RADMEP 2023 Workshop at CERN

Radiation Effects on Electronics lessons learnt from Accelerators Facilities

Rubén García Alía – SY/STI-BMI

On behalf of the R2E team at CERN

8th December 2023
https://indico.cern.ch/event/1350062/

With the support of the Erasmus+ Programme of the European Union

Outlook

- **Why R2E? Radiation exposed electronics + impact on availability**
- **Radiation Hardness Assurance for LHC electronics**
  - Radiation Environment
  - Component Level Testing
  - System Level Testing (as final RHA validation)

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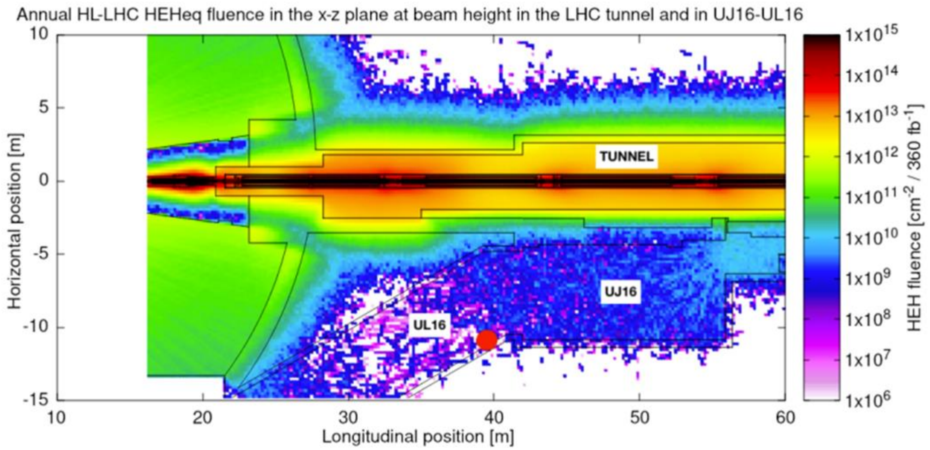
Key point: “unavoidable” radiation exposure of critical accelerator systems

The “Radiation to Electronics” (R2E) challenge in high-energy accelerators

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

Tens of thousands of electronic boards in the LHC (and millions of individual components), all capable of negatively affecting its operation through radiation effects



Expected HL-LHC radiation levels around the ATLAS interaction point (IP1), as simulated in FLUKA

R2E mandate: to ensure the successful operation of CERN accelerators in view of radiation effects on electronics

Impact of beam losses on accelerator operation

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 071003 (2019)

Editors' Suggestion

Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider

A. Lechner,* B. Auchmann,† T. Baer,‡ C. Bahamonde Castro, R. Bruce, F. Cerutti, L. S. Esposito, A. Ferrari, J. M. Jowett, A. Mereghetti, F. Pietropaolo, S. Redaelli, B. Salvachua, M. Sapinski,§ M. Schaumann, N. V. Shetty, and V. Vlachoudis

European Organization for Nuclear Research (CERN), Esplanade des Particules 1, 1211 Geneva, Switzerland

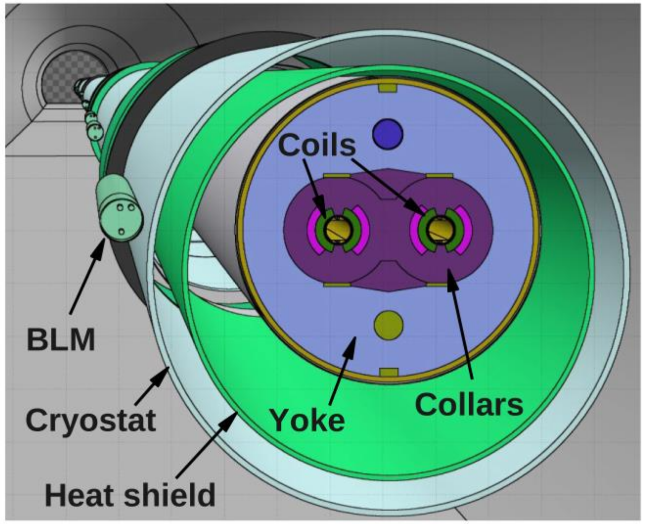
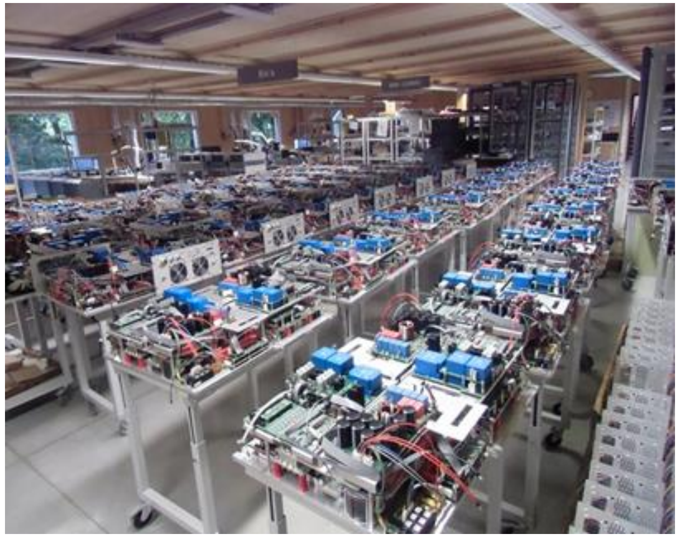


FIG. 1. Geometry model of a main arc dipole embedded in the LHC tunnel, with a BLM mounted on the outside of the magnet cryostat. A more detailed picture of the BLM model is shown in Fig. 2.

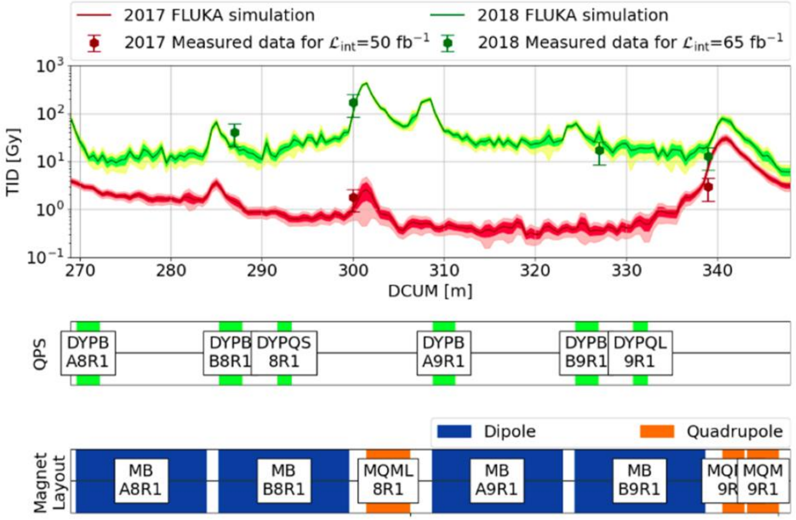
Beam losses and the resulting showers adversely affect collider operation, experiments, equipment, and personnel in several ways. For example, they can lead to magnet quenches, i.e., the sudden loss of superconductivity [21]; they contribute to the heat load to the cryogenic system [22,23]; they cause long-term radiation damage and aging of equipment components [22–25]; they lead to the production of radioactive isotopes and are therefore a concern for radiation protection [26]; they give rise to background in experiments [27]; and they can induce single-event effects in equipment electronics [28]. In the worst case, if the beam is lost in an uncontrolled way, it can induce destructive damage because of the thermal shock or because of phase transitions if the temperatures are high enough. In order to assess the consequences of beam losses …

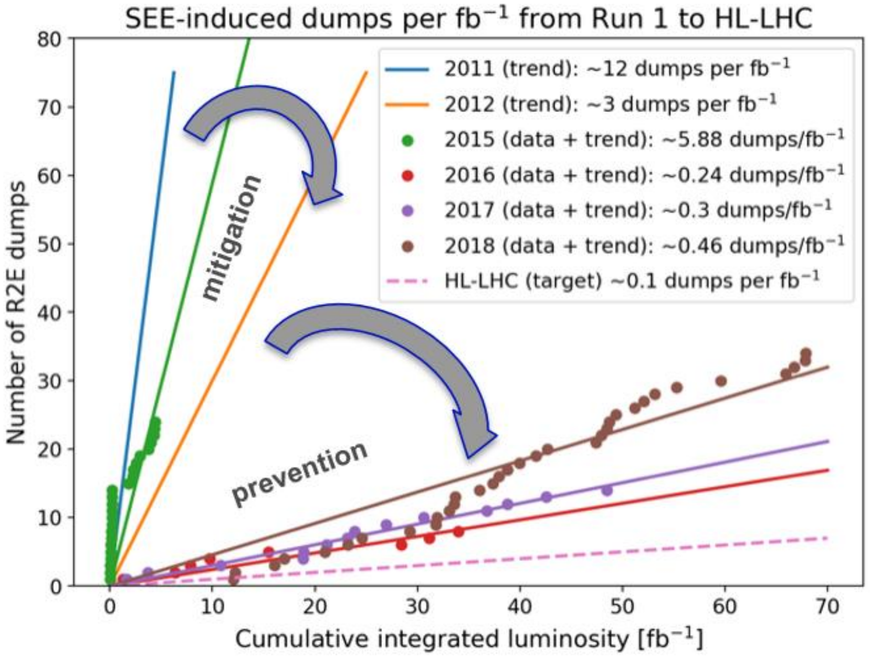
Radiation Hardness Assurance at CERN



Radiation tolerant design and production (standards, guidelines, quality assurance, reviews…)

Radiation effects facilities and tests





Follow-up and mitigation of radiation effects impact on operation; mission-critical also for HL-LHC objectives

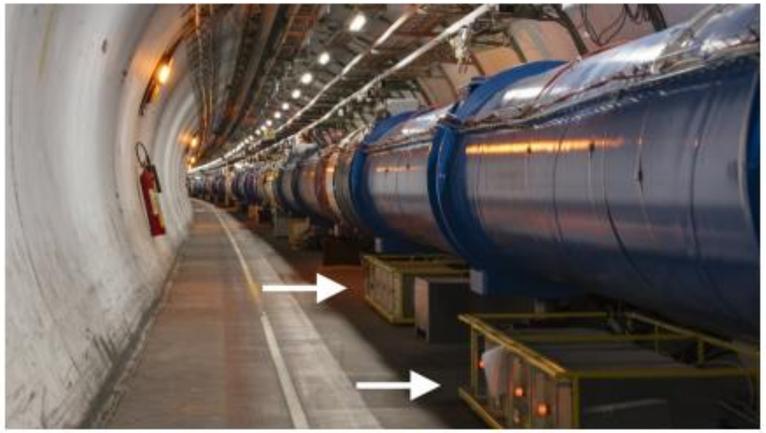
Radiation environment simulation and monitoring

What are the relevant systems, and where are they located?

Electronic systems at the LHC can contain up to thousands of COTS-based units. Some examples:

- **Power converters:** carrying the necessary currents from the external supplies into the magnets.
- **Quench Protection System (QPS):** protecting the superconducting equipment from incidents (quenches) caused by excessive heat.
- Many others (**vacuum, beam instrumentation, cryogenics, RF,** etc.).

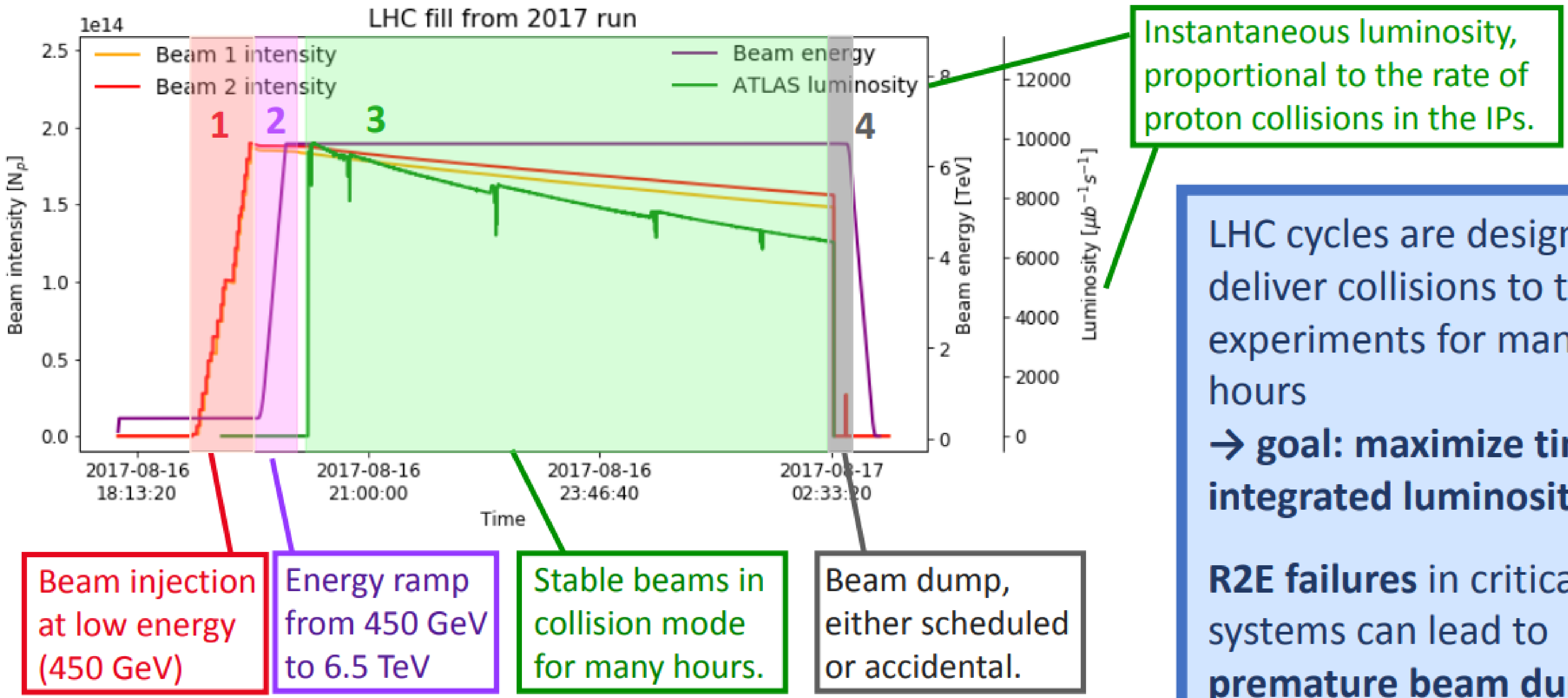
The racks can be in the tunnel, to reduce cabling distance from the equipment, or in nearby shielded areas with lower radiation levels.



LHC tunnel racks below the beam line

LHC racks in a shielded area

Focusing on the LHC: a typical cycle



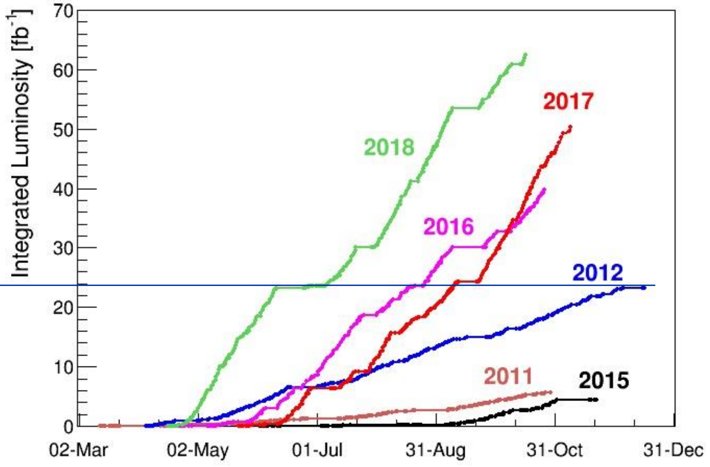
LHC fill: simplified sequence

LHC cycles are designed to deliver collisions to the experiments for many hours

→ **goal: maximize time-integrated luminosity.**

R2E failures in critical systems can lead to **premature beam dumps.**

R2E impact on machine availability



Proceedings of IPAC2015, Richmond, VA, USA TUPTY053

ROADMAP TOWARDS HIGH ACCELERATOR AVAILABILITY FOR THE CERN HL-LHC ERA

A. Apollonio, M. Brugger, L. Rossi, R. Schmidt, B. Todd, D. Wollmann, M. Zerlauth,
CERN, Geneva, Switzerland

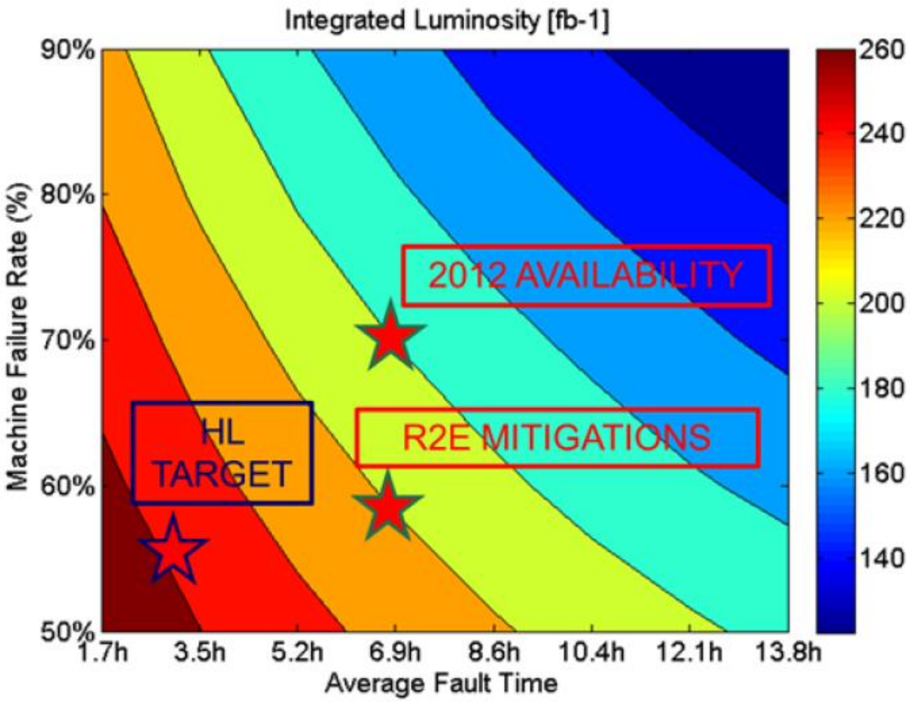


Table 2: Maximum Acceptable Number of Dumps (target, TG) and Relative Fault Time Due to R2E-Induced Failures in the HL-LHC Era

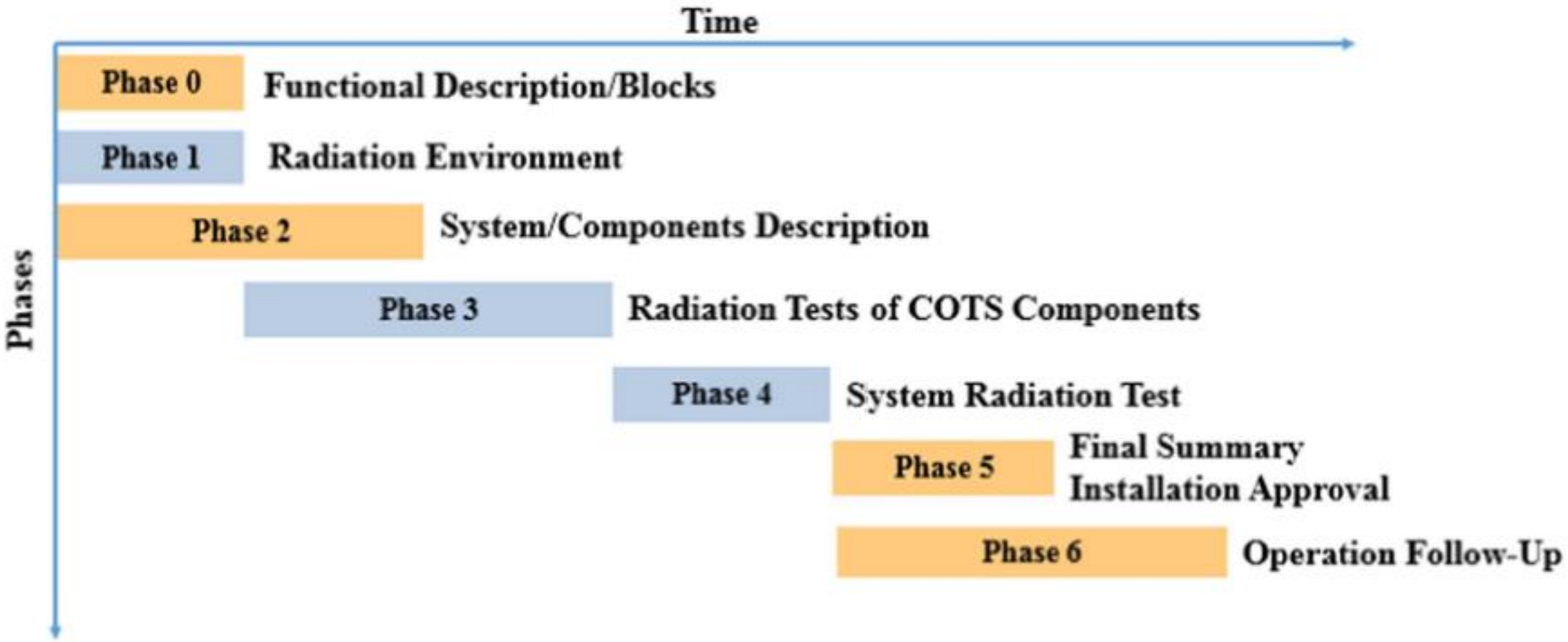
System	R2E dumps (2012)	R2E downtime (2012)	R2E dumps (HL TG)	R2E downtime (HL TG)
QPS	31	80 h	9	32 h
PC	14	60 h	4	14 h
Cryo	4	70 h	1	3.5 h
Vacuum	4	20 h	1	3.5 h
Others	3	30 h	1	3.5 h

R2E order of magnitude levels and effects (very approximative!)

