Reliable electronics in a radiation environment

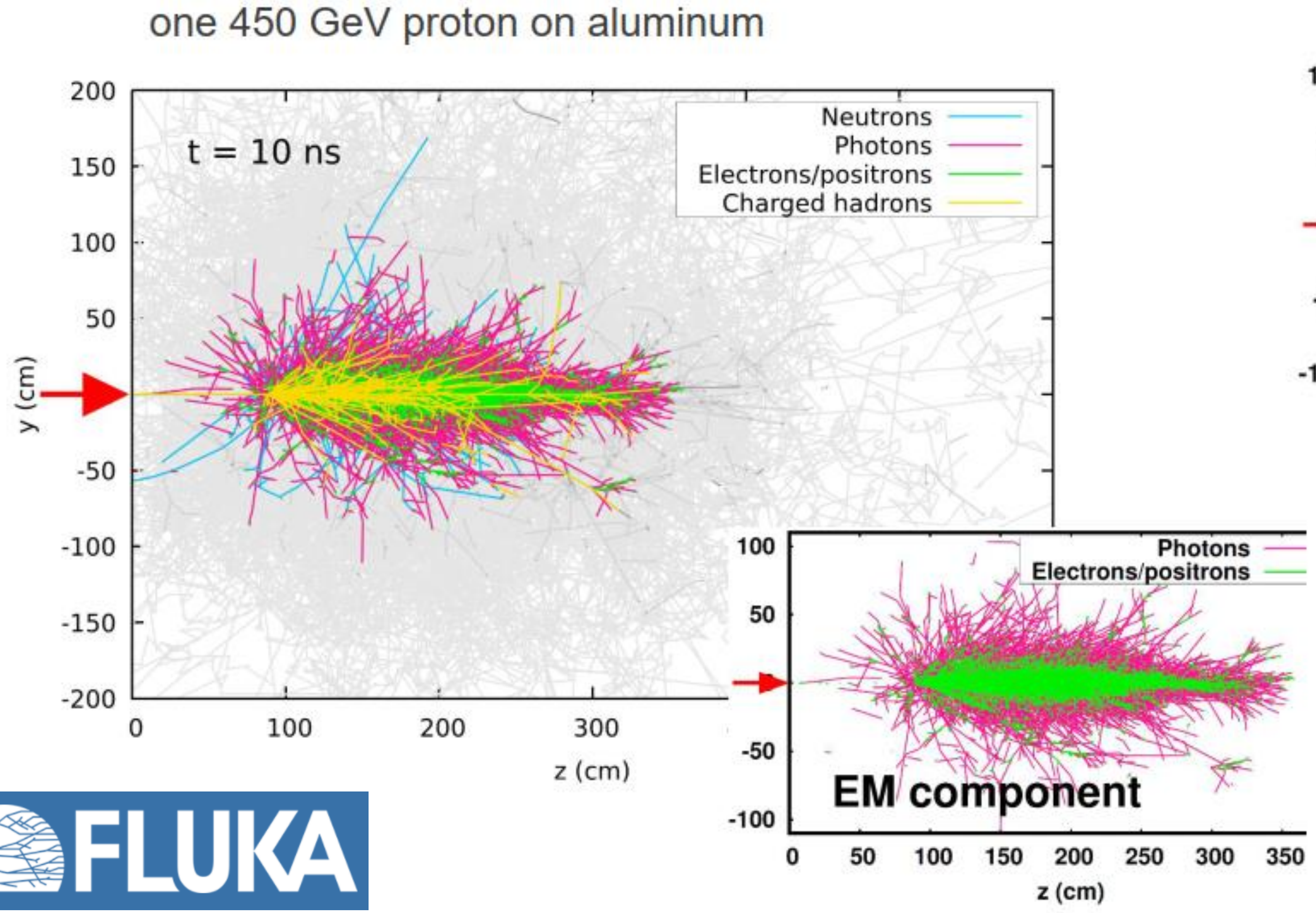
Rubén García Alía, for the R2E project at CERN

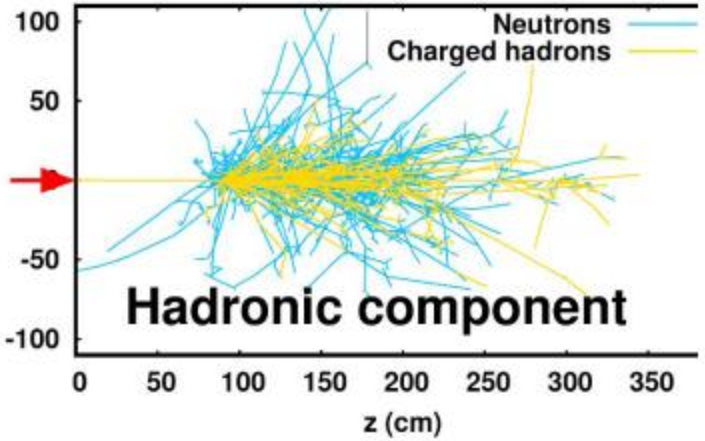
KUKA-CERN Meeting
28 March 2022, at CERN
https://indico.cern.ch/event/1137792/

Agenda

- Why do radiation effects matter for high-energy accelerators?
  - Radiation environment
  - Sensitivity of accelerator equipment to radiation
- How do R2E effects impact the accelerator performance, and what can be done to mitigate or prevent this negative impact?
  - Impact on accelerator availability
  - Radiation Hardness Assurance procedure
    - System architecture and part testing & selection
    - System level radiation testing
- Some examples of component level R&D on COTS devices

One (single) 450 GeV proton on aluminum



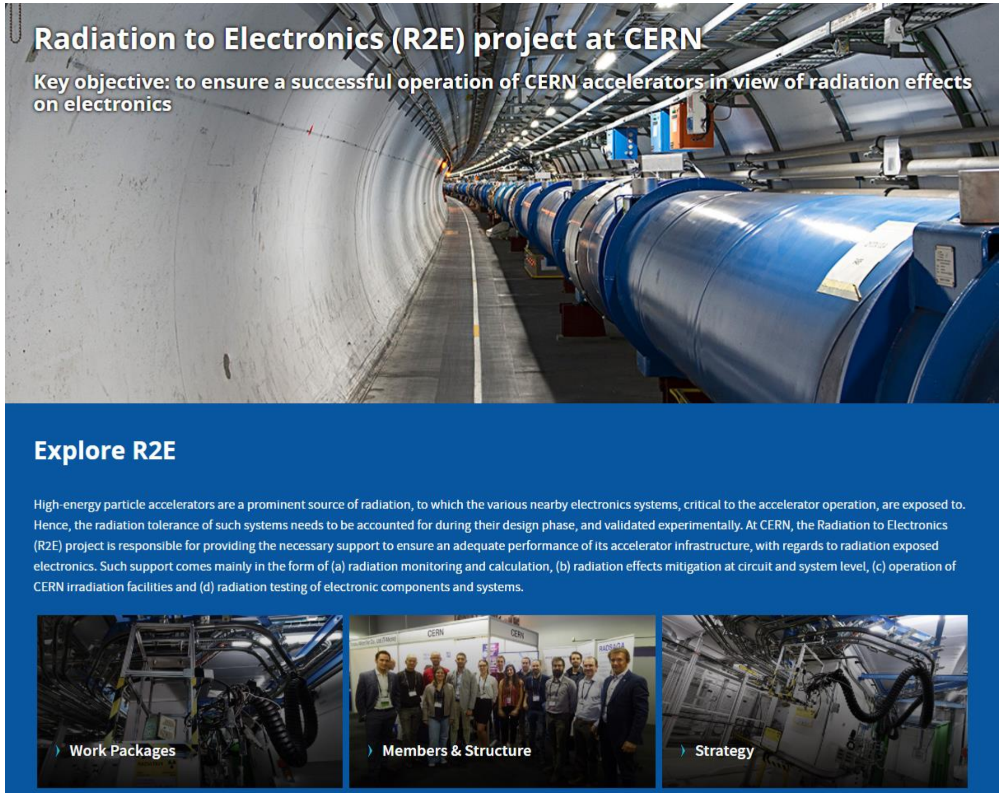


→ *Dose (ionizing and non-ionizing) and Single Event Effects*

→ *Dose (ionizing)*

Radiation to Electronics (R2E) project at CERN

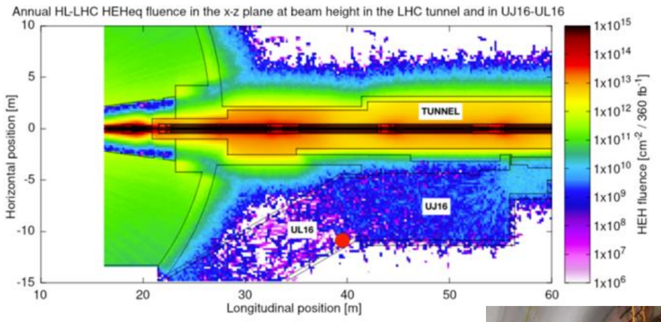
https://indico.cern.ch/event/r2e-2022

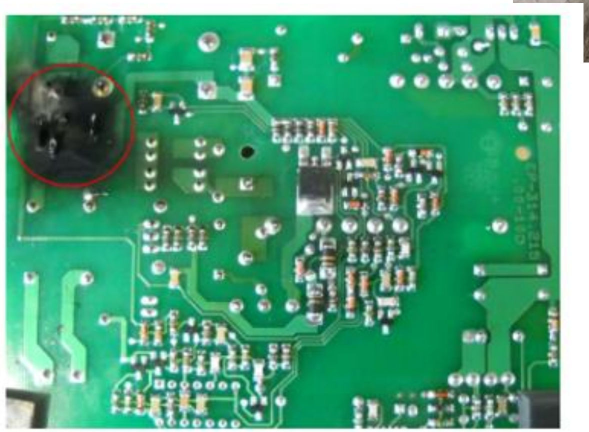


https://r2e.web.cern.ch/

Why do radiation effects matter for high-energy accelerators?

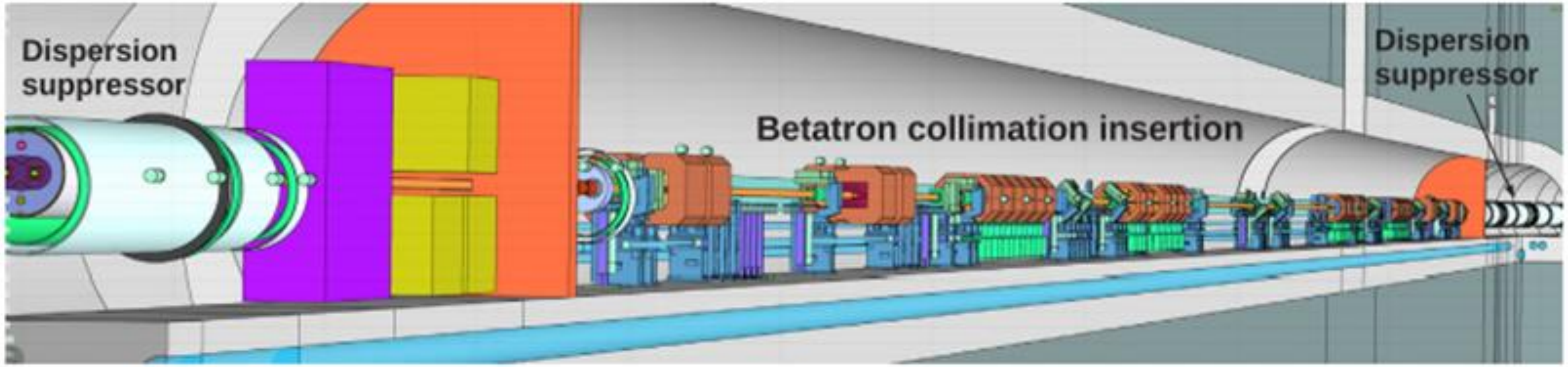
- High-energy accelerators are subject to beam losses and hence generate radiation in their vicinity
- Part of the accelerator equipment needs to be installed near the machine itself, and is hence subject to such radiation environment
- Such equipment, which can be critical for the successful operation of the accelerator, uses microelectronic components which are sensitive to radiation



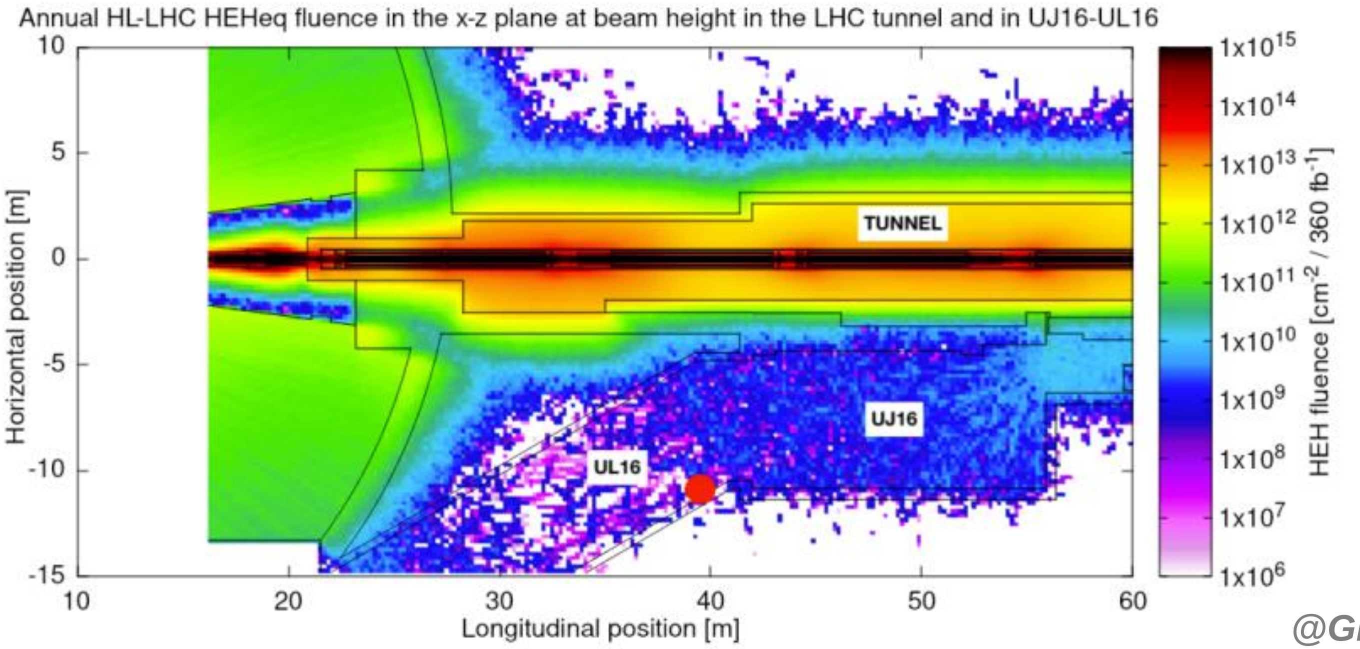


LHC radiation environment

- Main sources of radiation:
  - **Collision debris** from interaction points
  - Interactions with **beam intercepting objects** (e.g. collimators)
  - **Beam-gas** interaction
- Hadronic and electro-magnetic showers originate from interaction of high-energy protons (or ions) with the different elements



