Rad-Tol High-Rel
Power Converter Controller for the LHC

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Outline

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2. Project Design Timeline
3. Hardware Evolution
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6. Production
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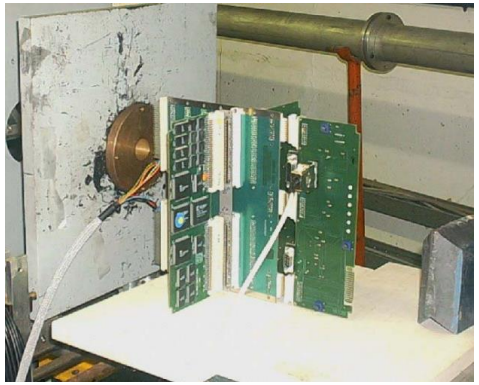
8. Deployment
9. Commissioning & Operations
10. Lessons learned & Conclusions

Availability driven project

Previous Controller was designed to sustain radiation



2002… tested **OK** with 60MeV protons
2009… tested in CNGS - **weaknesses identified** impacting availability
2010… estimated failure rate **inacceptable** in the future

Rad-Tol High-Rel replacement needed

Design requirements:

- Mechanically & Electrically **plug-in compatible**
- **Transparent** for the **Hardware integration**
- **Transparent** for **Software integration**

Reliability requirements **for all installed units**

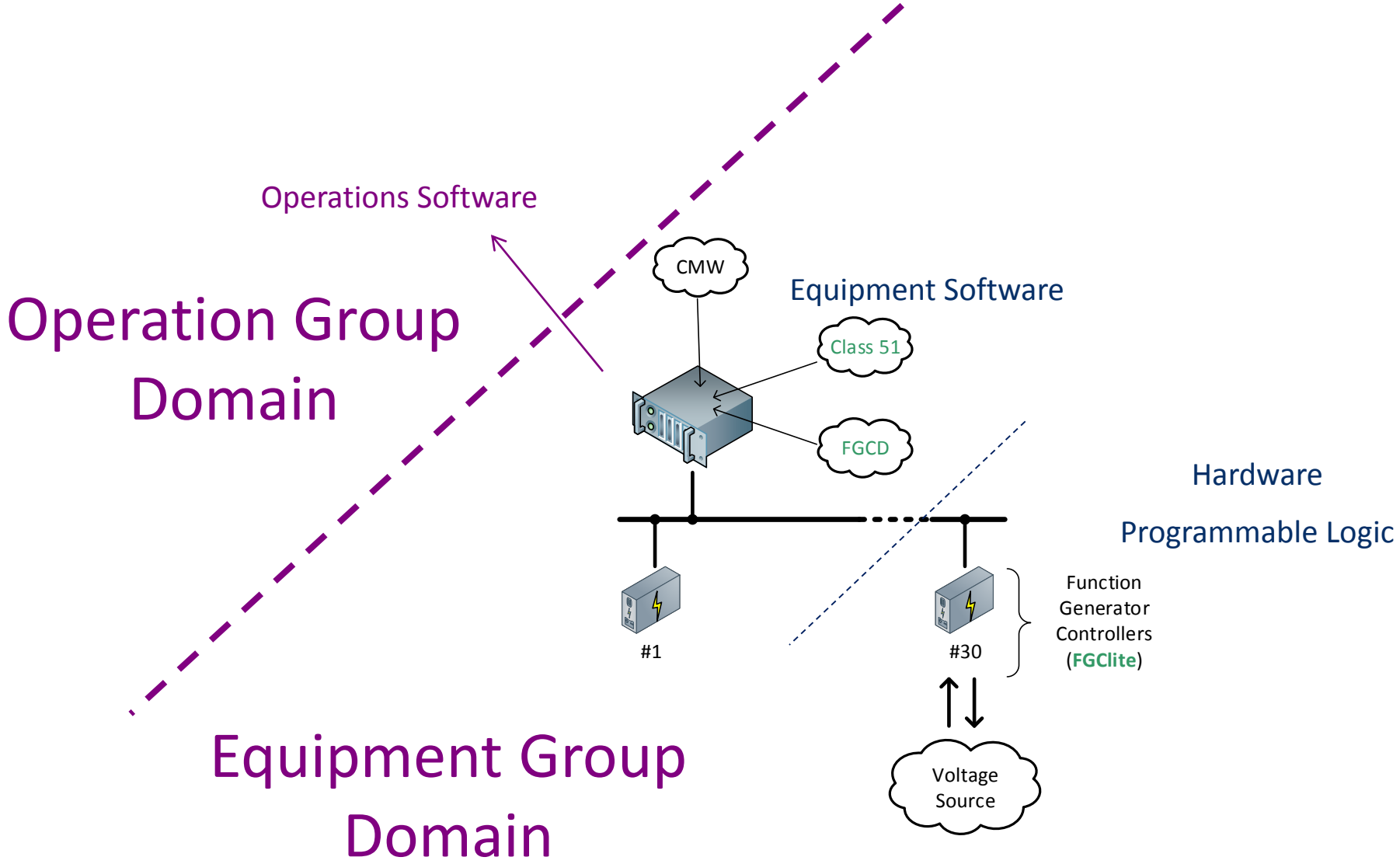
- **<5** beam dumps per year due to radiation in HL-LHC
- **>200Gy** Total Dose = 20 years of HL-LHC
- **<5** beam dumps due to electrical failure (**>1Mh of MTBF/system)**