High-energy hadron fluence (cm^{-2} $year^{-1}$)	Total Ionizing Dose for 10 years (Gy)	Effects on Electronics
10^5	<<1	Possible SEE impact for commercial systems with MANY units and VERY demanding availability and reliability requirements
10^7	<1	SEE impact for systems with multiple units and demanding availability and reliability requirements
10^9	10	SEE mitigation (e.g. redundancy) at system level; cumulative effects can start to play a role
10^{11}	1000	SEE mitigation (e.g. redundancy) at system level, very challenging TID level for COTS
10^{15}	10 MGy	Rad-hard by design ASICs

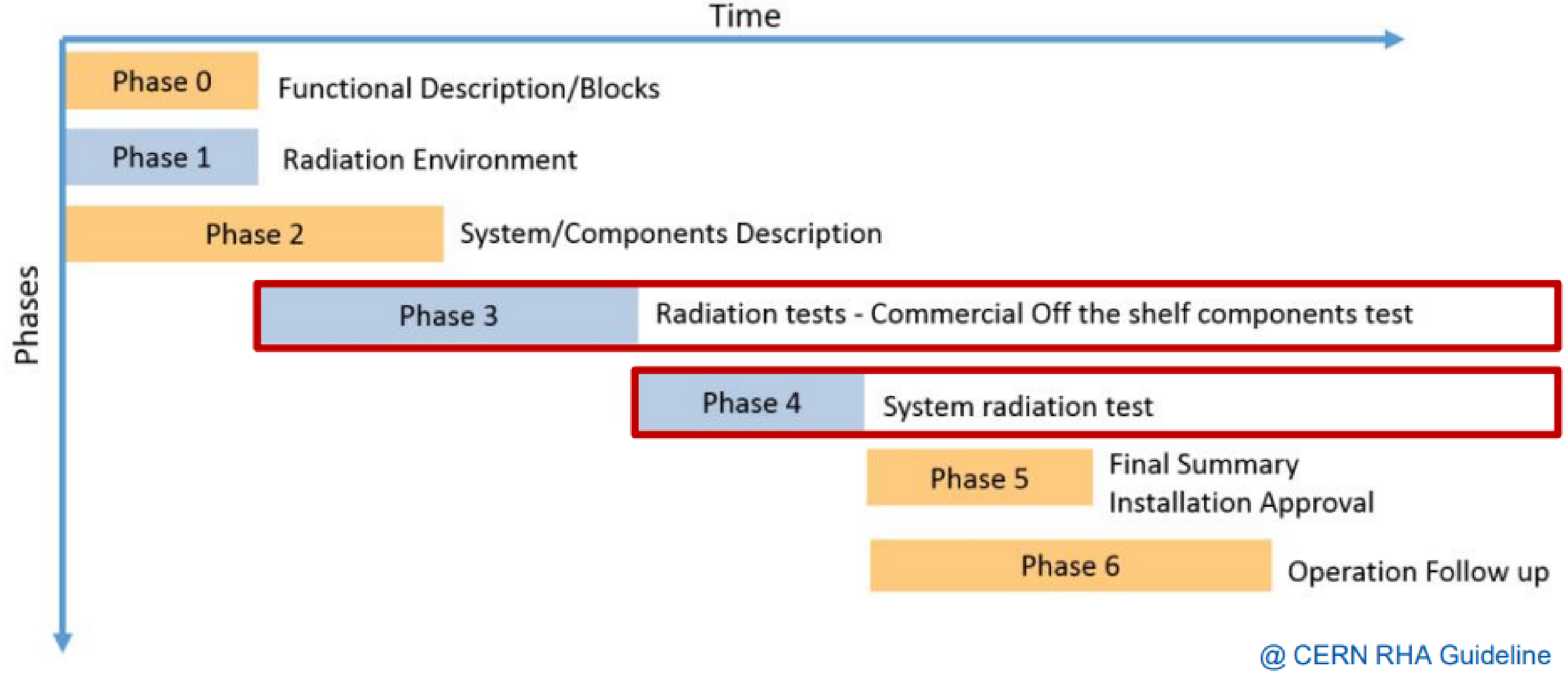
Approximation (mainly for high-energy accelerator environment): 10^9 HEH/cm^2 ~ 1 Gy

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*

From component to system level qualification:



Component level tests:
- **TID:** Gamma (Co_{60})
- **DD:** Neutrons
- **SEE+TID+DD:** Protons
- **SEL:** Heavy Ions
- **SEE:** Thermal neutrons

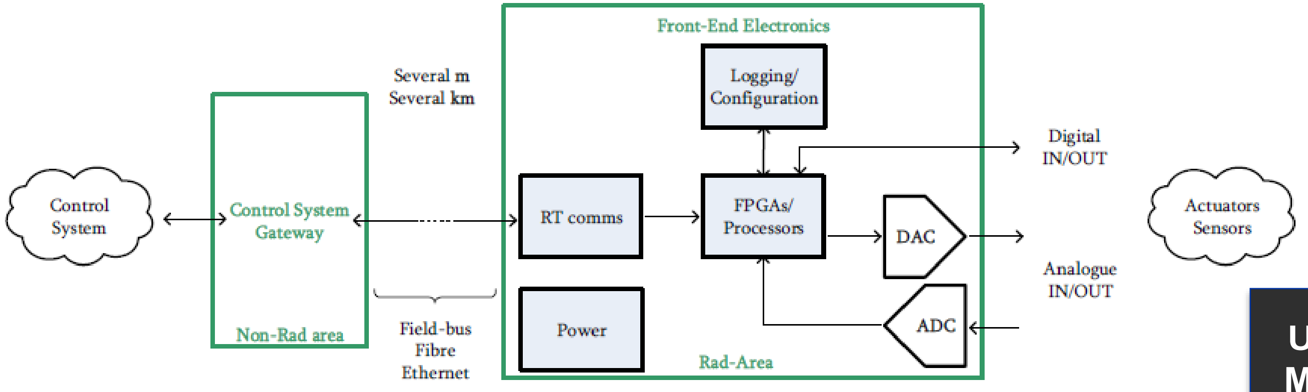
System level tests
- **SEE+TID+DD:** Mixed-Field

- **Validation** of radiation tolerance at system level before final production
- **Identification** of possible unpredicted system failure modes

→ System level tests performed at CHARM Facility

Example of rad-tol COTS-based system architecture

Crucial point: electronic systems based on COTS, but relying on in-house designs



Uznanski, MAPLD'18

Many different radiation tolerant electronics system developments across CERN

Each with up to hundreds or even thousands of units across the accelerator

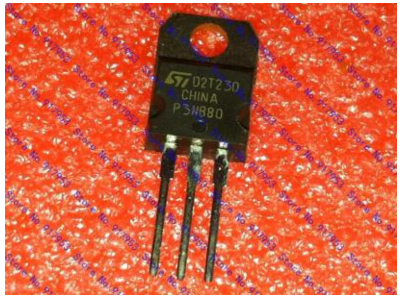
Each unit with several tens of different active semiconductor part types, and hundreds of parts in total

Mitigation techniques at many different levels (component, circuit, board, sub-system…)

Why COTS modules ("black boxes") are typically excluded from radiation exposed critical systems

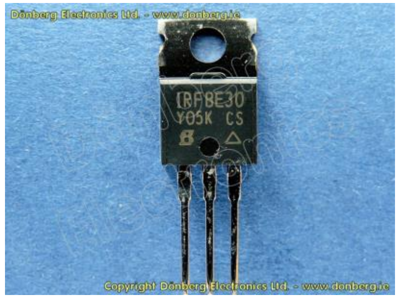
Example of COTS module risk: same "black-box", different power MOSFET

- 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



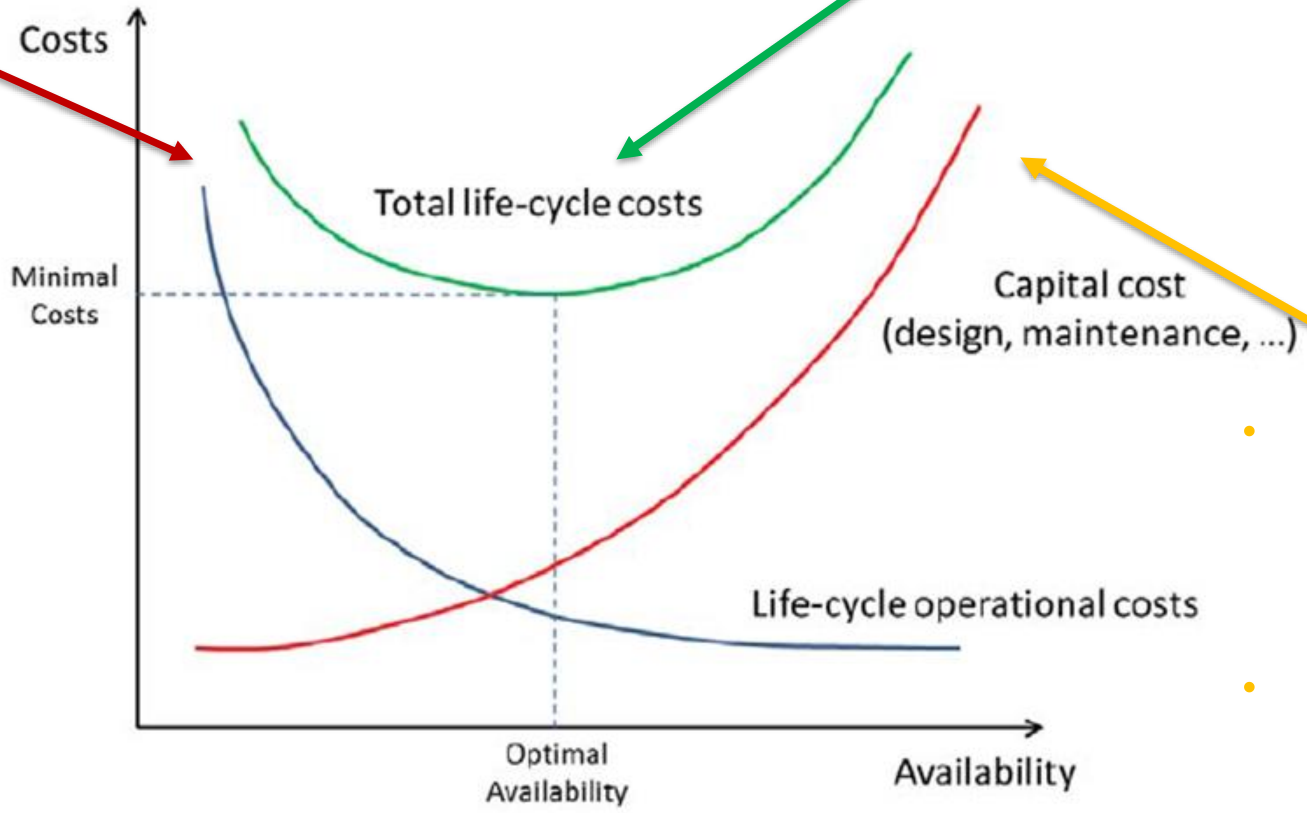
IRFBE30
(N-channel, 800V)

One destructive event before LS1

LHC approach: from mitigation to prevention

- Radiation tolerant design based on qualified COTS

- No information about radiation levels and sensitivity of critical components and systems to radiation
- Use of purely commercial modules and systems in radiation areas, even if radiation tested



- Active electronics operating only in radiation safe areas (e.g. shielding, relocation)
- Rad-hard-by-design components

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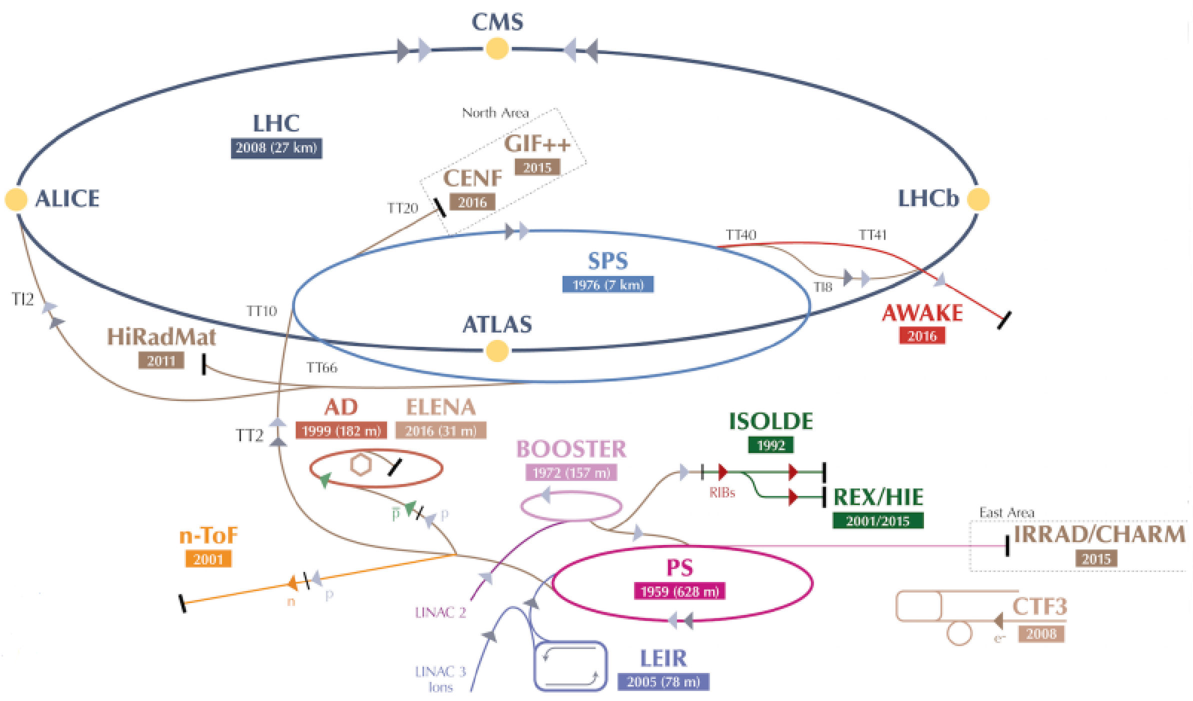
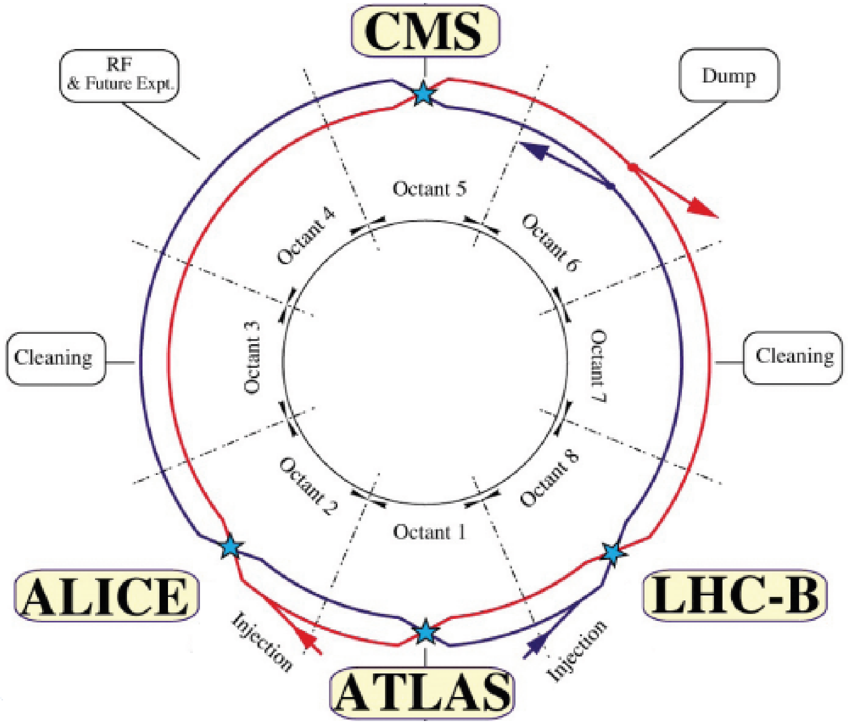
The LHC accelerator complex

- Long sequence of accelerators and transfer lines to reach the LHC, for proton and ion operation.
- Energy increase by a factor ≈30 at each step.
- Four LHC Interaction Points (ATLAS, CMS, ALICE and LHCb detectors).
- Many experiments and facilities (e.g. CHARM test facility, discussed later).



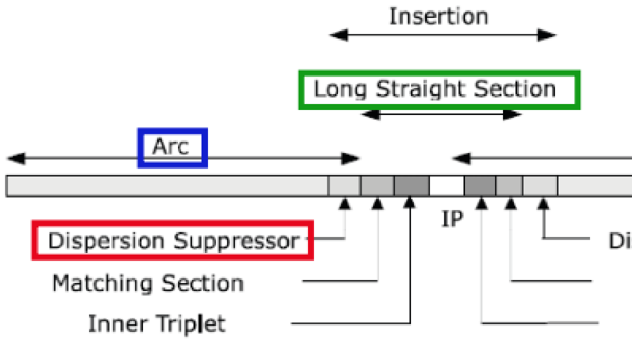
Layout of the LHC

The LHC radiation levels **depend on the location**. The **layout** consists of **eight octants** with left/right sides of 34 **cells**.



STRUCTURE OF EACH OCTANT

- **Long Straight Section (LSS)**, cells 1-7: key LHC elements (Interaction Points, collimators..).
- **Arc**, cells 14-34: curved section with sequence of dipole and quadrupole magnets.
- **Dispersion Suppressor (DS)**, cells 8-13: curved section connecting LSS and arc.



LSS+DS = Insertion Region (IR)

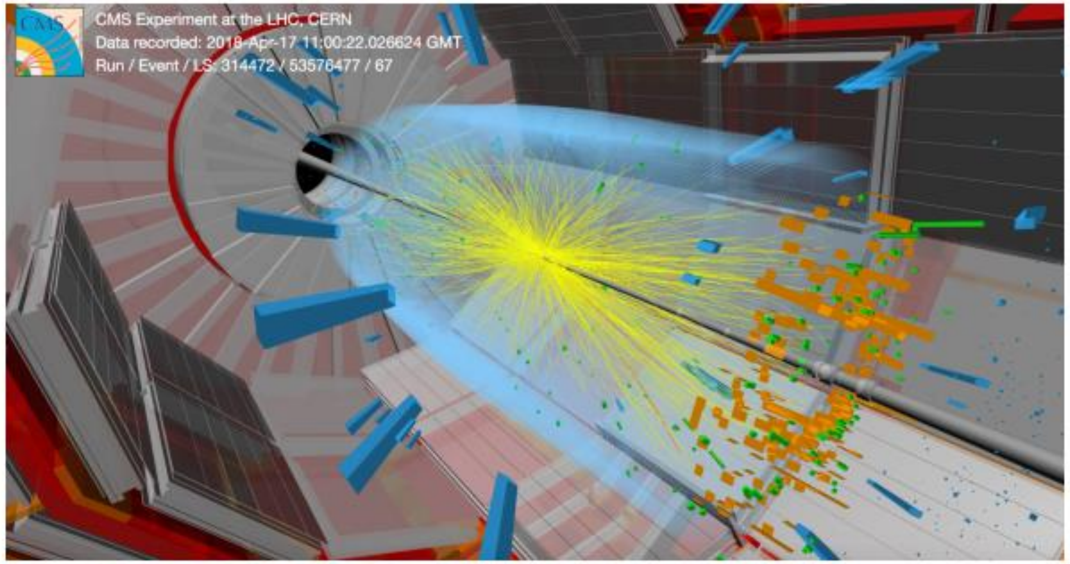
Sources of radiation: LHC collisions

Inelastic scattering collisions in the IPs:

$$N_{coll-inel} = \sigma_{inel} \cdot \mathscr{L}_{int}$$

Cross section:
≈ 80 mb for 13-14 TeV collisions

Integrated luminosity in the main IPs (ATLAS and CMS):
≈ 50 fb^{-1}/y in Run 2 (2015-18)
≈ 250 fb^{-1}/y in HL-LHC



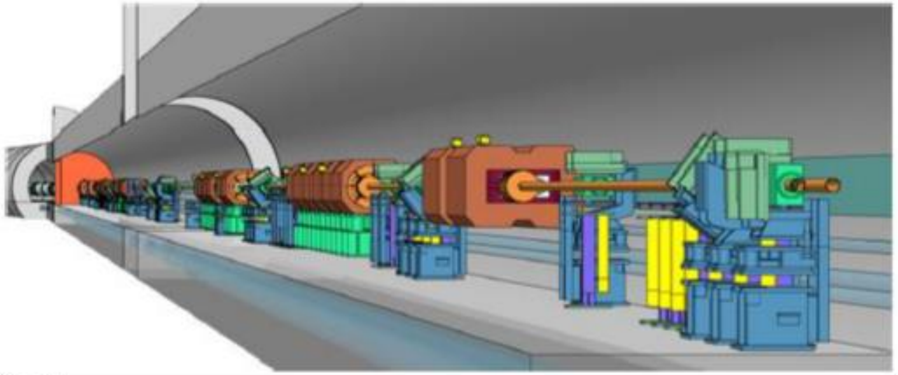
→ ≈ $4 \cdot 10^{15}$ inelastic collisions per year in ATLAS/CMS in Run 2, ≈ $2 \cdot 10^{16}$ per year in HL-LHC.

The collisions produce particles in all directions, but a major fraction of high-energy products are scattered at **low angles** → they **propagate in the tunnel around the IPs (LSS and DS)** causing **luminosity-driven radiation showers**.

Sources of radiation: beam-machine and beam-gas interactions

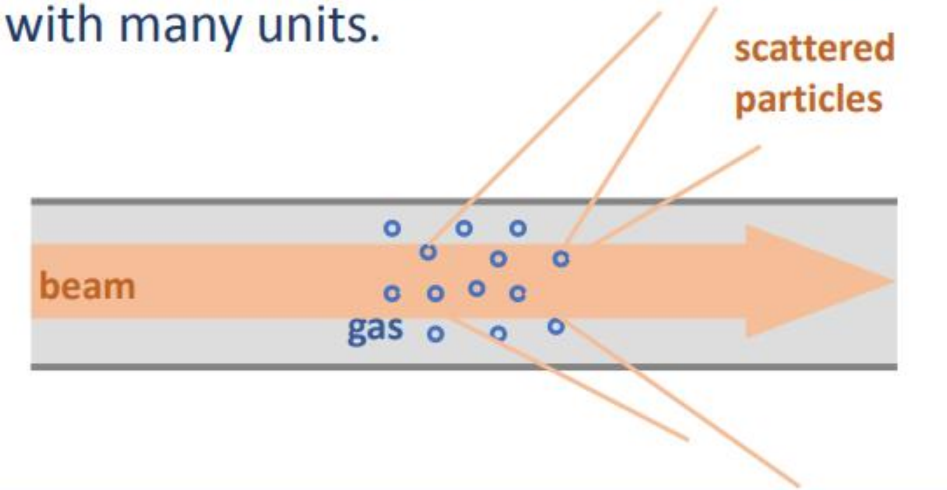
Beam-machine interactions

- Before reaching the tunnel, LHC particles typically interact with machine elements, e.g. collimators, absorbers, magnets.
- This is true both for collision products (e.g. IR1-IR5) and in IRs where no collisions are produced, where beam-machine interactions can be seen as the primary source of radiation.



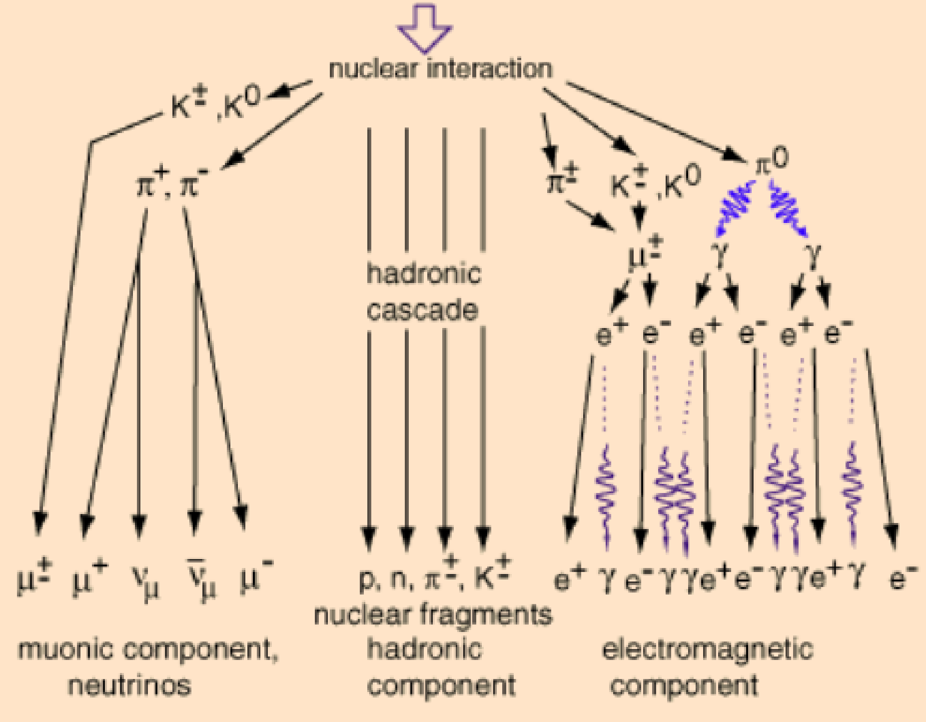
Beam-gas interactions

- Despite the vacuum system, the beam pipes are not empty → the beams can interact with residual gas molecules.
- Sub-dominant effect compared to other sources. Relevant in the arcs, where it can cause R2E issues in distributed systems with many units.



