

Radiation tolerant issues for LHC accelerator

Dr. Salvatore Danzeca EN-STI-ECE

TWEPP 2016 - Topical Workshop on Electronics for Particle Physics

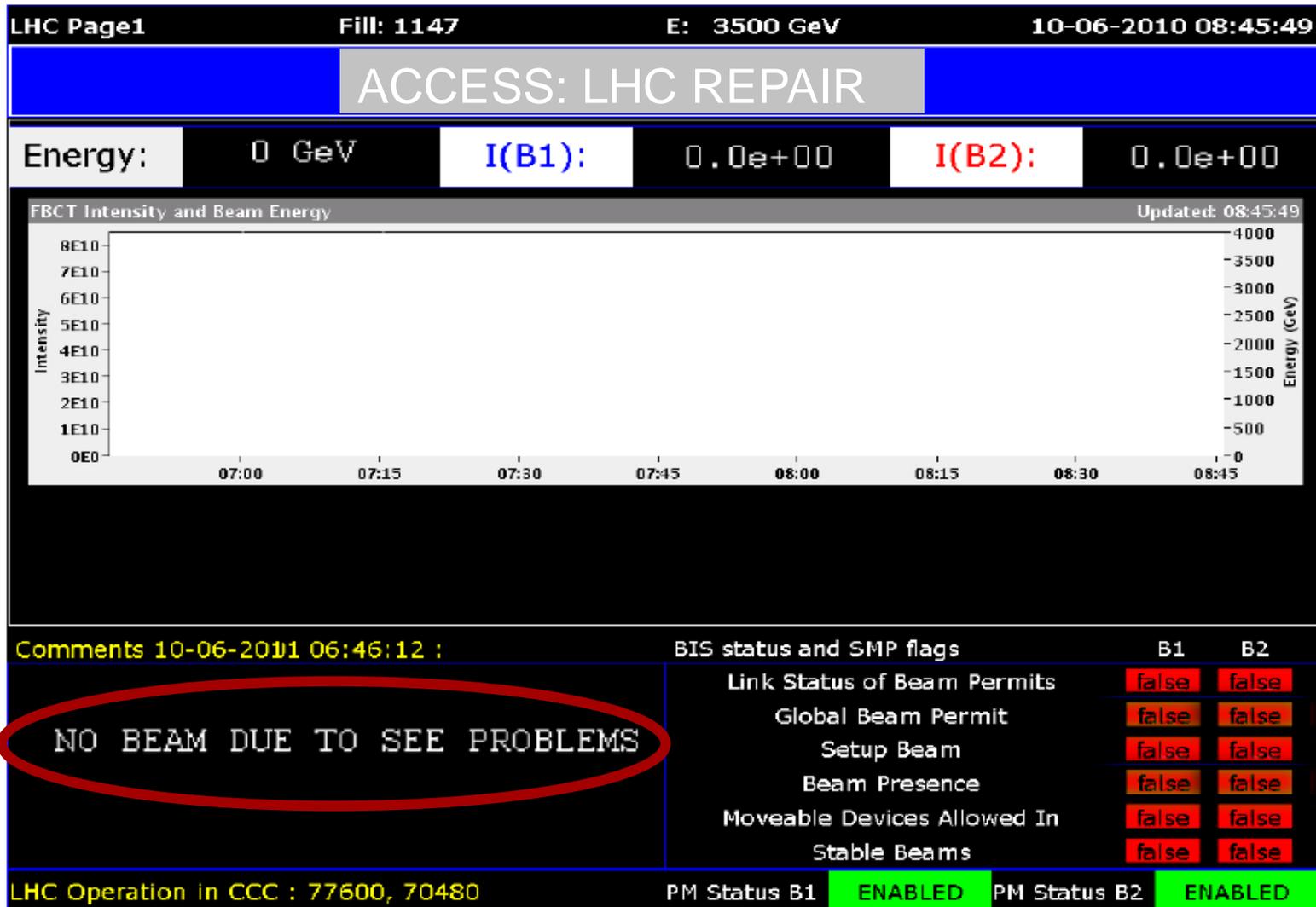
On behalf of the R2E project



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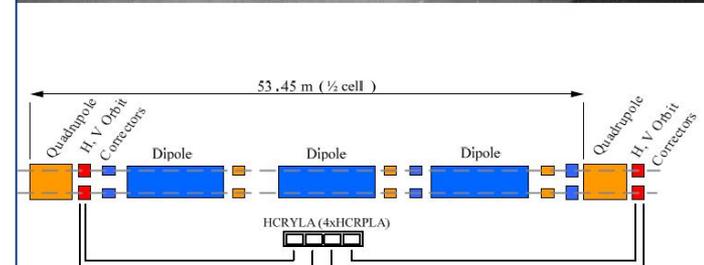
What has to be avoided!



The challenge

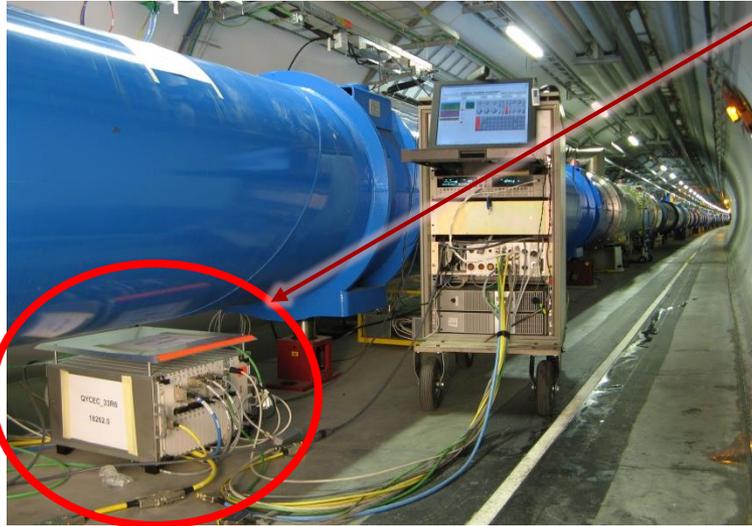
- The **reliability** is a main concern for the CERN equipment
- The **criticality** of the equipment can be very high
 - 2 proton beams at 6.5 TeV of $\sim 3 \times 10^{14}$ p+ each
 - Total stored energy of 0.7 GJ
Sufficient to melt **1 ton of Cu**
 - Tiny fractions of the stored beam suffice to **quench a superconducting LHC magnet** or even to destroy parts of the accelerator
- The radiation effects on the LHC electronics can lead to a **beam dump**
 - Lost time for physics
- The radiation effects on the LHC electronics can lead to a **failure of the safety system** of the LHC
 - Part of the machine can be destroyed
- High number of devices (N):

$$N_{Failure} = N * \sigma * fluence$$



Equipment in radiation areas

Cryo



800 Cryo WorldFIP electronic crates

© N.Trikoupis

Active channels:

- 6500 Temperature
- 800 Pressure
- 500 Liquid He level gauges
- 1500 Cold Mass Heaters
- 500 Beam Screen Heaters
- 1100 Mechanical Switches (I/O)

LHC: Installed below dipoles in all arcs from cell 8 and in shielded areas.

QPS

© J.Steckert

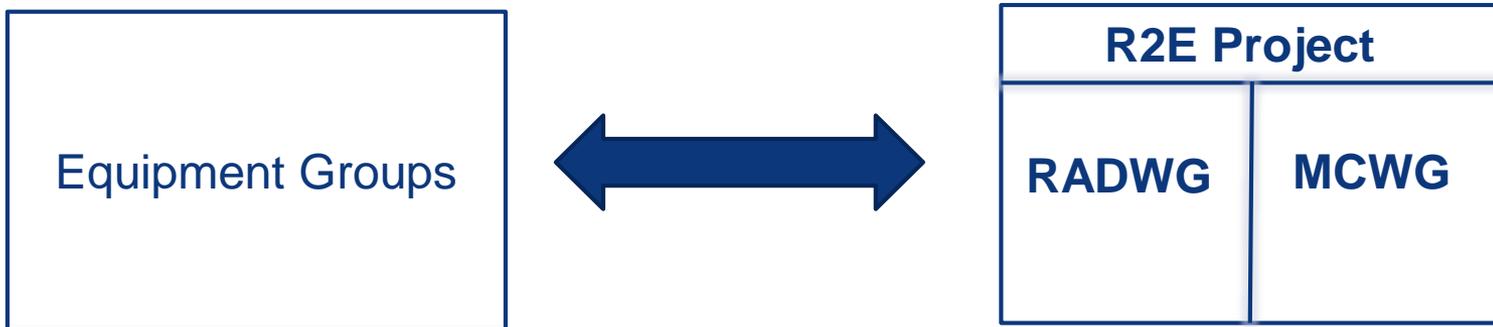
Area	Type	Equipment code(s)	QTY (QTY DS)
Tunnel ARC (DS)	Crate controller/ Field bus coupler	DQAMGS DQAMC	436 (64) 1624 (64)
	Symmetric quench detection	DQQDS	1632 (128)
	Splice supervision	DQQBSH	2500 (160)
	Quench detection	DQQDL	4032 (256)
	Heater supervision	DQHSU	1232 (128)
	Internal crate controller	DQCSU	1232 (128)
RR P1, RR P5, RR P7	Crate controller/Field bus coupler	DQAMGA, DQAMGB DQAMGC DQAMS600 DQAMS13kA	134
	Quench detector 600A rad tol	nDQQDG	208
	Quench detector IPQ/IPD/IT rad tol	nDQQDI	200
			13230

13230 QPS cards installed in radiation areas

These are only a part of the equipment installed in the LHC ARCs and RR!

