QDS R2E events during 2023 LHC ion run

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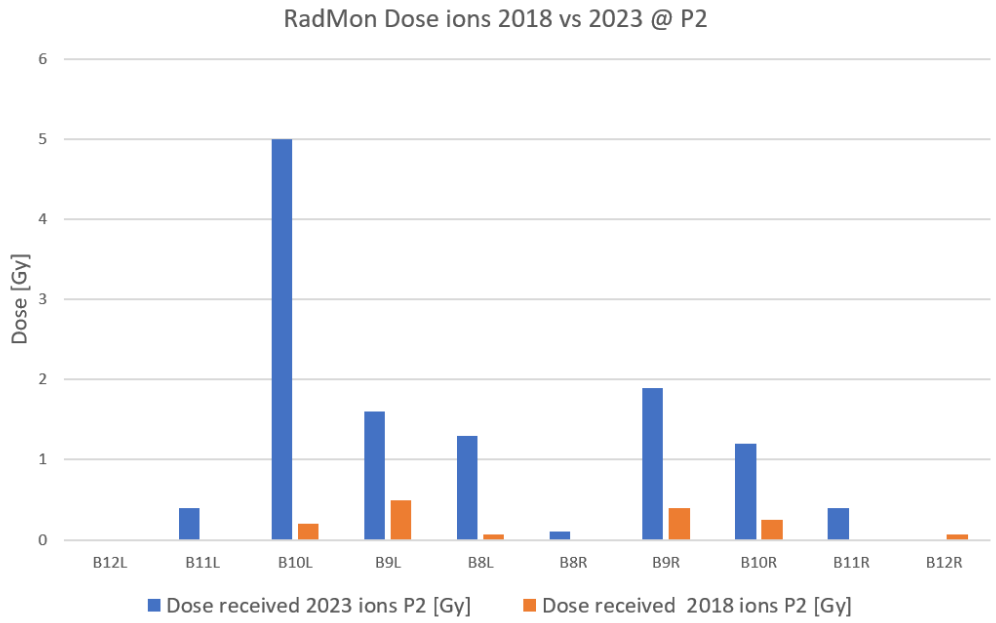
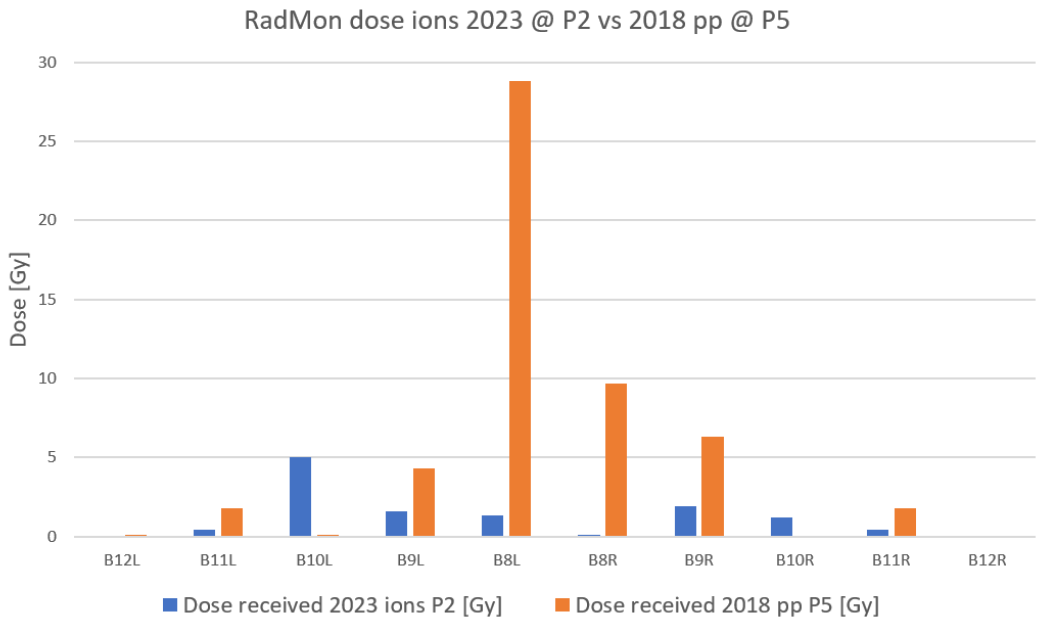
Thanks to R2E and RadWG

