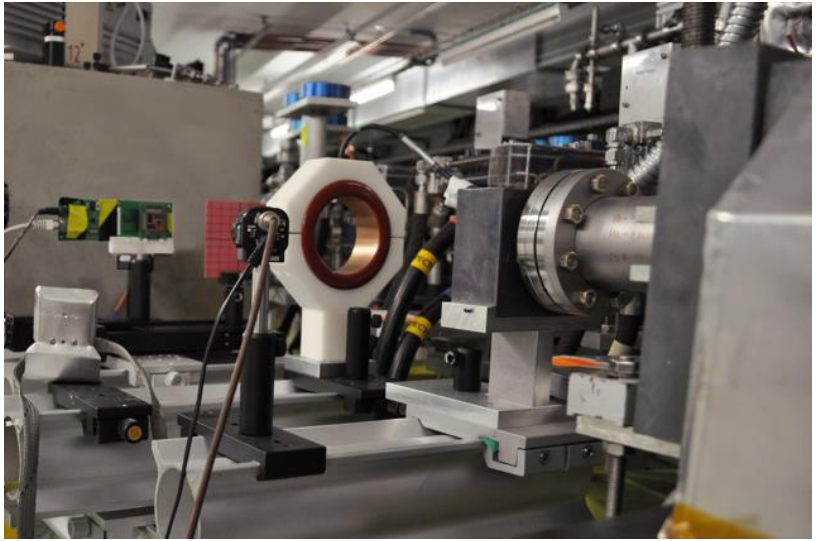
High-performance reliable electronics in radiation environments: an overview of the RADSAGA ITN



Rubén García Alía

STREAM 3rd Annual Meeting

25-01-2019

RADSAGA

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Outline

- RADSAGA Introduction and Structure
- Accelerator applications: R2E project at CERN
- COTS: what, why and how?
- SEE testing according to standards
- RADSAGA: SEE testing beyond standards
  - Ultra-high energy and penetration heavy ion beams
  - System level testing
- Outlook

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Innovative Training Networks (ITN)
Call: H2020-MSCA-ITN-2016

“RADSAGA”

“**RAD**iation and Reliability Challenges for Electronics used in **S**pace, **A**vionics, on the **G**round and at **A**ccelerators”

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie-Sklodowska-Curie grant agreement number 721624.

RADSAGA challenges

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Societal impact

Online article published in Feb 2017 by Vanderbilt University

- *"A router farm like those used by Internet providers with only 25 gigabytes of memory may experience one potential **networking error** that interrupts their operation **every 17 hours**."*
- *"A person flying in an airplane at 35,000 feet (where radiation levels are considerably higher than they are at sea level) who is working on a **laptop** with 500 kilobytes of memory may experience **one potential error every five hours**."*
- *"The **semiconductor manufacturers** are very **concerned about the SEE problem** because it is getting more serious as the size of the transistors in computer chips shrink and the power and capacity of our digital systems increase"*
- *"The **16-nanometer study** was funded by a group of top **microelectronics companies**, including Altera, ARM, AMD, Broadcom, Cisco Systems, Marvell, MediaTek, Renesas, Qualcomm, Synopsys, and TSMC"*
- *The good news, Bhuva said, is that the **aviation, medical equipment, IT, transportation, communications, financial and power industries** are all **aware of the problem** and are **taking steps to address it**. "It is only the consumer electronics sector that has been lagging behind in addressing this problem."*

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What can we do about radiation on electronics?

- Non-qualified COTS systems
- No radiation level criterion

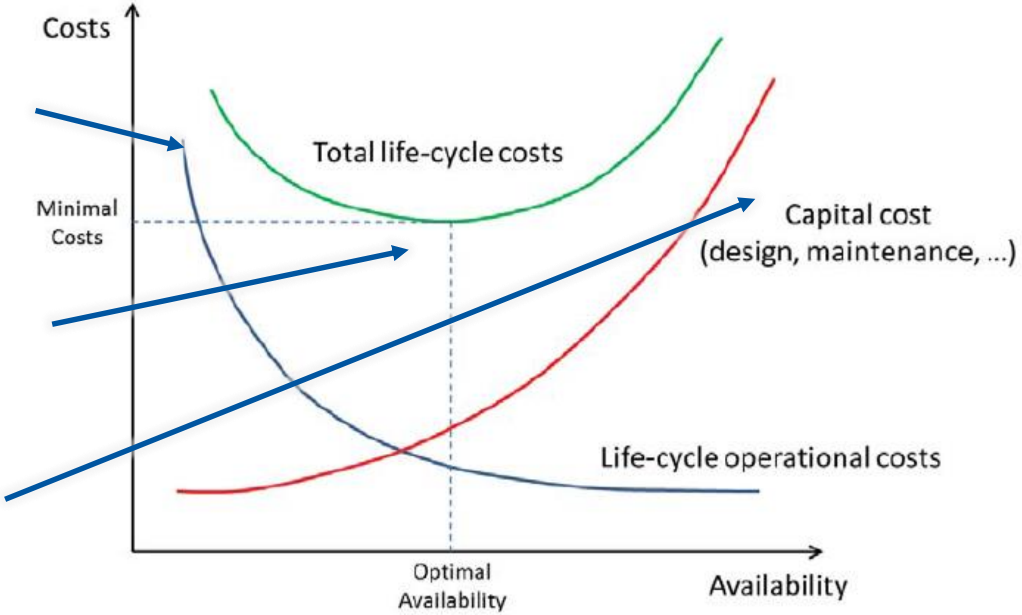
(standard ground-level applications)

- COTS components for rad-tolerant system designs
- Rad-hard by design for critical components
- Qualification at system level, radiation environment analysis

(RADSAGA objective)

- Rad hard-components
- Heavy ion SEE qualification at component level

(critical space applications)



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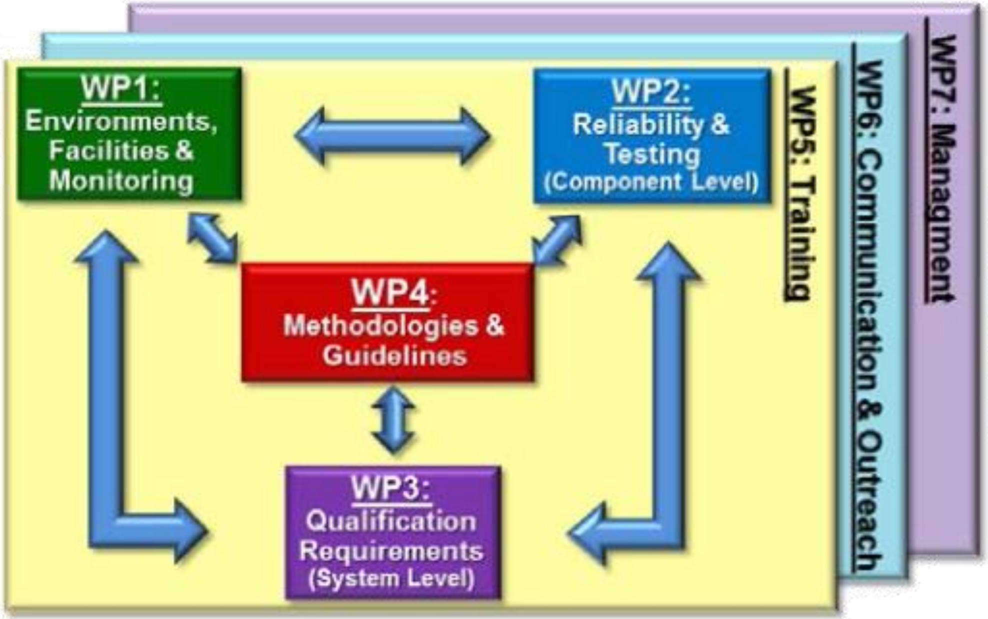
RADSAGA structure



RADSAGA ESRs

RADSAGA 2018 Summer School in Jyvaskyla

ESR profile pages available on RADSAGA website ***(cern.ch/radsaga)***

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RADSAGA beneficiaries

- **Beneficiaries** are organisations that are **full partners** of a network and are signatories to the Grant and Collaboration Agreements.
- They contribute directly to the implementation of the research training programme by **appointing, supervising, hosting and training researchers**.
- Beneficiaries take complete responsibility for executing the proposed programme and other requirements of the project.

