Radiation to electronics aspects for SPS gamma-factory

Gamma Factory meeting (25-28 March 2019)
Indico link: https://indico.cern.ch/event/802131/

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With input from:

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Outline

- Introduction to R2E challenges for accelerators
- R2E radiation monitors
- SPS LSS4/LSS6 radiation levels
- LHC radiation levels for ion operation

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- **Introduction to R2E challenges for accelerators**
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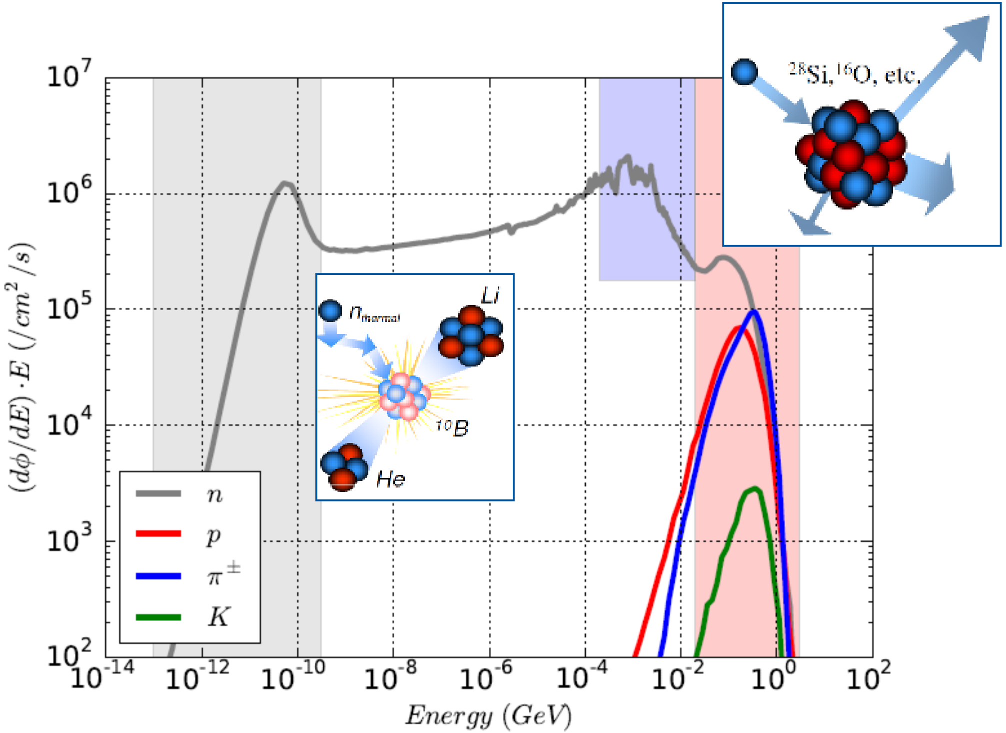
Introduction: mixed field environment and SEEs



- **SEEs** are induced by indirect energy deposition (nuclear reactions) from hadrons
- Two main intervals can be distinguished: **thermal neutrons** (causing SEEs through ^{10}B capture) and **high-energy hadrons (HEH,** defined as hadrons above 20 MeV + intermediate energy neutron contribution)
- Therefore, the HEH and thermal neutron (if relevant) sensitivities need to be **qualified**
- Annual levels in areas with COTS-based systems range from 10^5 (ground-level) to 10^9 HEH/cm^2 (LEO-orbit)
- **Cumulative radiation effects:** Total Ionizing Dose (main contributions: electromagnetic showers, charged hadrons) and Displacement Damage (main contributors: neutrons)

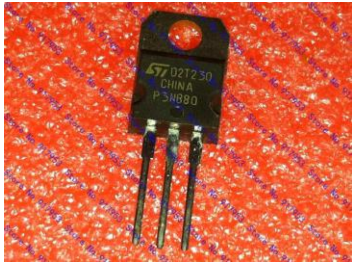
Introduction to R2E problematic and approach

- For **critical LHC systems** (e.g. power converters, quench protection system, beam instrumentation, vacuum, cryogenics…) and areas with radiation levels above **10^7 HEH/cm^2/yr**:
  - The use of commercial modules with active electronics is (as a general principle) excluded
  - Rad-tol approach relies on in-house custom COTS-based design and qualification (typically requiring 3-5 year timeframe, from conception up to machine installation)
    - For complex/high-performance systems (e.g. cameras, high-power DCDC converters) an in-house solution might not be possible, and the alternative is (i) to use rad-hard modules (e.g. for space, very expensive!) or (ii) to partner with industry for rad-tol solution
- For areas with lower radiation levels, or **non-critical applications**, “black-box” modules can be used, however the information gained from their radiation testing is limited, as:
  - There is no traceability of the individual components used
  - The test is purely functional (it works or it doesn’t), with no option of selecting alternative references or redesigning
    - (Rare) exceptions: companies willing to share Bill-Of-Materials and schematics, and to adapt proposed BOM/layout changes to R2E recommendations
- Main Gamma Factory R2E concern: laser system (only commercial solutions available? Possible rad-hard option from e.g. electron machines?)

Risks linked to box-level testing

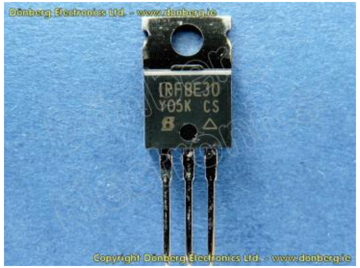
SE PULS SL5.300 unit

Conclusion: for rad-tol design, being in control of ***individual part selection*** *is* ***essential,*** *also linked to* ***re-design options***



STP3NV80
(N-channel, 800V)

22 destructive events in LHC before 2015

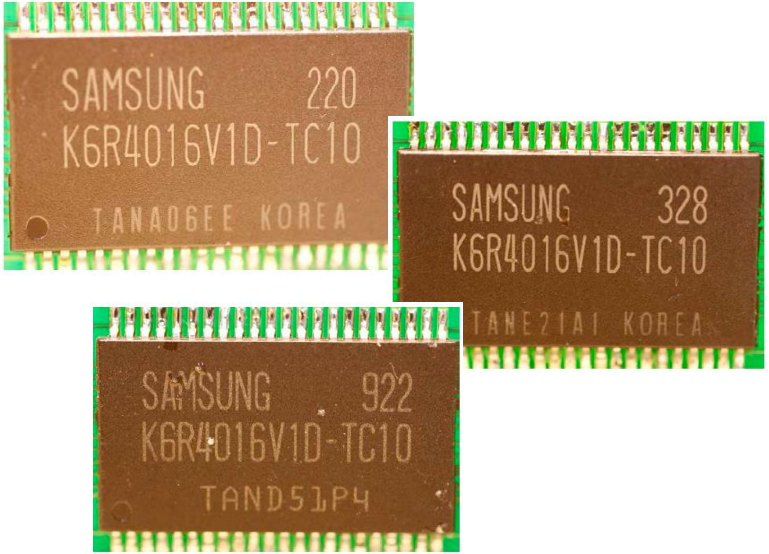


IRFBE30
(N-channel, 800V)