LHC radiation showers

1) **Primary nuclear interaction** (e.g. proton on machine element) producing a cascade of hadrons (p, n, K, π).
2) The shower develops into an **EM component** (from fast $\pi^0 \rightarrow \gamma\gamma$ decay) and a **hadronic component**.
3) **Muons** (and neutrinos) appear from the decay of charged K and π.



Radiation **composition** and **energy spectra** depend on the **energy of the primary interaction**, the **distance travelled** and the **amount of shielding material**.

Monitoring and calculation tools

Main tools for the measurement and prediction of radiation levels at the LHC, often used in combination:

≈4000 **Beam Loss Monitors (BLMs)** in the tunnel.

Gas-filled ionisation chambers used for machine protection, also providing **online TID** measurements → used within the R2E team to perform radiation level analyses.

≈400 **RadMons** in tunnel and shielded areas

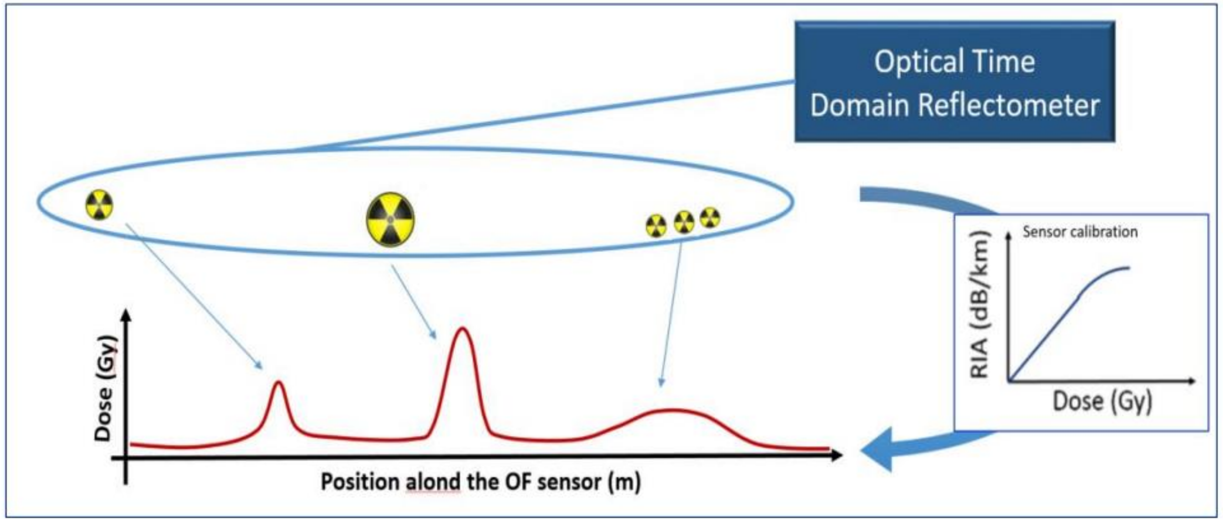
Each measures **TID** and **HEH**, **thermal neutron** and **1MeV neutron equivalent** fluences with COTS-based detectors.

FLUKA: Monte Carlo code that simulates radiation showers and is able to calculate R2E-relevant quantities (TID, fluences).

Monitoring and calculation tools

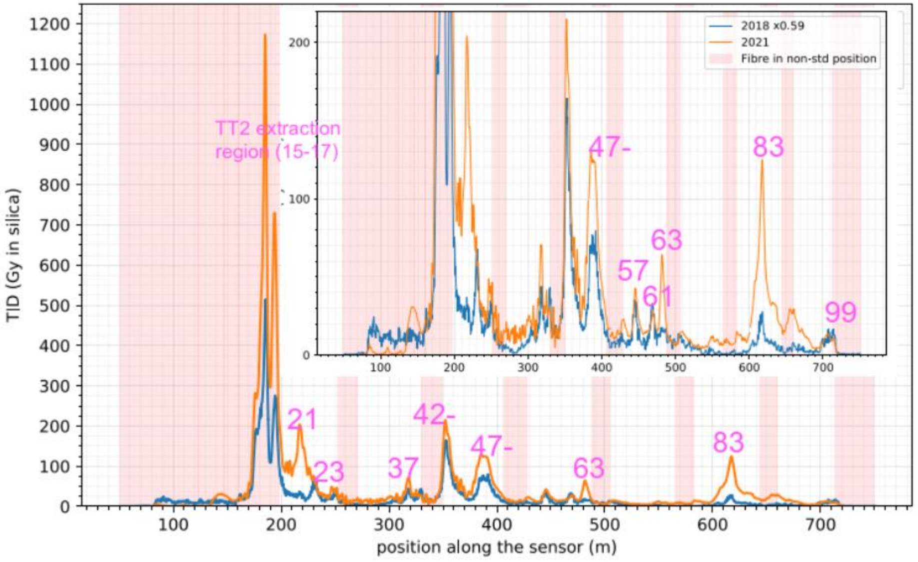
Distributed Optical Fiber Radiation Sensors

DOFRS is based on:
- **Radiation Induced Attenuation** (RIA) in suitable specialty OFs (*not any optical fibre*)
- **Optical Time Domain Reflectometry**



First implementation reported by *H. Henschel et al., Nucl. Instr. & Meth. in Phys. Res. A, vol. 526, no. 3, pp. 537–550, 2004*

"Optical Fibre Dosimetry", D. Di Francesca, R2E Annual Meeting 2022

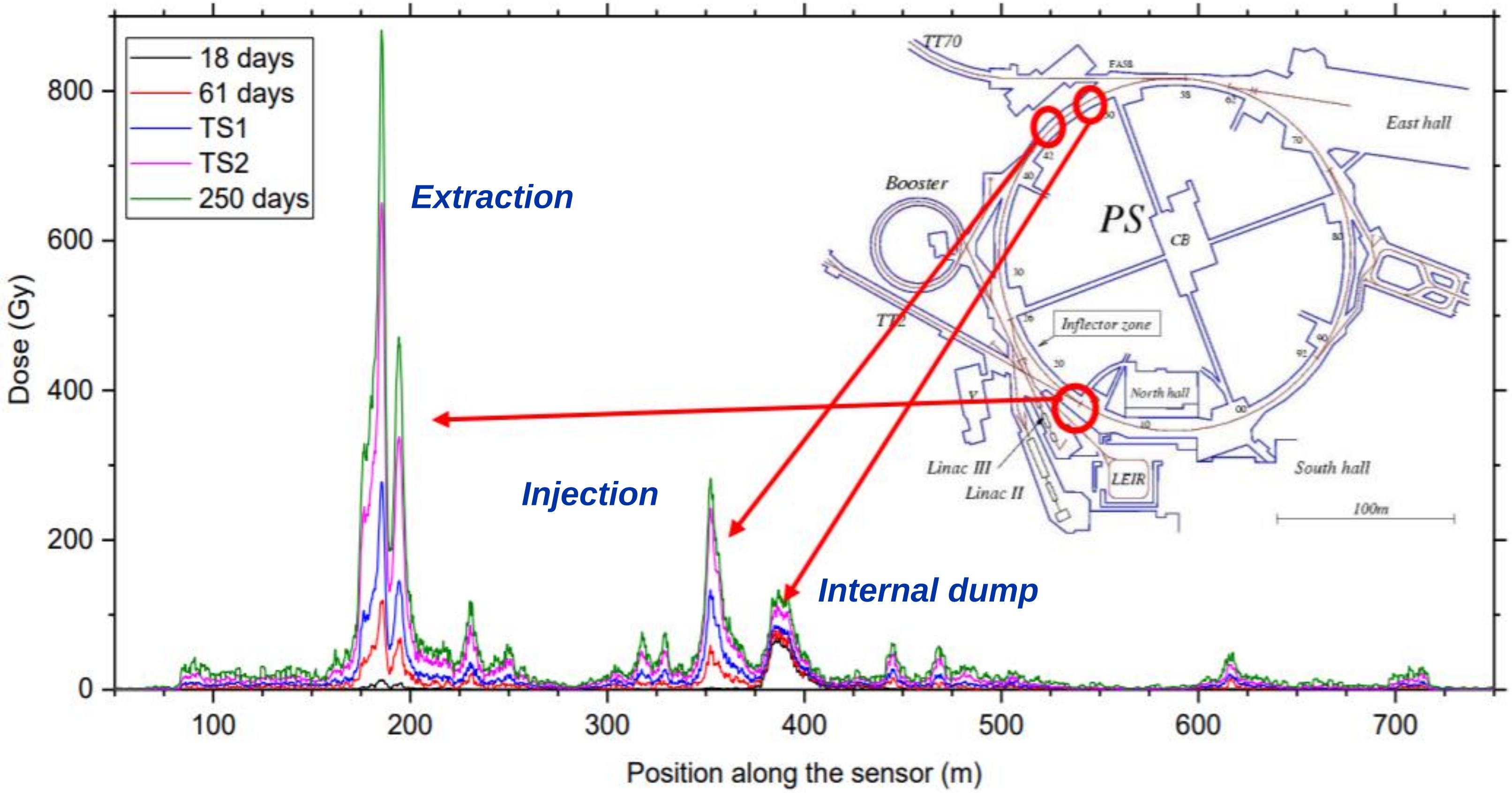


PS

"Overview of 2021 prompt radiation levels in the injector chain" , K. Bilko, IPP meeting 13th January 2022

Optical fiber dosimetry at CERN

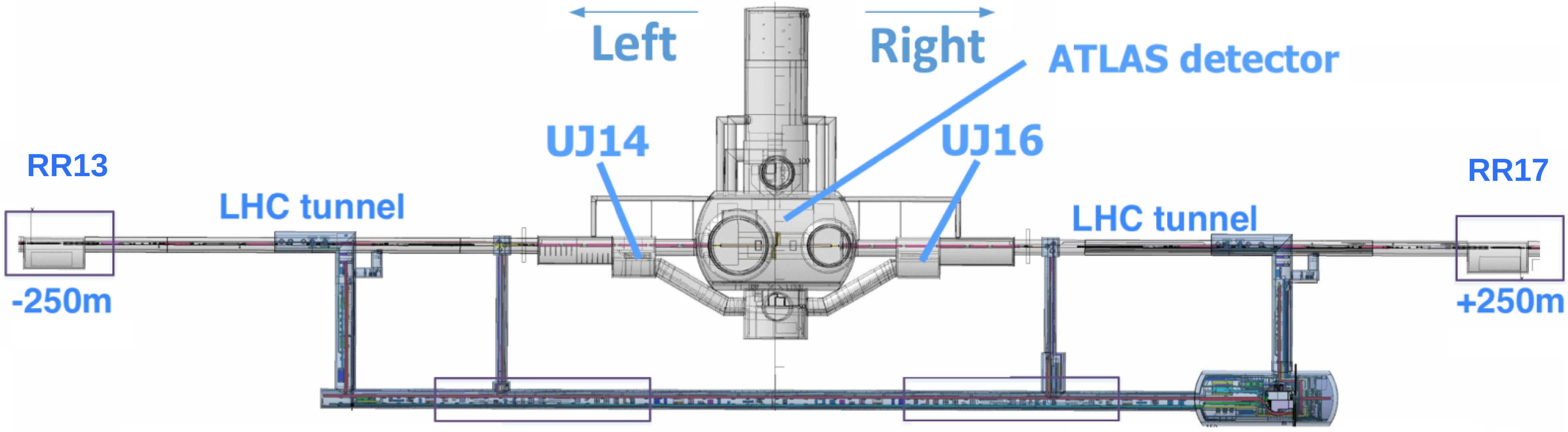
Example of operation: 2018 in PS



The ATLAS Insertion Region (IR1)

Highest radiation levels in the Insertion Regions hosting the interaction points. Below I show **IR1** (ATLAS) but **IR5** (CMS) has a similar geometry (with few layout differences).

The ATLAS cavern, the LHC tunnel (LSS of IR1, ± ≈250m from ATLAS) and several shielded areas (e.g. UJ16, see next slides) are shown in the layout below:

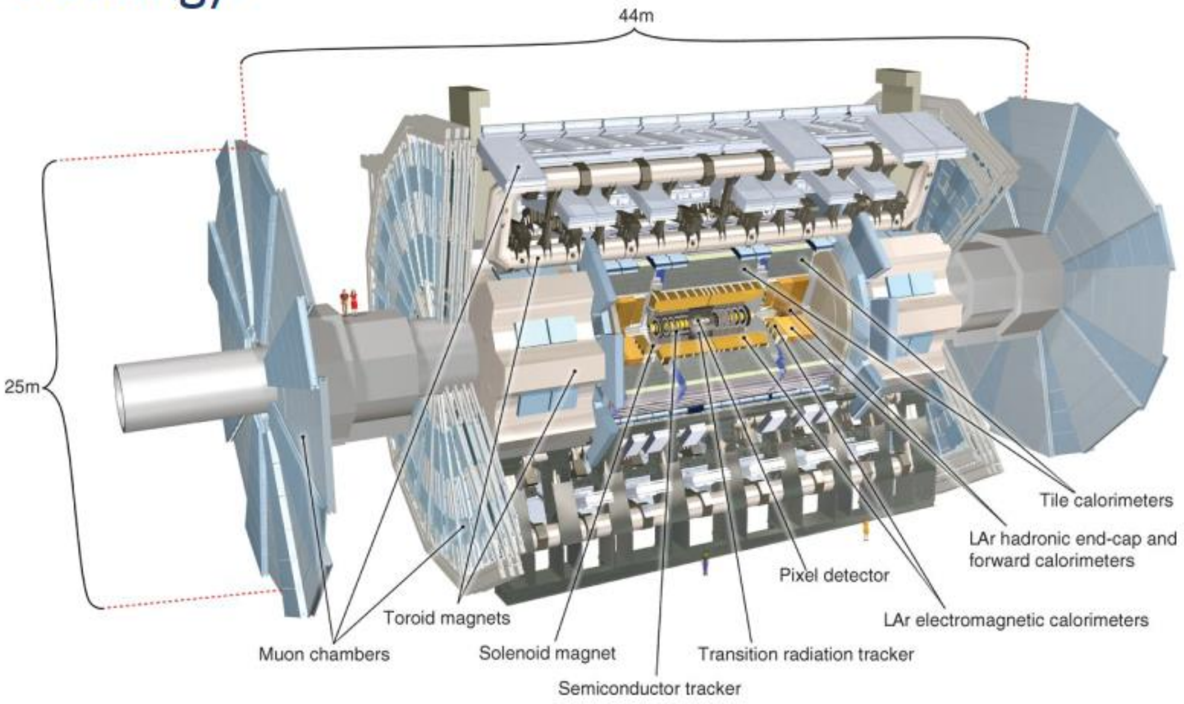


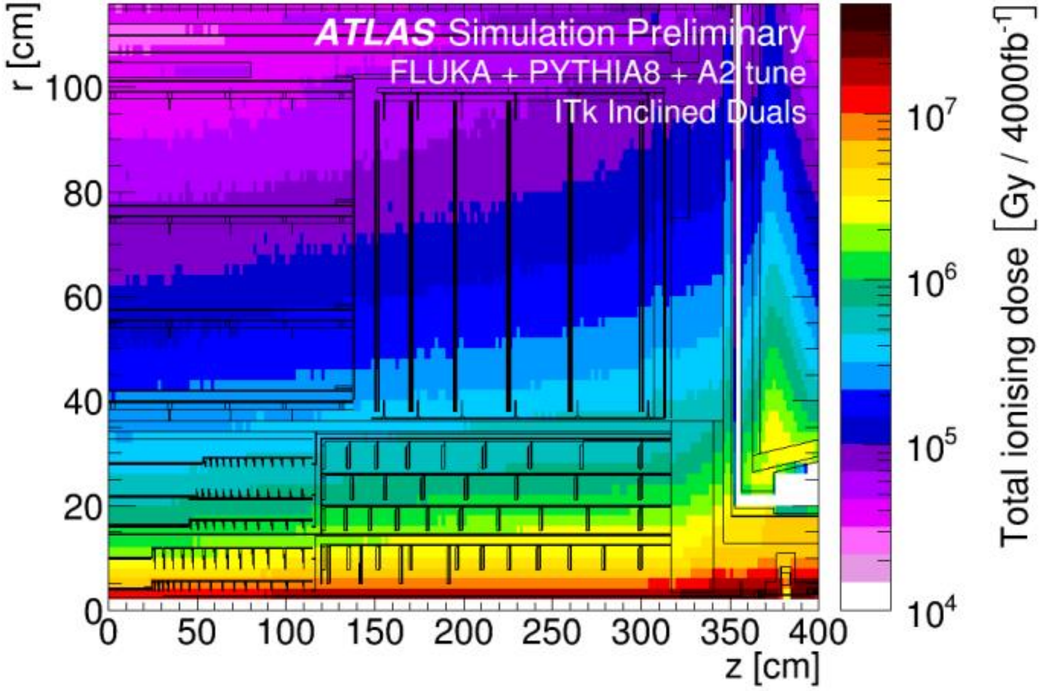
Radiation levels in the ATLAS detector

Cylindrical shape around the Interaction Point where the collisions take place → highest radiation levels in the inner layers (silicon detectors for particle tracking).

Up to **10 MGy** and **10^{16} $n_{1MeV\text{-}eq}$/cm²** for HL-LHC (4000 fb^{-1} in 12 years).

Requires rad-hard electronics.





IR1 (ATLAS) and IR5 (CMS) Long Straight Sections (LSS)

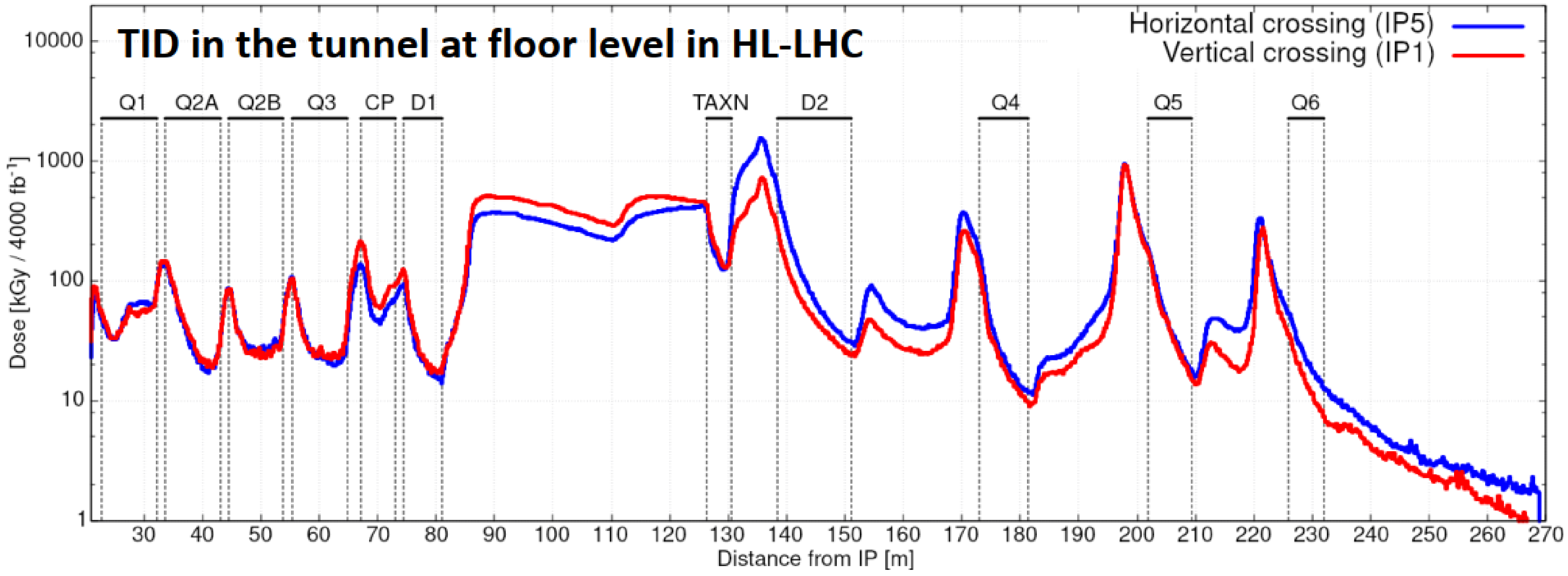
Collision products leak from the interaction region at the centre of the experiments into the LSS (and DS). The levels vary with the **distance from the IP** due to the interactions with different beamline elements.

Main message: the levels in the LSS are too high for COTS electronics.

For 4000 fb^{-1}:

- **TID: 1 kGy-1MGy.**
- **$n_{1MeV\text{-}eq}$ fluence: 10^{12}-10^{16} cm^{-2}.**
- **HEH fluence: 10^{12}-10^{15} cm^{-2}.**

Total HL-LHC dose 80cm below the beam in the LSS of IP1 and IP5

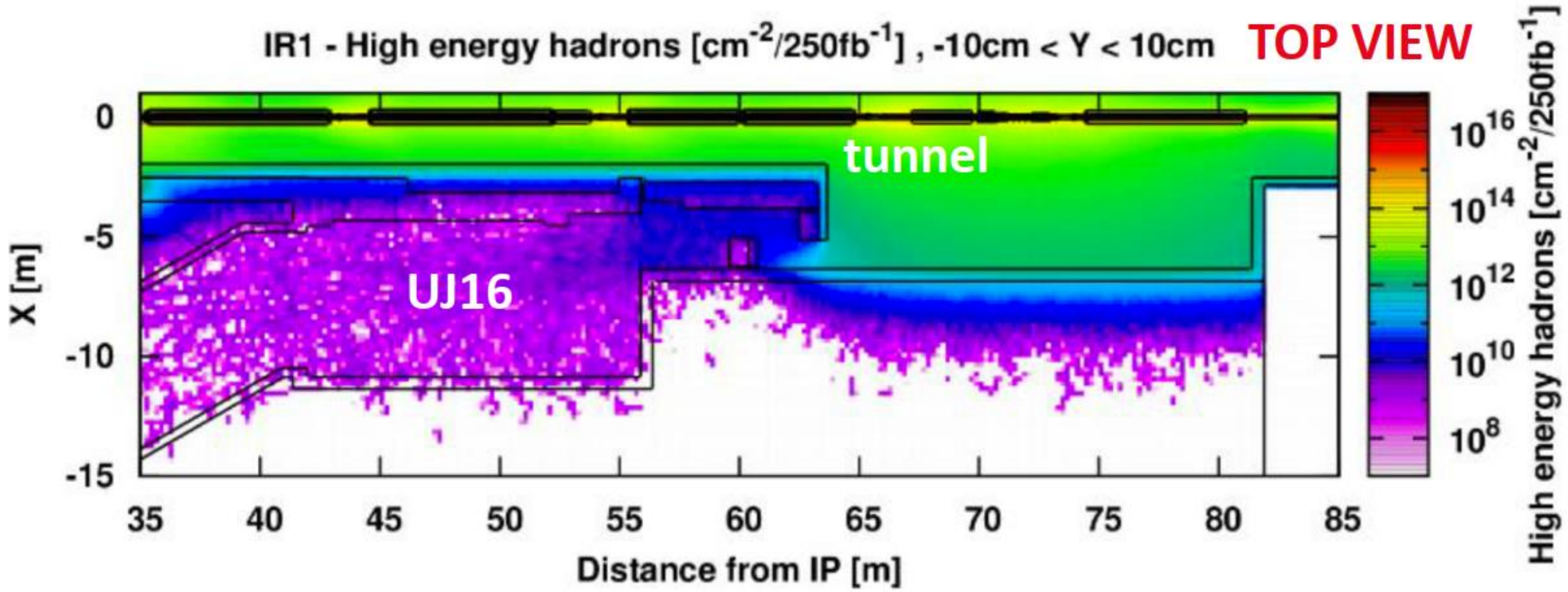


Radiation levels in the UJ

A lot of electronics relocated away from the UJs (and e.g. into the ULs) during Run 1 and LS1

UJ16: heavily shielded area (2m of concrete and cast iron, maze-shaped entrance) close to ATLAS (IR1). It hosts **active electronics** → we focus on **HEH fluence for SEE risks.**

Heavy shielding → HEH fluence from ≈10^{13} cm^{-2}/y in the tunnel to ≈10^{9} cm^{-2}/y in the UJ.