LHC Power Converters

Converter Requirements			Quantity
Typical Use	Current	Voltage	
Main Dipoles	13000	190	8
Main Quadrupoles	13000	18	16
Individually Powered Quadrupoles/ Dipoles and Inner Triplets	4-6-8000	8	189
Orbit Correctors 600A Sextupole correctors	600	40	37
600A Multipole correctors	600	10	400
Orbit Correctors	120	10	290
Orbit Correctors	60	8	752
		Total	>1700

≈1050 in LHC radiation areas

Scope - Controls Infrastructure



Project timeline

2009
Specification

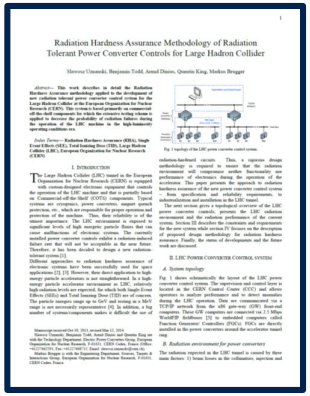
2009 CNGS tests showed
Radiation sensitivity

Project timeline

2009
Specification

2012
Kick-off

Design **methodology**
& feasibility studies



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Radiation Hardness Assurance Methodology of Radiation Tolerant Power Converter Controls for Large Hadron Collider

Slawosz Uznanski, Benjamin Todd, Arend Dinius, Quentin King, Markus Brugger

abstract— **This work describes in detail the Radiation Hardness Assurance methodology for the design and feasibility study of a new radiation tolerant power converter control system for the Large Hadron Collider at the European Organization for Nuclear Research (CERN). This system is based primarily on commercial off-the-shelf components for which the extensive testing scheme is required to ensure the reliability and availability of the system during the operation of the LHC machine in the high-luminosity operating conditions era.**

Index Terms— **Radiation Hardness Assurance (RHA), Single-Event Effects (SEE), Total Ionizing Dose (TID), Large Hadron Collider (LHC), European Organization for Nuclear Research (CERN)**

I. Introduction

The Large Hadron Collider (LHC) tunnel in the European Organization for Nuclear Research (CERN) is equipped with custom-designed electronic equipment that controls the operation of the LHC machine and that is partially based on Commercial-off-the-Shelf (COTS) components. Typical examples are beam instrumentation, beam interlocking, machine protection, etc., which are responsible for proper operation and protection of the machine. Thus, these reliability is of the utmost importance. The LHC environment is exposed to significant levels of high energetic particle fluxes that can cause failures of the electronic equipment. Thus, commercial-certified power converter controls exhibit a radiation-induced failure rate that will not be acceptable in the near future. Therefore, it has been decided to design a new radiation-tolerant system [1].