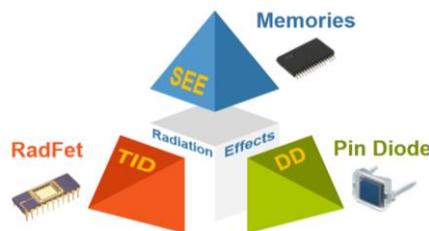
How we can reduce the failure rate?

- Recipe:
 1. Radiation Monitoring
 2. Equipment inventory
 3. Follow the new developments to be installed in radiation areas by means of dedicated guidelines
- Request a strong collaboration between the equipment groups and the Radiation Working group (RADWG) and the Monitoring and Calculation Working group (MCWG)



The LHC Radiation Levels – the monitoring tools

- The **RadMon system** is installed in all the LHC to monitor the radiation to electronics
- **379** monitors are installed in the LHC and in the experimental caverns where the electronics is installed
- It is a **distributed** system capable of covering the three axis of the radiation effects
 - Total Ionizing Dose
 - Displacement Damage
 - High Energy Hadron
 - Thermal Neutrons

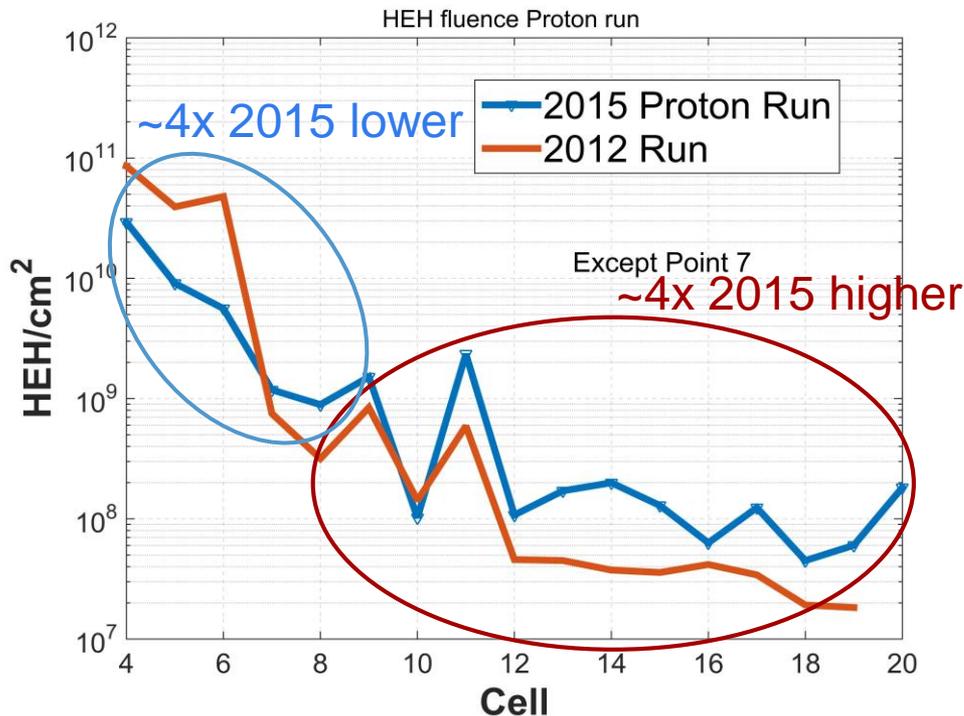


- We use also the LHC **Beam-Loss Monitoring System** (BLM) to cross check the RadMon measurements
- The BLMs are installed on the MB-MQ but also on the collimators but not close to electronics!



The radiation levels: a complex matter in the LHC

- In the **2012** the total integrated luminosity was **20fb-1**
- In the **2015** the total integrated luminosity was **4fb-1**
- In the **2015** the bunch spacing changed from 50ns to 25ns

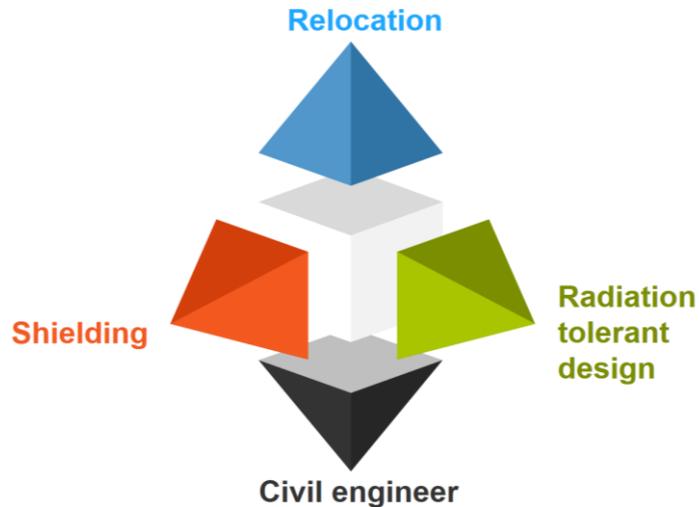


- Analysis based on the **RadMon** measurements up to end November (proton run)
- 2012 vs 2015 highlights the impact of the **25ns operation**
- 2015 HEH fluence higher than 2012 in cells >8 due to the higher **beam-gas interaction**
- **2015 low luminosity** impacts the cell <8 with less fluence
- This was foreseen by the R2E calculations

In the ARC (cell 12>) the increased radiation levels should bring to higher failure rate, **but...**

Mitigations and Failures in the LHC

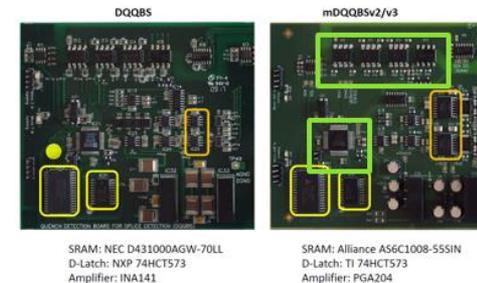
The mitigation actions carried out by the R2E project have been demonstrated to be effective



Equipment	Dumps 2012	Dumps 2015 (After TS2)
QPS	32	3
Power Converter	15	5
Cryo	4	0
EN/EL	1	0
Vacuum	4	0
Collimation	1	0
RF	1	4**