CERN	*Coordinator, WP4 & WP7 leader, 2 ESRs*
3D plus (a HEICO company)	*1 ESR*
JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ	*WP1 leader, 2 ESRs*
KU LEUVEN	*WP5 & WP6 leader, 4 ESRs*
UNIVERSITÉ DE MONTPELLIER	*WP2 leader, 4 ESRs*
b-tu Brandenburgische Technische Universität Cottbus	*WP3 leader, 1 ESR*
rijksuniversiteit groningen	*1 ESR*

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RADSAGA partners

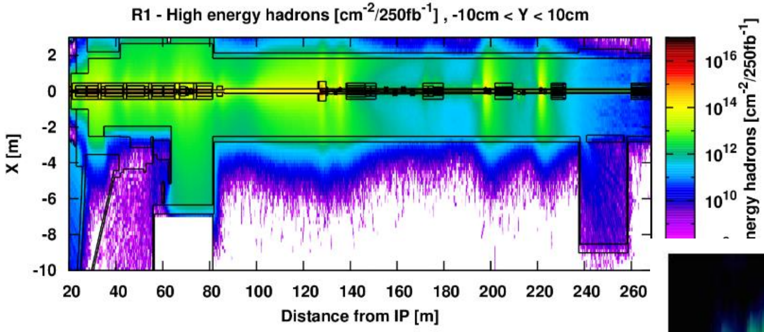
- **Partner Organisations** are not signatories to the Grant Agreement and do not employ the researchers within the project. Partner organisations provide additional **training** and/or host researchers during **secondments**.

Facilities & Research Institutes

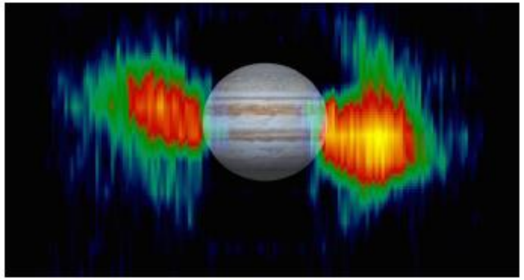
Universities

Industry

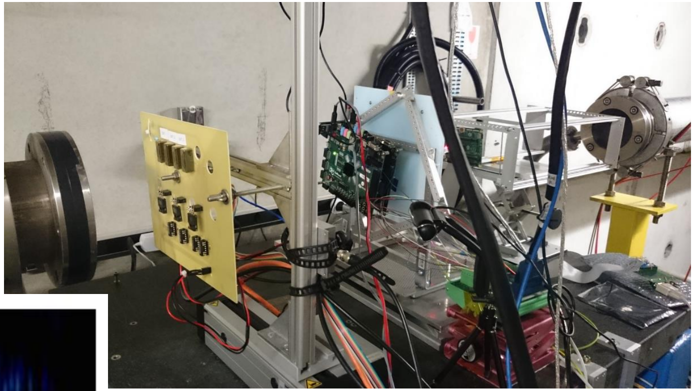
WP1: Environments, facilities & monitoring



Future HL-LHC (LHC upgrade, CERN FLUKA team)



Jovian environment and impact of trapped electrons (E. Roussos, RADECS 2016 short-course)



Electronics radiation test in the SPS North Area at CERN

WP1: Environments, facilities & monitoring

- to evaluate and adapt European radiation test facilities to the **emerging qualification needs**, including e.g. ground-level applications and new-space satellite constellations
- to **harmonize** the beam monitoring and **dosimetry methodologies** in European test facilities to increase their effectivity and flexibility
- to assist the European component industry rendering it more competitive with respect to other electronic companies worldwide by **benchmarking** European test facilities

"The committee has found that the [US] radiation-testing infrastructure system is **fragile**; it is already experiencing **long wait times and rising testing prices**, and it could easily suffer **major strains** if even a single major facility closes down suddenly"

State of U.S. Electronic Parts Space Radiation Testing Infrastructure report, 2017

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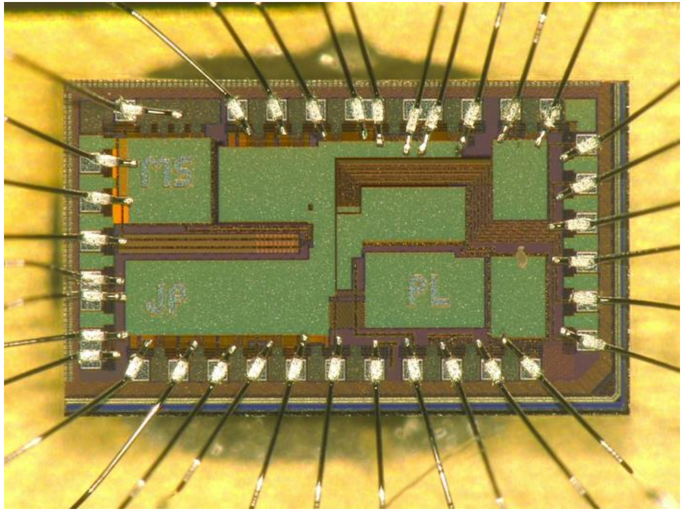
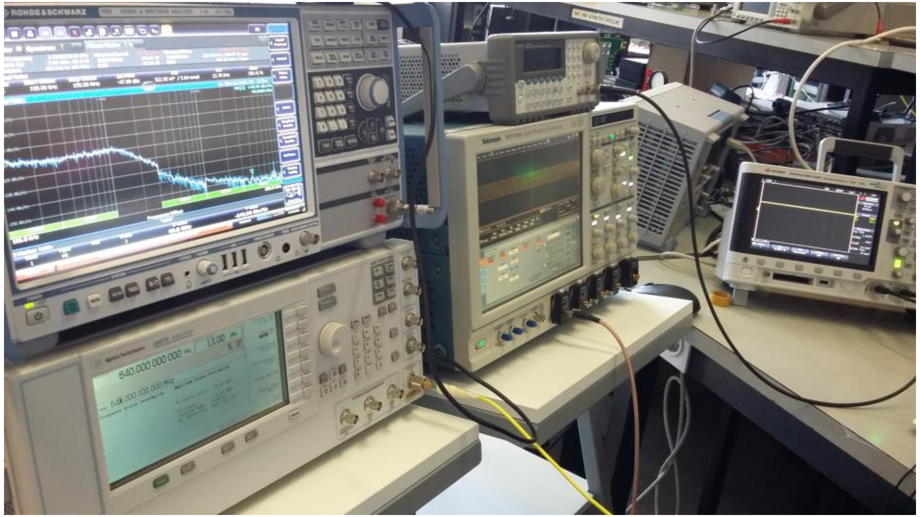
WP2: Reliability and testing at component level





Electronic chip and equipment at KU Leuven

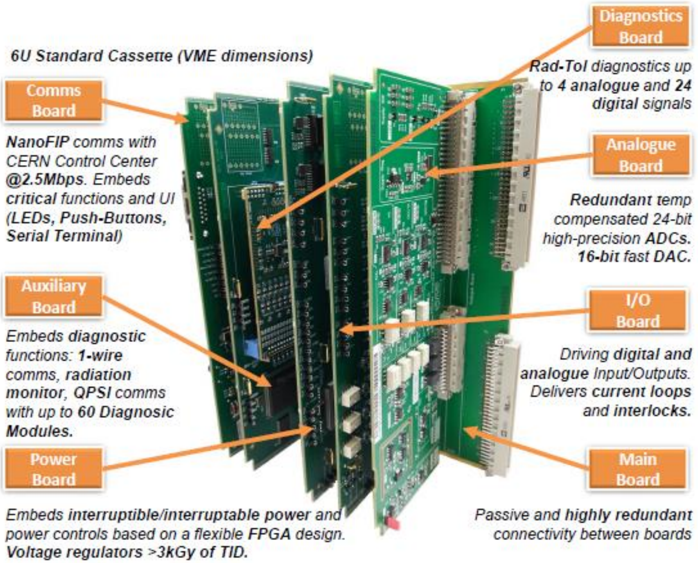
WP2: Reliability and testing at component level

