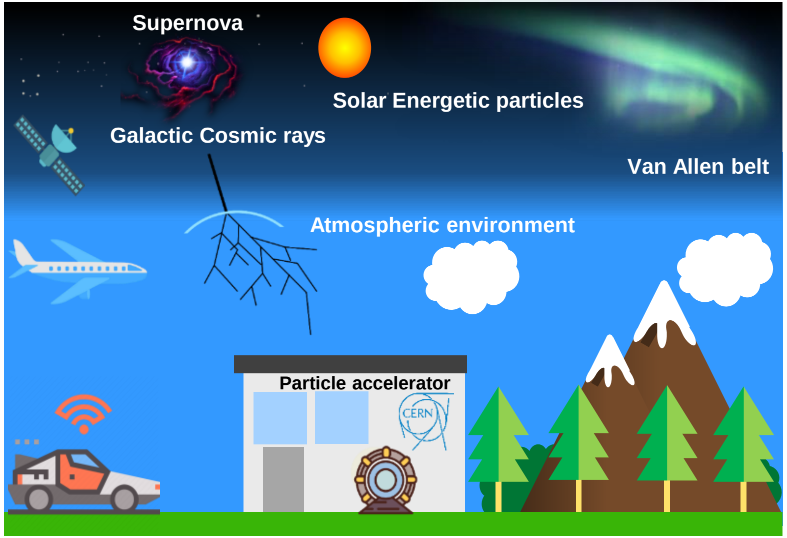
Geostationary Orbit (GEO)
Telecommunication Satellites

Low Earth Orbit (LEO)
International Space Station (ISS)

Aviation
Commercial Airplanes

Ground and Accelerators
Autonomous cars
Hospitals and accelerators

Altitude
35Mm
400km
18km
9km
0km



Environments

Space
Mainly protons
Heavy-ions
X-rays, gamma-rays, etc.

Atmospheric
Mainly neutrons and protons

Accelerators
Ex: High energy Hadrons

- Which kind of digital systems can be exposed in those applications?

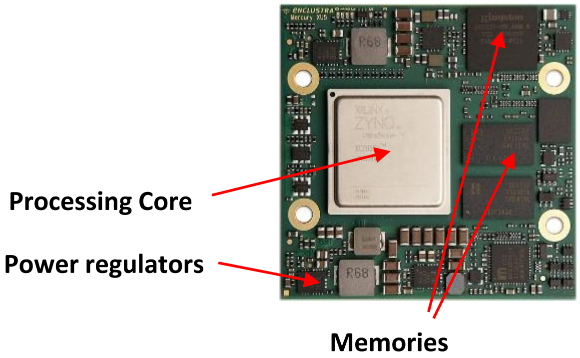
Digital system and component definitions

- Systems can be classified in different ways:
  - Application dependent
  - RADSAGA context system definition
  - Different system classes are proposed
- In this work:
  - **Component** defined as an Integrated Circuit (IC)
  - **System** defined as an assembly of components
  - New trend on embedded digital systems
    - System-on-modules
    - Typical Embedded System components

RADSAGA system definition classes

Class	Systems considered
Extra Small	SoC, System-in-package and Package-on-Package
Small	Typical small-form-factor SoM
Medium	Typical two-sided SBC
Large	Cubesat-like small system
Extra Large	50cm x50cm box (Maximum size)

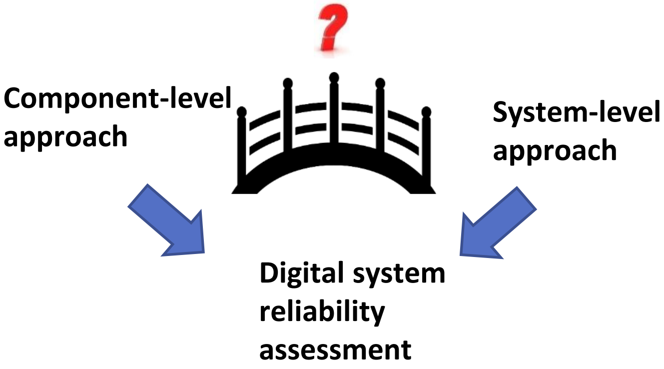
System-on-Module(SoM)



- How to assure the radiation hardness of those systems?

Motivation: Transition between component to system-level approach

	Component-level approach	System-level approach
Direct obtention of system reliability	☹	☺
Total cost	☹	☺
Component observability	☺	☹
Reusability of results	😐	☹

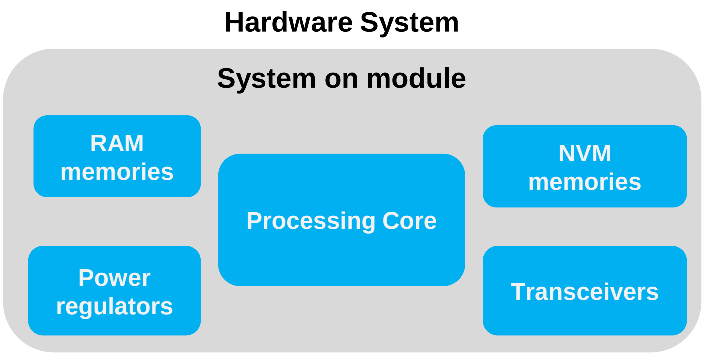


- Re-use component-level RHA knowledge and methods
- Re-use component-level data
- Make the system-level approach more reliable
- Facilitate the cultural transition