** To be confirmed

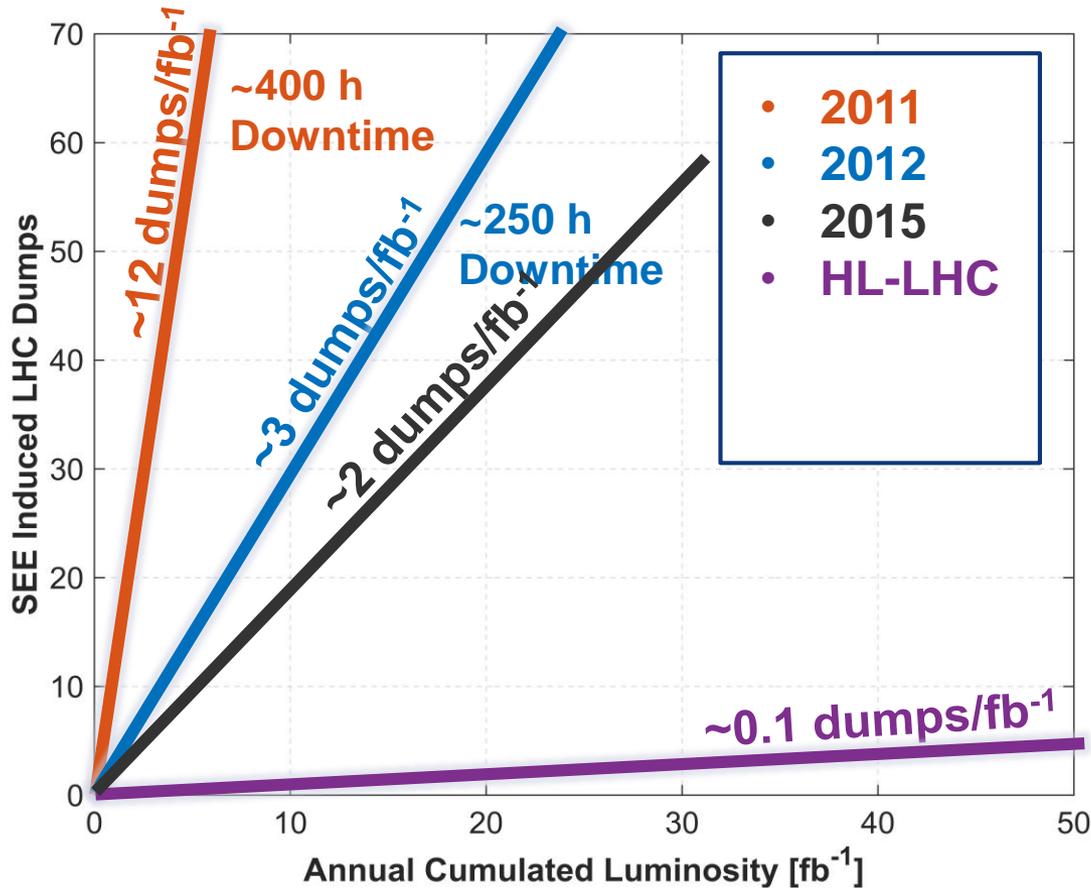
- The time period considered is after the TS2 because before that the availability was limited by a QPS card failing due to single event.
- The mDQQBs card was upgraded during the LS1
- Few components were changed
- The new SRAM was very sensitive to non-destructive single event latchup
- All the cards were substituted during the TS2



SRAM: NEC D43100AGW-70LL
D-Latch: NXP 74HCT573
Amplifier: INA141

SRAM: Alliance A56C1008-55SIN
D-Latch: TI 74HCT573
Amplifier: PGA204

The effectiveness of the R2E strategy



Several shielding campaigns prior 2011 + Relocations 'on the fly' + Equipment Upgrades

2011/12 xMasBreak 'Early' Relocation + Additional Shielding + Equipment Upgrades

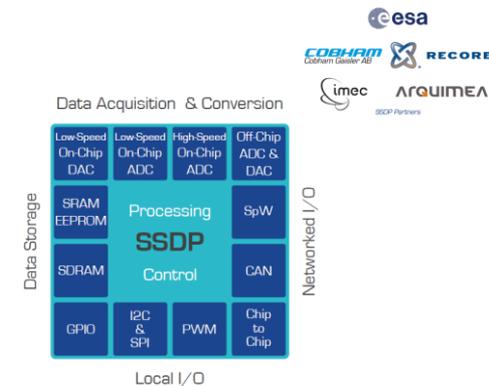
LS1 (2013/2014) Final relocation and shielding

LS1-LS2 (2015-2018) Tunnel equipment and power converters

LS3-HL-LHC Tunnel Equipment (Injectors + LHC) + RRs

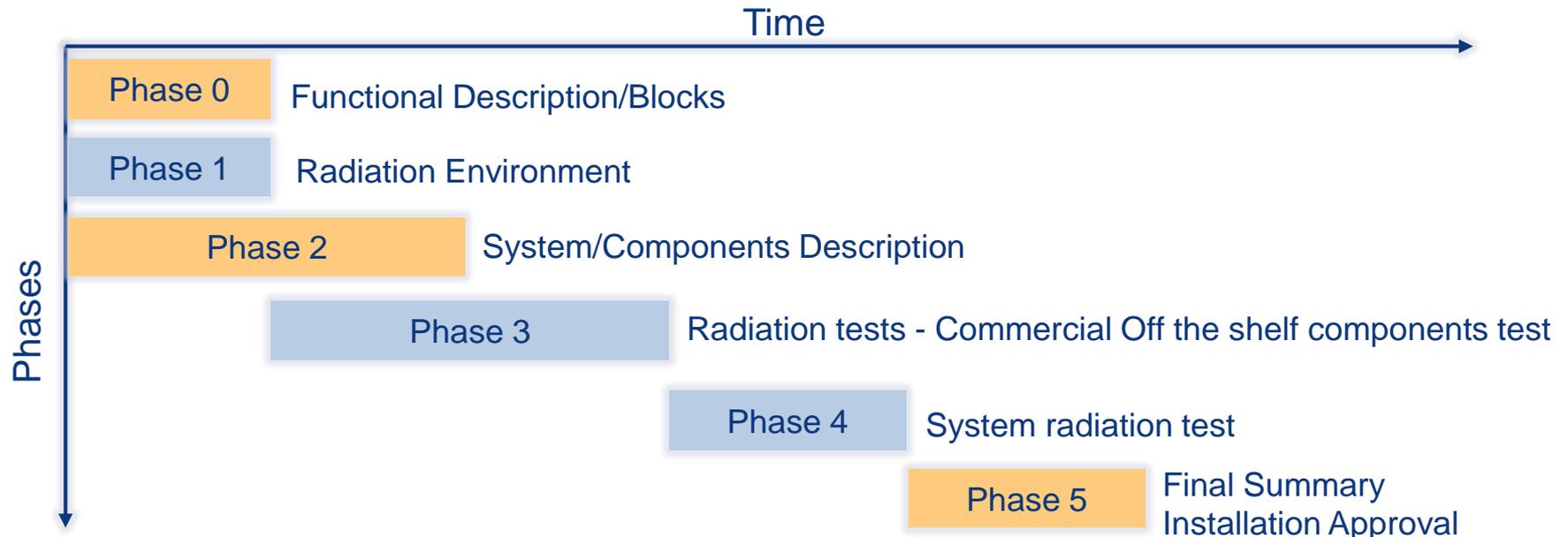
New initiatives and developments

- RADWG is the interface with all the ATS equipment groups
 - BE-CO in view of the CO3 initiative for the new CERN **fieldbus** foreseen for the LS3
 - Collaboration with **EP** for the embedding of the elink in the **SSDP** processor
 - BE-BI in view of the upgrade of the BPM frontend
 - TE-MPE splice protection system for HL and consolidation of existing hardware
 - TE-VSC in view of the new readout of the pressure sensors
 - BE-RF for the pickup amplifier for the transverse feedback in the PSB

