Radiation Tolerant Power Converter Design for the LHC

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Outline

1. **Review of LHC Power Converters :**
   a. Systems
   b. Radiation Environment
   c. Availability in 2012
   d. Availability in the future

2. **Design methodology :**
   a. Requirements
   b. Design flow
   c. Component selection
   d. Component characterization tests
   e. Lot acceptance tests

3. **Conclusions**

Review of LHC Power Converters: Systems

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

Controller = box with electronics

Todd,Thurel, CERN'11

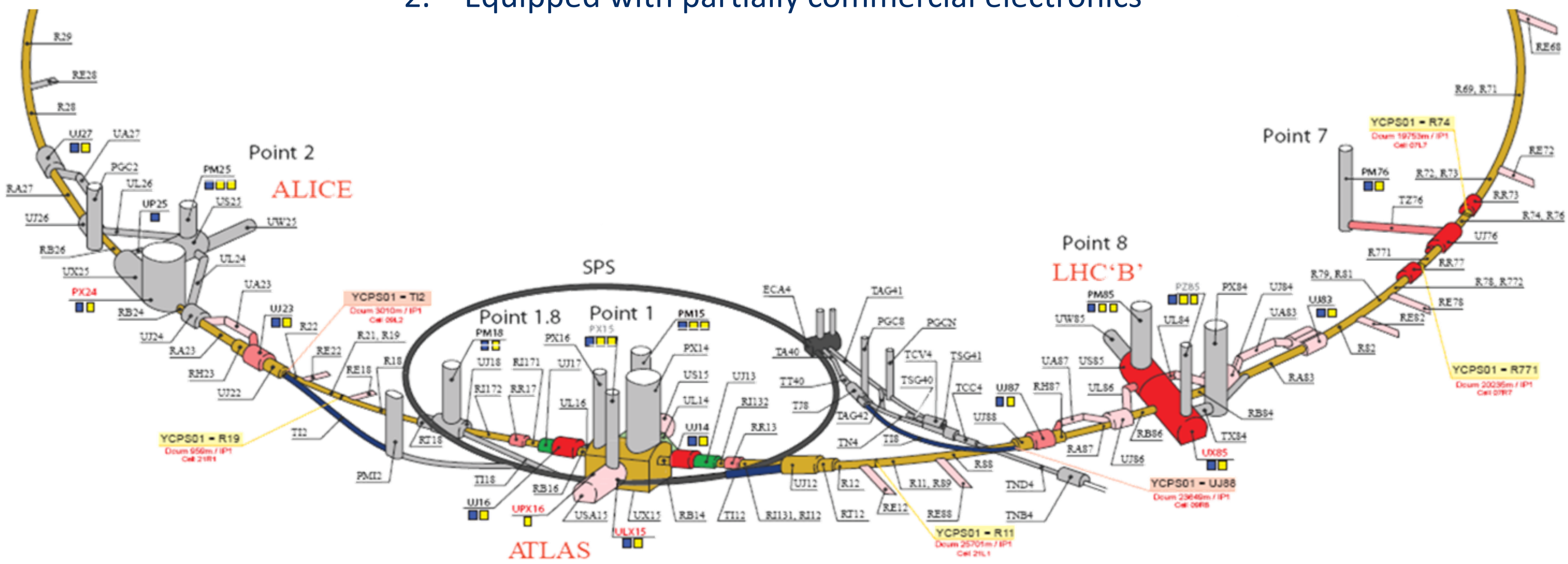
Mixed-Field radiation composed of n, p, pi+, pi- mainly due to

1. **Direct losses** in the accelerator
2. Particle **collisions** at 4 LHC experiments
3. **Residual gas** in the beam pipe