Case study objectives

- To develop a RHA methodology case study for providing component and system-level data:
  - Select a representative **Hardware system**
  - Develop a **case study** on the target hardware
  - Design an **experimental setup**

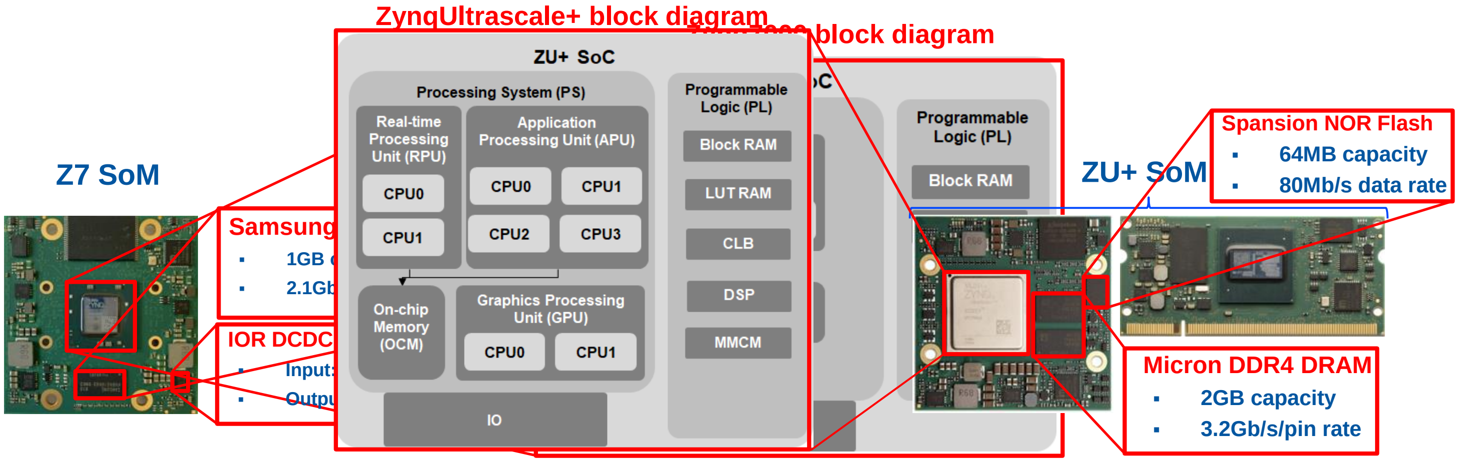
- **Selected hardware system:**
  - Commercial Industrial **System on modules** (SoM)
  - Requires a **Carrier board** for external interfaces
  - Based on Programmable System-on-Chips
  - Also include external memories, transceivers and power regulators



Target Hardware

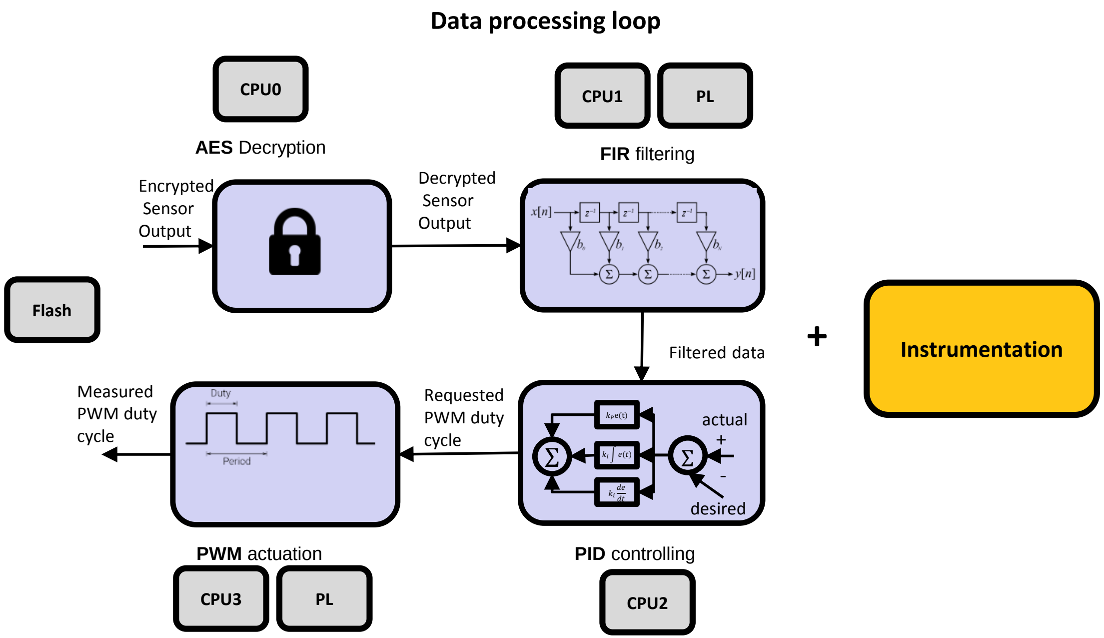
SoM generations from Enclustra

- **Z7 SoM**
  - Based on 28nm Planar Zynq7000 SoC
- **ZU+ SoM**
  - Based on 16nm FinFET ZynqUltrascale+ SoC