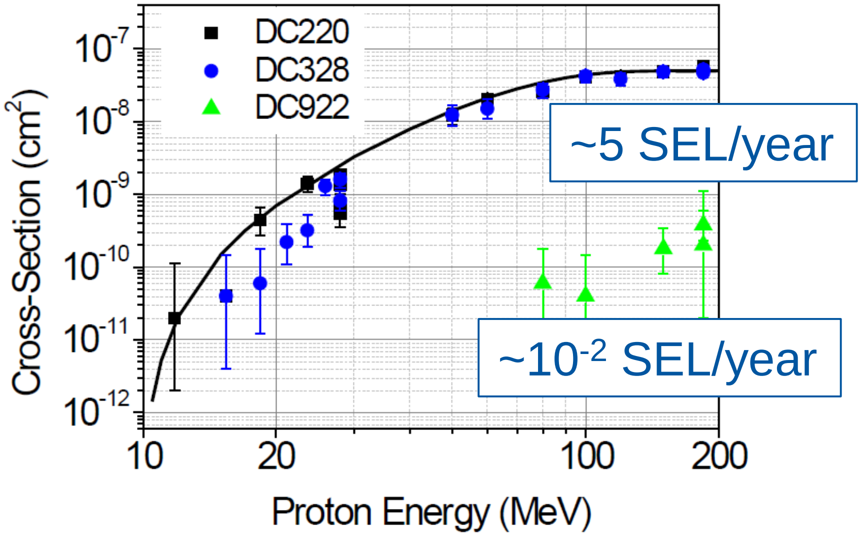
One destructive event in LHC before 2015

Risks linked to 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

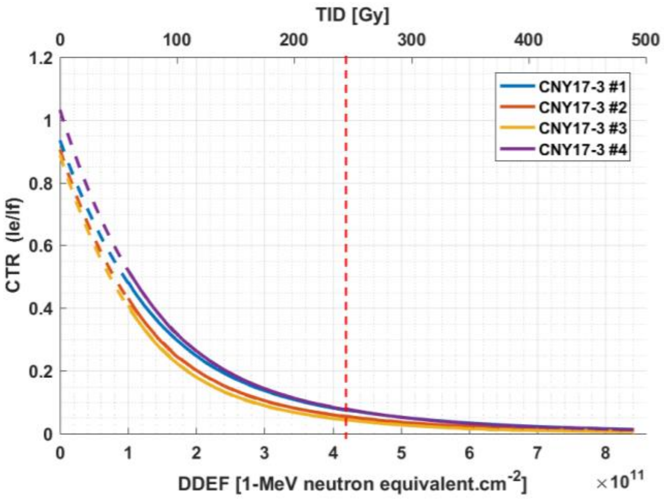


SEL rate considering 10^8 HEH/cm²/year



R2E component level testing

- Typically carried out at PSI, with **200 MeV protons**, capable of inducing:
  - TID effects: common targeted lifetimes for COTS are 200 Gy – 1 kGy
    - Can also be tested in a more accessible manner through **cobalt-60 source** at CERN
  - Displacement damage effects: common targeted lifetimes for COTS are $2 \cdot 10^{12}$-10^{13} n_{eq}/cm^2
  - Single Event Effects: common target is SEE free for a proton fluence of ~10^{12}-10^{13} cm^{-2}
- Results reported and structured in on-line database (very useful for rad-tol COTS-based system designers)



PSI test example: Current Transfer Ratio (CTR) degradation of opto-coupler, mainly due to displacement damage (Rudy Ferraro, EDMS 2002401)

R2E component level testing (II)

CERN Radiation Working Group

HOME MANDATE RADIATION TEST DATABASE

Home

Radiation Test Database

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

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

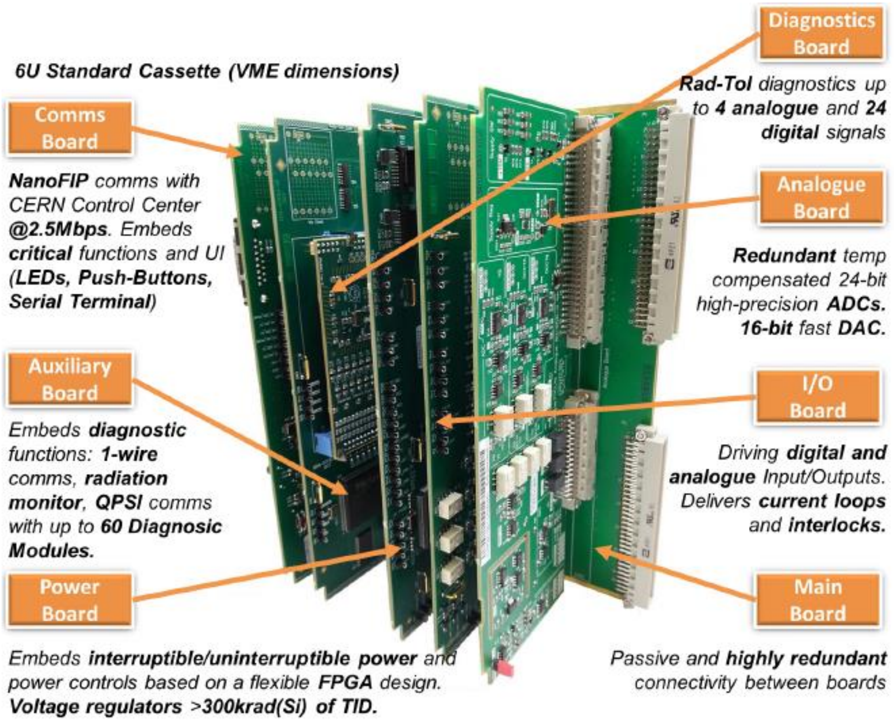
For more details contact : Salvatore Danzeca

List (302) Add Filter Admin

	Reference	Type	Device Function	Test Date	Test Characteristics	Edms Report Number
👁	TPS7B6850	Voltage Regulator	High-Voltage Ultralow Quiescent-Current Watchdog LDO Voltage Regulaor	2019-02-16	ΔVOut,Icc, SEL, SET	2112895
👁	TL1431	Precision Programmable Reference	Precision Programmable Reference	2019-02-16	ΔVOut,Icc, SEL, SET	2113396
👁	74HC74D	D Flip Flop	D-type flip flop	2019-02-15		2100780

