Why do we (still) need R2E?

Rubén García Alía

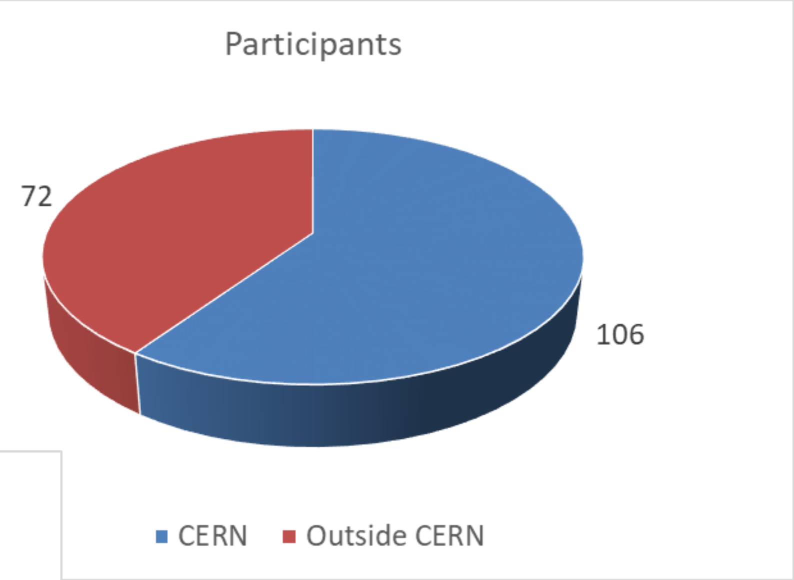
R2E Annual Meeting – 2-3 Feb, 2021
https://indico.cern.ch/event/971222/

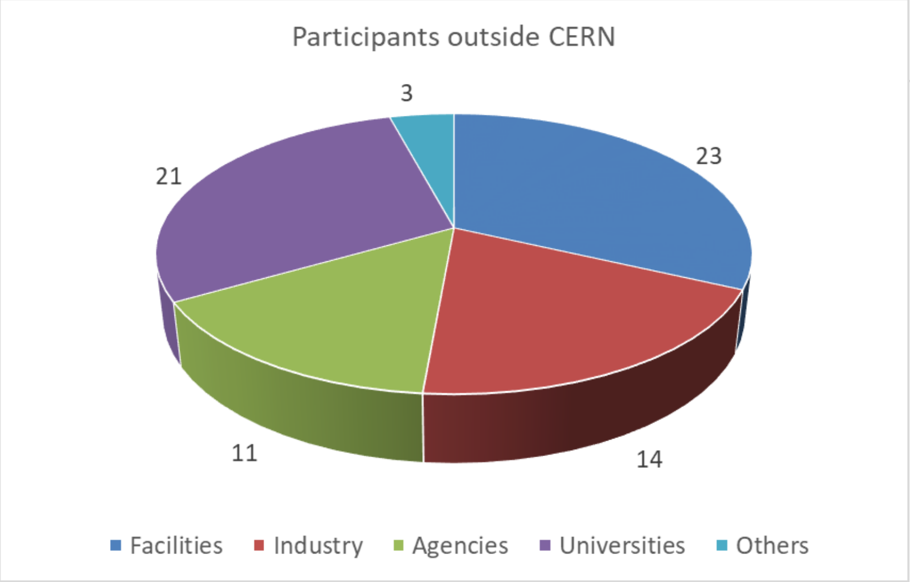
R2E annual meeting intro

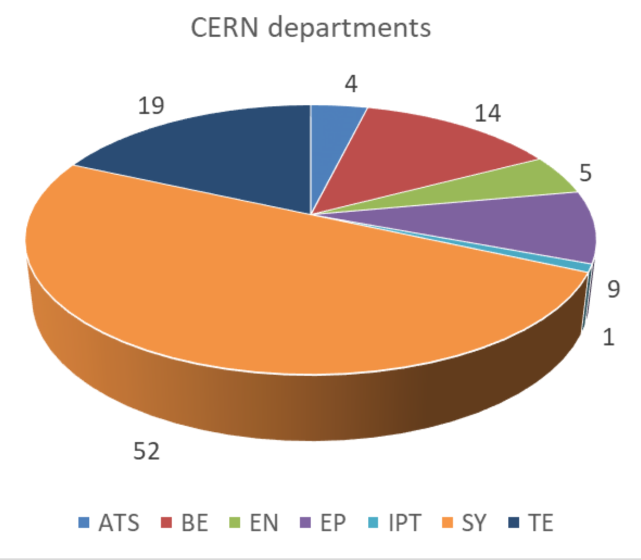
- Many thanks for having joined us!!
- Varied and dense program, over two full days, and structured in three main sessions: **services, applied research and developments**
- Last R2E annual meeting: 2 years ago (2020 cancellation due to sanitary crisis)
  - Related material available on Indico: https://indico.cern.ch/event/760345/
- Remember to keep your **mics muted**, and please use the **chat for questions** – we will do our best to pick them up after the talks, or during the dedicated Q&A session

R2E annual meeting intro

- **178 registered participants**, 60% from CERN, 40% external (R2E collaborators)
- Externals include industry, facilities, agencies and universities
- CERN record group by registration: SY/BI → congrats!







@Andrea Coronetti

Agenda

1. **Introduction**
2. **Constraints (other than COTS sensitivity)**
3. **Constraints (linked to COTS sensitivity)**
4. **Main takeaways**

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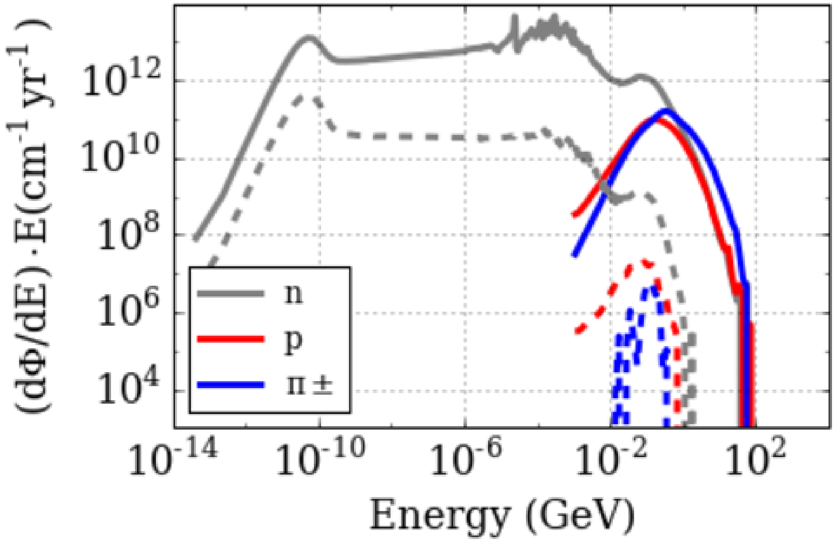
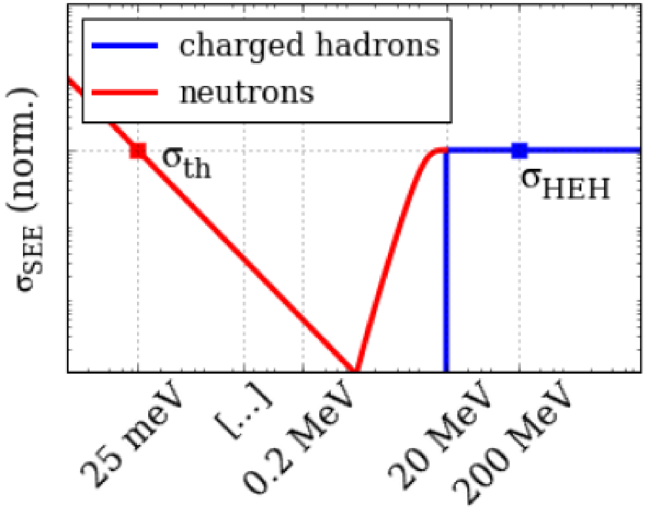
Talk intro

- During the next 15-20 min, I will try to show ***why*** we believe that R2E is (still) important in view of a successful accelerator operation
- After the ***why*** is covered, most of the rest of the presentations will focus on the ***how*** (which I will therefore hardly touch in my slides)
- The content is somewhat technical, but I also allow myself a number of **simplifications, approximations and assumptions**. Still, these to do affect the general conclusions and messages.