Other quantities:

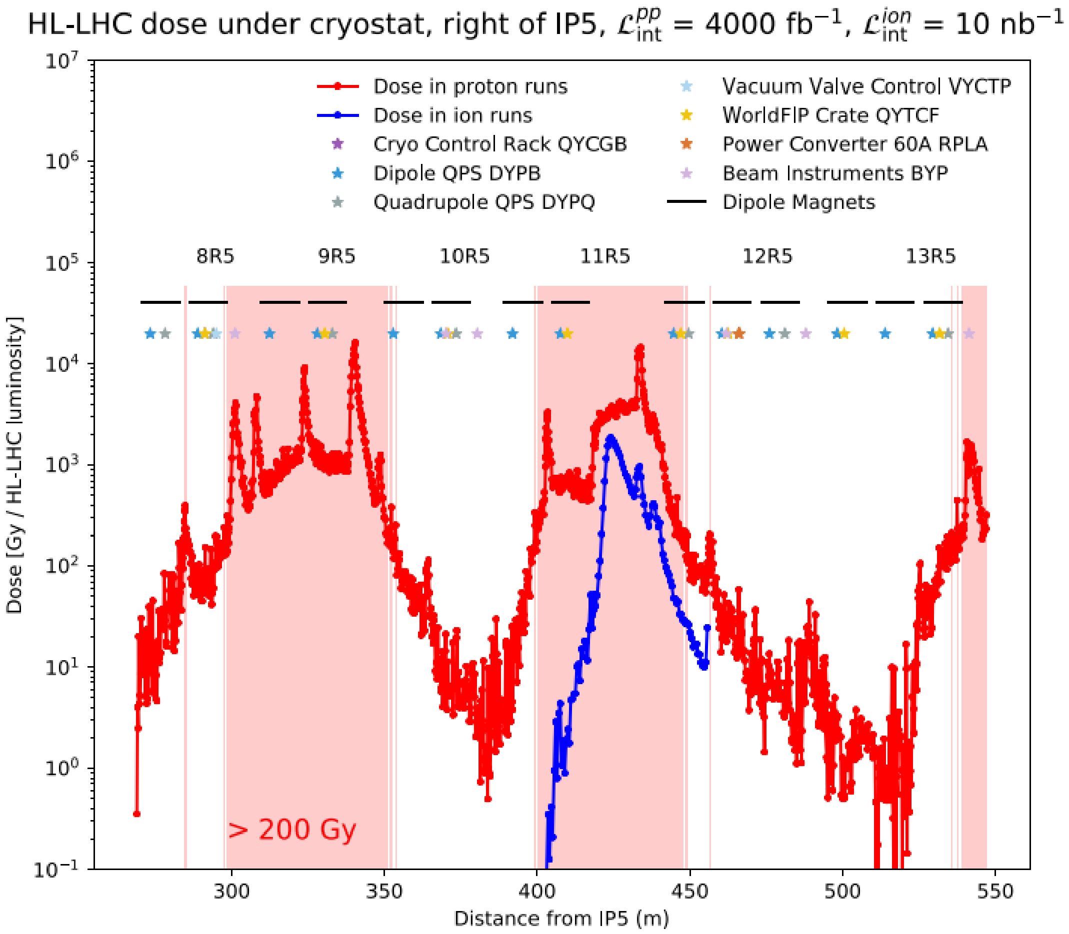
- **TID ≈1 Gy/y**
- **thermal neutrons >10^{10} cm^{-2}/y, R-factor ≈ 50**

IR1 and IR5 Dispersion Suppressor (DS): TID

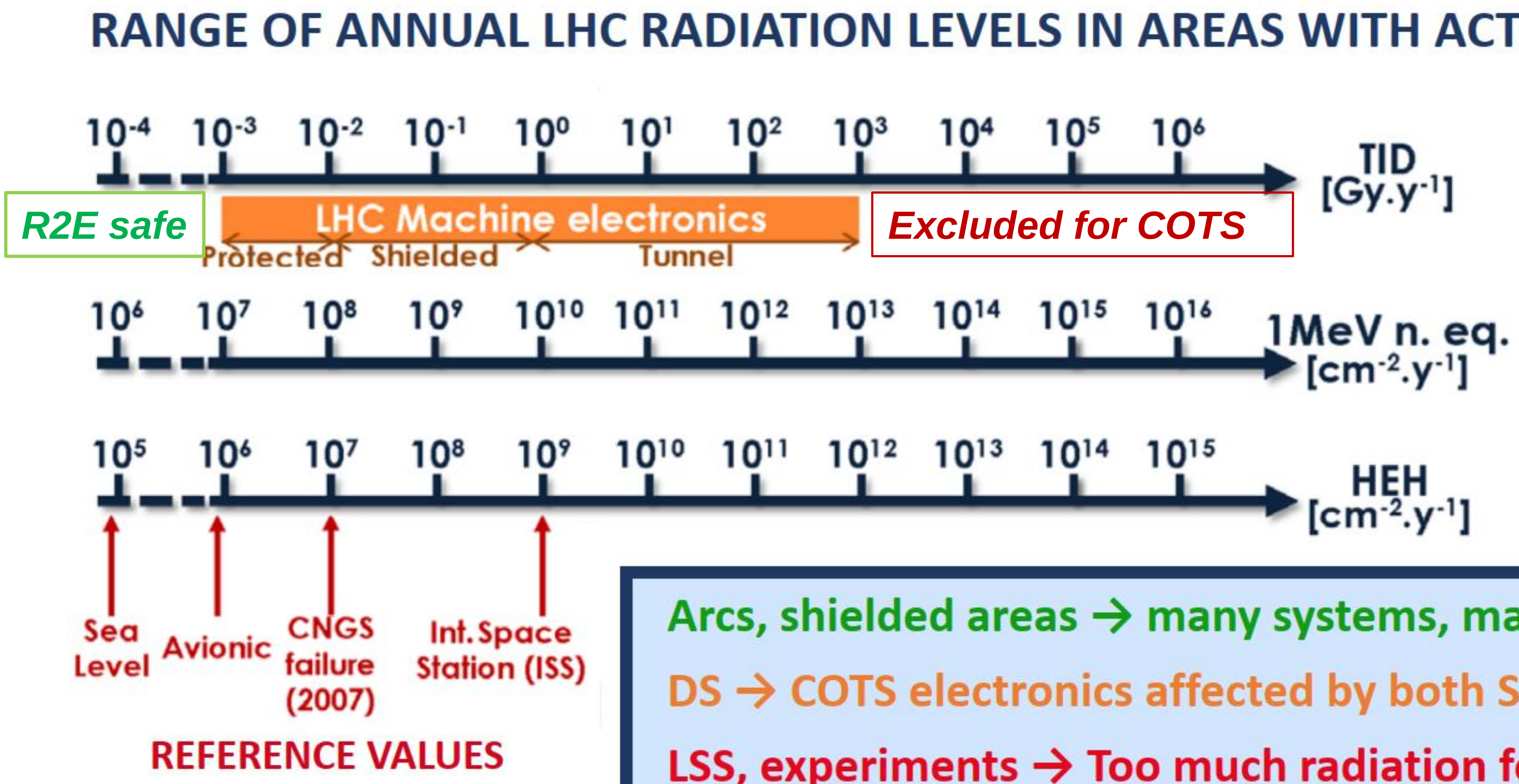
Scattered protons from the IPs can reach the **DS.**

HL-LHC FLUKA TID below the beamline for **proton operation (4000 fb^{-1})** and **ion operation (10 nb^{-1})**:

- TID in the **10Gy - 10kGy** range (peaks in cells 9-11): less than in the LSS but still significant.
- ion TID peak caused by the **Bound Free Pair Production (BFPP)** process: high radiation levels cumulated locally (cell 11) in short runs.
- Typical qualification limit for electronic racks: **200 Gy**. Dedicated strategies where these levels are exceeded.



Summary of radiation levels at the LHC



Remember than the exact levels are strongly dependent on the position and on operational machine parameters

Arcs, shielded areas → many systems, mainly affected by SEEs.

DS → COTS electronics affected by both SEE and TID issues.

LSS, experiments → Too much radiation for COTS electronics.

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COTS vs rad-hard ASIC

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)
- Plus, radiation tolerance for space-grade, rad-hard parts, might not be sufficient (and will anyway require testing)

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

5 USD

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

600 EUR

COTS may be cheap, but testing them is expensive

- 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.**

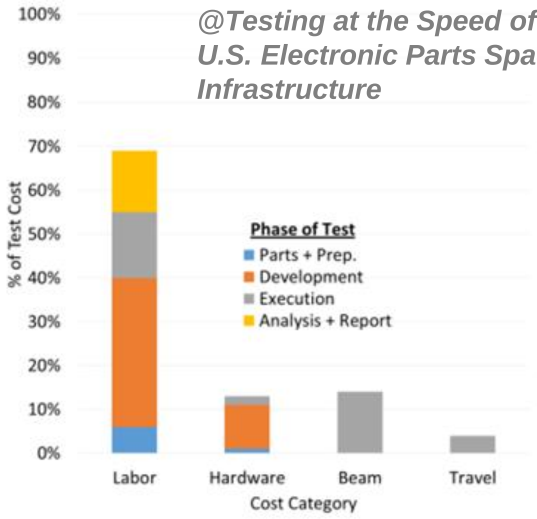
BOX 3.2 Continued

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.

Radiation test service @ BE-CEM-EPR

Request collection

The requests for radiation testing are collected and processed selecting the most suitable methodology and facilities

Test planning and structure

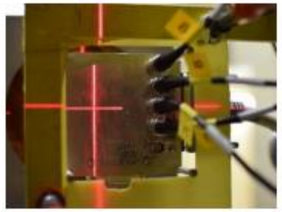
Each component/system is analyzed, and all the possible radiation effects are taken into account for planning the test and structure it

Board and instrumentation preparation

For each component a dedicated set of test board is prepared and the associated instrumentation is chosen to face the complexity of the radiation test

Testing

The test are carried out at CERN facilities such as CHARM or Co60 and in external facilities. The transport, personnel and instrumentation are selected considering the peculiar aspect of each facility



Result analysis

The results are analyzed during and after the tests for each component considering the end application and the possible operational issues

Database and Publication

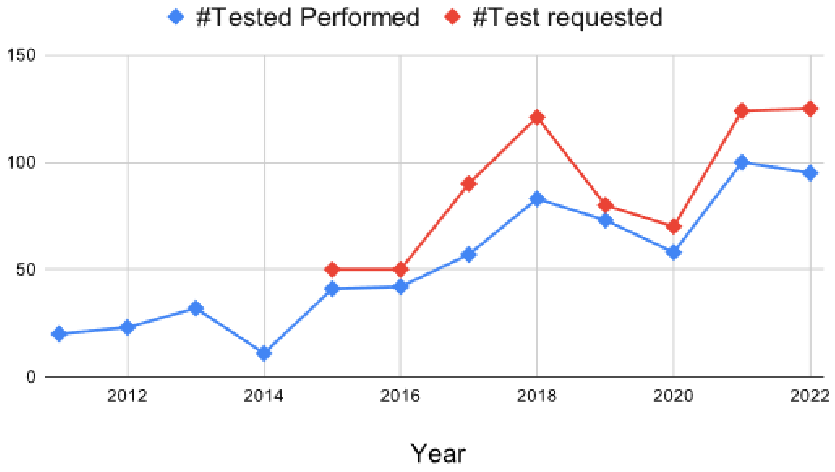
The results are collected, stored and in EDMS and published in the RADWG database to allow an easy research of the best candidates for the new radiation tolerant des

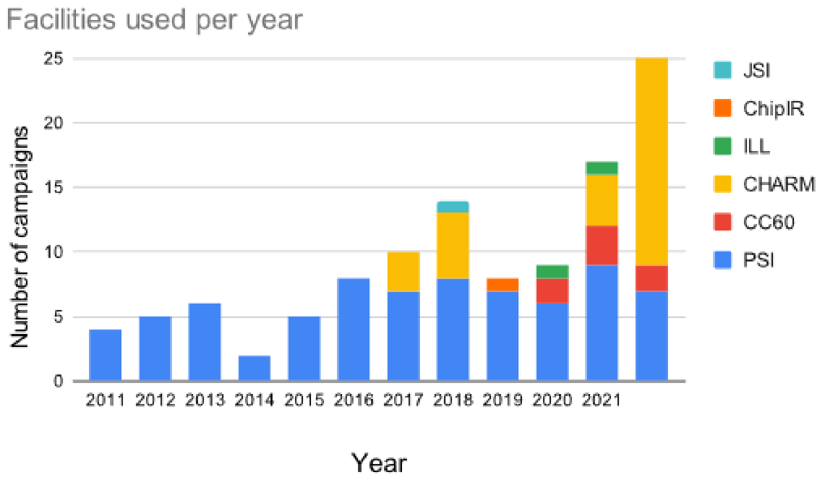
01 02 03 04 05 06

Radiation test service @ BE-CEM-EPR

2022 In Numbers

- 100 components tested
- 55 component requests pending for next year
- 25 Radiation campaigns done (7*PSI, 16*CHARM, 2*CC60)





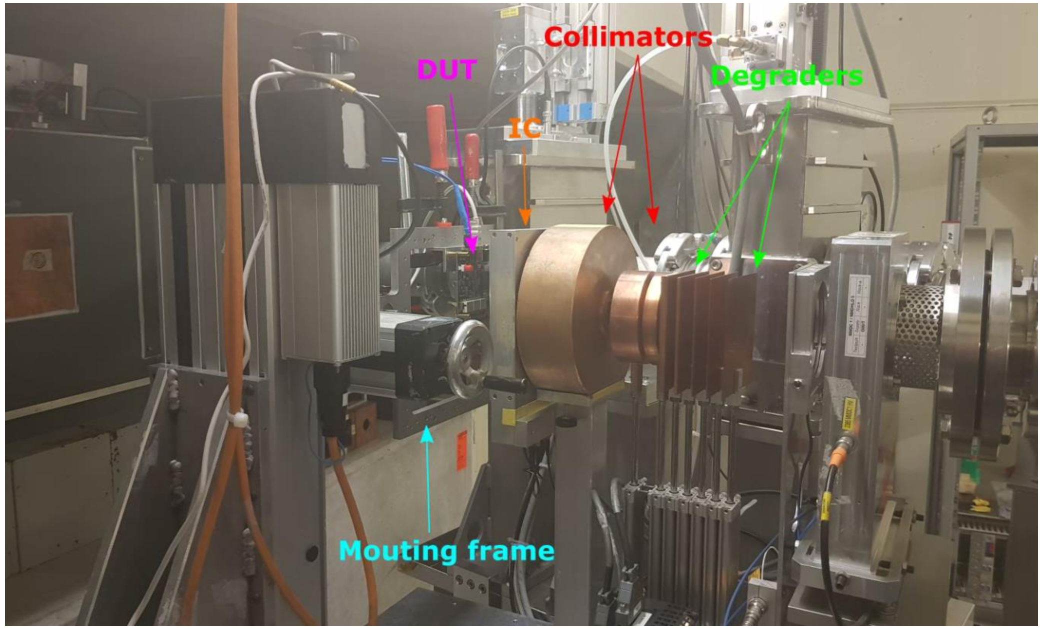
Many different type of components tested, across multiple CERN ATS groups

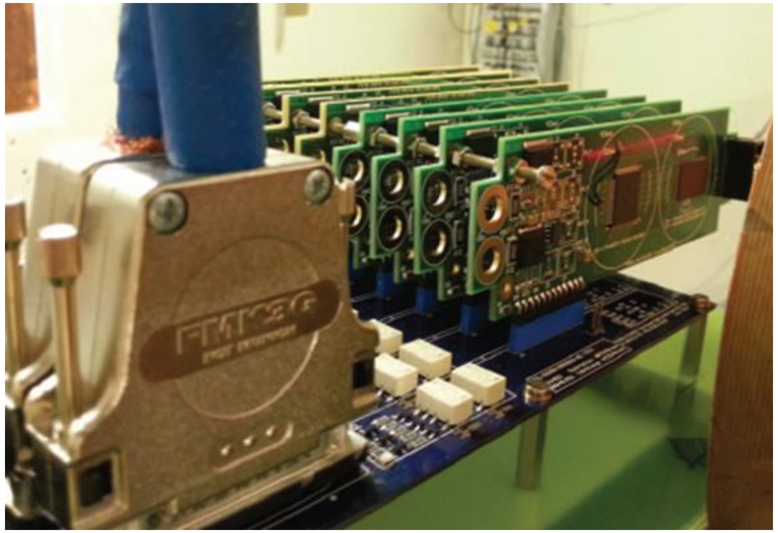
Importance of component level testing

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



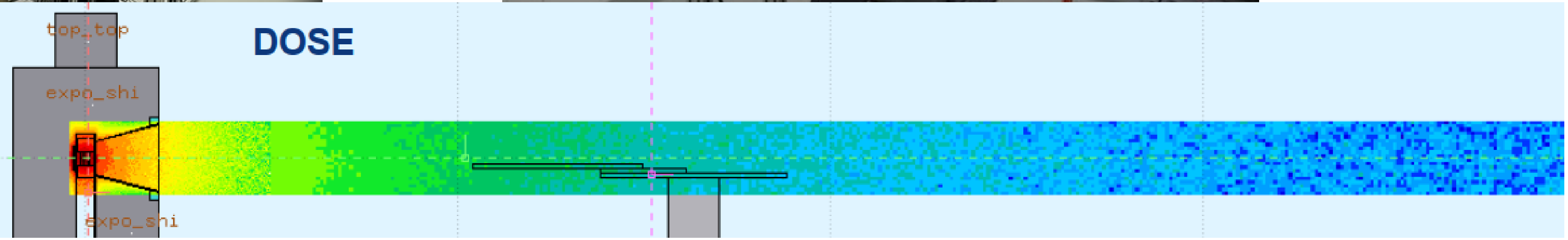


PAUL SCHERRER INSTITUT

TID testing: Cobalt-60 radioactive sources

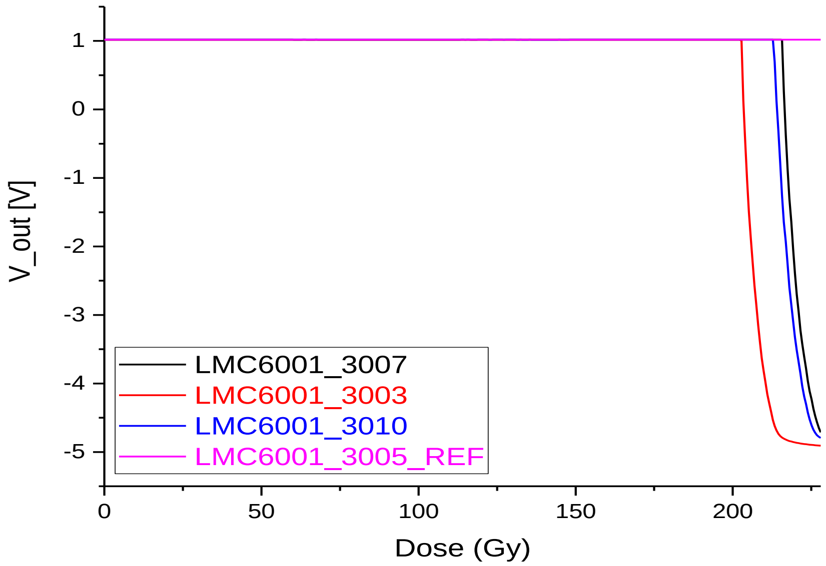
(alternative: x-ray TID testing)

CC60 facility at CERN

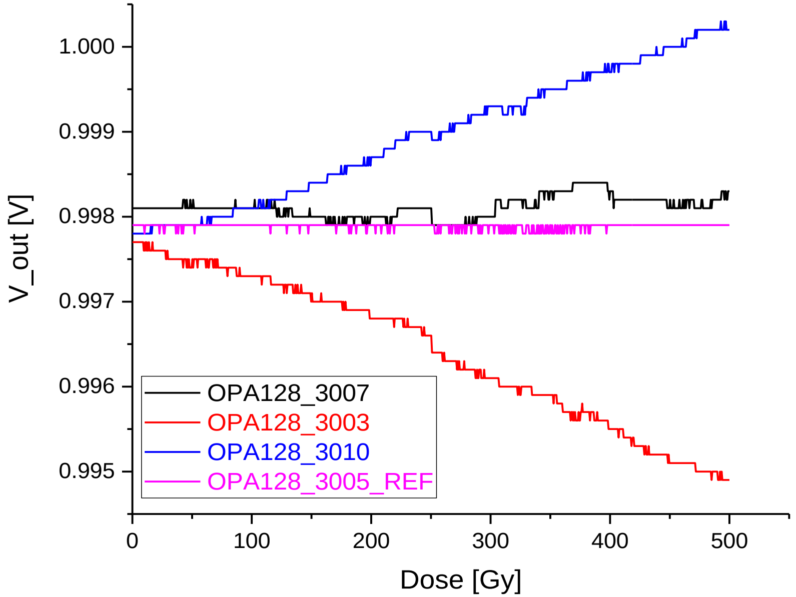


Total Ionizing Dose Effects – Integrated Circuit level

REJECTED



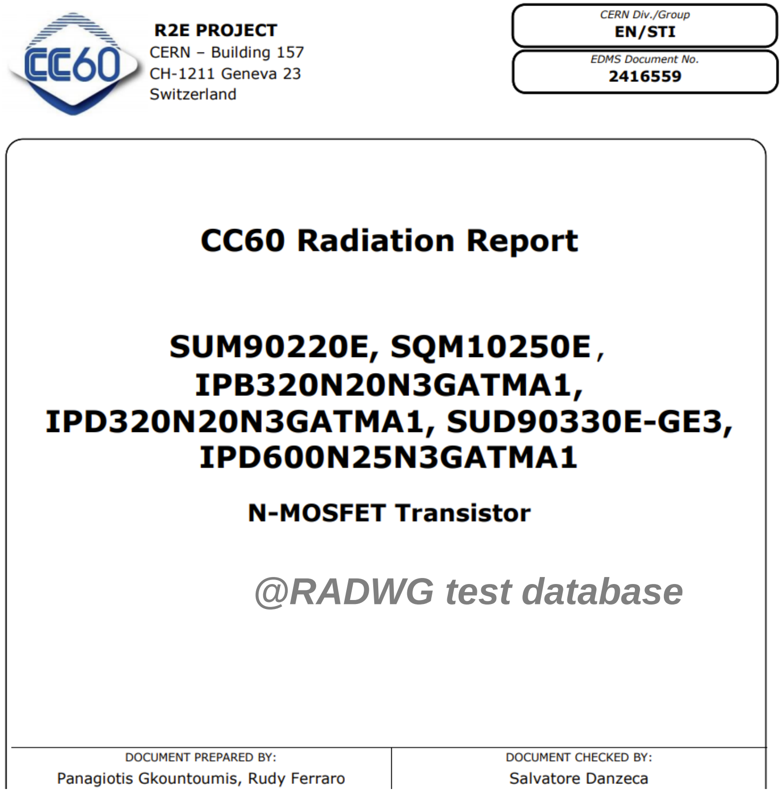
ACCEPTED



Example of competitive ultra-low bias current amplifiers for measuring ion current of Penning design