R2E system level testing

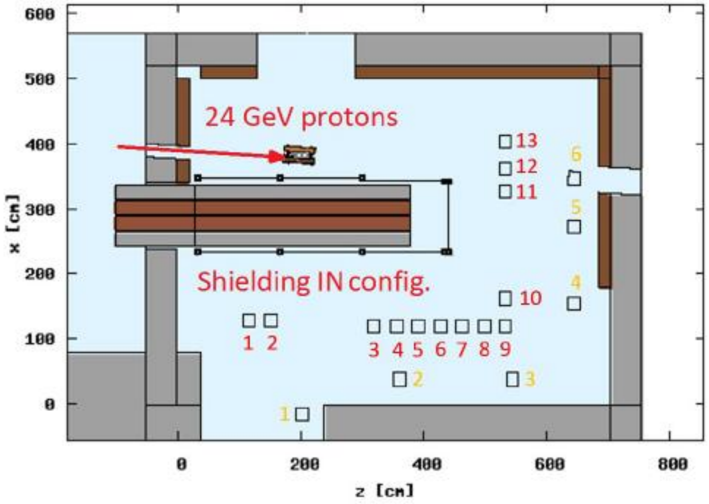
- Efficiently combining **top-down** (from system to sub-system/component) and **bottom-up** (discrete testing of critical components) approaches
- Importance of intelligent design of experiment in order to enhance failure **observability** (e.g. self-diagnose systems, system modularity)
- Importance of defining **failure modes** and associated **criticality**
- Importance of **common component qualification** and **sub-system development** (e.g. versatile communication link)

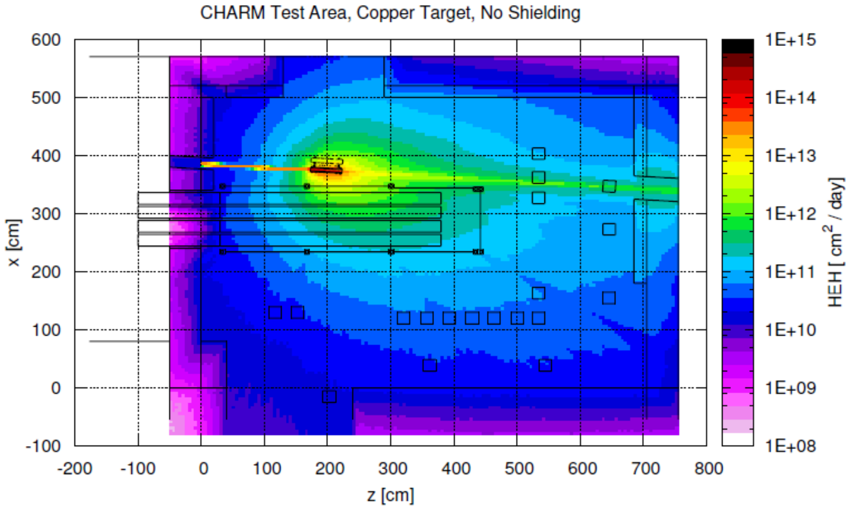


FGClite system for LHC power converter controls (S. Uznanski, TE-EPC), qualified for HL-LHC ARC and shielded alcove levels, in operation since 2017

R2E system level testing: CHARM

- Radiation field generated by interaction of **24 GeV proton beam** with **50 cm copper target**
- Highly unique, at it provides:
  - A **radiation environment** closely resembling that of the **accelerator** (different particle energy spectra possible by combining location, target and shielding)
  - A **very large irradiation volume**, enabling the qualification of large quantities of components and boards in parallel, and of full systems





R2E system level testing: CHARM (II)

- **Automatic conveyer** with cable chain for connection, capable of transporting a full rack
- **Movable shielding** system to modulate radiation environment
- Test carried out in **operational conditions** for systems under qualification



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- SPS LSS4/LSS6 radiation levels
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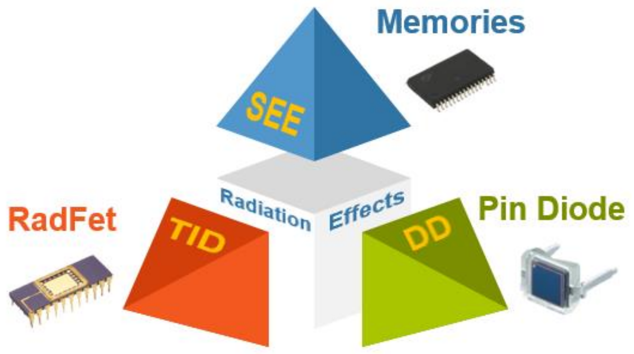
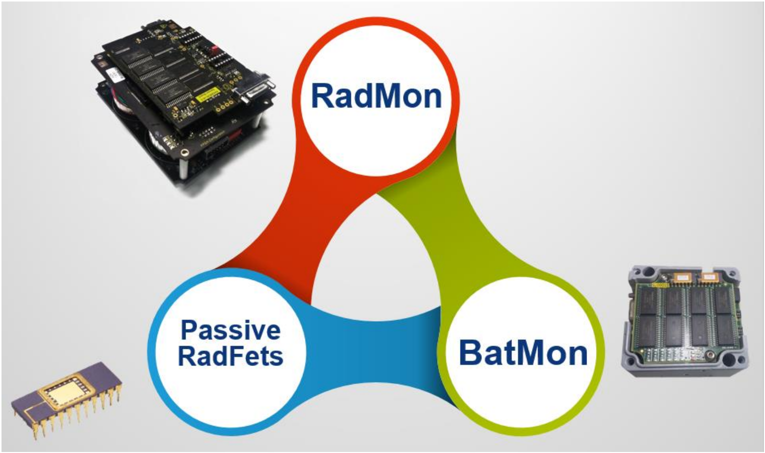
RadMON monitoring system