Embedded application

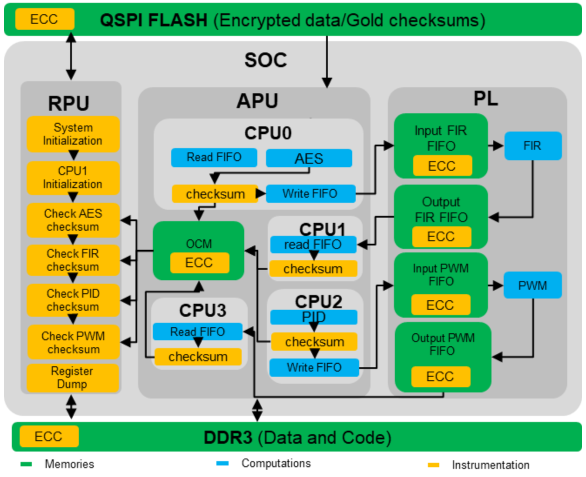
- Representative application of an aerospace embedded digital system

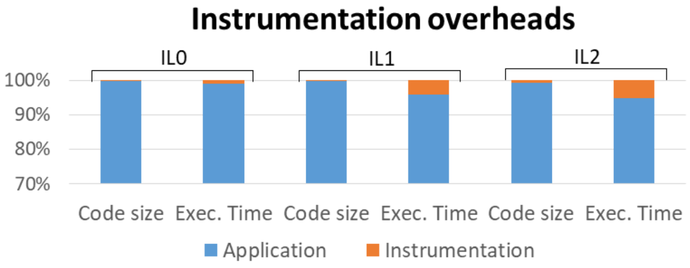


SEE code-instrumentation development

- **Instrumentation Level (IL) functions:**
  - **IL0**
    - Application output (PWM) checksum
    - Watchdogs for control flow verification
  - **IL1**
    - External memories (DDR and Flash) built-in ECCs
    - Intermediate steps (AES, FIR…) checksum
  - **IL2**
    - Internal memories observability (OCM, and PL FIFO) built-in ECC
    - Exception abort status reporting (cache)

Control loop Co-design

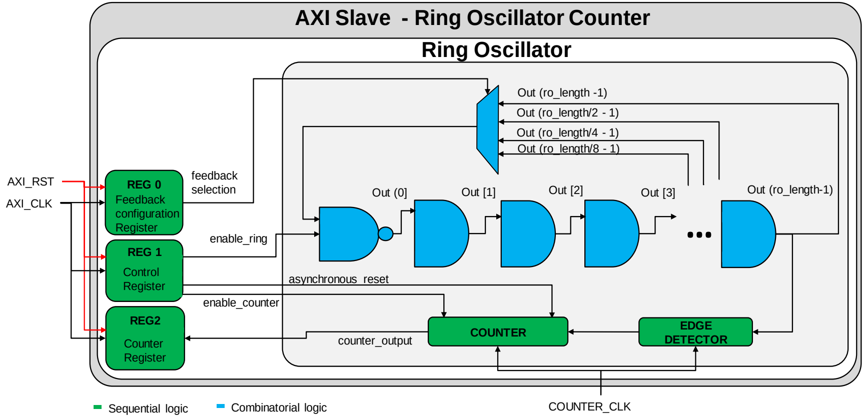




TID IP-core and code-instrumentation

- **TID instrumentation for monitoring parametric degradation:**
  - **PL:**
    - RO IP-core for sensing gate delay variations
    - Configurable RO lengths and feedback
  - **PS:**
    - Software for measuring the RO frequencies

Ring Oscillator IPCore schematic



Implementation results

	Z7	ZU+
Number of ROs	27	21
RO length	1024, 3000	1500
RO frequency at 78℃(kHz)	1900, 580	2000

Experiment objectives and timeline

- **Objectives:**
  - To obtain component-level and system-level data:
    - To irradiate the entire system containing different package thicknesses
  - To validate the instrumentation layer:
    - Error capturing capability
    - Observability increase

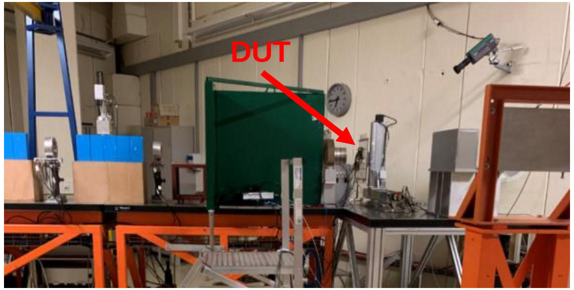
- **Experiment motivations:**
  - Atmospheric neutrons
    - High penetration and atmospheric representation
  - 184MeV protons
    - High penetration and space representation
  - X-ray experiment
    - Localized and fast experiments
  - Laser experiments
    - Get insight on the SoC components