Simplifying stochastic radiation effects in accelerators





- The accelerator radiation fields is very complex, with a broad variety of particles over very large energy intervals
- As to what concerns stochastics effects (SEEs), things are simplified due to the similar nuclear reaction probabilities, independently of the hadron species and energy
- Therefore, in first approximation (and excluding thermal neutron induced soft errors), the SEE rate can be estimated through the product of the related flux (so-called, **high-energy hadron flux**, or HEH) (cm^{-2} time^{-1}) and **SEE cross section** (cm^{2}, related to the probability of an SEE occurring)

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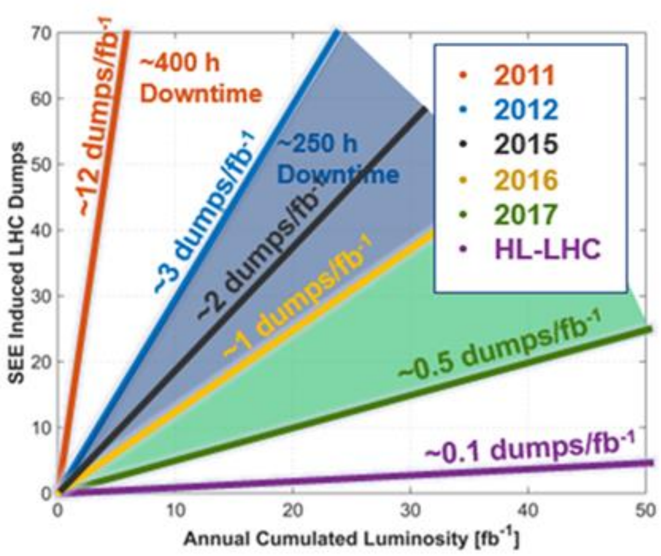
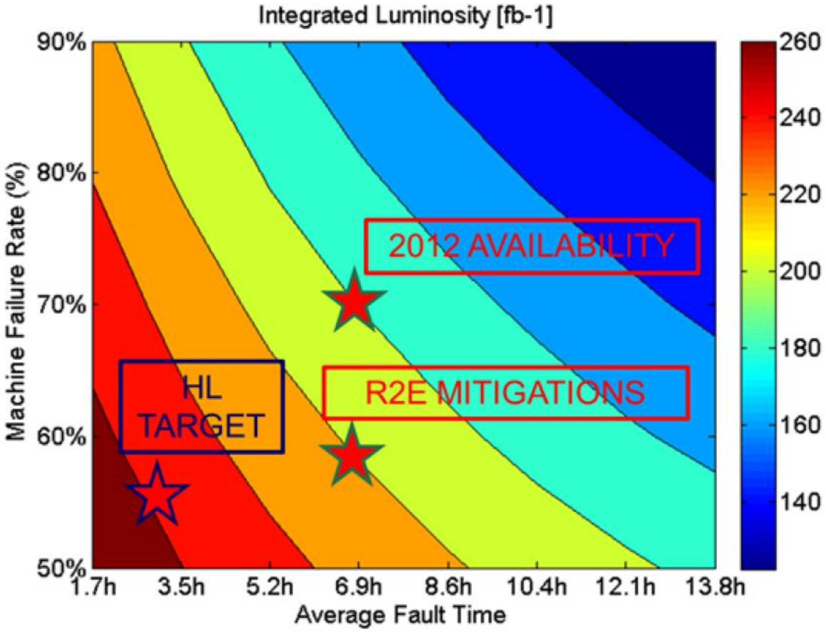
R2E challenges: machine availability requirements

- Many “space guys” will tell us: “you guys in the accelerator are lucky. In case of R2E issues, you can repair”. While this is true, having to repair *too often* involves losing a significant fraction of physics production, which is LHC’s main mission.
- In this sense, the situation improved significantly thanks to the **Run 1 and LS1 R2E mitigations**, but further improvements are needed to meet the HL-LHC goals

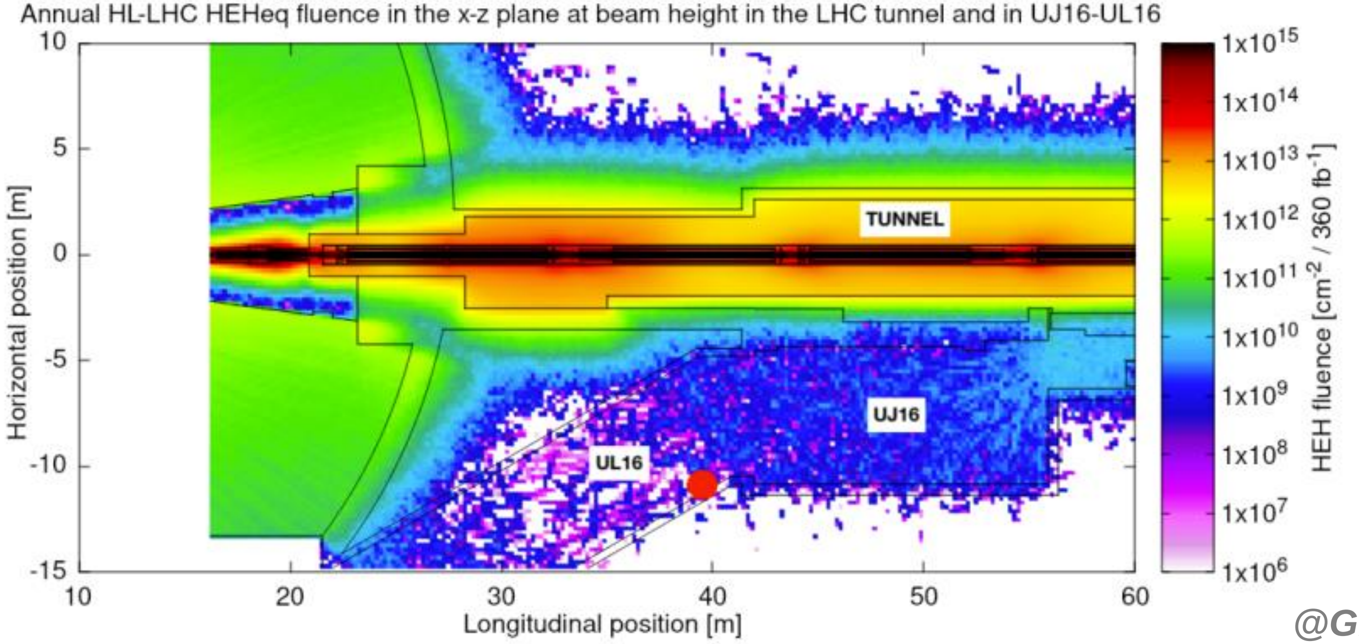


Data for Run 1 (2011-12), target values for Run 2 (2015-17) and HL-LHC



@Andrea Apollonio

R2E challenges: infrastructure constraints



@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)

R2E challenges: commercial versus rad-hard

- The R2E issue would be solved 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)