Roed, RADECS'11

LHC tunnel and cavern areas

1. Mixed-field radiation with energies up to several GeV
2. Equipped with partially commercial electronics



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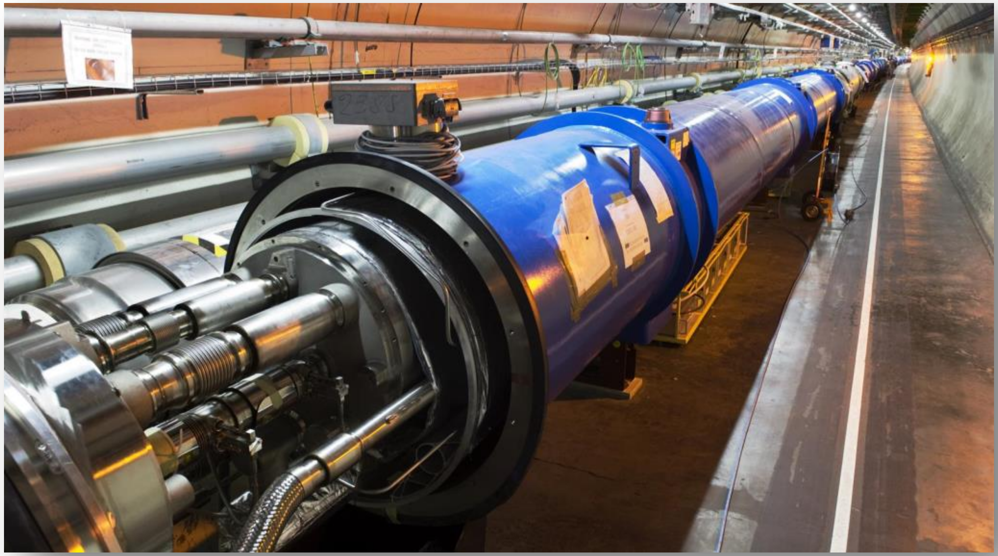
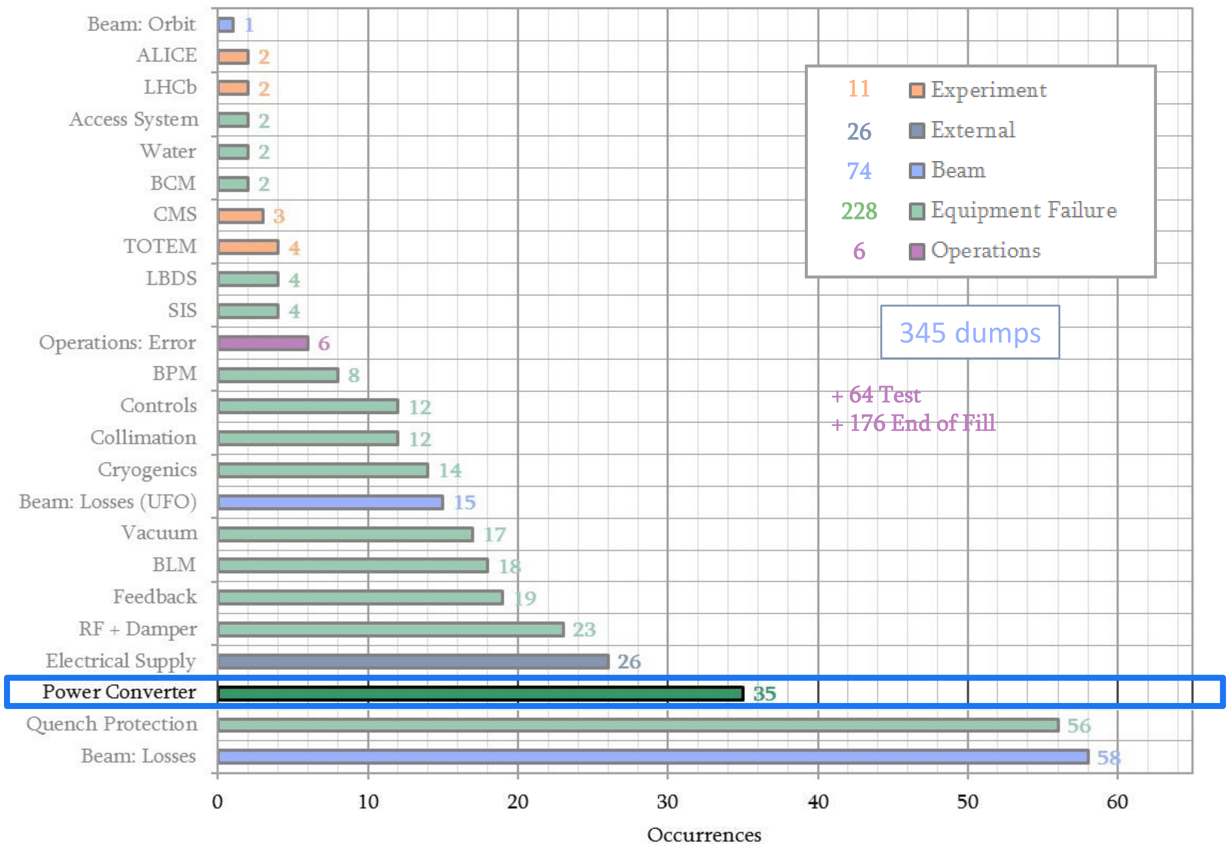
Tunnel