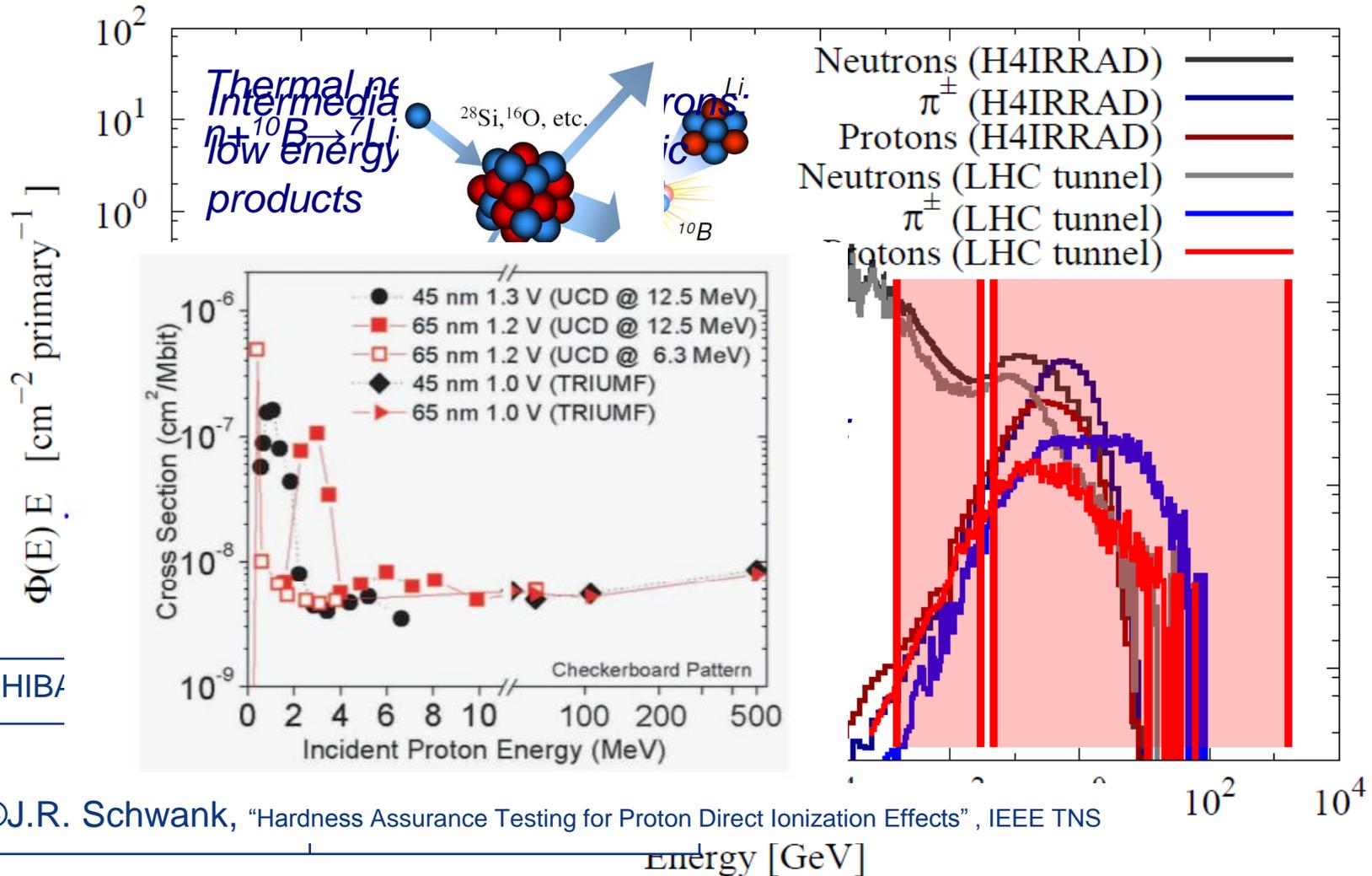


R2E: from mitigation to prevention

- In order to push radiation tolerance to levels compliant with HL-LHC requirements (~ 0.1 dumps/fb⁻¹) mitigation is not enough
- A **pre-emptive approach** needs to be implemented taking into account the response to radiation from a very early stage of the project
- Radiation testing is a phase of a new development
- Radiation constraints have to be considered from day 0



The radiation environment spectra: intervals of interest



TOSHIBA

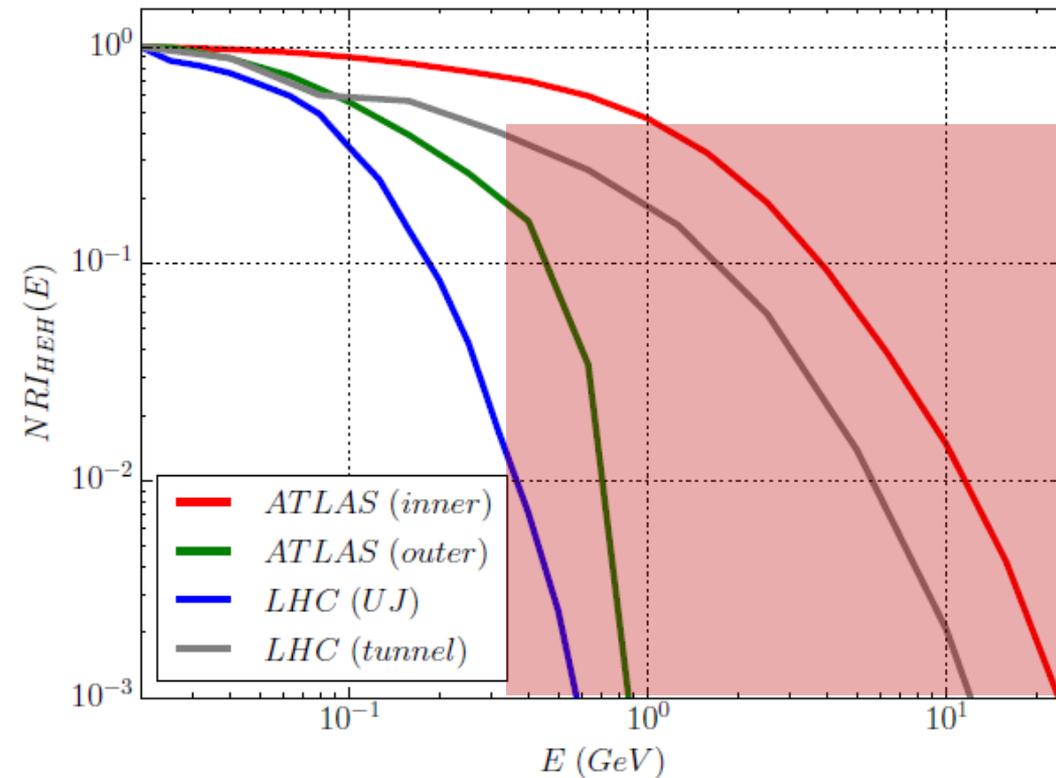
3V

5) ©J.R. Schwank, "Hardness Assurance Testing for Proton Direct Ionization Effects", IEEE TNS

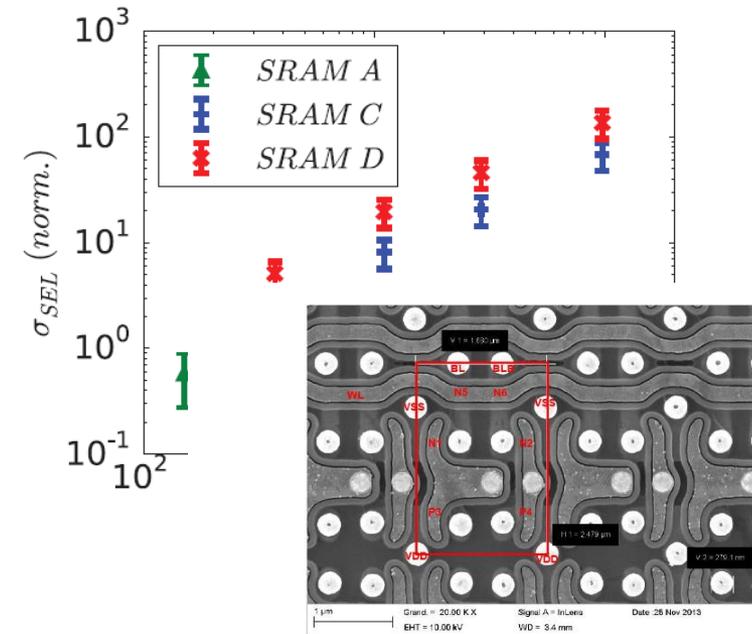
Energy [GeV]

Looking at the high energetic spectra

- The value in the vertical axis for a given energy corresponds to the proportion of HEH above that energy value
- ~50% of the LHC tunnel spectrum is above few hundreds of MeV.



Modern Technologies



©R.G.Alia et al, "SEL Hardness Assurance in a Mixed Radiation Field", IEEE Trans. Nucl. Sci.