Different approaches to radiation hardness assurance of electronic systems have been successfully used for space applications [2], [3]. However, these direct applications to high-energy particle accelerators is not straightforward. In a high-energy particle accelerator environment at LHC, relatively high radiation levels are expected, for which both Single-Event Effects (SEEs) and Total Ionizing Dose (TID) are of concern. The radiation environment in the LHC tunnel is very wide in range or not necessarily representative [4]. In addition, a big number of systems/components makes it difficult the use of radiation-hardened circuits. Thus, a express design methodology is required to ensure that the radiation environment will compromise neither functionality nor performance of the system. This work describes the design methodology. The paper presents the approach to radiation hardness assurance of the new power converter control system – from specification and reliability requirements, to industrialization and installation in the LHC tunnel.

The next section gives a topological overview of the LHC power converter controls, presents the LHC radiation environment and the radiation hardness assurance of the new system. Section III describes the constraints and requirements for the new system while section IV focuses on the description of proposed design methodology for radiation hardness assurance. Finally, the status of developments and the future work are discussed.

II. LHC Power Converter Control System

A. System topology

Fig. 1 shows schematically the layout of the LHC power converter control system. The supervision and control layer is located in the CERN Control Center (CCC) and adheres approximately to a multiple-processor and multi-tasking operating system. The communication between the supervisory and the TCP/IP network from the x86 gate-way (GW) front-end computers. These GW computers are connected via 2.5 Mbps WorldFIP fieldbuses [5] to embedded computers called Function Generators/ Controllers (FGCs). FGCs are directly installed in the power converters around the accelerator tunnel area.

B. Radiation environment for power converters

The radiation expected in the LHC tunnel is caused by three main factors: 1) beam losses in the collimators, injection and

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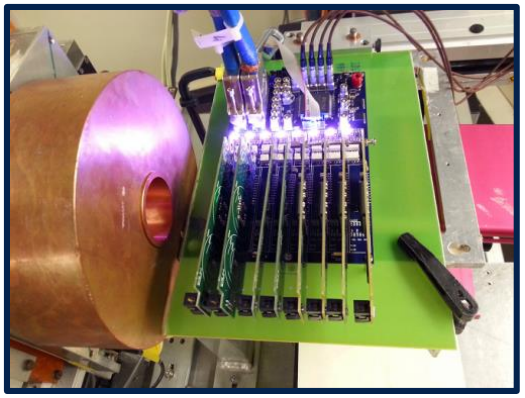
Fig. 1 topology of the LHC power converter control system.

Project timeline

2009 Specification → 2012 Kick-off → 2013 Proof-of-concept

Component **selection** & Rad-testing

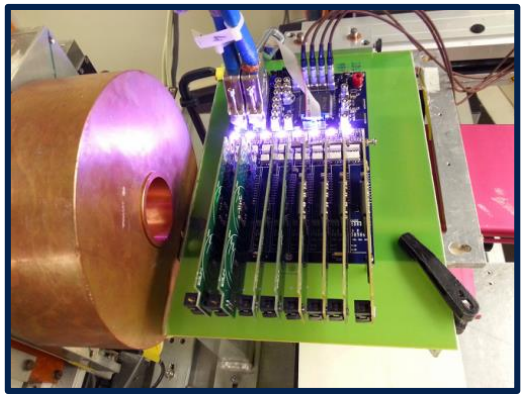


Proof-of-concept critical functions validated under radiation

Project timeline

2009 Specification → 2012 Kick-off → 2013 Proof-of-concept → 2014 Prototype

Component **selection** & Rad-testing



First implementation of The **full functionality**

Project timeline

2009 Specification → 2012 Kick-off → 2013 Proof-of-concept → 2014 Prototype

2015 Industrialization

Industrialization :
Design for **test** and **reliability**

System Rad-tests
at CERN

Project timeline

2009 Specification → 2012 Kick-off → 2013 Proof-of-concept → 2014 Prototype → 2015 Industrialization → 2016 Production & Validation