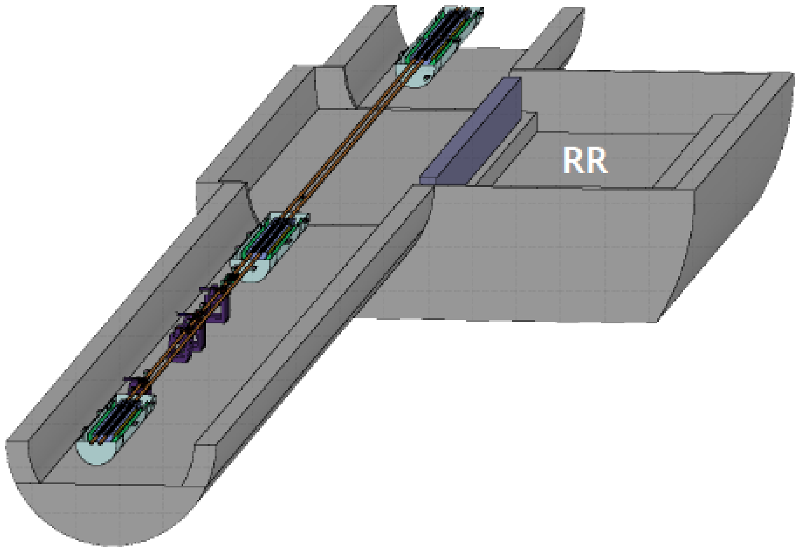
Shielding example for collision debris

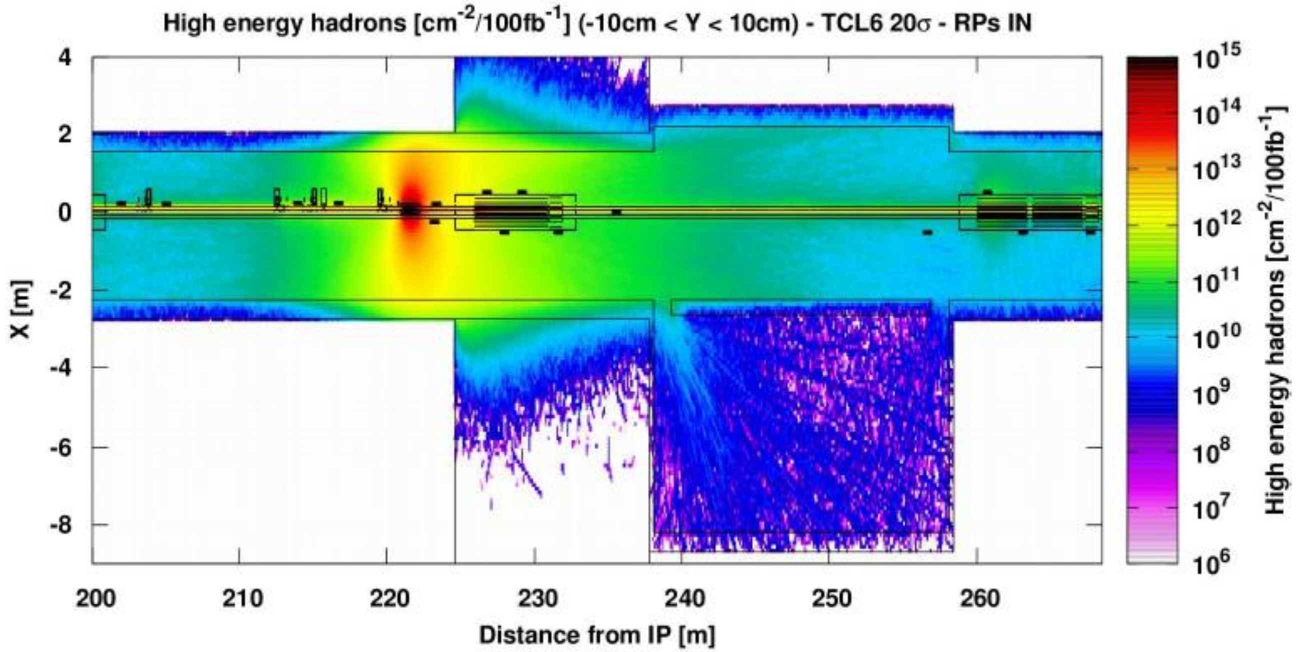


@Giuseppe Lerner

- Even heavily shielded areas around the LHC can have significant radiation levels (e.g. UL16: ~10^7 HEH/cm^2/year for HL-LHC, a factor ~100 above cosmic neutron radiation background at sea level)
  - Civil engineering is expensive, especially underground…
- If we throw in some simple numbers, a part with a destructive SEE cross section of **10^{-8} cm^2**, present in **100 systems** exposed to **10^7 HEH/cm^2/year**, would lead to **10 events per year** (which, depending on the criticality, may not be acceptable)

Shielding example for collimation debris

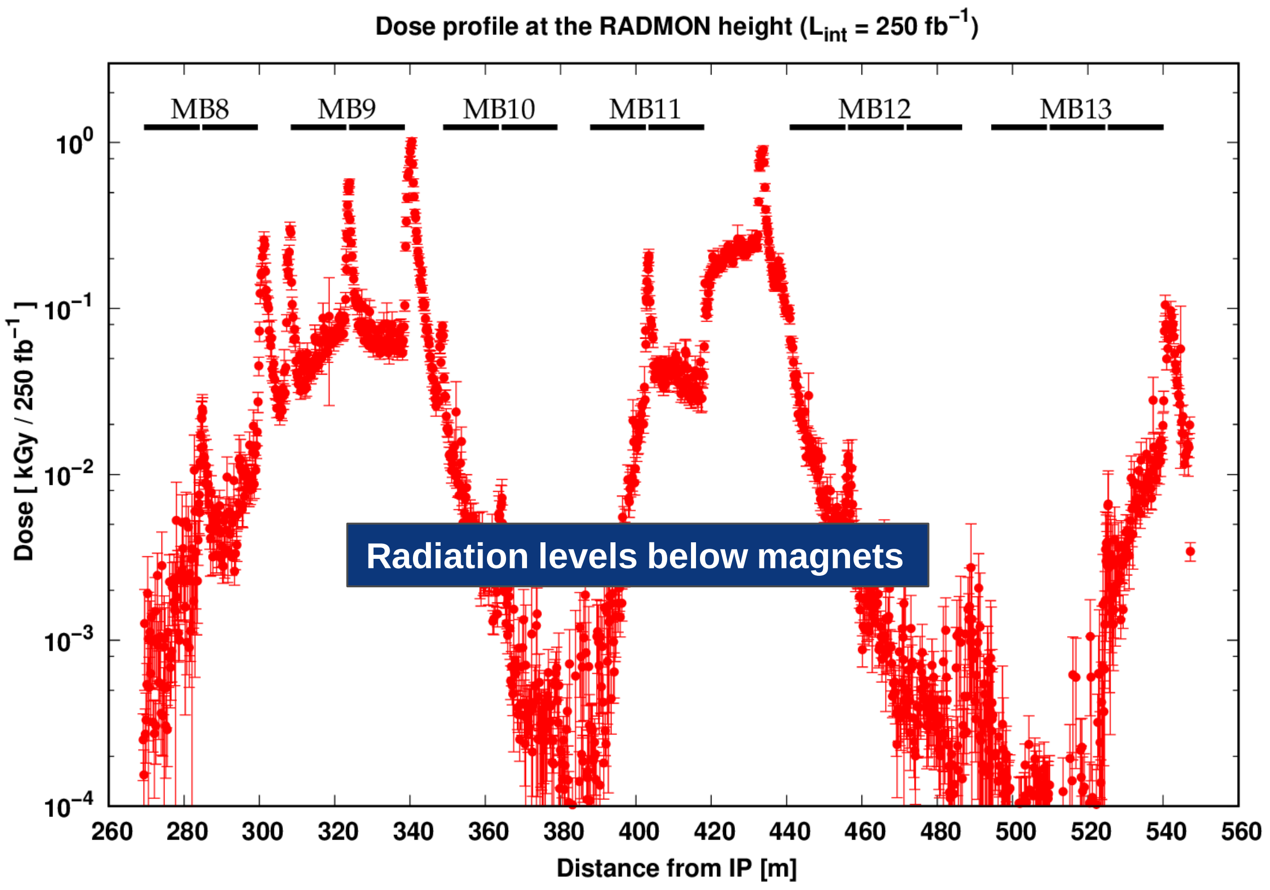




- **Lightly shielded alcove**, with 40 cm cast iron, partially opened
- Very near debris collimator(*), which is main source of radiation
- Shielding reduces radiation levels from **~10^{10}** (tunnel) to **~10^{9} HEH/cm^{2}/year**

(*) Collimator downstream interaction point, cleaning the beam from collision debris (i.e. protons in the beam halo)

Radiation levels in DS of Point 1 and 5



- Remember: in interaction and collimation points, lifetime TID levels of up to **hundreds of kGy**
- In the DS, lifetime TID levels of **~1kGy** for cell 9 and parts of cell 11
- Most DS region with levels below **200 Gy**, typically considered as qualification limit

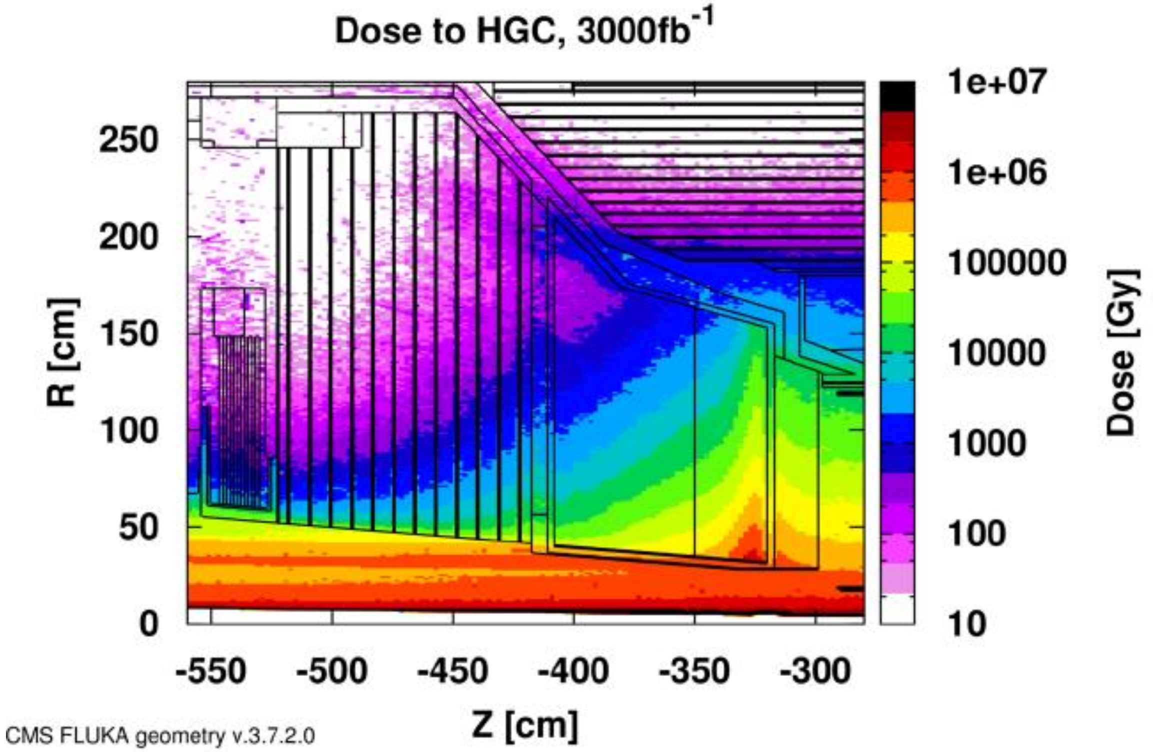
Summary of LHC tunnel and shielded alcoves

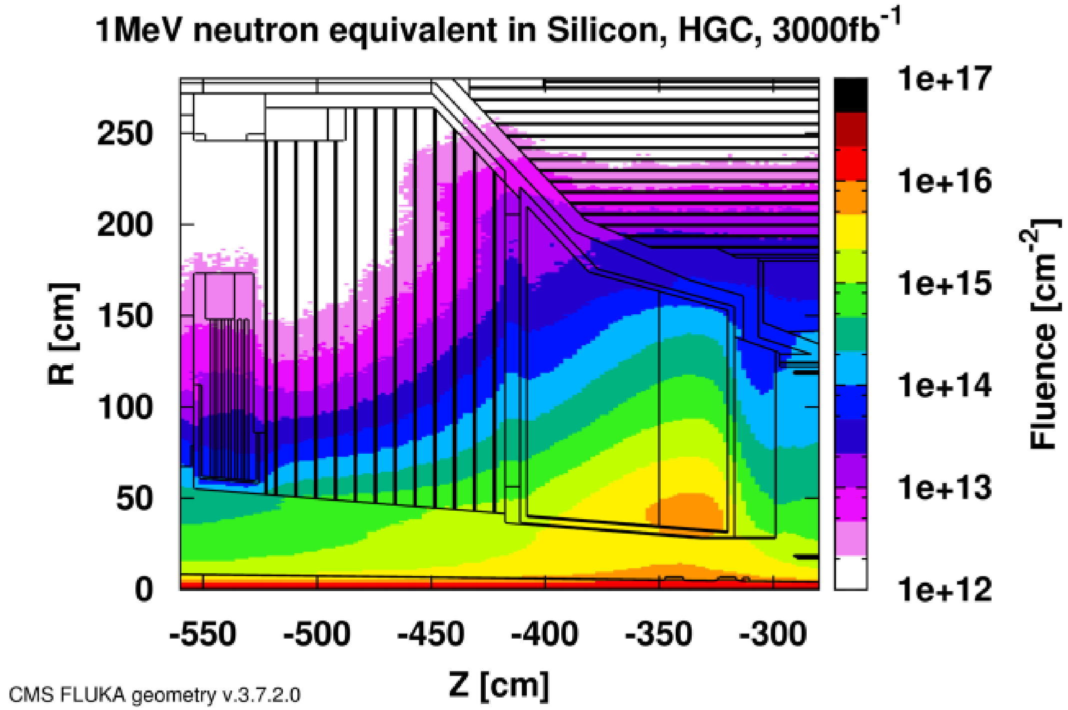
Indicative values for HL-LHC conditions – not to be taken as specifications!
[NB: actual values strongly depend on exact position and operational conditions]