Content

- Radiation data
- Event Overview
- R2E event classes of the QDS during 2023 ion Run
- Mitigation measures

Setting the scene – Doses 2023 vs 2018





- **During 2023 ions, dose recorded by RadMons is 10x higher than in ions 2018 while luminosity increased only by a factor of 2**
- **Compared to 2018 pp in P5, doses in P2 ions 2023 is 5x smaller**
- **Based on received dose and in comparison to previous runs we did not expect so many R2E events (expected x2 compared to 2018 ions)**

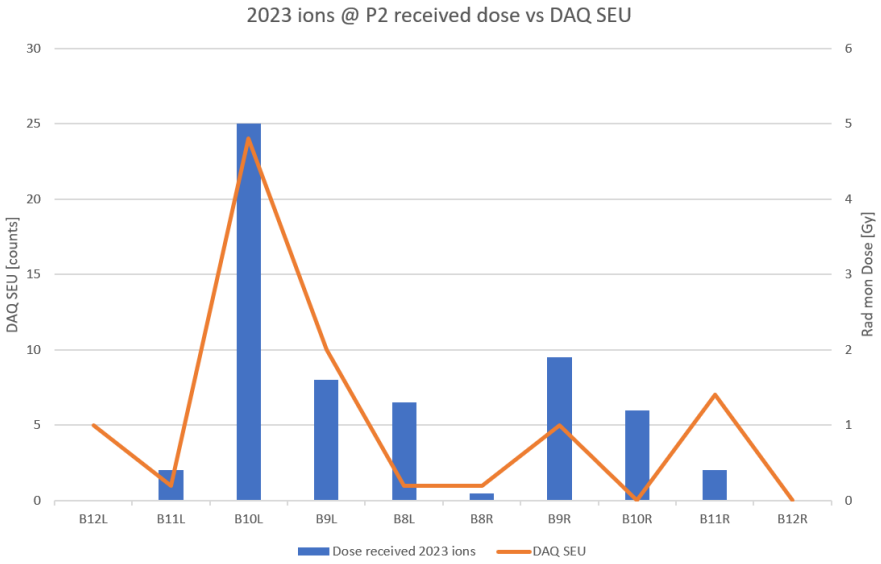
Event Type Overview

Class	Equipment	Fault mechanism	Consequence	# events 2023 ions	# events 2018 ions
1	DQQDL (MB) Base layer QD	SEU bit flip in digital isolator	Mitigated	188	129
2	DQQBS (bus bar splice detector)	SEU in microcontroller (uC)	Fast power abort (FPA)	5	2
3a	DQQDL (MQ) Base layer QD	SEL in op amp (non-destructive)	FPA & Quench MQ remote power cycle	1	0
3b	DQQDL (MQ) Base layer QD	SEL in op amp (destructive)	FPA & Quench MQ access to replace quench detector	1	0
4a	DQAMC (com board)	SEL in uC (destructive)	Loss of communication Access for board exchange	1	0
4b	DQAMGS	SEL in uC (destructive)	Com loss, FPA, access	2	0
4c	DQAMGS	SEL in uC (destructive)	Com loss, FPA, Quench MB, access	2	0

- **Class1 & Class 2 were known and (to a certain extent) expected**
- **Class 3 & Class 4 did not happen before**
  - DQQDL (MQ) was only installed in LS2 but was tested in CHARM
  - One Class 4b event during 2018 pp and one Class 4c during 2022 pp run but were not recognized as such at that time

Class 1 events – DAQ triggers (mitigated)

- **Known R2E issue of the base layer QDS for dipoles**
- **Digital isolator changes logic level due to SEU**
- **Mitigated in firmware since many years**
- **Used as a “radiation detector:**



Rack 10L2 is in reverse orientation to R2, cannot be moved due to other equipment (slight mitigation by changing sequence of modules could “win” 1-2m)