RADSAGA

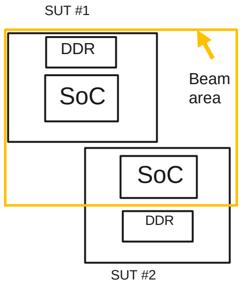
184MeV Proton experiments

- **Facility parameters:**
  - **Facility:** KVI-CART in Netherlands
  - **Spectrum:** 184MeV
  - **Flux:** 1-3E+06 p/cm2/s
- **Test methodology**
  - **Beam layout:**
    - Z7: Two Z7 SoMs in parallel (one partially)
    - ZU+: Single SoM
- **Result summary**
  - Lack of observability on analog parts and power regulators
  - AES SEFI has the lowest cross-section in both technologies
  - No external memory MBU observed (Flash and DDR)
  - Exception aborts observed
  - Most of events observed thanks to the IL0 and IL1

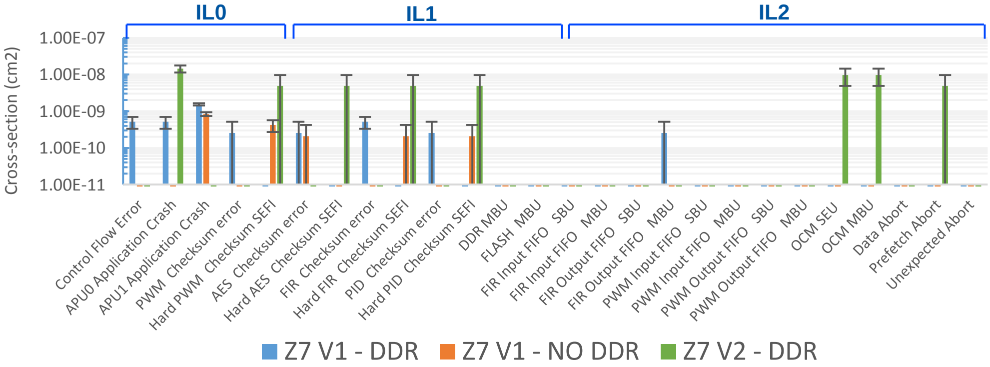
KVI-CART beam line



Z7 beam layout



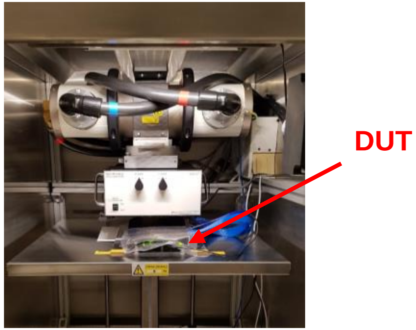
Z7 Proton results



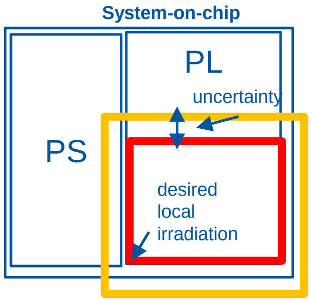
X-ray experiment

- **Facility parameters:**
  - **Facility:** PRESERVE facility at IES
  - **Spectrum:** <300KeV photons
  - **Dose rate:** 8.33 rad/s
- **Test methodology**
  - **Beam layout:**
    - Only one group of ROs was irradiated

Test setup picture



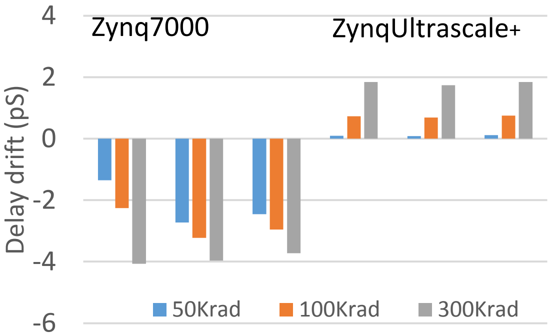
Beam layout schematic



- **Z7 vs ZU+ comparison summary**

	Z7	ZU+
Delay Drift	Negative	Positive
Spatial variability	High	Low
Maximum Recovery	<40%	>90%
Maximum Delay drift	~-4pS	~2pS
Dose resistance	>430krad	340krad