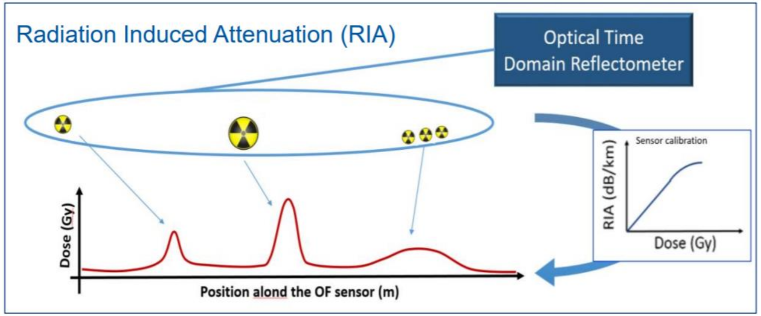


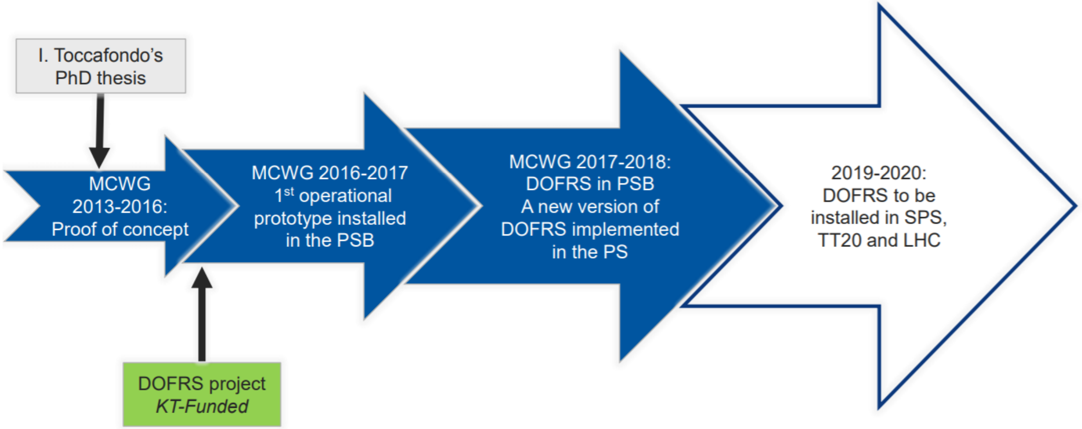
- Full in-house design, production and calibration/qualification
- Based on COTS components; capable of actively measuring HEH fluence, 1-MeV neutron equivalent fluence and Total Ionizing Dose (TID)
- 392 RadMONs in LHC; in critical areas (+ more in injectors and experimental areas), deported modules (active RadFET) placed at equipment location
- v6 upgraded version almost fully deployed in LHC for 2018 operation
  - Enhanced TID and HEH fluence sensitivity
  - Direct thermal neutron fluence measurement
  - TID lifetime improved from 80 to 250 Gy
  - Reprogrammable, modular and upgradable



Optical fiber dosimetry at CERN

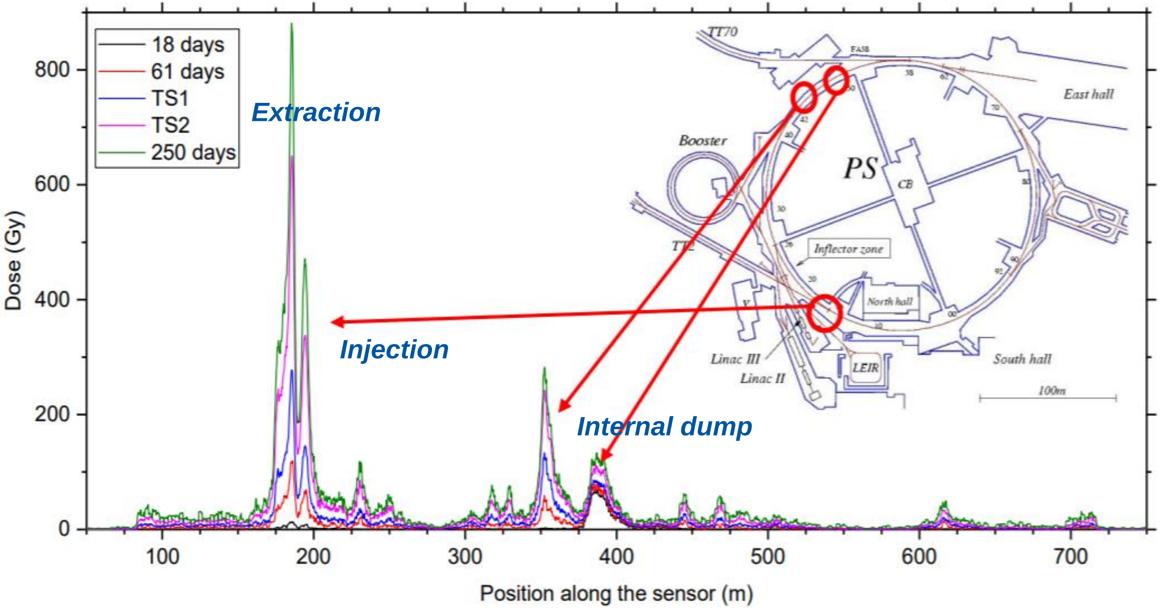
- Provides online 1D radiation maps of accelerators with single (or limited amount) of interrogators
- Future LS2 installations:
  - SPS and TT20 (ECR EDMS 1969746)
  - DS regions of IP1, IP5 and IP7 (ECR EDMS 1978574)
- Applications go beyond R2E (e.g. high-resolution spatial distribution of losses in SPS and TT20 for extraction optimization)