HL-LHC area	HEH fluence (cm^{-2}/year)	Lifetime TID	Lifetime 1MeV n_{eq} (cm^{-2})
Shielded alcoves	10^9	10 Gy	10^{11}
ARC	10^9	10 Gy	10^{11}
DS	10^{11}	1 kGy	10^{13}
LSS	10^{13}	100 kGy	10^{15}

Areas hosting large quantity of systems, mainly impacted by SEEs
Both SEE and cumulative lifetime threat for COTS components
Use of COTS excluded; possible material damage

Detector environment and electronics

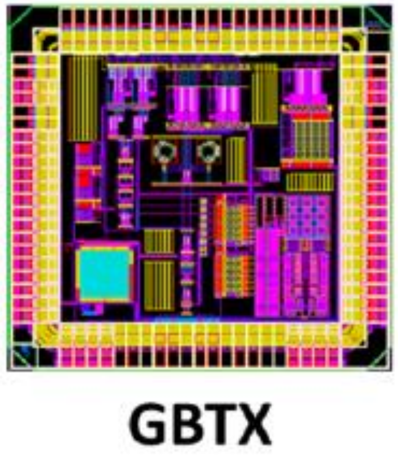




*For the **HL-LHC** (High-Luminosity LHC) detector electronics, to operate between 2025 and 2035, radiation levels of up to **10 MGy** and **10^{16} n_{eq}/cm^2** are expected, thus requiring the use of **rad-hard by design electronics***

Detector environment and electronics

- Example of rad-hard design for high-energy accelerator detector electronics: Giga-Bit Transceiver (**GBT**)
  - Started in 2007 as a rad-hard bi-directional optical link for the LHC detector upgrade program
  - Data transmission between front-end detector, exposed to radiation, and back-end, in radiation safe area
  - Radiation constraints: **SEE-free**, **1 MGy TID** (and no DD limit as it can be neglected for CMOS)
  - Qualification: **X-rays** for TID, **heavy ions** for SEE
  - Timeline and cost for development & qualification are beyond the scope of systems for the accelerator sector

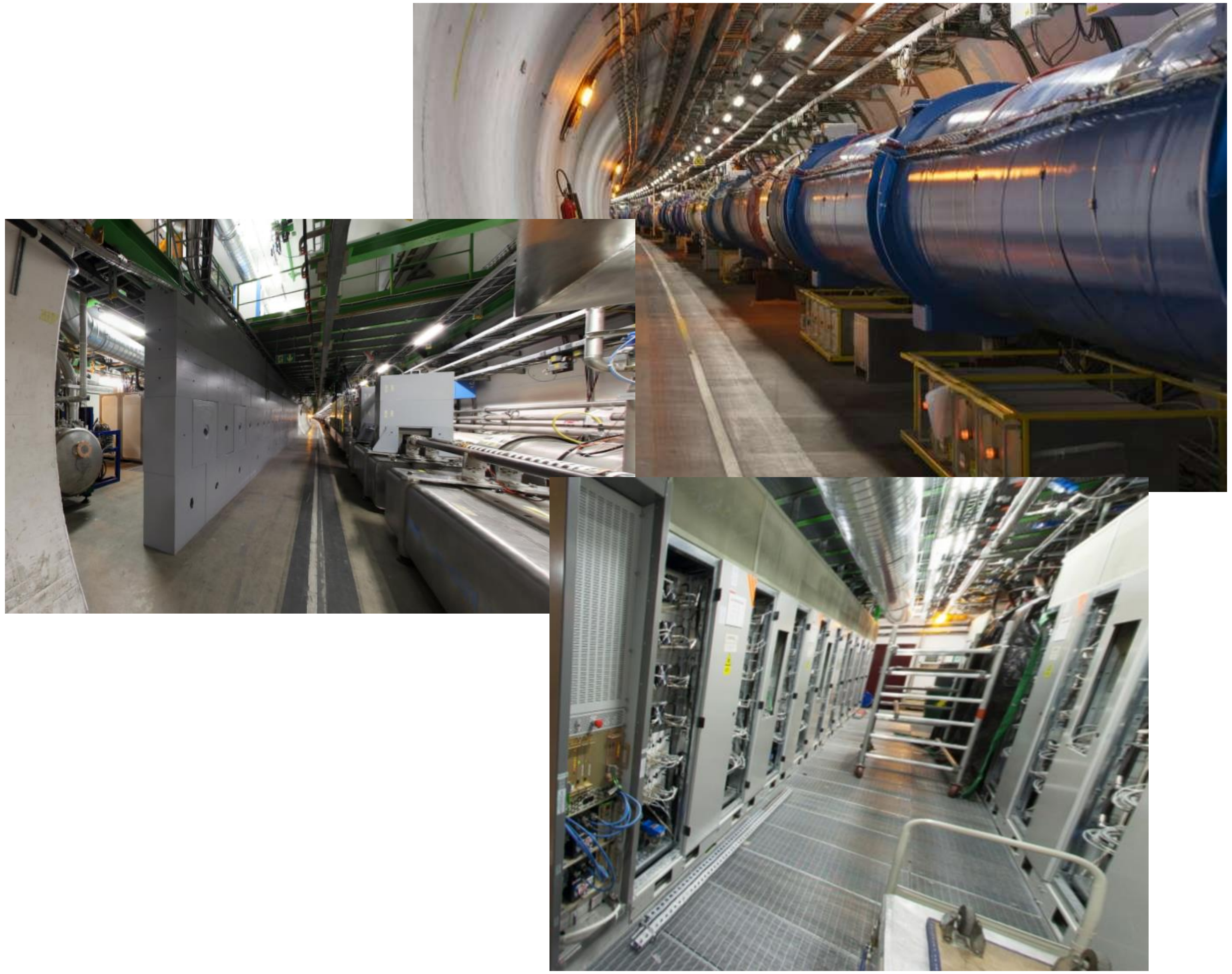


ASIC designed in framework of GBT program

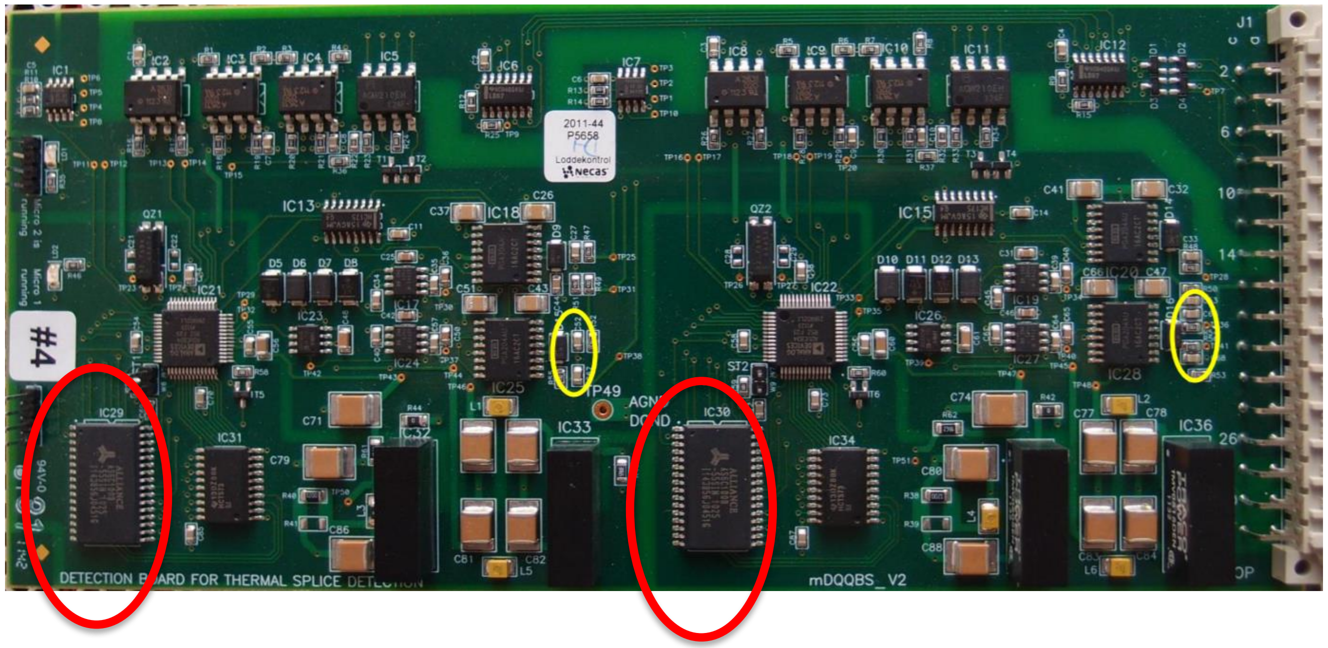
Uznanski, RADECS Short Course 2017

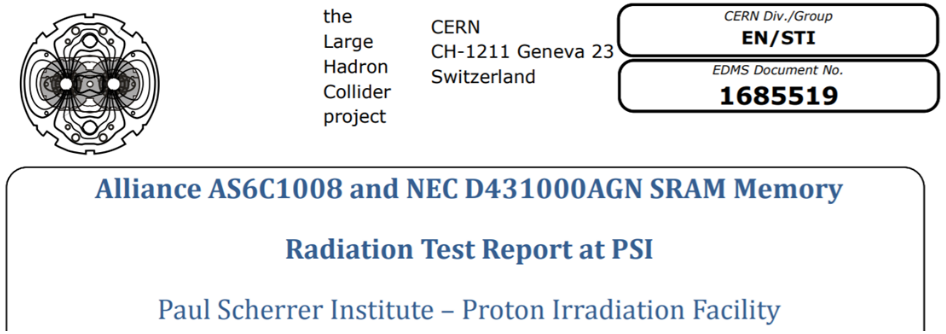
COTS-based critical equipment near accelerator

- Main reason requiring operation near accelerator:
  - Cable distance to accelerator elements (magnets, vacuum, cryogenics, RF, beam instrumentation…)
  - Lack of radiation-safe areas around accelerator (underground machine)
- Main drivers for use of COTS:
  - Cost
  - Performance
  - Availability and timeline
- Typical example of system level SEE requirement: one R2E failure per critical system per year



R2E challenges: COTS component SEE sensitivity




the
Large
Hadron
Collider
project

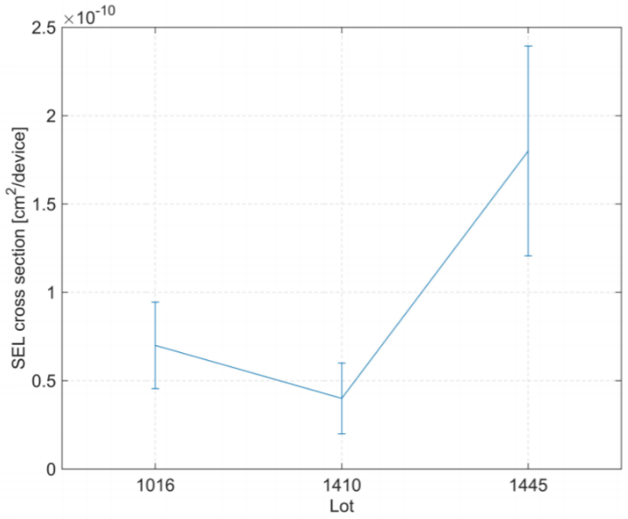
CERN
CH-1211 Geneva 23
Switzerland

CERN Div./Group
EN/STI
EDMS Document No.
1685519

Alliance AS6C1008 and NEC D431000AGN SRAM Memory

Radiation Test Report at PSI

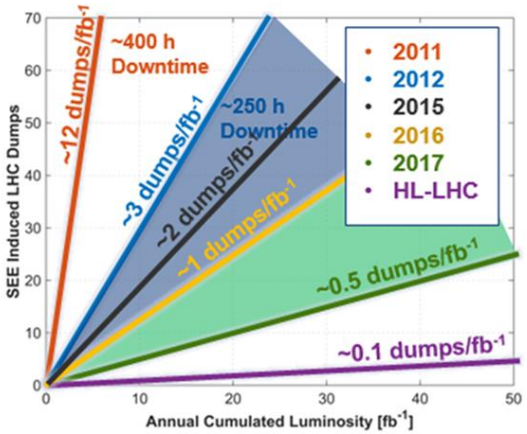
Paul Scherrer Institute – Proton Irradiation Facility



- SEL sensitive SRAM performing critical function in critical system (in red)

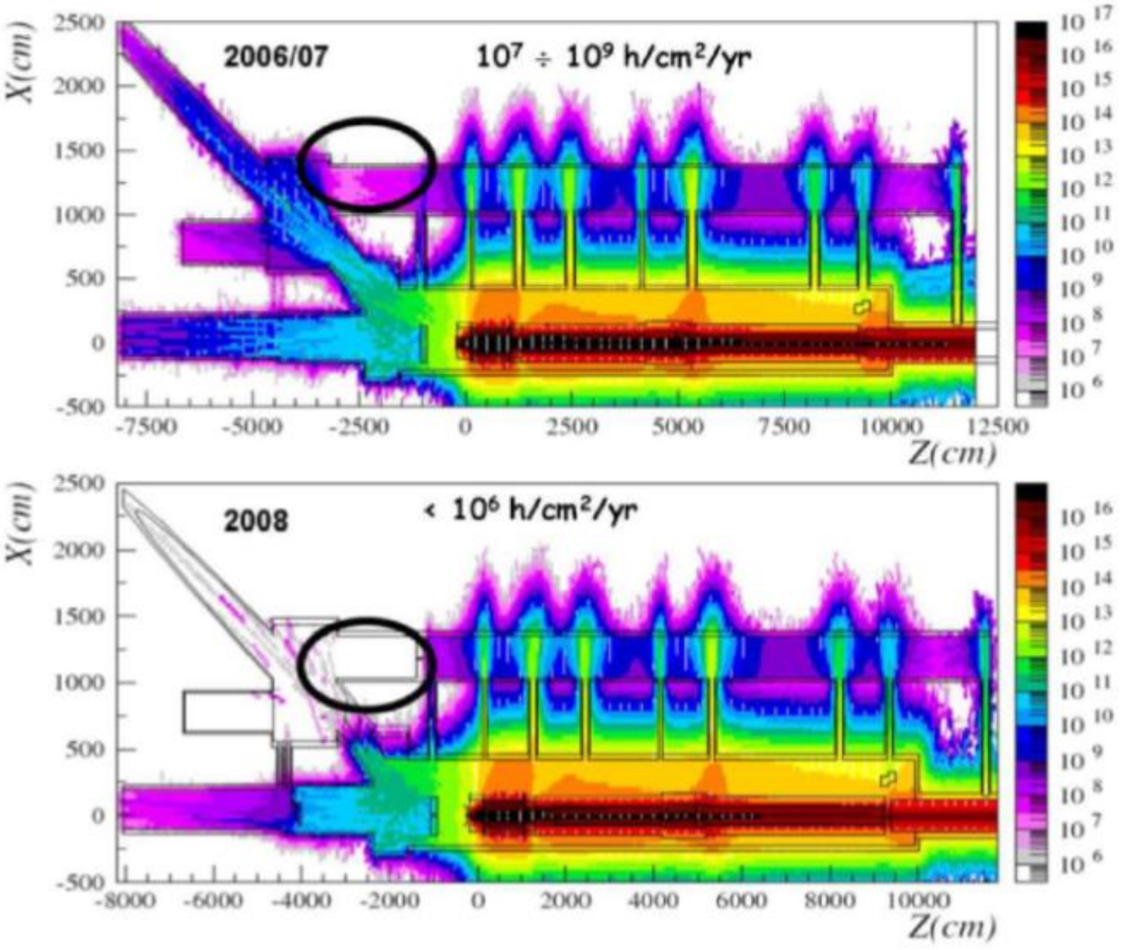
How do R2E effects impact the accelerator performance, and what can be done to mitigate or prevent this impact?