- to address the study of radiation effects on **complex emerging technologies** for space, avionics, ground and accelerators
- to develop **simulation tools** to predict the sensitivity to radiation at a device level and optimize the component selection and design
- to provide results to be used at **system level** in WP3

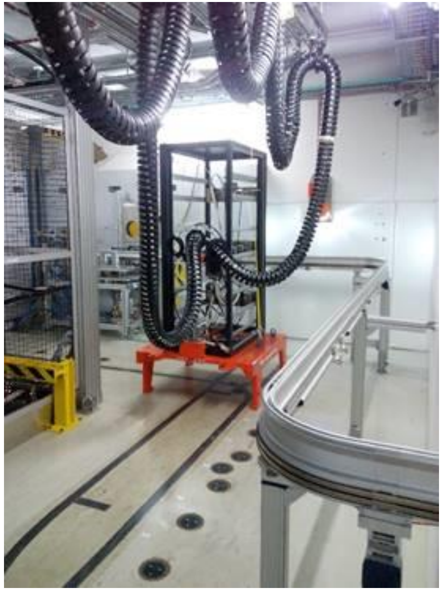
"The space sector as a whole is **evolving rapidly.** In the coming decade, the number of spacecraft as well as the number of operators in space is expected to **increase by one or two orders of magnitude.** Commercial operators, especially those proposing smaller, less expensive satellites, are **more inclined to use COTS parts** and simultaneously **less inclined to conduct high-cost radiation tests**."

State of U.S. Electronic Parts Space Radiation Testing Infrastructure report, 2017

WP3: Qualification requirements at system level



Example of full system test, Slawosz Uznanski, FGClite project, CERN



System test at CHARM facility, CERN

WP3: Qualification requirements at system level

- to develop and propose relevant test approaches to characterize the radiation sensitivity at electronic component and **equipment/system level**
- to evaluate the possible **strategic advantage** (cost, system development time) of system level testing for complex systems with a large number of components when compared to traditional component level testing based on existing standards

"Another step to reduce the cost of tests is to perform **testing at the board level**. This is a common approach for CubeSats. In this way, **a full function/subsystem can be tested at once** (communication, power management, etc.). The drawback of board testing is that **observability is reduced**. If the test fails, it may be difficult to **identify the part that caused the failure** and the **impact on planning** to find a solution may be significant."

Christian Poivey (ESA), NSREC 2017 short-course

WP4: Methodologies & Guidelines

- to derive from the RADSAGA project results **methodologies & guidelines** of combined electronic component and system level qualification
- to optimize and harmonize such approach with a focus on COTS based systems for commercial applications

"The rapid development of semiconductor devices means that **the body of knowledge for the field advances more rapidly than it can be accommodated in test standards**. As a result, the standards are a mix of specific data and general guidelines, and significant experience and skill are required to adapt these resources to the requirements for testing a new part or technology.."

State of U.S. Electronic Parts Space Radiation Testing Infrastructure report, 2017

WP4: overview of activity

- Analysis of existing **radiation test standards** and identification of shortcomings when dealing with emerging effects and applications
- Coordination of a variety of **test campaigns** with a focus on the global objectives and implications on the **guideline development**
- Preparation of **complete space system** (On-Board Computer + payload) test setup for CHARM irradiation

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WP5: Training

Initial Training Event (Oct 2017)
During RADECS 2017 conference, providing a perfect occasion for ESRs to interact and network with experts in radiation effects community
Technical focus: introduction to radiation effects to electronics

Saint Etienne Summer School (Sep 2018)
Including laboratory and facilities hands-on work
Technical focus: optical fibers, optoelectronics

Initial Workshop (Mar 2018)
Including round-table expert open discussion and test facility visit
Technical focus: guidelines and standards for radiation effects testing

Jyvaskyla Summer School (Aug 2018)
Including laboratory and test facility visits
Technical focus: basic mechanisms and evolution with technology scaling

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WP6: Outreach and Dissemination

- RADSAGA has been very active in **Outreach & Dissemination activities** (Researcher's Night in Jyvaskyla, 150th birth anniversary of Marie-Sklodowska-Curie, "Universcience" outreach event for high-school students, RADSAGA exhibitor booth at RADECS 2018 international conference…)
- Regularly updated **website**, including information about RADSAGA related events and news (5.3k visits over last year)
- **Social media**: LinkedIn, Facebook and Twitter
- Very strong involvement and commitment from the ESRs!

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WP7: Network events

- **Kick-off meeting** (April 2017, Geneva/CERN)
- **Initial training event** (October 2017, Geneva)
- **Initial workshop** (March 2018, Geneva/CERN)
- **Jyvaskyla Summer School** (August 2018)
- **Saint Etienne Summer School & Mid-Term Review** (September 2018)

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WP7: RADSAGA associate status

- The Project has been met with **great interest from the research community at large**, with numerous enquiries as to the possibility of participating in the Project without formally acceding to the Grant and Consortium Agreements.
- The RADSAGA Supervisory Board resolved, at its meeting of 6 October 2017, to respond to this demand by **creating the status of a RADSAGA Associate**.
- A RADSAGA Associate may be involved in the Project in one or several ways:
  - possible requirements, specifications, development reviews, comments on the validity/use of the results etc., contributing in such a way to provide a **more practical and market-oriented focus to the project**
  - granting **access to technologies** (components, systems) as potential study cases for qualification
  - granting **access to test facilities** with the purpose of cross-calibrating its dosimetry through detectors and/or reference monitors and/or for testing emerging effects

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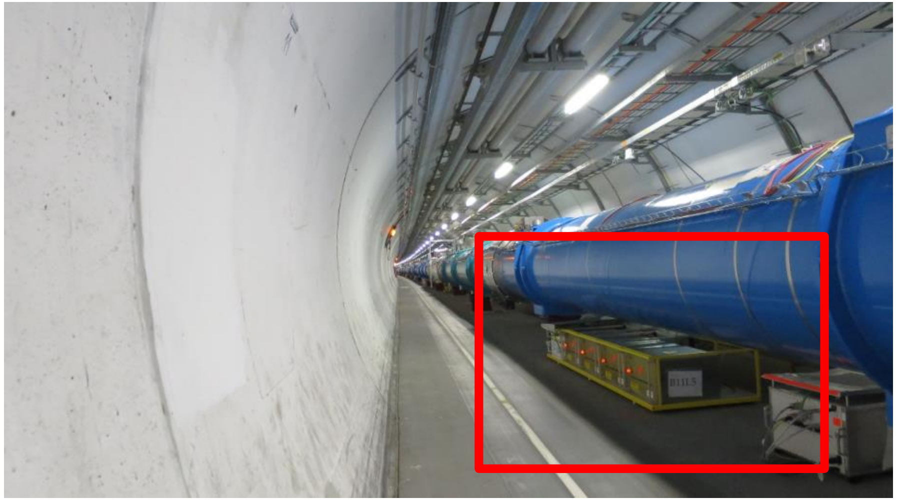
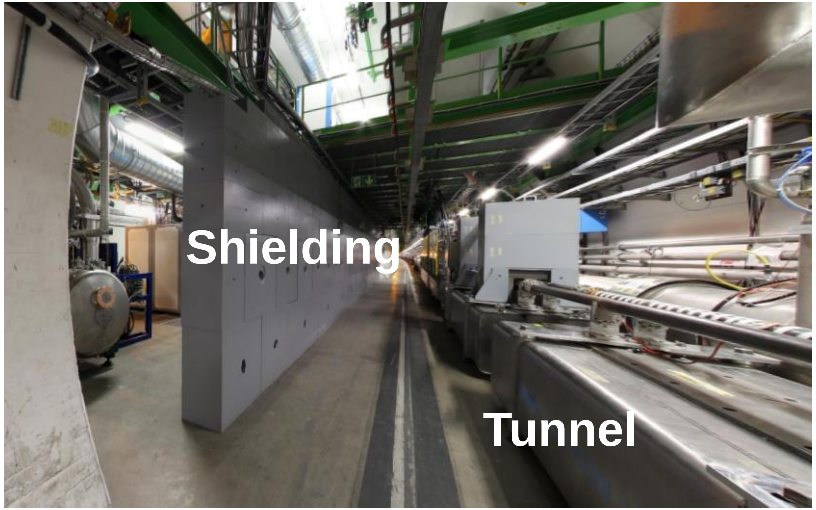
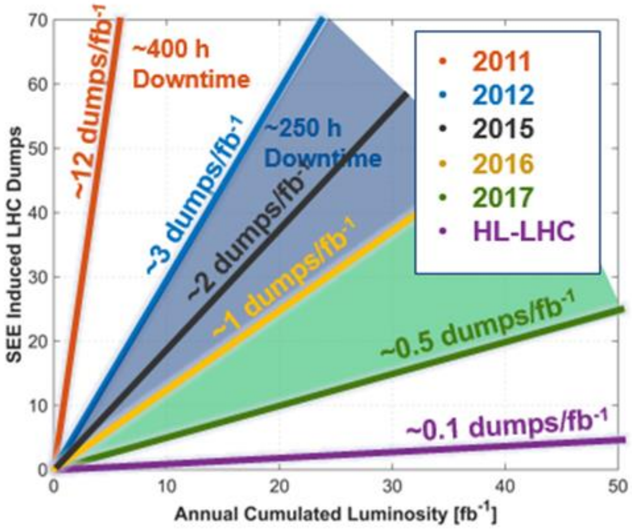
R2E Project at CERN

