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

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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 unacceptable 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)
### Converter Requirements

<table>
<thead>
<tr>
<th>Typical Use</th>
<th>Current</th>
<th>Voltage</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dipoles</td>
<td>13000</td>
<td>190</td>
<td>8</td>
</tr>
<tr>
<td>Main Quadrupoles</td>
<td>13000</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Individually Powered Quadrupoles/Dipoles and Inner Triplets</td>
<td>4-6-8000</td>
<td>8</td>
<td>189</td>
</tr>
<tr>
<td>Orbit Correctors</td>
<td>600</td>
<td>40</td>
<td>37</td>
</tr>
<tr>
<td>600A Sextupole correctors</td>
<td>600</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>600A Multipole correctors</td>
<td>600</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>Orbit Correctors</td>
<td>120</td>
<td>10</td>
<td>290</td>
</tr>
<tr>
<td>Orbit Correctors</td>
<td>60</td>
<td>8</td>
<td>752</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&gt;1700</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

≈1050 in LHC radiation areas
Scope - Controls Infrastructure

Operation Group Domain

Equipment Group Domain

Operations Software

Equipment Software

Hardware Programmable Logic

Function Generator Controllers (FGClite)

Voltage Source

CMW

Class 51

FGCD

#1

#30
2009 CNGS tests showed
Radiation sensitivity
Design methodology & feasibility studies
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

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Converter Control Electronics
CERN

Converter Control Electronics

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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
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
The design flow reviewed by ESA & NASA experts

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

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

1\textsuperscript{st}: Reliability-driven design of electronic systems

2\textsuperscript{nd}: From design to operations of highly reliable systems

3\textsuperscript{rd}: Feedback from operations and guidelines for future projects

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)


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

Expert Tools
OP Tools
PM Tools
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!
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

Failure rate \( \lambda \)

\[ MTTF_{Reception} \]

\[ MTTF_{Field+R} \]

\[ MTTF_{Prediction} \]

\[ MTTF_{Goal} \]

\[ MTTF_{True} \]

02'2017  09'2017  12'2018

92K dev*h  291K dev*h  1M dev*h

dev*h