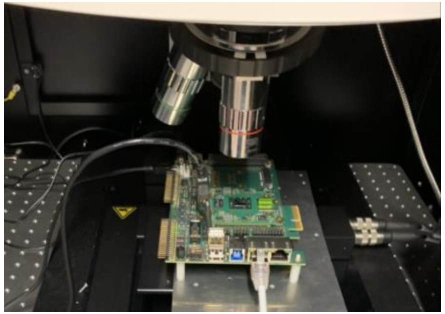
Z7 vs ZU+ worst case delay



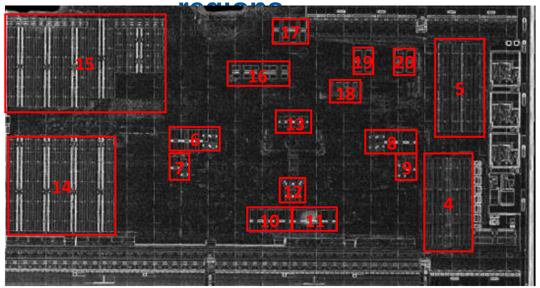
Laser experiments

- **Facility parameters:**
  - **Facility:** IES SPA laser facility
  - **Spectrum:** 189-310 pJ
  - **Equivalent LET:** 19-32 MeV/mg/cm2
  - **Flux:** 10-20 pulses per second
- **Test methodology**
  - **Samples:** Baredie Z7 and ZU+ SoCs
  - **Regions of Interest (ROI):**
    - SoC PL and PS resources
- **Result summary**
  - **Z7**
    - High error counts and cross-sections
    - Exceptions mainly generated by caches
    - Checksum Errors and SEFIs observed
    - BRAM errors not detected by FIFO ECC
  - **ZU+**
    - Only timeouts observed in the PL and PS

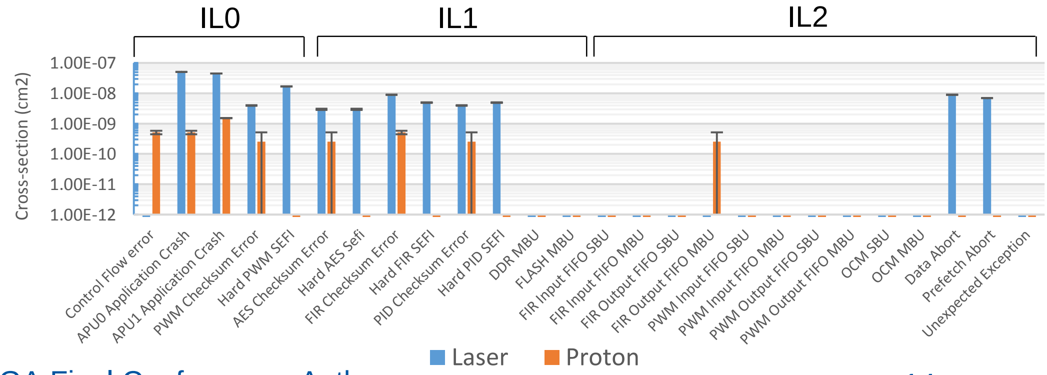
Test setup



Z7 PS scanned regions



Z7 Laser vs Proton results



System-level test guidelines

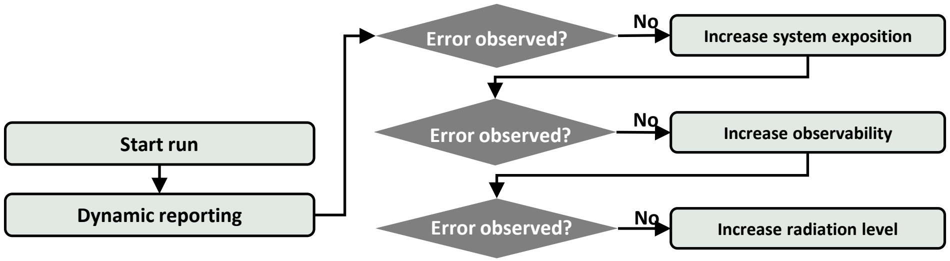
Experiment preparation

- The test plan should predict possible issues during the experiment
- Reliability on the experimental setup depends on adequate protocols
- Flexible benchmark for increasing system exposition (workload, memory usage…)
- To validate the instrumentation is essential