Class 2 events – DQQBS triggers

- **Well known issue, happens also sporadically during high intensity PP runs**
- **2018 pp run with modified TCL settings provoked 6 of these events**
- **DQQBS is based on ADuC834, a uC with integrated sigma delta ADC. SEU in this microcontroller lead to a spurious FPA**
- **Comparison 2023 vs 2018:**

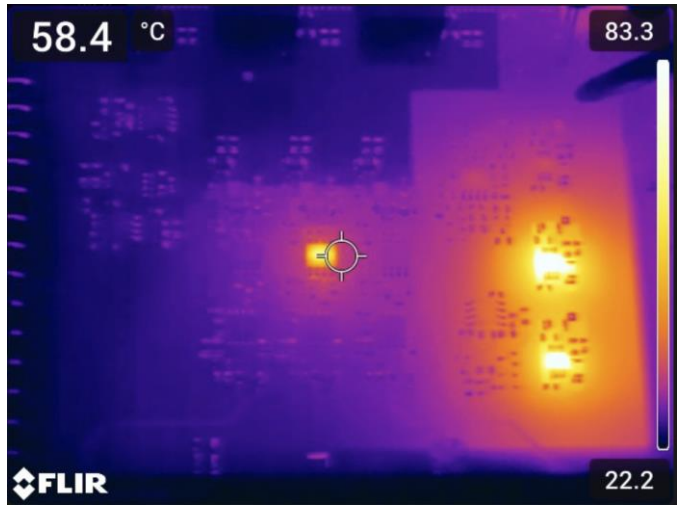
Year	Run type	Events	Integrated Lumi
2023	pp	1	30 1/fb
2023	ions	**5**	2.16 1/nb
2018	pp	6	66 1/fb
2018	Ions	2	0.905 1/nb

№	Location	Type	Circuit	Fill	Date
LHC ion run 2023					
1	B10L2	Power abort	RB.A12	9243	11/10/2023
2	B9L2	Power abort	RQD.A12	9247	12/10/2023
3	B12R1	Power abort	RB.A12	9258	15/10/2023
4	B11L1	Power abort	RQD.A81	9283	20/10/2023
5	B10L2	Power abort	RB.A12	9289	22/10/2023

- Statistics is low, but class 2 events seem to scale with P2 integrated luminosity for ions
- For pp, 2018 had more losses per lumi due to TCL settings and hence more class 2 events

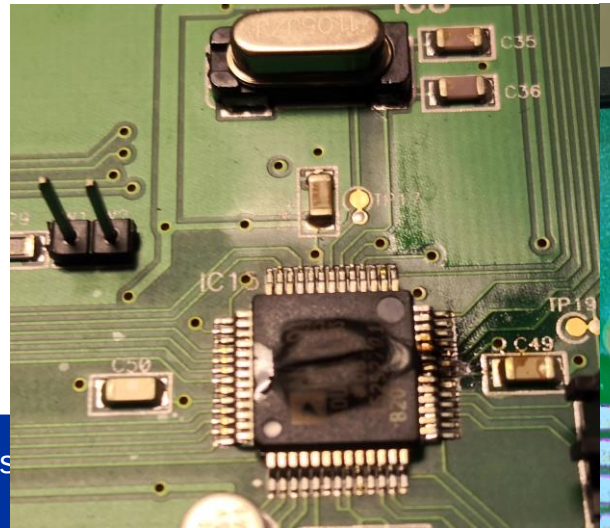
Class 3 events – DQQDL (MQ) SEL, FPA + HDS trigger