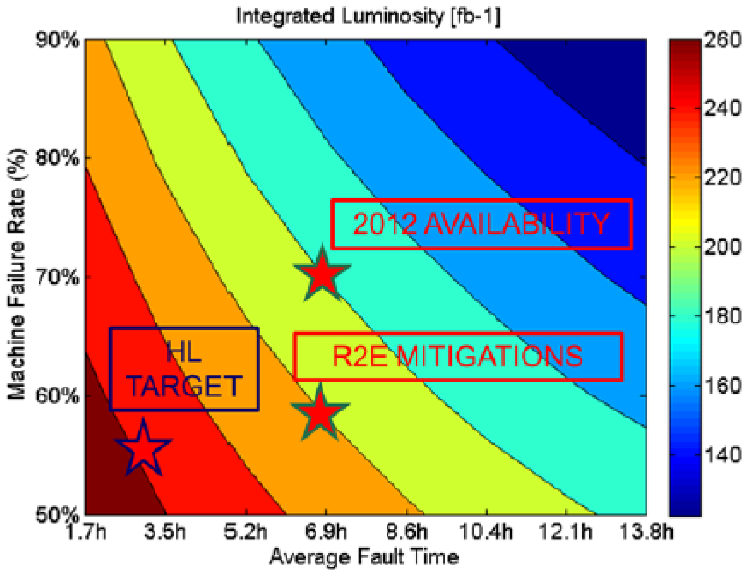




- Many COTS-based systems are constrained to **operate near the machine**, mainly due to cabling distance (e.g. ultra-fast monitoring and protection, high-current powering…)

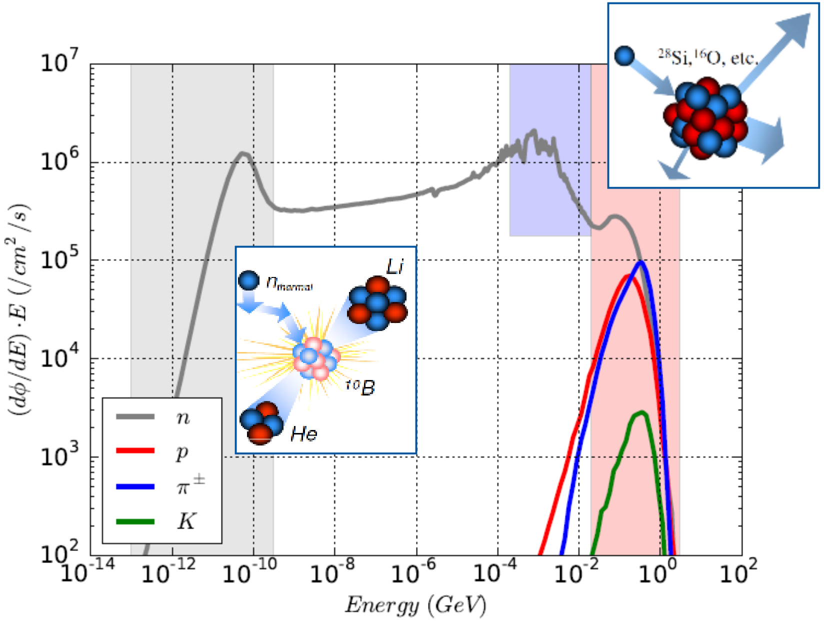
Impact on operation and performance

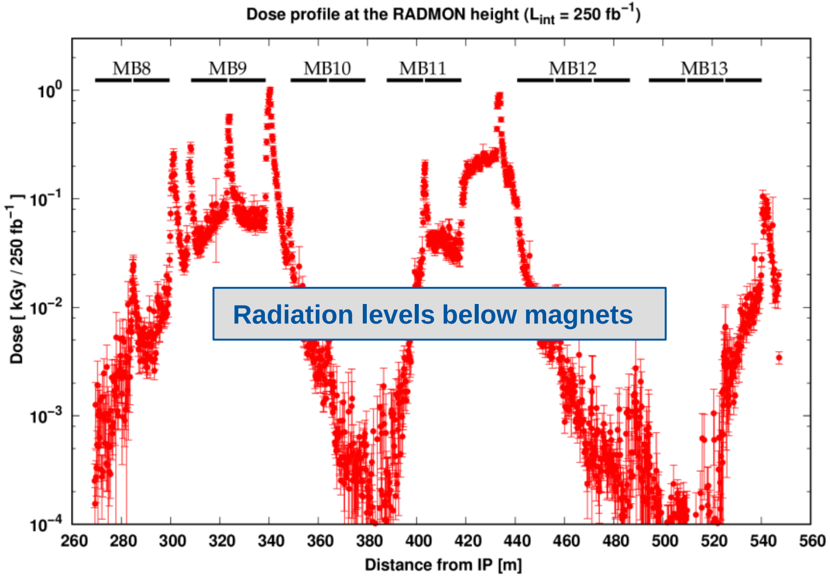




- A high machine availability is essential in order to meet the physics target of the machine
- This will be even more so the case in the HL-LHC era

Radiation environment and levels





- Highly dynamic, strong gradients, broad variety of energies and particles

Summary of LHC radiation levels

Values for HL-LHC conditions
[NB: actual values strongly depend on exact position and operational conditions]

HL-LHC area	HEH fluence (cm^{-2}/year)	Lifetime TID	Lifetime 1MeV n_{eq} (cm^{-2})
Shielded alcoves	10^9	10 Gy	10^{11}
ARC	10^9	10 Gy	10^{11}
DS	10^{11}	1 kGy	10^{13}
LSS	10^{13}	100 kGy	10^{15}

Areas hosting large quantity of systems, mainly impacted by SEEs
Both SEE and cumulative lifetime threat for COTS components
Use of COTS excluded; possible material damage

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A definition of COTS

- The European Cooperation for Space Standardization (ECSS-S-ST-00-01C) provides a definition of COTS.

"Commercial electronic component readily available and not manufactured, inspected or tested in accordance with military or space standards."

- The terms commercial component has been further defined in ECSS-Q-ST-60C Rev. 2.

"part neither designed, nor manufactured with reference to military or space standards" , here the important difference is in the word design.

Parts bought "as is", no liability from manufacturer beyond datasheet, lack of traceability, no alerts with respect to process/foundry change, no lot-to-lot variability control…

Philippe Armbruster (ESA), "EEE COTS Components – Overview"

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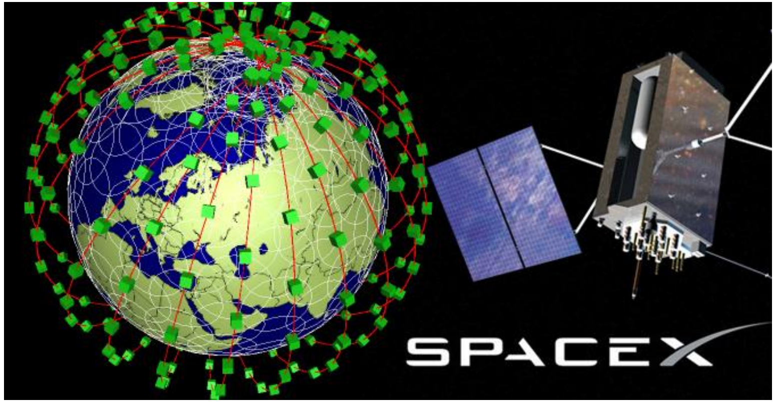
Space 4.0 era

- Time to market/mission shorter, reduced launch price (i.e. higher accessibility)
- Commercial focus, not directly linked to government agencies
- Broad range of LEO/MEO constellations (OneWeb, Starlink…)
- Context that clearly favors **use of COTS in space** – but how can we select and qualify them?