Radiation test strategy



1

- Component selection

2

- Component pre-screening in ^{60}Co facility and/or protons

3

- Batch procurement

4

- Batch Testing

5

- System level testing in CHARM

CHARM – Cern High Energy Accelerator Mixed-Field

PRIMARY PROTONS IMPINGE THE TARGET: A SECONDARY RADIATION FIELD IS CREATED

3 KEY ELEMENTS:

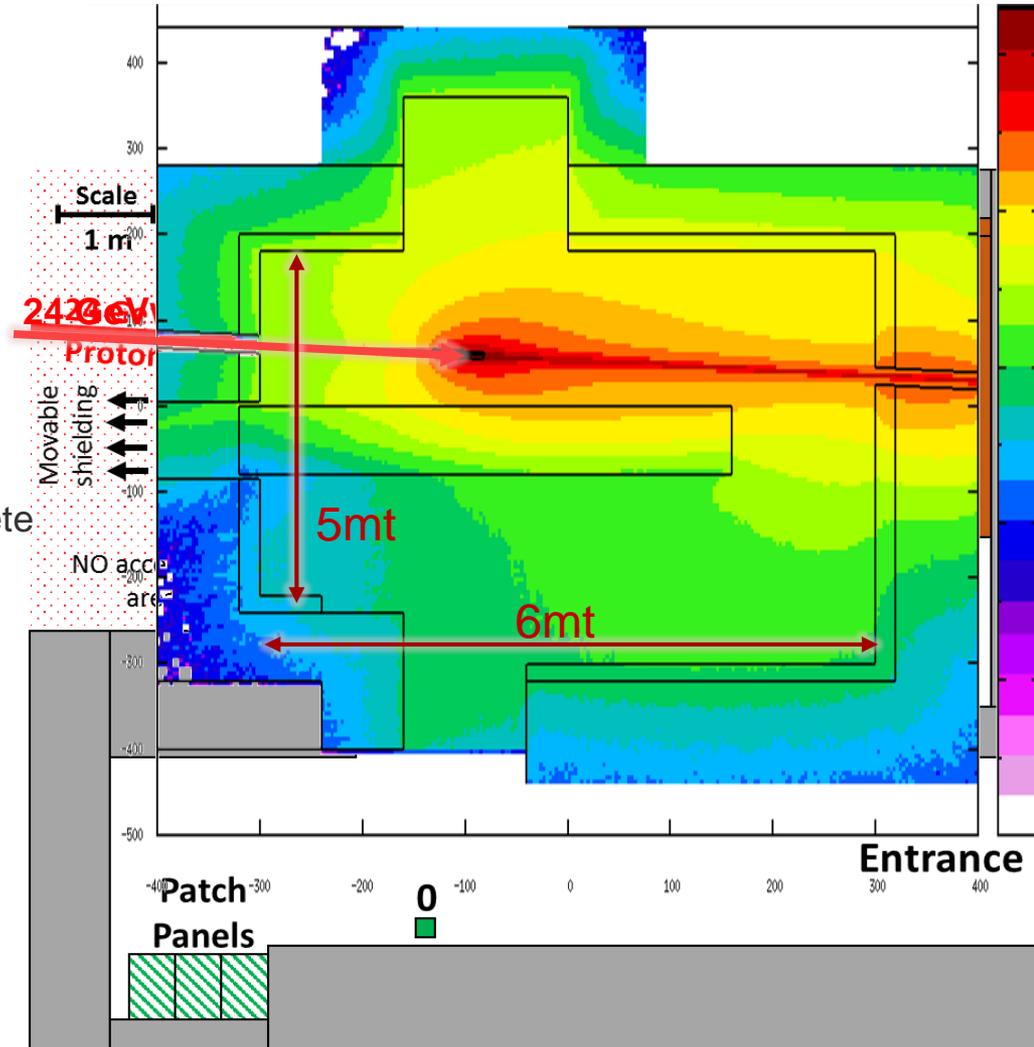
1. Target



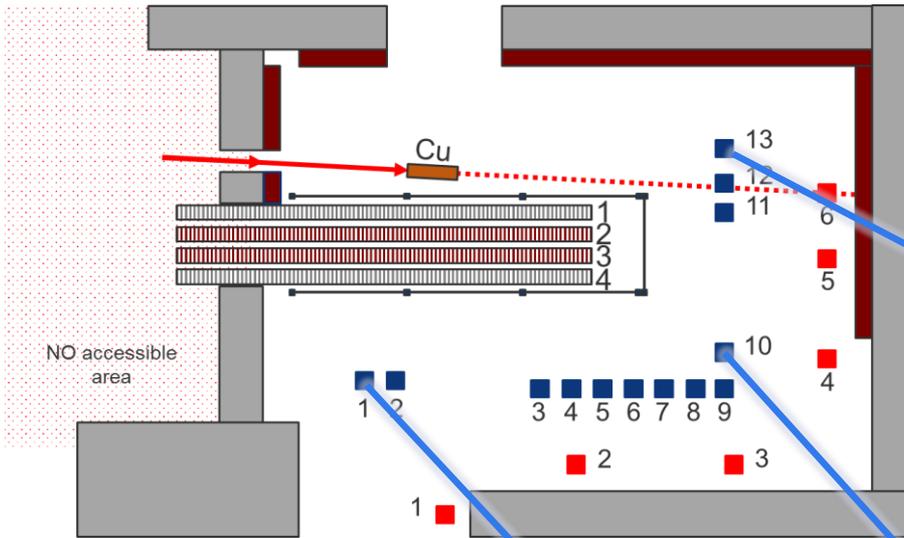
2. Movable Shielding



3. Positions

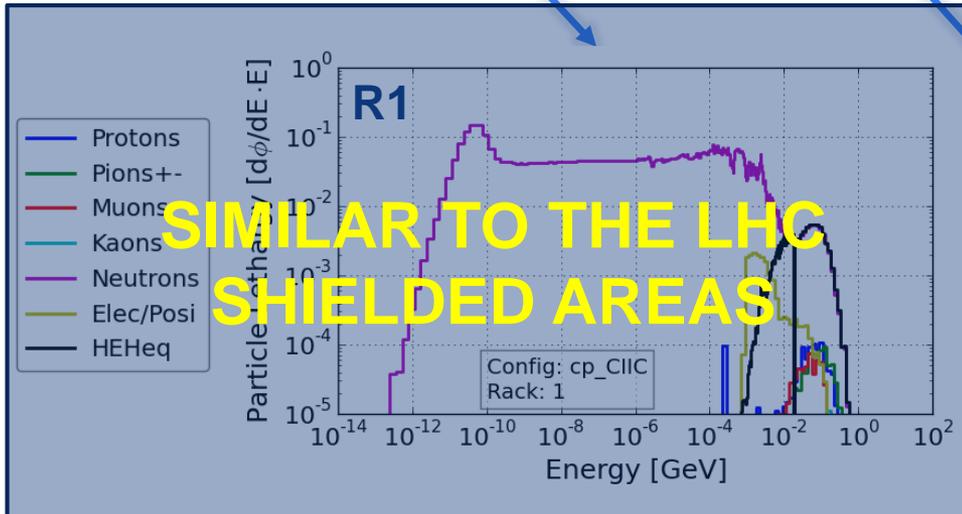
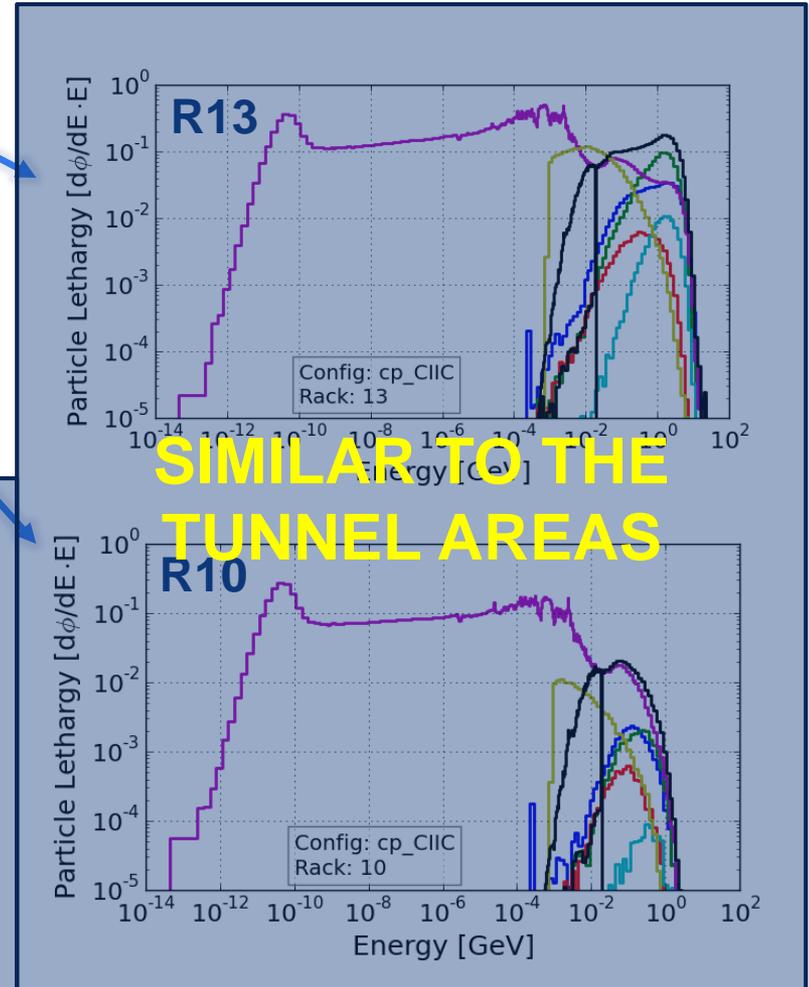