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

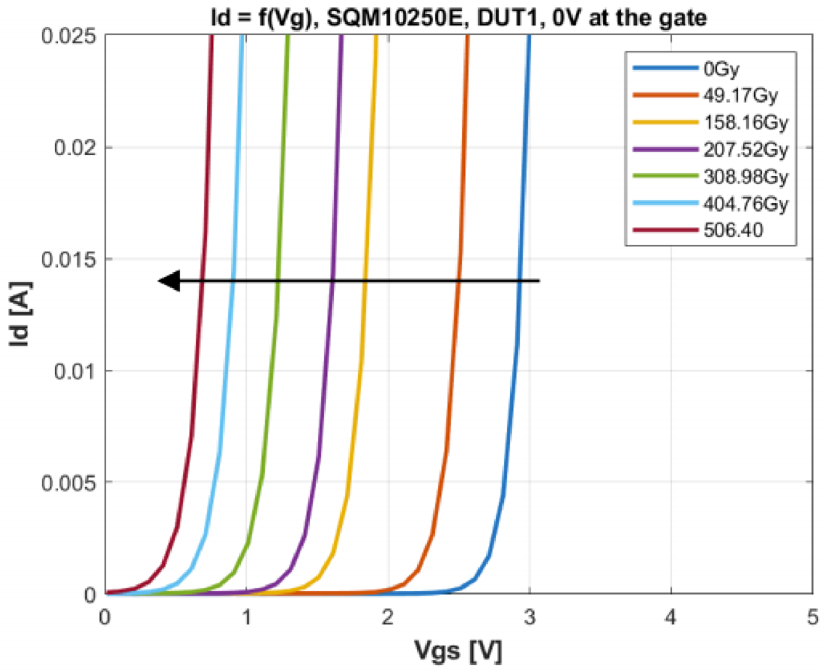
CC60 Radiation Report

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

N-MOSFET Transistor

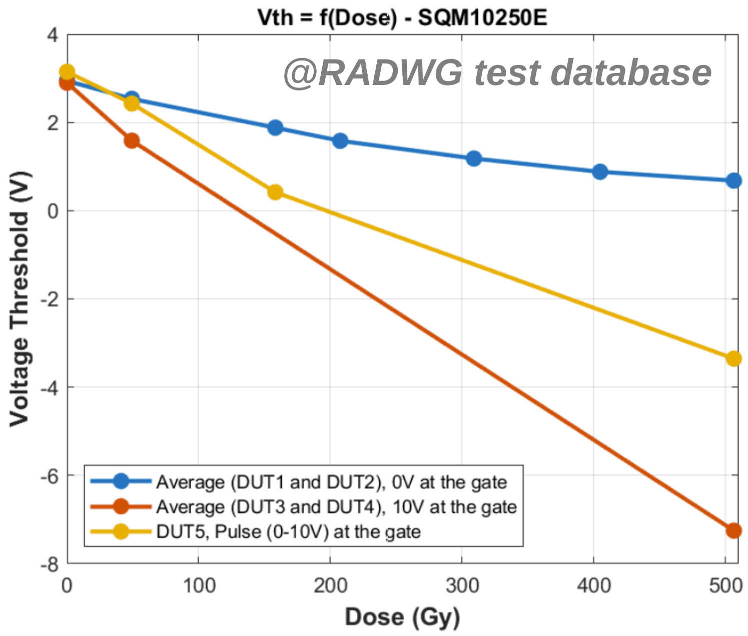
@RADWG test database

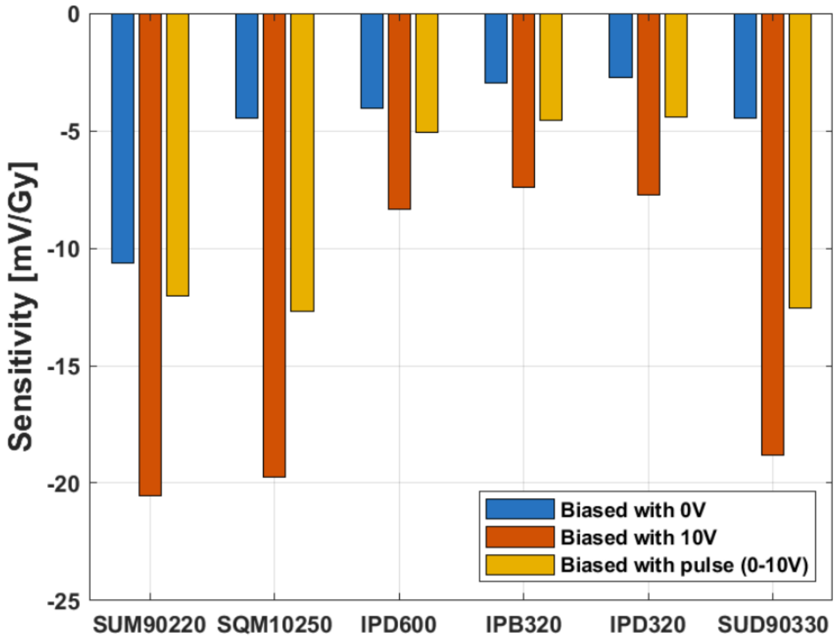
DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:
Panagiotis Gkountoumis, Rudy Ferraro	Salvatore Danzeca



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

Importance of component level testing

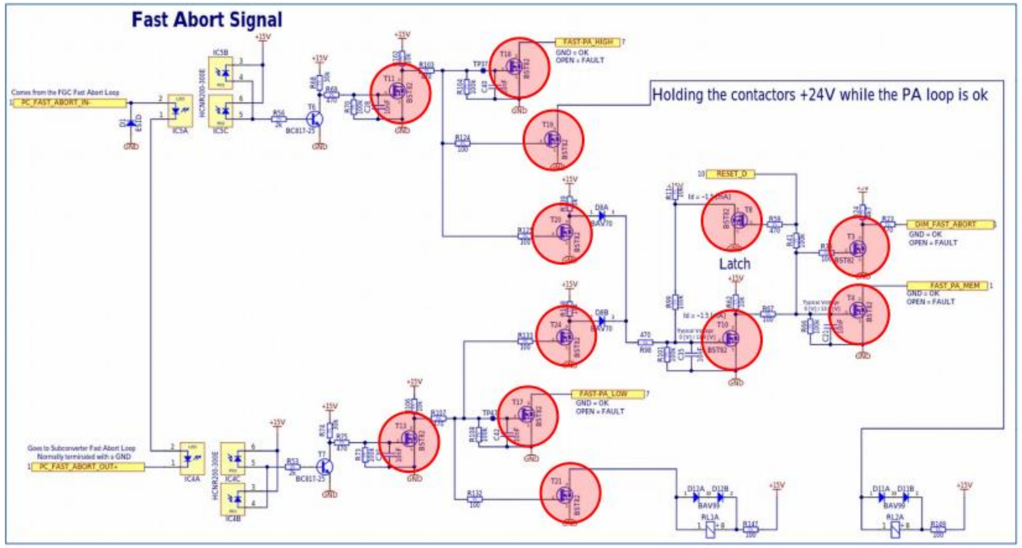




- Very different response from different power MOSFETs with similar electrical characteristics (i.e. all candidates for same development)
- Importance of screening component level effects of critical components before moving on to system level validation

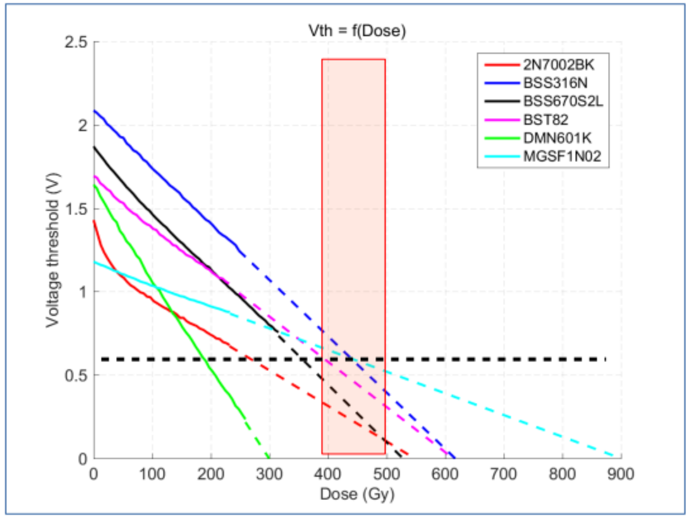
High component occurrence in 500 Gy radiation tolerant power converter design

Case of Very High Occurrence in the design = Low Power Mosfet



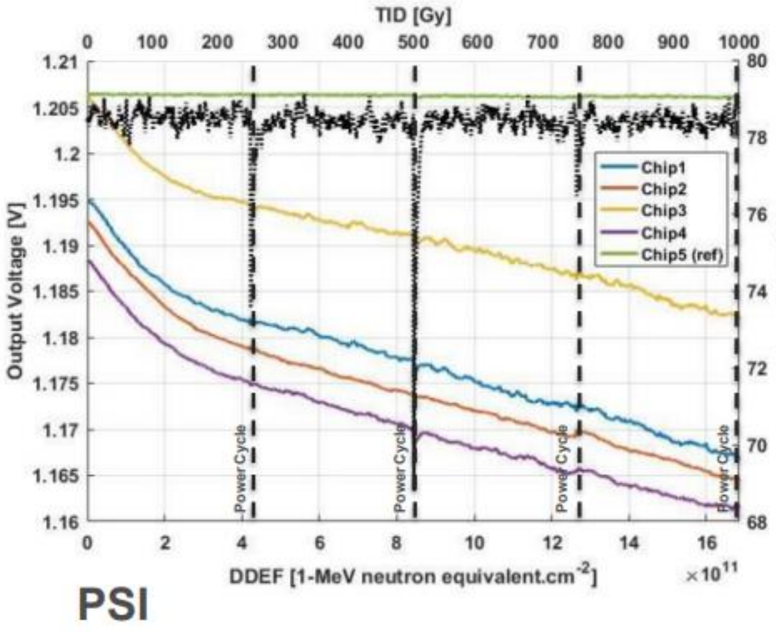
Case of Very High Occurrence in the design = Low Power Mosfet

- VGS threshold starts to be critical above 400 Gy | Robust candidate needed.



Voltage regulator qualification issue

- **Difference of behaviour between PSI and CHARM:** Start-up circuit failure at CHARM



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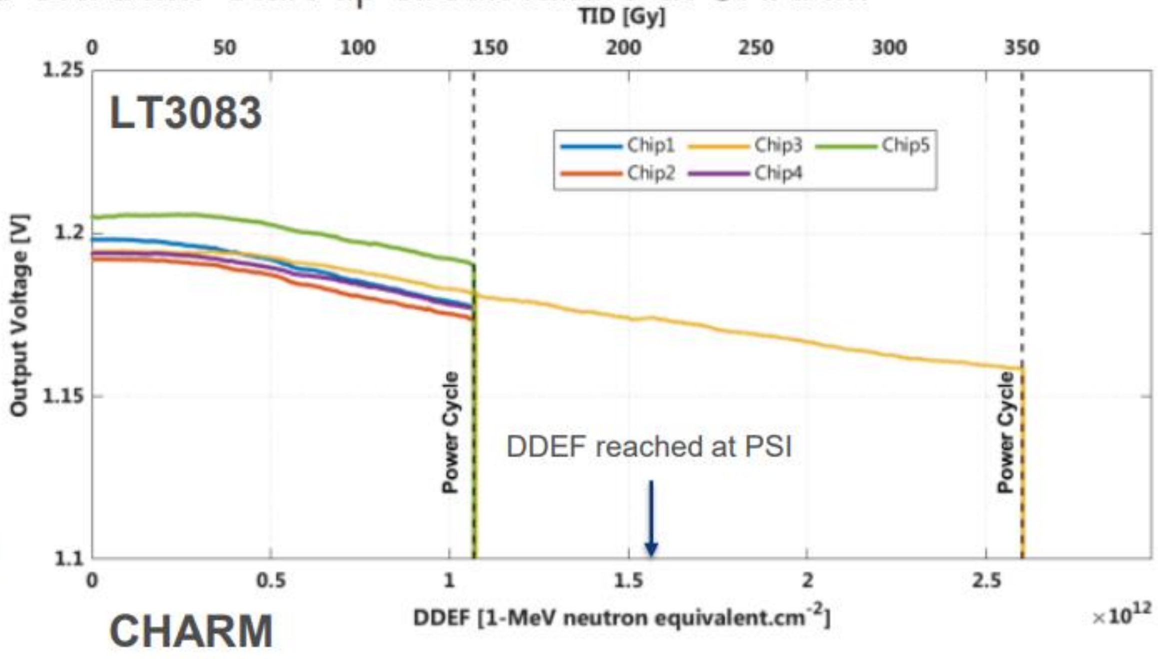


2734998

- Such differences where also observed with other bipolar components (like opamps) that was sometimes failing at a quarter of the dose/DDEF reached at PSI

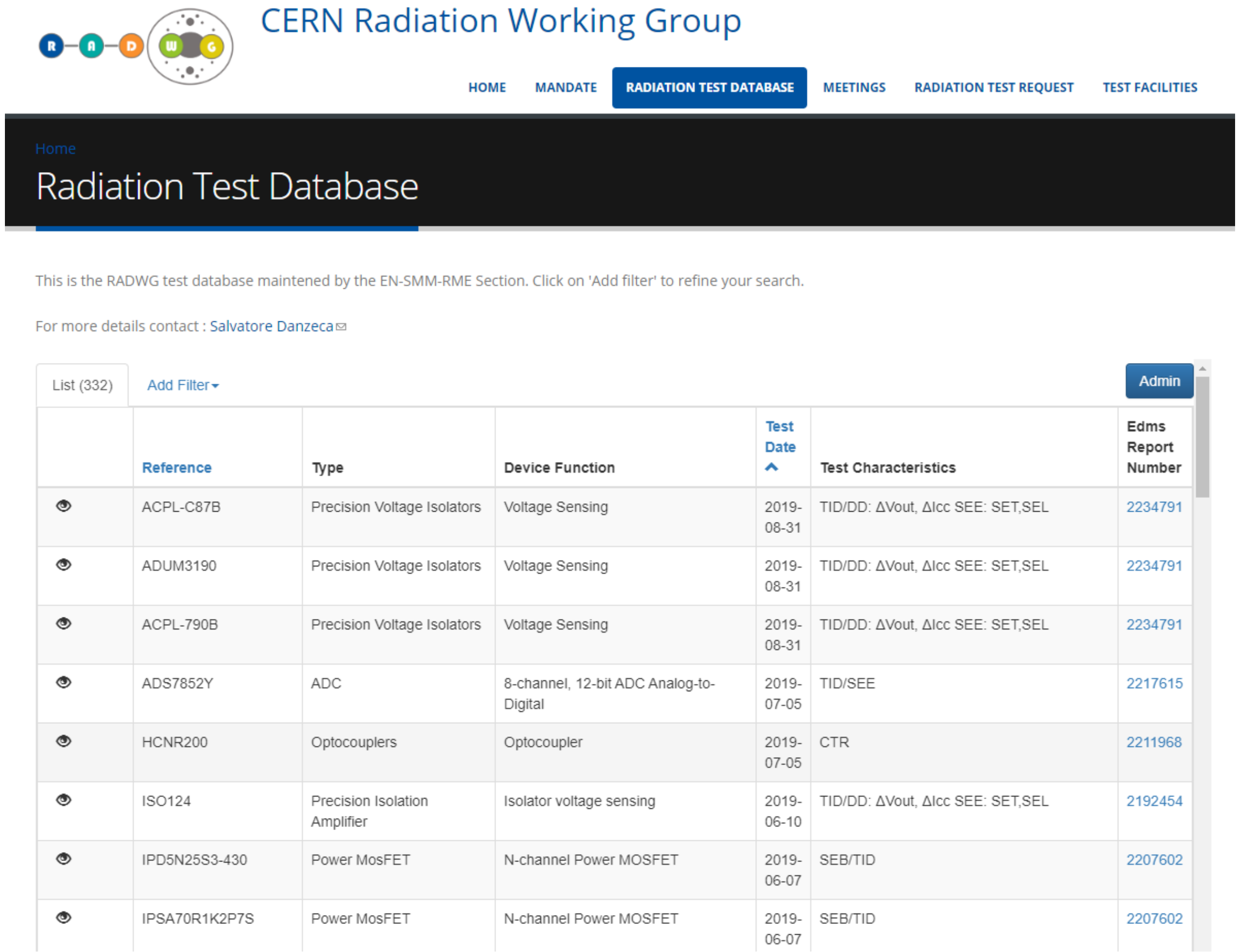
Discrepancy likely due to combined TID/TNID effects; very different ratios (by factor ~5) at PSI and CHARM
Affecting many of the currently ongoing R2E developments; specific and general mitigation measures applied

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

Still, batch qualification of newly procured lots is typically required! (as shown in an example later)



CERN Radiation Working Group

HOME | MANDATE | RADIATION TEST DATABASE | MEETINGS | RADIATION TEST REQUEST | TEST FACILITIES

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

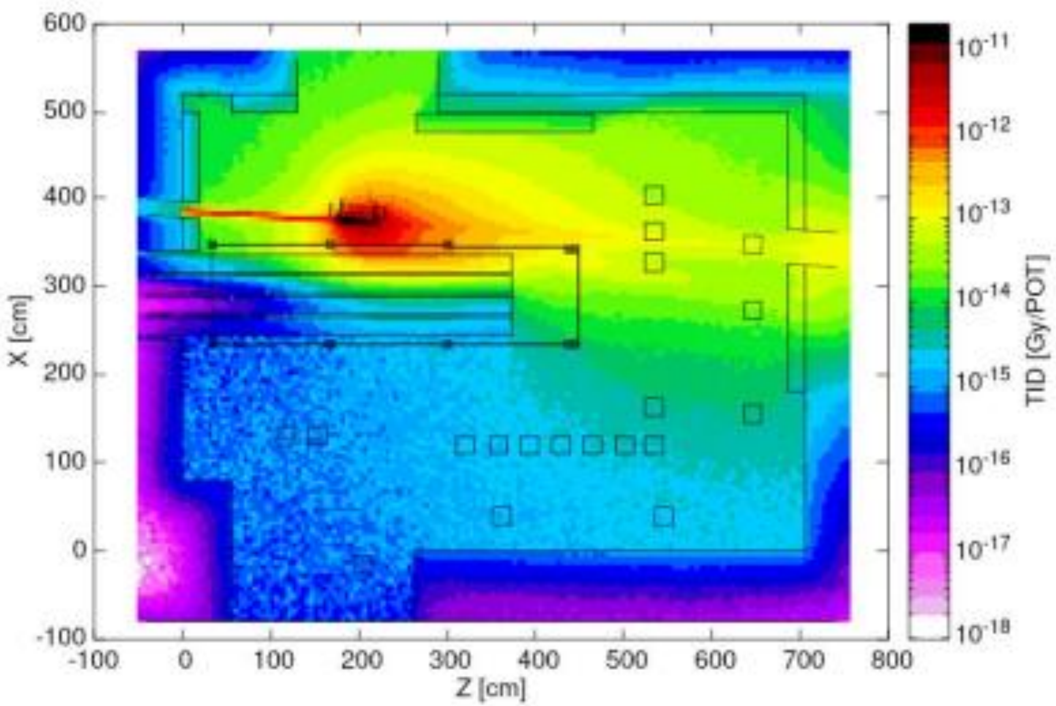
http://radwg.web.cern.ch/content/radiation-test-database

Outlook

- **Why R2E? Radiation exposed electronics + impact on availability**
- **Radiation Hardness Assurance for LHC electronics**
  - Radiation Environment
  - Component Level Testing
  - System Level Testing (as final RHA validation)

Importance of CHARM for system level testing(*)

(*) As final Radiation Hardness Assurance step, after radiation levels and tolerance requirement definition, architecture selection (including radiation effects mitigation solutions), component selection (based mainly on device level radiation effects testing), etc.

