CERN

Radiation Issues

CERN Accelerator School – May 2014

To Take Away Today

* 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.

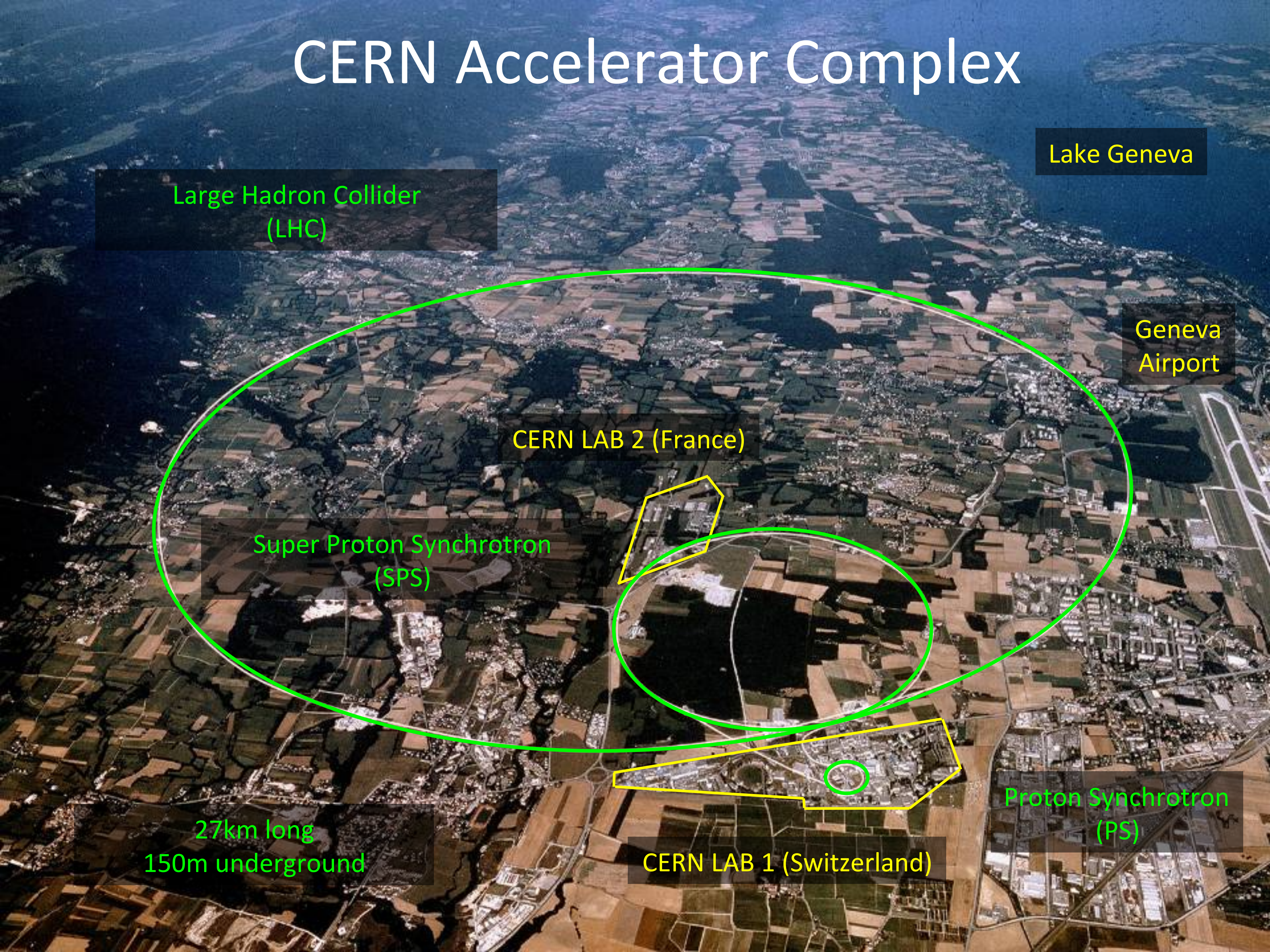
* radiation effects are difficult and costly to mitigate
  – by far the best thing to do is avoid exposure to radiation.

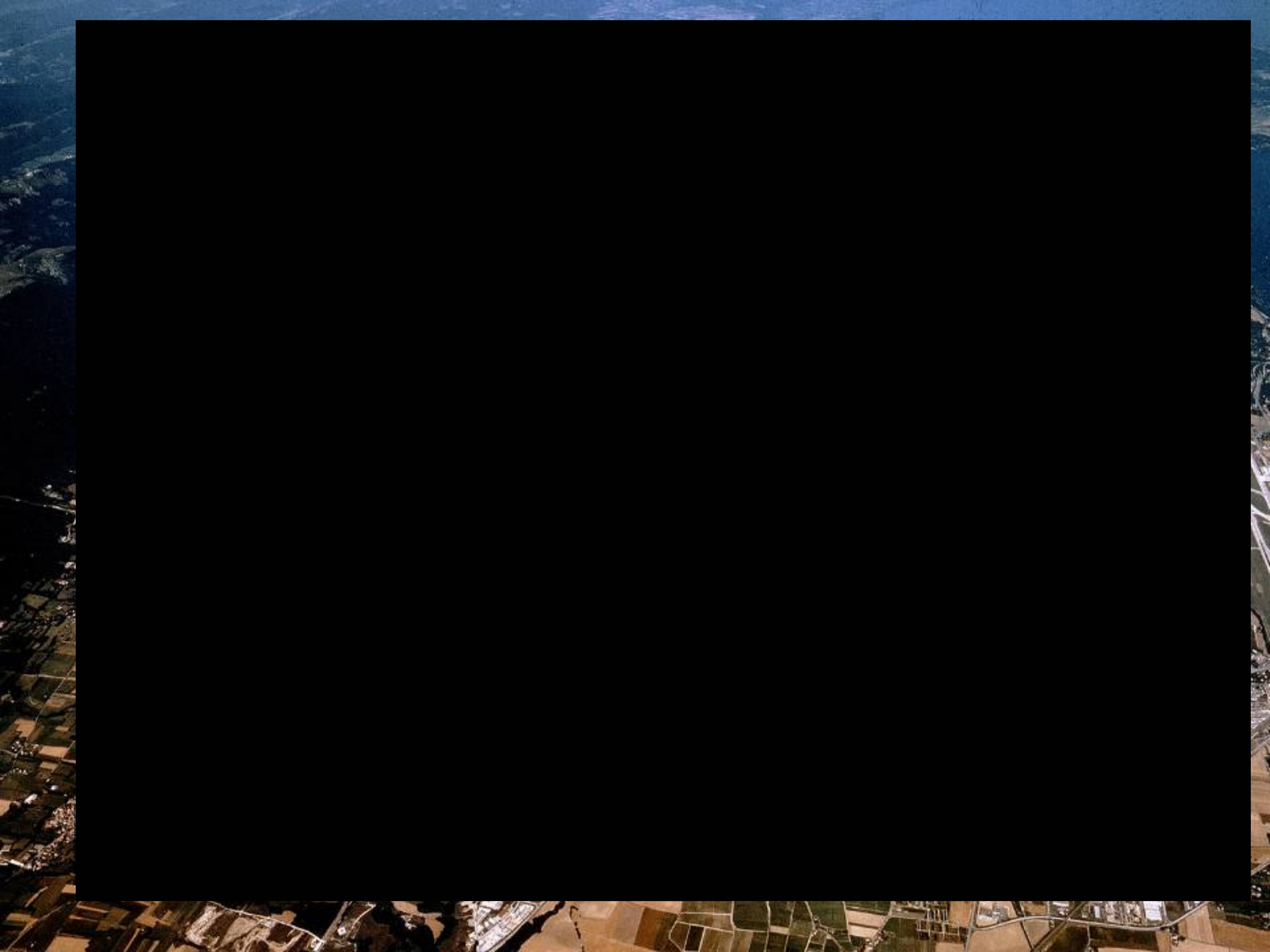
Contents

The Context…

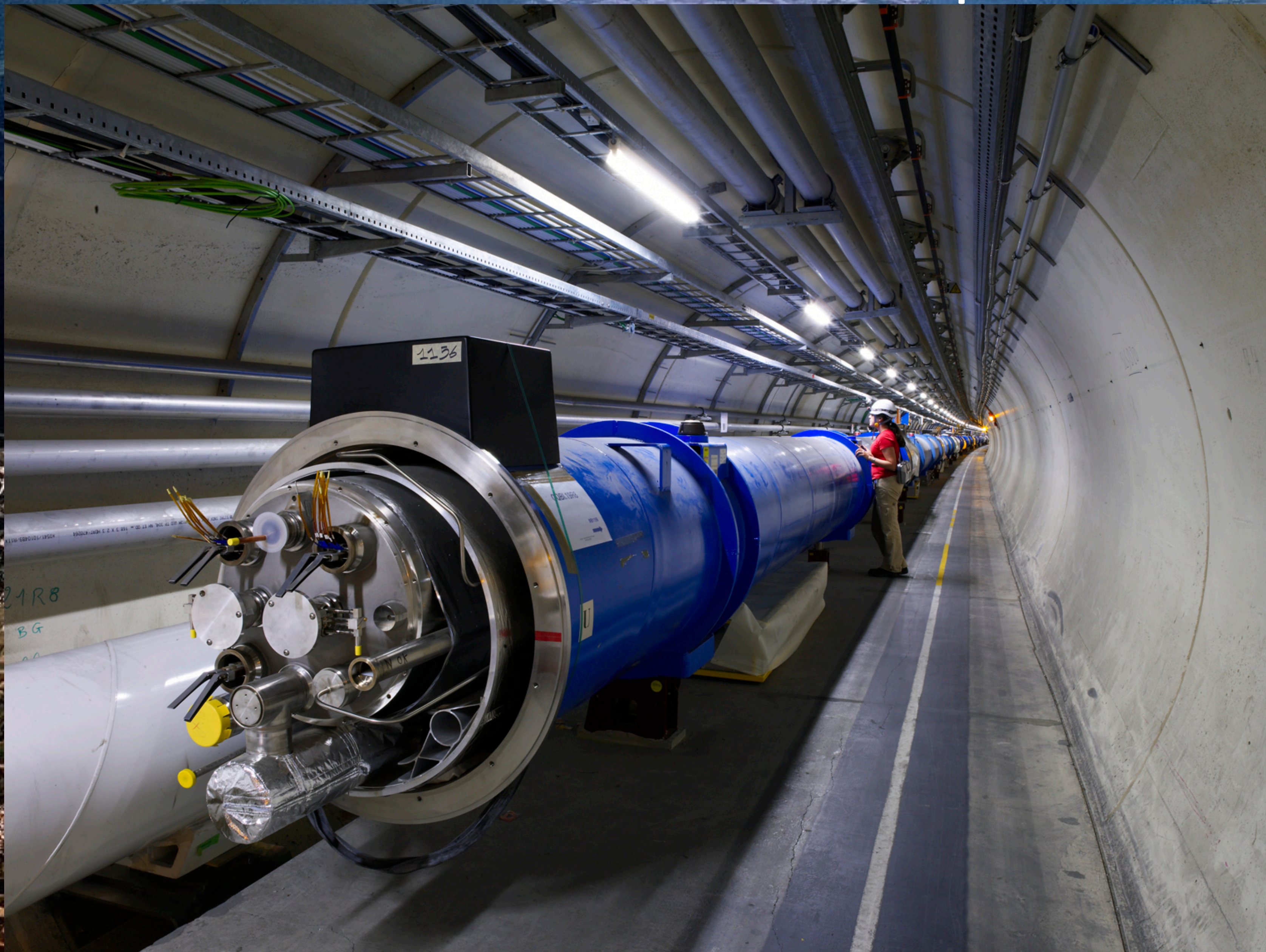
CERN Accelerator Complex

CERN Accelerator Complex





CERN Accelerator Complex



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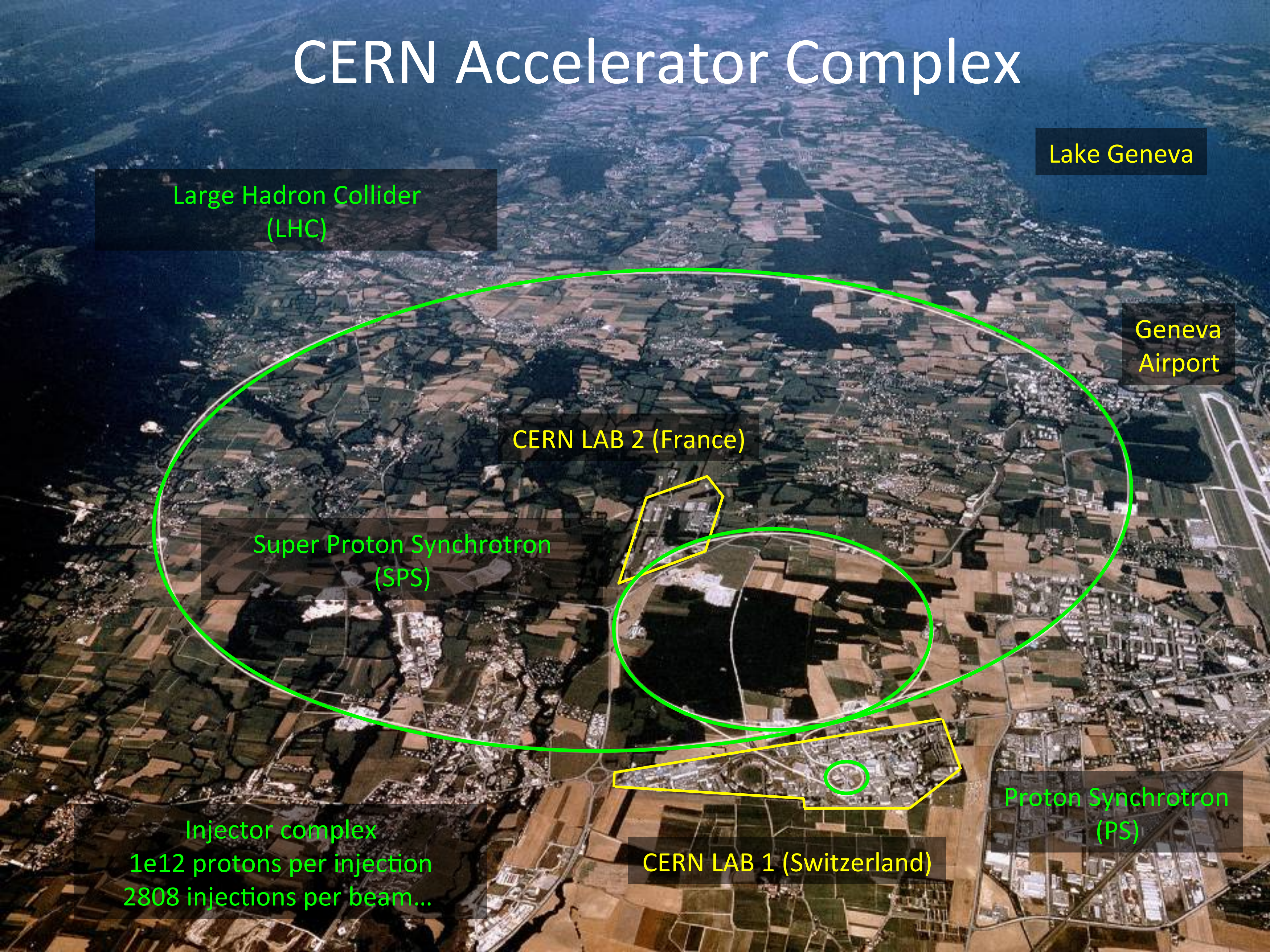
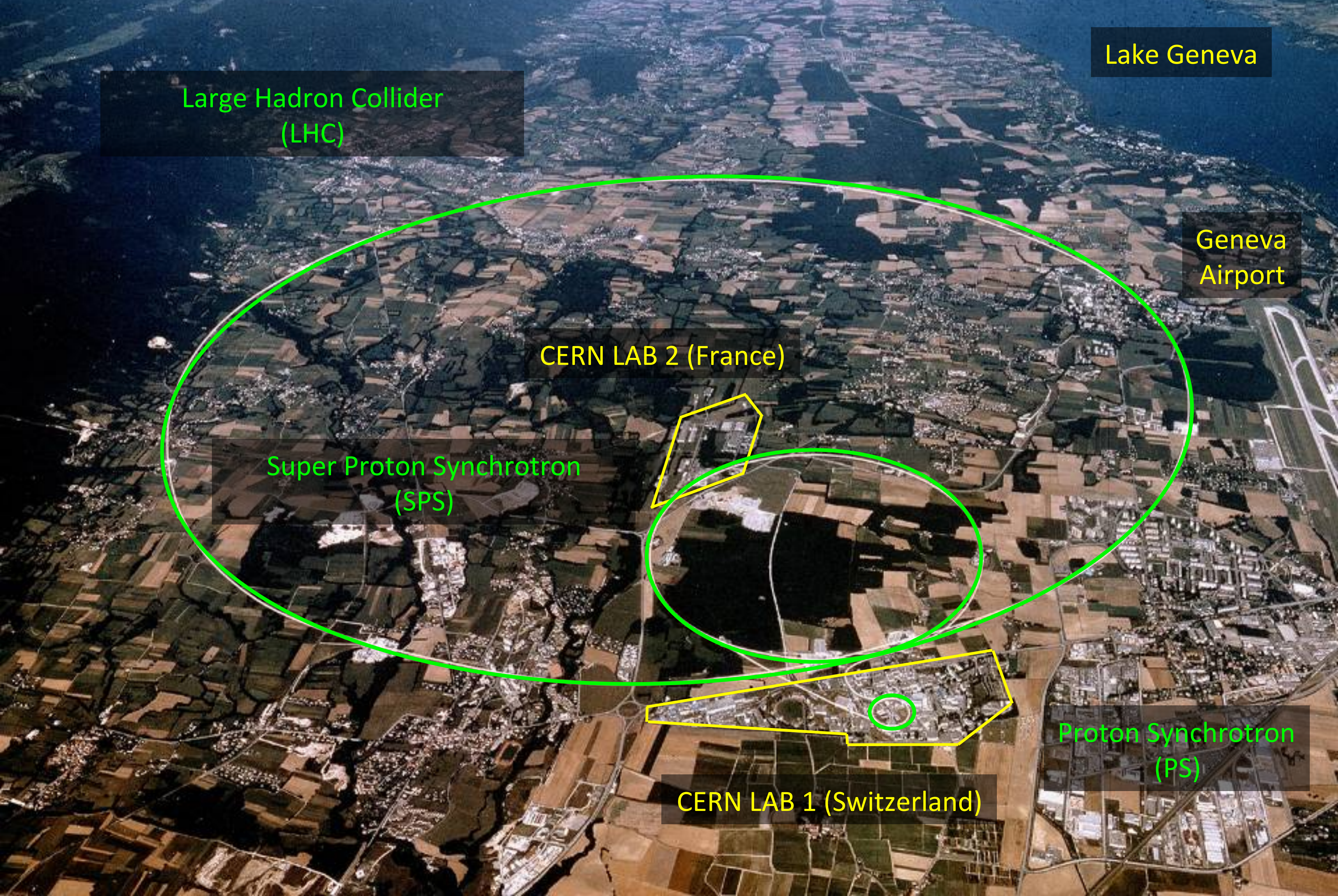

CERN Accelerator Complex
Lake Geneva
Large Hadron Collider
(LHC)
Geneva
Airport
CERN LAB 2 (France)
Super Proton Synchrotron
(SPS)
Proton Synchrotron
(PS)
Injector complex
1e12 protons per injection
2808 injections per beam…
CERN LAB 1 (Switzerland)

CERN Accelerator Complex



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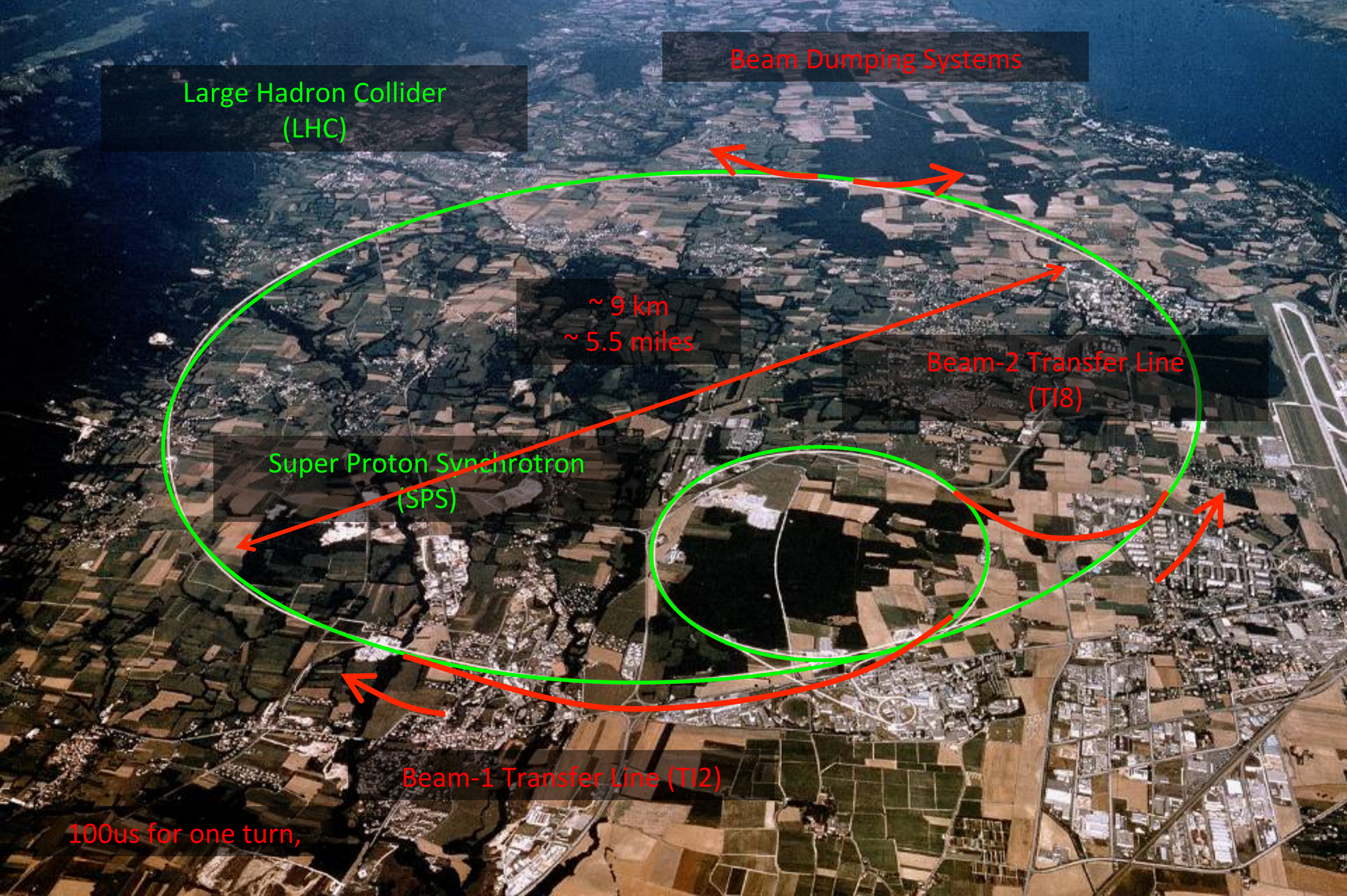