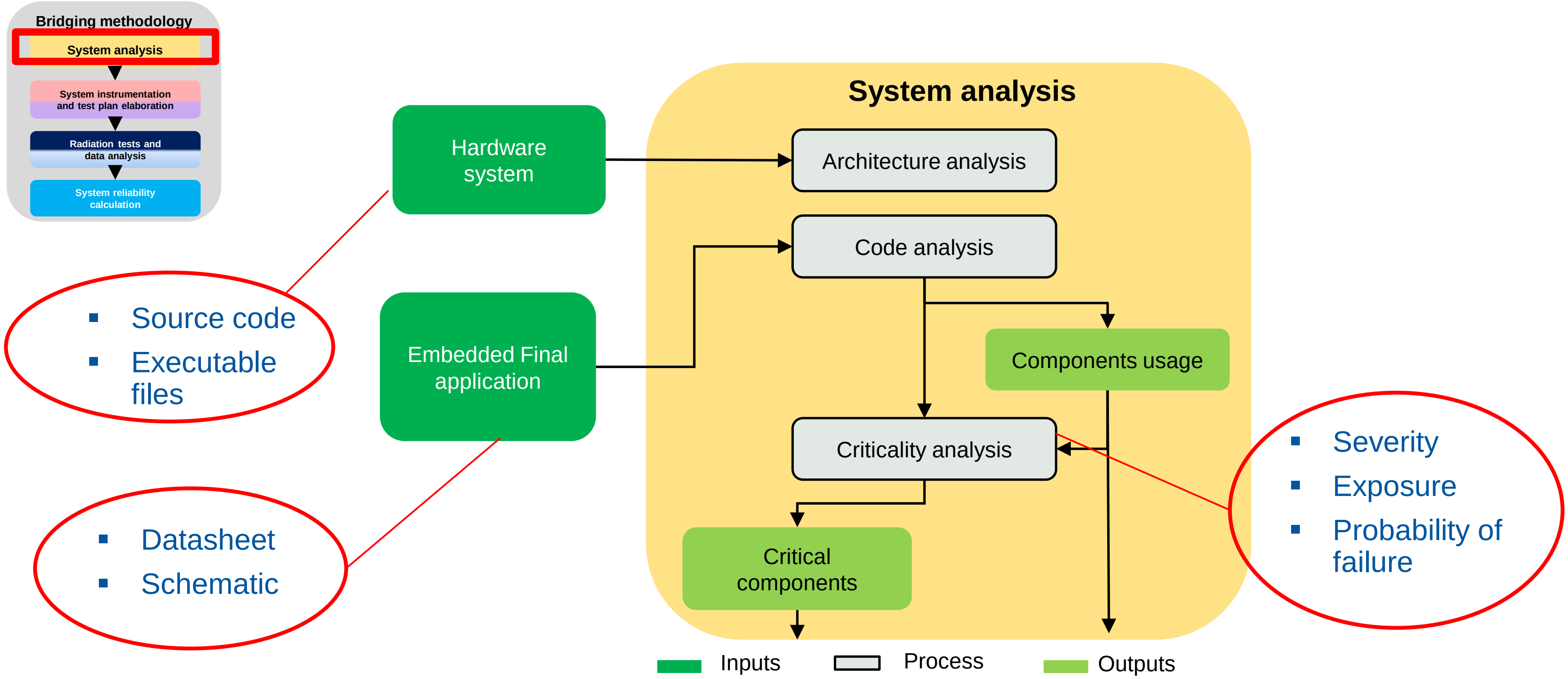
Experiment execution

- Dynamic reporting
- Increase system exposition
- Increase observability level
- Increase radiation level

