* radiation is everywhere, it can effect electronic systems
  – for dependable operation you cannot ignore this.
  – Particle accelerators actually create radiation fields.
  – certain failure modes are unique to radiation effects

* radiation effects on electronics are difficult and costly to characterise
  – by far the best thing to do is avoid exposure to radiation.

* radiation effects are difficult and costly to mitigate
  – by far the best thing to do is avoid exposure to radiation.
1. Context – CERN

2. Radiation – Basic Effects

3. Examples of Radiation Tolerant Design Flow

   An example of a radiation tolerant system in design
The Context...
CERN Accelerator Complex

CERN LAB 1 (Switzerland)

CERN LAB 2 (France)

Lake Geneva

Geneva Airport
CERN Accelerator Complex

- Large Hadron Collider (LHC)
- Super Proton Synchrotron (SPS)
- Proton Synchrotron (PS)
- CERN LAB 1 (Switzerland)
- CERN LAB 2 (France)
- 27km long
- 150m underground

Lake Geneva
Geneva Airport
CERN Accelerator Complex
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27 km long
150 m underground
CERN Accelerator Complex
CERN Accelerator Complex

Large Hadron Collider (LHC)

Super Proton Synchrotron (SPS)

Beam-1 Transfer Line (TI2)

Beam-2 Transfer Line (TI8)

Beam Dumping Systems

~ 9 km
~ 5.5 miles

100us for one turn,
\[10^9\] proton-proton collisions per second

Massive amounts of data generated – all must be processed
new particles are rare – only a few events per day
Radiation
“Cross-Section” = the probability of a particle interacting

- If you have a lot of parts, even at sea level, atmospheric effects can noticeably affect reliability
- Radiation effects cannot be ignored for highly reliable systems
The Golden Rules

If you only take one thing from this Saturday morning talk – let it be this:

To solve radiation issues:

1) **Remove** the function if not possible then
2) **Move** away from the radiation if not possible then
3) **Block** radiation if not possible then
4) and only then - **conceive** a radiation tolerant system

CNGS 2006 – PLC Crashed – FLUKA Simulation
The Golden Rules

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in a nutshell

1. Displacement Damage (DD)  
2. Total Ionising Dose (TID)  
3. Single Event Effects (SEE)

cumulative

prompt
1. Displacement Damage (DD)

2. Total Ionising Dose (TID)

3. Single Event Effects (SEE)

defects accumulate and gradually destroy the silicon lattice
in a nutshell

1. Displacement Damage (DD)
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accumulate and gradually degrade the transistor function
1. Displacement Damage (DD)  
2. Total Ionising Dose (TID)  
3. Single Event Effects (SEE)

- Displacement Damage (DD)
- Total Ionising Dose (TID)
- Single Event Effects (SEE)

- Electrons collected by junctions creating parasitic current
- SE Transient (SET)
- SE Upset (SEU)
- SE Functional Interrupt (SEFI)
in a nutshell

1. Displacement Damage (DD)
2. Total Ionising Dose (TID)
3. Single Event Effects (SEE)

CMOS parasitic bi-polar transistors...
Switch on = short drain to source...

SE Latch-up (SEL)
1. Displacement Damage (DD)  
   cumulative  
   Non-Ionising Energy Loss  
   lifetime!

2. Total Ionising Dose (TID)  
   cumulative  
   Grays  

3. Single Event Effects (SEE)  
   prompt  
   Cross-section

   SE Upset (SEU)  
   SE Transient (SET)  
   SE Functional Interrrupt (SEFI)  
   SE Latchup (SEL)  
   SE Burnout (SEB)  

random in time failure!
A System In Design Today
PROTON PHYSICS: STABLE BEAMS

Energy: 3500 GeV  I(B1): 2.43e+13  I(B2): 2.41e+13

FBCT Intensity and Beam Energy

Instantaneous Luminosity

Comments 22-03-2011 21:21:07 :

STABLE BEAMS

BIS status and SMP flags

Link Status of Beam Permits
Global Beam Permit
Setup Beam
Beam Presence
Moveable Devices Allowed In
Stable Beams

AFS: 75ns_200b_194_178_168_24bpl9inj

PM Status B1 ENABLED  PM Status B2 ENABLED
**Power Converters = Power Supplies**

Critical for operation of CERN’s machines

Direct impact on beam quality

Direct impact on machine availability

<table>
<thead>
<tr>
<th>Year</th>
<th>Peak Energy [TeV]</th>
<th>Peak Intensity [p]</th>
<th>Peak Luminosity [cm(^{-2}) s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>3.5</td>
<td>4 \times 10^{13}</td>
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<tr>
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</tr>
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**Power Converters = Power Supplies**