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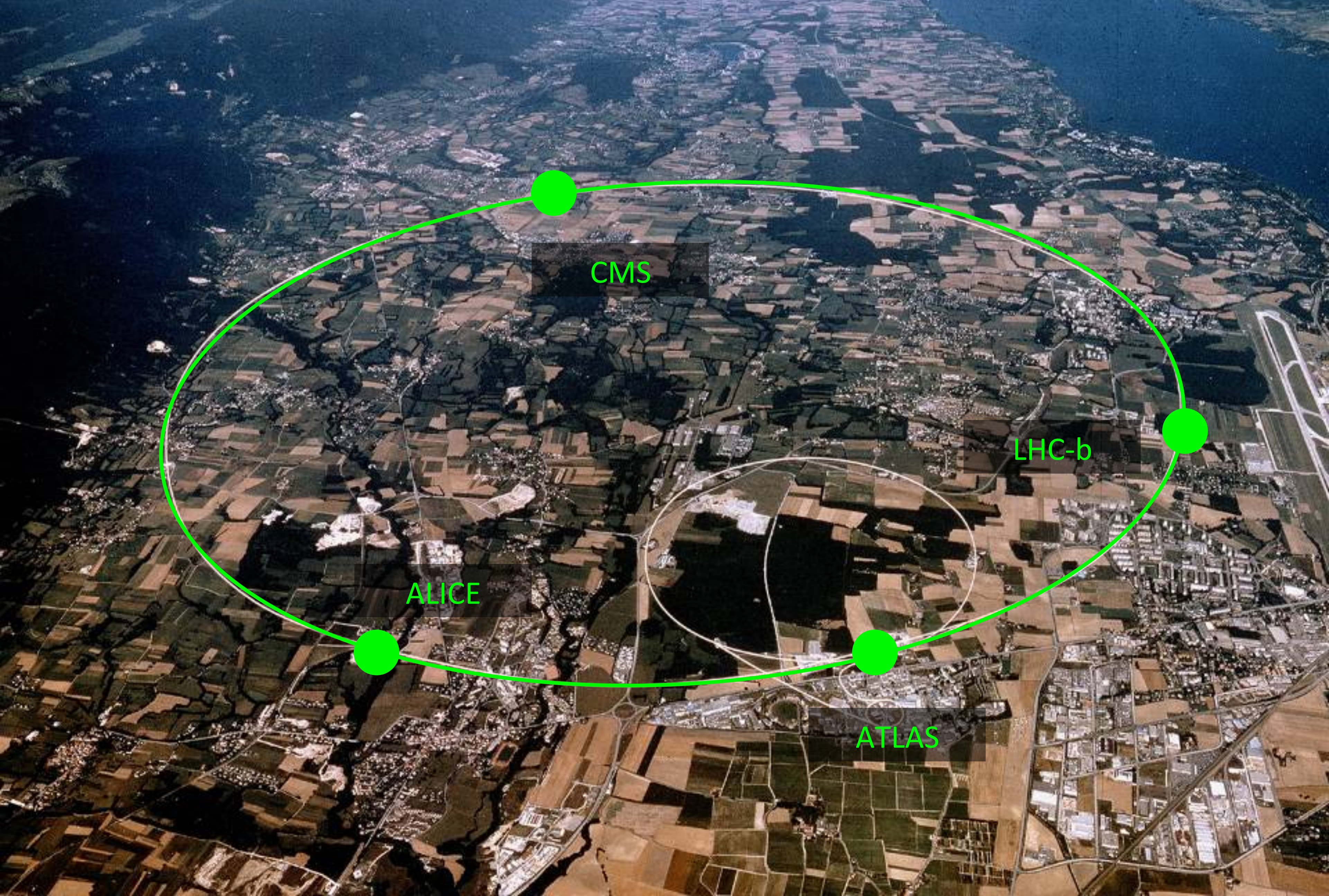
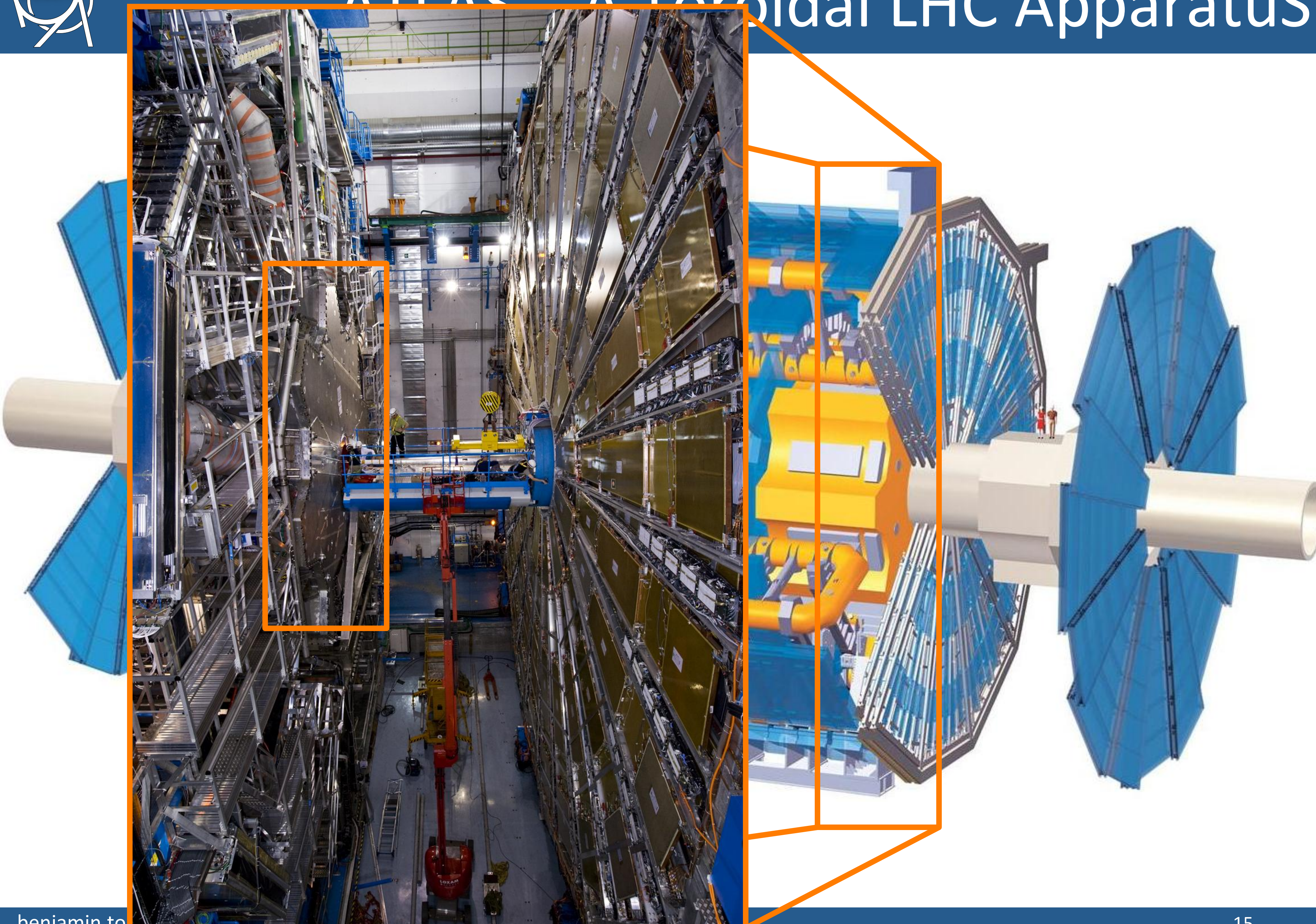


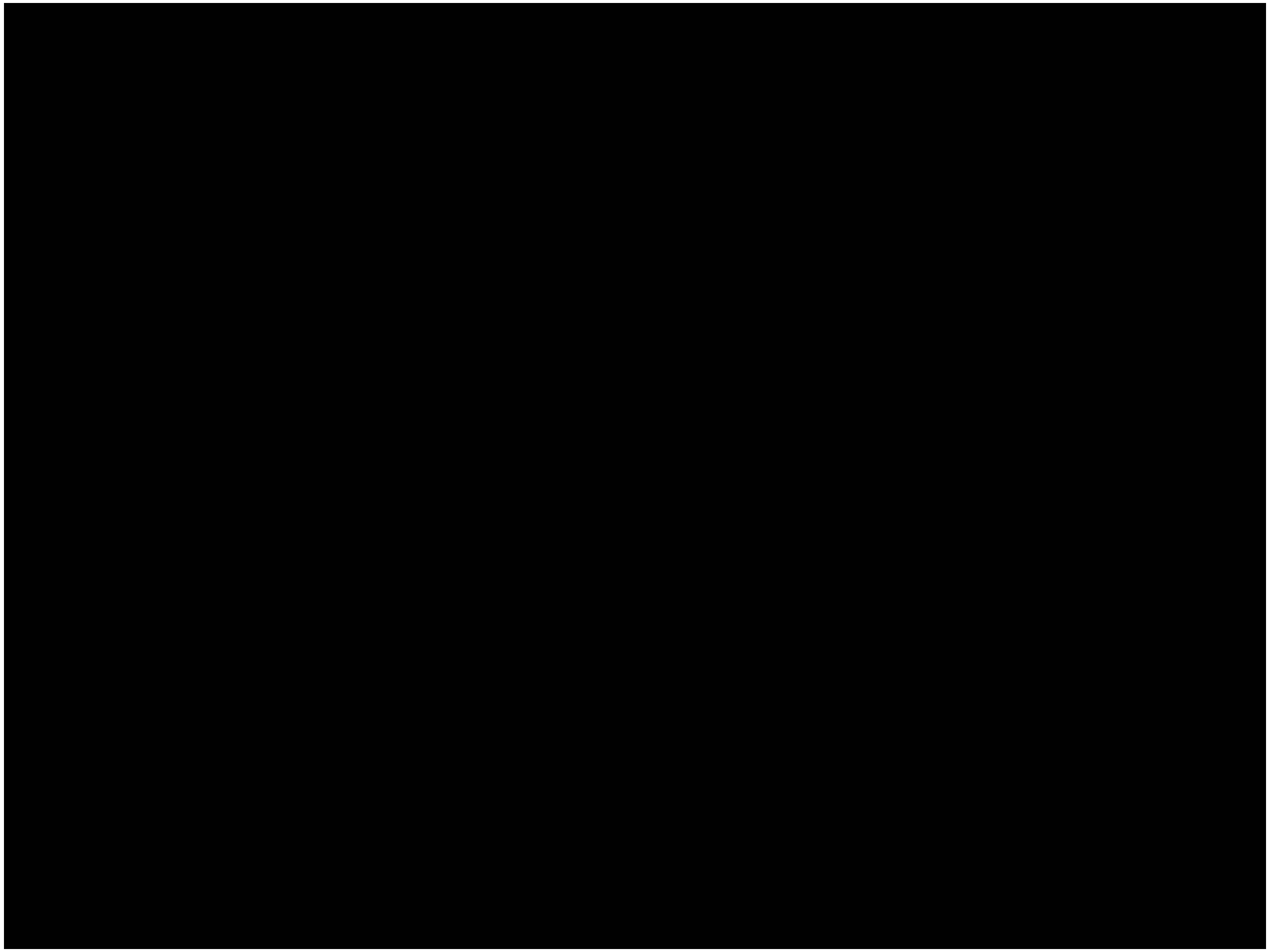
ATLAS – A Toroidal LHC ApparatuS



ATLAS – A Toroidal LHC ApparatuS

Collisions

~10^9 proton-proton collisions per second

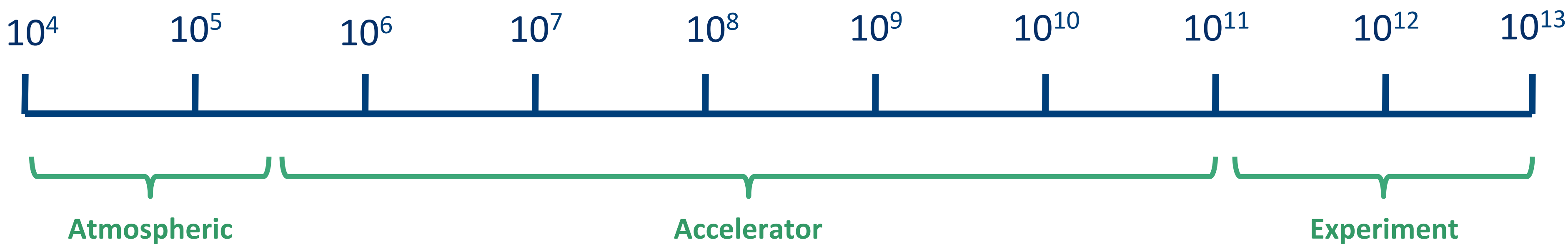


Massive amounts of data generated – all must be processed
new particles are rare – only a few events per day

Radiation

Example Particle Fluences

[particles (HEH) per cm^2 per year]



"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

[1]

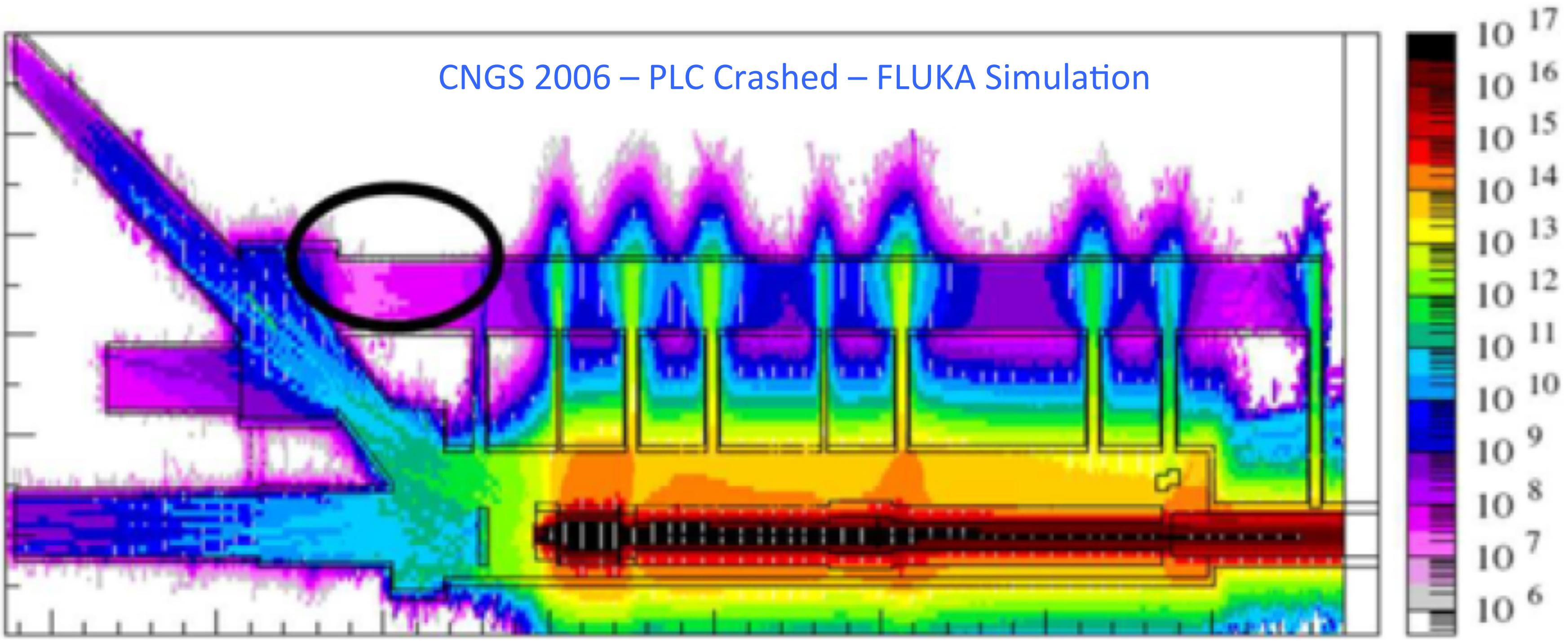
The Golden Rules

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



[1]

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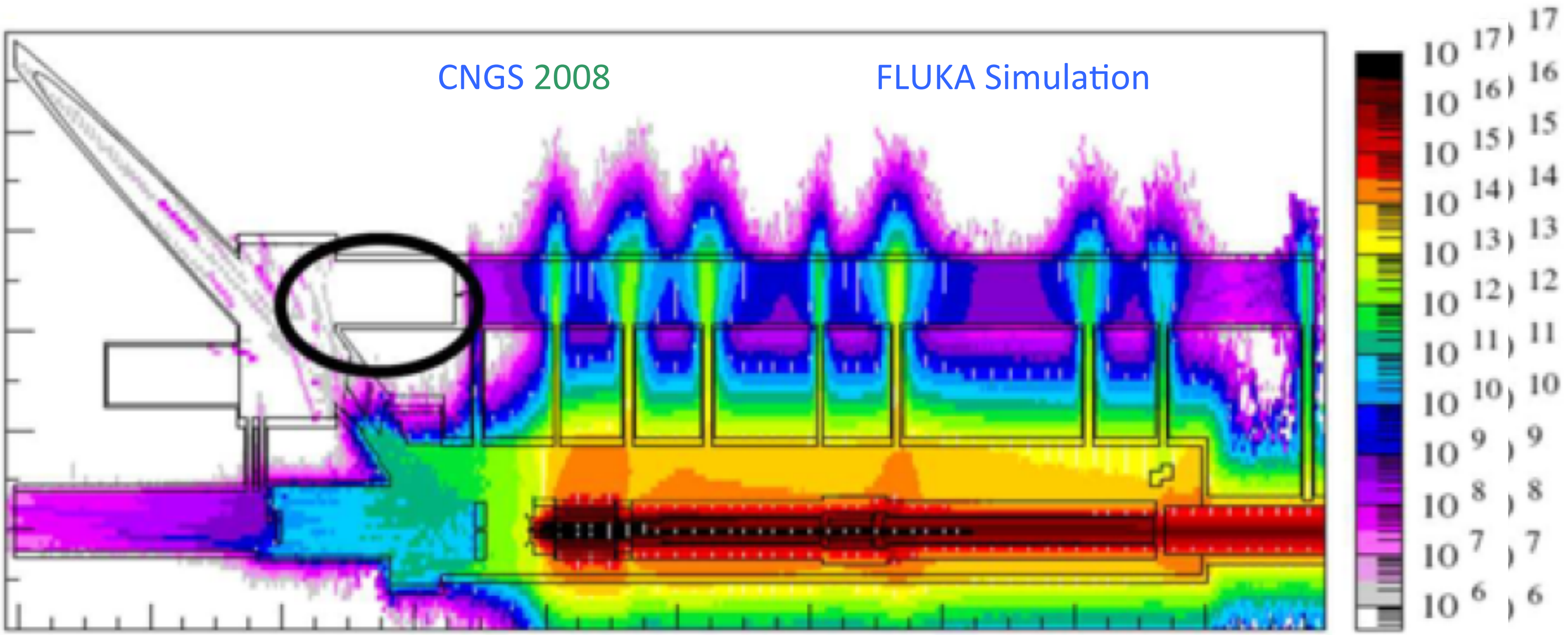


[1]

in a nutshell

1. Displacement Damage (DD)

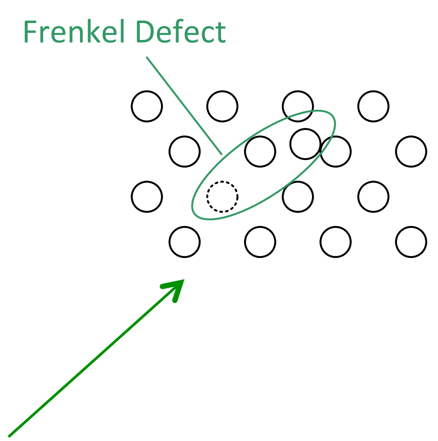
2. Total Ionising Dose (TID)

3. Single Event Effects (SEE)

cumulative (1, 2)

prompt (3)

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



defects accumulate and gradually destroy the silicon lattice

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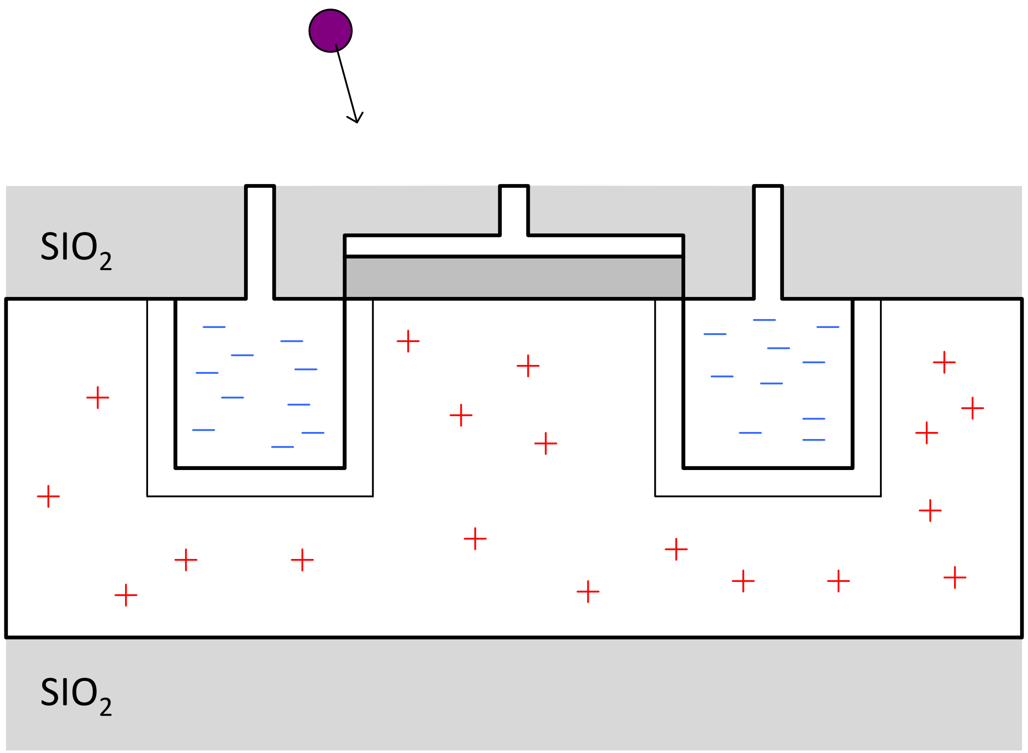