Spectra vs Position

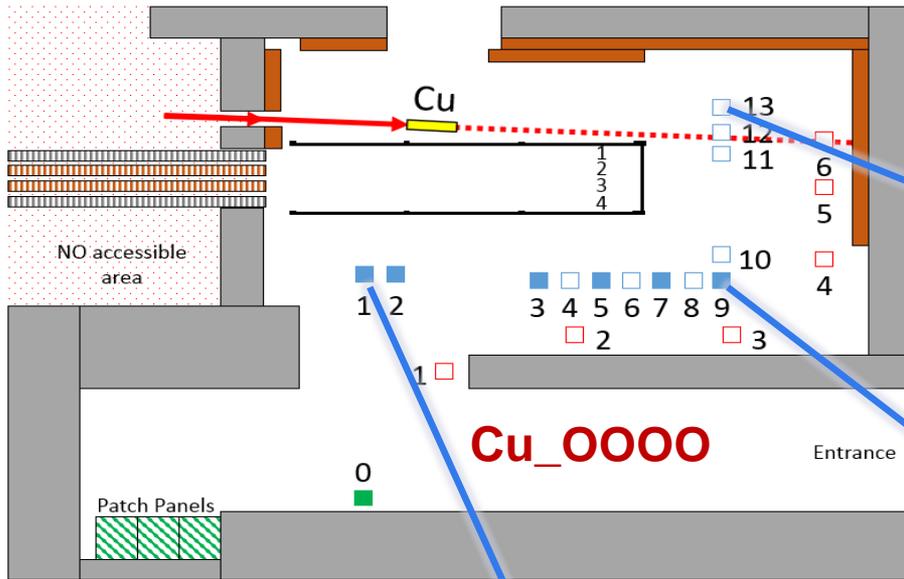


CHARM configuration: **Cu CIIC**

Data from FLUKA simulations



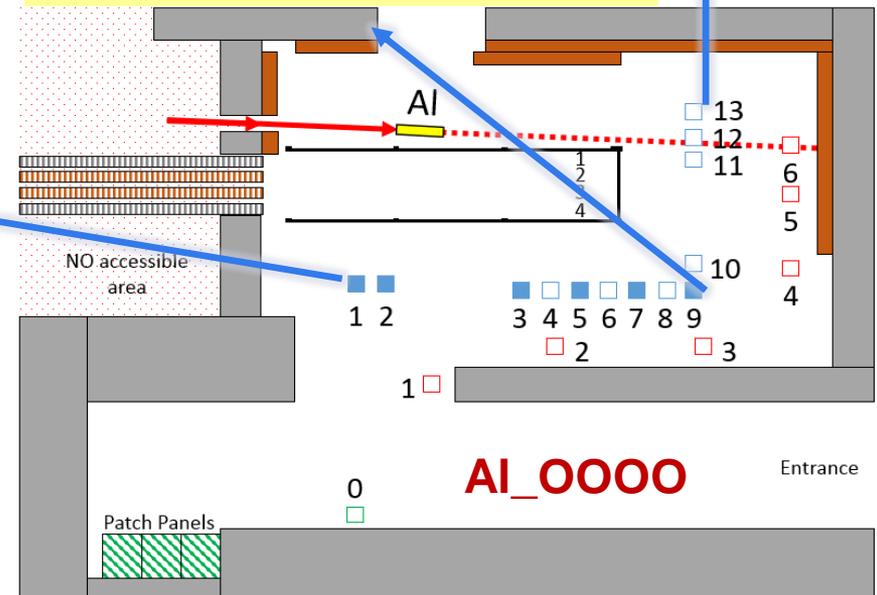
Target vs dose rate



Considering an average of POT/day = 1e15

Cu_0000	51 Gy/day
Al_0000	-

Cu_0000	23 Gy/day
Al_0000	16.8 Gy/day



Cu_0000	10 Gy/day
Al_0000	4.3 Gy/day

CHARM typical rates

Dose: 0.1 to 50Gy/day

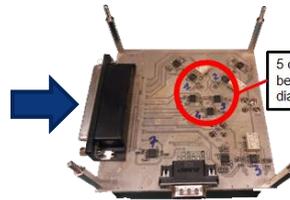
HEH: 10^7 to 10^{10} cm⁻²/day

Use of the CHARM Facility

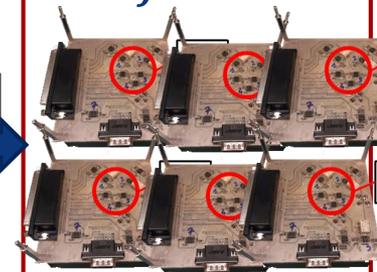
Main purpose

Radiation tests of electronic equipment and components in a radiation environment similar to the one of the accelerator

$$N_{Failure} = N * \sigma * fluence$$

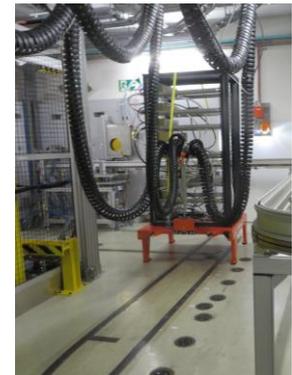


5 cm beam diameter



Large dimension of the irradiation room

- Large volumes electronic equipment
- High number of single components
- Full systems



CHARM!

Numerous representative radiation fields

- Mixed-Particle-Energy: Tunnel and Shielded areas
- Direct beam exposure (proton beam 24 GeV)

Conclusion

- CERN harsh radiation environment and challenges
- Criticality and reliability are key aspects for the LHC equipment located in the radiation areas
- Monitoring and Failure analysis are a part of the mitigations strategies operated by the R2E project
 - How the radiation levels changed during 2012 and 2015 and the failures due to radiation at equipment levels
 - Setting the target for HL-LHC to 0.1 dumps/fb-1
- The new developments should follow a dedicated guidelines which permit to prevent the radiation effects rather than mitigate during the operation
- The radiation test strategy now includes in his path a system level test to cope with the several effects due to the mixed field environment but also to have a clear overview of the entire system behaviour under irradiation



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Thank you



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BACKUP

R2E failures 2015-2016

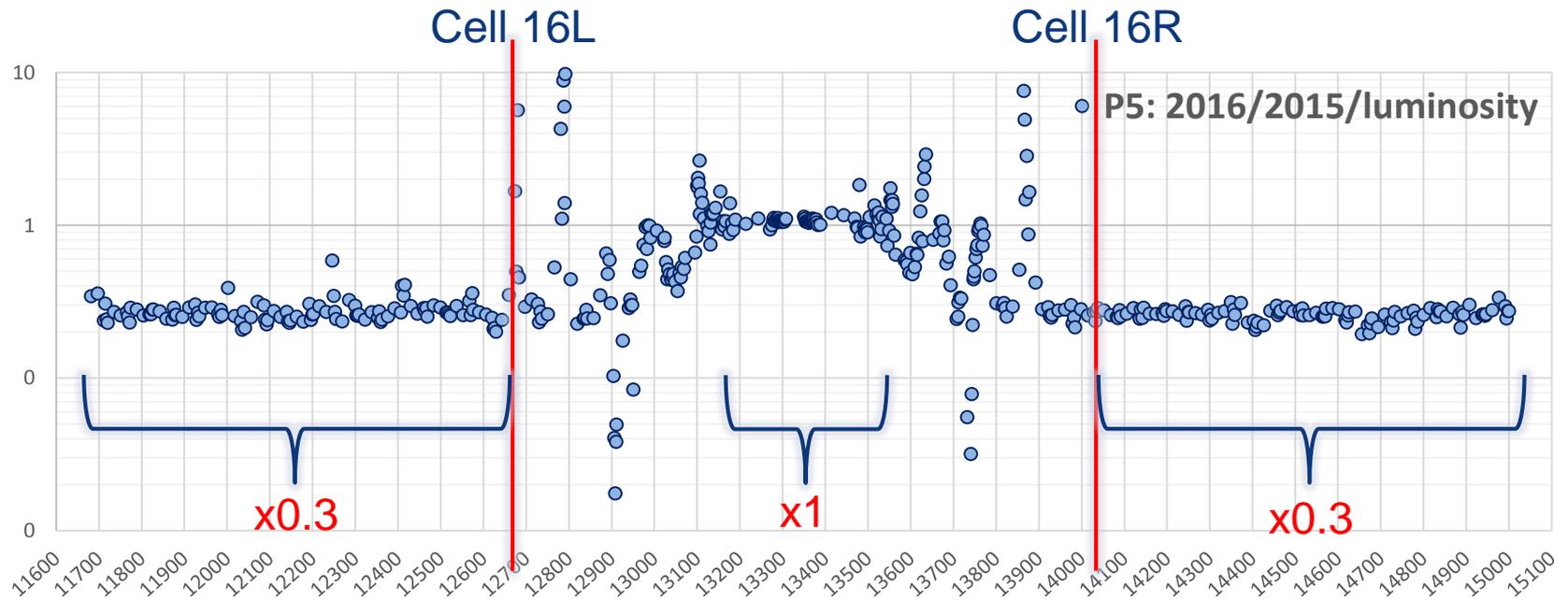
- **Few dumps in the 2016 with respect to the 2015**
- **The good mitigation strategy of QPS and RF are paying back**
 - **QPS deployed a new radiation tolerant design for the 600A protection system in the RRs**
 - **RF deployed a mitigation system for the arc detector based on the redundancy**
- **A possible new candidate happened on a PLC of the kicker system (TBC)**
- **The Power Converter was supposed to drive the dumps in the 2016 keeping the FGC2 controller in the tunnel**