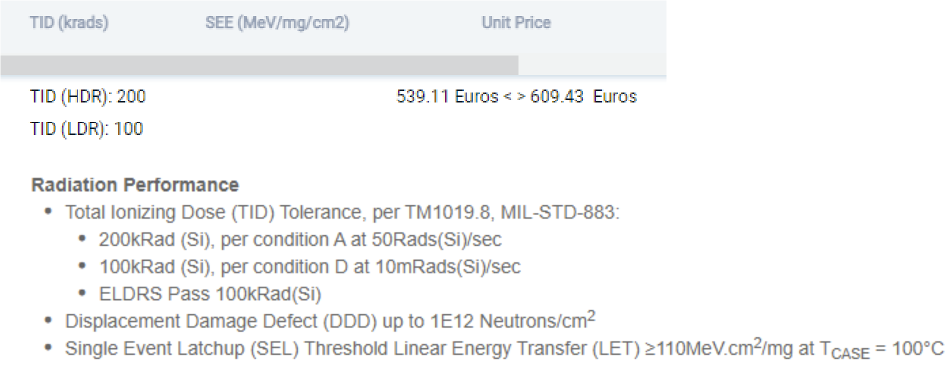
LT3080

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

RH3080MK DICE/DWF

Adjustable 0.9A Single Resistor Low Dropout Regulator



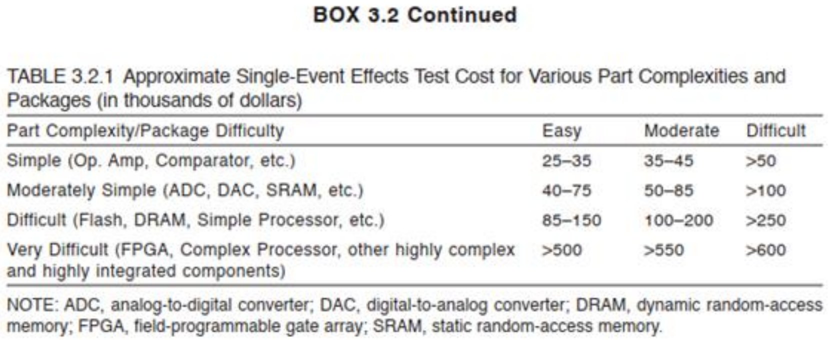
TID (krads)	SEE (MeV/mg/cm2)	Unit Price
TID (HDR): 200 TID (LDR): 100		539.11 Euros < > 609.43 Euros

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.**



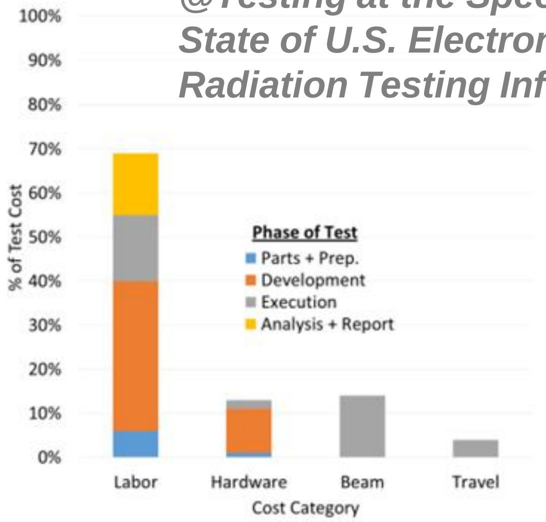
BOX 3.2 Continued

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 rcent of the cost is spent in the development phase. This makes it difficult to realize savings by “simplifying” the test.

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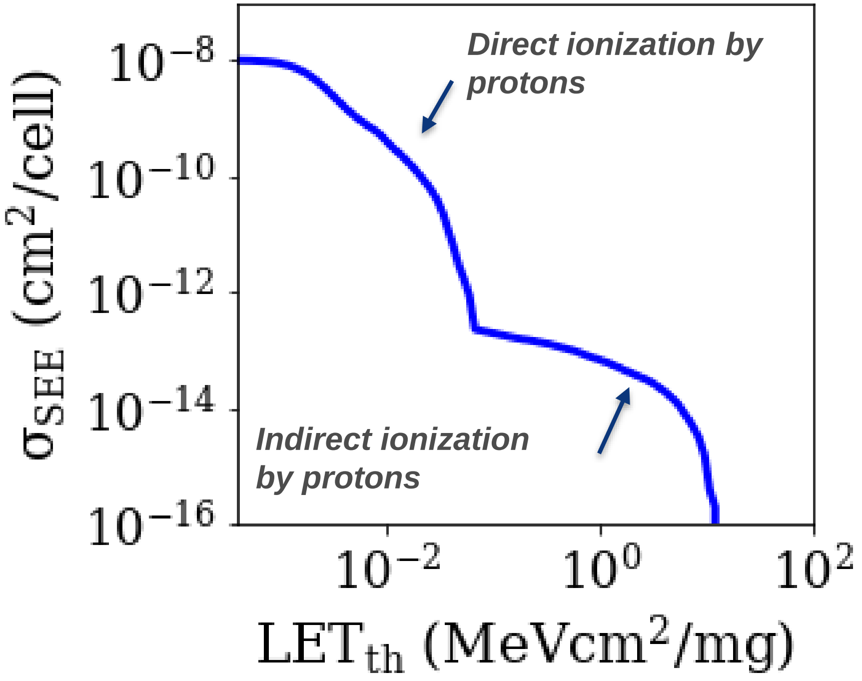
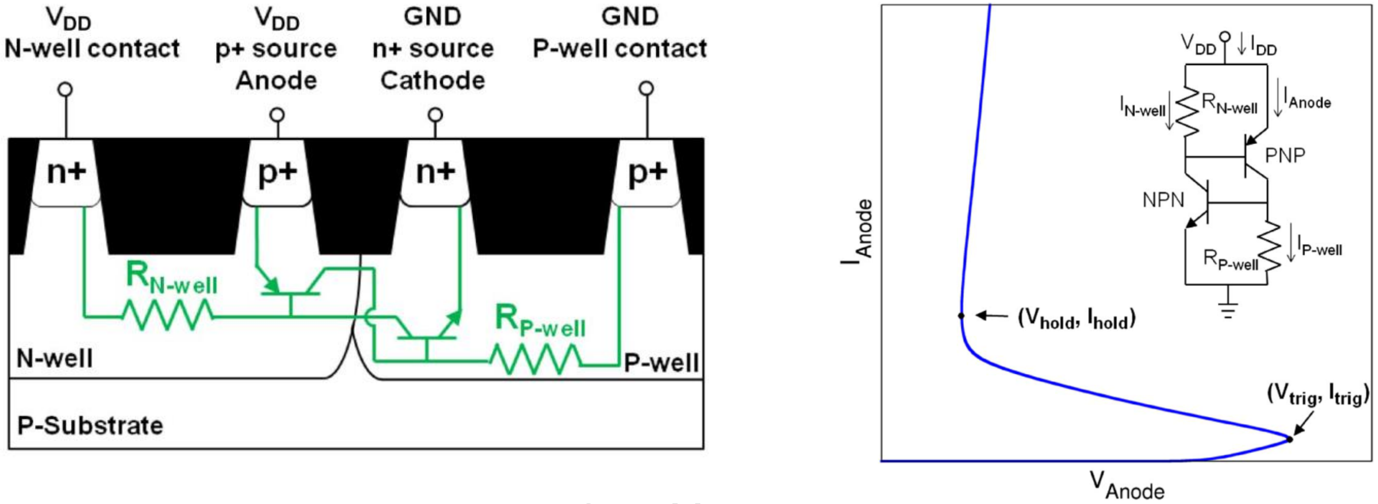
R2E challenges: COTS component SEE sensitivity

- SEE modelling via energy deposition distribution calculations
- The plot to the right shows the normalized probability of a particle (in this case, a 200 MeV proton) depositing an energy above the limit in the x-axis, expressed in Linear Energy Transfer (LET) units
- This applies to a simple silicon cube of 1 µm^3, in the center of a larger cube of 100 µm^3
- The y-axis is the probability normalized to the sensitive area, which in this case is 1 µm^2
  - The limit of the SEE cross section value for an LET threshold tending to zero corresponds to the sensitive surface of the device, i.e. all particles travelling through it would cause an SEE. For indirect ionization events, the probability is ~10^{-6}
- In first approximation, the device's SEE cross section will depend on two parameters: its total **sensitive surface** (or total number of sensitive cells) and the threshold energy (or **threshold LET**) above which the SEE occurs
- Example: a device with an LET threshold of 5 MeVcm^2/mg and a sensitive surface of 0.01 cm^2 would have an SEE cross section of **10^{-8} cm^2/device**