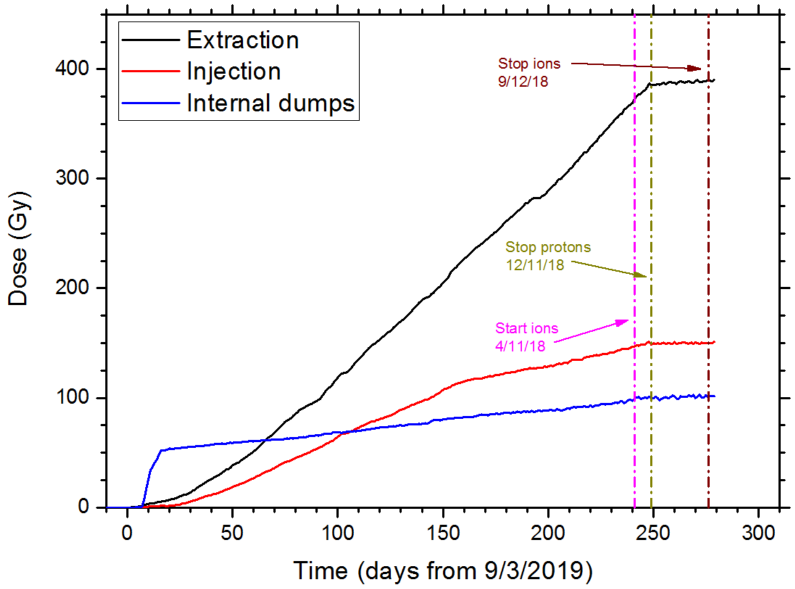


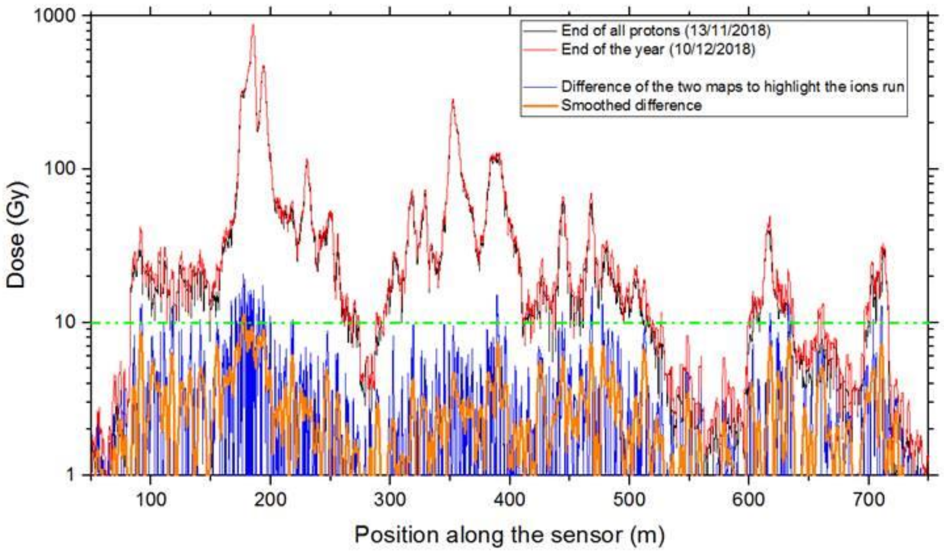
Optical fiber dosimetry at CERN (II)

- Example of operation: 2018 in PS
- To be installed in SPS (and parts of LHC) during LS2



Optical fiber dosimetry at CERN (III)





- Negligible contribution to PS dose from 2018 ion run (right plot: ion measurements below green line sensitivity limit of 10 Gy)

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"Report on the Radiation on Electronics measurements for Gamma Factory in SPS LSS4 and LSS6", M. Brucoli (EDMS 2080251)

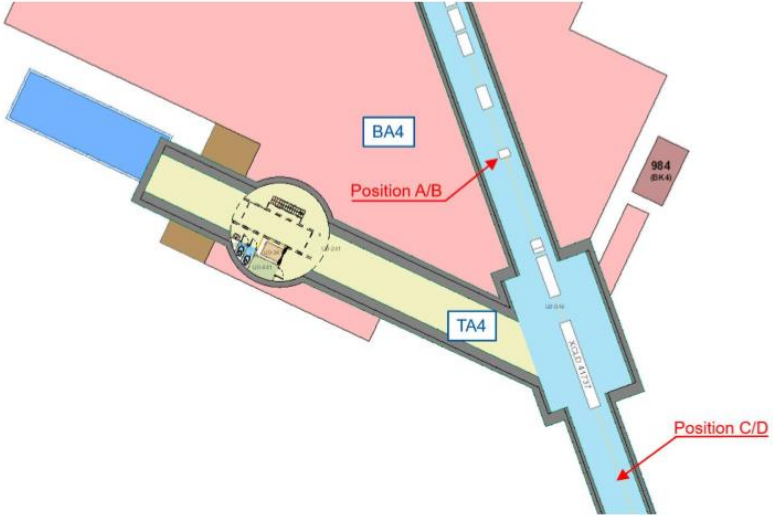
Run 2 BLM levels in SPS LSS4 and LSS6

*SPS BLM “LOSS_CYCLE” data, excluding negative values; __**data processing needs to be validated**__ in terms of noise and offset*

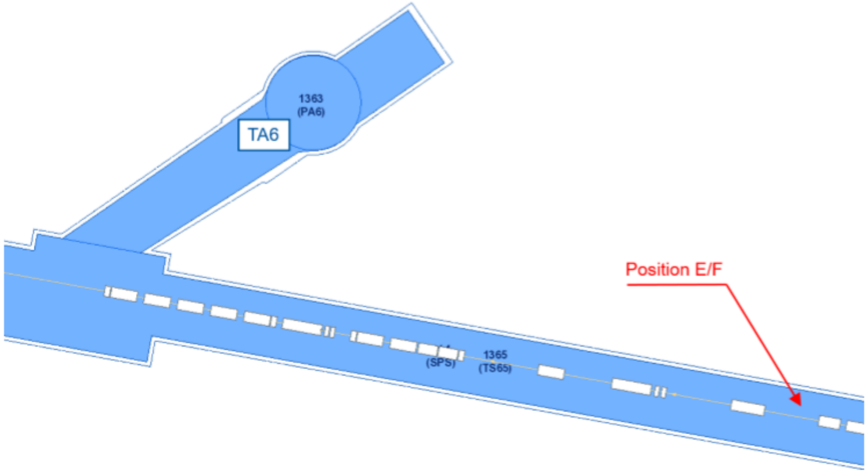
	BLM name	TID 2016 (Gy)	TID 2017 (Gy)	TID 2018 (Gy)	TID total (Gy)
0	SPS.BLM.61631.MKE1	<10	62	18	81
1	SPS.BLM.61634.MKE2	<10	128	81	211
2	SPS.BLM.61637.MKE3	<10	64	12	77
3	SPS.BLM.61651	<10	57	<10	61
4	SPS.BLM.616	42	143	102	289
5	SPS.BLM.415	<10	32	<10	34
6	SPS.BLM.416	<10	94	21	120
7	SPS.BLM.417	42	71	153	266

- High radiation level area for commercial electronics, with annual TID values for 2017 in **30-140 Gy** range
- __**2018 ion levels for LSS4/LSS6 below BLM sensitivity**__