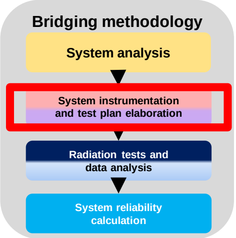
Experiment decision making Flowchart

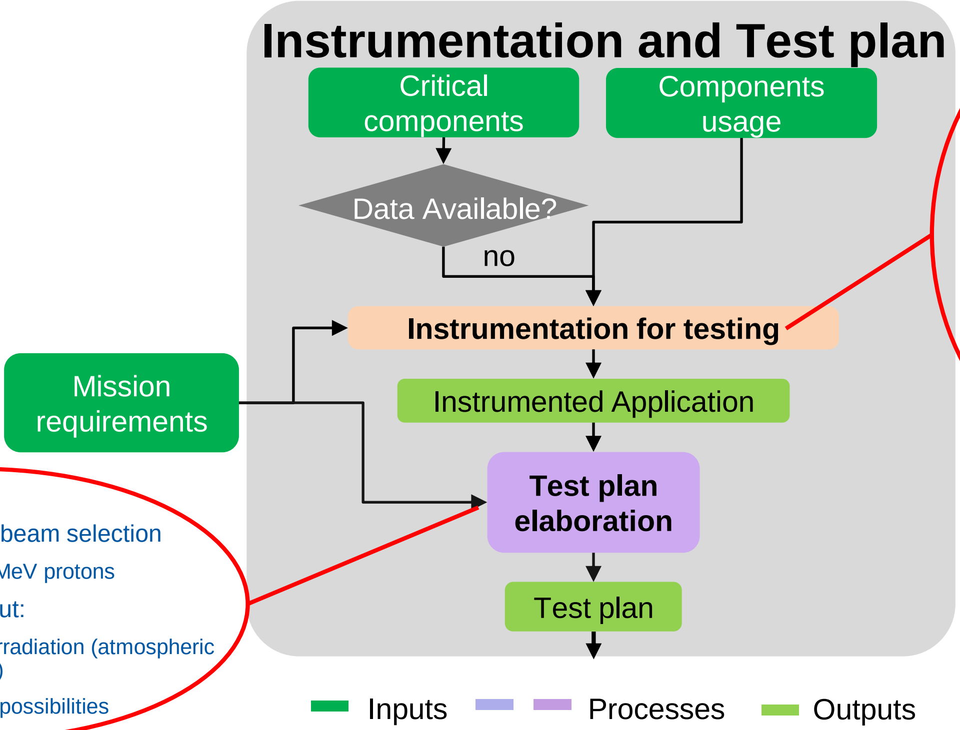


Bridging methodology: System analysis



Bridging methodology: System Instrumentation and Test plan

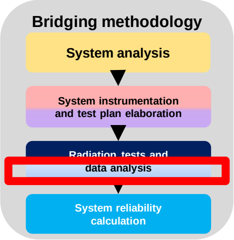


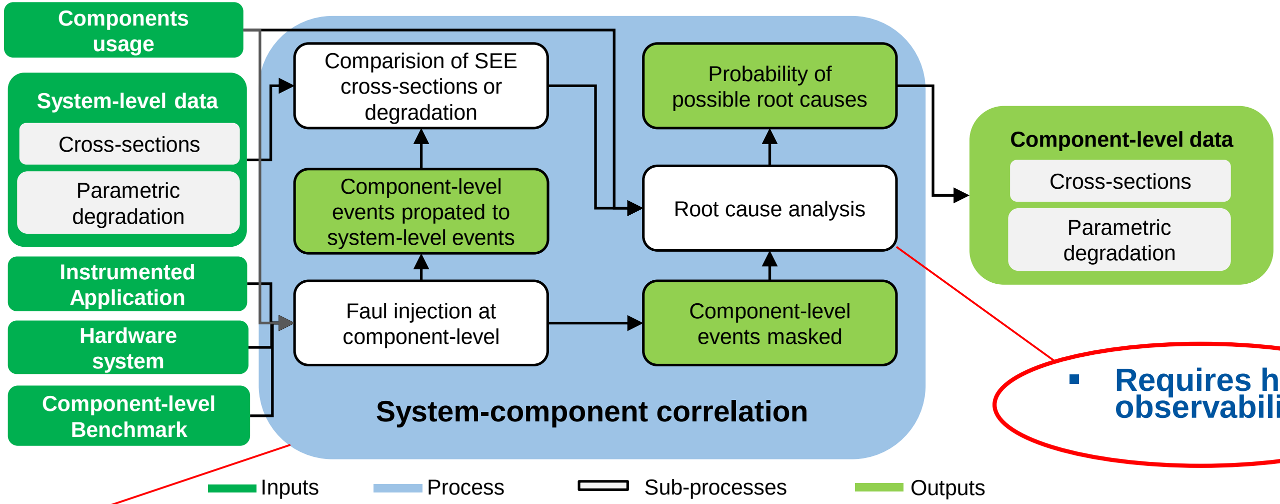


- **Software instrumentation**
  - Embedded checking mechanisms
  - Custom verification code
- **IP-core instrumentation**
  - Program Tracer decoder
  - Test structures
- **Minor Hardware modifications**
  - Shunt resistor

- High penetration beam selection
  - E.g. 200MeV protons
- Smart beam layout:
  - Parallel irradiation (atmospheric neutrons)
  - Masking possibilities