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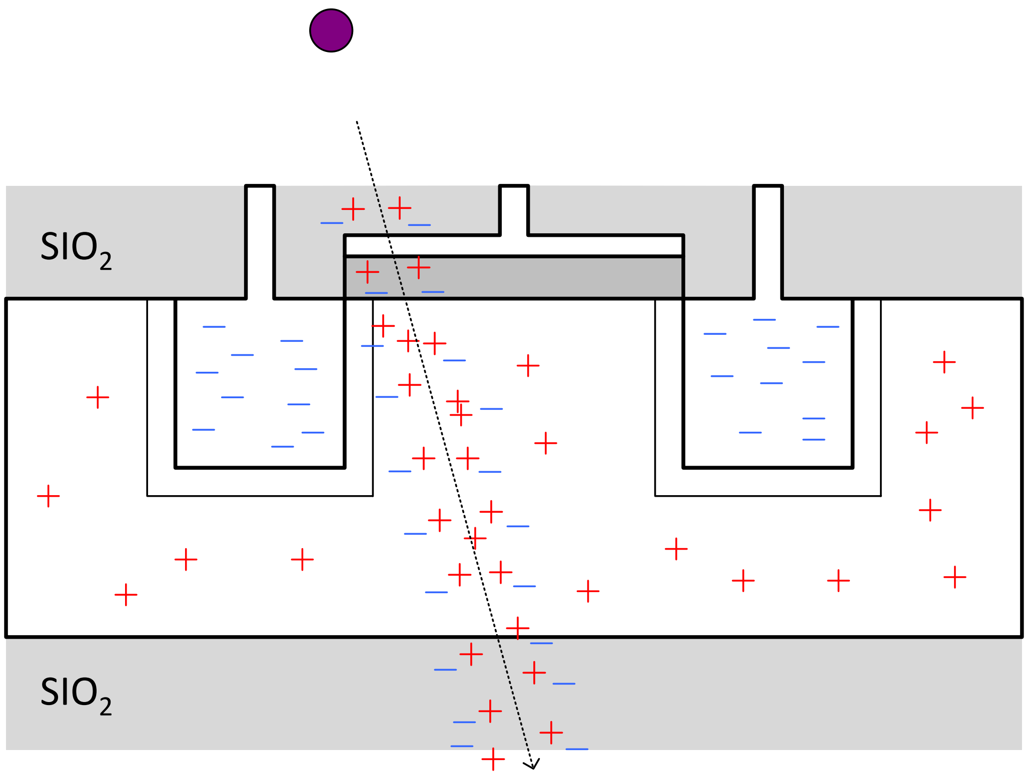

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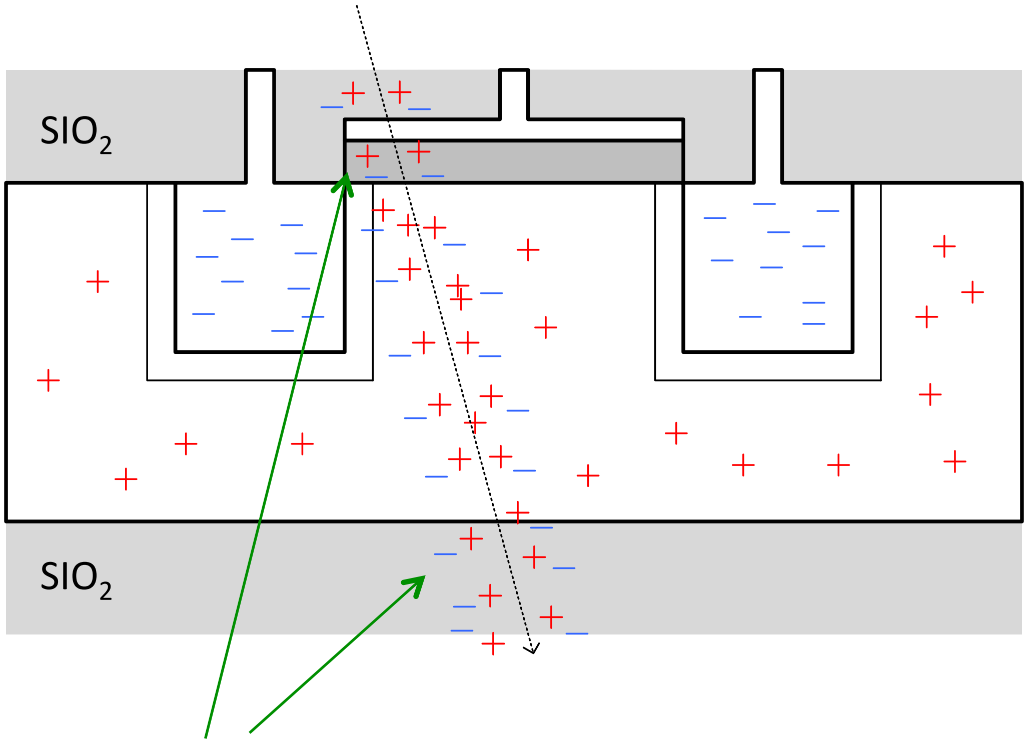

accumulate and gradually degrade the transistor function

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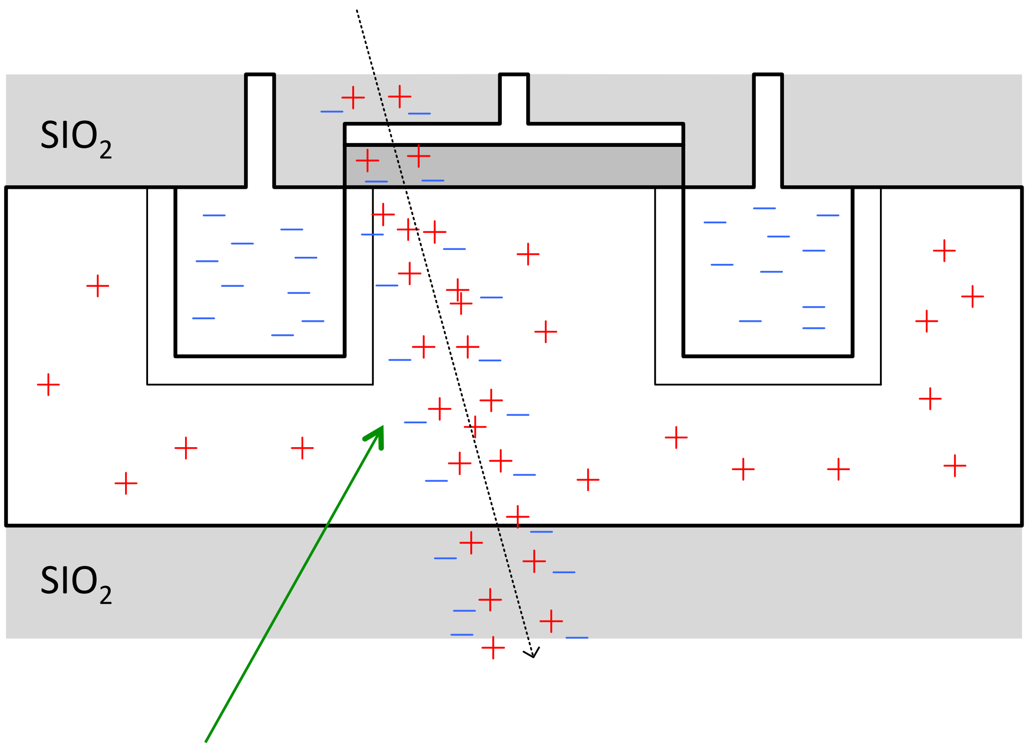
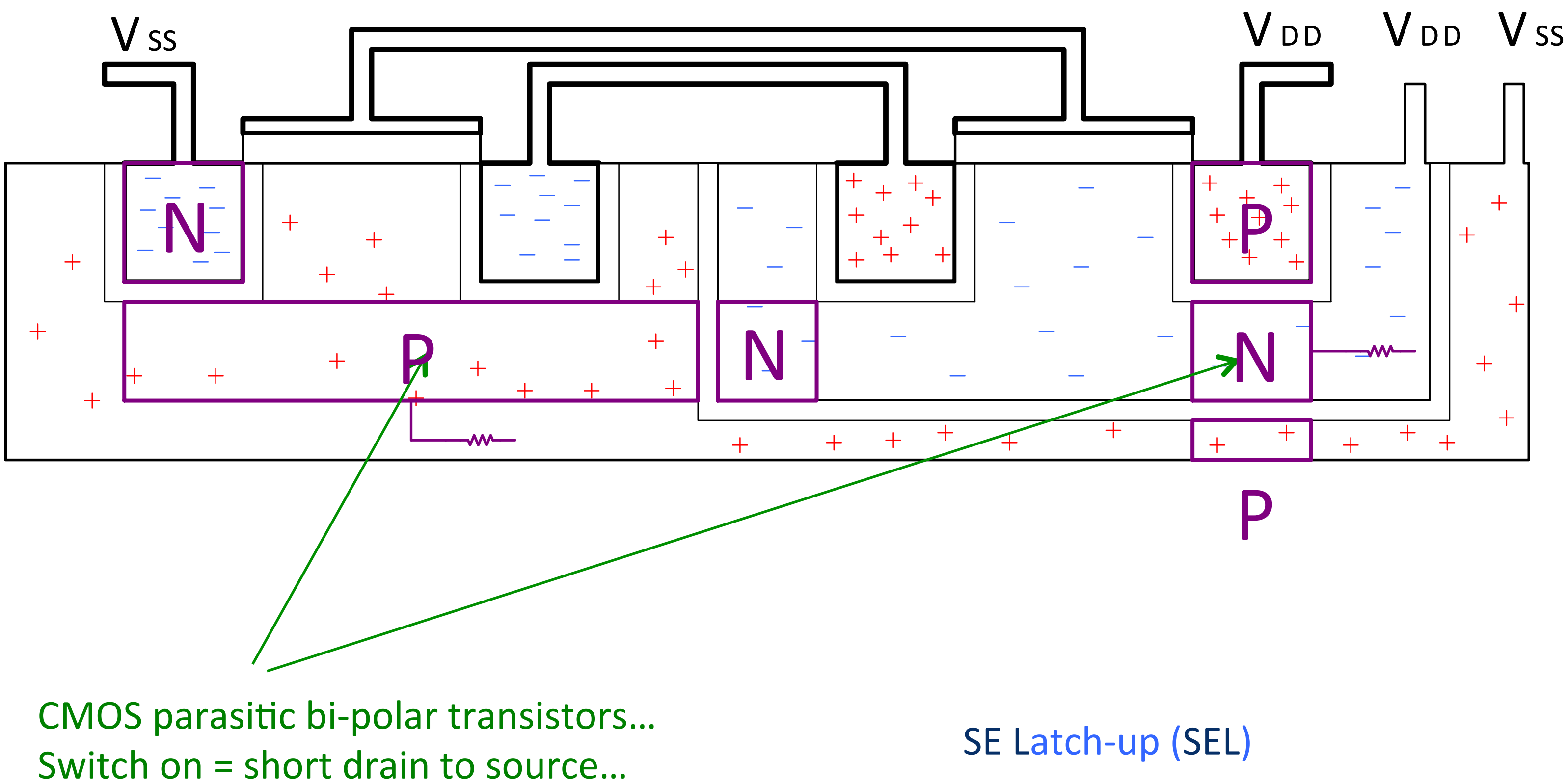


electrons collected by junctions creating parasitic current

SE Transient (SET) → SE Upset (SEU)
→ SE Functional Interrupt (SEFI)

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



SE Latch-up (SEL)

1. Displacement Damage (DD)

cumulative

Non-Ionising Energy Loss

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)

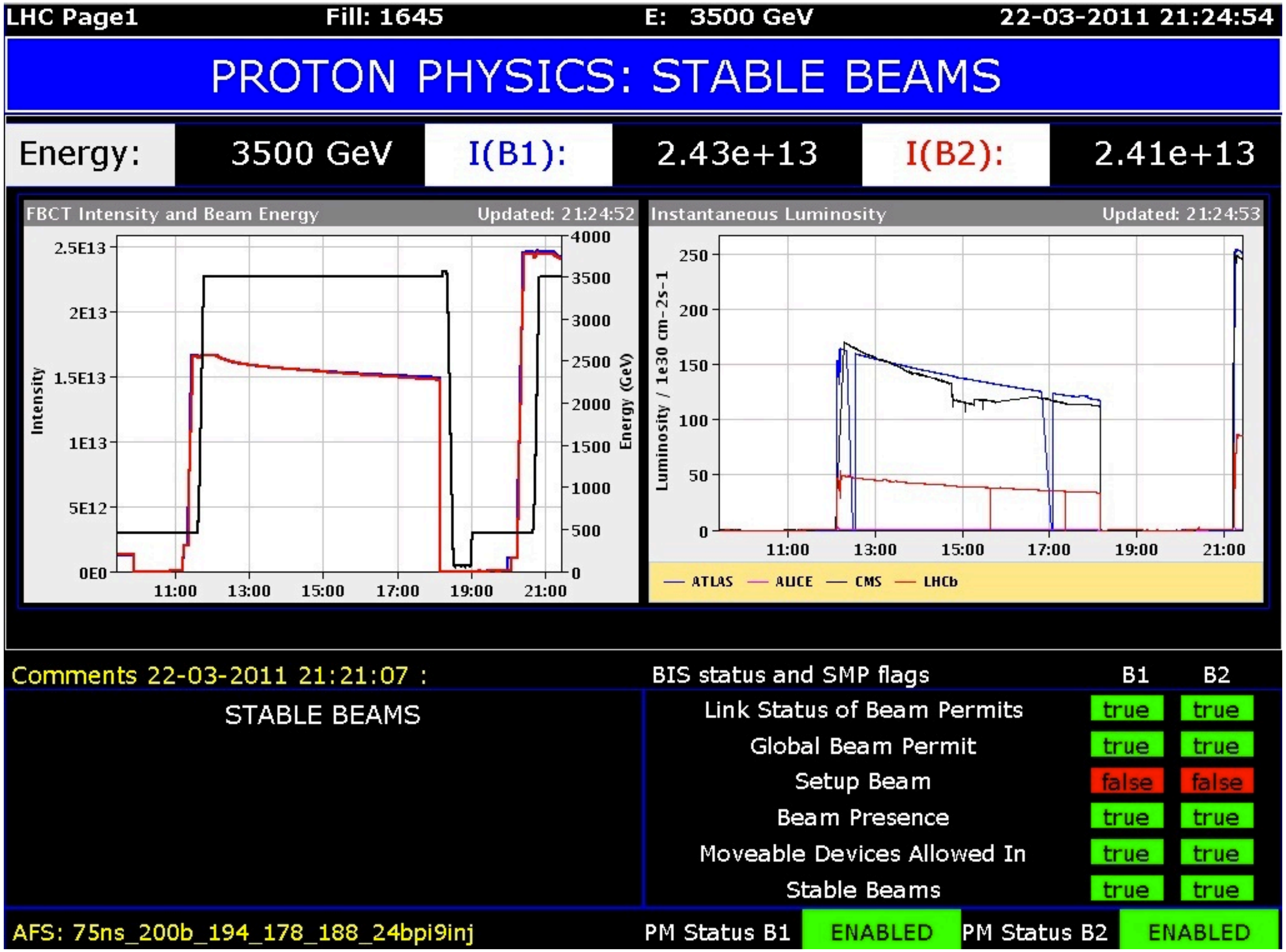
SE Latchup (SEL)

SE Burnout (SEB)

lifetime!

random in time failure!

A System In Design Today



LHC Page1
Fill: 1645
E: 3500 GeV
22-03-2011 21:24:54
PROTON PHYSICS: STABLE BEAMS
Energy:
3500 GeV
I(B1):
2.43e+13
I(B2):
2.41e+13
FBCT Intensity and Beam Energy
Updated: 21:24:52
Intensity
Energy (GeV)
Instantaneous Luminosity
Updated: 21:24:53
Luminosity / 1e30 cm-2s-1
ATLAS
ALICE
CMS
LHCb
Comments 22-03-2011 21:21:07 :
STABLE BEAMS
BIS status and SMP flags
B1
B2
Link Status of Beam Permits
true
true
Global Beam Permit
true
true
Setup Beam
false
false
Beam Presence
true
true
Moveable Devices Allowed In
true
true
Stable Beams
true
true
AFS: 75ns_200b_194_178_188_24bpi9inj
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

Year	Peak Energy [TeV]	Peak Intensity [p]	Peak Luminosity [cm^{-2} s^{-1}]
2010	3.5	4×10^{13}	2.0×10^{32}
2011	3.5	2.0×10^{14}	3.6×10^{33}
2012	4	2.2×10^{14}	7.7×10^{33}
LS_{1-2}	≈6.5	$\approx 3 \times 10^{14}$	$\approx 1 \times 10^{34}$

[2,3,4]

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[2,3,4]

LS1 = Long Shutdown #1 – from 2013 to 2014 – upgrade magnet interconnects
LS2 = Long Shutdown #2 …

Introduction

Power Converters = Power Supplies

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Direct impact on machine availability

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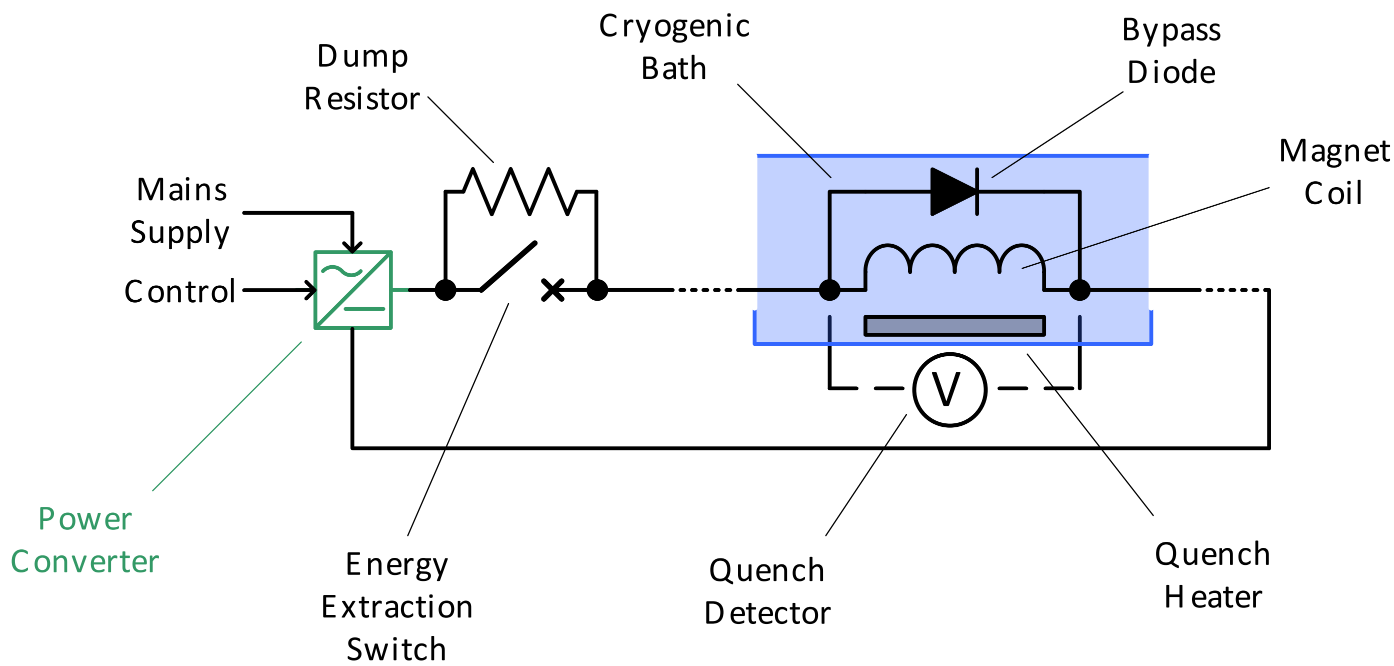
Increasing energy and intensity = increasing levels of radiation in machine environment [2,3,4]

existing converter controls would have low availability when higher energies and intensities are reached in the LS_{1-2} era