COTS testing for Orion Project

- Future NASA's spacecraft to send astronauts into space
- European contribution: European Service Module (ESM), developed by ESA with Airbus as prime contractor
- Providing power generation, thermal control, gas and water, and propulsion to the crew module
- **COTS test example**: PHY transceiver for Time Triggered Ethernet (TTECH) technology
  - **Budget** ratio between rad-hard development and COTS characterization is typically ~10 (but will depend strongly on individual cases!)
  - However, in this case budget is not the main driver for COTS consideration, but rather **performance and availability** (i.e. ITAR-free)

Cristina Plettner (Airbus), Sept 2017 - RADSAGA Initial Training

Ethernet PHY transceiver selection & qualification

- Analysis of **market-available products** based on functional, electrical, mechanical and single lot considerations
- Identification of three suitable parts
- Development of dedicated test board interfacing with Device Under Test
- Environmental tests: vacuum, thermal, ESD, **radiation**
  - **TID, Heavy Ions, Protons**
    - 50 krad target (sufficient for LEO)
    - Destructive SEEs need to be excluded
    - Nature and probability/frequency of soft SEEs needs to be determined

Cristina Plettner (Airbus), Sept 2017 - RADSAGA Initial Training

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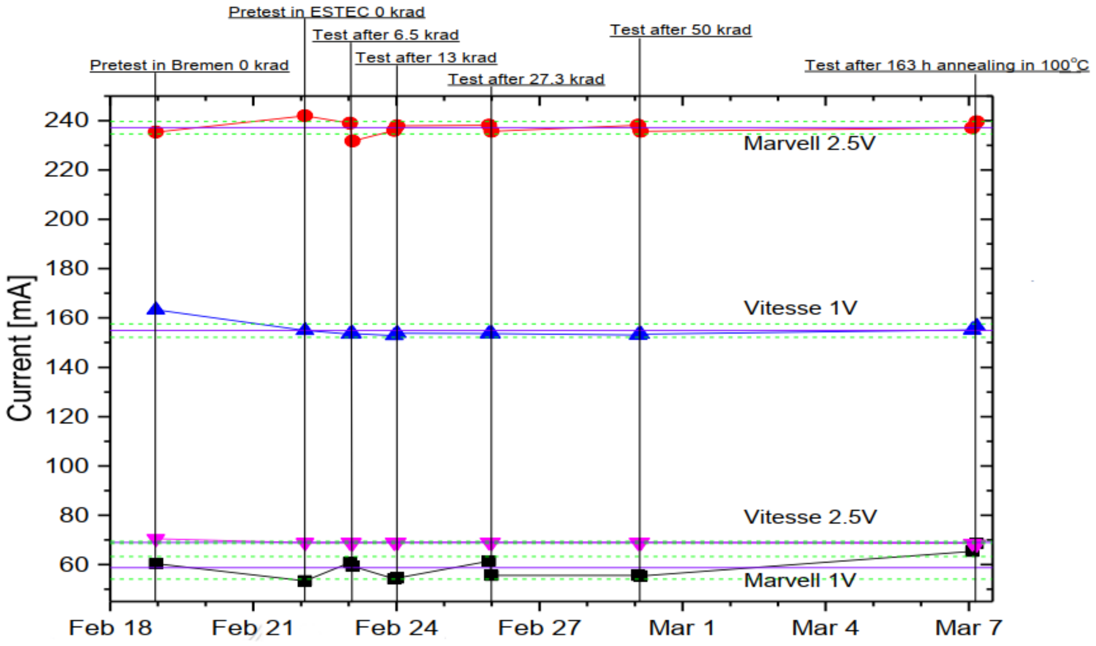
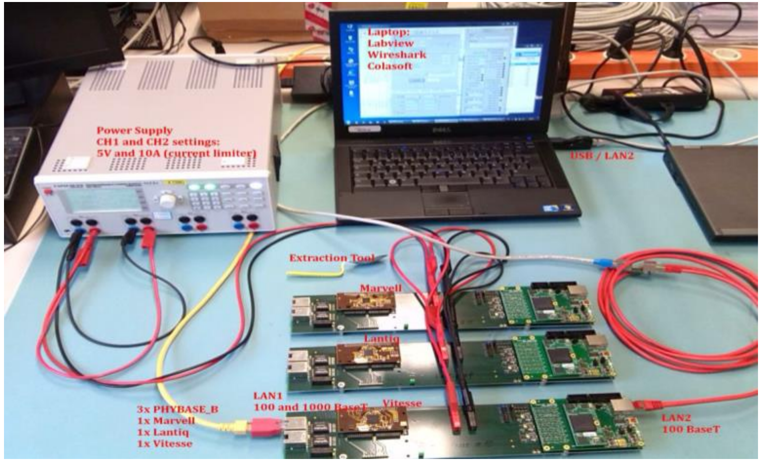
TID: Cobalt-60 source, worst case conditions, 50 krad



Cristina Plettner (Airbus), Sept 2017 - RADSAGA Initial Training

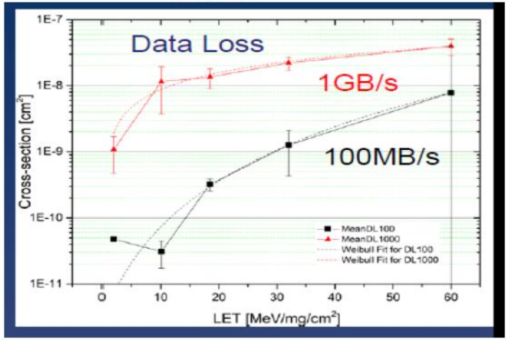
SEE testing

- Main results:
  - Marvell and Vitesse passed SEL test up to 60 MeVcm^2/mg, 125^{o}C (worst-case temperature)
  - Soft Error Effects (functional interrupt): acceptable in-flight error rate* + possibility to implement system level mitigation



For ISS and lunar environments, as well as solar storm conditions

Marvell



Parts accepted for flight

Cristina Plettner (Airbus), Sept 2017 - RADSAGA Initial Training

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Test methods and standards

ECSS:	European Cooperation for Space Standardization
ESCC:	European Space Component Coordination
MIL-STD:	US Military Standard
EIA-JESD:	Electronic industries Alliance / JEDEC Standard
JEDEC:	Joint Electron Device Engineering Council

MIL-STD-750 Method 1080 (Power MOSFETs),
ESCC 25100 (all other parts)
EIA/JESD 57.

SEE Test Methods

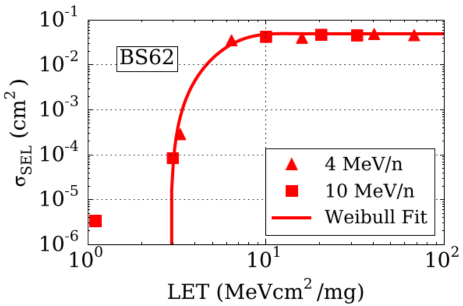
Francoise Bezerra (CNES), March 2018 RADSAGA Workshop

Traditional heavy ion testing

- “Traditional” heavy ion testing is performed with low-energy (~10 MeV/n) ions at **cyclotron facilities**, which have as main advantages:
  - their **availability** for other applications (e.g. medical, nuclear physics)
  - their capability of producing a very **large LET range**, especially by varying the ion species (in a so-called “cocktail”)
- The main shortcomings are linked to their **short range/penetration** (need of testing in vacuum, with opened parts, and not always being able to reach sensitive volume, or cover it with constant LET)
- Facilities providing ~30-100 MeV/n (TAMU, GANIL, KVI…) already partially overcome the challenges above, but part opening/thinning is still typically needed

Figure 1: Vacuum chamber at UCL.