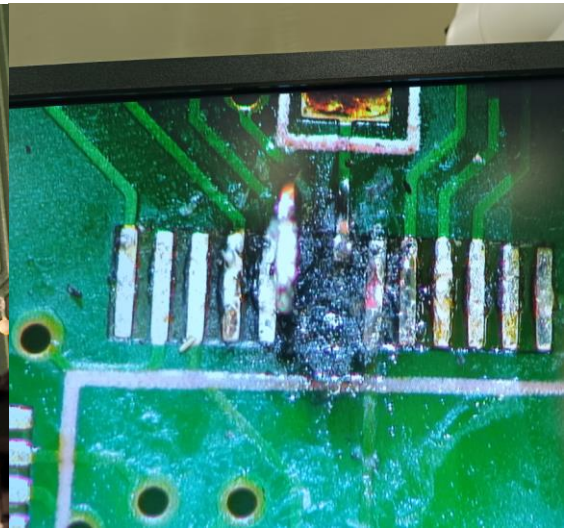
- **2 Events at Oct 14 and Oct 15, symmetrically around P2: A12L2 / A12R2**
  - 1st event, MQ11L2: one ADC channel saturated, isolated power supply indicates out of spec. voltages. Power cycle un-latched component and device resumed normal operation
  - 2nd event, MQ11R2: One complete isolate domain (3 ADC channels) saturated values, indication of bad isolated power. Power cycle did not restore function → piquet intervention to change card
- **Analysis on damage board found Single Event latch up in OPA2192 operational amplifier of the DQQDL for quadrupoles**
- **After replacing this opamp, DQQDL was fully functional again**
- **Crate A12L/R was already moved to be further away from empty cryostat**
- **This error did not show up during CHARM test**
- **No further event recorded after Oct. 14th/15th**



Class 4 events – nQPS FPA and HDS firing on 3xMB

- **Loss of communication to the nQPS (DQLPU-S) crate**
- **Instantaneous or delayed FPA and/or trigger of quench heaters by symmetric quench detection card, DQQDS**
- **Crate controller's microcontroller (ADuC831) physically destroyed by destructive SEL**
- **Quench detectors worked properly but in a cascade of events, fault of ADuC can cause:**
  - → **Loss of communication (4a)**
  - → **Loss of communication & Fast power abort (4b)**
  - → **Loss of communication & Fires heaters, quenching magnet (4c)**





Ion run 2023 – R2E Event overview

Date	Location	Event class	Consequence
Oct 5	B10L2	4b	FPA (precycle required)
Oct 7	B9R2	4c	FPA, Heater discharge MB (quench)
Oct 11	B10L2	2	FPA (precycle required)
Oct 12	B9L2	2	FPA (precycle required)
Oct 12	B8L5	4b	FPA (precycle required)
Oct 13	B12R2	4c	FPA, Heater discharge MB (quench)
Oct 14	A12L2	3a	FPA, Heater discharge MQ (quench)
Oct 15	A12R2	3b	FPA, Heater discharge MQ (quench)
Oct 15	B12R1	2	FPA (precycle required)
Oct 20	B11L1	2	FPA (precycle required)
Oct 22	B10L2	2	FPA (precycle required)
Oct 29	A10R2	4a	Loss of communication (access)

- **In 2023 ion run we saw 12 unmitigated R2E events leading to FPA or worse**
- **6 of the 12 events were destructive failures, requiring the exchange of a board**

Year	Run type	Events/destructive
2023	pp	1 / 0
2023	ions	**12 / 6**
2022	pp	1 / 1
2018	pp	7 / 1
2018	Ions	2 / 0

Events compared to previous runs

Year	Run type	Luminosity delivered a point	Peak RadMon dose @ point	Events/destructive
2023	Ions	P2: 2.16 1/nb	P2: 5 Gy (B10L2)	**12 / 6**
2018	Ions	P2: 0.905 1/nb	P2: 0.49 Gy (B9L2)	2 / 0
2023	pp	P5: 30 1/fb	P5: 0.8 Gy (B11L5)	1 / 0
2022	pp	P5: 41 1/fb	P5: 0.4 (B8R5)	1/1 (at dose of 0.3Gy)
2018	pp	P5: 66 1/fb	P5: 28.8 Gy (B8L5)	7 / 1