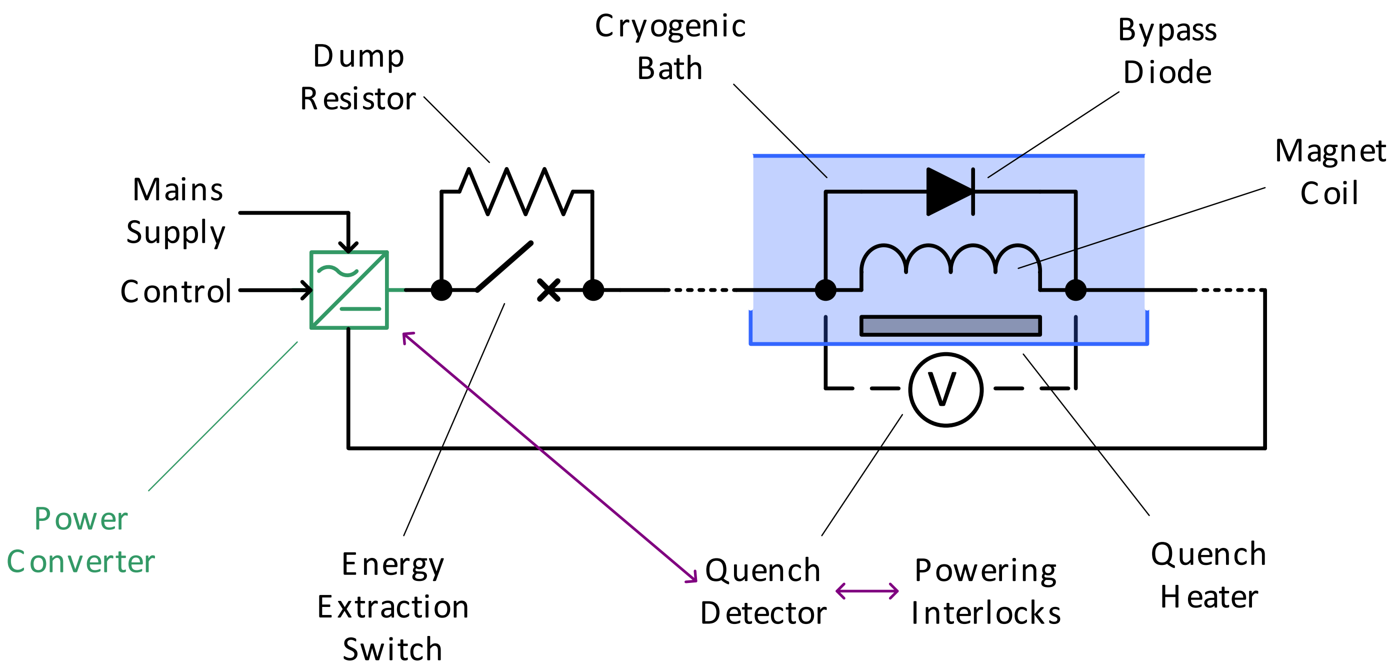
Function Generator Controller → Function Generator Controller lite

a design optimised for high availability in radiation = the next 25 years of LHC

Magnet Powering Circuit



Magnet Powering Circuit



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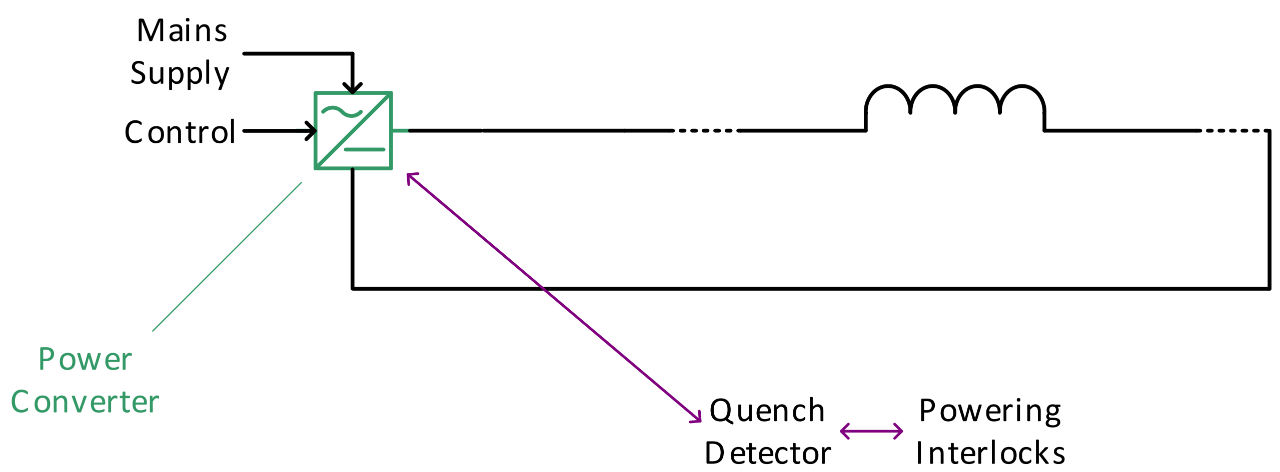
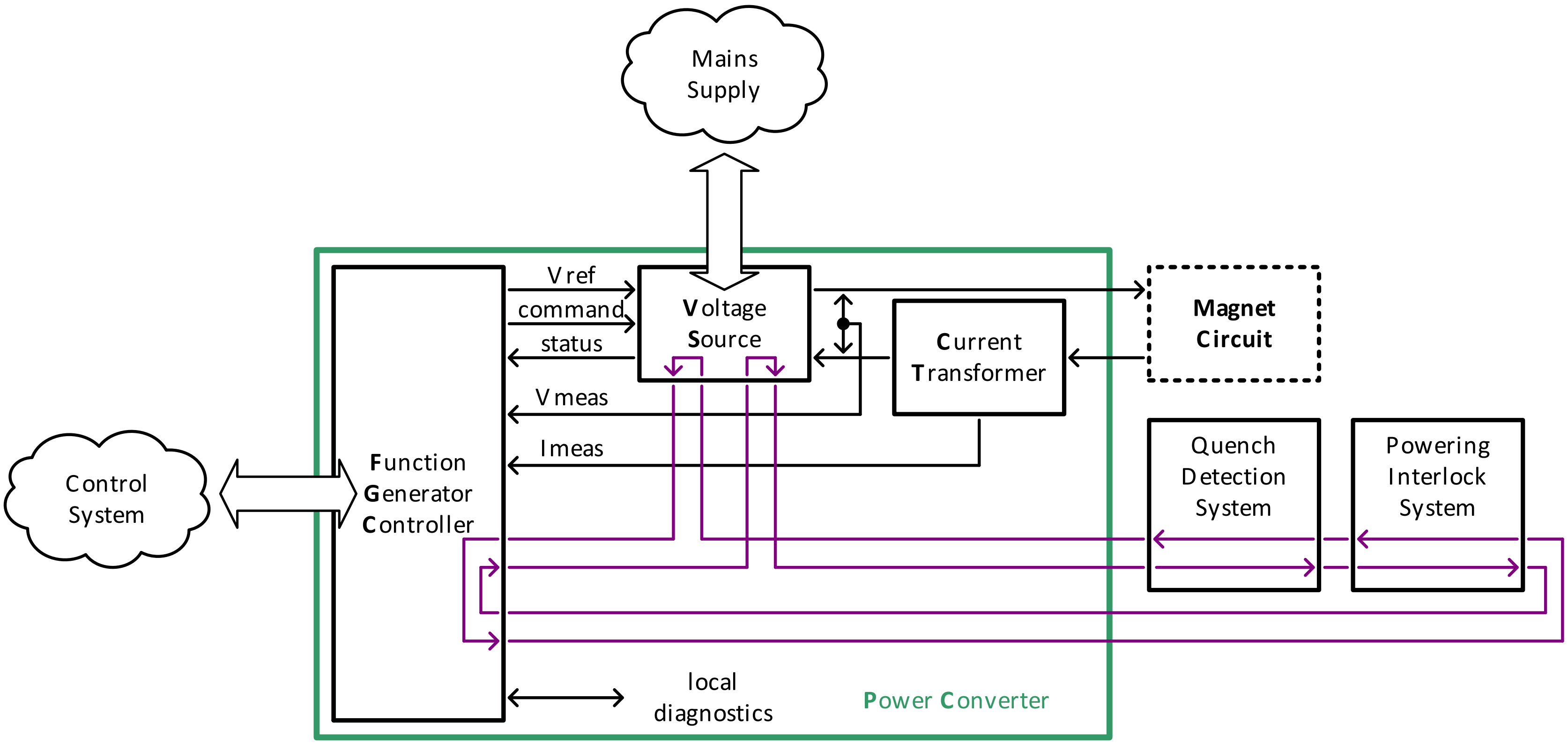
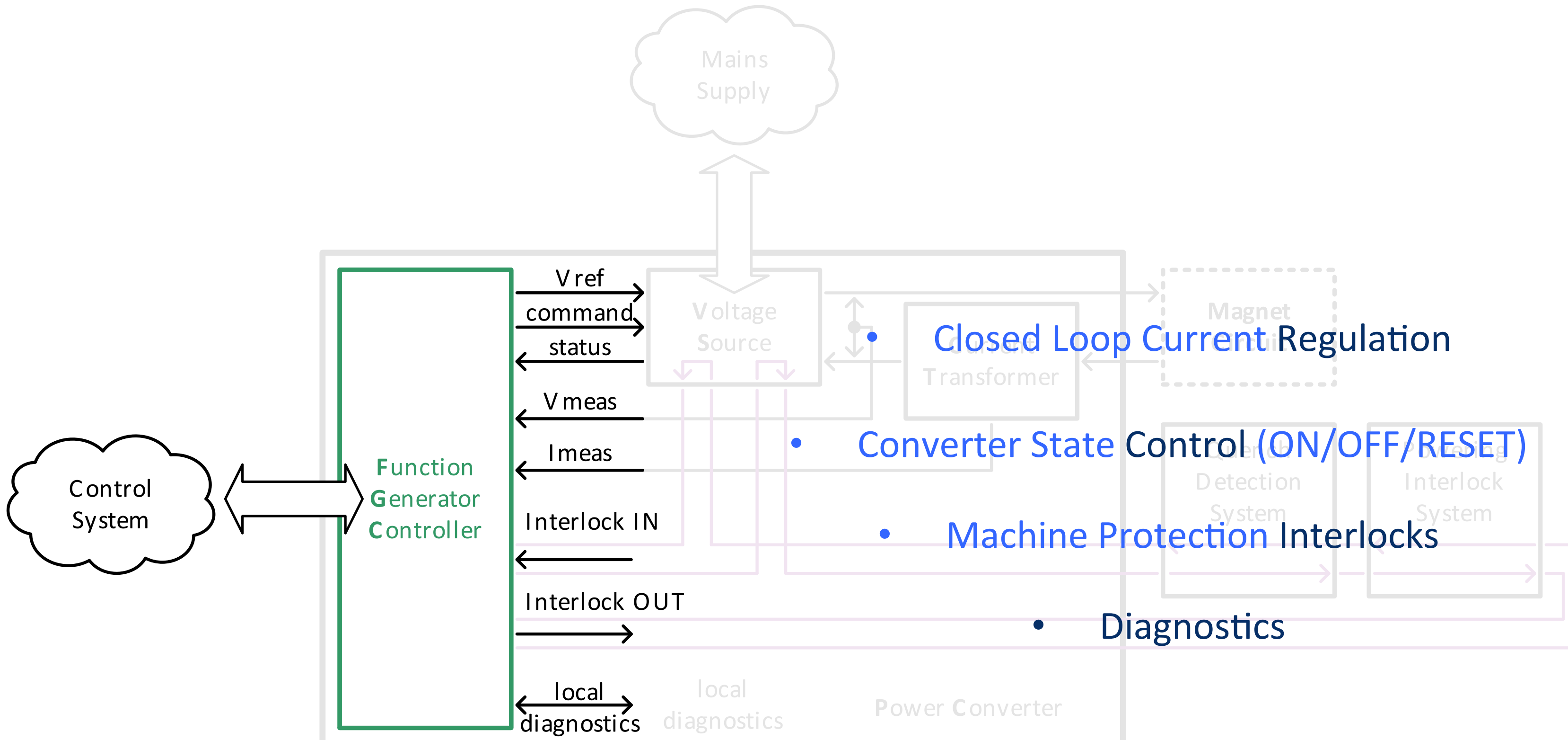


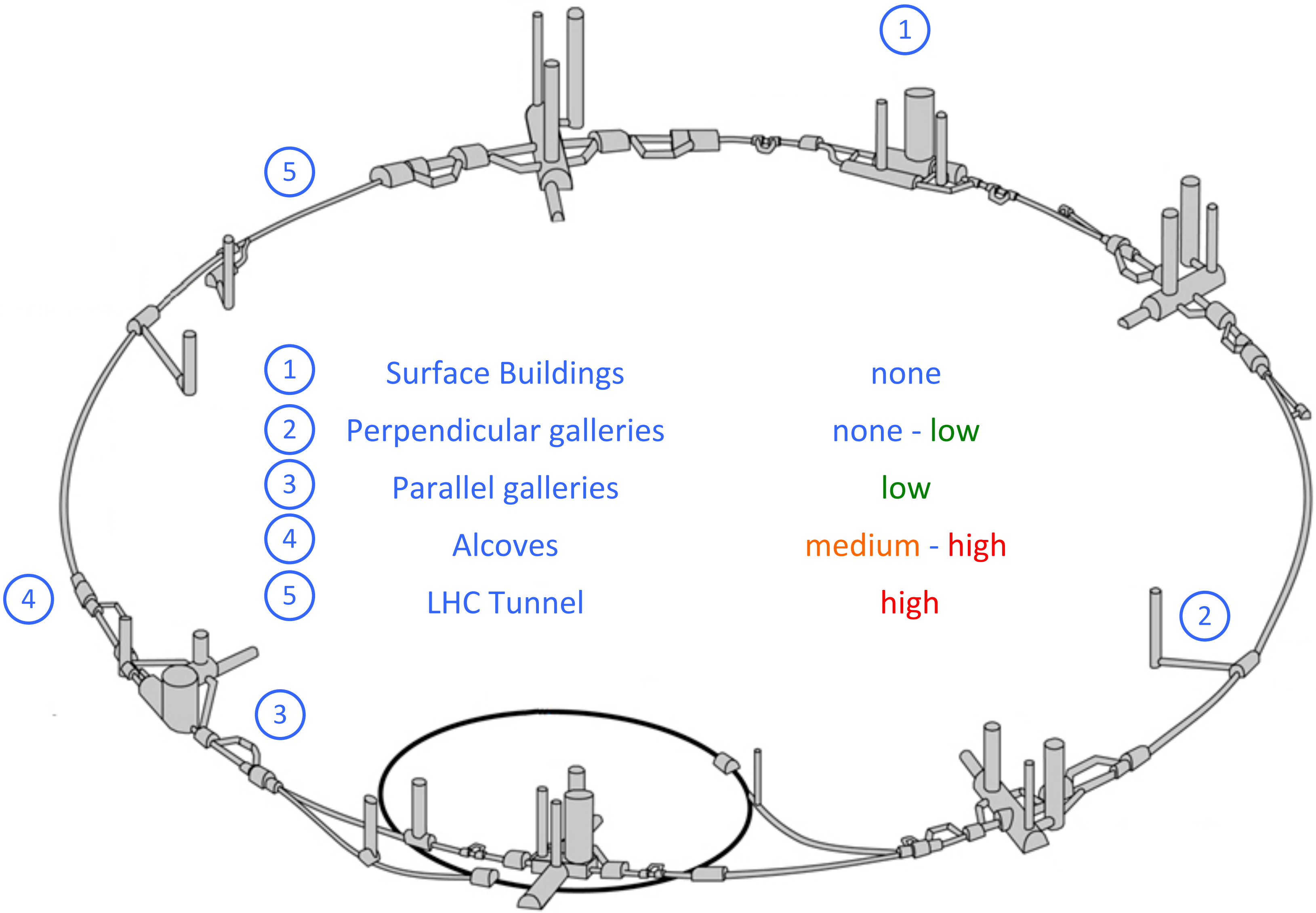
Power Converter





- 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:



[7]

Power converters are installed in one of five areas with machine radiation risks:

Power Converter Types

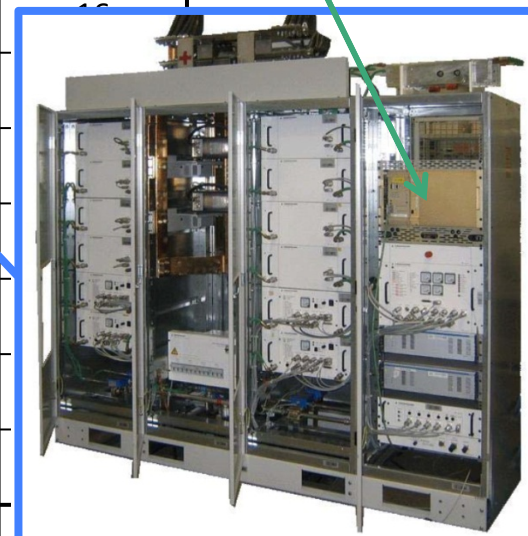
Converter Requirements			Quantity
Typical Use	Current	Voltage	
Main Dipoles	13000	190	8
Main Quadrupoles	13000	18	16
Quadrupole Circuits	4-6-8000	8	189
Warm Circuits	1000	450-950	16
Sextupole Circuits	600	40	37
Octupole Circuits	600	10	400
Orbit Correctors	120	10	290
Orbit Correctors	60	8	752
		Total	**>1700**

[5,6]

Power Converter Types

Function Generator Controller

...equirements	Current	Voltage	Quantity
	13000	190	8
	13000	18	
	4-6-8000	8	
	1000	450-950	
Sextupole Circuits	600	40	
Octupole Circuits	600	10	
...ectors	120	10	
...ectors	60	8	
		Total	



[5,6]

Power Converter Types

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	13000	190	8
	13000	18	[illegible]
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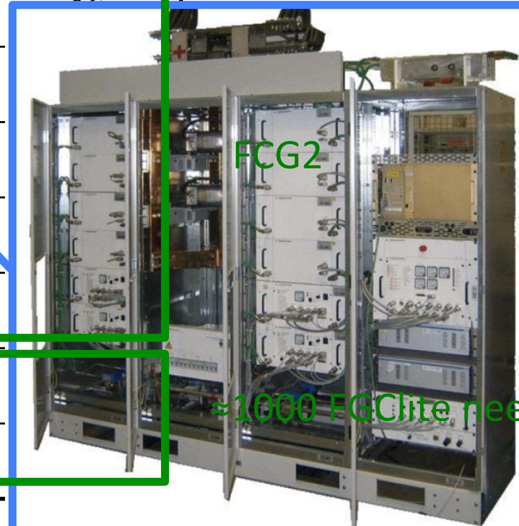
		Total	[illegible]

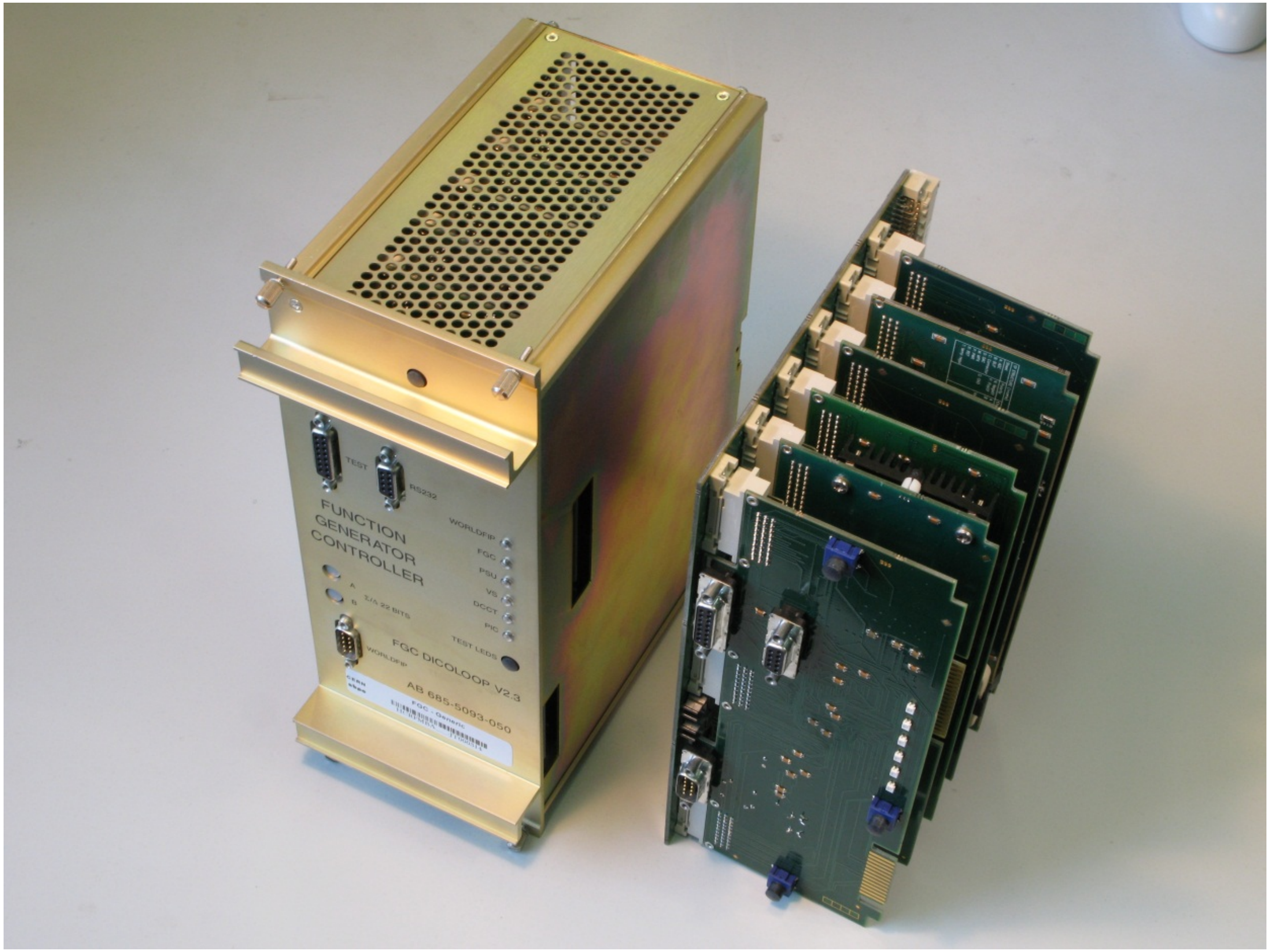


FCG2

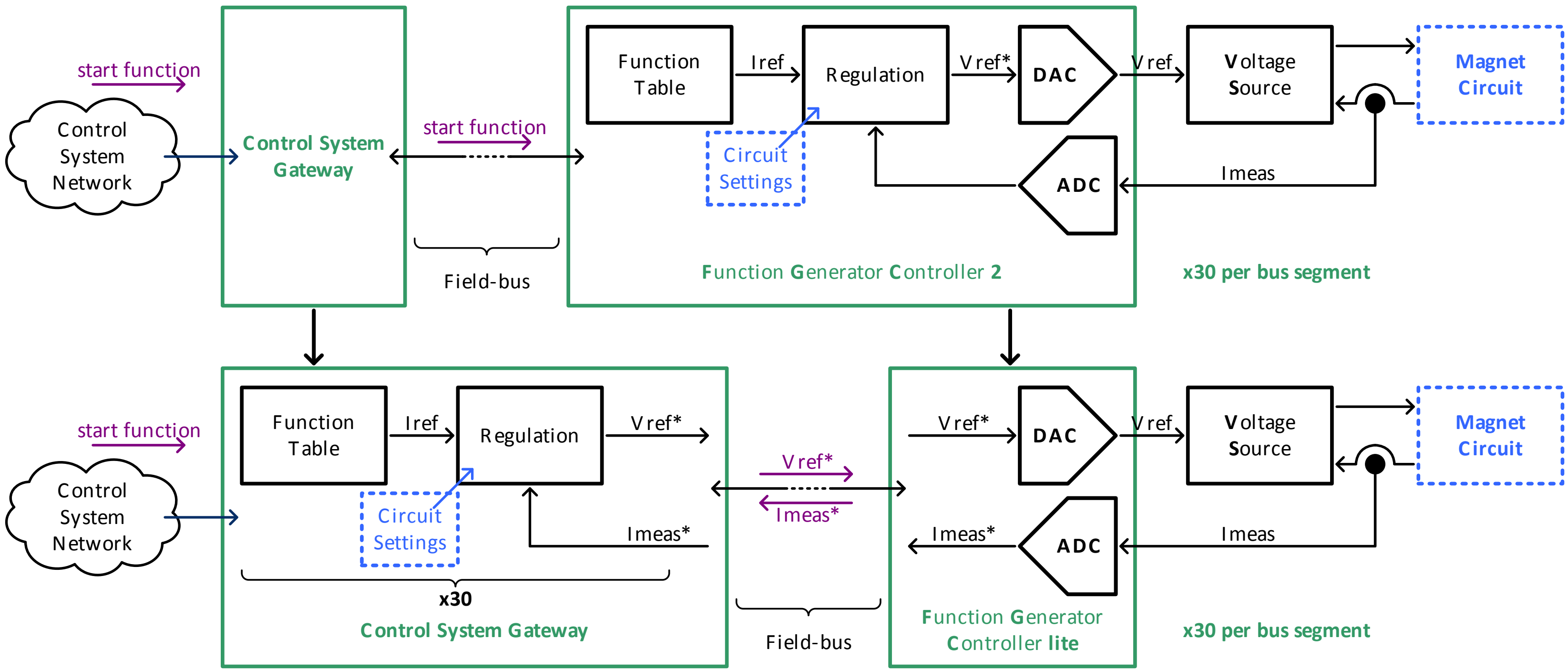
≈1000 FGClite needed…

[5,6]