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<tr>
<td>2010</td>
<td>3.5</td>
<td>4 x 10¹³</td>
<td>2.0 x 10³²</td>
</tr>
<tr>
<td>2011</td>
<td>3.5</td>
<td>2.0 x 10¹⁴</td>
<td>3.6 x 10³³</td>
</tr>
<tr>
<td>2012</td>
<td>4</td>
<td>2.2 x 10¹⁴</td>
<td>7.7 x 10³³</td>
</tr>
<tr>
<td>LS₁-₂</td>
<td>≈6.5</td>
<td>≈3 x 10¹⁴</td>
<td>≈1 x 10³⁴</td>
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</table>

LS₁ = Long Shutdown #1 – from 2013 to 2014 – upgrade magnet interconnects

LS₂ = Long Shutdown #2 ...
**Power Converter = Power Supplies**

Critical for operation of CERN’s machines

Direct impact on beam quality

Direct impact on machine availability

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Increasing energy and intensity = increasing levels of radiation in machine environment [2,3,4]

Existing converter controls would have low availability when higher energies and intensities are reached in the LS$_{1-2}$ era

**Function Generator Controller** → **Function Generator Controller lite**

A design optimised for high availability in radiation = the next 25 years of LHC
Magnet Powering Circuit

- Mains Supply
- Control
- Power Converter
- Dump Resistor
- Energy Extraction Switch
- Cryogenic Bath
- Bypass Diode
- Magnet Coil
- Quench Detector
- Quench Heater
- Voltage Indicator

benjamin.todd@cern.ch
Magnet Powering Circuit

- Mains Supply
- Control
- Dump Resistor
- Cryogenic Bath
- Bypass Diode
- Magnet Coil
- Powering Interlocks
- Quench Heater
- Quench Detector
- Energy Extraction Switch
- Power Converter

benjamin.todd@cern.ch
Magnet Powering Circuit
Power Converter

- Closed Loop Current Regulation
- Converter State Control (ON/OFF/RESET)
- Machine Protection Interlocks
- Diagnostics
Power converters are installed in one of five areas with machine radiation risks:

1. Surface Buildings - none
2. Perpendicular galleries - none - low
3. Parallel galleries - low
4. Alcoves - medium - high
5. LHC Tunnel - high
Power converters are installed in one of five areas with machine radiation risks:
## Power Converter Types

<table>
<thead>
<tr>
<th>Converter Requirements</th>
<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>
<td></td>
</tr>
<tr>
<td>Main Quadrupoles</td>
<td>13000</td>
<td>18</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Quadrupole Circuits</td>
<td>4-6-8000</td>
<td>8</td>
<td>189</td>
<td></td>
</tr>
<tr>
<td>Warm Circuits</td>
<td>1000</td>
<td>450-950</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Sextupole Circuits</td>
<td>600</td>
<td>40</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Octupole Circuits</td>
<td>600</td>
<td>10</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Orbit Correctors</td>
<td>120</td>
<td>10</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>Orbit Correctors</td>
<td>60</td>
<td>8</td>
<td>752</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&gt;1700</strong></td>
<td></td>
<td></td>
<td></td>
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</table>

[5,6]
### Power Converter Types

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- Sextupole Circuits: 600, 40
- Octupole Circuits: 600, 10
- Rectifiers: 120, 10, 60, 8

**Function Generator Controller**

[5,6]
### Power Converter Types

**Table: Power Converter Requirements**

<table>
<thead>
<tr>
<th>Circuit Type</th>
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<td>8</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>16</strong></td>
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</table>

*Source: [5,6]*
Software versus Programmable Logic

μP

DSP

Function Generator Controller 2

Gateway

Function Generator Controller lite

Gateway

Signal Processing

Control

Signal Processing

Control

WorldFIP & microFIP

WorldFIP & nanoFIP

Voltage Source

Magnet Circuit

Voltage Source

Magnet Circuit

I meas

I meas
Design Flow for Radiation Tolerance

1. Conceptual Design

2. Component Selection

3. Radiation Risk Classification
Design Flow for Radiation Tolerance

1. Conceptual Design
2. Component Selection
3. Radiation Risk Classification

Class 0 (C₀) components known to be resistant, or easily replaced, conceptual
design not influenced by these components.

Resistors, capacitors, diodes, transistors…

Class 1 (C₁) components potentially susceptible to radiation, in less-critical parts
of the system. Substitution of parts or mitigation of issues is possible with a re-design.

Regulators, memory, level translators…

Class 2 (C₂) components potentially susceptible to radiation, in more-critical parts of the system. The conceptual design is compromised if these components do not perform well. Substitution of parts or mitigation of issues would be difficult.