R2E challenges: COTS component SEE sensitivity

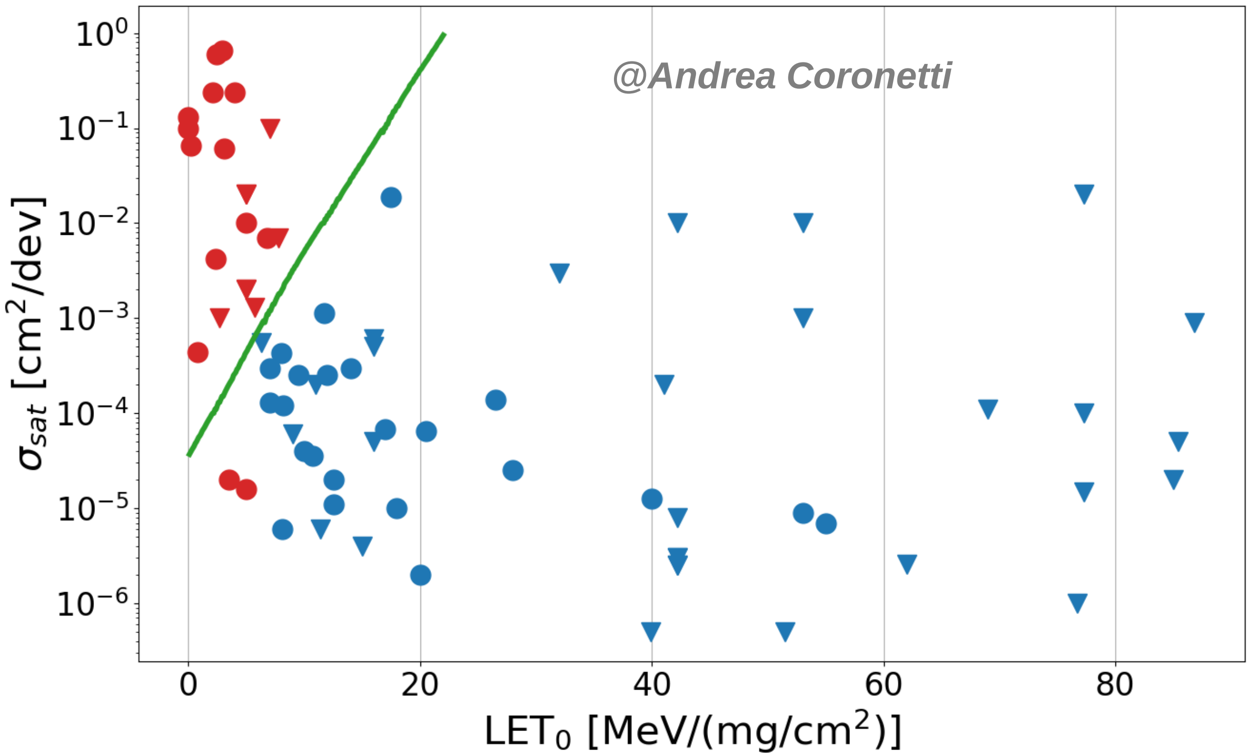
- **Example of destructive SEE event: Single Event Latchup**
  - Avalanche effect triggered by single ionizing event, which activates parasitic PNP or NPN bipolar transistor with positive feedback, leading to large currents and potential thermal breakdown
- We will consider **85 COTS CMOS components** selected from the literature and with heavy ion SEL data available
  - It is thought that roughly 50% of CMOS devices are SEL sensitive to heavy ions
- Combination of broad variety of parts (op-amps, regulators, ADCs, DACs, microcontrollers, SRAMs…)



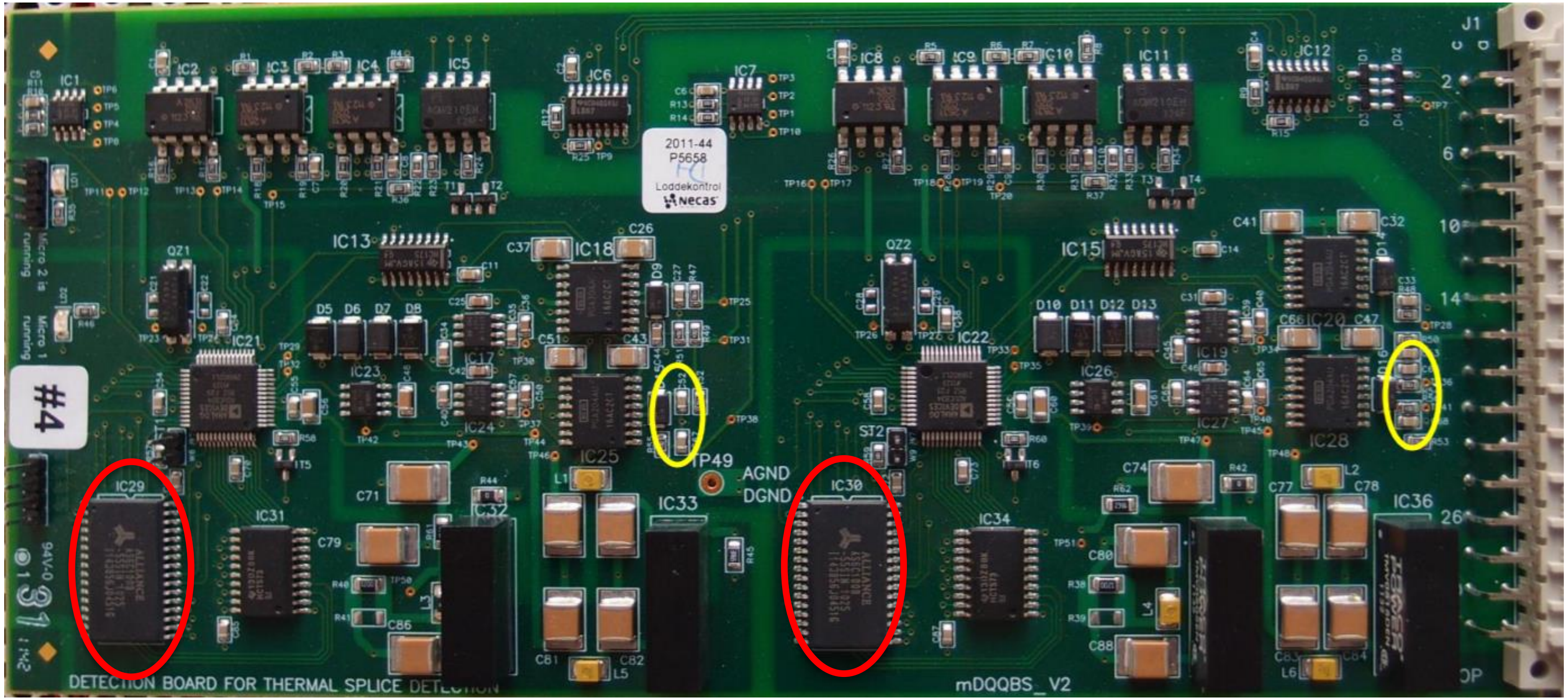
@Dodds 2010, IEEE TNS

R2E challenges: COTS component SEE sensitivity

- Plot to the right: parts with more than one event during one week of CHARM testing (10^{12} HEH/cm^2) in red; parts with less than one event in blue
- Out of the 85 SEL-sensitive parts, roughly half of them have LET thresholds low enough to be sensitive to protons, and 21 (i.e. 1 out of 4) would have SEL cross sections above 10^{-12} cm^2/device (hence problematic in terms of error rate for critical accelerator applications)
- COTS components show a large variability in their radiation sensitivity, even for components with similar electrical properties → by testing and selecting the "good" parts, we can **use this variability to our benefit**