FGC2


TEST
RS232
FUNCTION
GENERATOR
CONTROLLER
WORLDFIP
FGC
PSU
VS
DCCT
PIC
TEST LEDS
FGC DICOLOOP V2.3
AB 685-5093-050

Function



start function
Control
System
Network
Control System
Gateway
start function
Field-bus
Function
Table
Iref
Regulation
Vref*
DAC
Vref
Voltage
Source
Magnet
Circuit
Circuit
Settings
ADC
Imeas
Function Generator Controller 2
x30 per bus segment
start function
Control
System
Network
Function
Table
Iref
Regulation
Vref*
Circuit
Settings
Imeas*
x30
Control System Gateway
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Imeas*
Field-bus
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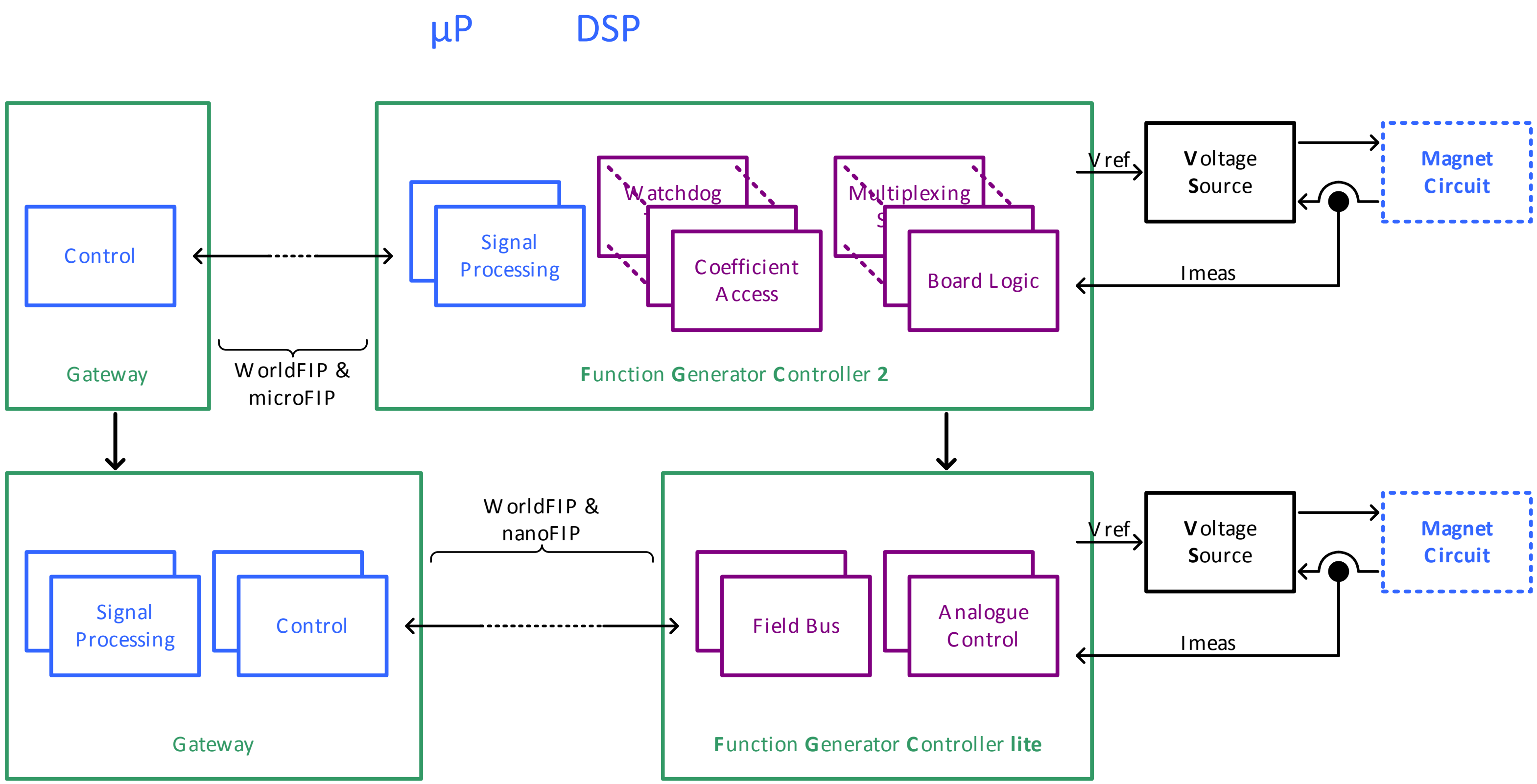
DAC
Vref
Voltage
Source
Magnet
Circuit
Imeas*
ADC
Imeas
Function Generator
Controller lite
x30 per bus segment

Software versus Programmable Logic



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 (C_0) components known to be resistant, or easily replaced, conceptual design not influenced by these components.

Resistors, capacitors, diodes, transistors…

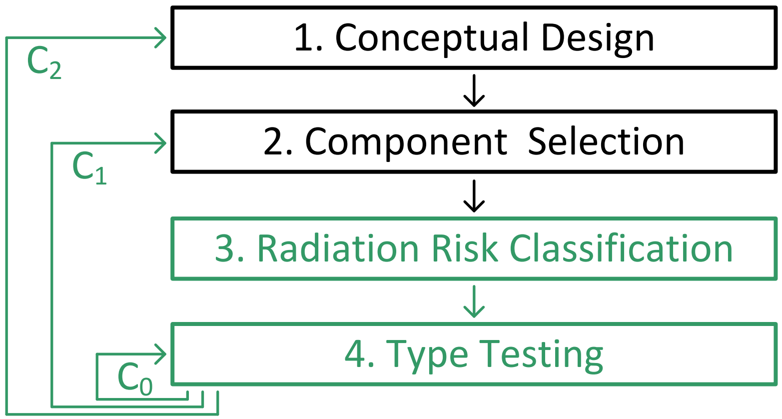
Class 1 (C_1) components potentially susceptible to radiation, in less-critical parts of the system. Substitution of parts or mitigation of issues is possible with a re-design.

Regulators, memory, level translators…

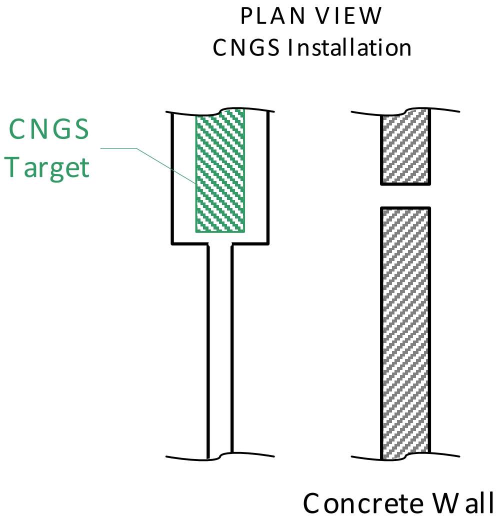
Class 2 (C_2) components potentially susceptible to radiation, in more-critical parts of the system. The conceptual design is compromised if these components do not perform well. Substitution of parts or mitigation of issues would be difficult.

ADC, FPGA, fieldbus driver

Design Flow for Radiation Tolerance



Principle for Test-bench "CIRX"



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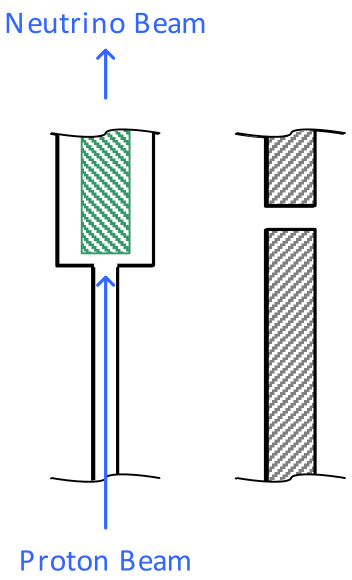

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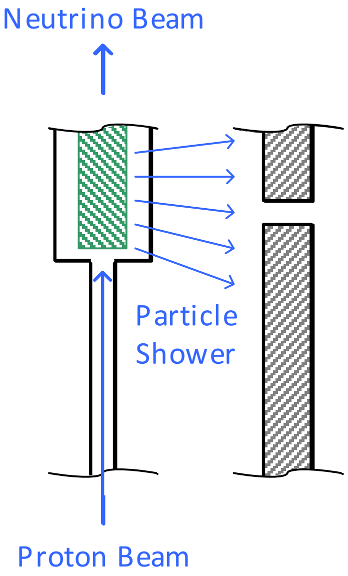

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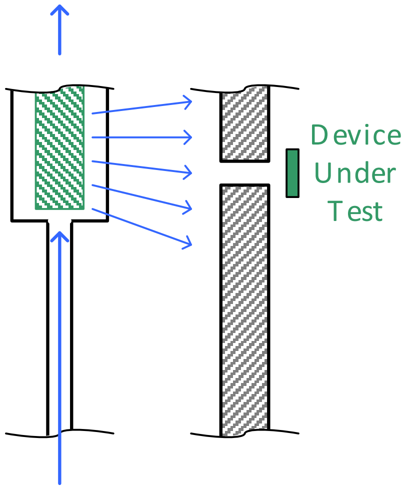

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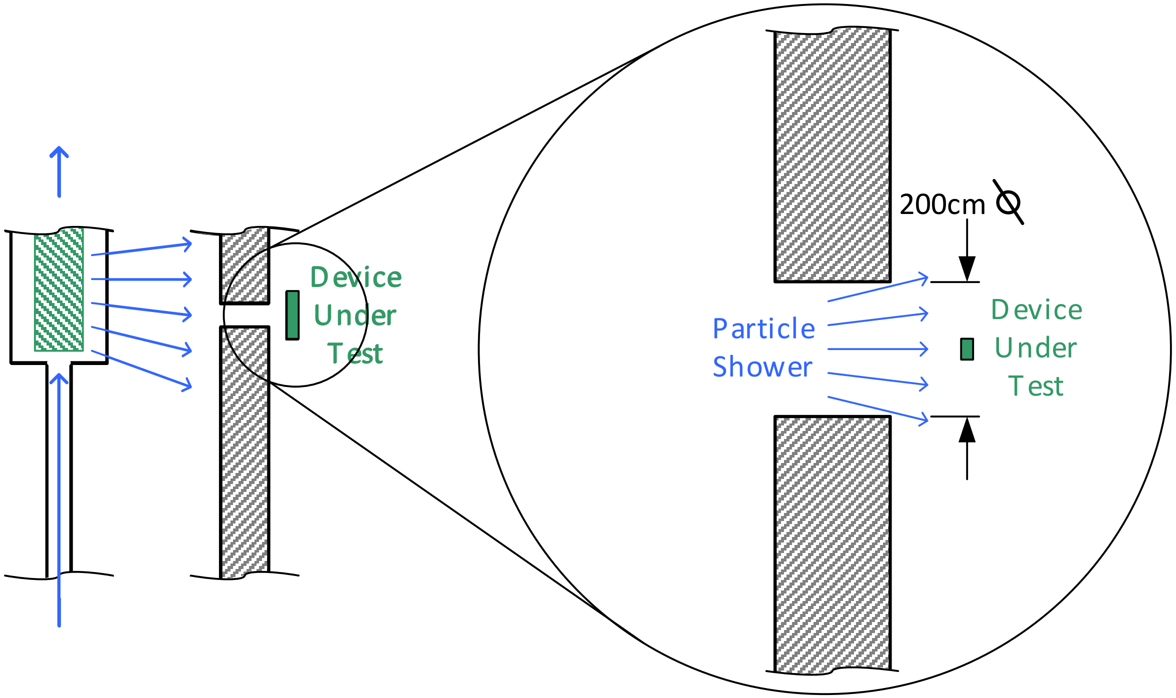

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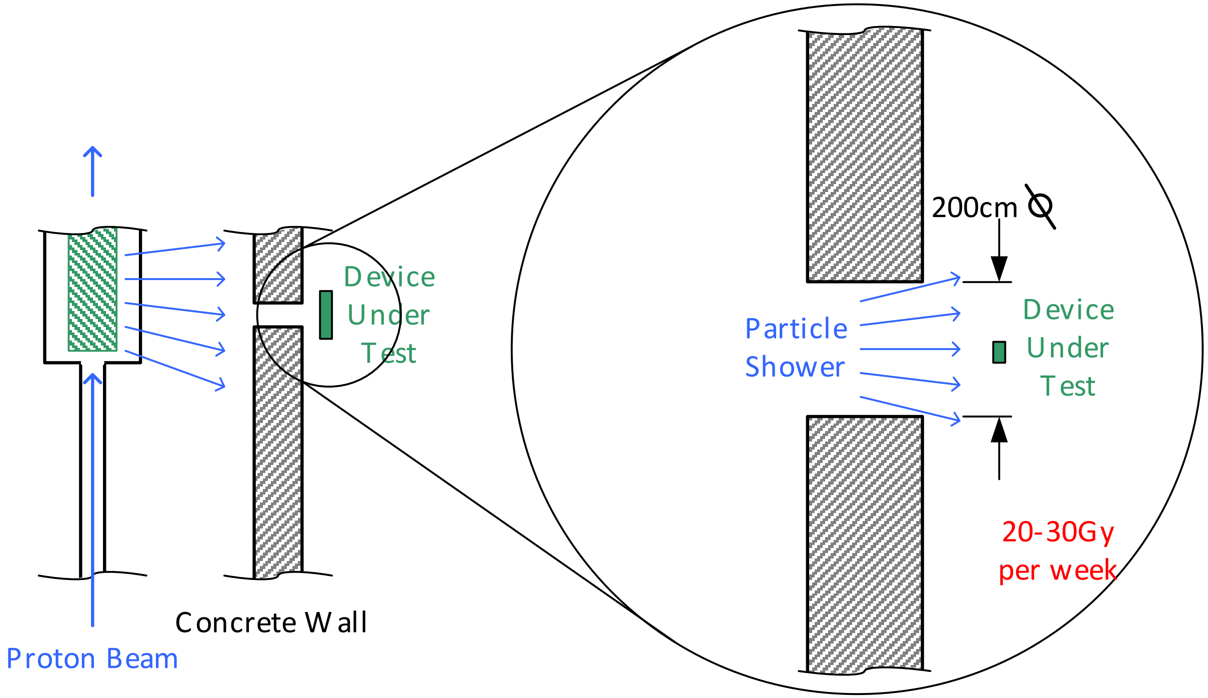

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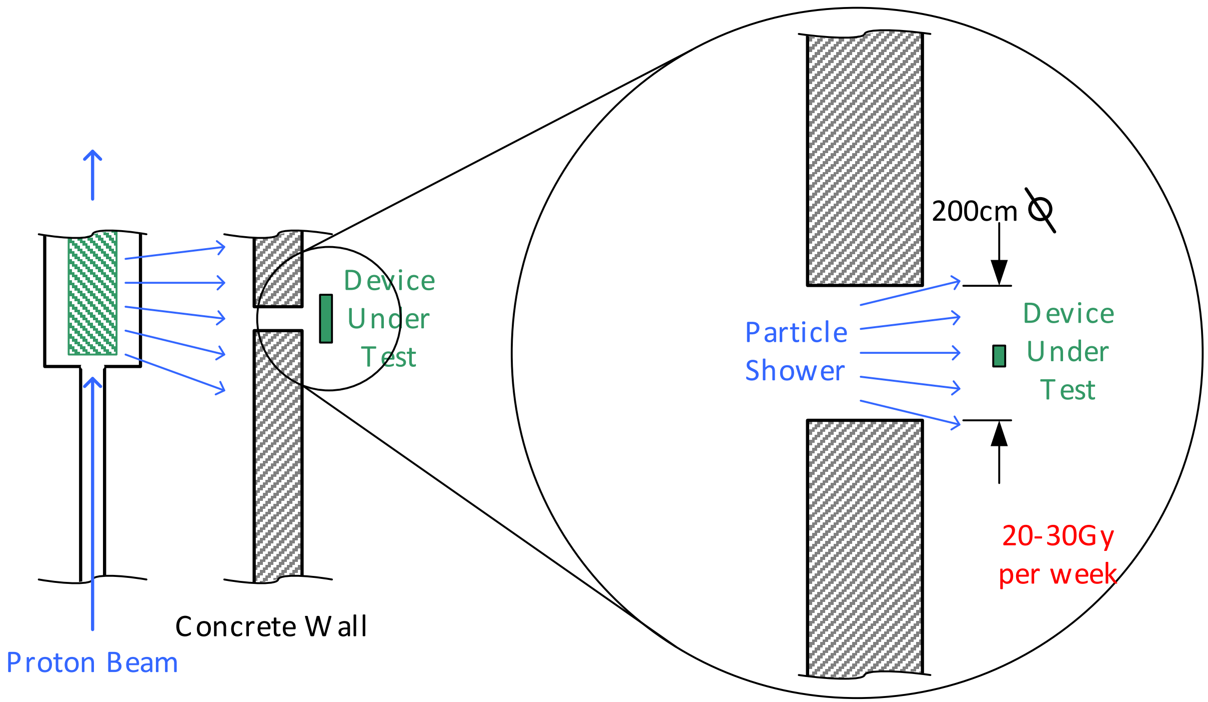
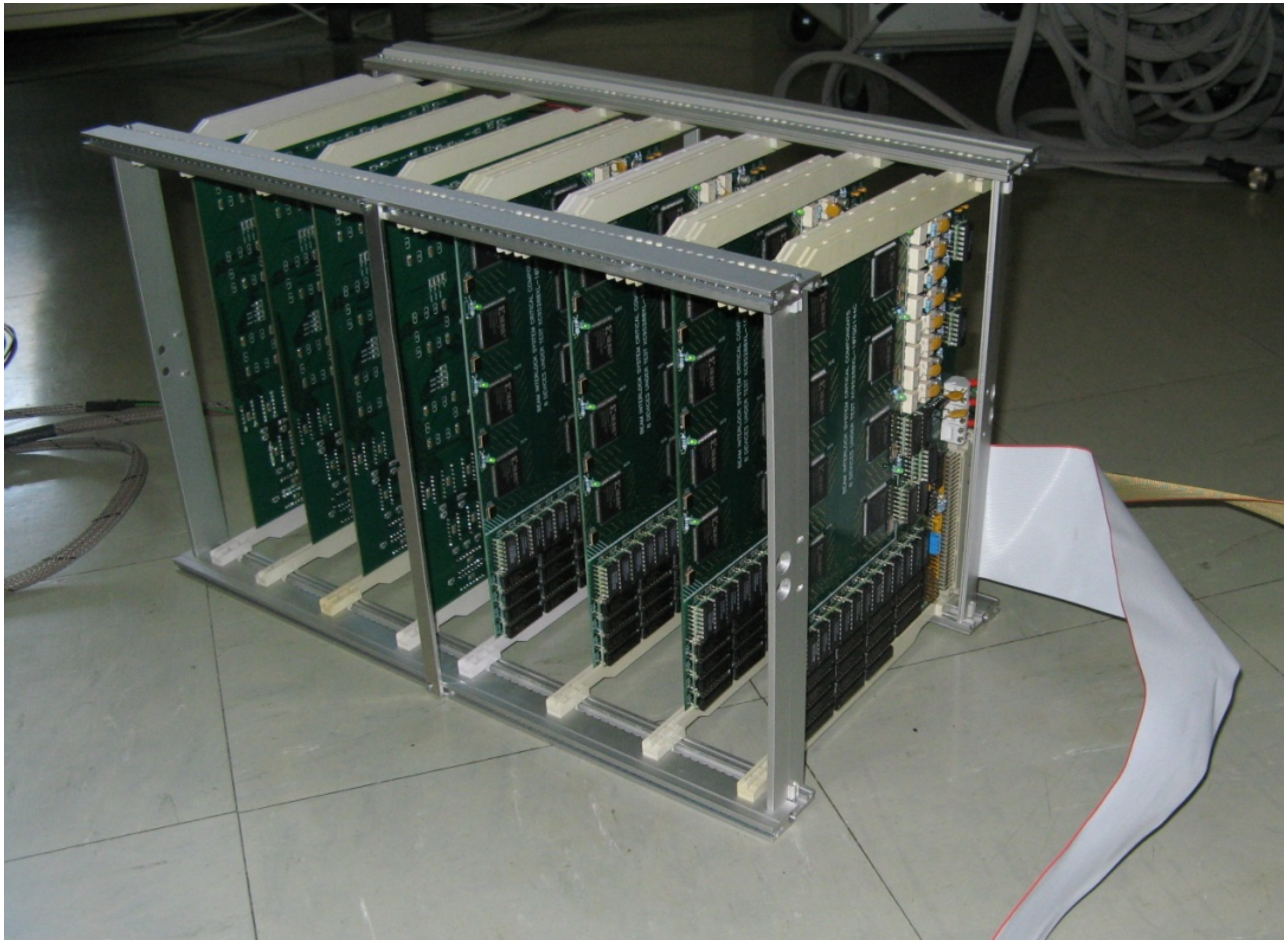
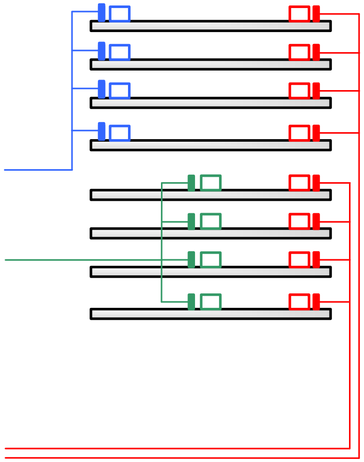