ADC, FPGA, fieldbus driver
Design Flow for Radiation Tolerance

1. Conceptual Design
2. Component Selection
3. Radiation Risk Classification
4. Type Testing
Principle for Test-bench “CIRX”
Principle for Test-bench “CIRX”
Principle for Test-bench “CIRX”

Neutrino Beam

Particle Shower

Proton Beam
Principle for Test-bench “CIRX”
Principle for Test-bench “CIRX”
Principle for Test-bench "CIRX"
Principle for Test-bench “CIRX”

- Proton Beam
- Concrete Wall
- Device Under Test
- Particle Shower
- 20-30Gy per week

XC95144 x 32
XC95288XL x 32
Testbench Electronic Functionality

XC95144 x 32
XC95288XL x 32
Testbench Electronic Functionality
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Testbench Electronic Functionality

“3U” Driver Board
CIRD – EDMS # 995296

“1U” Supply Board
CIRS – EDMS # 995299
Testbench Electronic Functionality
Testbench Electronic Functionality

“3U” Driver Board
CIRD – EDMS # 995296

Particle Shower
Testbench Electronic Functionality
Testbench Electronic Functionality

Labview PXI

Test Program

Test Results

Office Machine

Particle Shower
**Testbench Electronic Functionality**

---

### BB4

- **“3U” Driver Board**
  - CIRD – EDMS # 995296

### 2-3 Gy/wk

- **“3U” Driver Board**
  - CIRD – EDMS # 995296

### 20-30 Gy/wk

- **4 x PIC-Type Boards**
  - CIRP – EDMS # 995295

---

- **Particle Shower**
- **4 x BIS-Type Boards**
  - CIRB – EDMS # 995292

---

**Distance:**

- **1200m**
- **15m**
Every circuit which needs characterising needs a tester – here memory, FPGA and ADCs
Every circuit which needs characterising needs a test infrastructure
Then to be taken to a facility and tested = $$$$ and time+++
and a dedicated test team – who can make meaningful results
The packaging of components can effect interactions – here ADCs have had their plastic removed
Design Flow for Radiation Tolerance

1. Conceptual Design

2. Component Selection

3. Radiation Risk Classification

4. Type Testing
Design Flow for Radiation Tolerance

1. Conceptual Design
2. Component Selection
3. Radiation Risk Classification
4. Type Testing
5. Detailed Design
6. Dependability Analysis
7. Final Design
8. Component Batch Testing

Batch to batch deviation…
Wafer position deviation…
Work with vendors = $$$$
Design Flow for Radiation Tolerance

1. Conceptual Design
2. Component Selection
3. Radiation Risk Classification
4. Type Testing
5. Detailed Design
6. Dependability Analysis
7. Final Design

8. Component Batch Testing
9. Industrialisation
10. Fabrication
11. Board / Unit Testing
12. Burn-in / Run-in
13. Installation & Commissioning
14. Surveillance
acceptable failure rate < 40 per year...

Mean Time Between Failures > 200000 hours
(1000 units x 8800 hours per year) / 40

cross-section < $1 \times 10^{-12}$

SEE radiation electrical

> 300000 hours
FGClite Reliability Requirements

acceptable failure rate < 40 per year...

Mean Time Between Failures > 200000 hours

cross-section < $1 \times 10^{-12}$

> 300000 hours

SEE radiation
electrical

equipment lifetime > 25 years...

> 200 Grays

design for 25 years

DD / TID radiation
electrical
In Conclusion...
* radiation is everywhere, it can effect electronic systems
  – for dependable operation you cannot ignore this.
  – Particle accelerators actually create radiation fields.
  – certain failure modes are unique to radiation effects

As engineers building critical systems, you must consider the impact on your system

* radiation effects on electronics are difficult and costly to characterise
  – by far the best thing to do is avoid exposure to radiation.

  1) Remove the function          if not possible then
  2) Move away from the source    "
  3) Block radiation from the source    "
  4) Conceive a radiation tolerant system

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  – by far the best thing to do is avoid exposure to radiation.

Take a closer look.
Fin!
Thank You!
References and Further Reading

[1] M. Brugger and the R2E working group
http://www.cern.ch/r2e

http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=103957


[4] Extrapolated from W. Herr’s talk:
“Luminosity Performance Reach After LS1”

[5] Derived from

[6] Photographs courtesy Y. Thurel et al, from:
“LHC Power Converters the Proposed Approach”


[8] Figures and flow derived from work by Y. Thurel and S. Uznanski

[9] Pictures courtesy S. Uznanski, K. Motala, CERN