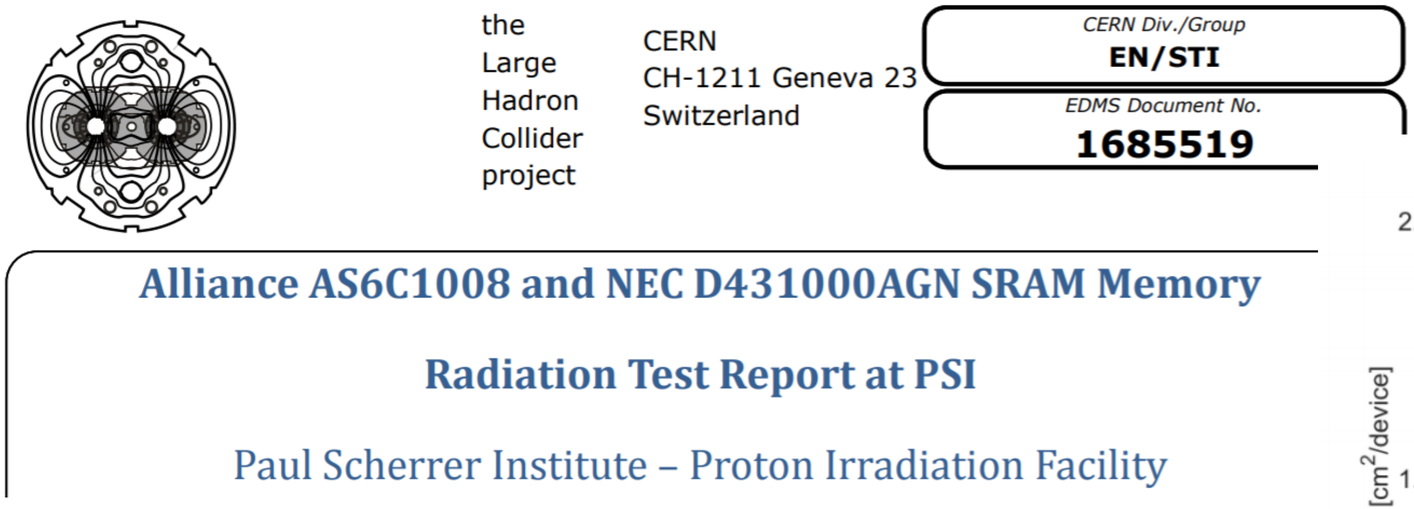


R2E challenges: COTS component SEE sensitivity



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

R2E challenges: COTS component SEE sensitivity



the
Large
Hadron
Collider
project

CERN
CH-1211 Geneva 23
Switzerland

CERN Div./Group
EN/STI

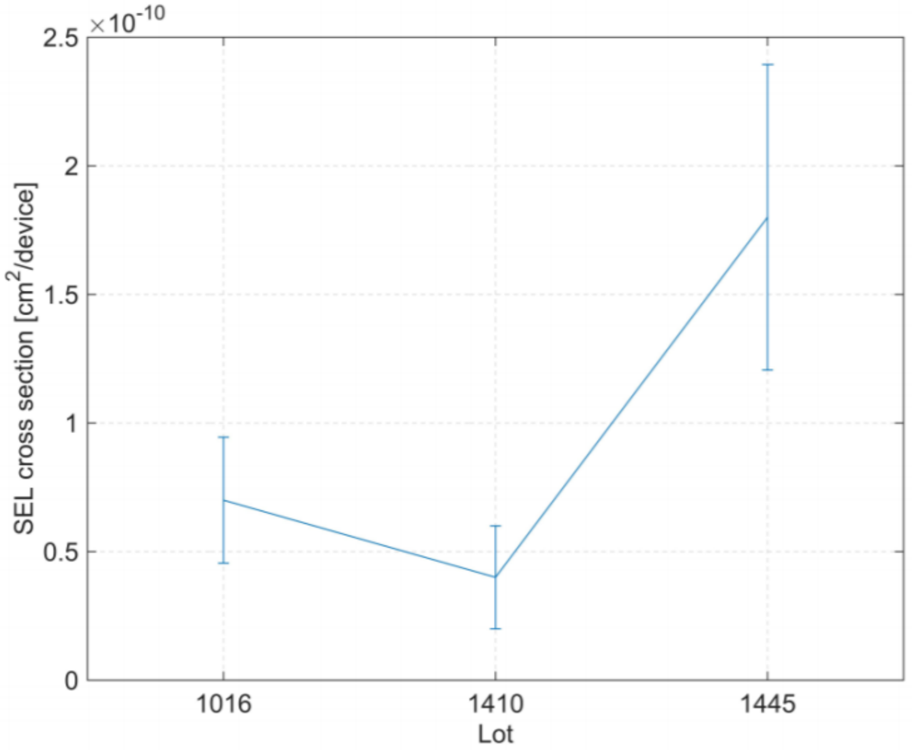
EDMS Document No.
1685519

Alliance AS6C1008 and NEC D431000AGN SRAM Memory

Radiation Test Report at PSI

Paul Scherrer Institute – Proton Irradiation Facility

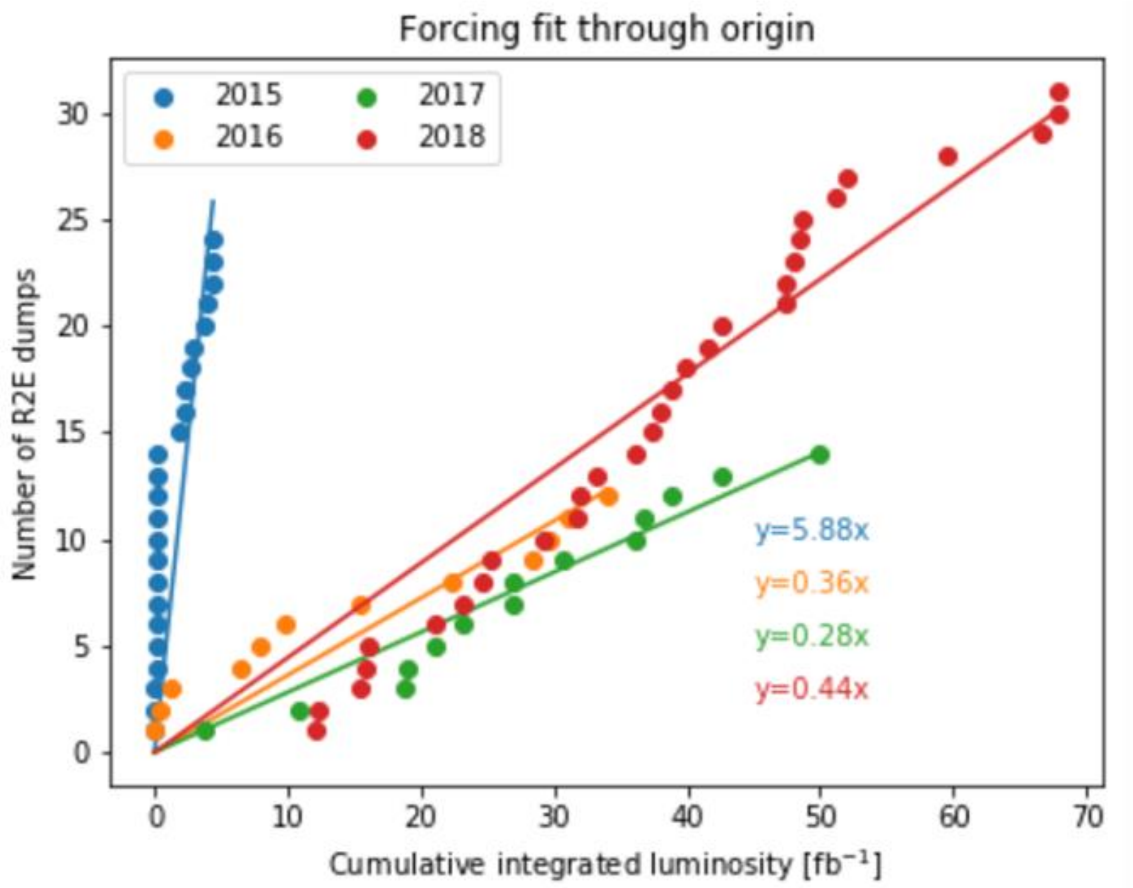
@RADWG test database



- Characterization of SEL sensitivity of SRAM memory (carried out in this case a posteriori)

R2E challenges: COTS component SEE sensitivity

- Impact on accelerator performance: in 2015, very steep R2E dump versus integrated luminosity, incompatible with a successful operation
- In this case, mitigation was rather quick: replacement with (already available) radiation tolerant versions of the board
- **Real-case example of how device level sensitivity propagates to system level, and ultimately accelerator (i.e. "system of systems") level**



@Giuseppe Lerner

R2E challenges: COTS component SEE sensitivity

- And just when you think that screening parts according to their SEE (e.g. SEL) sensitivity per part references is sufficient: in comes lot-to-lot variability…