BatMON/RadFET radiation monitor locations

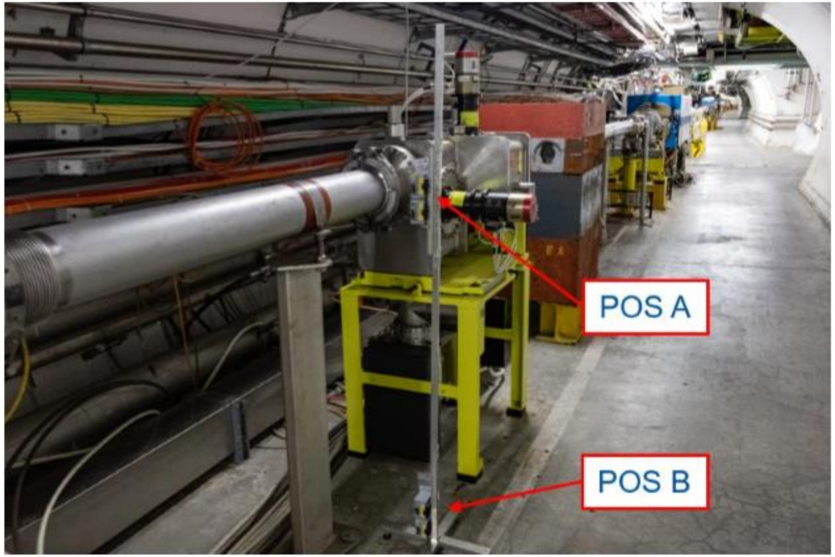


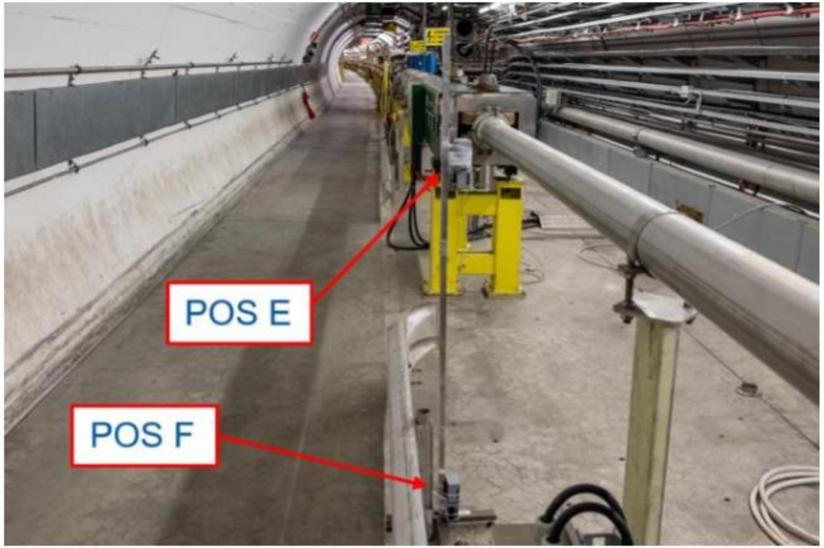
LSS4



LSS6

BatMON/RadFET radiation monitor locations (II)





Summary of SPS LSS4/LSS6 radiation level measurements

Location	Start date	End date
LSS4	18/09/2018 (TS2)	17/01/2019
LSS6	18/09/2018 (TS2)	17/01/2019

Long Straight Section	Position	Height	R-factor	Φ_{HEH} [pp/cm²]	Φ_{ThN} [pp/cm²]
LSS4	A	Beam	0.1	8.88×10^9	8.30×10^8
	B	Floor	1.9	8.80×10^8	1.64×10^9
LSS6	E	Beam	0.1*	1.50×10^{10}	1.40×10^9
	F	Floor	1.9*	2.04×10^9	3.81×10^9

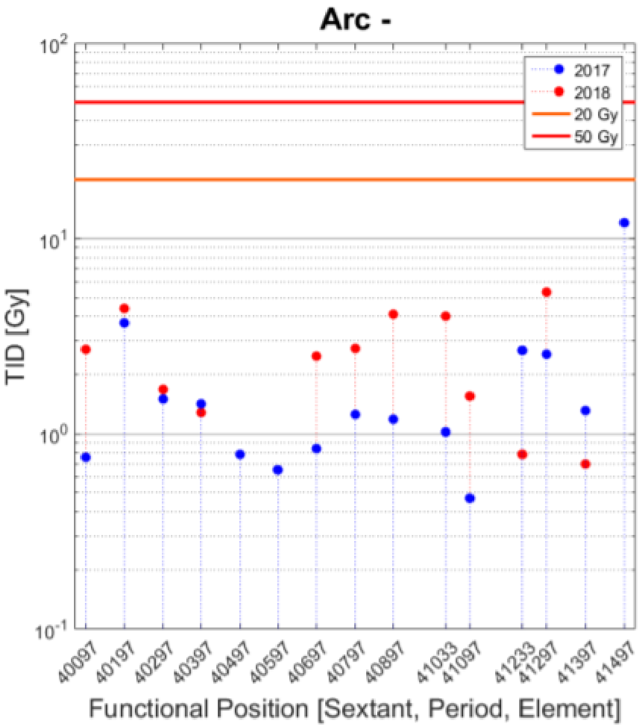
- LSS4/LSS6 BatMON/RadFET measurement summary (2018 TS2 – end of run*):
  - At beam height:
    - **~10^{10} HEH/cm², ~10 Gy**
  - At floor level:
    - **~10^9 HEH/cm², ~5 Gy**

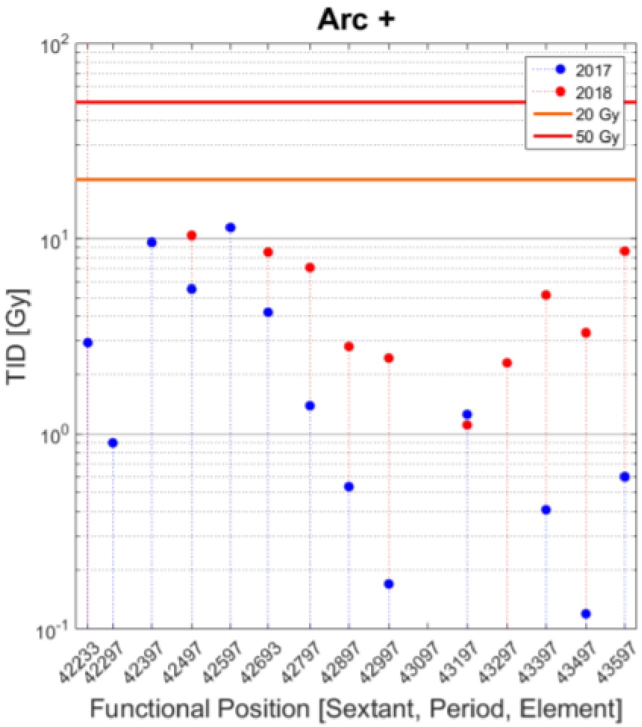
Long Straight Section	Position	Height	TID [Gy]
LSS4	A	Beam	10.5
	B	Floor	4.8
LSS4	C	Beam	5.4
	D	Floor	3.9
LSS6	E	Beam	9.8
	F	Floor	4.0

**including both protons and ions (after 12.11.18)*

Radiation levels in nearby SPS ARCs (Sextant 4)