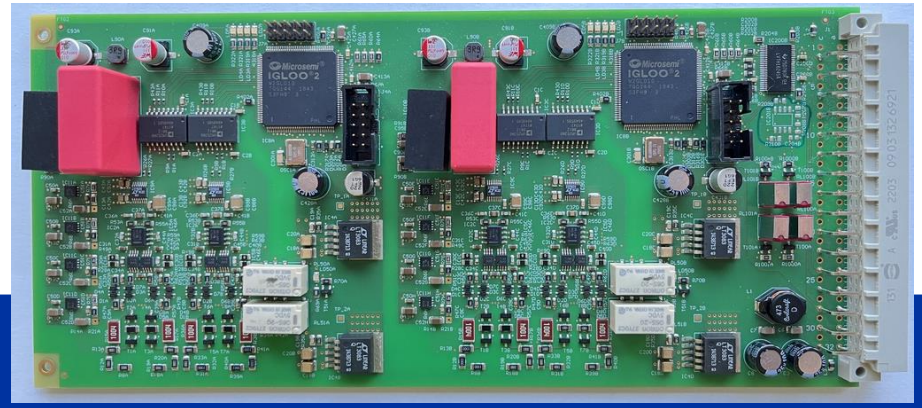
If we look at peak RadMon Doses and delivered luminosities we find:

- **Total number of events does not scale with delivered Lumi comparing same species runs**
  - Ions 23 vs 18: twice lumi vs. 6x R2E events
  - pp: 23 vs. 18: half the lumi, 1/7x of R2E events → TCL settings in 2018 lead to more losses in QDS
- **What made 2023 ions so “toxic” ?**

Mitigation

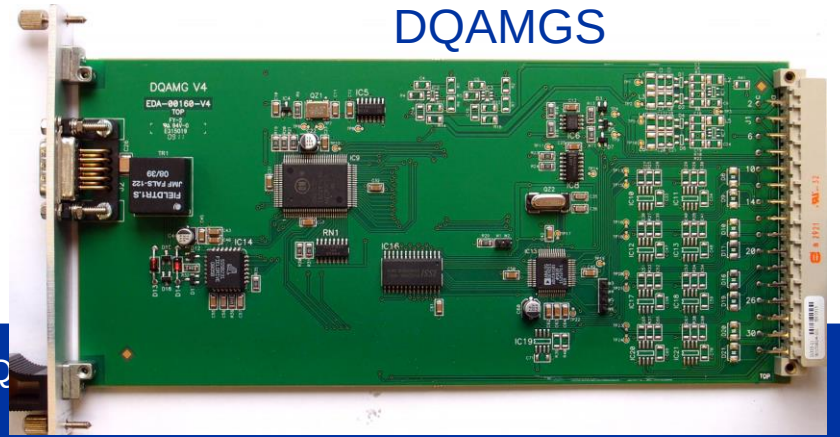
Class	Element	Mitigation	Time frame / Status
Class 2	DQQBS	New implementation of DQQBS with FPGA and rad tol SAR ADC. Already tested in CHARM and good to 700 Gy Produce 200 boards & Install around P1, P2, P5	End of EYETS 2023/2024 Plan “B”: install in TS Production launched with BE-CEM-EPR
Class 3	DQQDL (MQ)	Replace op amp by compatible type in different technology on 4 DQQDL and 2 DQCSU in racks A12 L2 & R2 (if possible also in P1 & P5)	EYETS 2023/2024 (boards already in preparation)
Class 4	DQAMGS	Produce new version with enhanced latch up protection (resettable fuse) ~ 30 Boards to be installed around P2, P1 & P5	End of EYETS 2023/2024 Plan “B”: install in TS

DQQBSv2



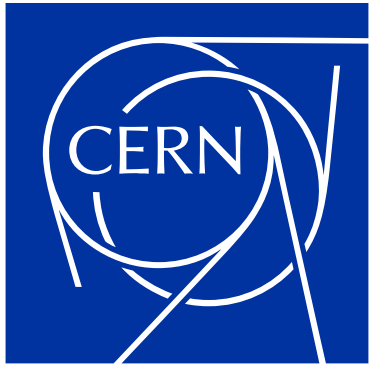
DQQDL

DQAMGS



Conclusion

- **2023 ion run lead to an overproportional amount of radiation induced events in the QDS compared to the delivered lumi**
- **Only frequency of class 2 events scaled with P2 integrated luminosity during ion run**
- **Two of the four error classes (3 and 4) were unknown so far, and not expected at all.**
- **CHARM testing strategy (system level qualification) seems not sufficient anymore**
- **Mitigation measures for the three un-mitigated event classes are underway, completion foreseen until end of EYETS (or in TS if late)**
- **A potential 2024 ion run would confirm the effectiveness of the mitigation methods**



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