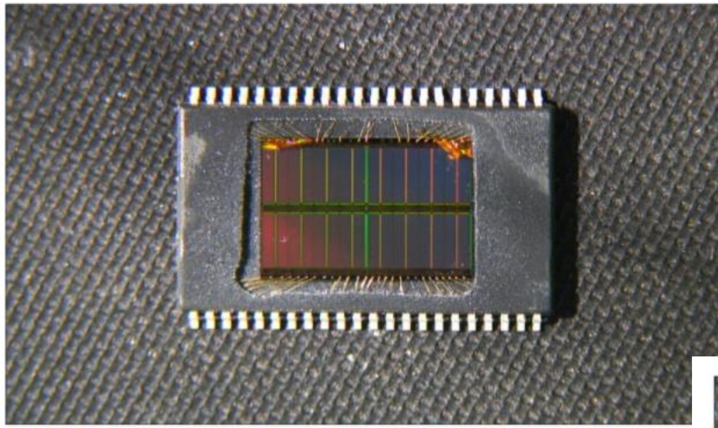


Figure 5: Open Brilliance, date code 11254

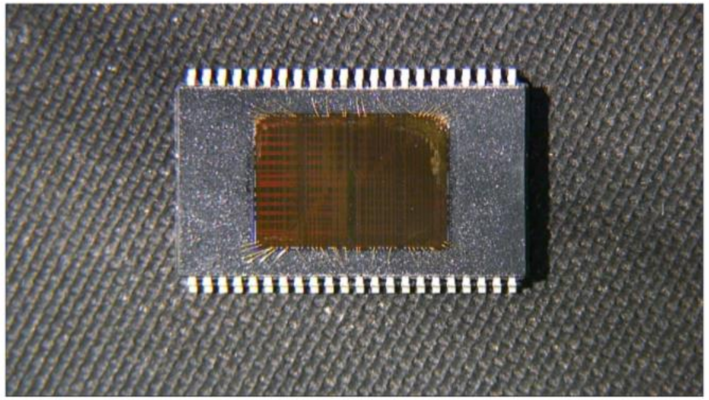
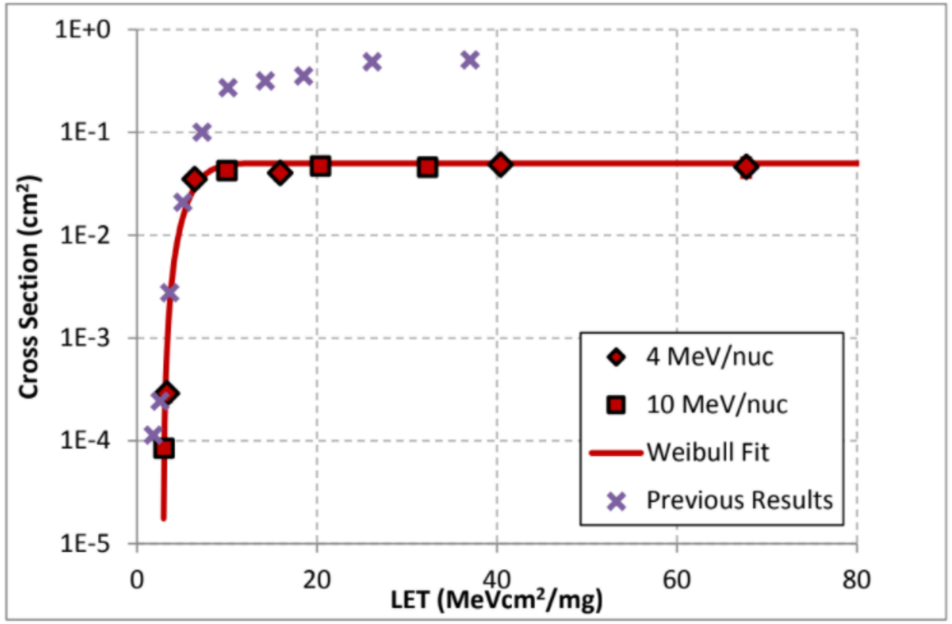
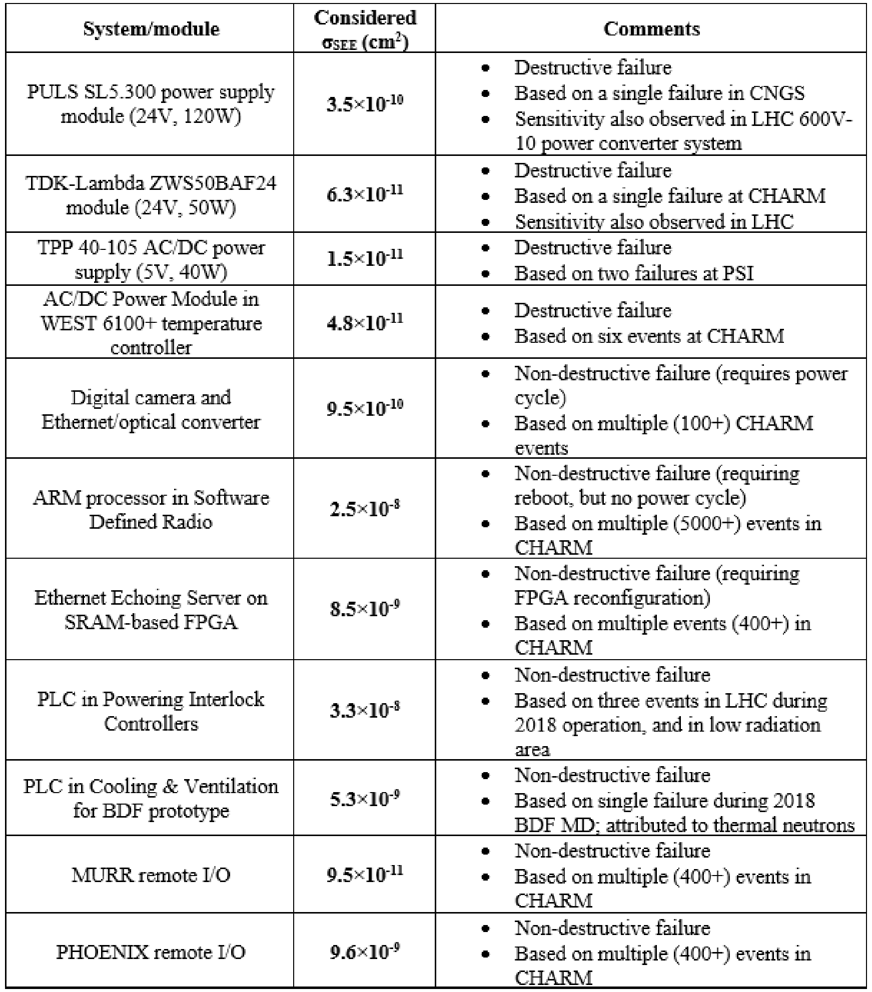


Figure 6: Open Brilliance, date code 12094



R2E challenges: COTS module SEE sensitivity

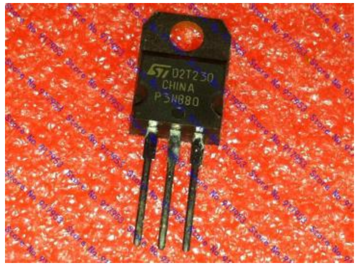
- The **system-level SEE sensitivity** of commercial electronics modules (i.e. black boxes) or custom systems developed without radiation tolerance in mind (i.e. in terms of part selection and architecture) gives us a hint of what the R2E impact on the machine performance would be without the necessary preventive measures (i.e. design and qualification)
- The table to the right provides some examples of system-level SEE cross sections of accelerator candidate equipment, showing a large variability, with values reaching **few 10^{-8} cm^2/system**
- Qualification of COTS modules provides information of very limited value:
  - If the outcome is a “pass”, we can hardly be convinced that the installed units will have the same component references or lots than the qualified ones
  - If the outcome is a “fail”, there is not much that can be done about it (in terms of mitigation, re-design, etc.)
- Therefore, the key R2E approach to this respect is to **avoid using commercial modules for critical applications in radiation exposed areas → dedicated radiation tolerant developments are needed instead**