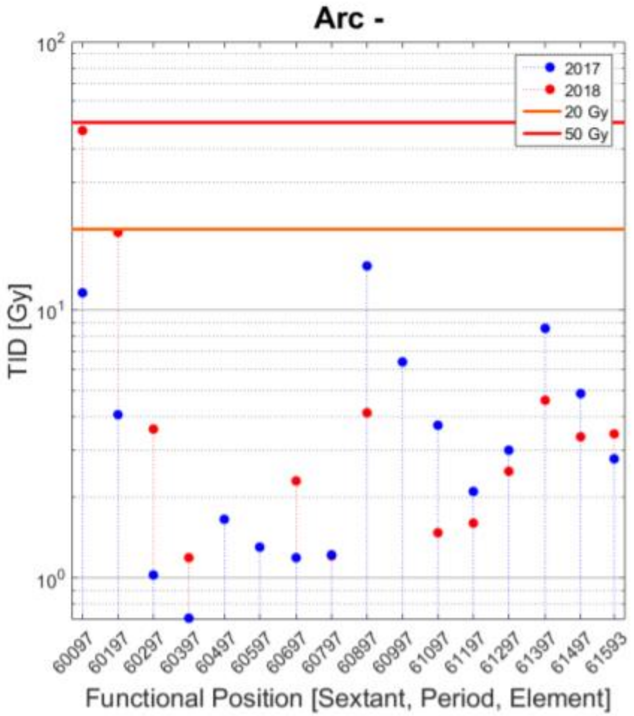
Slightly lower but similar levels in ARC than in LSS [as opposed to “hot” LSSs such as LSS1 (dump) or LSS2 (NA extraction)]

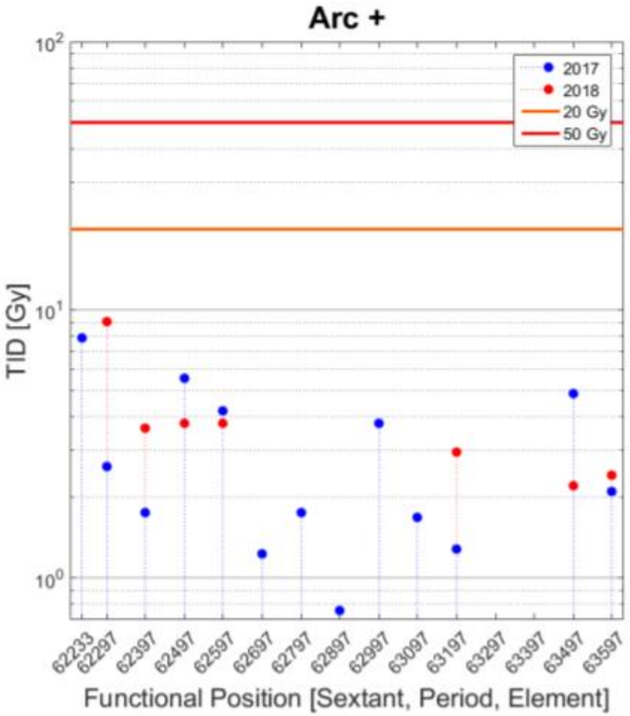




Radiation levels in nearby SPS ARCs (Sextant 6)

Slightly lower but similar levels in ARC than in LSS [as opposed to “hot” LSSs such as LSS1 (dump) or LSS2 (NA extraction)]





Implications of LSS4/LSS6 radiation levels

- For **ion operation**:
  - Losses are expected to be much smaller than for protons (<1 Gy/ion operation period), and therefore not an issue in terms of cumulative effects on commercial electronics
  - Single Event Effects (SEEs) could still be a concern, especially in terms of soft errors in digital electronics
    - Further analysis: RadMON values (i.e. online measurements) for ion operation in SPS arc are under investigation in the MCWG
- For **proton operation**:
  - Levels of ~5-10 Gy and ~10^9-10^{10} HEH/cm^2 are clearly a threat for commercial electronics, both in terms of SEEs and cumulative (i.e. lifetime) effects
  - Keeping Gamma Factory electronics off (i.e. unbiased) during proton operation would spare it from SEEs and (most) TID effects, but would still induce significant displacement damage effects (bipolar transistors, opto-electronics, sensors, LEDs…)
    - Optimal solution would be not to have it in tunnel during proton operation

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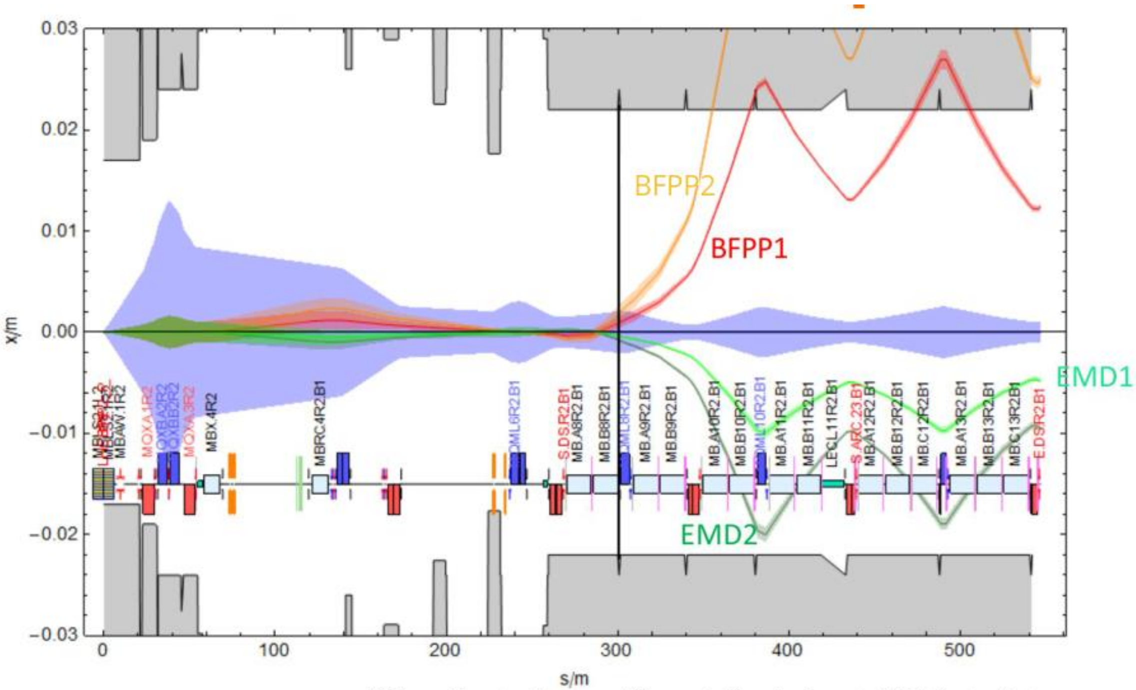
- **LHC radiation levels for ion operation**

BFPP losses in LHC

$$^{208}Pb^{82+} + ^{208}Pb^{82+} \longrightarrow ^{208}Pb^{82+} + ^{208}Pb^{81+} + e^{+}$$