14000 electronic boards

Manufactured , tested & assembled

Run-in, burn-in, reliability assessed

hardware and regulation tested in A7 and in the LHC

Project timeline

2009 Specification → 2012 Kick-off → 2013 Proof-of-concept → 2014 Prototype → 2015 Industrialization → 2016 Production & Validation → 2017 Deployment ARC

750 systems deployed in the LHC Tunnel

Project timeline

2009 Specification → 2012 Kick-off → 2013 Proof-of-concept → 2014 Prototype → 2015 Industrialization → 2016 Production & Validation → 2017 Deployment ARC → 2018 Deployment RR

300 systems
in the LHC shielded areas

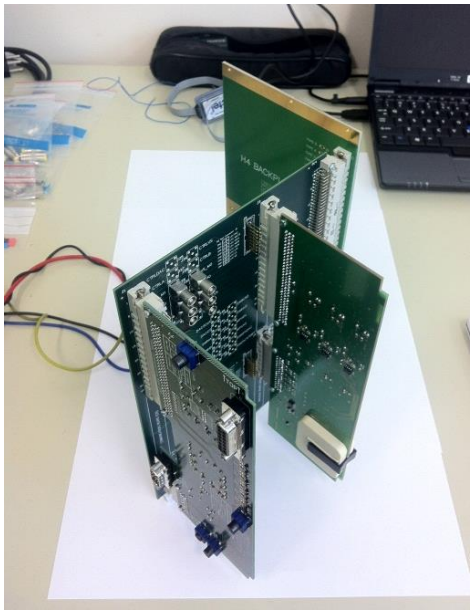
Hardware evolution

Annual iteration of hardware to achieve a final implementation:

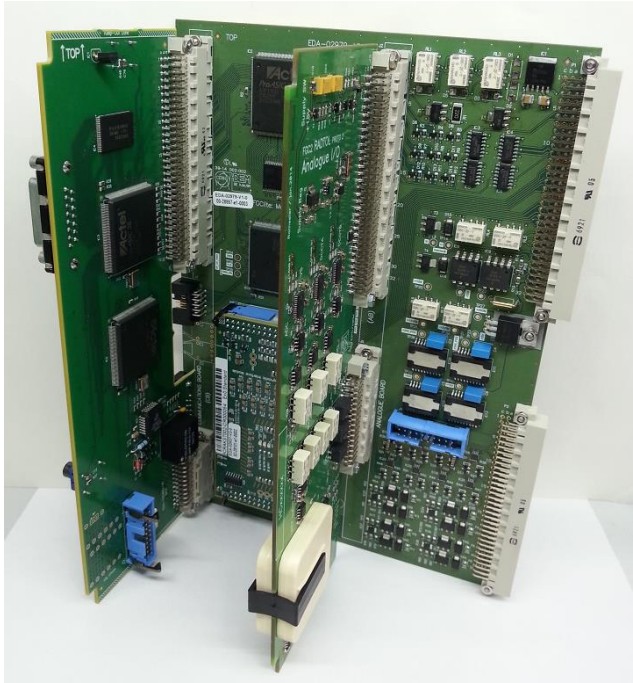
2013: **Proof-of-concept** validation of **critical functions** under radiation

2014: Fully **functional prototype** embedding all functions needed for the future controller

2015: Fully **industrialized** modular FGClite designed for reliability and testability