- R2E effects impact the accelerator performance by **reducing its availability**, potentially in a severe way, and hence also compromising the related scientific exploitation of the infrastructure
- **For equipment already installed:** mitigation measures such as shielding, relocation, or replacement of sensitive elements (crossing fingers the alternative option works better!)
  - **Very expensive**, both in terms of loss of machine availability, and cost linked to mitigation solutions
- **For equipment under development:** make it radiation tolerant! In a nutshell:
  - Define the radiation levels in which it will operate, and its related availability requirements
  - Select a system architecture and list of parts with the required radiation tolerance objective in mind
    - This often involves **a lot of radiation testing** at component level!
  - Validate the radiation tolerance at system level in a representative environment, and if needed, re-iterate part selection or system architecture to obtain targeted radiation tolerance

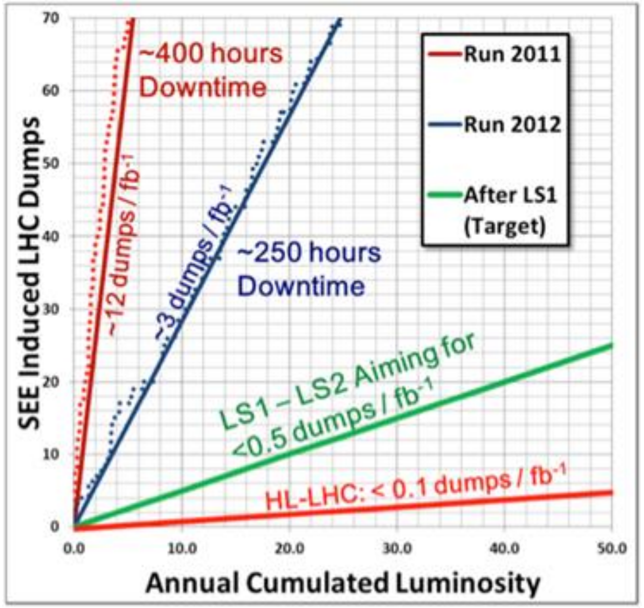


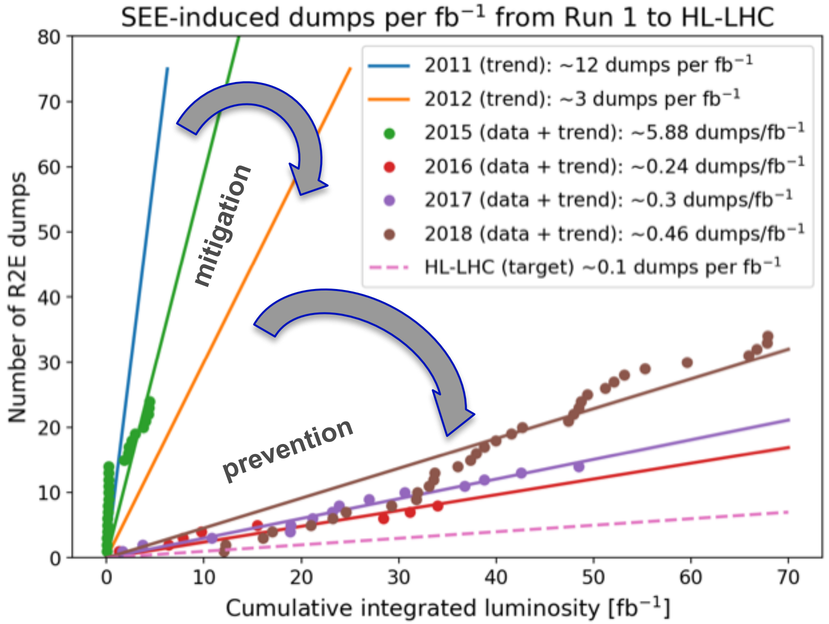
R2E: what can happen? Early example

- CERN Neutrinos to Grand Sasso (CNGS) experiment
- Muon-neutrinos generated through interaction of 400 GeV protons with target
- **Shutdown** at an early stage due to successive failures in the ventilation system
- **SEEs in microcontrollers**, mitigated by reinforced shielding



R2E: what can happen? Impact on LHC





Run 1 R2E failure rate reduction down to ~3 dumps/fb^{-1} was mainly achieved by ***mitigation*** *measures (shielding and relocation)*

Run 2 objective of <0.5 dumps/fb^{-1} was achieved, mainly thanks to R2E ***radiation-tolerant developments and qualification***

R2E: what can happen? More recent impact on SPS

Beam Availability Overview 2021
(since the start of SPS North Area physics)

Facility	Destination	Expected 2021 Total [%]	Achieved 2021 Total [%]*
LINAC4	-	95	97.3
PSB	PS, ISOLDE	90	94.5
PS	SPS, nTOF, AD, East Area	87	88.1
SPS	LHC, North Area, AWAKE, HiRadMat	84	73.4

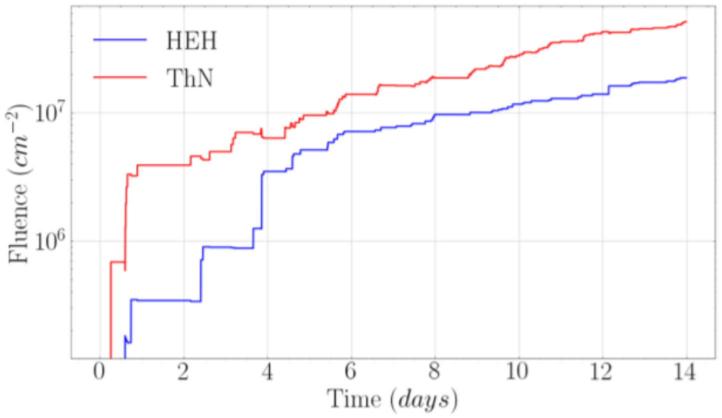
R. Steerenberg | FOM - Facilities Operations Meeting

Start: 12 August 2021 - Reading: 26 August 2021

BatMon result **inside** the rack

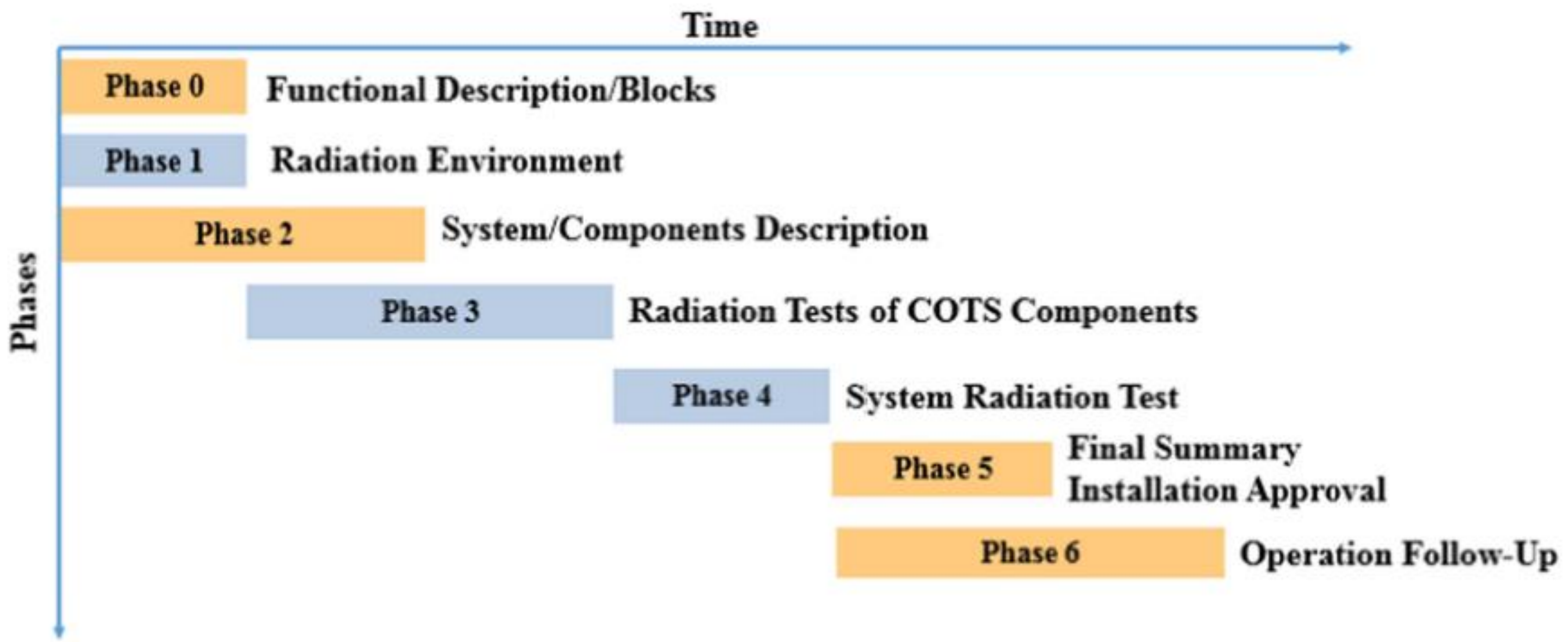
HEH = $2*10^7$ [cm^{-2}]

ThN = $5*10^7$ [cm^{-2}]



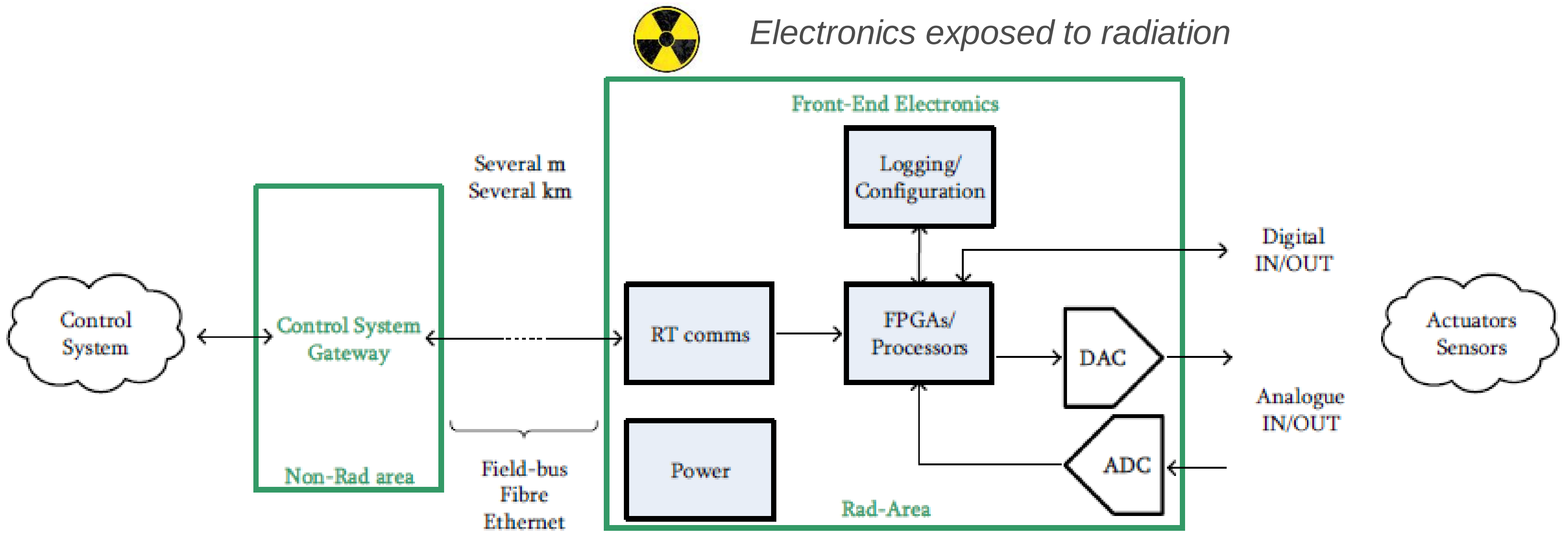
- R2E issues in the SPS during 2021 operation due to SEUs in commercial electronics of access system
- Even relatively low radiation levels can lead to trouble for sensitive electronics
- Not necessarily linked to “new” systems, but rather consolidated versions of older ones

R2E prevention through radiation tolerant COTS based systems



- *Considering radiation tolerance constraints at very early stage of design*
- *Validation of radiation tolerance at system level before final production*

Example of rad-tol COTS-based system architecture



Uznanski, MAPLD'18

- *COTS-based, but custom design (i.e. full control of schematics and part selection). Use of COTS modules (black boxes) for critical applications in radiation is excluded.*
- ***Front-end:** no microcontrollers/DSP performing computationally intensive tasks, which are moved to control system through gateway, **high availability rad-tol communication** between front-end and gateway required*

Importance of component level testing

- Some parts are clearly better than others when it comes to radiation, despite their very similar electrical characteristics… as mentioned before, this can be exploited by testing