System/module	Considered σ_{SEE} (cm^2)	Comments
PULS SL5.300 power supply module (24V, 120W)	**3.5×10^{-10}**	• Destructive failure • Based on a single failure in CNGS • Sensitivity also observed in LHC 600V-10 power converter system
TDK-Lambda ZWS50BAF24 module (24V, 50W)	**6.3×10^{-11}**	• Destructive failure • Based on a single failure at CHARM • Sensitivity also observed in LHC
TPP 40-105 AC/DC power supply (5V, 40W)	**1.5×10^{-11}**	• Destructive failure • Based on two failures at PSI
AC/DC Power Module in WEST 6100+ temperature controller	**4.8×10^{-11}**	• Destructive failure • Based on six events at CHARM
Digital camera and Ethernet/optical converter	**9.5×10^{-10}**	• Non-destructive failure (requires power cycle) • Based on multiple (100+) CHARM events
ARM processor in Software Defined Radio	**2.5×10^{-8}**	• Non-destructive failure (requiring reboot, but no power cycle) • Based on multiple (5000+) events in CHARM
Ethernet Echoing Server on SRAM-based FPGA	**8.5×10^{-9}**	• Non-destructive failure (requiring FPGA reconfiguration) • Based on multiple events (400+) in CHARM
PLC in Powering Interlock Controllers	**3.3×10^{-8}**	• Non-destructive failure • Based on three events in LHC during 2018 operation, and in low radiation area
PLC in Cooling & Ventilation for BDF prototype	**5.3×10^{-9}**	• Non-destructive failure • Based on single failure during 2018 BDF MD; attributed to thermal neutrons
MURR remote I/O	**9.5×10^{-11}**	• Non-destructive failure • Based on multiple (400+) events in CHARM
PHOENIX remote I/O	**9.6×10^{-9}**	• Non-destructive failure • Based on multiple (400+) events in CHARM

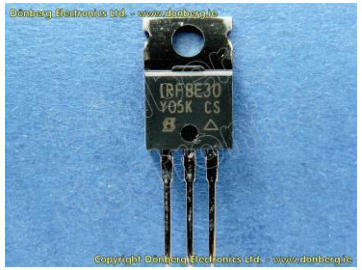
R2E challenges: COTS module SEE sensitivity

- 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



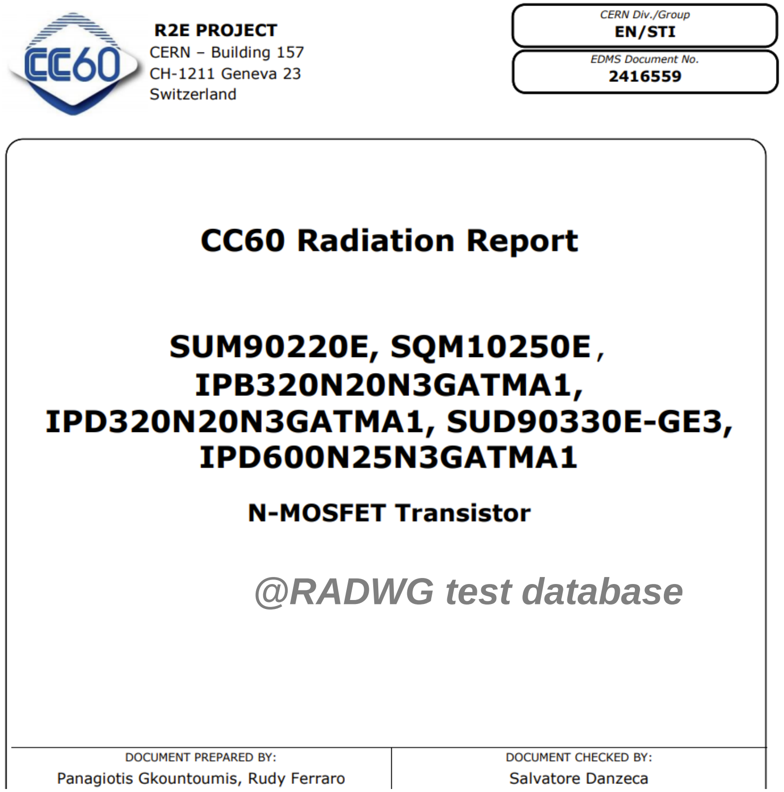
IRFBE30
(N-channel, 800V)