XC95144 x 32
XC95288XL x 32

Testbench Electronic Functionality





XC95144 x 32
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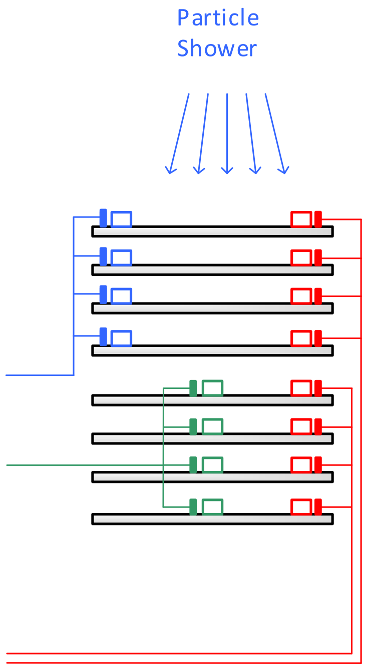

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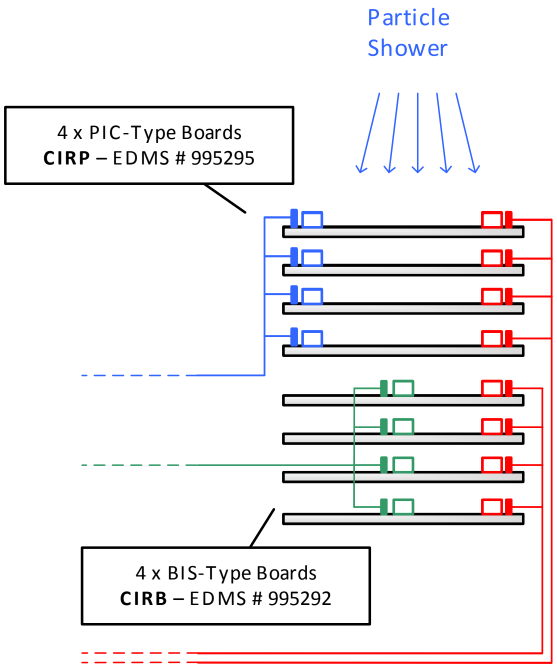

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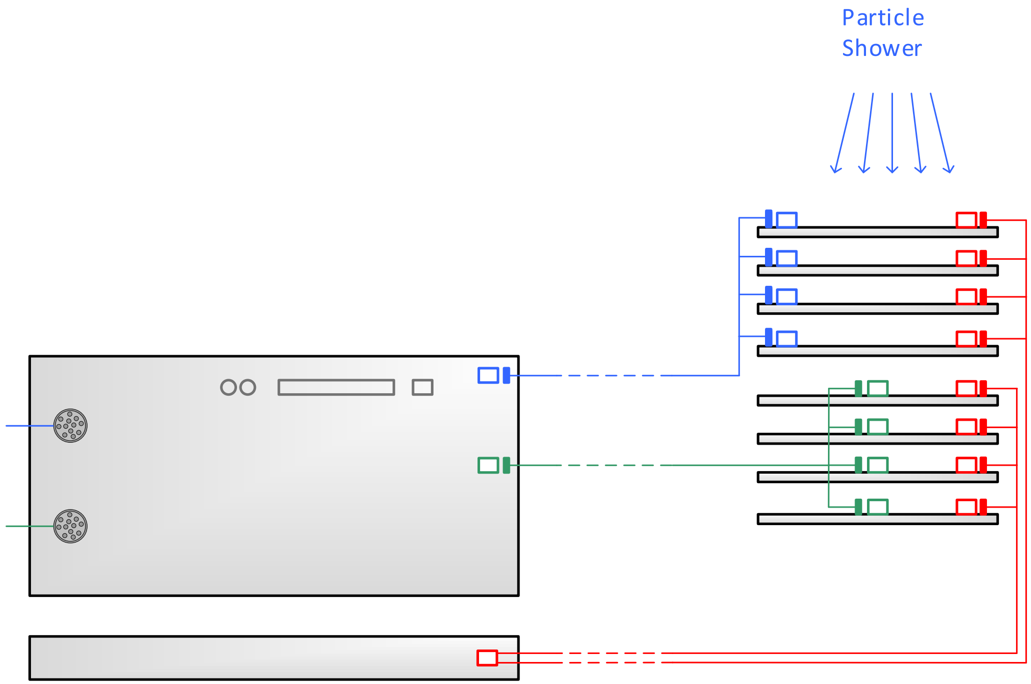

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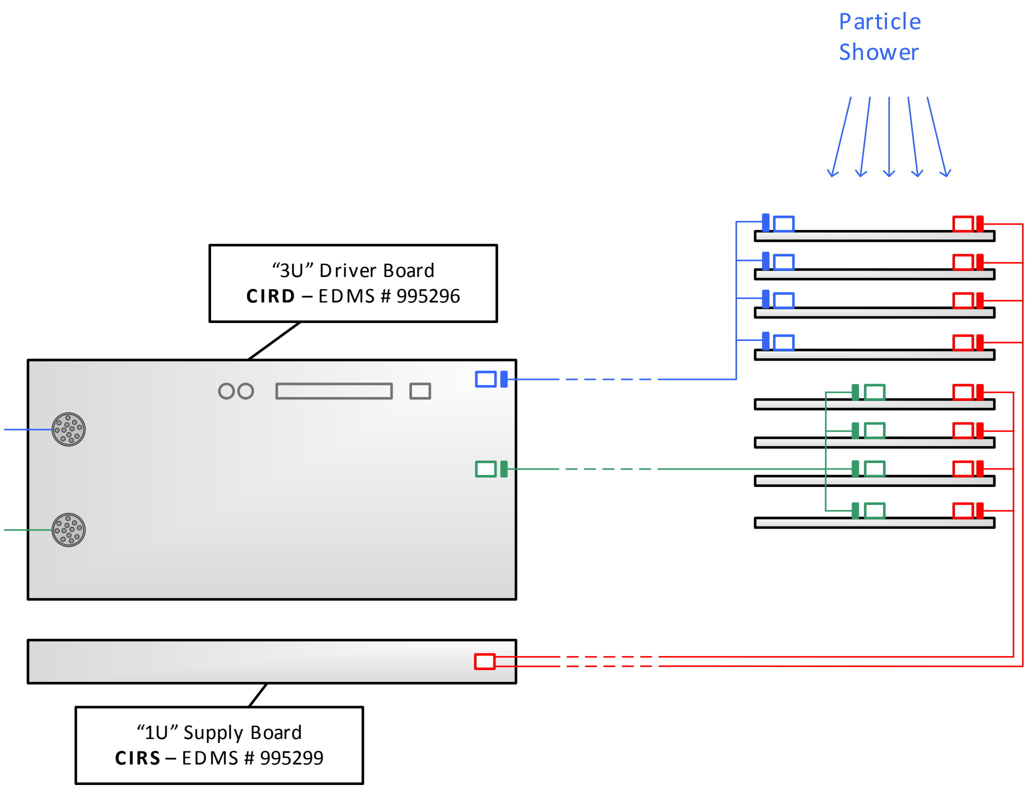

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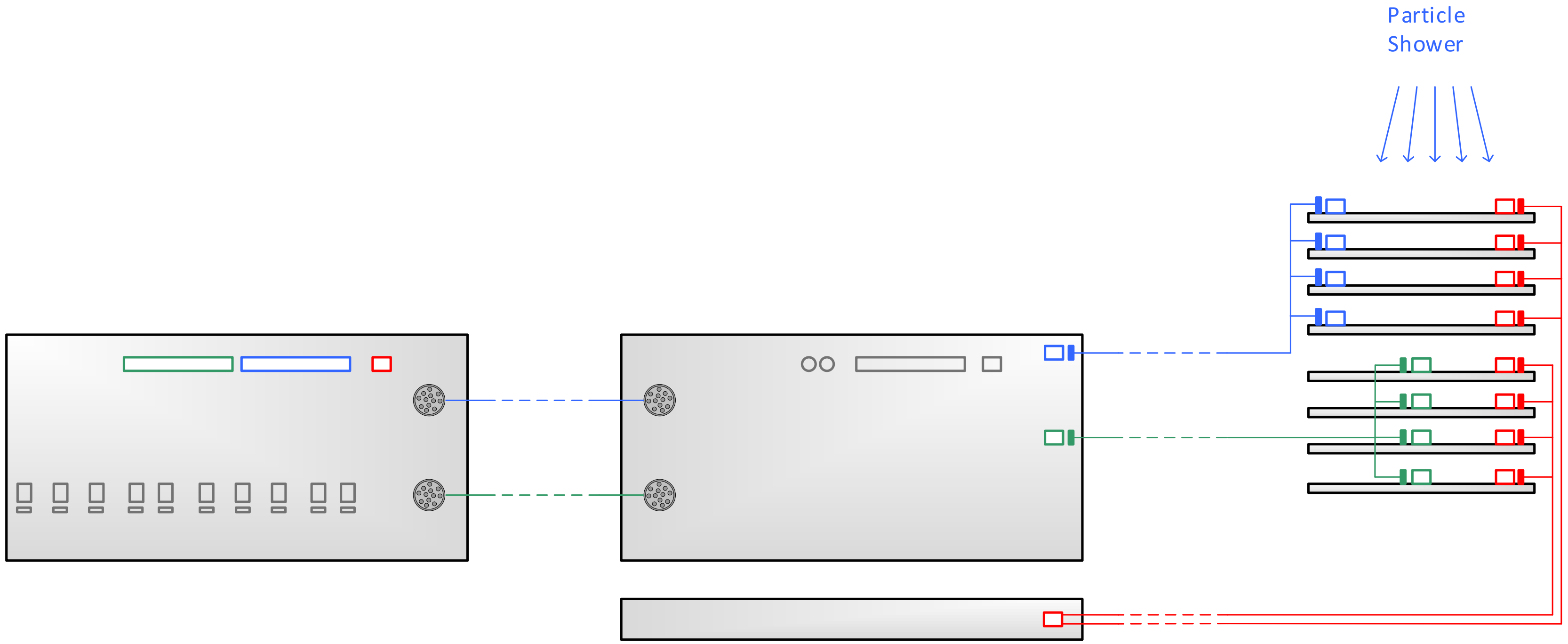

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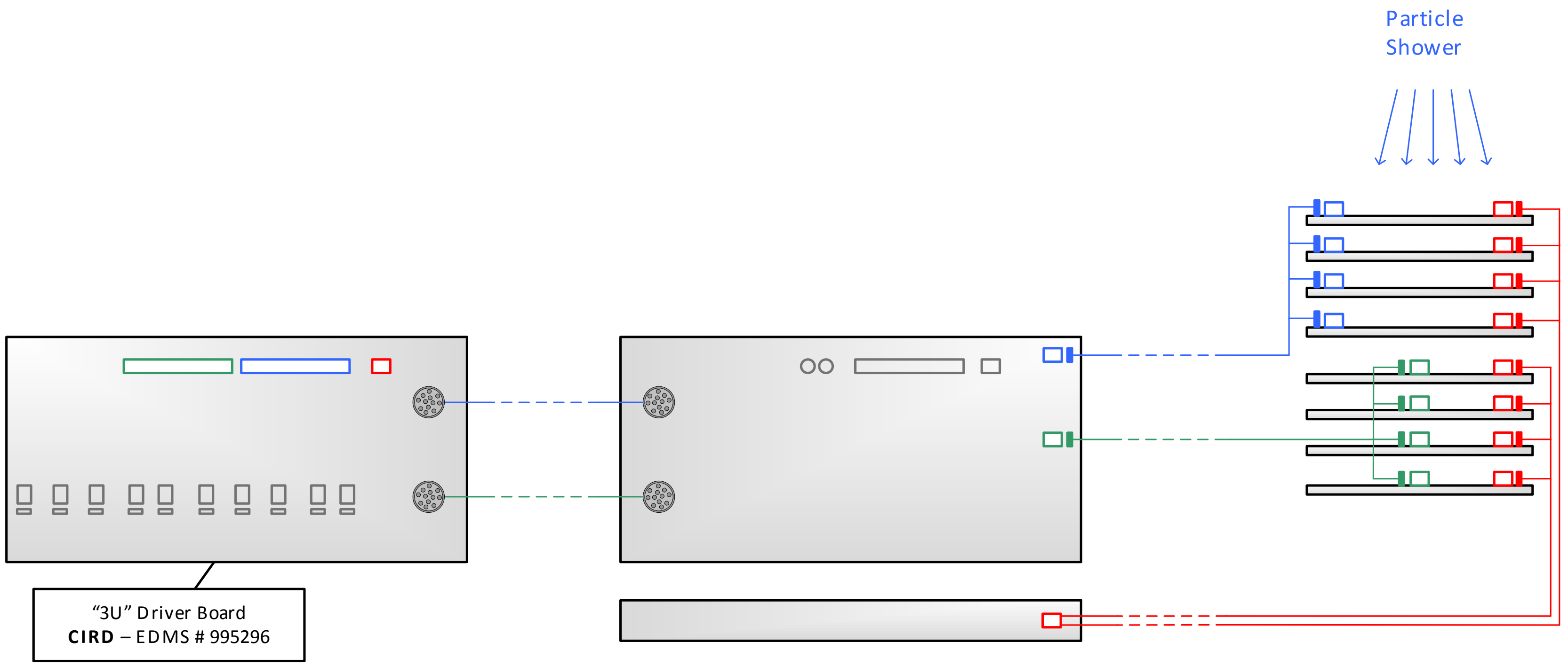

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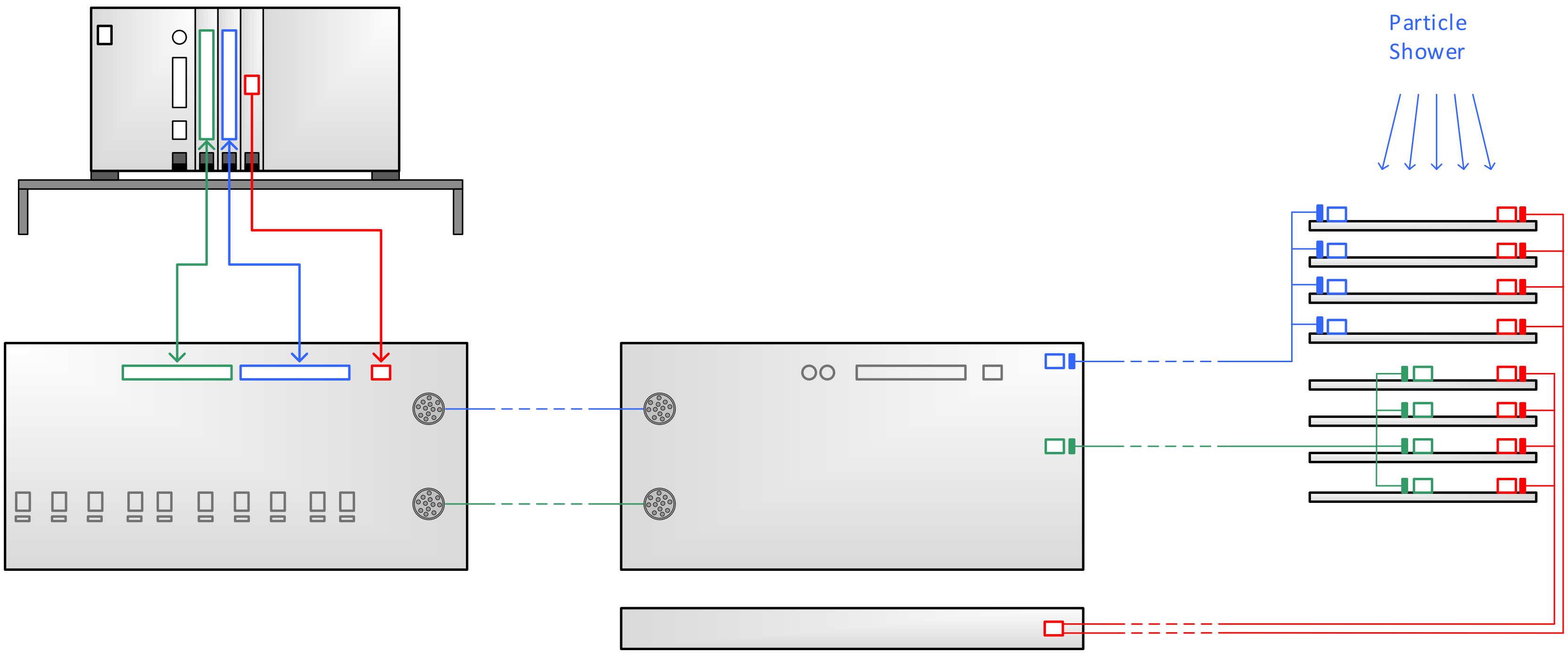
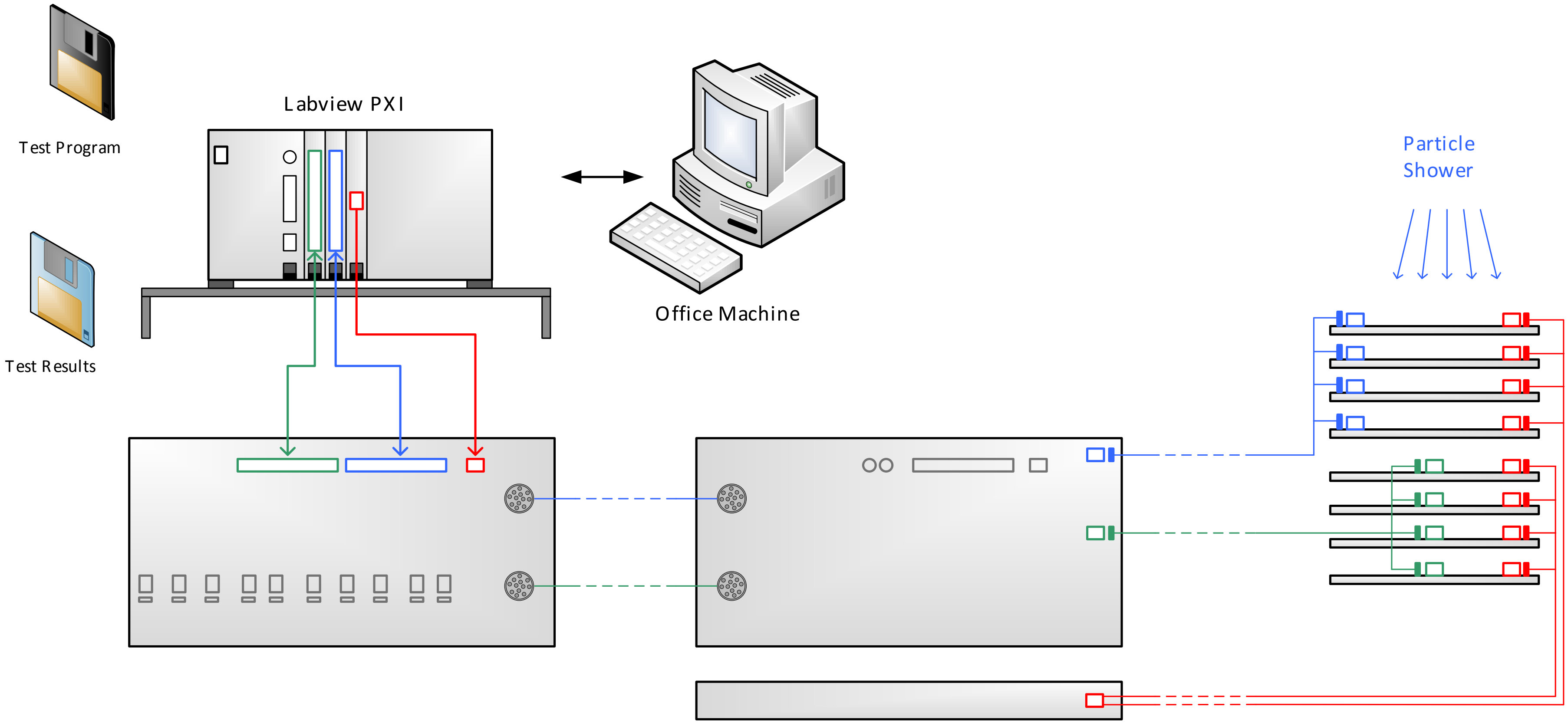
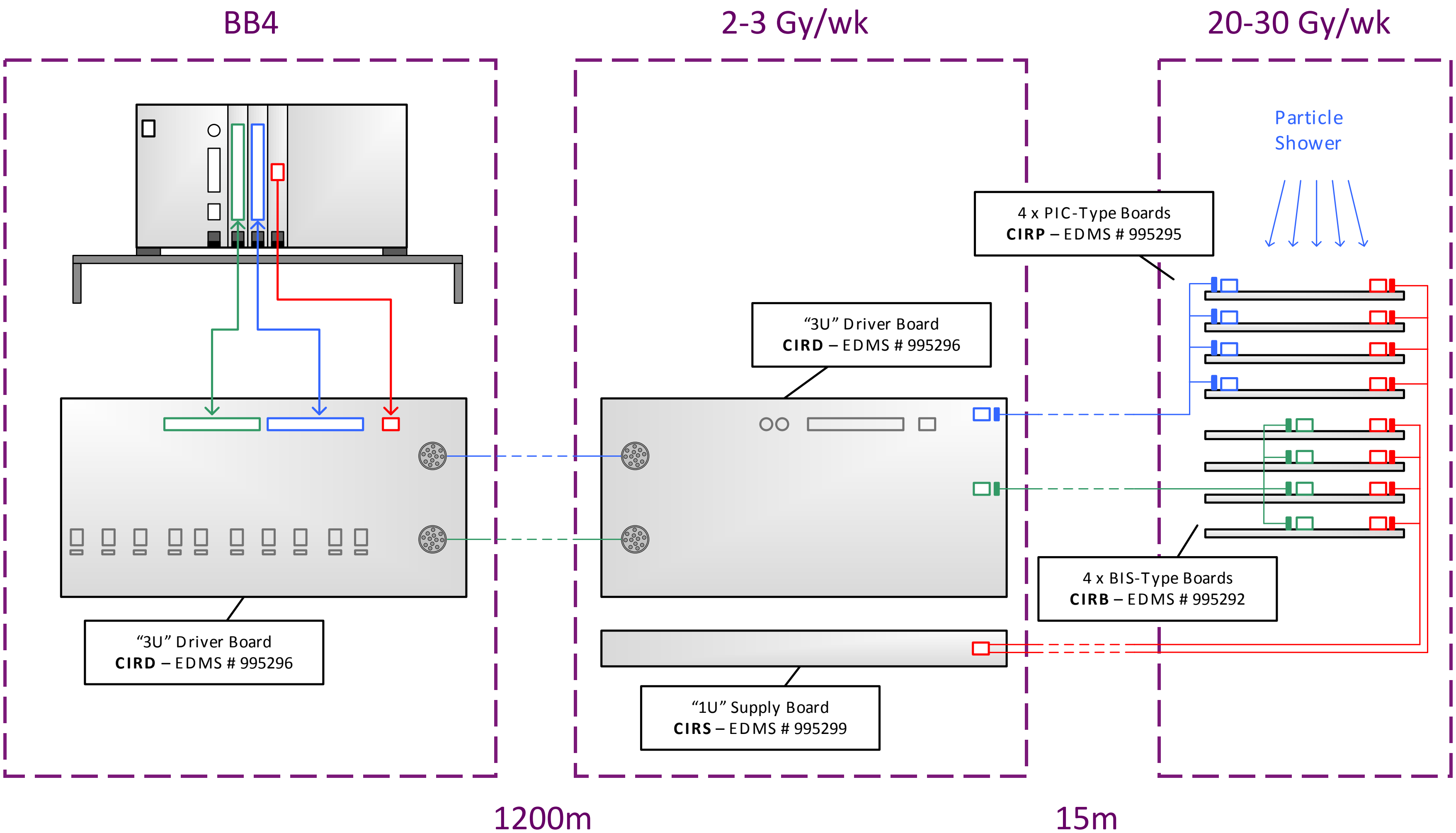