Equipment	Dumps 2015 (After TS2)		Dumps 2016 (20fb-1)
QPS	3	QPS strategy →	0
RF	4	RF strategy →	0
TE/ABT	0	→	1*
Power Converter	5	→	2
Cryo	0	→	0
EN/EL	0	→	0
Vacuum	0	→	0
Collimation	0	→	0
Others (hidden)	-		(i.e TE/ABT)

*to be confirmed

Radiation Levels 2016 - 2015

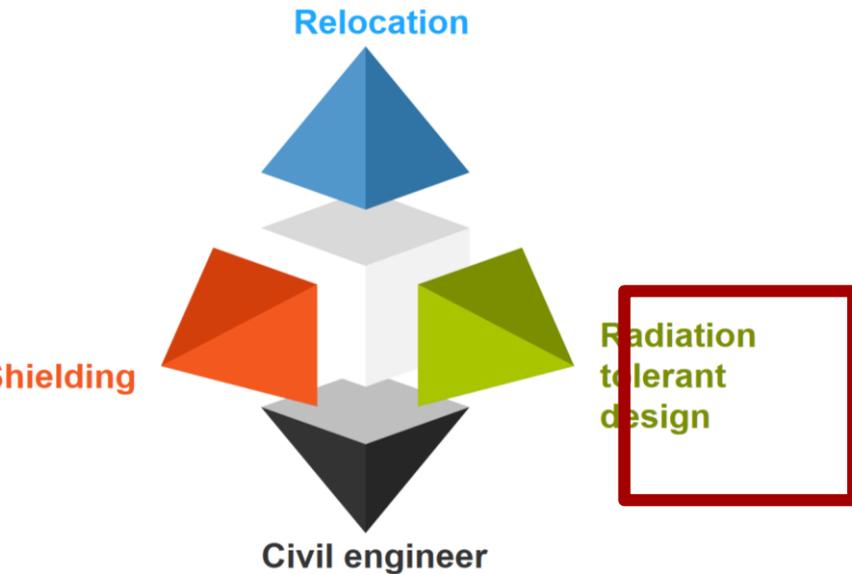
- We take **point 5** as reference but the same applies for the other points
- The analysis is based on the **BLM** and checked with **RadMons** up to the 7/08/2016: integrated luminosity of **20fb-1**
- The average **ratio 2016/2015 per unit luminosity** in the **IR** is the same between 2015/2016
- The average **ratio** in the **ARC** is around **0.3** (in other point always <0.5)



DCUM

S. Danzeca - TWEPP 2016

Mitigation Options



1st Safety Critical



Immediate Relocation

2nd Shielding



“Fast” & Global Improvement

3rd Most Sensitive



Highest Impact on Operation:
(1) Relocation
(2) Shielding
(3) Re-Design

4th Remaining



(1) Relocation
(2) Shielding
(3) New Design

The long term total ionizing dose TID problem

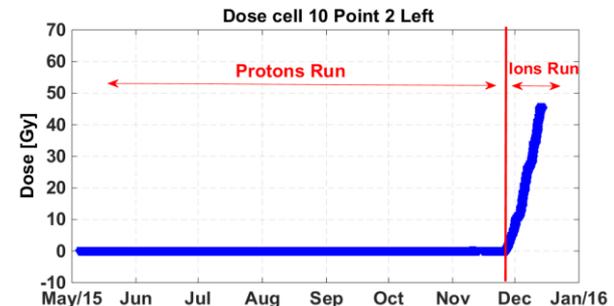
LHC Era	Machine Energy	Integrated Luminosity	Radiation Dose in Arc	Radiation Dose in DS
	[GeV]	[fb ⁻¹]	[Gy/year]	[Gy/year]
Run 1	3.5/4.0	~30	<<1	~10
Run 2	6.5/7.0	~100	~1	~20
Run 3	7	~300	~2-4	~40
HL-LHC	7	~3000	~4-8	~80-160

from R2E Availability workshop 2014

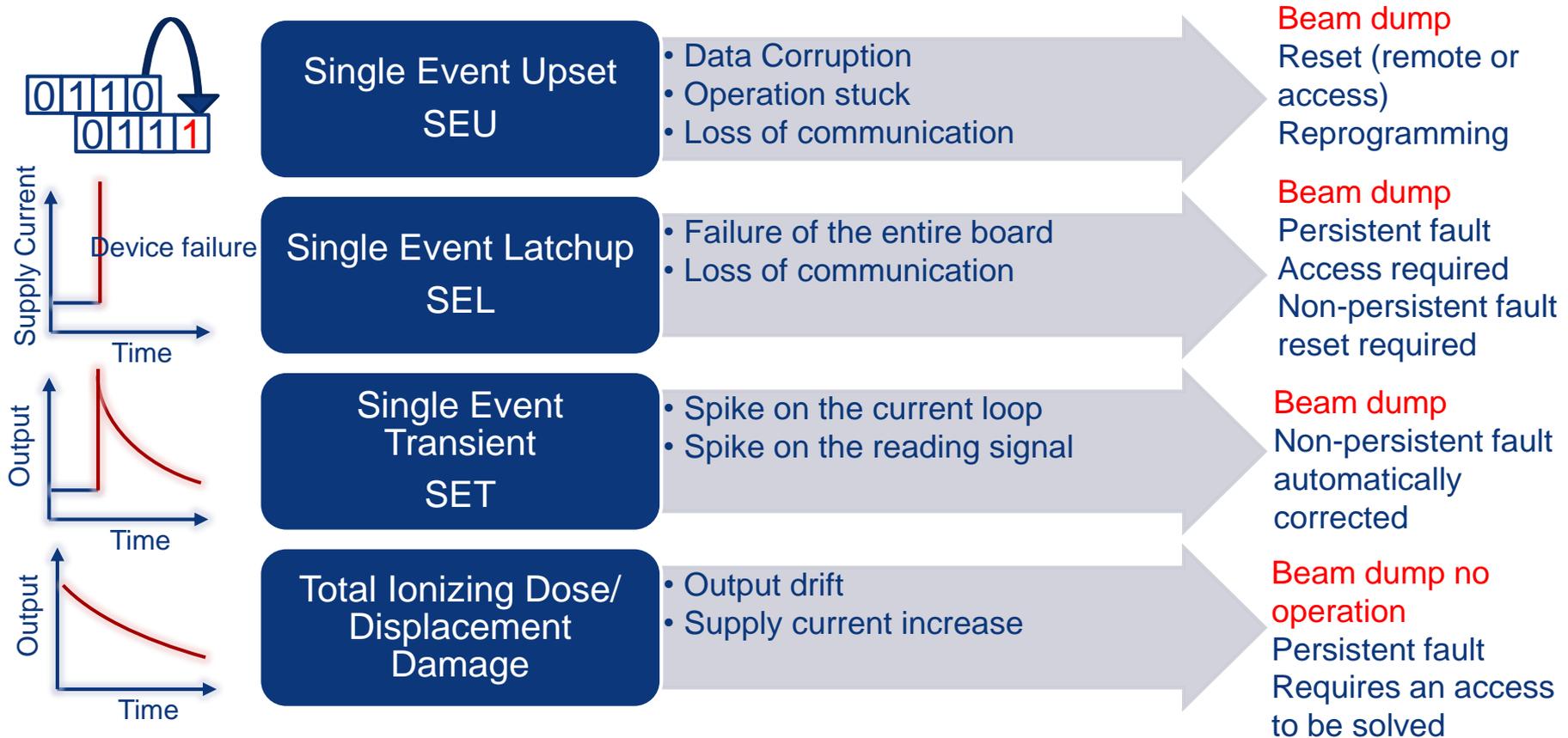
- We should **not forget the ions runs**

- Due to the Bound-Free Pair Production (BFPP), even for short runs, radiation levels can be up to 50 times those of a proton run (Very localized)

- The solution before the HL is rotate/substitute the equipment where the level are too high (DS)