M/Q	Ion	DUT energy [MeV]	Range [µm Si]	LET [MeV/mg/cm²]
3.25	$^{13}C^{4+}$	131	269.3	1.3
3.14	$^{22}Ne^{7+}$	238	202.0	3.3
3.37	$^{27}Al^{8+}$	250	131.2	5.7
3.33	$^{40}Ar^{12+}$	379	120.5	10.0
3.31	$^{53}Cr^{16+}$	513	107.6	16.0
3.218	$^{58}Ni^{18+}$	582	100.5	20.4
3.35	$^{84}Kr^{25+}$	769	94.2	32.4
3.54	$^{124}Xe^{35+}$	995	73.1	62.5



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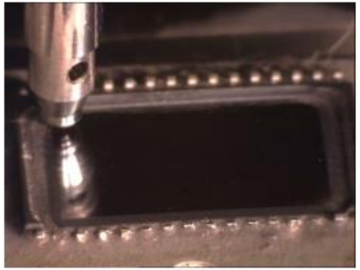
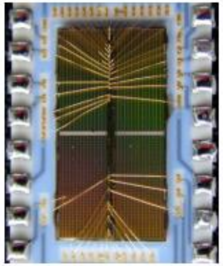
Traditional heavy ion testing

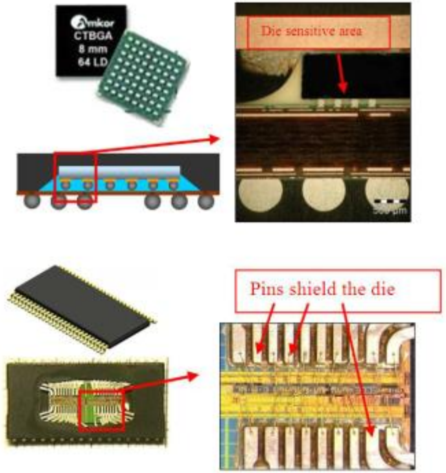
Sample preparation (SEE in Vacuum)

- Some packages cannot be opened while keeping the DUT functional
  - Flip chip assembled packages
  - Lead frame on top of the die

=> Backside irradiation after thinning or re-bonding







After F. Courtade & al., RADECS 2005.

Francoise Bezerra (CNES), March 2018 RADSAGA Workshop

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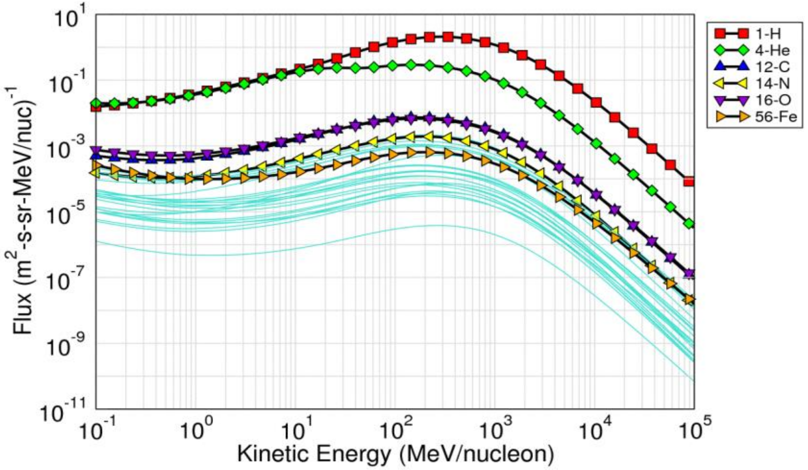
Possible applications of VHE/UHE ion beams

- **Scientific/research:**
  - Qualifying components at energies for which Galactic Comic Rays still have a significant flux
  - Possible RHA implications with respect to qualification at standard energies
- **Practical: highly penetrating beams**
  - Possibility of testing multiple components/boards, in parallel
  - No need of opening component packages (especially relevant for e.g. flip-chip, 3D structures)
  - Accelerator applications: heavy ion testing can be used to exclude SEEs in mixed-field environment



Standard Energy (SE)	< 10 MeV/n
High Energy (HE)	10-100 MeV/n
Very-High Energy (VHE)	100 MeV/n-5 GeV/n
Ultra-High Energy (UHE)	5-150 GeV/n

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SEE testing with UHE ion beams: accelerator applications

Radiation beam/field	Example facility	SEE-free qualification fluence (cm^{-2})	Required Beam Time	Associated TID levels	Test Type
High-energy protons	PSI	10^{14}	~140h	~100 kGy	Component/board level
Accelerator mixed-field environment	CHARM*	10^{14}	~20 weeks	~20 kGy	System level
Standard energy ions	RADEF, UCL	10^{7}	~tens of minutes	~tens of Gy	Component level, in vacuum, de-lidded
UHE ions	CERN accelerator complex, GSI/FAIR	10^{7}	~tens of minutes	~tens of Gy	Component/board level

**considering 5 system units tested in parallel*

High-energy ion beams can potentially provide "best of both worlds": high penetration and irradiation surface/volumes (protons, mixed-field) + high LET/low fluence (ions)

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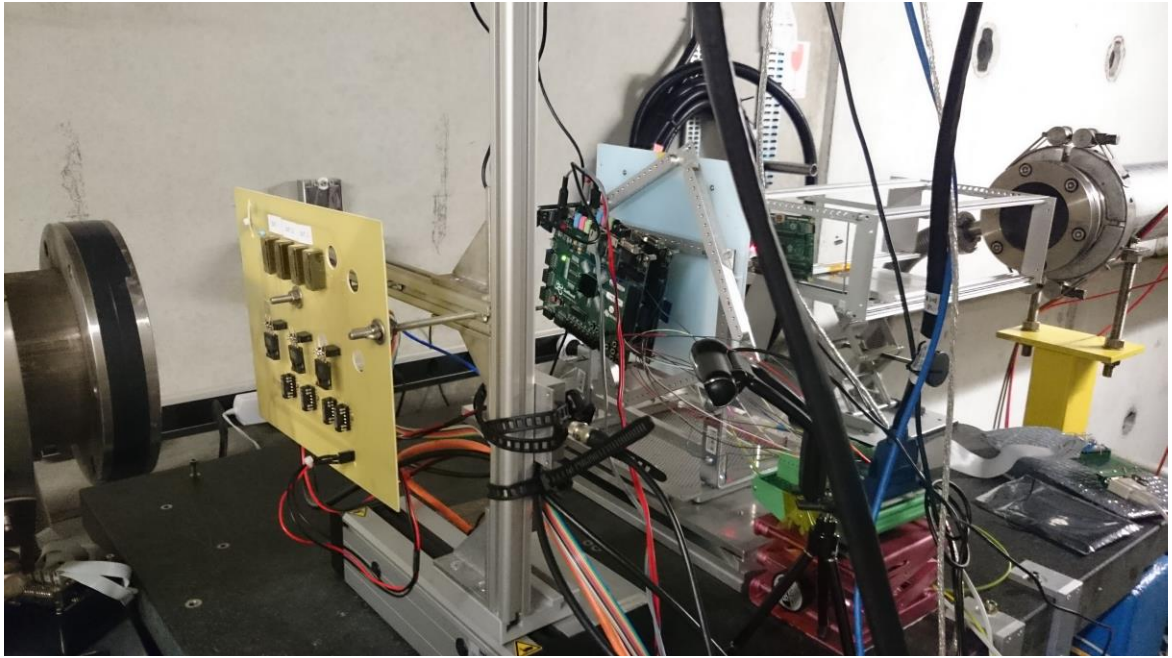
SEE testing with UHE ion beams



- Possibility of testing multiple boards **in air, with packaged parts**
- If LET is large enough* components/boards can be qualified as SEE-free in accelerator environment with relatively low fluences**

**typically >15 MeVcm^2/mg*
*** ~10^7 ions/cm^2, thus requiring short beam time and inducing negligible cumulative effects*