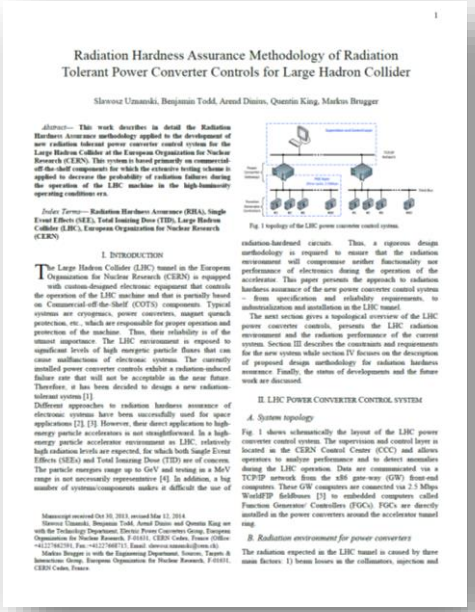
2013



2014

2015

The design flow **reviewed by ESA** & **NASA** experts



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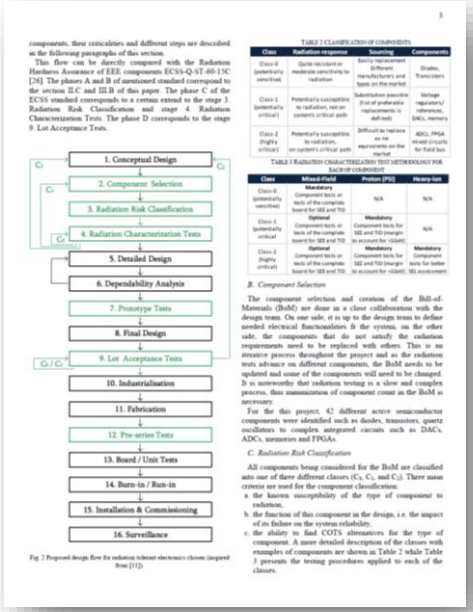


Uznanski, NSS'13 RADECS'17

How to approach design of rad-tol electronic system based on COTS components?

Classification of components based on certain criteria

Radiation **Characterization** Tests of types of components

Lot **Acceptance Tests** of production batches

Radiation **System Validation** in the **representative environment**

High-Rel Assurance

Electrical reliability was one of the main design requirements for a new system

Long term collaboration established with the **IMA Stuttgart** :

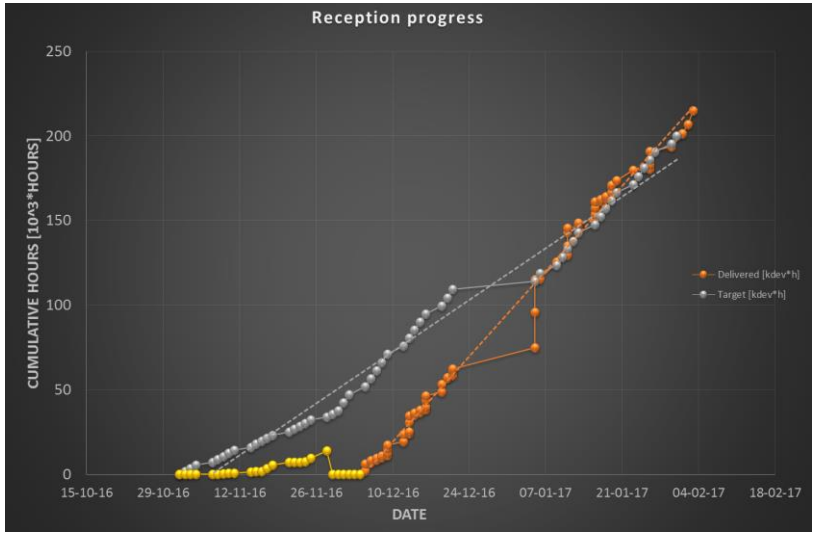
1st : Reliability-driven design of electronic systems