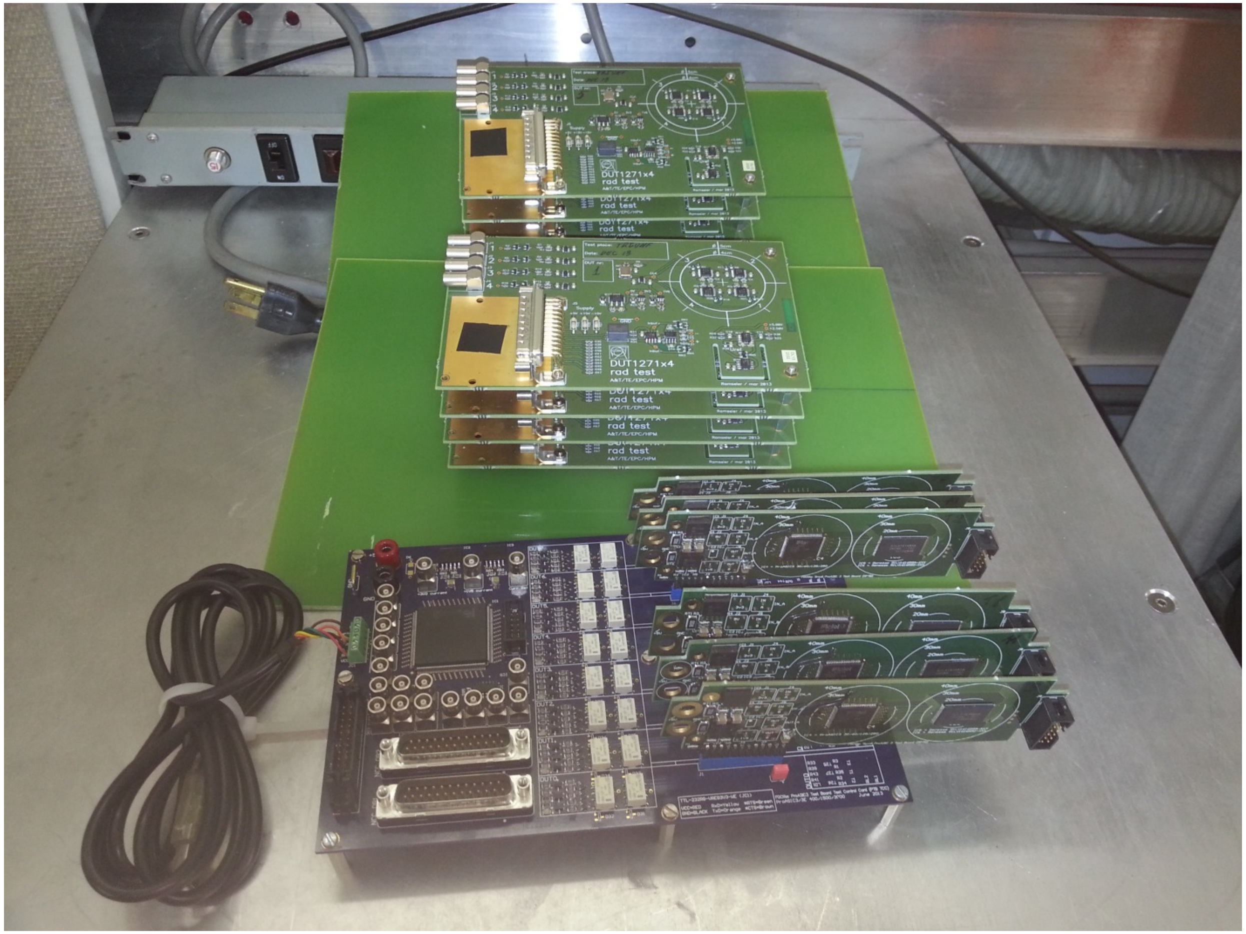
benjamin.todd@cern.ch

Testbench Electronic Functionality



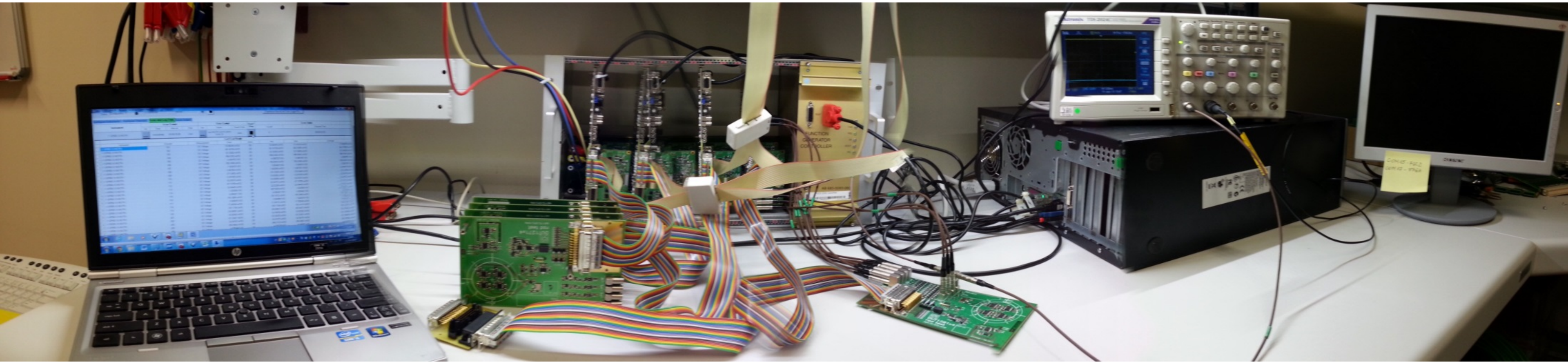
Testbench Electronic Functionality





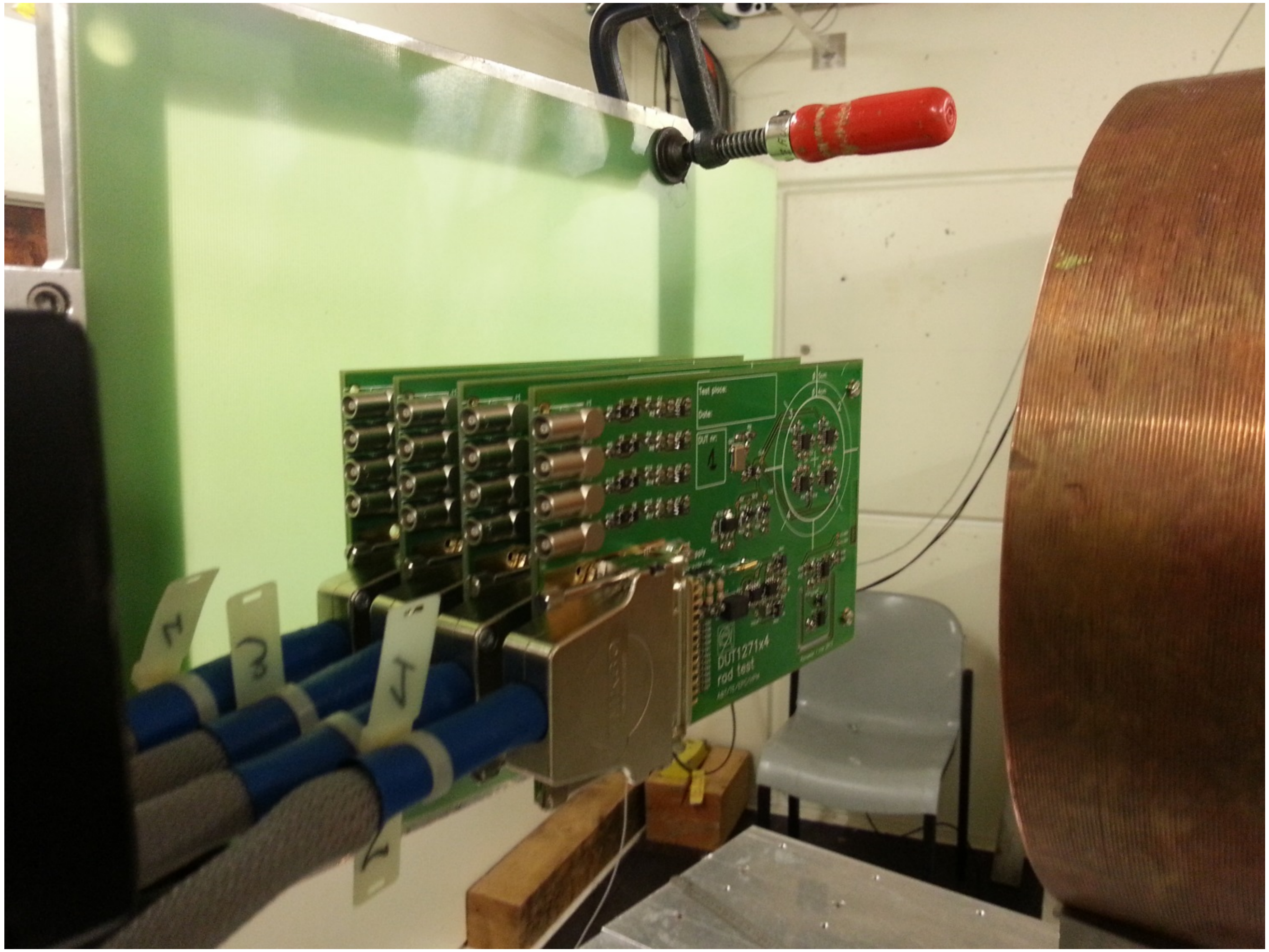
Every circuit which needs characterising needs a tester – here memory, FPGA and ADCs

[9]



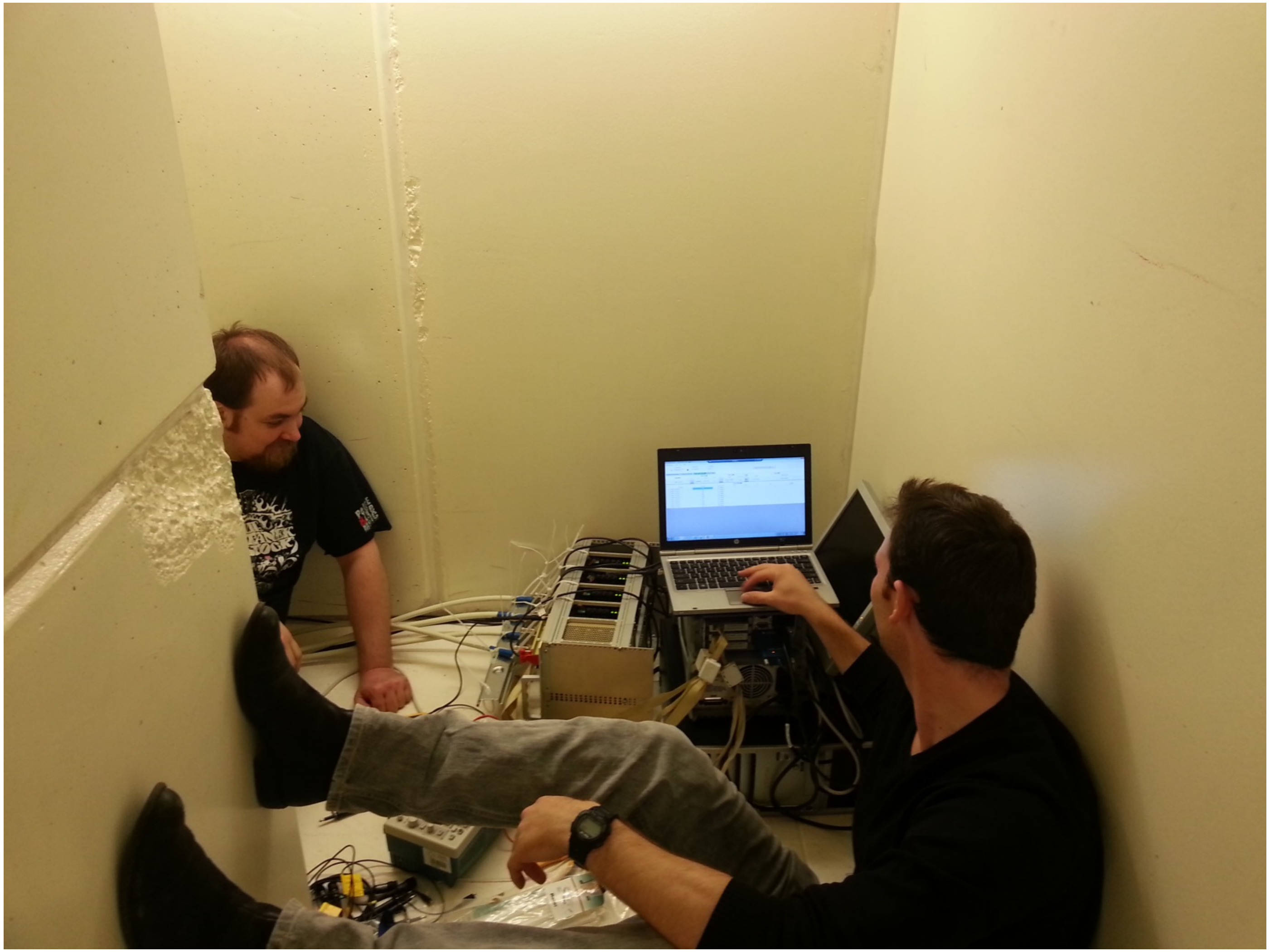
Every circuit which needs characterising needs a test infrastructure

[9]



Then to be taken to a facility and tested = $$$$ and time+++

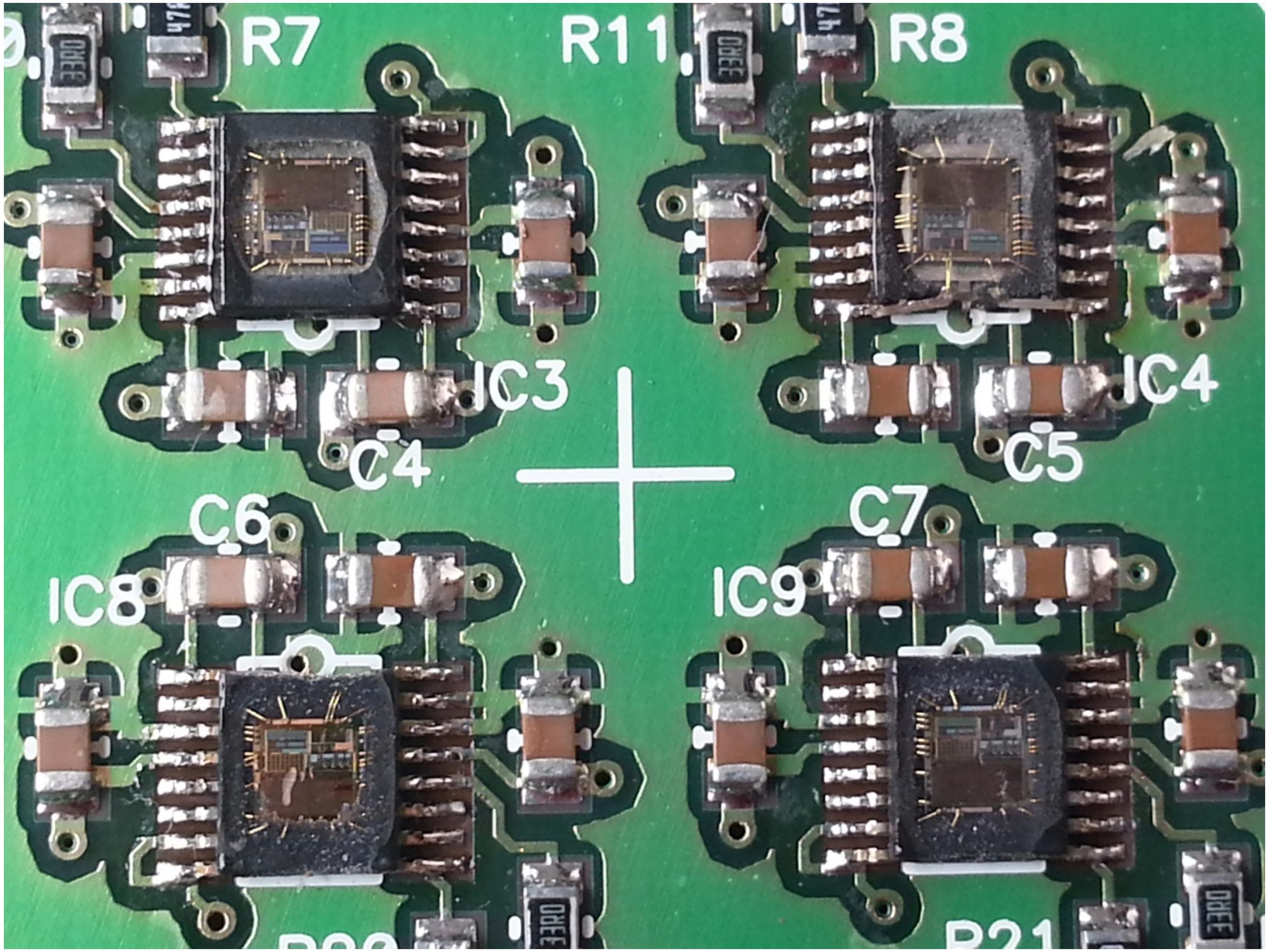
[9]



and a dedicated test team – who can make meaningful results

[9]

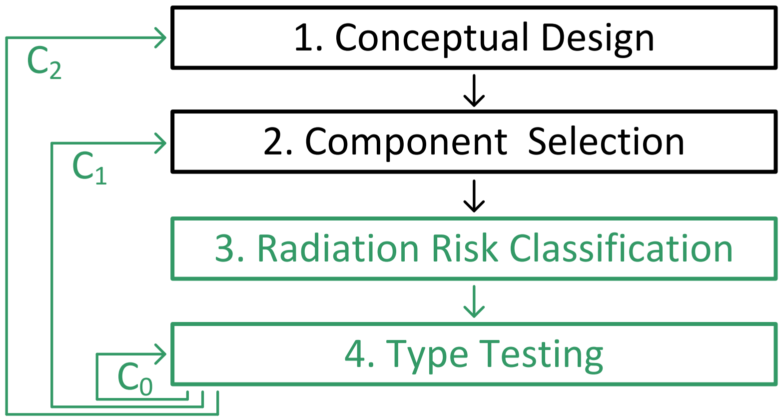
benjamin.todd@cern.ch



The packaging of components can effect interactions – here ADCs have had their plastic removed