R2E PROJECT
CERN – Building 157
CH-1211 Geneva 23
Switzerland

CERN Div./Group
EN/STI

EDMS Document No.
2416559

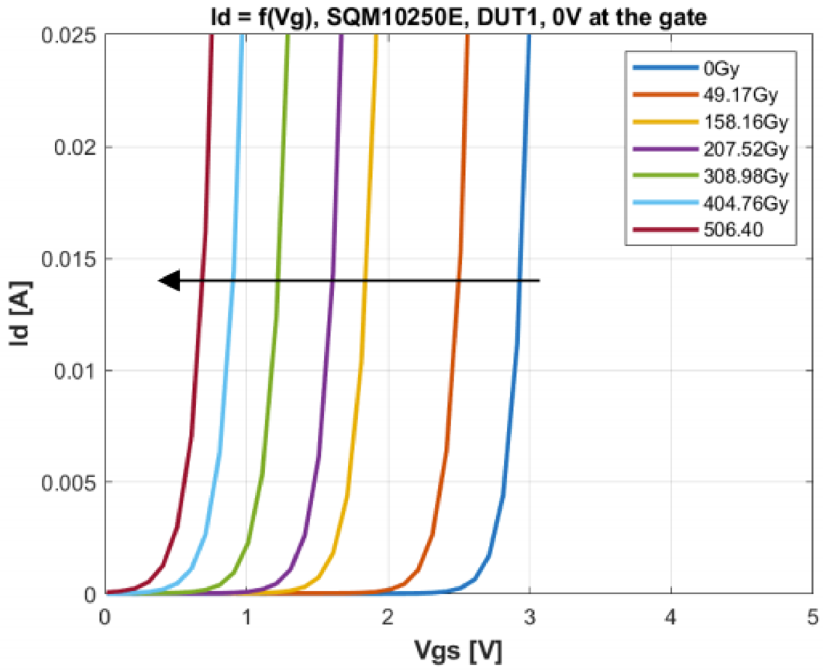
CC60 Radiation Report

SUM90220E, SQM10250E, IPB320N20N3GATMA1, IPD320N20N3GATMA1, SUD90330E-GE3, IPD600N25N3GATMA1

N-MOSFET Transistor

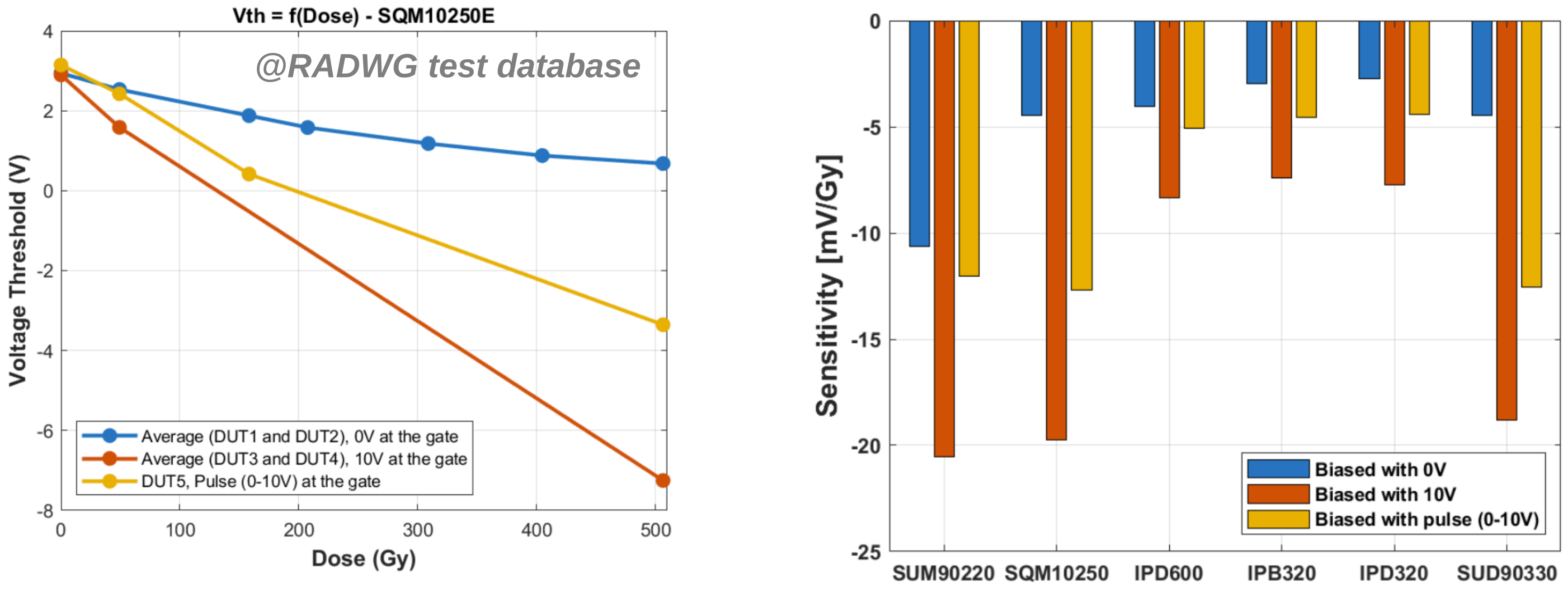
@RADWG test database

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:
Panagiotis Gkountoumis, Rudy Ferraro	Salvatore Danzeca



One example (out of many): voltage threshold drift in power MOSFETs due to TID effects

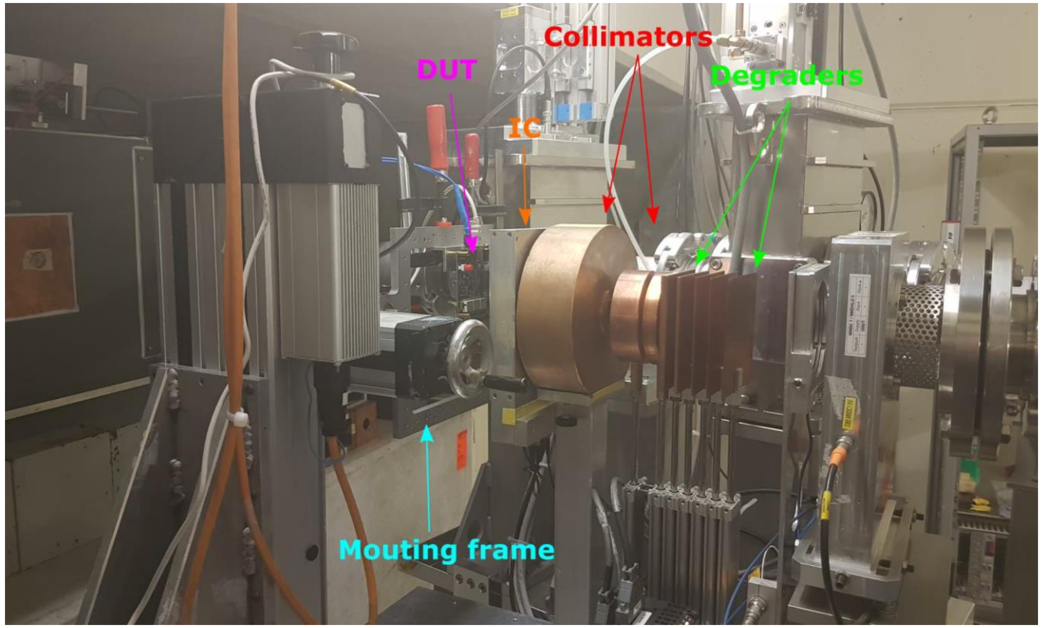
Importance of component level testing

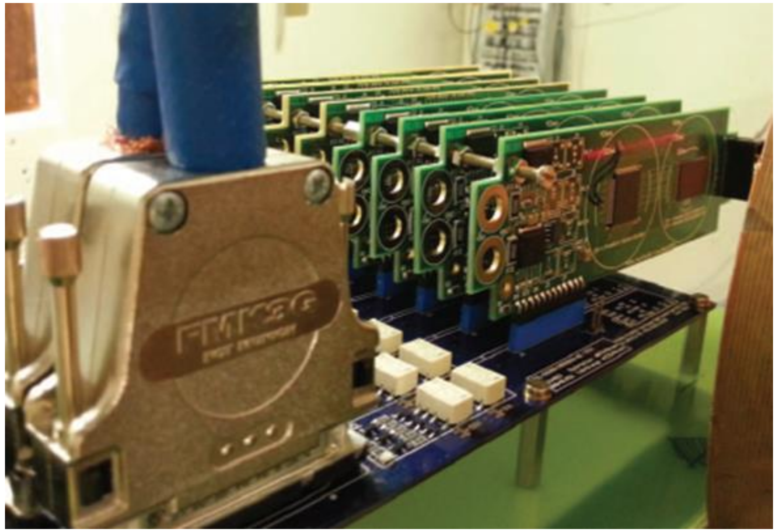


- Very different response from different power MOSFETs with similar electrical characteristics (i.e. all candidates for same development)
- Importance of screening component level effects of critical components before moving on to system level validation

Importance of component level testing

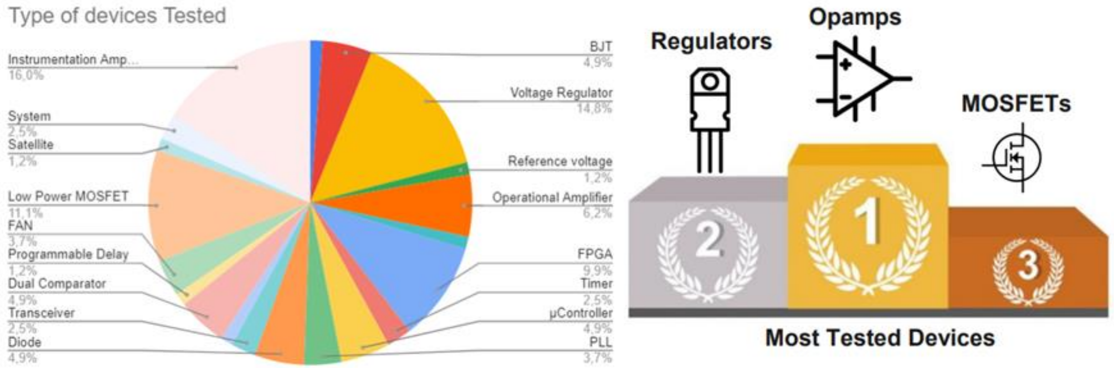
- Component level tests typically carried out at PSI (200 MeV protons), covering all three effects (SEEs, TID, displacement damage)
- Typical annual figures for R2E at PSI: ~250h beam time, ~50-80 different COTS references tested
- Standard component level requirements: Destructive SEE free, lifetime of 200 Gy and $2 \cdot 10^{12}$ n_{eq}/cm^2

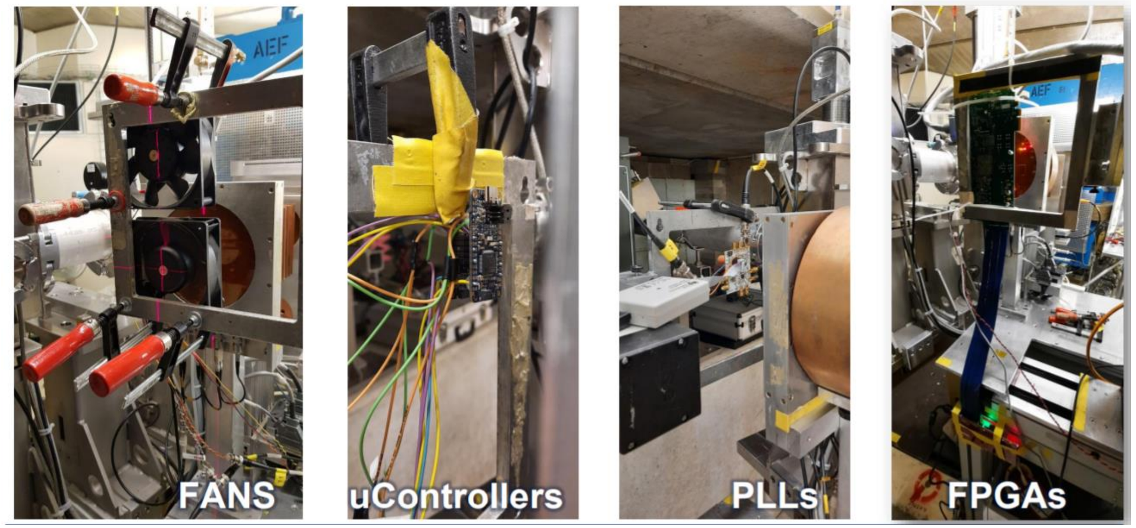


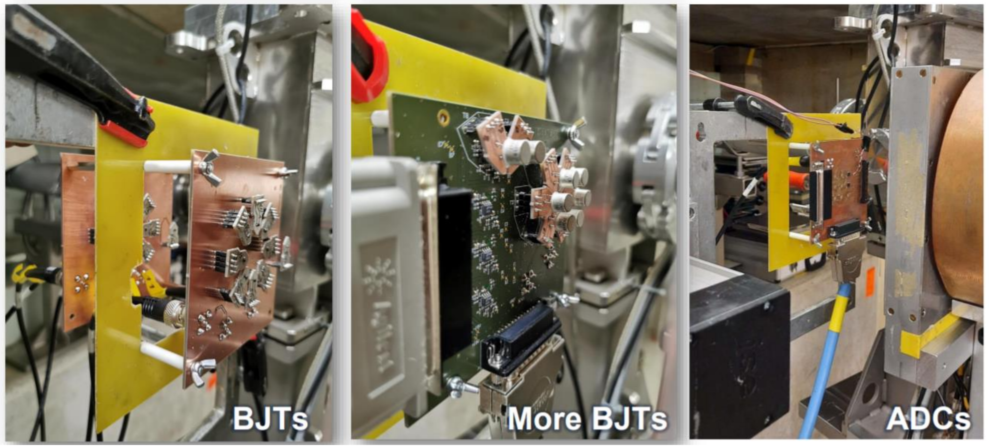


Importance of component level testing

- We tested from the simplest component (BJT) to the most complex ones (FPGAs) and even complete systems.