One destructive event before LS1

@Yves Thurel

R2E challenges: COTS component cumulative effect sensitivity

- 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

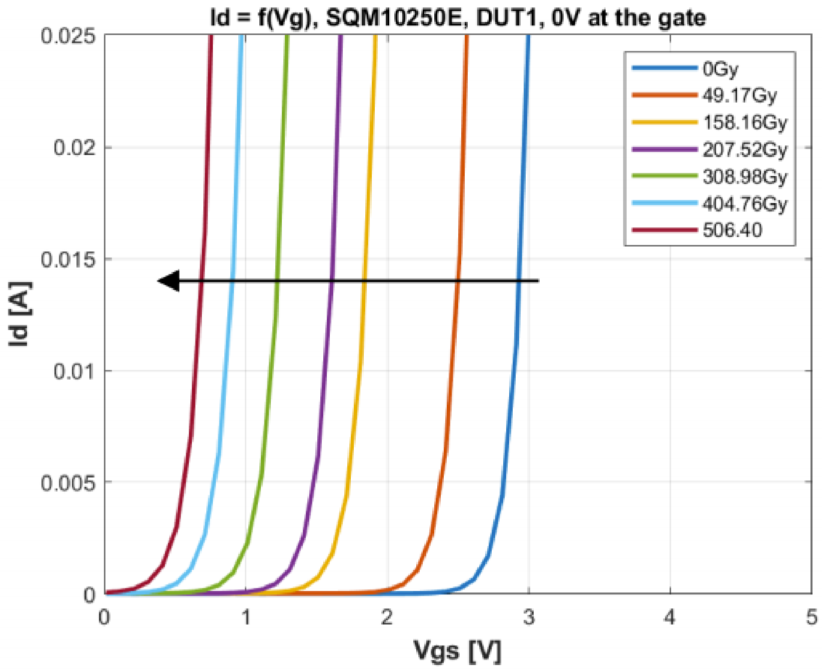
CC60 Radiation Report

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

N-MOSFET Transistor

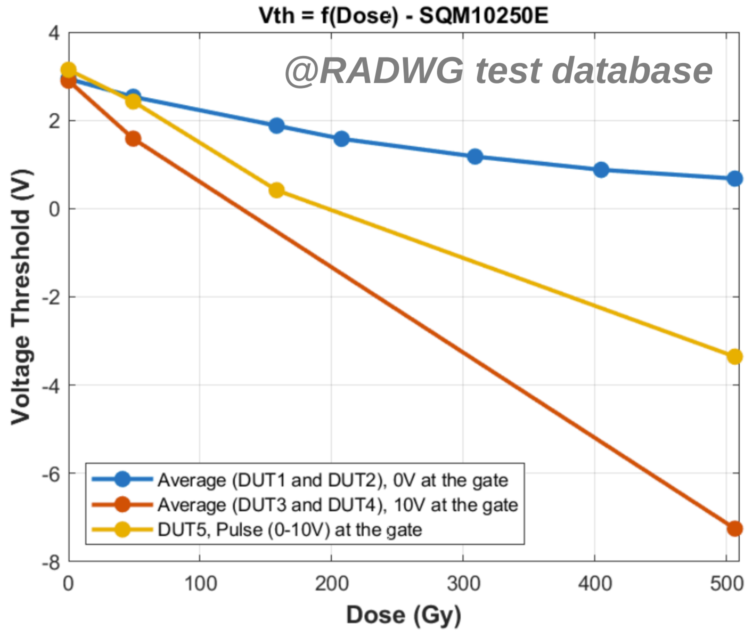
@RADWG test database

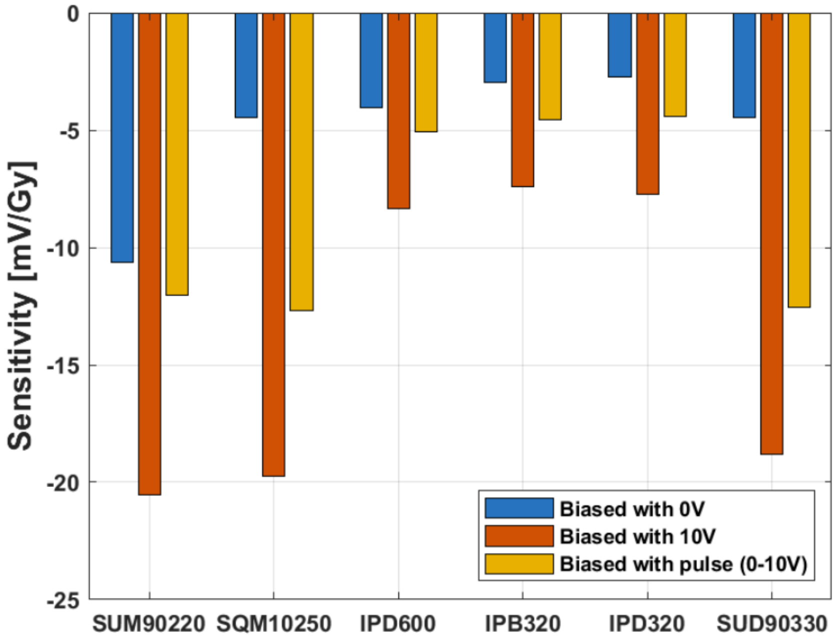
DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:
Panagiotis Gkountoumis, Rudy Ferraro	Salvatore Danzeca



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

R2E challenges: COTS component cumulative effect sensitivity

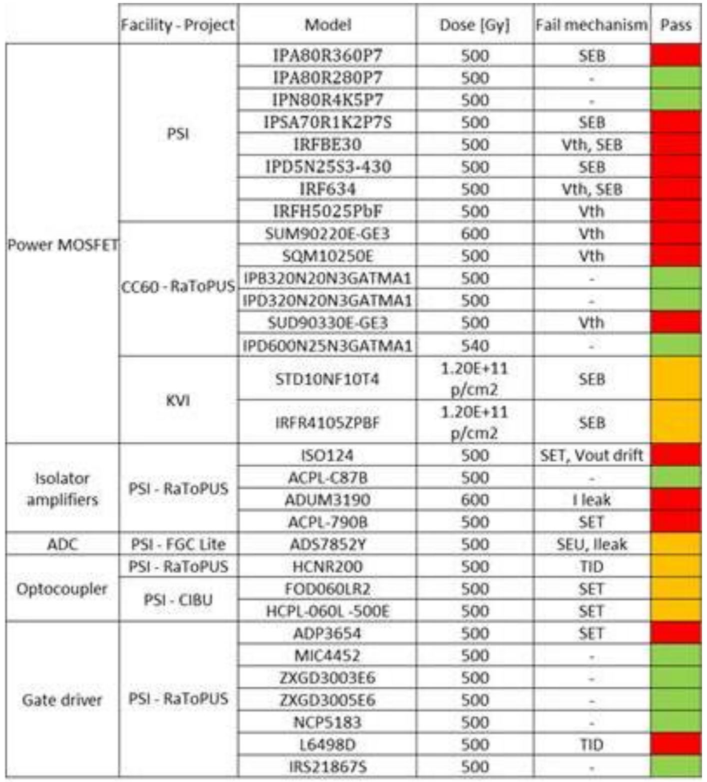




- Very different response from different power MOSFETs with similar electrical characteristics (i.e. all candidates for same development)
- Importance of screening component level effects of critical components before moving on to system level validation

R2E challenges: COTS component radiation effects

- Example: test results from June 2019 – September 2020 period, from a pass/fail perspective
- Main message: some parts pass, but a large fraction fail, hence the importance of testing



	Facility - Project	Model	Dose [Gy]	Fail mechanism	Pass
Power MOSFET	PSI	IPA80R360P7	500	SEB	🟥
		IPA80R280P7	500	-	🟩
		IPN80R4K5P7	500	-	🟩
		IPSA70R1K2P7S	500	SEB	🟥
		IRFBE30	500	Vth, SEB	🟥
		IPD5N25S3-430	500	SEB	🟥
		IRF634	500	Vth, SEB	🟥
		IRFH5025PbF	500	Vth	🟥
	CC60 - RaToPUS	SUM90220E-GE3	600	Vth	🟥
		SQM10250E	500	Vth	🟥
		IPB320N20N3GATMA1	500	-	🟩
		IPD320N20N3GATMA1	500	-	🟩
		SUD90330E-GE3	500	Vth	🟥
		IPD600N25N3GATMA1	540	-	🟩
	KVI	STD10NF10T4	1.20E+11 p/cm2	SEB	🟧
		IRFR4105ZPBF	1.20E+11 p/cm2	SEB	🟧
Isolator amplifiers	PSI - RaToPUS	ISO124	500	SET, Vout drift	🟥
		ACPL-C87B	500	-	🟩
		ADUM3190	600	I leak	🟥
		ACPL-790B	500	SET	🟥
ADC	PSI - FGC Lite	ADS7852Y	500	SEU, Ileak	🟧
Optocoupler	PSI - RaToPUS	HCNR200	500	TID	🟧
	PSI - CIBU	FOD060LR2	500	SET	🟧
		HCPL-060L -500E	500	SET	🟧
Gate driver	PSI - RaToPUS	ADP3654	500	SET	🟥
		MIC4452	500	-	🟩
		ZXGD3003E6	500	-	🟩
		ZXGD3005E6	500	-	🟩
		NCP5183	500	-	🟩
		L6498D	500	TID	🟥
		IRS21867S	500	-	🟩

	Facility - Project	Model	Dose [Gy]	Fail mechanism	Pass
Ethernet PHY	PSI - Powerlink PHY	DP83849	30	SEU	🟥
		DP83822	120	SEU	🟥
RF amplifiers	PSI - RF group	GRF5040	500	-	🟩
		PMA5455	500	-	🟩
		HMC539ALP3E	500	-	🟩
		MAAD-007082	500	TID	🟥
		HMC472ALP4E	500	-	🟩
PWM controller	PSI - RaToPUS	MIC38HC45YM	300	TID	🟥
		TL2843BDR	500	-	🟩
		UC3845AD8TR	500	TID	🟧
Op. Amplifier	PSI - Batmon	LTC6255	500	-	🟩
		LTC6256	500	-	🟩
	PSI - PIRANI	OPA128	500	-	🟩
Voltage regulator	PSI	EDA02878	210	-	🟩
DC/DC converter	PSI - UDQS Interlock	TMR 6-0513	500	TID	🟧
		TMR 6-0523	500	TID	🟧
Transceiver	PSI - CIBU	MAX3430CSA+	500	-	🟩
Trigger	PSI - CIBU	74LVT14D	500	-	🟩
System	PSI - CIBU	CIBU	500	SET	🟧
Timmer	PSI - Humidity IoT	LMC555	354	TID	🟥
Current sensor	PSI - UDQS Interlock	CPC0-12009-160	500	TID, Ileak	🟧
Bipolar transistor	PSI - Penning	2N3810	500	-	🟩
Current module	PSI - PWM Controller	Current module	1000	-	🟩
FPGA	PSI	NG-MEDIUM FPGA	1000	SEU, SEFI	🟥

@RADWG test database (summary by @Mario Sacristán)

Agenda

1. **Introduction**
2. **Constraints (other than COTS sensitivity)**
3. **Constraints (linked to COTS sensitivity)**
4. **Main takeaways**

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)
  - 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, notably 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**
- Such ingredients are the main topics of this R2E project annual meeting

Overview of “Service” session during R2E annual meeting

- The session will cover the various **sector-wide services** that the R2E provides in relation to radiation effects and Radiation Hardness Assurance
  - Three talks on **radiation monitors** (RadMON, optical fiber, high-level dosimetry)
  - Two talks on **radiation level monitoring, analysis and calculation**
  - Two talks on **radiation testing services** (electronics and materials)
  - Two talks on **irradiation facility operation and user support** (CHARM and CC60)
- All complemented with **applied research** activities aimed at improving the quality and efficiency of the related services and procedures (presented in the “research” session)
- All providing direct support to the ongoing and planned radiation tolerant **developments** throughout the Accelerator Technology Sector at CERN (presented in the “developments” session)

Thank you for your attention!

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