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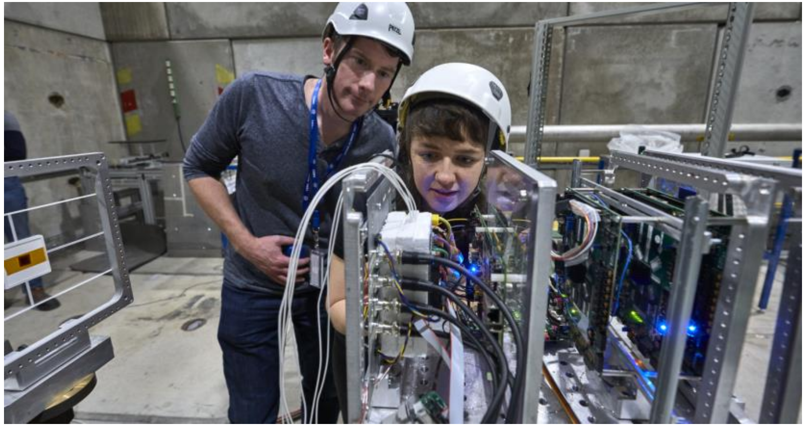
STREAM

ESA artificial intelligence chip test at CERN



- Strong RADSAGA involvement in preparation, test campaign and analysis
- Highly complex chip, not testable with traditional heavy ion beam

RADSAGA

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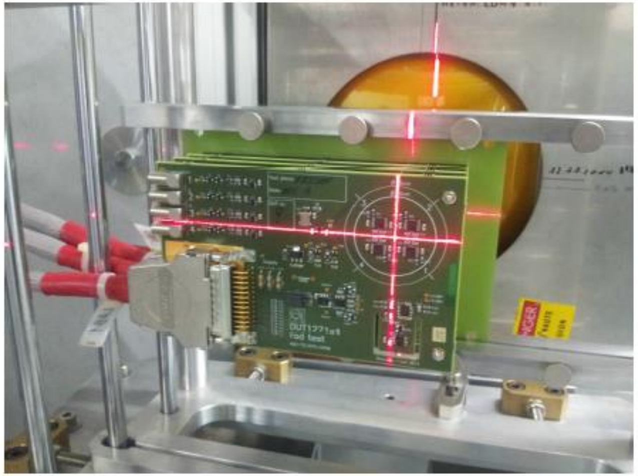
Outline

- RADSAGA Introduction and Structure
- Accelerator applications: R2E project at CERN
- COTS: what, why and how?
- SEE testing according to standards
- **RADSAGA: SEE testing beyond standards**
  - Ultra-high energy and penetration heavy ion beams
  - **System level testing**
- Outlook

CHARM test facility at CERN



Traditional radiation testing: beam (~5cm) collimated on components under test

CHARM mixed-field facility: GeV proton beam on copper target; tailored to test multiple boards or full systems

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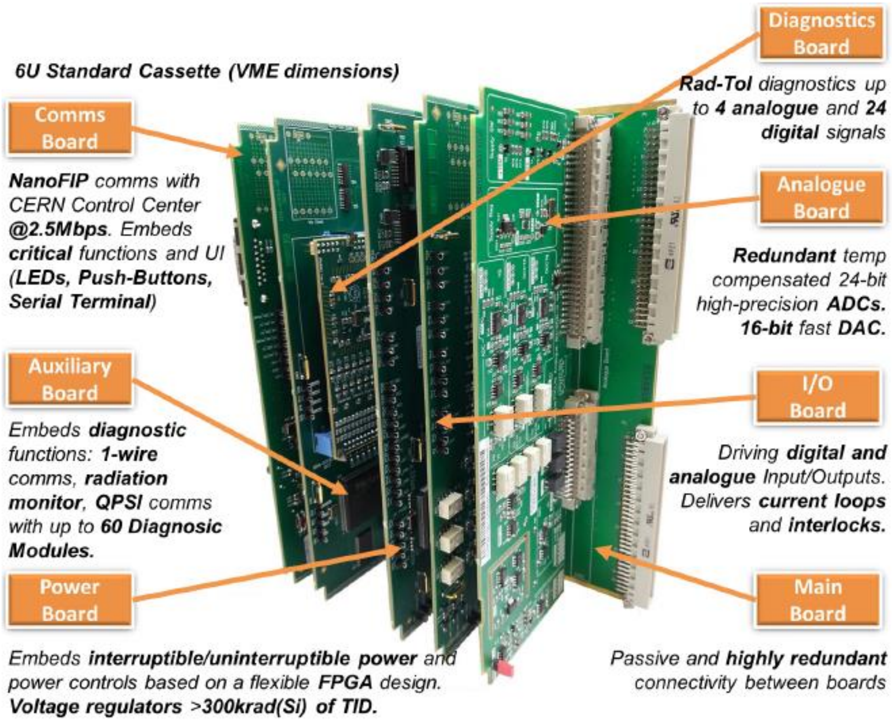
System level testing

- Efficiently combining **top-down** (from system to sub-system/component) and **bottom-up** (discrete testing of critical components) approaches
- Importance of intelligent design of experiment in order to enhance failure **observability** (e.g. self-diagnose systems, system modularity)
- Importance of defining **failure modes** and associated **criticality**
- Importance of **common component qualification** and **sub-system development** (e.g. versatile communication link)



FGClite system for LHC power converter controls (S. Uznanski, TE-EPC), qualified for HL-LHC ARC and shielded alcove levels, in operation since 2017

RADSAGA tests in CHARM

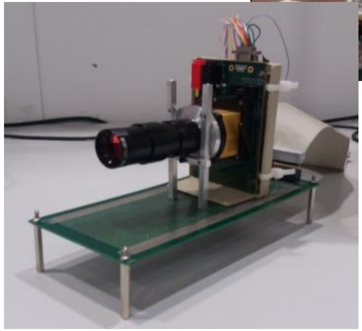
- **CMOS image sensor** system for space missions (Earth observation, monitoring, star tracker…)
- High performance (deep sub-micron technology, low and stable noise, integrated and compact, 3Mgate FPGA…)
- Tested with COTS based on-board computer (i.e. full platform + payload system)
- Challenges related to system level testing: **methodology, observability, correlation with operational environment…**

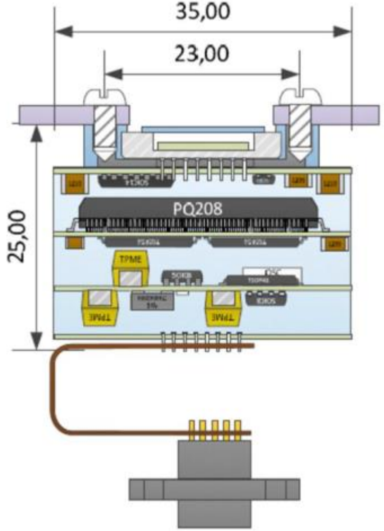
COTS CIS

+ Available
+ Low price
- Find the best
- Dedicated qualification

Custom CIS

- Design and process time
- High price
+ Based on requirement
- Dedicated qualification





Cedric Virmontois (CNES), NSS MIC 2018

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- **Outlook**

RADSAGA objectives linked to board/system level testing

- Definition of methodology to be used in broad range of systems and applications
- Top/down and bottom/up approach combination
- Importance of test plan definition and observability
- Evaluation of necessary irradiation conditions and link to existing test facilities
- Integration of methodology in **RADSAGA handbook for system level testing**:
    - Key project deliverable
    - Strong interest from possible end-users, especially in “new space” and ground level applications

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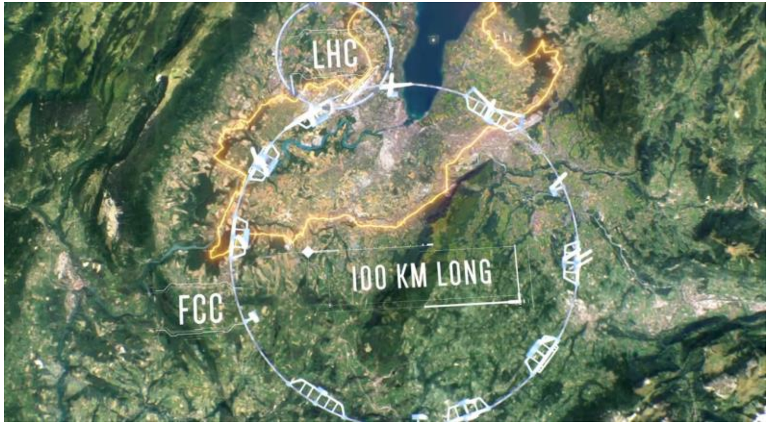
Thinking further ahead… FCC accelerator study