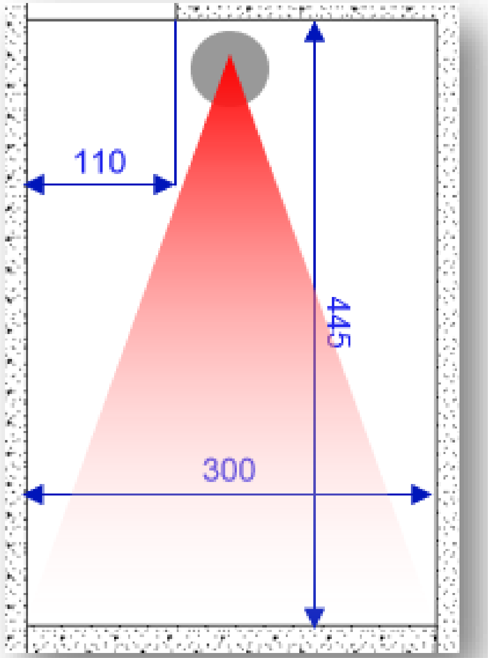






Importance of component level testing

- Located in Prévessin (bld 772), operational since 2015
- Equipped with two sources: 110 TBq ^{60}Co (in 2019) and 10 TBq ^{60}Co (in 2015)
- Multiple users running in parallel are allowed in the facility
- The room is 3x4.5 m^2
- Dose rate from 0.1 to 450 Gy/h



The facility is used to:

- Qualify electronic components and systems
  - Can be used for screening before CHARM or PSI tests
- Material testing
- calibration of dosimeters and R&D (Floating Gate, RadFET, Optical Fiber, NMOS)

Importance of component level testing

- Database with over 400 COTS component test report (mainly PSI: proton SEE, TID and DDD)
- Extremely valuable asset for CERN engineers designing radiation tolerant systems
- For CERN internal use only (or through collaborations)
- Still, **batch qualification of newly procured lots is typically required!** (as shown in an example later)

CERN Radiation Working Group

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Home

Radiation Test Database

This is the RADWG test database maintened by the EN-SMM-RME Section. Click on 'Add filter' to refine your search.

For more details contact : Salvatore Danzeca

List (332) | Add Filter | Admin

	Reference	Type	Device Function	Test Date	Test Characteristics	Edms Report Number
	ACPL-C87B	Precision Voltage Isolators	Voltage Sensing	2019-08-31	TID/DD: ΔVout, ΔIcc SEE: SET,SEL	2234791
	ADUM3190	Precision Voltage Isolators	Voltage Sensing	2019-08-31	TID/DD: ΔVout, ΔIcc SEE: SET,SEL	2234791
	ACPL-790B	Precision Voltage Isolators	Voltage Sensing	2019-08-31	TID/DD: ΔVout, ΔIcc SEE: SET,SEL	2234791
	ADS7852Y	ADC	8-channel, 12-bit ADC Analog-to-Digital	2019-07-05	TID/SEE	2217615
	HCNR200	Optocouplers	Optocoupler	2019-07-05	CTR	2211968
	ISO124	Precision Isolation Amplifier	Isolator voltage sensing	2019-06-10	TID/DD: ΔVout, ΔIcc SEE: SET,SEL	2192454
	IPD5N25S3-430	Power MosFET	N-channel Power MOSFET	2019-06-07	SEB/TID	2207602
	IPSA70R1K2P7S	Power MosFET	N-channel Power MOSFET	2019-06-07	SEB/TID	2207602

R2E challenges: commercial versus rad-hard

- The R2E risk would be (at least largely) removed if system developers could fully rely on rad-hard parts
- This is not feasible for various reasons, notably:
  - Price → typical price differences between COTS and rad-hard counter part are **factor ~100** (see example below)
  - Lead time
  - Performance (in some cases, dedicated ASIC developments would be needed “from scratch”, requiring 5+ years)

LINEAR TECHNOLOGY

LT3080

Adjustable1.1A Single Resistor Low Dropout Regulator

QTY	UNIT PRICE	EXT PRICE
1	$4.74000	$4.74
10	$4.26000	$42.60
25	$4.02760	$100.69
100	$3.31150	$331.15
250	$2.97140	$742.85
500	$2.86400	$1,432.00
1,000	$2.38070	$2,380.70

LINEAR TECHNOLOGY

RH3080MK DICE/DWF

Adjustable 0.9A Single Resistor Low Dropout Regulator

TID (krads)	SEE (MeV/mg/cm2)	Unit Price
TID (HDR): 200		539.11 Euros < > 609.43 Euros
TID (LDR): 100		

Radiation Performance

- Total Ionizing Dose (TID) Tolerance, per TM1019.8, MIL-STD-883:
  - 200kRad (Si), per condition A at 50Rads(Si)/sec
  - 100kRad (Si), per condition D at 10mRads(Si)/sec
  - ELDRS Pass 100kRad(Si)
- Displacement Damage Defect (DDD) up to 1E12 Neutrons/cm^2
- Single Event Latchup (SEL) Threshold Linear Energy Transfer (LET) ≥110MeV.cm^2/mg at T_{CASE} = 100°C

R2E challenges: commercial versus rad-hard

- Commercial parts are attractive due to performance, availability (including short lead times) and cost
- However, in order to use them in radiation, they need to be qualified, which also comes at a high cost
- For space applications, the "cost of ownership" of COTS parts is typically dominated by radiation testing
  - It is estimated that **the full cost of characterizing a COTS device for space ranges between 25 and 600 kUSD**, depending on its complexity. Most of the costs are linked to **labor during the test development phase.**

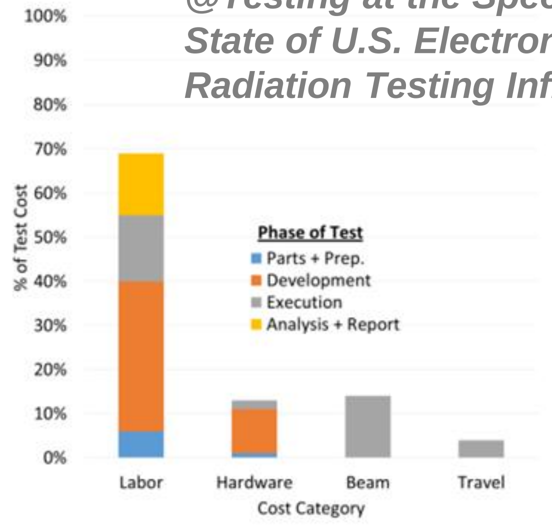
BOX 3.2 Continued

TABLE 3.2.1 Approximate Single-Event Effects Test Cost for Various Part Complexities and Packages (in thousands of dollars)

Part Complexity/Package Difficulty	Easy	Moderate	Difficult
Simple (Op. Amp, Comparator, etc.)	25–35	35–45	>50
Moderately Simple (ADC, DAC, SRAM, etc.)	40–75	50–85	>100
Difficult (Flash, DRAM, Simple Processor, etc.)	85–150	100–200	>250
Very Difficult (FPGA, Complex Processor, other highly complex and highly integrated components)	>500	>550	>600

NOTE: ADC, analog-to-digital converter; DAC, digital-to-analog converter; DRAM, dynamic random-access memory; FPGA, field-programmable gate array; SRAM, static random-access memory.

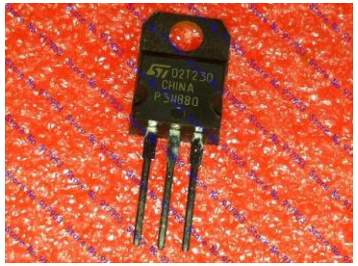
@Testing at the Speed of Light: The State of U.S. Electronic Parts Space Radiation Testing Infrastructure



GURE 3.2.1 Although the high cost of single-event effects testing is driven by many factors, direct costs for beam ne are among the less significant drivers. Nearly 70 percent of test costs are for highly skilled labor, and more than 50 ercent of the cost is spent in the development phase. This makes it difficult to realize savings by "simplifying" the test.

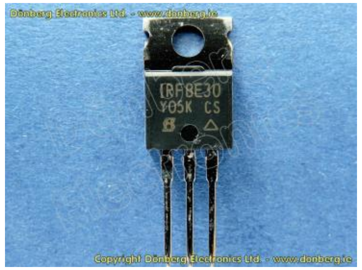
Extra challenge and common pitfall: don't trust black boxes

- Example of COTS module risk: same "black-box", different power MOSFET
  - The module passed the radiation test, but some units started failing very early after installation in the LHC



STP3NV80
(N-channel, 800V)

22 destructive events before LS1



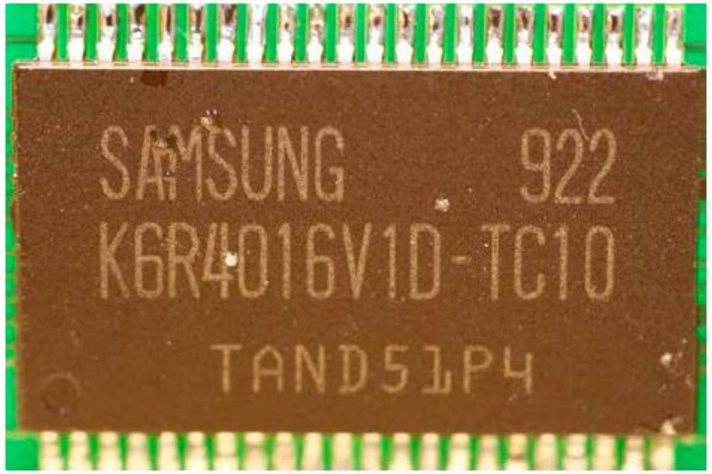
IRFBE30
(N-channel, 800V)

One destructive event before LS1

@Yves Thurel

Extra challenge and common pitfall: Lot-to-lot variability

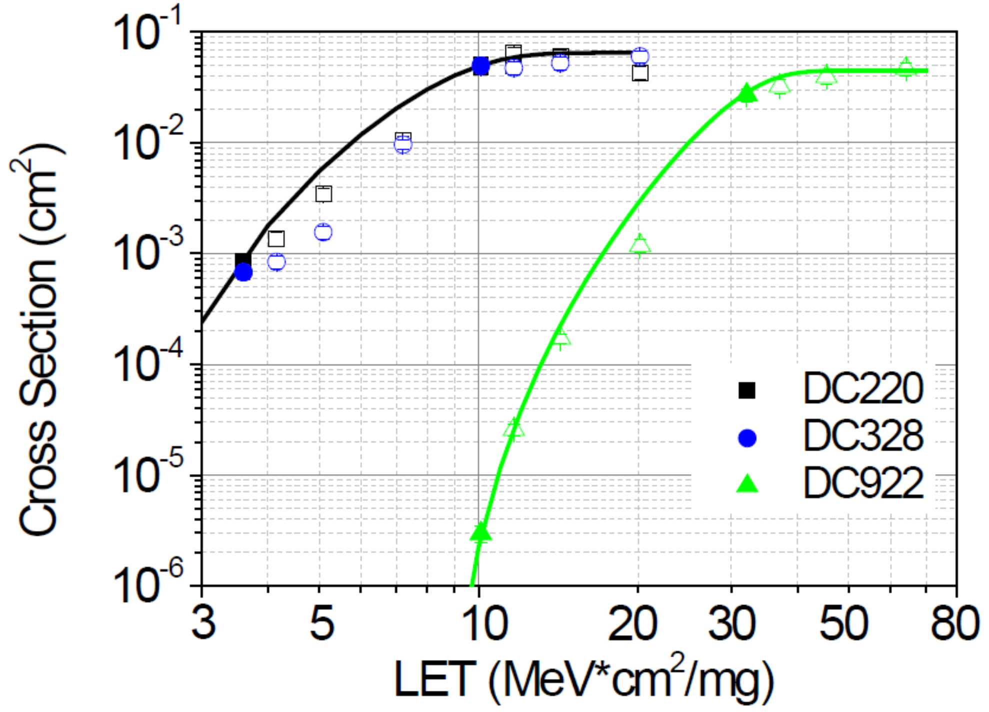
- Example: same reference but different date codes



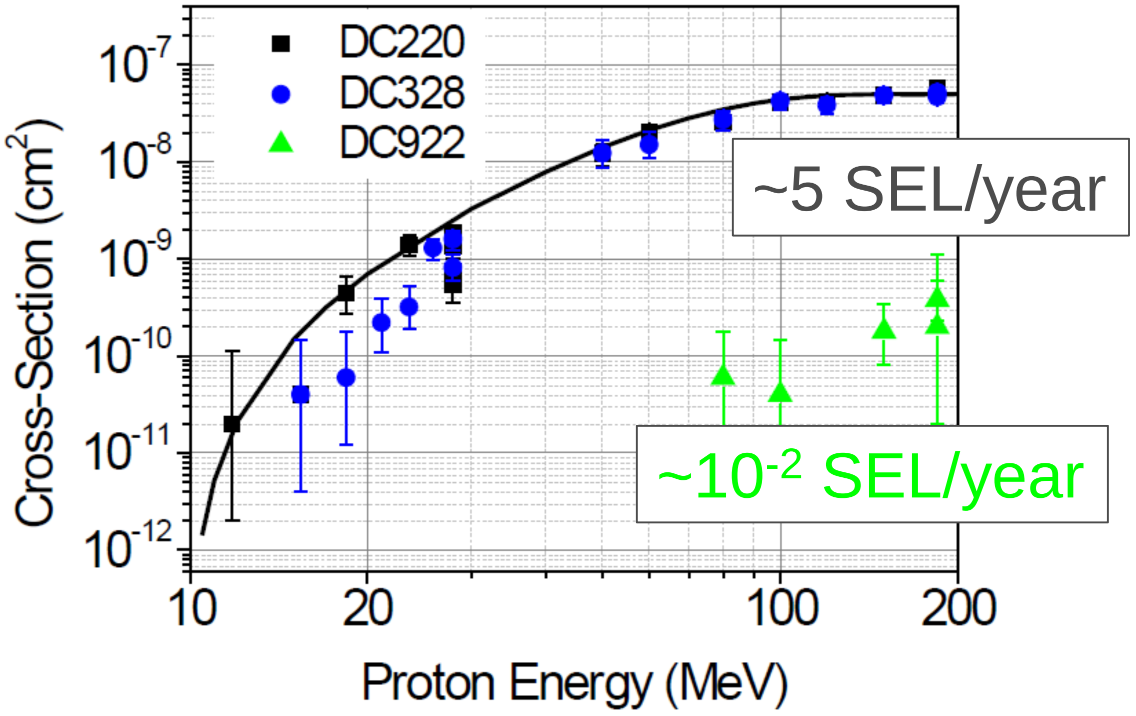
“Single Event Latch-up (SEL) analysis of the 256k x 16 SRAM Samsung K6R4016V1D-TC10 Heavy ion and Proton Test Report Comparison with the Proba-2 GPS Phoenix SEL rate”, V. Ferlet-Cavrois, M. Muschitiello, M. D’Alessio, ©ESA

Extra challenge and common pitfall: Lot-to-lot variability

- Same reference and different date code with SEL sensitivity difference of factor ~500
- Importance of lot/batch traceability and common component purchase