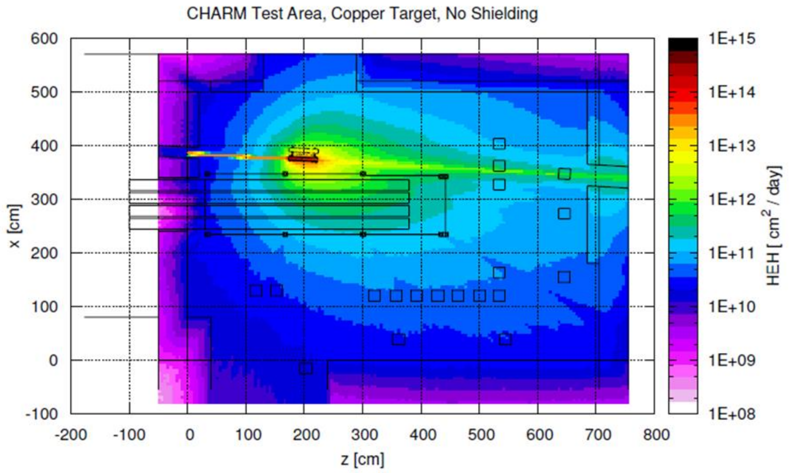


System level testing in CHARM

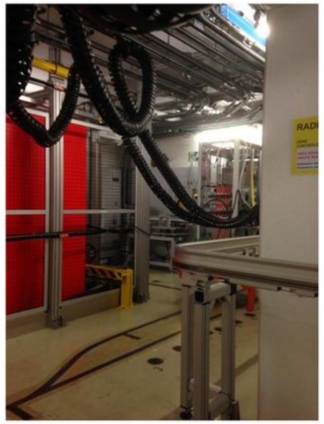
System level testing at CHARM:

- 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 1.5·10^{16} protons on target): 350 Gy, 2.5·10^{12} n_{eq}/cm^2, 7.5 ·10^{11} HEH/cm^2

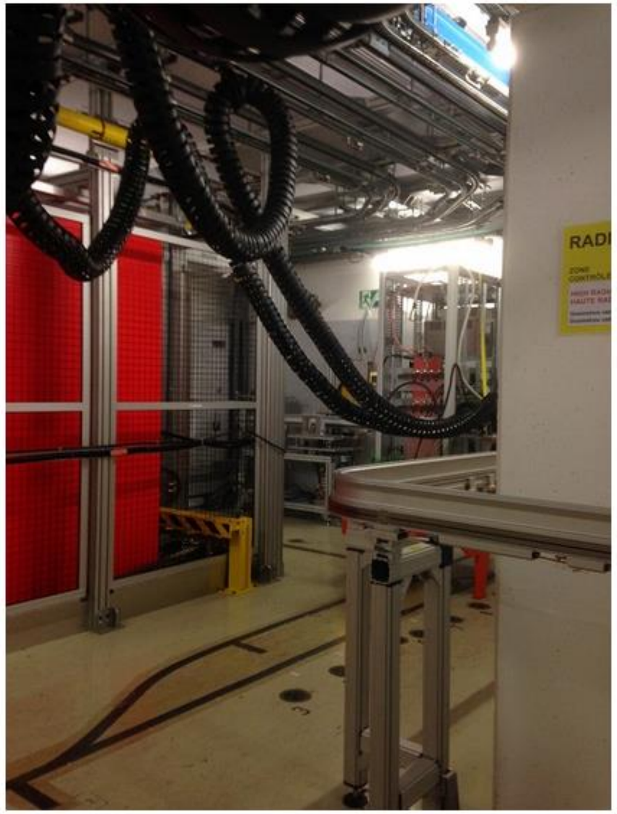


Mimicking the hadron accelerator environment in CHARM



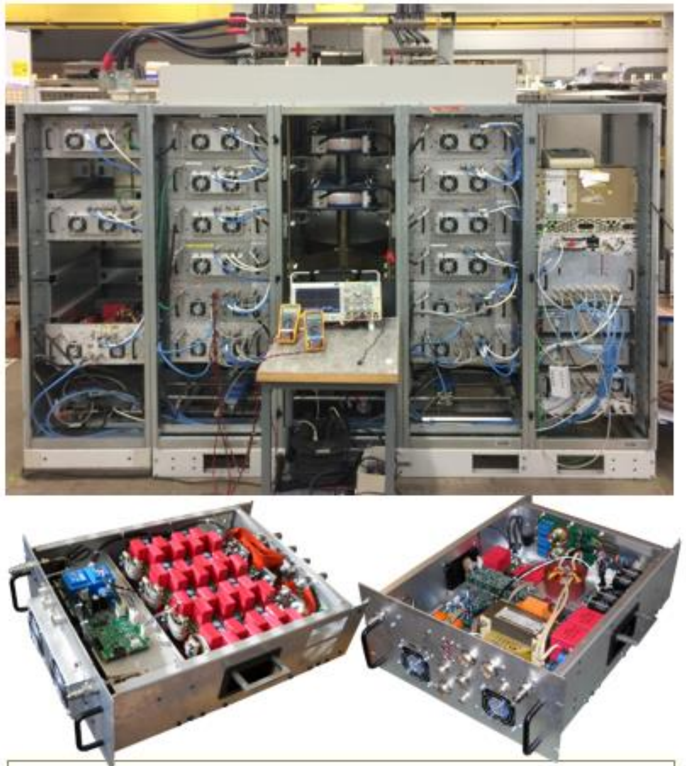
Power converters: 600A and 4-6-8 kA

System level testing



@Yves Thurel, Vicente Raul Herrero, Julien Chanois

Radiation tolerant RR power converters (LS2)



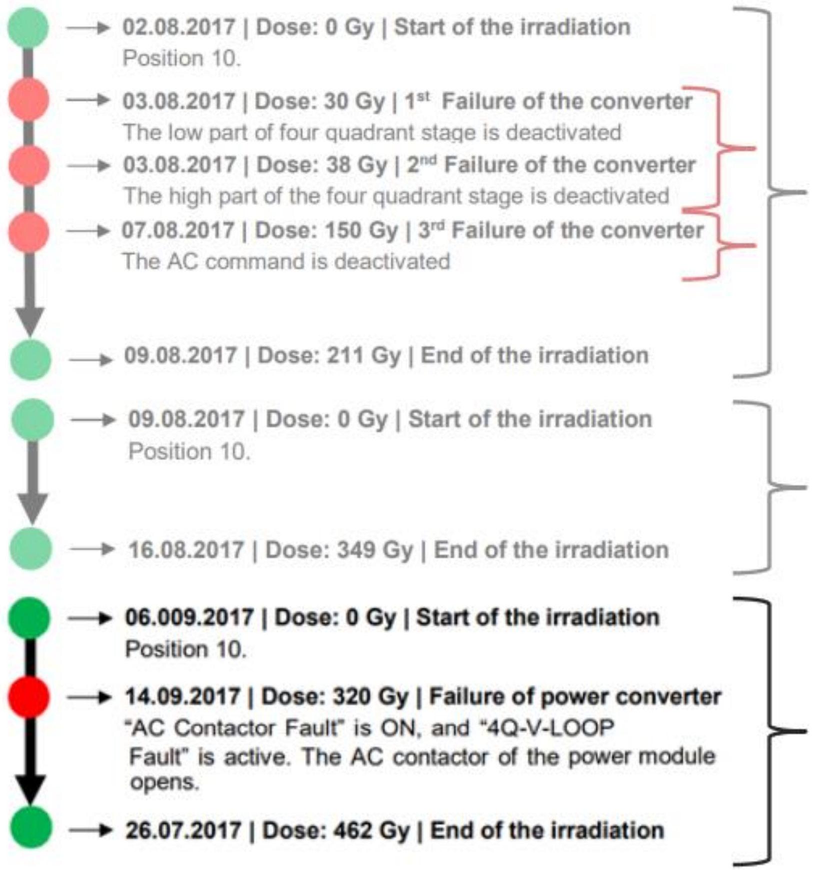
[8kA-8V] – 1 quadrant
60 units

[600A-10V] – 4 quadrant
120 units

TID ~ 300 Gy; TNID ~ 3×10^{12} n/cm^{2}; SEE < 10^{-12} cm^{2}

No radiation induced failures during 2022 LHC operation

R2E power converters: importance of radiation tolerance validation at system level



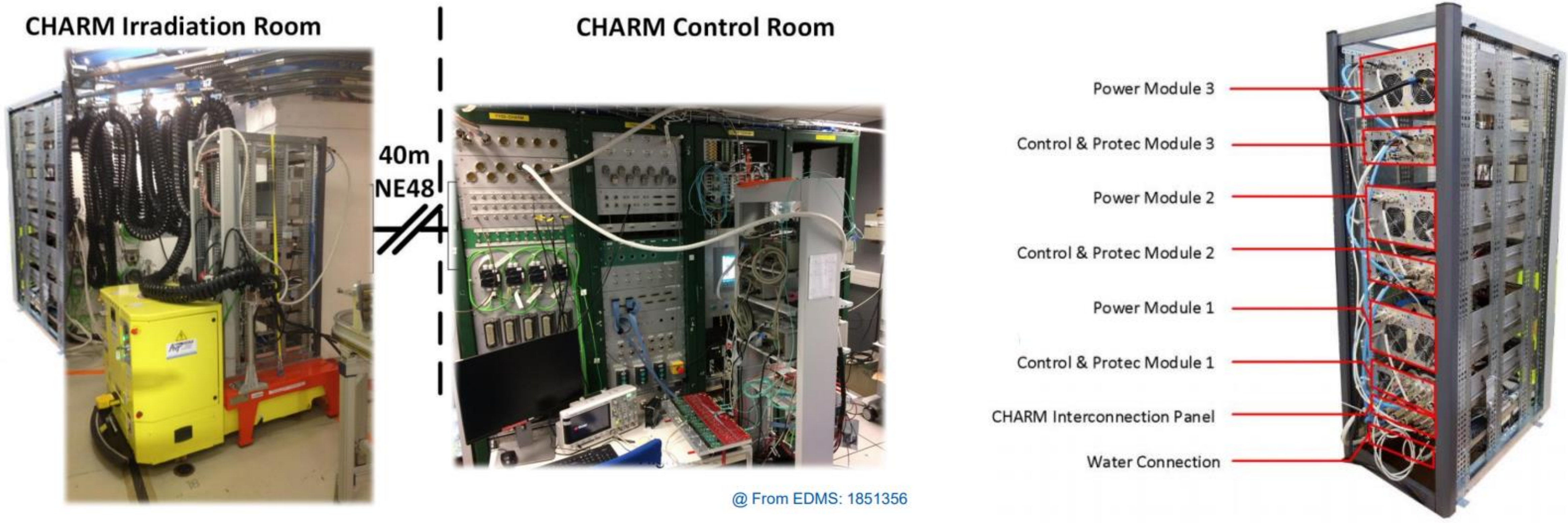
RUN1: Failed (1 system tested)
- Premature failure of the system
- **Post-irradiation analysis revealed two failure modes:**
  1) **An underestimated TID-DD circuit effect (~ 35 Gy)**
  2) **High current leakage of an analog switch (~150 Gy)**
- Circuits re-designed to increase their tolerance to degradation.

RUN2: Success (1 system tested)
- No permanent system failure observed up to 350 Gy.
- **Systems overpassed largely the target.**

RUN3: Success (2 systems tested)
- **Systems suffered from the failure mode (1) but at 320 Gy and 420 Gy instead of ~35 Gy**

@ From EDMS: 1851356

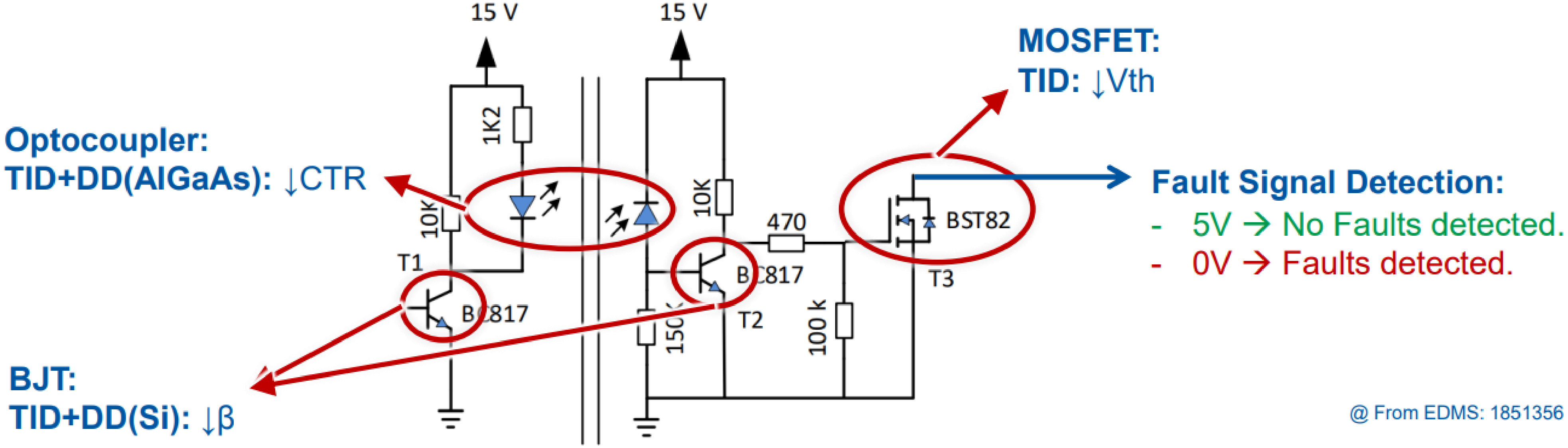
R2E power converters: importance of radiation tolerance validation at system level



R2E power converters: importance of radiation tolerance validation at system level

Failure Mode: Fault detection circuit signal blocked to 0V (Fault detected)

Failure Cause: Impossible to drive the circuit output ON due to the combined degradation of the input/output BJTs, the optocoupler and the output MOSFET.

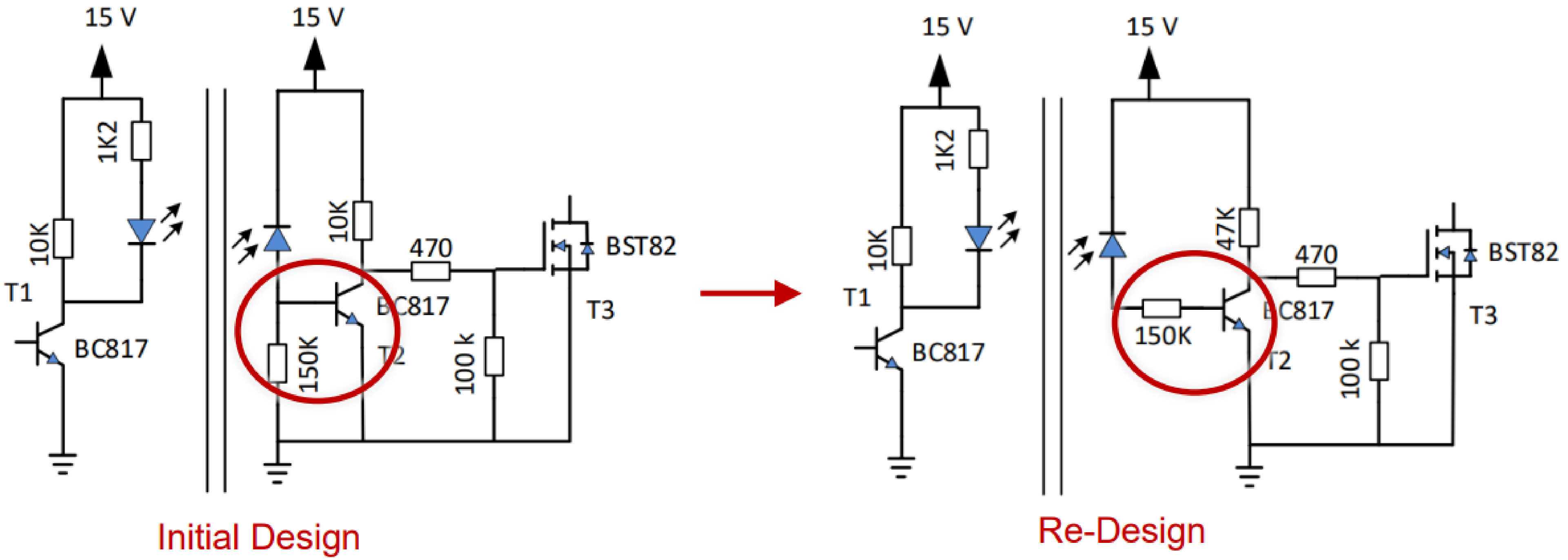


@ From EDMS: 1851356

➢ **Clear example of the need to have representative TID/DD ratio and DD spectra (for AlGaAs)**

R2E power converters: importance of radiation tolerance validation at system level

Solution: Modify the circuit to increase the current going to the base of the output bipolar transistor T2
→ Lower current from the optocoupler required to drive the transistor ON



@ From EDMS: 1851356

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB013

RADIATION TO ELECTRONICS IMPACT ON CERN LHC OPERATION: RUN 2 OVERVIEW AND HL-LHC OUTLOOK

Y. Q. Aguiar, G. Lerner, R. García Alía, D. Prelipcean, A. Apollonio, F. Cerutti,
S. Danzeca, M. Sabaté Gilarte
CERN, CH-1211, Geneva 23, Switzerland

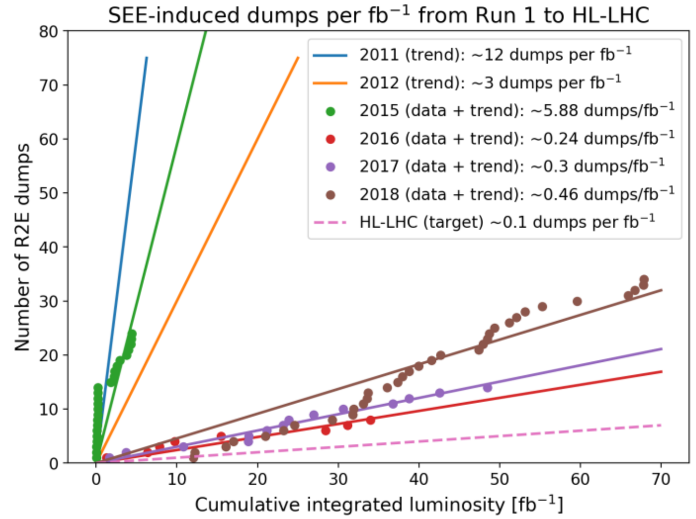
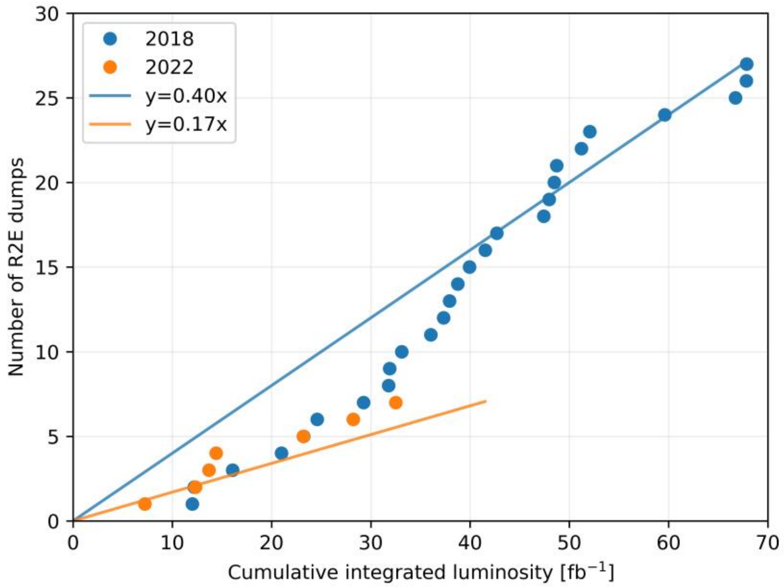


Figure 1: Number of LHC beam dumps induced by R2E failures as a function of the cumulative integrated luminosity in 2011-2012 (Run 1, trend only), 2015-2018 (Run 2, data and trend) and HL-LHC (target).

Table 1: Number of radiation to electronics faults by system and the annual integrated luminosity (fb^{-1}) delivered to the ATLAS experiment during the LHC Run 2 (2015-2018)

System	**2015** 4 fb^{-1}	**2016** 40 fb^{-1}	**2017** 50 fb^{-1}	**2018** 65 fb^{-1}	**Total R2E**
PC	5	7	10	13	35
QPS	15	0	0	13	28
MC	0	0	3	7	10
RF	4	0	0	0	4
Others	0	1	1	1	3
Total	24	8	14	34	80



Improvement in 2022 versus 2018 mainly due to: (a) reduced Point 1 & 5 DS levels and (b) ***R2E power converters in RRs***

R2E power converters: importance of radiation tolerance validation at system level

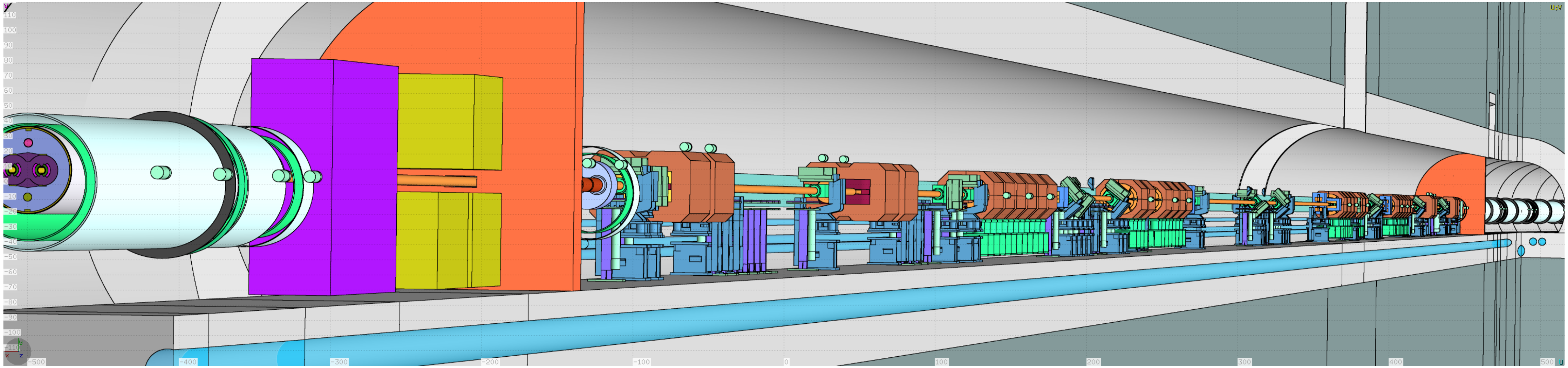
Nothing beats a CHARM test!!

Main take-aways of LHC radiation tolerant electronics design

Simplified overview of key ingredients to a successful operation of critical electronics in radiation areas:

- detailed knowledge of **radiation environment** (measurement, simulations) and its **effects** on electronics
- **in-house design of electronic systems**, with full control of bill-of-material (i.e. parts selection) and circuit/system architecture
- experienced **radiation testing service** and associated “preferred parts list”
- **in-house facility for system level radiation tolerance validation**

Many thanks for your attention!