- ***Centralised* versus *Embedded/Distributed* approach**, exploiting evolution of **communication networks** (i.e. processing higher in network as opposed to closer to the equipment under control)
- New system level reliability design approach: **"total availability"**, based on: (i) degraded mode operation, (ii) failure self-diagnose, (iii) online hot-swap and (iv) remote handling capability



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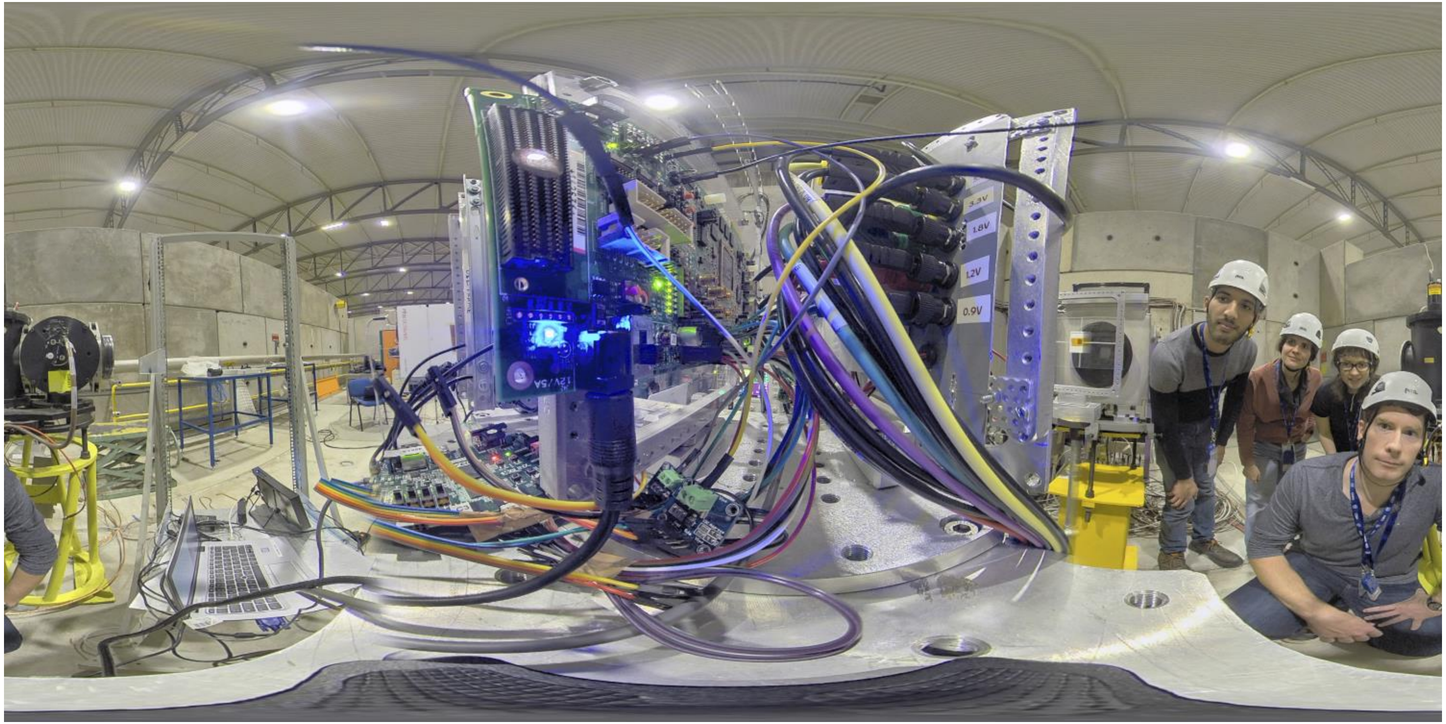

Many thanks for your attention!!

RADSAGA publications and contributions

- ✓ *Analysis of the charge sharing effect in the SET sensitivity of bulk 45nm standard cell layouts under heavy ions*, **Y. Q. Aguiar (ESR9**), F. Wrobel, J,L. Autran, P. Leroux, F. Saigné, A. D. Touboul and V. Pouget, to be published in Microelectronics Reliability, Elsevier, 2018. This work will also be presented at the 29th ESRREF in Denmark in October 2018 and will be published in the conference proceedings.
- ✓ *Impact of Complex Logic Cell Layout on the Single Event Transient Sensitivity*, **Y. Q. Aguiar (ESR9)**, F. Wrobel, J,L. Autran, P. Leroux, F. Saigné, A. D. Touboul and V. Pouget, accepted in the RADECS 2018 Conference (Sweden); to be submitted to the IEEE Transactions on Nuclear Science journal
- ✓ *An SRAM Based Radiation Monitor with Dynamic Voltage Control in 0.18 µm CMOS technology*, J.Prinzie, S.Thys, B. Van Bockel, **J. Wang (ESR5)**, V. De Smedt, P.Leroux. Publication accepted in the journal review IEEE Transactions on Nuclear Science and presented in the NSREC 2018 conferences
- ✓ *Poster in the RADECS 2018 Data Workshop (Sweden):"Aging and gate bias effects on TID sensitivity of wide bandgap power devices", **K. Niskanen (ESR7)** , A. D. Touboul, R. Coq Germanicus, A. Michez, F. Wrobel, J. Boch , V. Pouget, F. Saigné.*
- ✓ *Presentation at RADFAC 2018 in Montpelier (France) on 6 April 2018 (see https://radsaga.web.cern.ch/content/radfac-2018):*
  - "Bridging methodology from component to system-level for the assessment of coupled radiation and degradation constraints in digital systems", **I. Da Costa Lopez (ESR13)**,
  - "Response of the Standard Radiation Environment Monitor (SREM) mounted onboard the Rosetta mission to high energetic heavy ions", **V. Wyrwoll (ESR4)**:
  - "Monte-Carlo Predictive Tool for SEU and SET", **Ygor Aguiar (ESR9)**.

Further references

- “FLUKA Simulations for SEE Studies of Critical LHC Underground Areas”, K. Roed et al, IEEE TNS, 2011
- “LHC RadMon SRAM Detectors Used at Different Voltages to Determine the Thermal Neutron to High Energy Hadron Fluence Ratio”, D. Kramer et al, IEEE TNS 2011
- “Method for Measuring Mixed Field Radiation Levels Relevant for SEEs at the LHC” K. Roed et al, IEEE TNS, 2012
- “SEU Measurements and Simulations in a Mixed Field Environment”, R. Garcia Alia et al, IEEE TNS, 2013
- “Qualification and Characterization of SRAM Memories Used as Radiation Sensors in the LHC”. S. Danzeca et al, IEEE TNS, 2014
- “SEL Cross Section Energy Dependence Impact on the High Energy Accelerator Failure Rate”, R. Garcia Alia et al, IEEE TNS, 2014
- “A New RadMon Version for the LHC and its Injection Lines”, G. Spiezia et al, IEEE TNS, 2014
- “SEL Hardness Assurance in a Mixed Radiation Field”, R. Garcia Alia et al, IEEE TNS, 2015
- "CHARM: A Mixed Field Facility at CERN for Radiation Tests in Ground, Atmospheric, Space and Accelerator Representative Environments,“ J. Mekki et al, IEEE TNS 2016
- "Monte Carlo Evaluation of Single Event Effects in a Deep-Submicron Bulk Technology: Comparison Between Atmospheric and Accelerator Environment," A. Infantino et al, IEEE TNS, 2017.
- “Single event effects in high-energy accelerators”, R. Garcia Alia et al, Semicond. Sci. Technol, 2017
- “High-energy Electron Induced SEUs and Jovian Environment Impact”, M. Tali et al, IEEE TNS, 2017
- “Simplified SEE Sensitivity Screening for COTS Components in Space”, R. Garcia Alia et al, IEEE TNS, 2017
- "LHC and HL-LHC: Present and Future Radiation Environment in the High-Luminosity Collision Points and RHA Implications,“ R. Garcia Alia et al, IEEE TNS, 2018