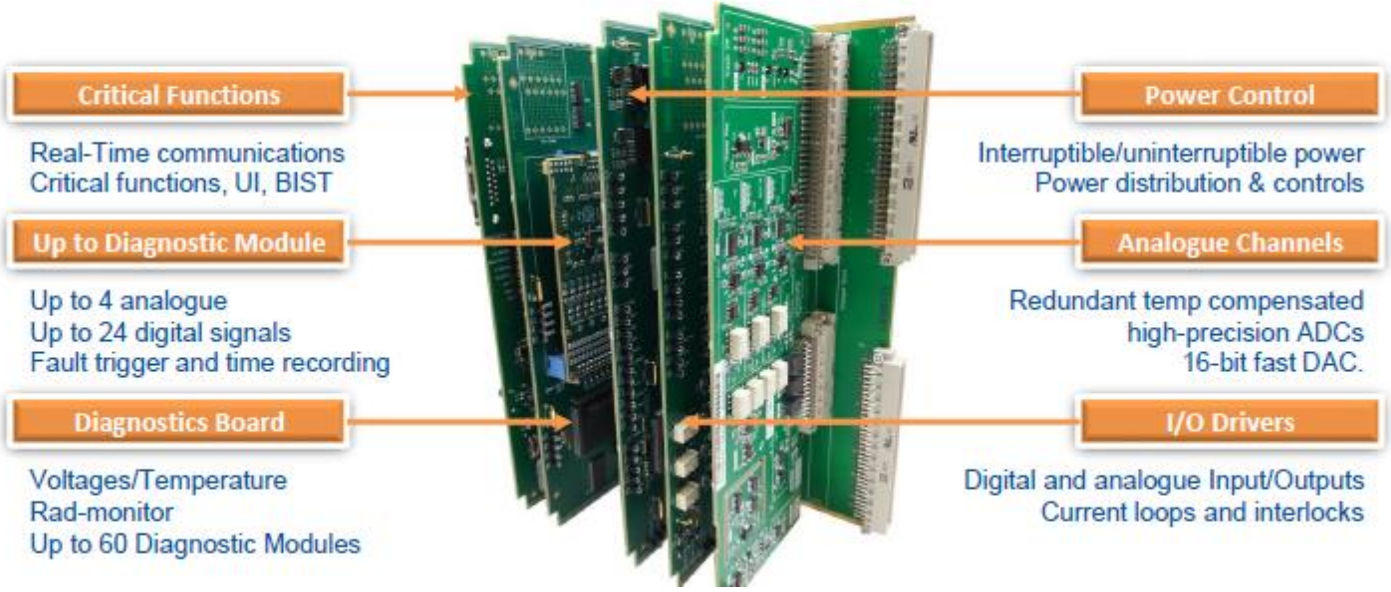


SEL rate considering 10^8 HEH/cm²/year



Example of R2E developments: power converters controls

- Radiation tolerant, high-reliability replacement of FGC2
- First "full" R2E development (i.e. with radiation constraints considered already from initial stage of the project)
  - Component selection according to type tests at device level
  - Radiation tests of production lots, hence mitigating COTS traceability risk
  - System level radiation tolerance validation at CHARM
  - Radiation tests included ~50 semiconductor references, ~10 facilities and >1000 hours of beam time
- Deployed in LHC ARCs during EYETS 2016/17, and in RRs during LS2

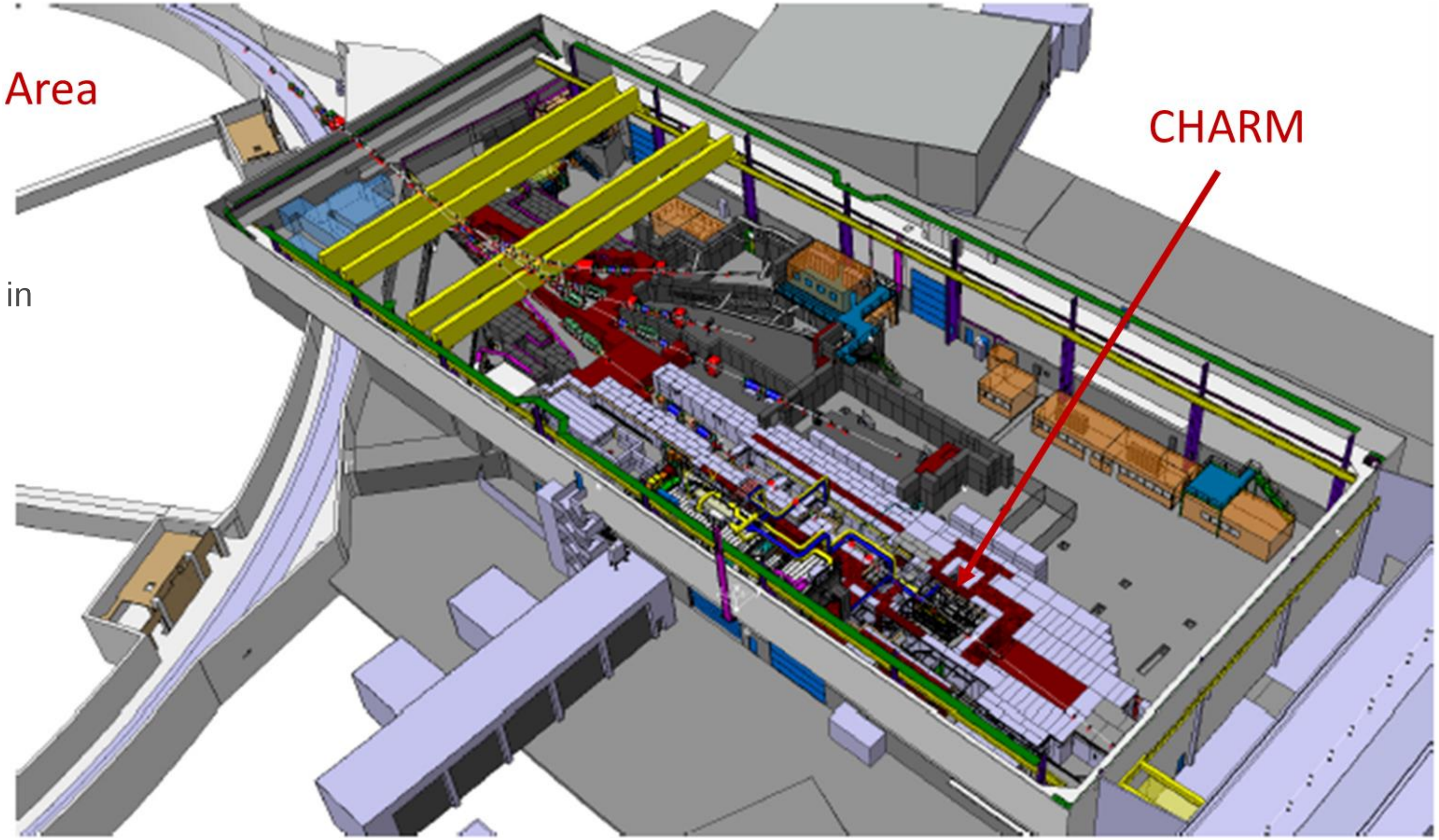


1600x	3.4 MCHF	2012-2017
Production	Budget	Time Frame

@Slawosz Uznanski

System level testing in CHARM

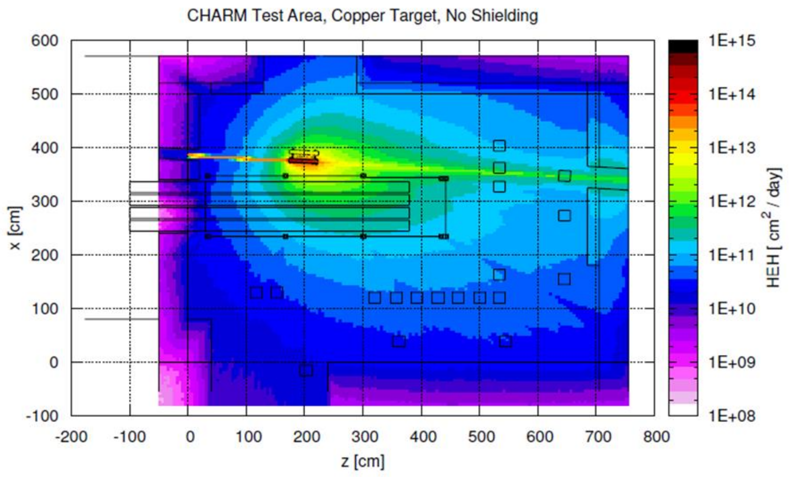
Proton Synchrotron accelerator:
- 24 GeV/c protons
- Circumference of 628m
- Injects beam into SPS (which in turn injects into LHC) but also provides beam to PS East Experimental Area



CHARM:
- Slow-extracted beam from PS (350ms spills every ~10s, i.e. quasi-continuous)
- Roughly $5 \cdot 10^{11}$ protons per spill
- Generation of mixed radiation field through interaction of proton beam with 50 cm copper target
- Access to facility once per week; flux can be varied through shielding and target

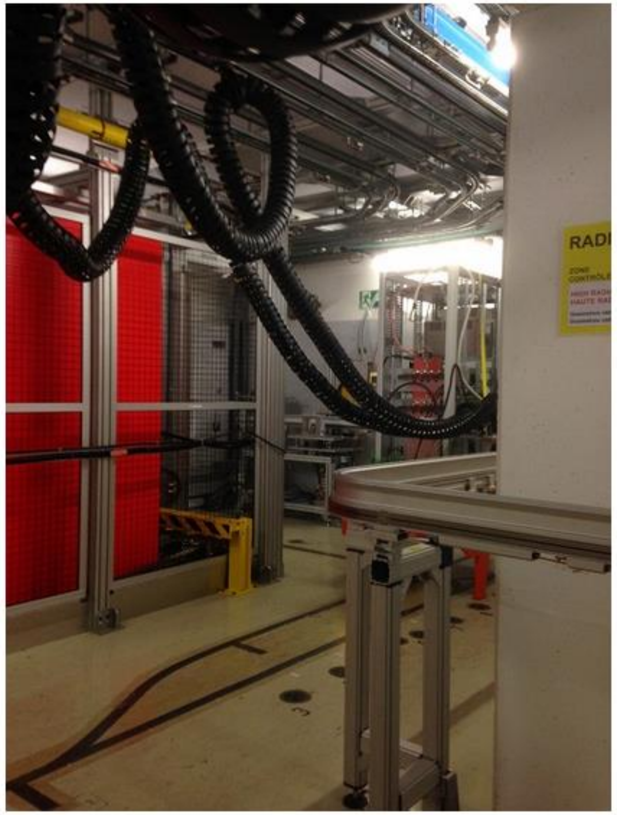
System level testing in CHARM

- System level testing at CHARM:
  - System level testing is applied as validation under operational conditions and in representative radiation environment (i.e. the part selection & qualification, plus system level mitigation have already been carried out beforehand, therefore system level validation is expected to be successful)
  - Systems are built modularly and with self-diagnose capability, therefore in case of failures or errors at a rate larger than that specified, re-design without major changes is typically possible
- Typical weekly radiation levels (considering position R10 and $1.5 \cdot 10^{16}$ protons on target): 350 Gy, $2.5 \cdot 10^{12}$ n_{eq}/cm^2, $7.5 \cdot 10^{11}$ HEH/cm^2



Power converters: 600A and 4-6-8 kA

System level testing



@Yves Thurel, Vicente Raul Herrero, Julien Chanois

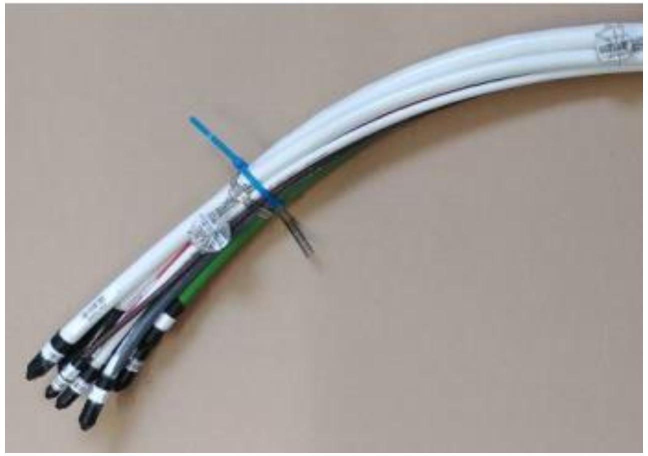
Power converters: 600A and 4-6-8 kA

Nothing beats a CHARM test!!

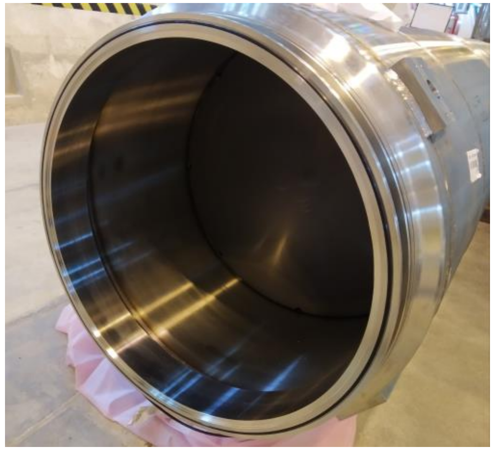
Polymer Material (R2M) Tests in Commercial Gamma Facilities

Magnet spacers (grout)

Instrumentation wires



Cables for high-rad areas



Elastomeric seals for Beam Intercepting Devices

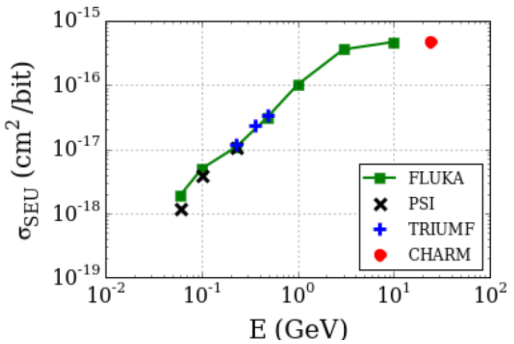
Protective covers for magnets

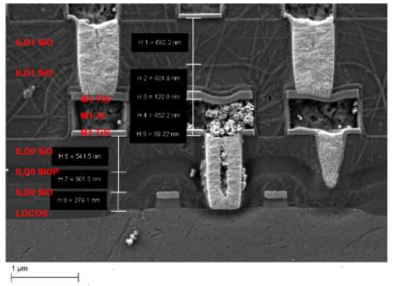
Vacuum assemblies

Lubricated equipment

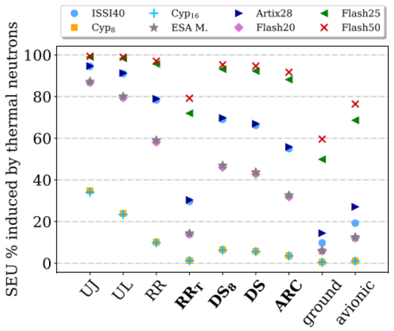
Large variety of commercial and custom-made materials and components whose **radiation resistance is unknown: <u>irradiation tests are needed</u>**