Shielded Location

Hardware failures leading to a beam dump from Post Mortem



After Todd, Evian'12

2012 data

	Power		Controller		Unknown Origin	Total
	Electrical	Radiation	Electrical	Radiation		
Run1: 4TeV operation	29	*15 -> 1	5	10	6	65

Post LS1 – increased radiation levels, increased VS load

	Power		Controller		Unknown Origin	Total
	Electrical	Radiation	Electrical	Radiation		
Run2: ±6.5TeV operation	<47	2	5	20	6	74
Run3: Increasing Radiation	<47	4	5	44	6	98
HL-LHC: Increasing Radiation	<47	9-18	5	90-190	6	150-260

Radiation Levels

Brugger, CERN'14

Simulation tool

Thurel, CERN'12

⇩ ⇩

Known unreliable parts fixed

New radiation tolerant controller needed!

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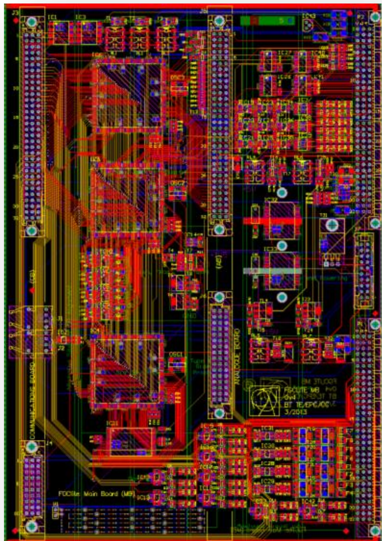
	Power		Controller		Unknown Origin	Total
	Electrical	Radiation	Electrical	Radiation		
HL-LHC	<47	9-18	5	<10	6	<80

New Radiation-Tolerant design on-going optimized for high availability in radiation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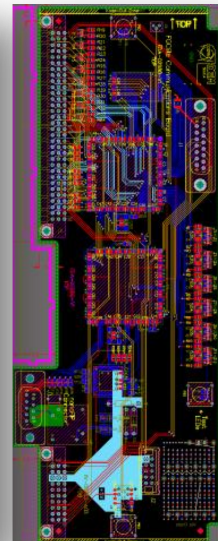
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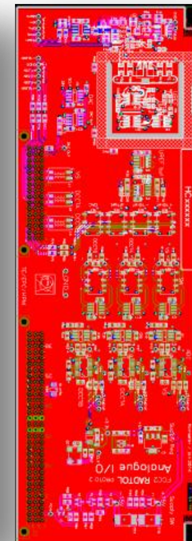
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x3900

	Semiconductor			
	Board 1	Board 2	Board 3	Board 4
Diodes	8	13	59	6
LED		6		3
Quartz	1	2	2	1
Opto			4	
Transistor	7	20	27	
IC	22	5	26	30
Total	38	46	118	40

0.5M semiconductors (~50 different types)
2.3M electronic components

Uznanski, MIXDES'14

Design challenges:

1. **Rad-Tol** system for uninterrupted LHC operation (improvement of **x20**)
2. No **Rad-Hard ASICs, FPGA-based** for flexibility, based on **Commerial-Off-The-Shelf (COTS)**
3. Assure **high reliability** each module

Standard Design Flow

- Conceptual Design
- Component Selection
- Detailed Design
- Prototype Tests
- Final Design
- Industrialization
- Fabrication
- Board / Unit Tests
- Burn-in / Run-in
- Installation and Commissioning
- Surveillance

After Todd, TWEPP'12

Radiation Tolerant Design Flow

- Conceptual Design
- Component Selection
- Radiation Risk Classification
- Rad. Characterization Tests
- Detailed Design
- Prototype Test
- Final Design
- Lot Acceptance Tests
- Industrialization
- Fabrication
- Pre-series Tests
- Board / Unit Testing
- Burn-in / Run-in
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- Surveillance

Todd, TWEPP'12

Component Selection Process

1. Joint work between the design (electrical function)/radiation testing team (component susceptibility)
2. Iterative process throughout the design
3. Optimization of Bill-of-Materials = huge impact on component qualification

Radiation Risk Classification

1. Impossible to extensively test all semiconductors. **Minimize risk!**
2. Classification criteria: Known **susceptibility** to radiation, **Criticality** of failure, **Availability** of component alternatives