2nd : From design to operations of highly reliable systems

3rd : Feedback from operations and guidelines for future projects

Schramm
Tevetoglu
Schwenk
IMA'16 '17 '18

Dedicated Reliability Demonstration by running-in to screen failures



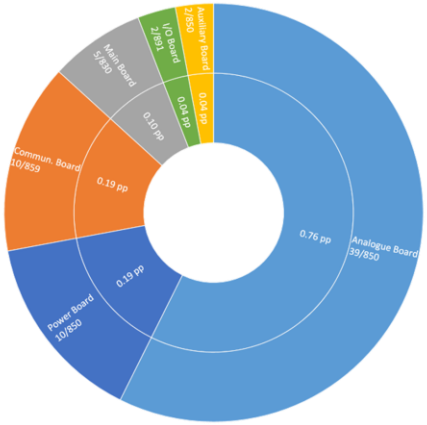
Over **300k dev*h** accumulated system tests before deployment

PCB production & board assembly subcontracted but tests at CERN

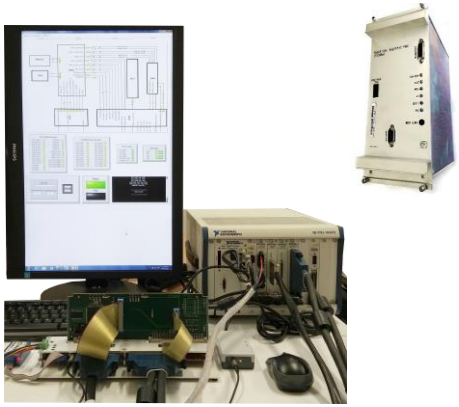
CERN designed all electronic boards
CERN purchased & qualified all active semiconductors
PCB & assembly of was subcontracted
CERN tested each board at the reception before **assembly** in the cassette

Mass Production

Yield Assessment



Board Test & Assembly

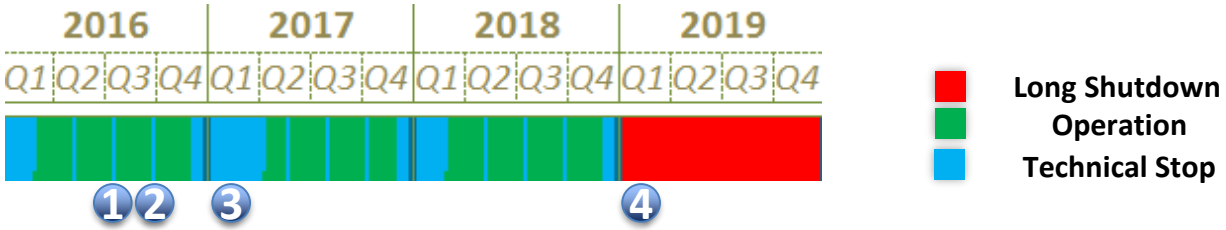


14 000 PCBs received at CERN between **Sep 2016 & Jan 2017**
Boards tested with overall **yield of 99.18%**

Functional system validation tests with Hardware and Software

Performance measured on **Warm Magnets** (A7) & **Superconducting Magnets** (LHC – TS2/TS3)

System validation roadmap published in Jan'2016.



1. **TS2:** First use from CCC (**~30x** devices)
2. **TS3:** Validation of the first segment (**~30x** devices)
3. **EYETS2016:** Deployment ARCs (**750x** devices)
4. **LS2:** Deployment RR locations (**300x** devices)