Questions? Comments? Thoughts?

ruben.garcia.alia@cern.ch

home.cern

Outlook

- **Why R2E? Radiation exposed electronics + impact on availability**
- **Radiation Hardness Assurance for LHC electronics**
  - Radiation Environment
  - Component Level Testing
  - System Level Testing (as final RHA validation)
- **A few additional examples beyond LHC protons**
  - LHC ions
  - SPS
  - Medical Linacs
  - CLEAR
  - North Area ion beams

Localized ion losses: bound-free pair production

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 121003 (2020)

Bound-free pair production from nuclear collisions and the steady-state quench limit of the main dipole magnets of the CERN Large Hadron Collider

M. Schaumann,* J. M. Jowett, C. Bahamonde Castro, R. Bruce,
A. Lechner, and T. Mertens
CERN, 1211 Geneva 23, Switzerland

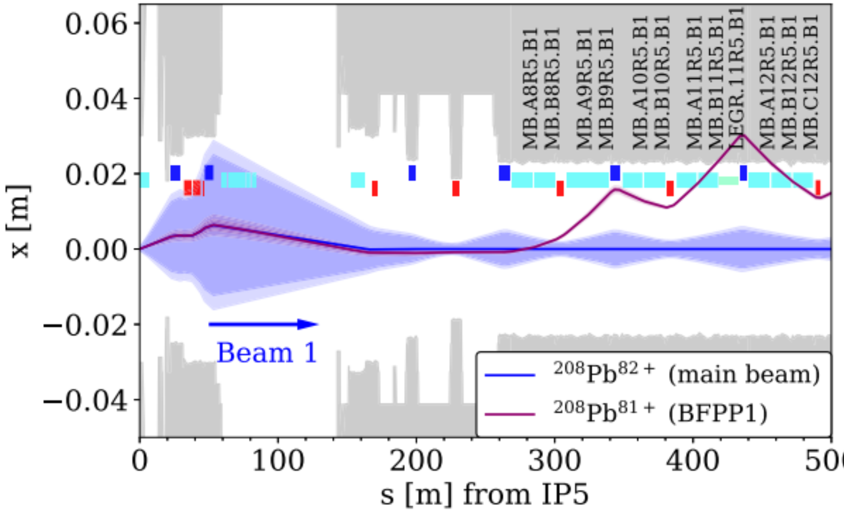
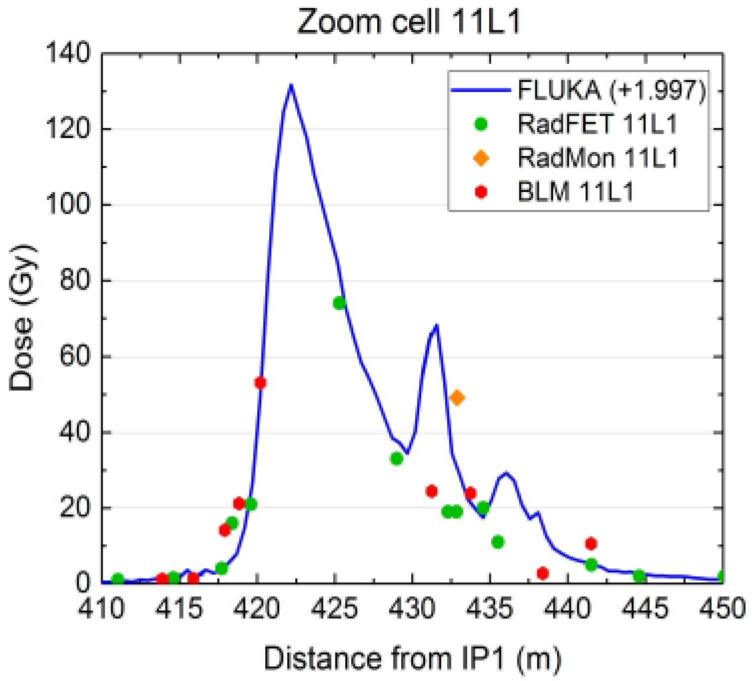


FIG. 1. Example of main $^{208}Pb^{82+}$ (blue, $10-12\sigma$) and BFPP1 $^{208}Pb^{81+}$ beam (red, $1-2\sigma$) envelopes, and aperture (grey) in the horizontal plane, Beam 1 direction right of IP5 (at $s=0$). Beam-line elements are indicated schematically as rectangles. Dipoles in light blue, quadrupoles in dark blue (focusing) and red (defocusing). While the main beam travels through the center of the beam-line elements in the dispersion suppressor (starting at about 250 m), the BFPP1 beam separates and impacts in the aperture of the second superconducting dipole magnet of cell 11.

CERN-ACC-NOTE-2018-073
23-11-2018
corinna.martinella@cern.ch

Radiation levels in the LHC during the 2015 Pb-Pb and 2016 p-Pb run and mitigation strategy for the electronic systems during HL-LHC operation

Corinna Martinella[1], Cristina Bahamonde Castro[2], Anton Lechner[2], Salvatore Danzeca[3], Yacine Kadi[1], Markus Brugger[1], Rubén Garcia Alia[2]



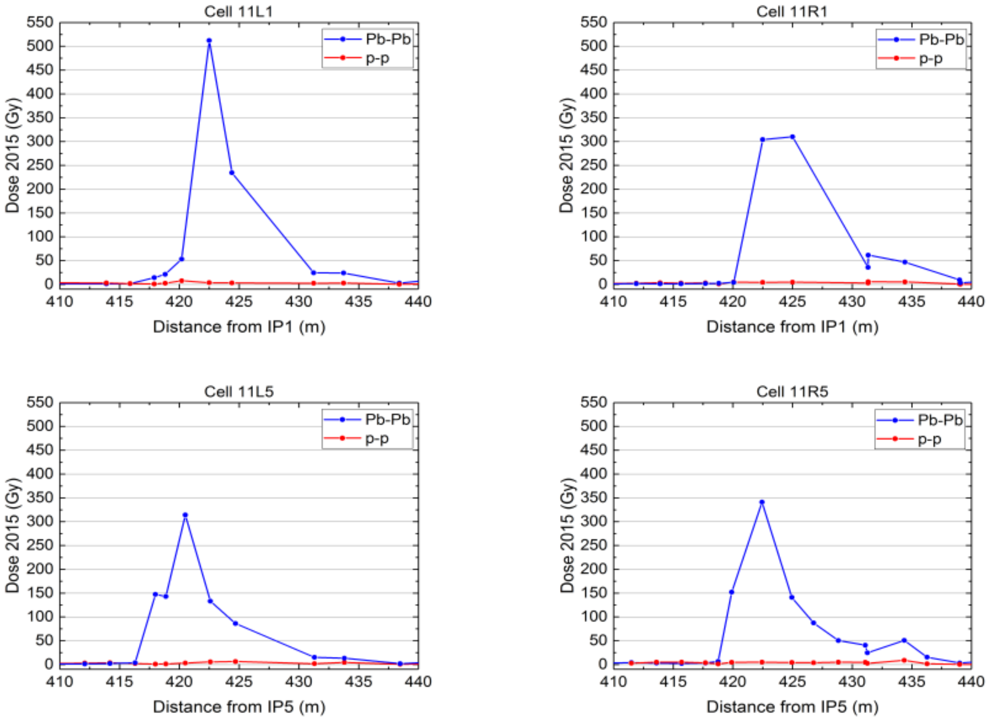
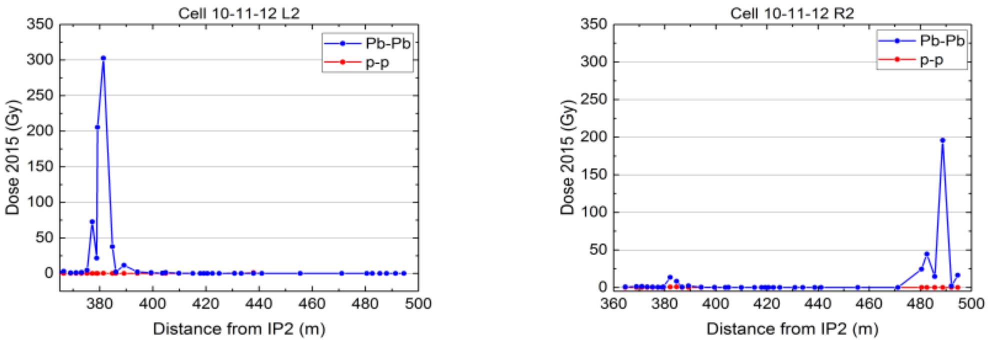
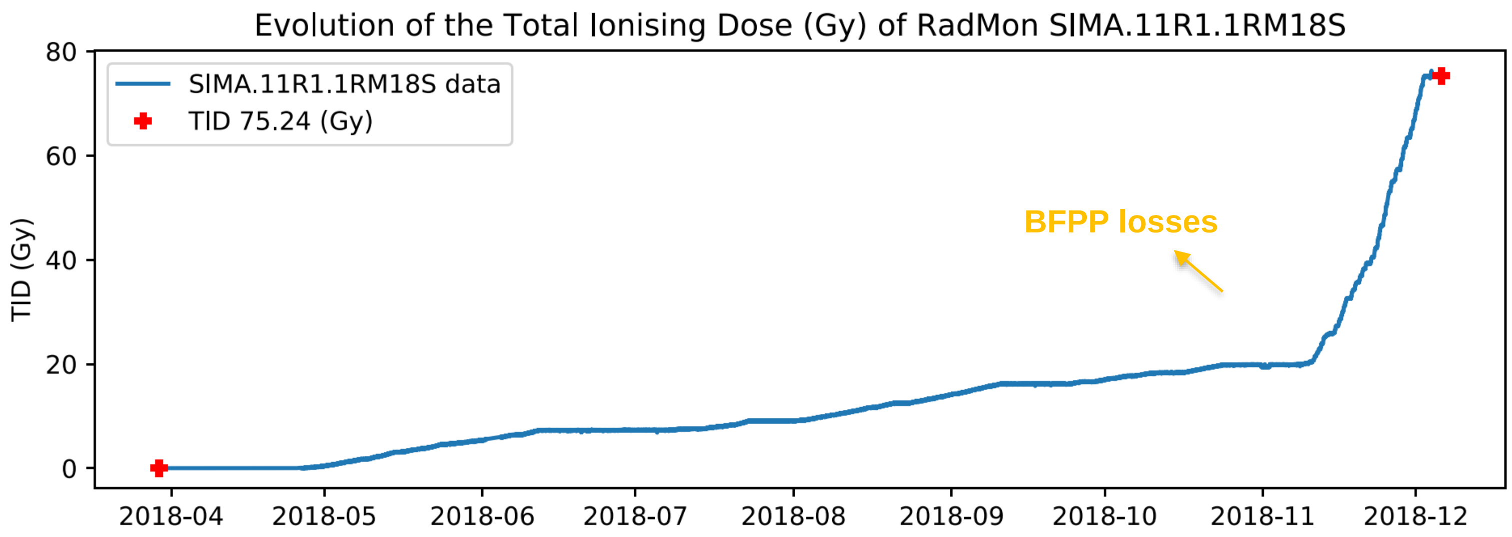
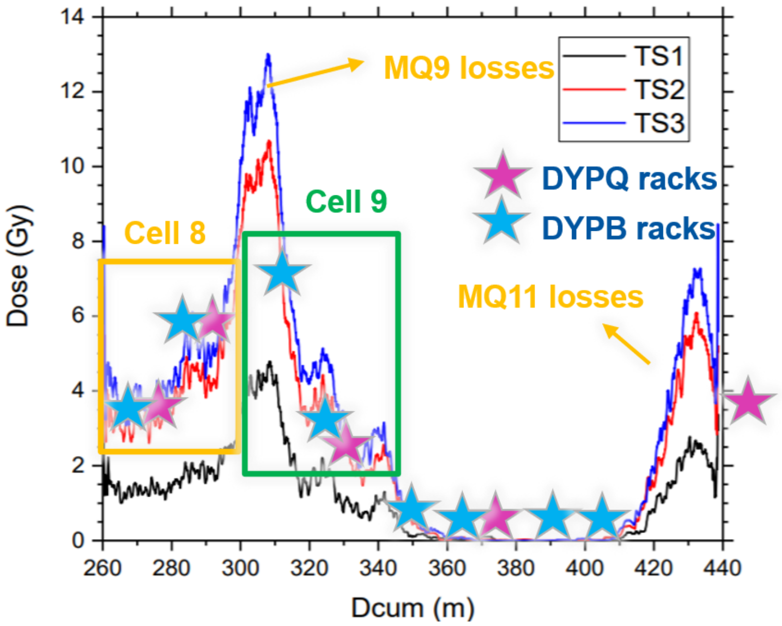


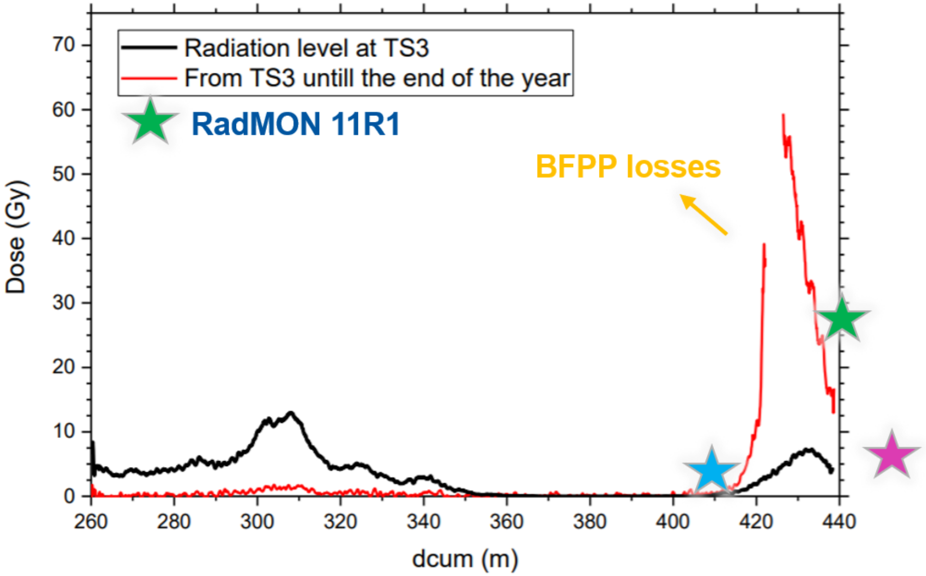
Fig. 3: BLM measurements in IP1 and IP5 during the p-p and the Pb-Pb run in 2015.





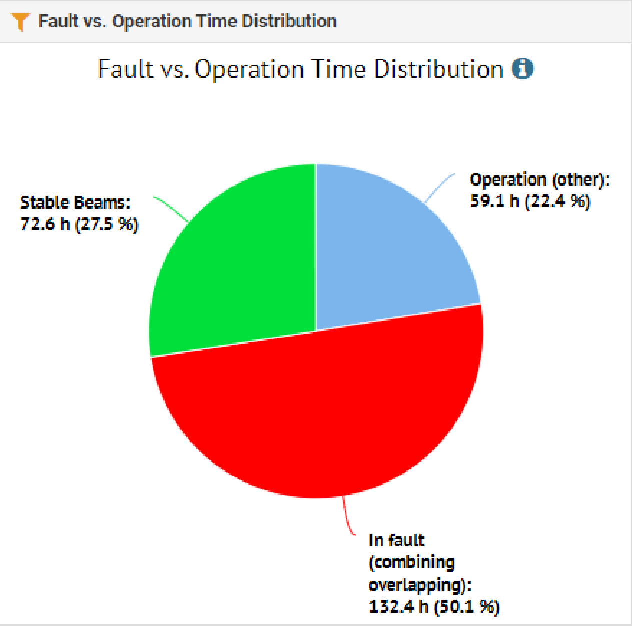
Protons up to TS (technical stop) 3, ions after that (for 2018)

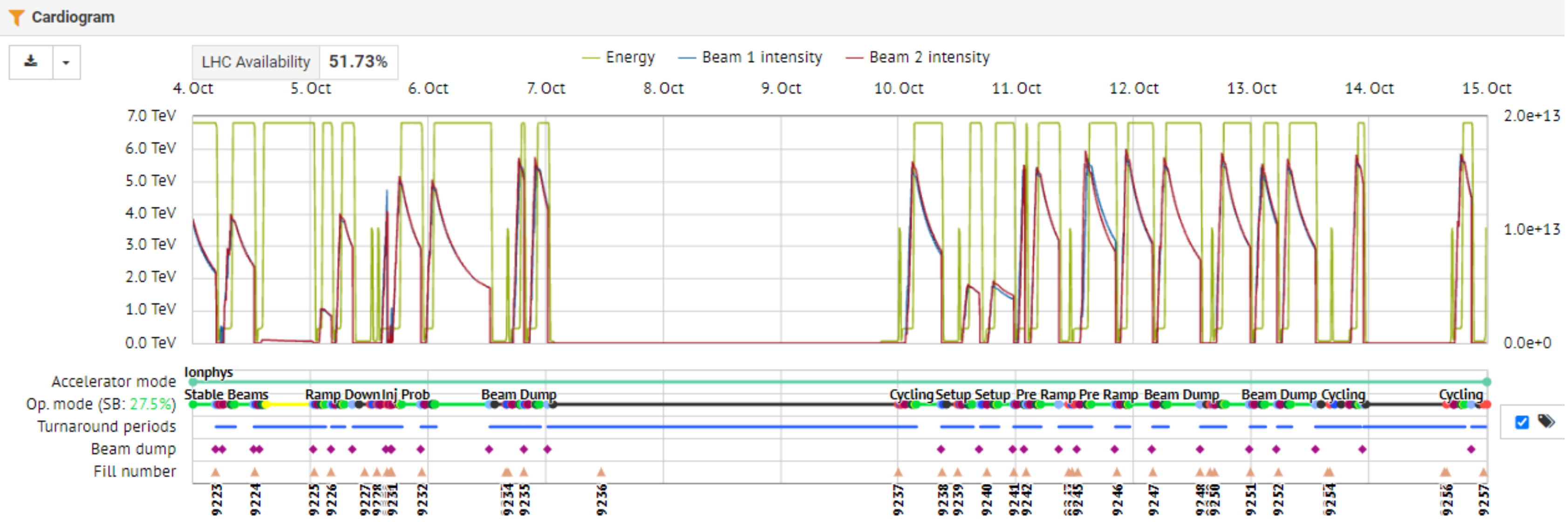




Compromised LHC ion run availability due to R2E events, just some weeks ago

Availability	Stable beams (SB)
51.7%	27.5%





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  - SPS
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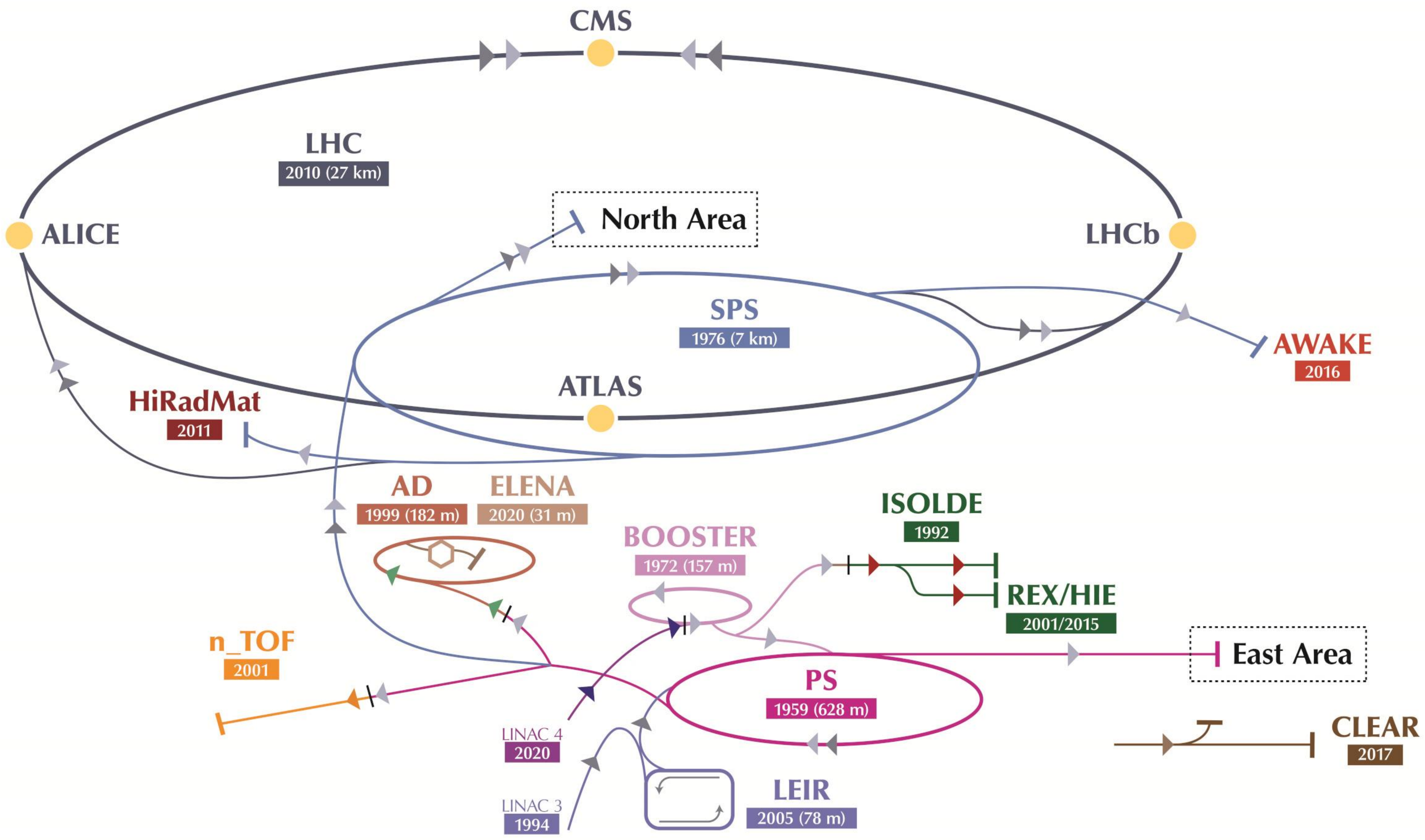
  - North Area ion beams

Quick look at the SPS



Quick look at the SPS: levels up to 100s of kGy

OVERVIEW OF THE RADIATION LEVELS IN THE CERN ACCELERATOR COMPLEX AFTER LS2

A. Canesse*, S. Danzeca, D. Di Francesca, R. Garcia Alia, G. Lerner,
D. Prelipcean†, D. Ricci, A. Zimmaro, CERN, Geneva, Switzerland

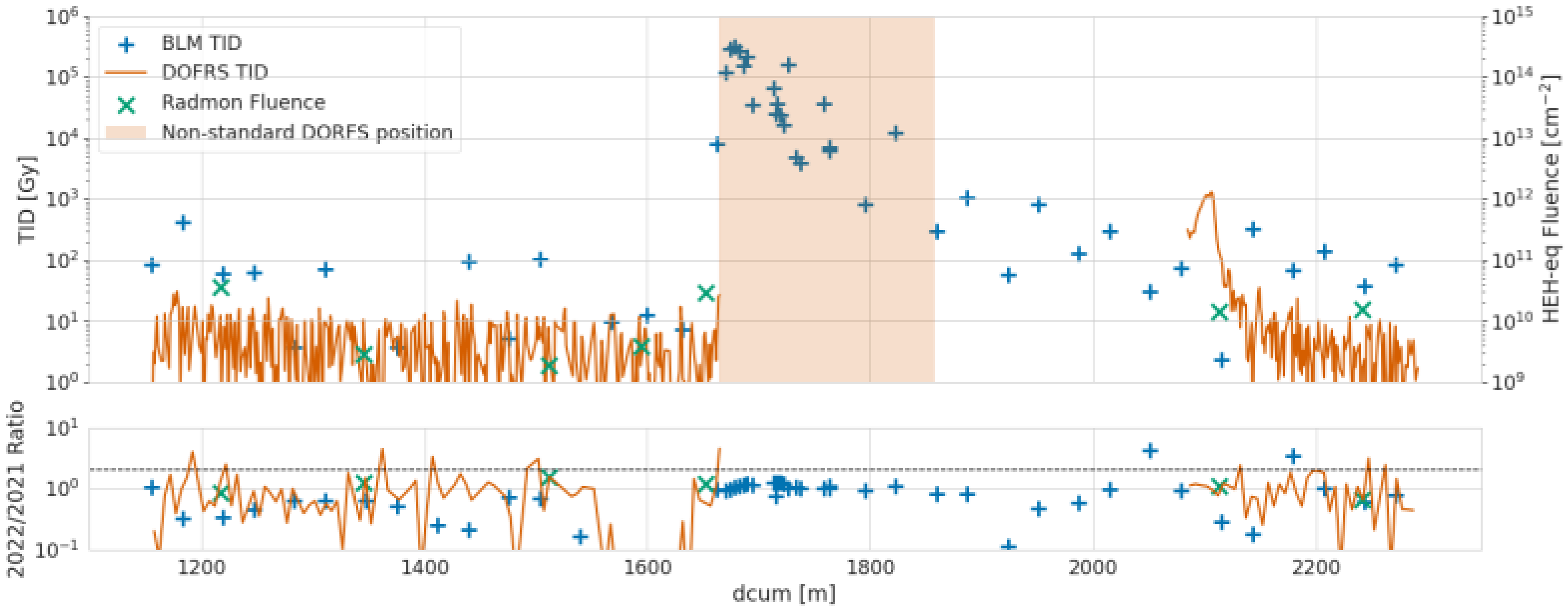


Figure 3: Radiations levels in the sector 2 of the SPS tunnel as a function of position in 2022 (top). Ratio of radiation levels between 2022 and 2021 for comparison (bottom). Due to its higher radiation hardness (compared to PSB and PS), the DOFRS used for the SPS cannot resolve to doses below ~10 Gy.