Class	Radiation response	Sourcing	Components
Class-0 (potentially sensitive)	Quite resistant or moderate sensitivity to radiation	Easily replacement Different manufacturers and types on the market	Diodes, Transistors
Class-1 (potentially critical)	Potentially susceptible to radiation, not on system's critical path	Substitution possible (list of preferable replacements is defined)	Voltage regulators/ references, DACs, memory
Class-2 (highly critical)	Potentially susceptible to radiation, on system's critical path	Difficult to replace as no equivalents on the market	ADCs, FPGA mixed circuits for field bus

Radiation characterization challenges

1. High energies representative to LHC
2. Very low failure rates
3. High number of components to be tested

Different procedures developed for different classes

Class	Mixed-Field	Proton (PSI)	Heavy-ion
Class-0 (potentially sensitive)	**Mandatory** Component tests or tests of the complete board for SEE and TID	N/A	N/A
Class-1 (potentially critical	**Optional** Component tests or tests of the complete board for SEE and TID	**Mandatory** Component tests for SEE and TID (margin to account for >1GeV)	N/A
Class-2 (highly critical)	**Optional** Component tests or tests of the complete board for SEE and TID	**Mandatory** Component tests for SEE and TID (margin to account for >1GeV)	**Mandatory** Component tests for better SEL assessment

230MeV protons at PSI
safety margins applied (PhD program)

Heavy ion tests at UCL. Single Event Latch-up threshold :

< 20 MeV×cm^2/mg **NOT SAFE**
20-40 MeV×cm^2/mg **CHIP ANALYSIS**
> 40 MeV×cm^2/mg **SAFE**

The use of COTS components implicates

1. Poor component traceability (Silicon lot codes, Packaging date codes)
2. Lack of information concerning process changes
3. Necessity to assess component-2-component variability

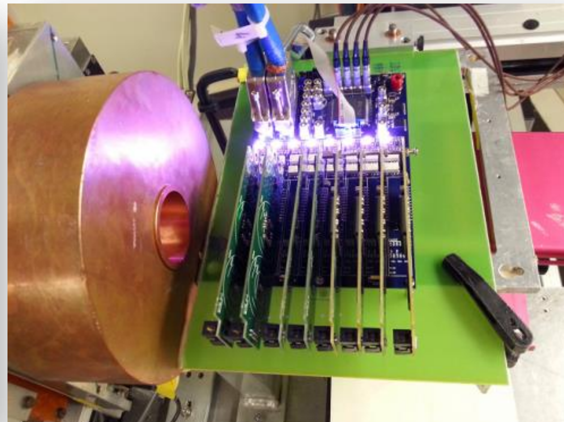
Procurement of component lots

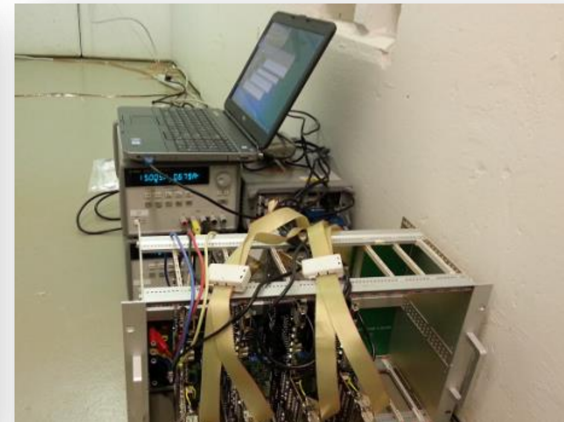
1. Silicon control when possible (price vs component criticality)
2. Always single packaging date code
   - Samples from each date code to be rad-tested
   - Components cheaper than rad qualification
3. Dedicated tests, test setups, test facilities needed…

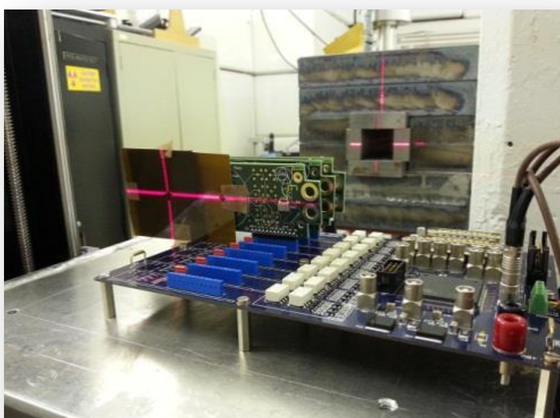
Dedicated modular testing infrastructure