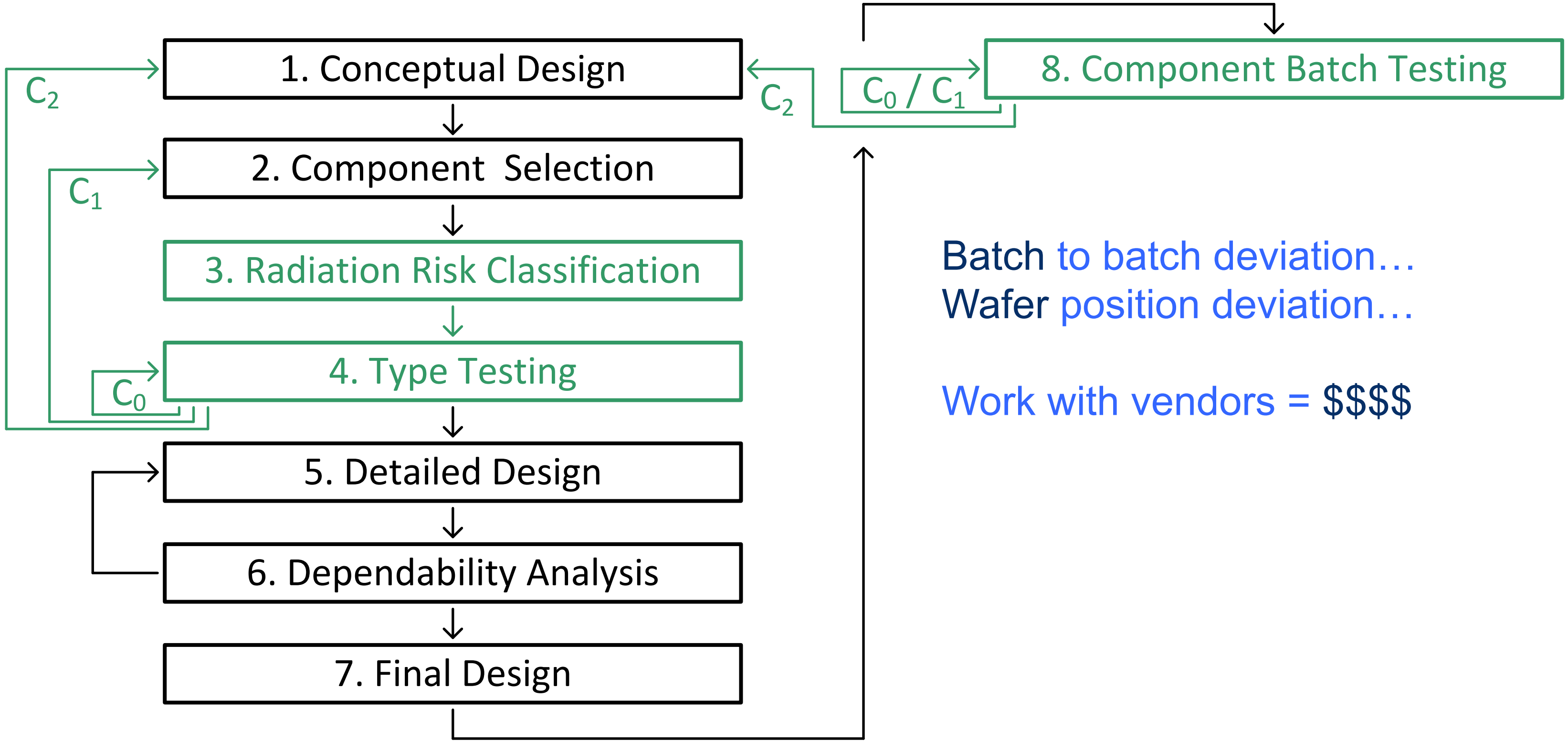
[9]

Design Flow for Radiation Tolerance



[8]

Design Flow for Radiation Tolerance

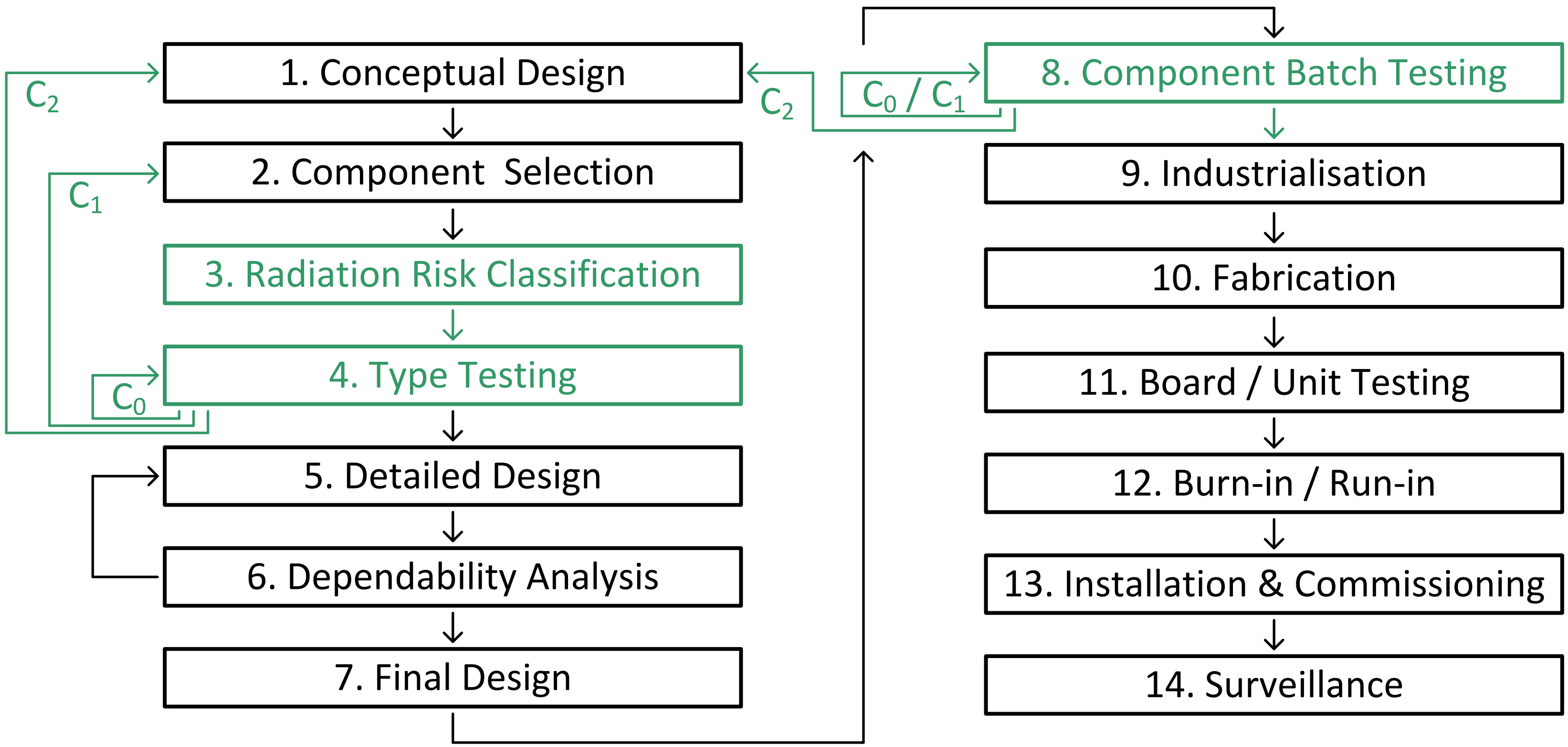


Batch to batch deviation…
Wafer position deviation…

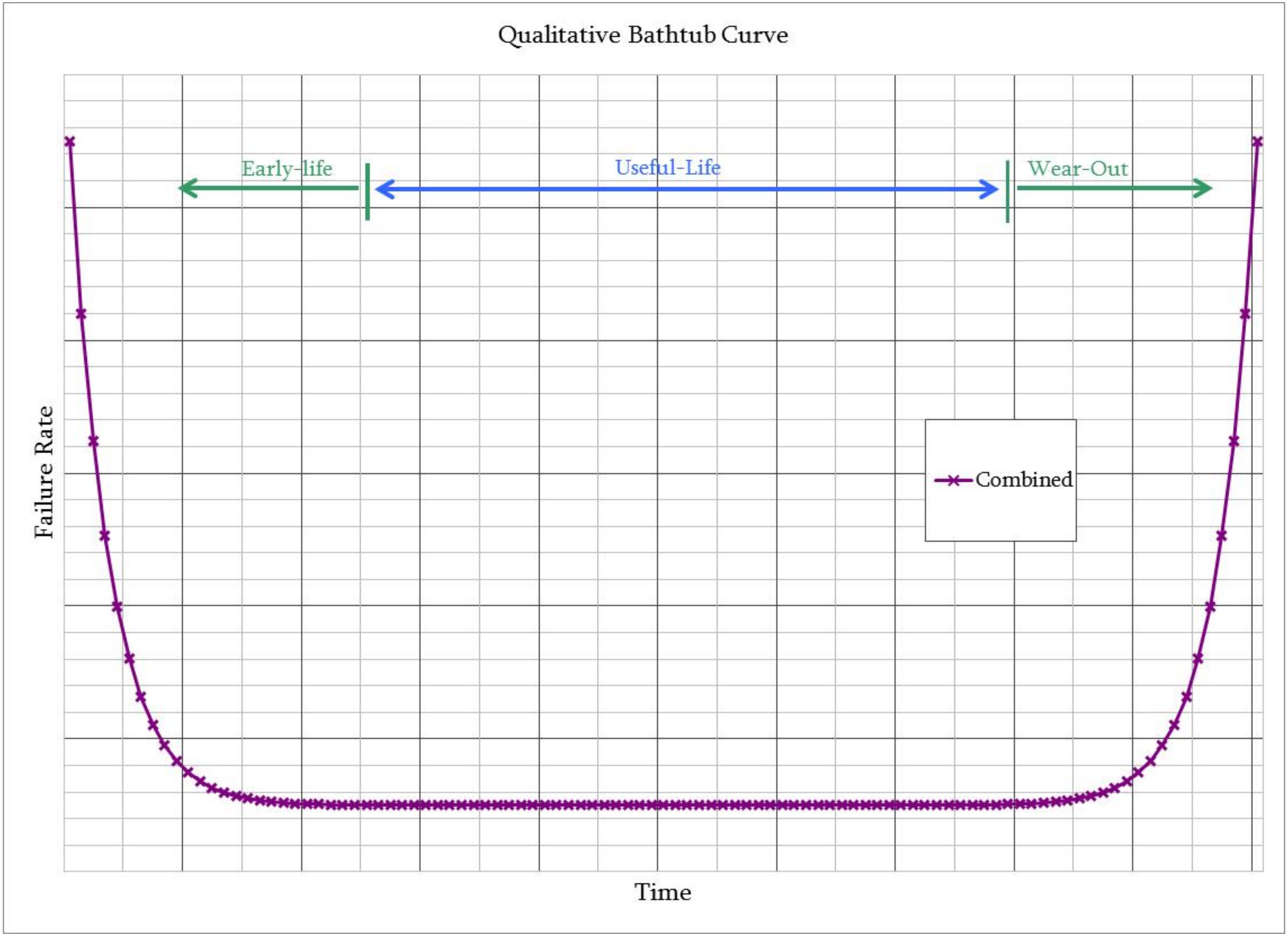
Work with vendors = $$$$

[8]

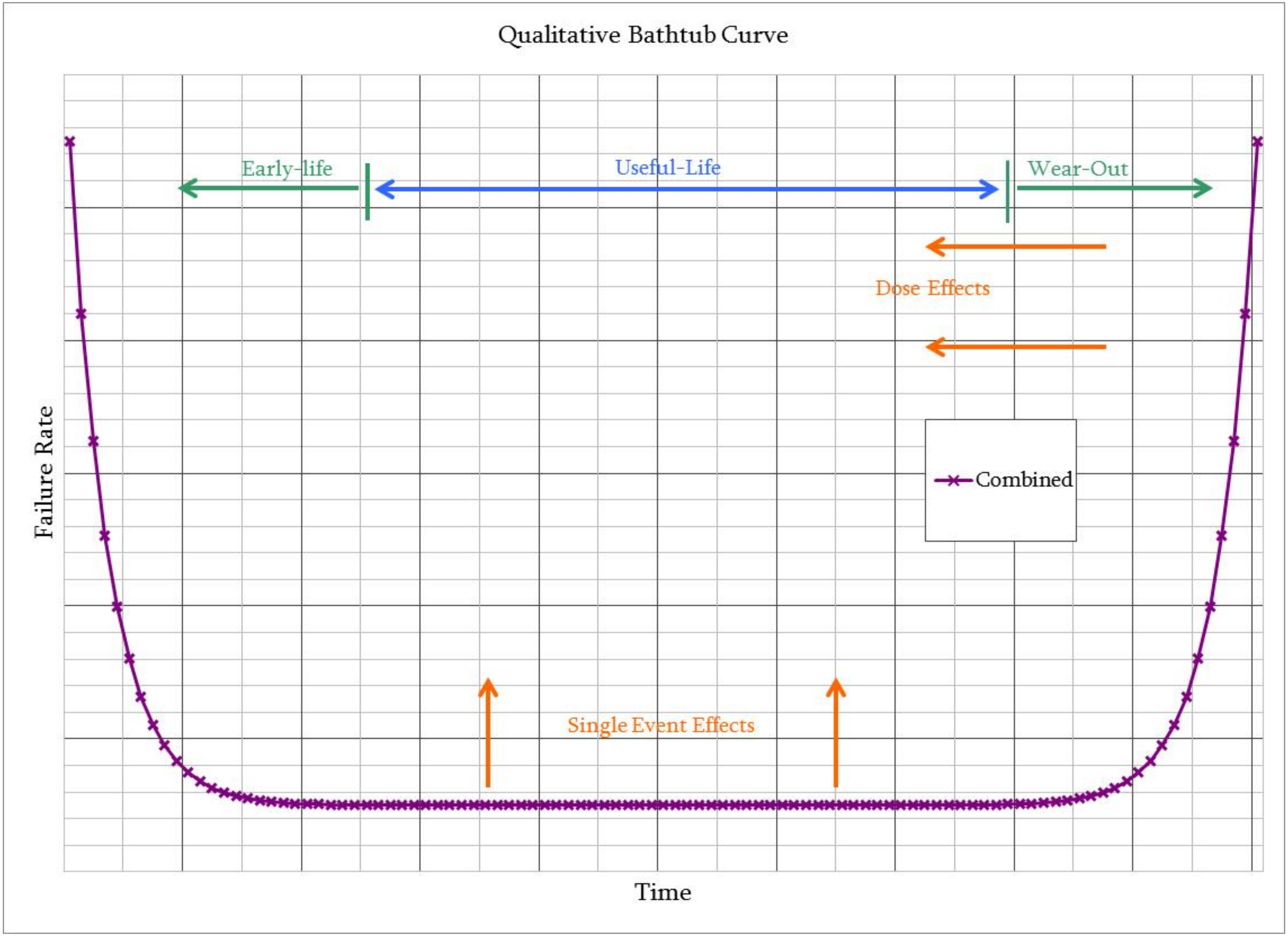
Design Flow for Radiation Tolerance



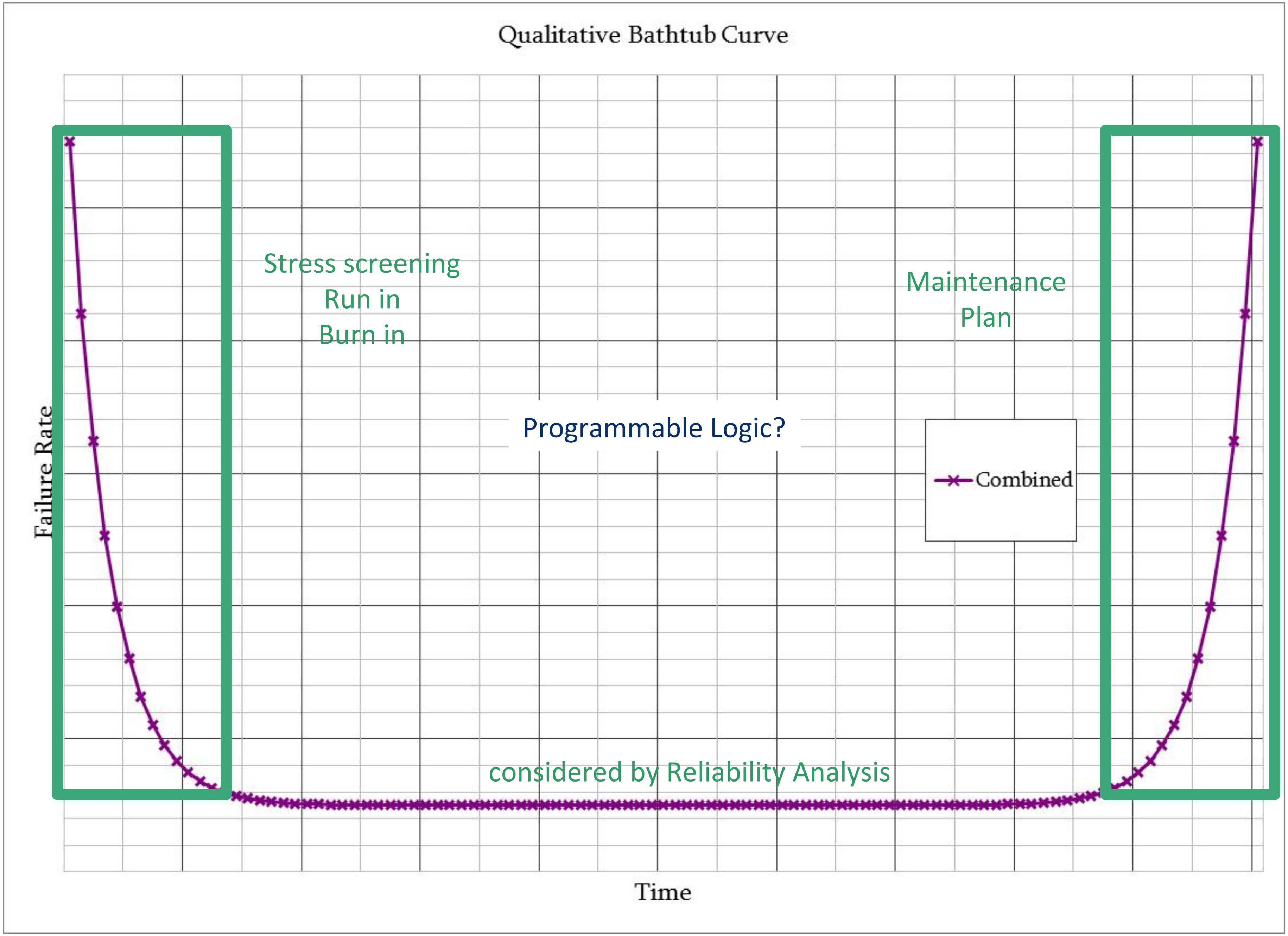
[8]



Qualitative Bathtub Curve
Early-life
Useful-Life
Wear-Out
Combined
Failure Rate
Time



Qualitative Bathtub Curve
Early-life
Useful-Life
Wear-Out
Dose Effects
Combined
Failure Rate
Single Event Effects
Time


Qualitative Bathtub Curve
Stress screening
Run in
Burn in
Maintenance
Plan
Programmable Logic?
Combined
considered by Reliability Analysis
Failure Rate
Time

FGClite Reliability Requirements

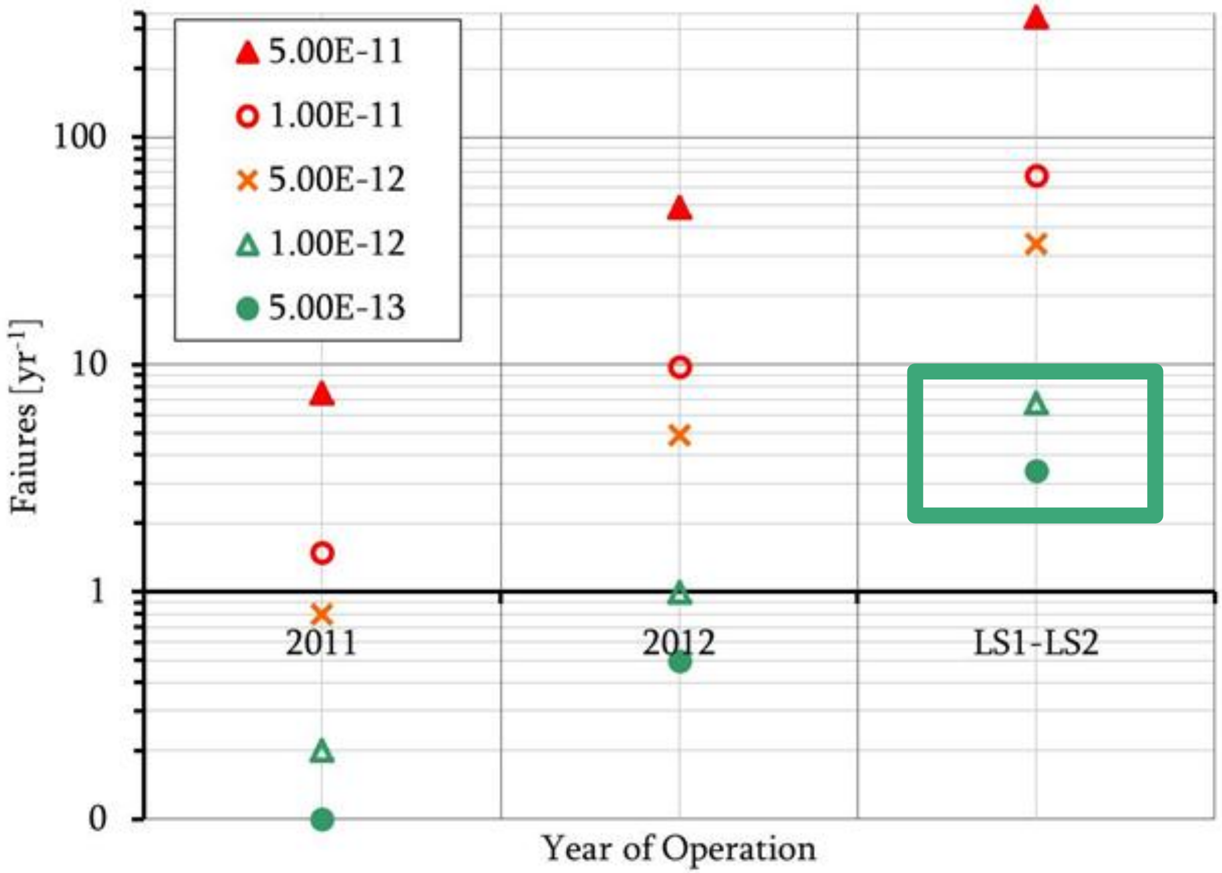
acceptable failure rate < 40 per year…

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

cross-section <1 x 10^{-12} SEE radiation

> 300000 hours electrical

cross-section



[8]

FGClite Reliability Requirements

acceptable failure rate < 40 per year…

Mean Time Between Failures > 200000 hours → cross-section <1 x 10^{-12} — SEE radiation
→ > 300000 hours — electrical

equipment lifetime > 25 years… → >200 Grays — DD / TID radiation
→ design for 25 years — electrical

In Conclusion…

To Take Away Today

* 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

* radiation effects are difficult and costly to mitigate
  – 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

[2] From the Chamonix Performance Workshop 2011
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=103957

[3] Extracted from http://lhc-statistics.web.cern.ch/LHC-Statistics/index.php

[4] Extrapolated from W. Herr's talk:
"Luminosity Performance Reach After LS1"

[5] Derived from
http://cdsweb.cern.ch/record/1123729/files/LHC-PROJECT-REPORT-1133.pdf?version=1

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

[7] Diagram background is from http://cdsweb.cern.ch/record/842349/

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

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