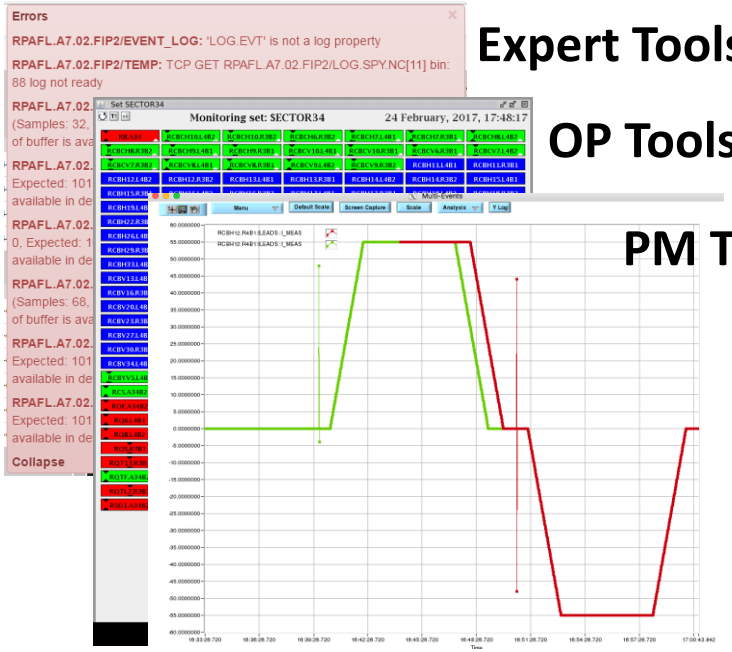
Montabonnet, Chamoinx'16

Phase 1: ARC deployment

750 systems deployed in 8 days… then… communication bug was discovered

Problems never observed in laboratory = memory access arbitration issue
Occurrence = **once per month** in laboratory conditions, **once per day** in LHC
1 week: to **reproduce** in lab conditions
1 week: to **fix** & **validate**
1 week: to **deploy correction** in the LHC.

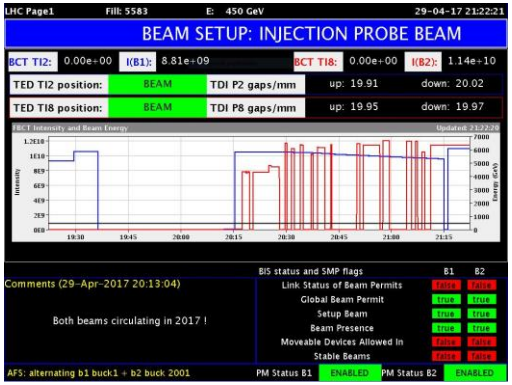
A great Hardware integration was assured... **but software interfaces failed**



Commissioning & Operations

Arriving to the maturity of software involved equipment & operation groups

4 weeks: Impressive amount of work and **great collaboration** in the final phases of commissioning



Phase 1 deployment is complete:

Success of electronics project

Radiation tolerance meets requirements

Excellent **Electrical Reliability.** 2 failures in >**5.2M dev*h** up to date

Software not as Transparent as thought…

Voltage Source – **compatibility assured**

Software **some assumptions** did not hold due to **much faster development cycle**

Lessons Learned & Conclusions

How to improve the overall process for Phase 2?

The review between groups -> Recommendations for future projects

When designing & producing your system:

Some components go obsolete impacting the rad-qualification -> **Buy upfront**
Components/PCBs lost & destroyed during production -> **Send/manufacture more?**
Operational software & diagnostic tools late impacting system integration tests -> **Early software development**

When Deploying your system:

Hardware Reliability Excellent thanks to detailed modeling & testing…
… Still a bug occurred, but solved during commissioning period -> **Did our testing failed?**

When commissioning your system:

Integration challenges due to short software life cycle, multiple unidentified users & dynamically changing tools -> **new tools to track dependencies & improved communication**

Field reliability of both Hardware and Software closely followed

Thank you for your attention!

Rad-Tol systems: Key lessons

When specifying your system:

Is your system really needed/can it be **simplified**?
Mitigate risks by **relocating** equipment outside of radiation area
Use **shielding** to decrease radiation to an acceptable level

When specifying your bill-of-materials:

Does your budget **allow Rad-Hard/Rad-Tol** components?
Can you afford **COTS qualification/testing**?

If your bill-of-materials contains COTS:

Component **traceability** is critical, **obsolescence** problems
Assess the **spread of radiation response within component lot**
Test in **representative conditions** and configuration

Reliability demonstration