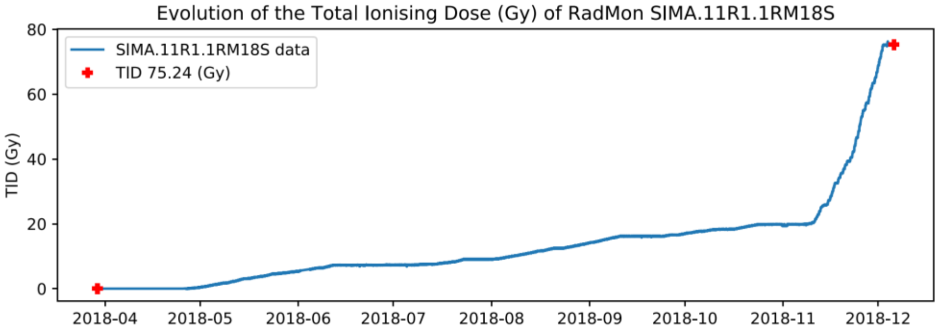
281 barns at HL-LHC (7*Z* TeV) [1]

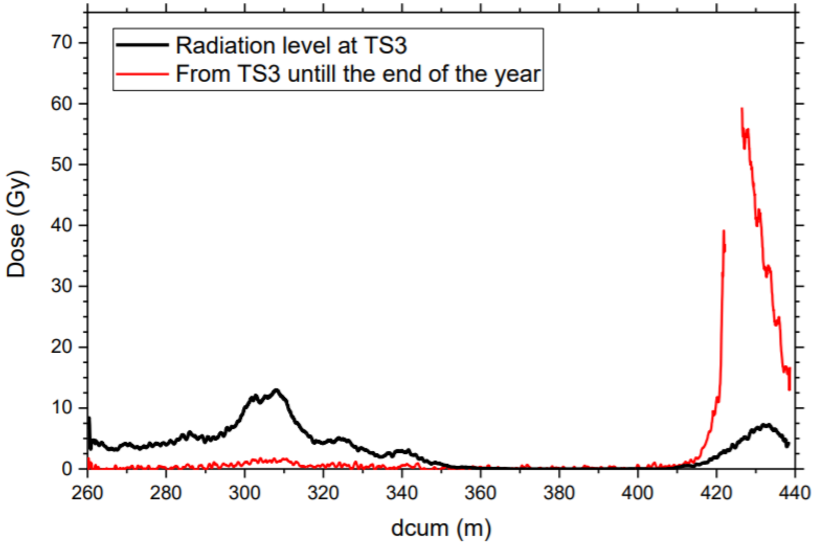
[1] Meier, H. et al., "Bound-Free Electron-Positron Pair Production in Relativistic Heavy Ion Collisions", Phys. Rev. A, 63:032713, 2001.



J.M. Jowett, Dispersion Suppressor Collimators for Heavy-Ion Operation, LHC Collimation Review 2013

Ion dominance of 2018 LHC losses in IP1/5 DS

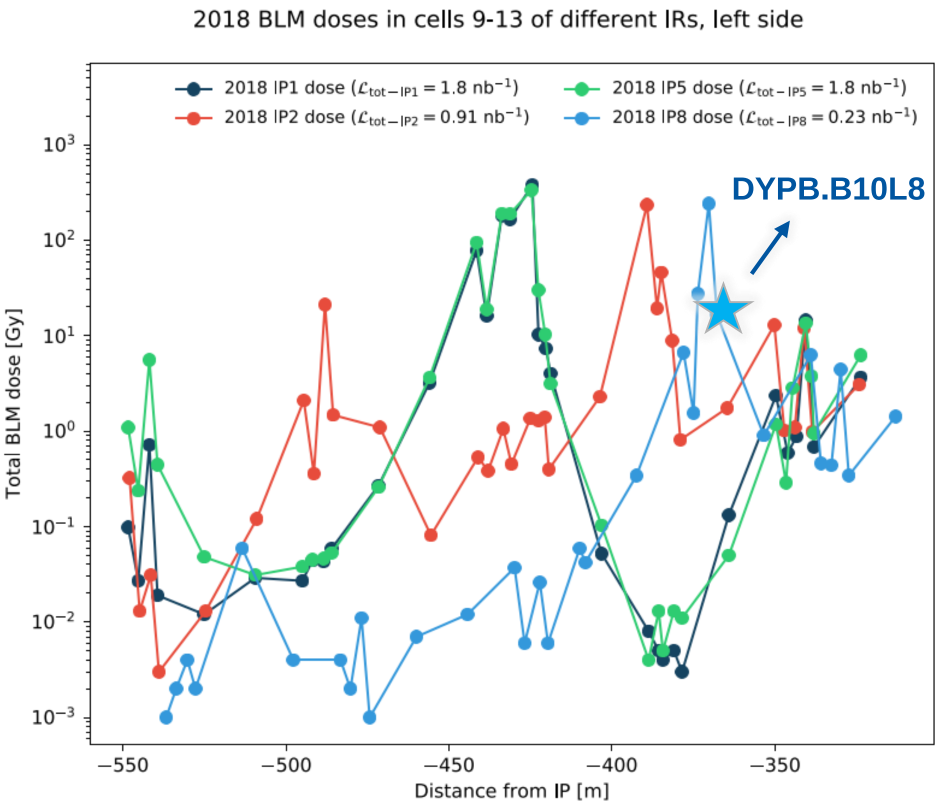




RadMON (left) and optical fiber (right) DS losses for 2018, showing overall dominance of ion losses with respect to protons, having however a limited impact on operation as they are shifted to connection cryostat (no equipment racks below it)

2018 ion run: IP1/2/5/8

- Large integrated luminosities, leading to **peak BLM levels of ~500 Gy in all experiment IPs**
- QPS failures during ion run: B10L8 (x3), B8R1, B9R5, B9L2
- Not critical for operation, but further analysis and relocation required for **Run 3**, which plans to accumulate a significant fraction of the **10 nb^{-1} HL-LHC ion luminosity** target



Summary and Outlook

- Radiation levels in the LHC injector chain for ion operation are low (typically below radiation monitor sensitivity*)
  - Possible additional radiation source terms for gamma factory operation?
- Such levels are not expected to be a threat to electronics in terms of cumulative effects (TID, DD) but if above ~10^7 HEH/cm^2/year could cause SEE issues, especially in terms of soft errors in digital electronics
- Laser systems (e.g. opto-electronics) can be highly sensitive to displacement damage, which will also induce degradation even if the components are unbiased (i.e. non-active) → possible issue if equipment is left in SPS during proton operation
- Radiation qualification of commercial modules ("black-boxes", with no control of individual part selection and traceability) is highly challenging (especially for distributed systems) and only provides a very limited amount of information

(*) Improved sensitivity of SPS ARC measurements for ion run will be achieved through RadMONs after 2018 analysis

Thank you for your attention!

R2E