Quick look at the SPS: focus on electronics

CERN Super Proton Synchrotron radiation environment and related Radiation Hardness Assurance implications

Kacper Biłko, Rubén García Alía, *Member, IEEE*, Diego Di Francesca, Ygor Aguiar, *Member, IEEE*, Salvatore Danzeca, Simone Gilardoni, Sylvain Girard, *Senior Member, IEEE*, Luigi Salvatore Esposito, Matthew Alexander Fraser, Giuseppe Mazzola, Daniel Ricci, Marc Sebban, Francesco Maria Velotti

Fig. 4. Standard positions of the radiation sensors in the SPS arc sections, with the electronic rack of the ALPS system (with nMOS dosimeter on top, ~0.9 m distance from the beamline), directly exposed to the mixed-field radiation. Behind the magnets, at the cable tray (~1.3 m distance), as of 2021 the DOFRS monitor is installed. Before 2021, the Total Ionizing Dose was assessed by the RPL dosimeters (~1 m distance), in each arc half-period one installed at the cable tray, and one at the magnet coil. Each arc half-period contains one Beam Loss Monitor, installed either at the side of the beamline (~30 cm distance) or under the first dipole magnet, as in the presented location. Additionally, in some half-periods RadMons are deployed under the magnets.

Quick look at the SPS: losses within the cycle

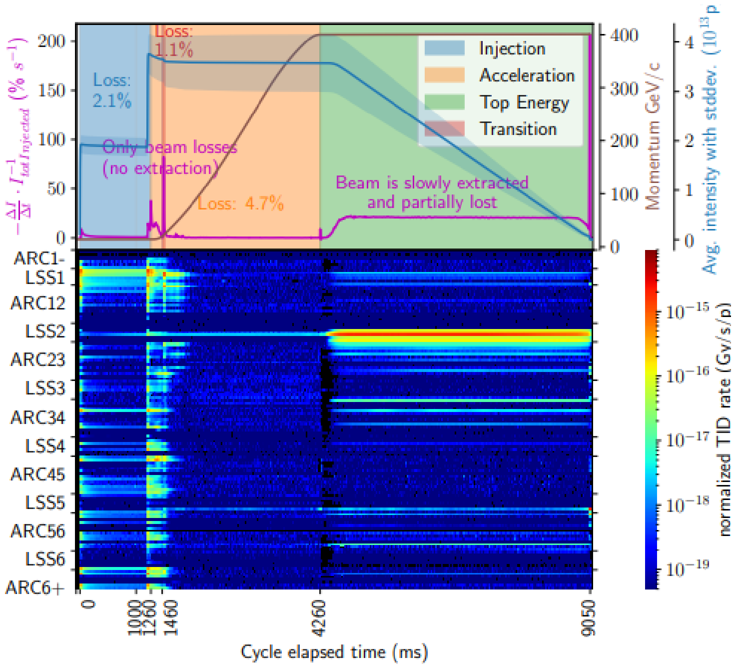


Fig. 5. The intensity loss rate normalized to the total injected intensity, as measured in 2022 during SFTPRO cycles. The loss rate includes lost, extracted and dumped protons. For comparison purposes, the beam momentum, together with an averaged beam intensity and its standard deviation is depicted. Only cycles with at least 10^{13} protons injected were considered. In these cycles, 2.1% of the total injected intensity was lost in the machine during the *Injection* period and 4.7% during the *Acceleration* phase (including 1.1% lost at *Transition* crossing). The bottom plot illustrates the injected-intensity normalized dose rate values along the accelerator as measured by the side BLMs in 2022 (until 13.09) during SFTPRO cycles.

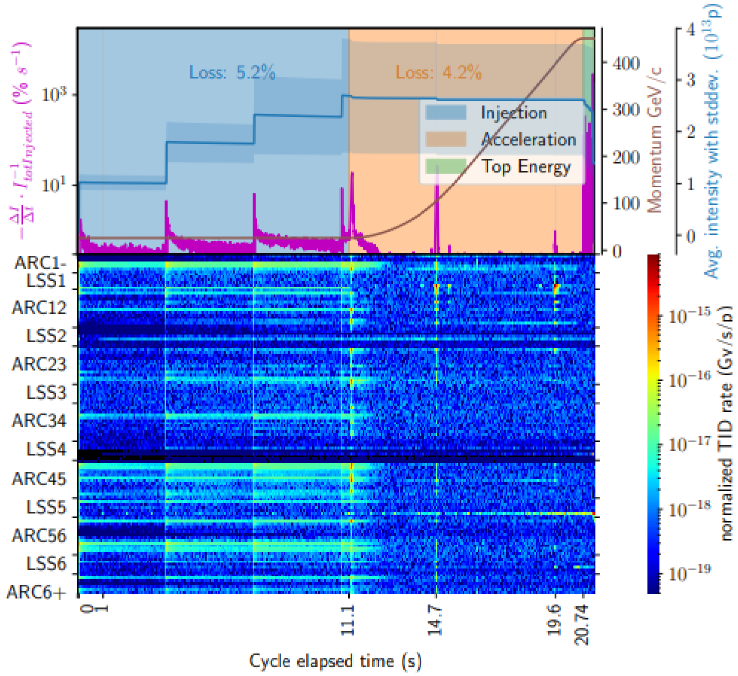


Fig. 6. The intensity loss rate normalized to the total injected intensity, as measured in 2022 during LHC cycles. The loss rate includes lost, extracted and dumped protons. For comparison purposes, the beam momentum, together with an averaged beam intensity and its standard deviation is depicted. Only cycles without dump occurring before the *Top Energy* period were considered. In these cycles, 5.1% of the total injected intensity was lost in the machine during the *Injection* period and 4.2% during the *Acceleration* phase (at the very beginning of acceleration due to uncaptured beam, and during the beam scrapping at 14.7/19.6 s.). The bottom plot illustrates the injected-intensity normalized dose rate values along the accelerator as measured by the side BLMs in 2022 (until 13.09) during the LHC cycles.

Quick look at the SPS: levels in the arc, hosting electronics

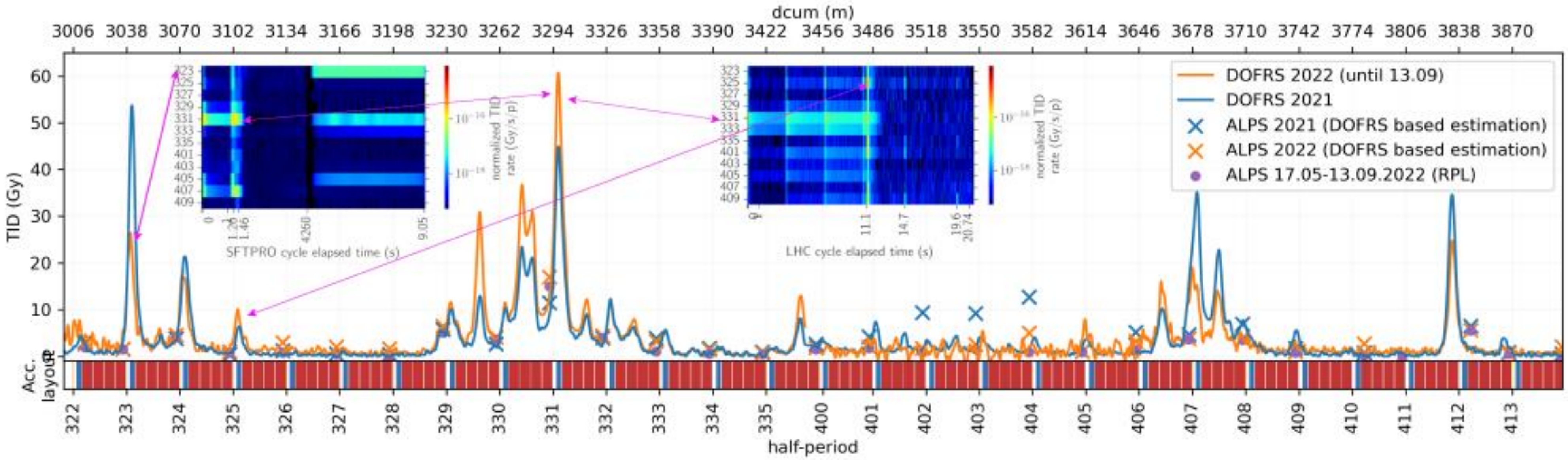


Fig. 7. TID (Gy in SiO_2, 2 m spatial resolution) in the arc sector 34 as measured by DOFRS in the years 2021 and 2022 (until September), with the schematic magnet layout. Additionally, the TID levels at the ALPS equipment are depicted, by means of RPL measurements from 2022; together with DOFRS-based estimates for 2021 and 2022. By focusing Fig. 5 and Fig. 6 on the arc sector 34, the detailed radiation peak analysis can be performed. For example, in 2022 the peak in half-period 323 was due to North Area cycles, with the majority of the TID registered during the Top Energy. The peak in half-period 325, was driven by the LHC cycles and happened at the beginning of acceleration, likely due to the loss of the uncaptured beam. The peak in 331 is due to the SPS vertical aperture restriction [27], and the losses can be observed for both SFTPRO and LHC cycles.

Quick look at the SPS: levels in the side galleries

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IMPLICATIONS AND MITIGATION OF RADIATION EFFECTS ON THE CERN SPS OPERATION DURING 2021

Y. Q. Aguiar, G. Lerner, M. Cecchetto, R. García Alía, K. Bilko, A. Zimmaro,
M. Brucoli, S. Danzeca, T. Ladzinski, A. Apollonio, J. B. Potoine
CERN, CH-1211, Geneva, Switzerland

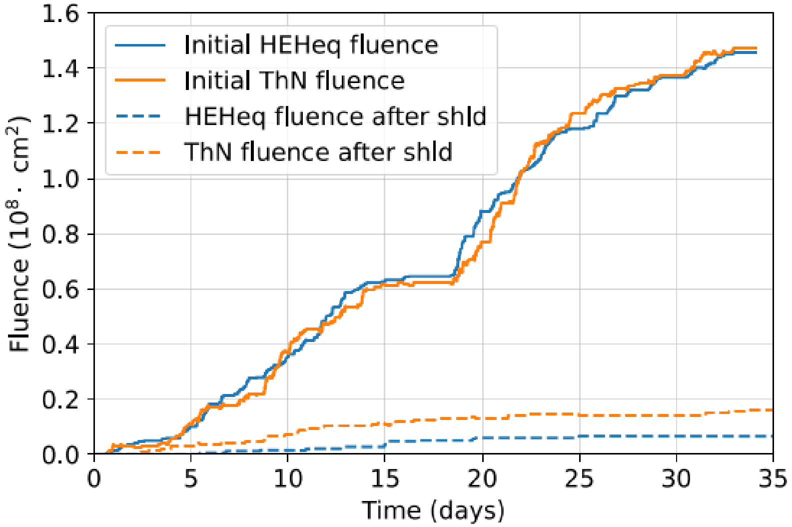


Figure 4: Particle fluences in BA1 measured by BatMons [8] before and after the installation of the iron shielding.

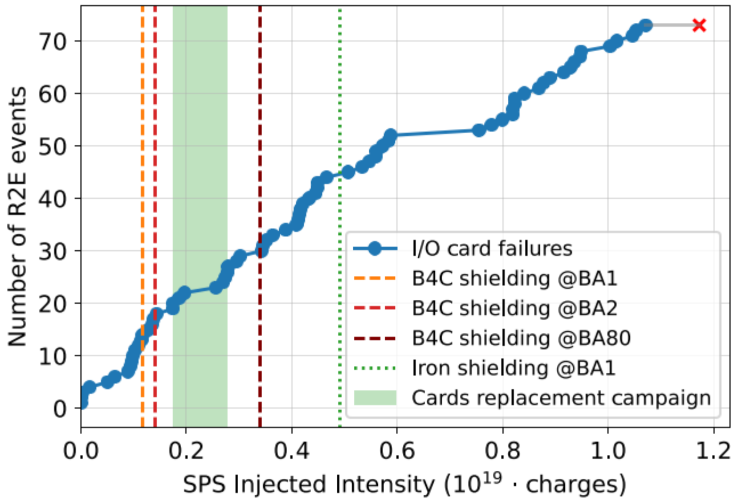
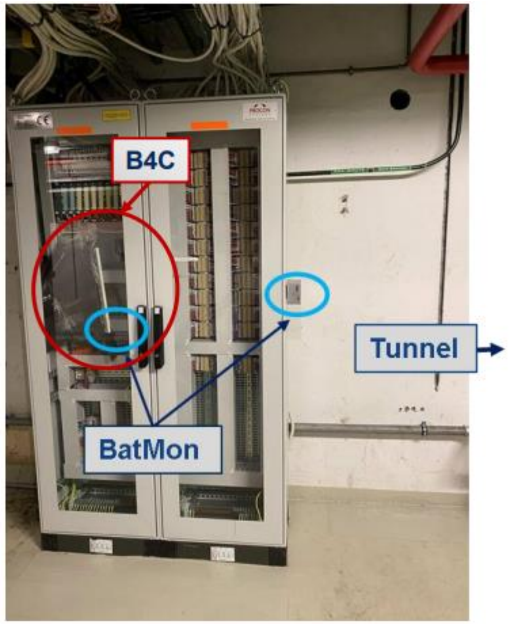


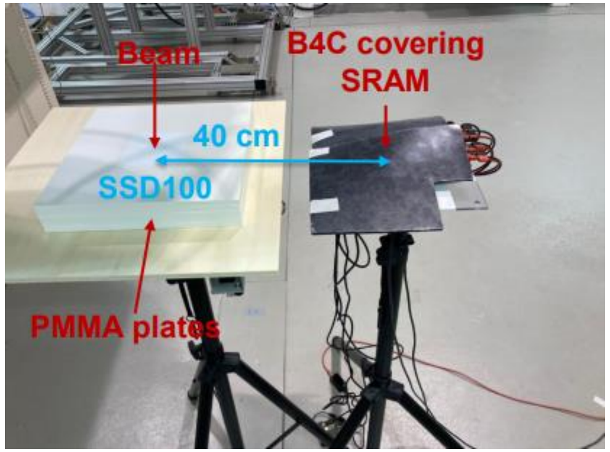
Figure 1: Number of R2E-induced I/O card failures as a function of the integrated injected intensity.

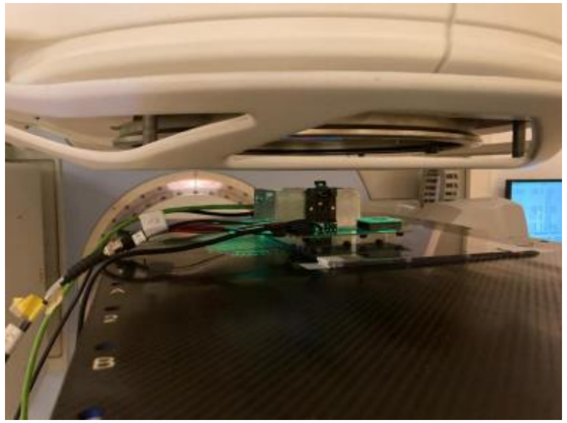


Outlook

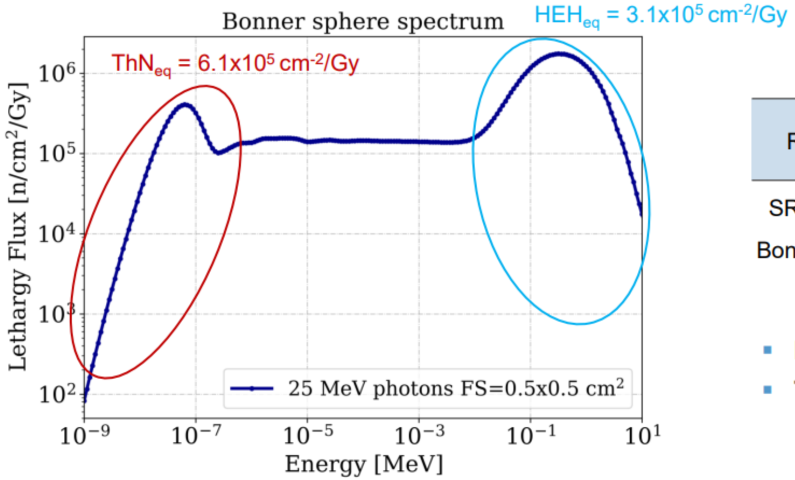
- **Why R2E? Radiation exposed electronics + impact on availability**
- **Radiation Hardness Assurance for LHC electronics**
  - Radiation Environment
  - Component Level Testing
  - System Level Testing (as final RHA validation)
- **A few additional examples beyond LHC protons**
  - LHC ions
  - SPS
  - Medical Linacs
  - CLEAR
  - North Area ion beams

25 MeV medical linac at PTB





Cecchetto, Matteo, et al. "Neutron measurements in medical LINACs through SRAMs." R2E Annual Meeting (2022)



Run	E [MeV]	Field size [cm²]	HEHeq [cm⁻²/Gy]	ThNeq [cm⁻²/Gy]
SRAMs	25	0.5x0.5	4.1x10⁵ ±20%	6.7x10⁵ ±24%
Bonner S.	25	0.5x0.5	3.1x10⁵	6.1x10⁵

- **HEHeq** fluence agreement ~ **30%**
- **ThNeq** fluence agreement ~ **10%!**

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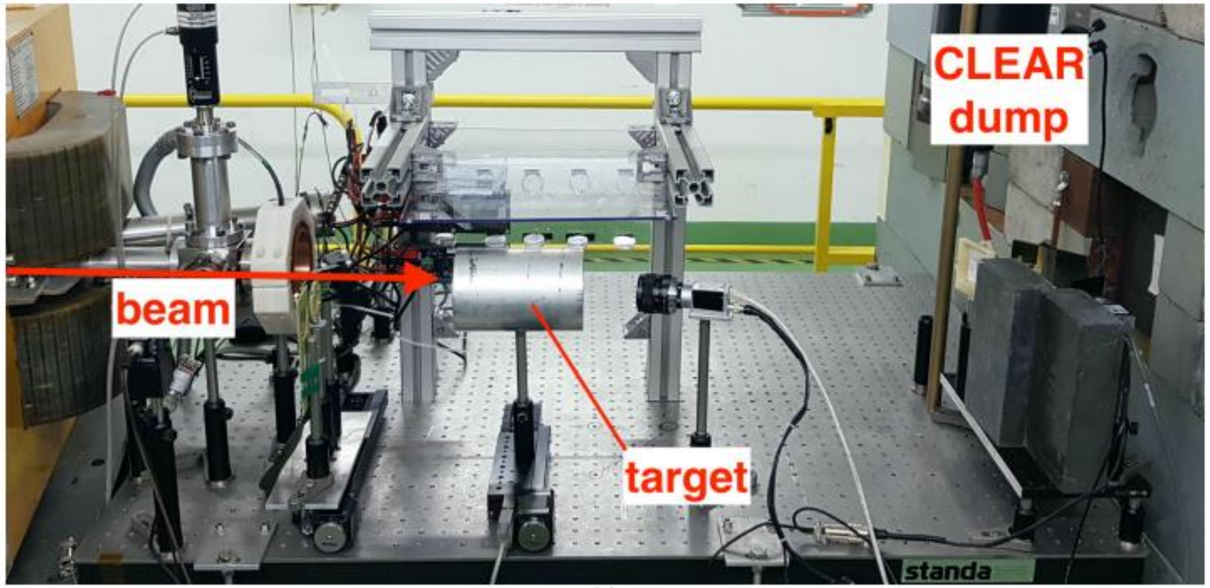
Analysis of the Radiation Field Generated by 200-MeV Electrons on a Target at the CLEAR Accelerator at CERN

Giuseppe Lerner, Pierre Pelissou, Ygor Q. Aguiar, *Member, IEEE*, Mario Sacristan Barbero, *Member, IEEE*, Matteo Cecchetto, Kacper Biłko, Louise Coussen, Natalia Emriskova, Rubén García Alía, *Member, IEEE*, Luke Dyks, and Wilfrid Farabolini



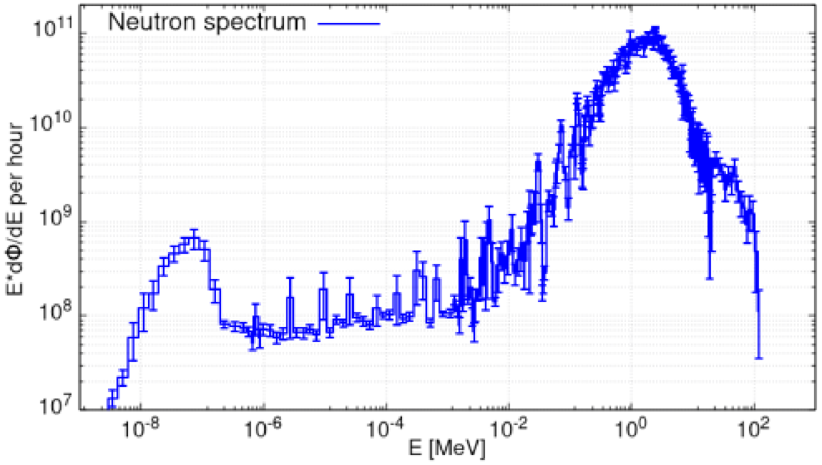


Fig. 5. FLUKA simulation of neutron lethargy spectrum on the target side.

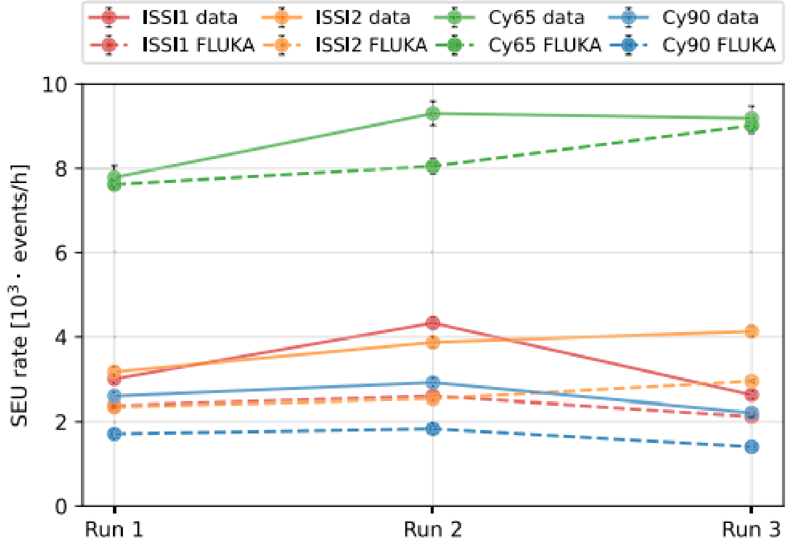


Fig. 8. SRAM SEU rate per hour scaled to high-intensity CLEAR operation, in comparison with FLUKA-based predictions. The error bars include the Poisson statistics and the Monte Carlo uncertainty, respectively.

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How does a high-energy heavy ion beam really look like?