Bridging methodology: System-component correlation

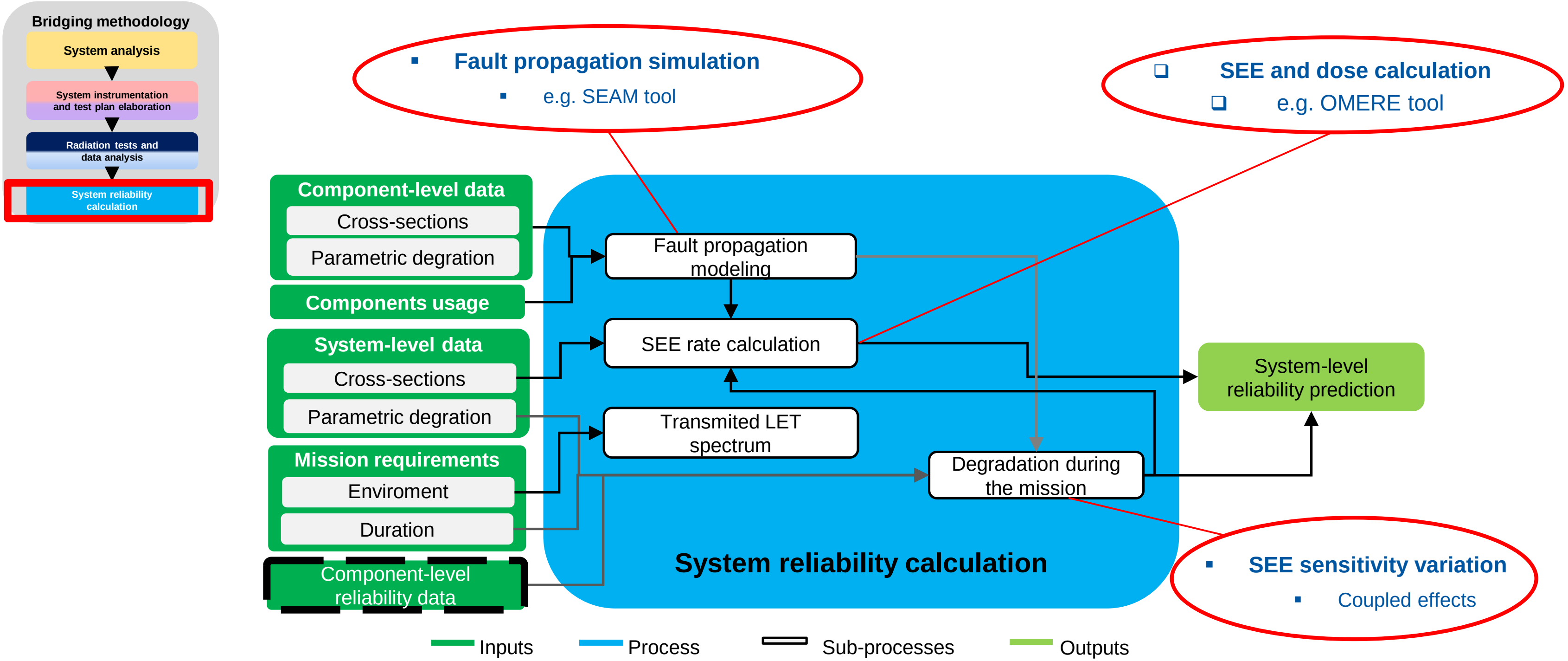




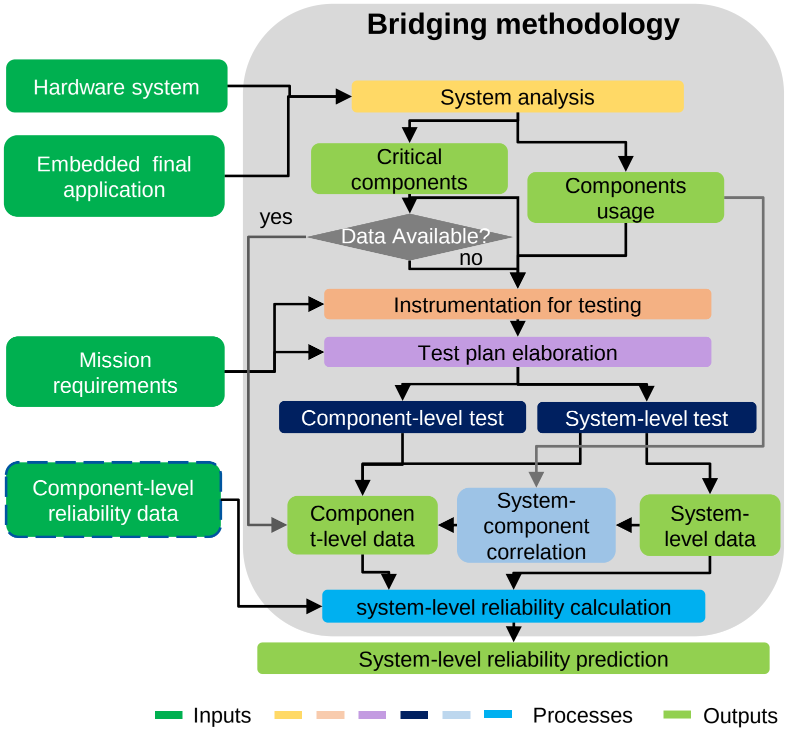
- **Requires high observability**

- ❑ Laser fault injection
- ❑ Software fault injection
- ❑ PL partial reconfiguration

Bridging methodology: System reliability calculation



Bridging methodology summary



- **Decisive steps:**
  - Adding instrumentation for increasing observability
  - Combining both component and system-level data for calculating system-level reliability
- **Methodology limitations**
  - Requirement of final application
  - Hardware documentation requiremnt
  - Critical vs non-critical erro classification
- **Case study limitations**
  - Lack of observability on analog parts
  - Limited number of events
- **Case study improvements**
  - Automated instrumentation addition
  - Cross-platform instrumentation library

Case study event rate estimation

- **Data used for the calculations:**
  - Component-level cross-section from literature multiplied by bits used
  - System-level cross-sections extracted from 184MeV protons experiments
- **Rate calculation at OMERE for LEO ISS mission**
  - Combination of component and system-level data
- **Optimistic estimation** could validate a short mission (0.25 years)
- **Conservative estimation** would not validate short mission
  - Based on safety margins

SEE rate prediction

Predictions	SoM	Event	SEE rate (events/day)
Optimistic	Z7	Soft failures	2.47E-04
		Hard failures	7.12E-06
		Resettable failures	6.63E-03
	ZU+	Soft failures	2.91E-04
		Hard failures	5.51E-03
		Resettable failures	1.14E-03
Conservative	Z7	Soft failures	4.94E-04
		Hard failures	2.85E-05
		Resettable failures	1.99E-02
	ZU+	Soft failures	5.82E-04
		Hard failures	1.65E-02
		Resettable failures	3.41E-03

Similar values

Big Difference Z7 SoM

Conclusions and prospective

- The possibility of a **Bridging RHA methodology** from component to system-level was investigated
- A digital System-on-module **case study** including additional instrumentation were developed
- **Neutron, 184MeV protons, X-ray and laser radiation experiments** were conducted for accumulating data
- The **lessons learned** and experience acquired during the **system-level experiments** was shared
- Available component-level tools, data and methods were used for **developing a bridging methodology**
- The challenging comprehension of **fault propagation in SoCs** could be explored thanks to the instrumentation and laser testing
- **Several paths were identified for improving the proposed methodology:**
  - Standardization, portability and automation of the instrumentation
- **The question of predicting system-level SEE rate is still a challenging task:**
  - A first-step was taken towards the objective
  - Extension of the proposed methodology
    - Different systems, technologies and instrumentations approaches
    - The inclusion of coupled-effects on the SEE rate prediction