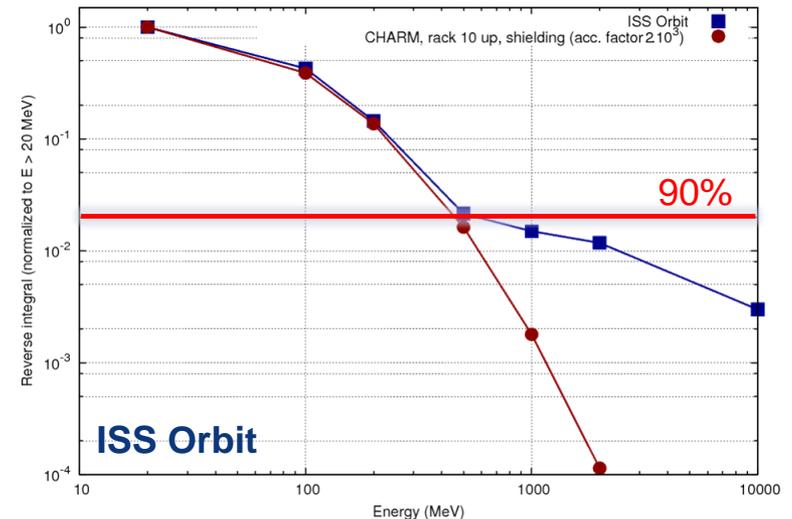
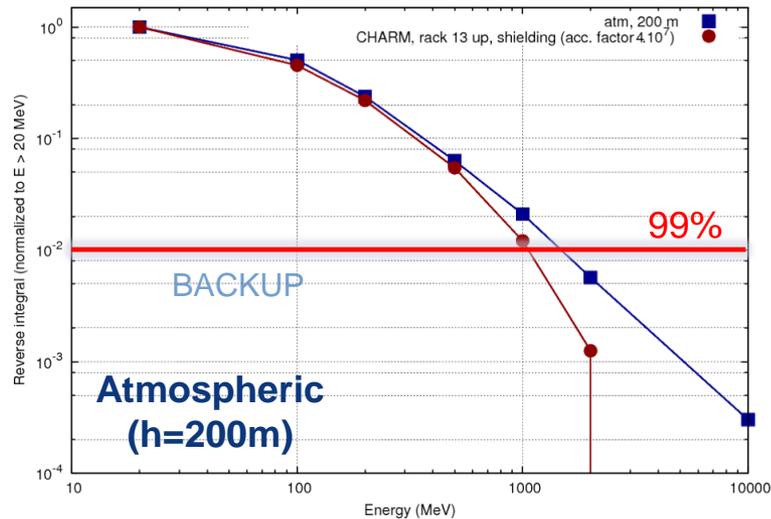
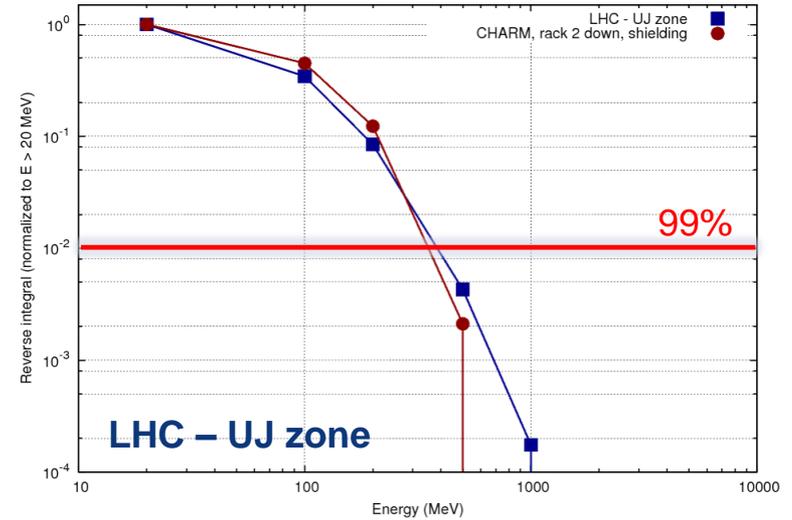
The impact of the radiation effects



Spectra vs. position

CHARM can reproduce different scenarios of radiation environments:

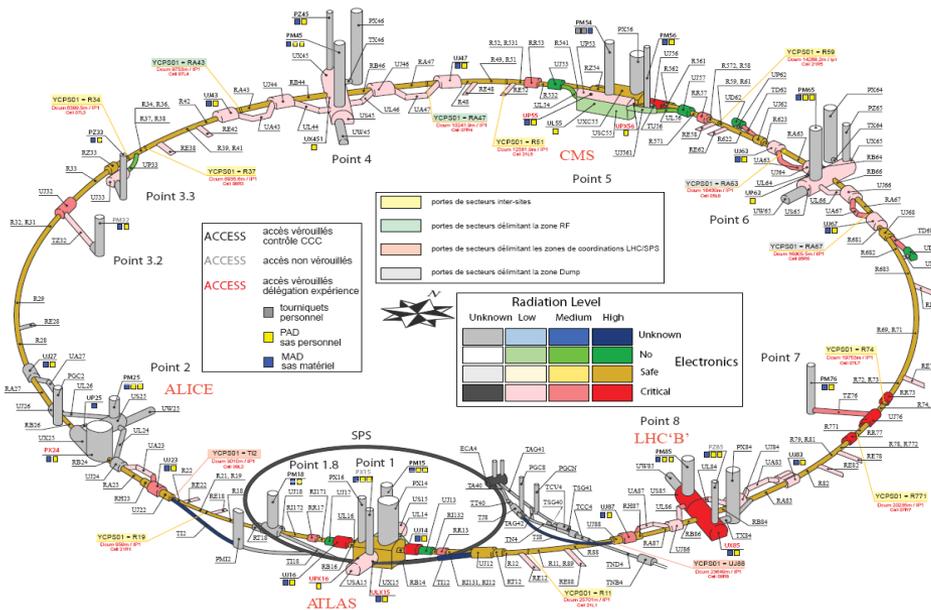
- LHC UJ zone
- LHC shield zone
- ISS Orbit
- Atmospheric 200m



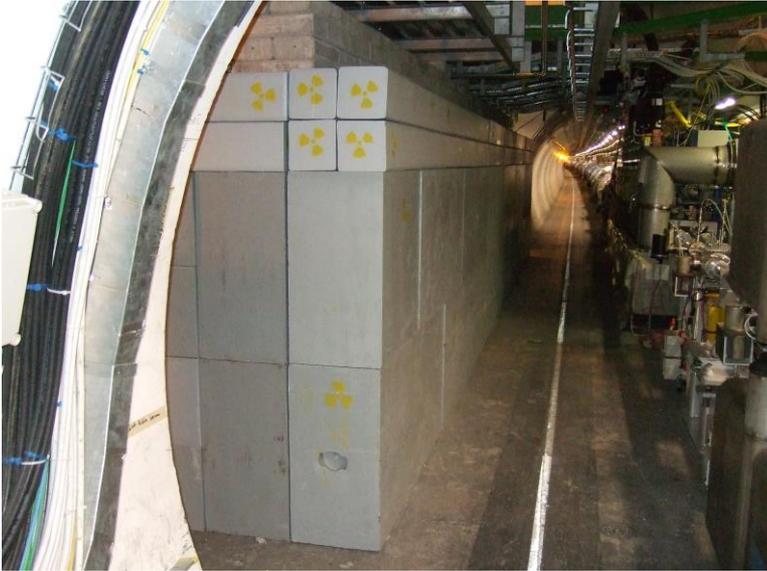
Tunnel: LSS/DS/ARC

Tunnel areas can be divided in three main parts:

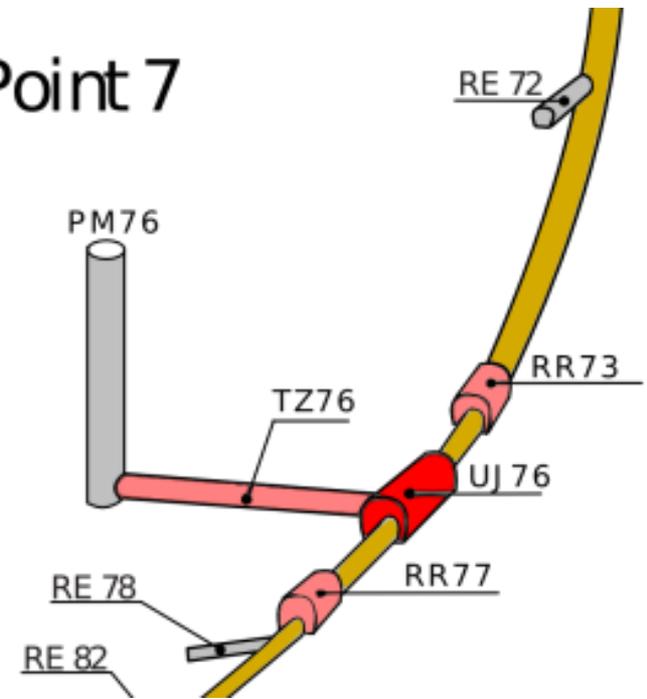
1. long straight section (LSS): cells 1-7
2. Dispersion suppressor (DS): cell 8-11
3. ARC region: cell 12-34



Shielded areas



Point 7



Radiation level				
Unknown	Low	Medium	High	
Grey	Light Blue	Blue	Dark Blue	Unknown
White	Light Green	Green	Dark Green	No
Light Grey	Yellow	Orange	Red-Orange	Safe
Dark Grey	Pink	Red	Dark Red	Critical

Electronics