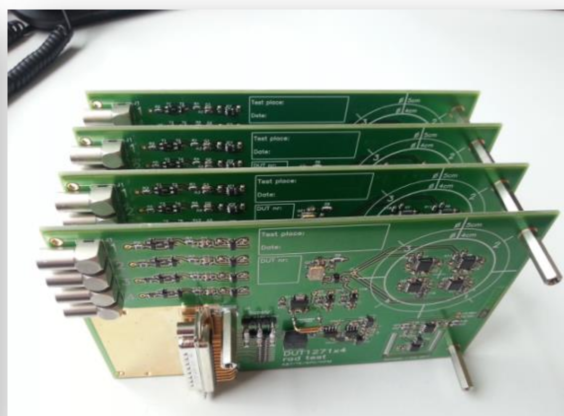
1. To optimize the beam time – parallel testing of multiple components
2. To achieve high statistics of events
3. To reuse same setup to test many different components


Actel





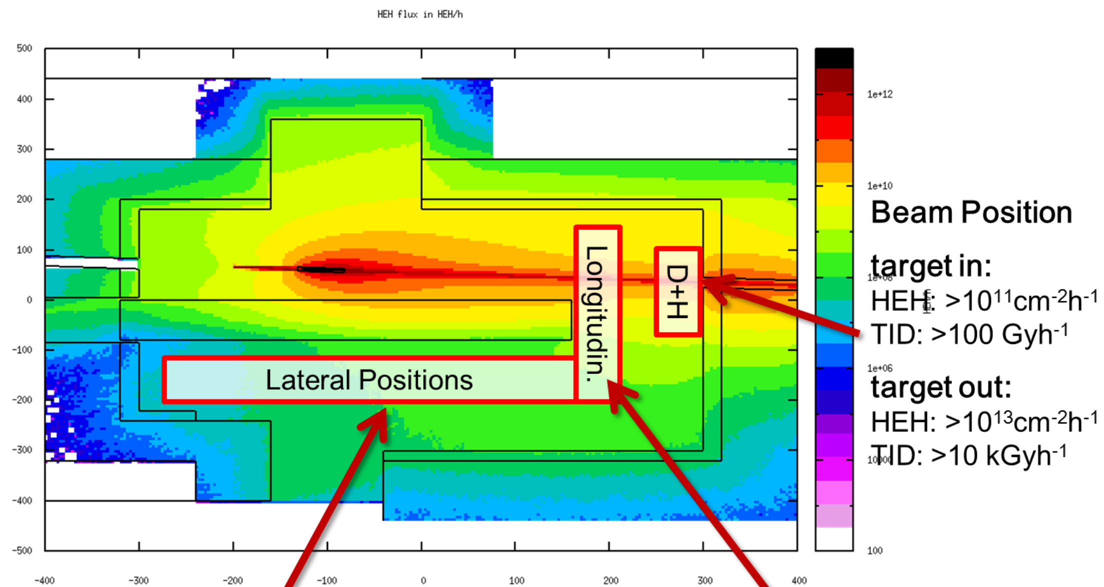





FUNCTION
GENERATOR
CONTROLLER

Testing challenges: Have you ever thought of irradiating… 100 components… or a system… in a representative environment?

Thurel, CERN'11



HEH: $10^8 cm^{-2}h^{-1} – 10^{11} cm^{-2}h^{-1}$
TID: $0.1 Gyh^{-1} – 100 Gyh^{-1}$
(gradients to be considered)

Full racks, crates, set of cards, components

HEH: $10^7 cm^{-2}h^{-1} – 10^{10} cm^{-2}h^{-1}$, TID: $10 mGyh^{-1} – 10 Gyh^{-1}$

Mekki, CERN'13

A quick overview of power converters

Significant radiation levels raging from thermal to extremely high energies
COTS-based systems distributed around the accelerator ring

Design/Testing methodology

LHC power converter controls as example
Use of COTS requires extensive testing

Test facilities, Test setups, Test labs

Dedicated test setups have been developed to cover project requirements
CHARM was constructed to be able to test in representative conditions

When specifying your system:

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

When specifying your bill-of-materials:

Does your budget **allow Rad-Hard/Rad-Tol** components?
Can you afford **COTS qualification/testing**?
Follow strict development plan and testing methodology

If your bill-of-materials contains COTS:

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

Thank you for your attention

More information…

CHARM facility

http://charm.web.cern.ch/CHARM/

Test results on COTS performed by CERN

http://radwg.web.cern.ch/RadWG/Pages/summary_table.aspx