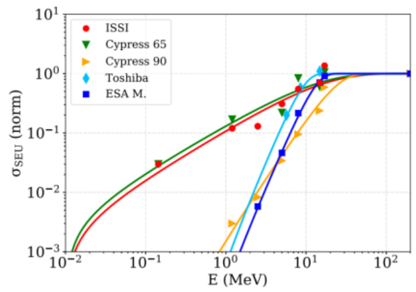
COTS R&D activities: SEE impact from different mixed-field particles and energy ranges



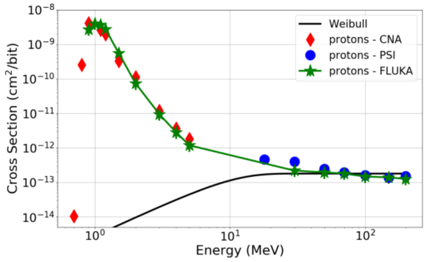


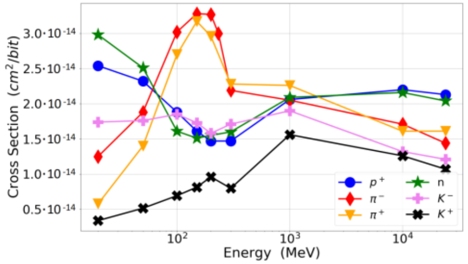
- Enhanced high-energy SEE cross section due to high-Z materials (e.g. tungsten near sensitive volumes), ***Garcia Alia 2018, IEEE TNS***





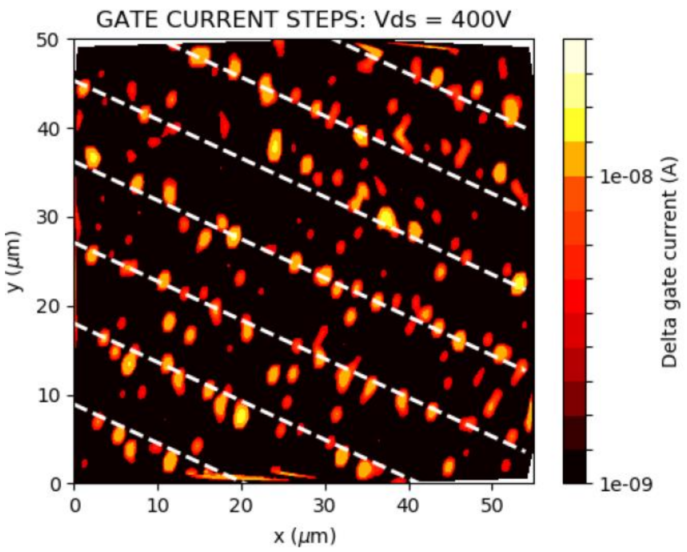
- Impact of thermal and intermediate (0.1-20 MeV) neutrons on accelerator soft error rate, ***Cecchetto 2020, IEEE TNS & Cecchetto 2021, IEEE TNS***





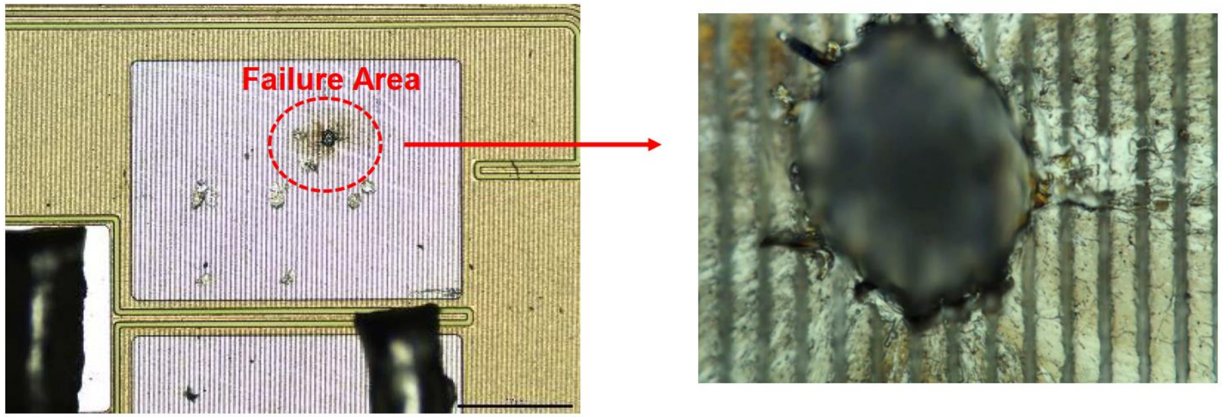
- Effect of pions and low energy protons, ***Coronetti 2020, IEEE TNS & Coronetti 2021, IEEE TNS***

COTS R&D activities: SiC power MOSFETs

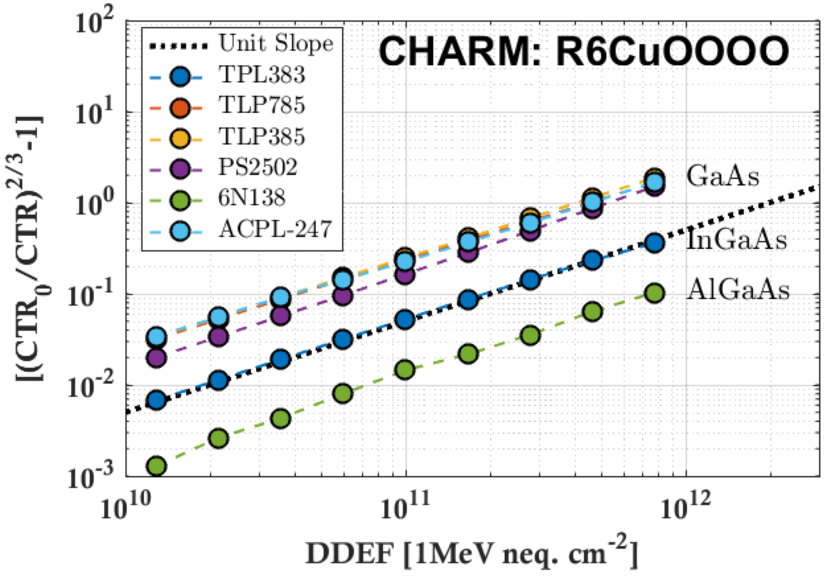


- Promising technology for space, but also for accelerators (e.g. fast-switching magnets)
- Inherently TID and DDD robust, but SEE sensitive, with mechanisms still to be understood

Corinna Martinella, RADECS 2019



COTS R&D activities: opto-couplers

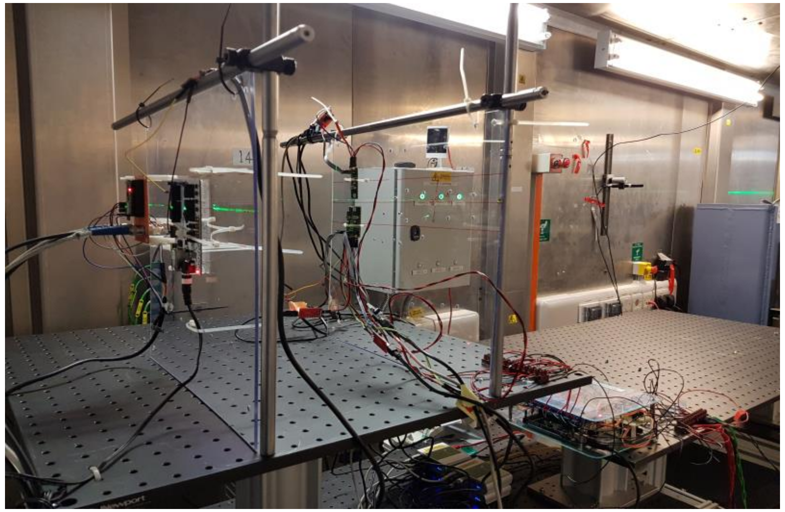


Rudy Ferraro, RADECS 2019

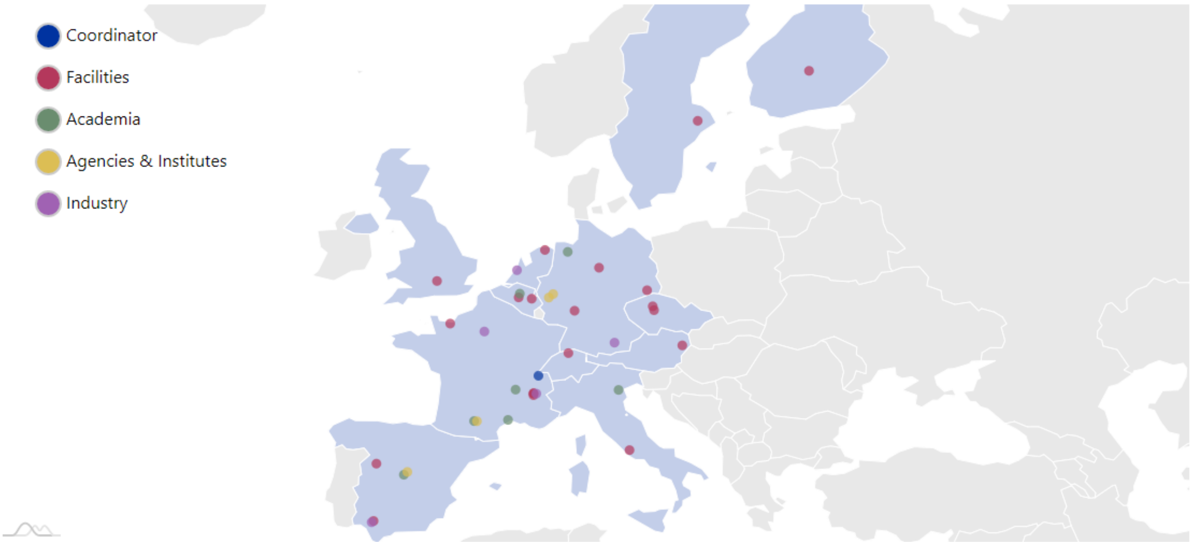
- Impact of LED semiconductor material on opto-coupler Current Transfer Ratio (CTR) degradation
- Weak point in terms of radiation lifetime in a broad range of accelerator COTS based systems
- Differences in DDD when applying NIEL approximation to neutron, proton and mixed-field environments

Coordination of EU projects on radiation effects

- Transnational access to beam time in a very broad facility network for radiation effects R&D testing through RADNEXT



Partners & Associates



cern.ch/radnext

Main takeaways

- The need for **radiation tolerant design and qualification** results from a combination of constraints and requirements, mainly linked to:
  - The accelerator availability requirements in order to fulfill its physics objectives
  - The accelerator infrastructure and civil engineering (i.e. having to operate systems in radiation exposed areas) → can be tailored/adapted in case of projects in early definition phase
  - The very high cost and long lead times for rad-hard component designs
  - The radiation sensitivity (and variability thereof) of COTS components
- The good news is that, with an adequate strategy and approach, **radiation tolerant design based on COTS parts is compatible with a successful accelerator operation**
- The related approach includes a broad variety of ingredients, including radiation level monitoring and calculation, simulation of radiation effects, operation of irradiation facilities, radiation tolerant designs, and notably **a lot of (smart and efficient) testing**, featuring also system level radiation tolerance validation
- **A lot of exciting and challenging R2E work ahead!**

Further reading

- M. Brucoli et al., "Investigation on Passive and Autonomous Mode Operation of Floating Gate Dosimeters," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1620-1627, July 2019.

- M. Brucoli et al., "Investigation on Passive and Autonomous Mode Operation of Floating Gate Dosimeters," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1620-1627, July 2019.

- R. Ferraro et al., "Study of the Impact of the LHC Radiation Environments on the Synergistic Displacement Damage and Ionizing Dose Effect on Electronic Components," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1548-1556, July 2019.
- M. Cecchetto et al., "SEE Flux and Spectral Hardness Calibration of Neutron Spallation and Mixed-Field Facilities," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1532-1540, July 2019.
- P. Fernández-Martínez et al., "SEE Tests With Ultra Energetic Xe Ion Beam in the CHARM Facility at CERN," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1523-1531, July 2019.
- R. G. Alía et al., "Ultraenergetic Heavy-Ion Beams in the CERN Accelerator Complex for Radiation Effects Testing," in IEEE Transactions on Nuclear Science, vol. 66, no. 1, pp. 458-465, Jan. 2019.
- C. Martinella et al., "Current Transport Mechanism for Heavy-Ion Degraded SiC MOSFETs," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1702-1709, July 2019.

Further reading (part 2)

- “FLUKA Simulations for SEE Studies of Critical LHC Underground Areas”, K. Roed et al, IEEE TNS, 2011
- “LHC RadMon SRAM Detectors Used at Different Voltages to Determine the Thermal Neutron to High Energy Hadron Fluence Ratio”, D. Kramer et al, IEEE TNS 2011
- “Method for Measuring Mixed Field Radiation Levels Relevant for SEEs at the LHC” K. Roed et al, IEEE TNS, 2012
- “SEU Measurements and Simulations in a Mixed Field Environment”, R. Garcia Alia et al, IEEE TNS, 2013
- “Qualification and Characterization of SRAM Memories Used as Radiation Sensors in the LHC”. S. Danzeca et al, IEEE TNS, 2014
- “SEL Cross Section Energy Dependence Impact on the High Energy Accelerator Failure Rate”, R. Garcia Alia et al, IEEE TNS, 2014
- “A New RadMon Version for the LHC and its Injection Lines”, G. Spiezia et al, IEEE TNS, 2014
- “SEL Hardness Assurance in a Mixed Radiation Field”, R. Garcia Alia et al, IEEE TNS, 2015
- "CHARM: A Mixed Field Facility at CERN for Radiation Tests in Ground, Atmospheric, Space and Accelerator Representative Environments,“ J. Mekki et al, IEEE TNS 2016
- "Monte Carlo Evaluation of Single Event Effects in a Deep-Submicron Bulk Technology: Comparison Between Atmospheric and Accelerator Environment," A. Infantino et al, IEEE TNS, 2017.
- “Single event effects in high-energy accelerators”, R. Garcia Alia et al, Semicond. Sci. Technol, 2017
- “High-energy Electron Induced SEUs and Jovian Environment Impact”, M. Tali et al, IEEE TNS, 2017
- “Simplified SEE Sensitivity Screening for COTS Components in Space”, R. Garcia Alia et al, IEEE TNS, 2017
- "LHC and HL-LHC: Present and Future Radiation Environment in the High-Luminosity Collision Points and RHA Implications,“ R. Garcia Alia et al, IEEE TNS, 2018

Thank you for your attention!