Update on expected HL-LHC radiation levels

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HL-LHC WP10

Outline

- Introduction
- Radiation levels in IP1 and IP5
    - RRs and other shielded areas
    - Tunnel: Dispersion Suppressor and Inner Triplet
- Radiation levels in IP7
- Radiation levels in the ARC
- Summary & Conclusions

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Estimating radiation levels for HL-LHC

- Radiation levels around the LHC and its injectors with focus on impact to equipment: mandate of the Monitoring and Calculation Working Group (**MCWG**)
- Necessary tools/studies: monitoring of present machine, analysis of scaling and dependence on operational parameters, dedicated FLUKA simulations (**FLUKA team**)
- Expected values used to determine target cumulative levels (total ionizing dose, displacement damage) and upper failure cross sections (Single Event Effects)
- LHC systems → typically custom designs based on Commercial-Off-The-Shelf Components (Radiation Working Group, **RADWG**):
  - Categorization of system components based on criticality and possible radiation sensitivity; careful **selection of COTS** devices based on R2E/RADWG database and/or literature
  - **Qualification** at device (critical components, batch testing) and system (mixed-field irradiation at CHARM) levels, with **operational radiation environment/levels as target**

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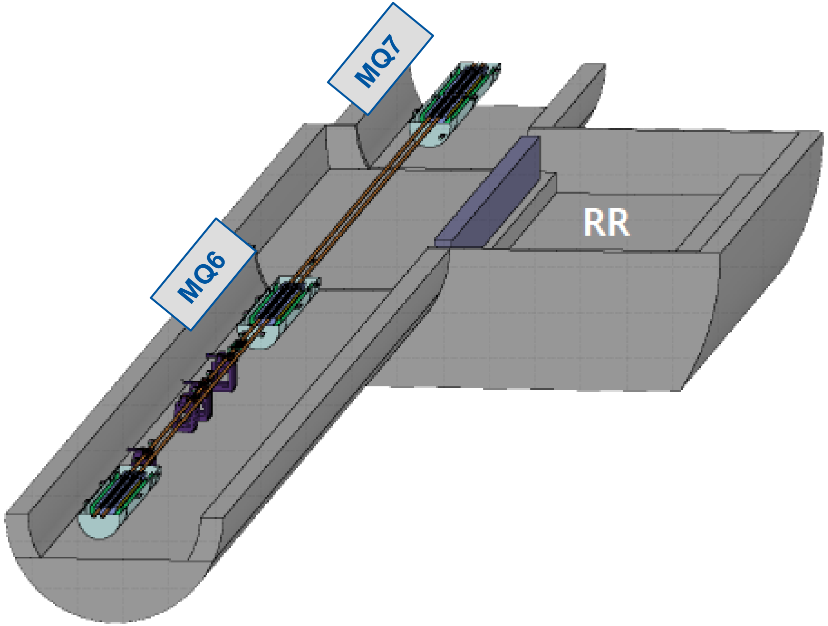
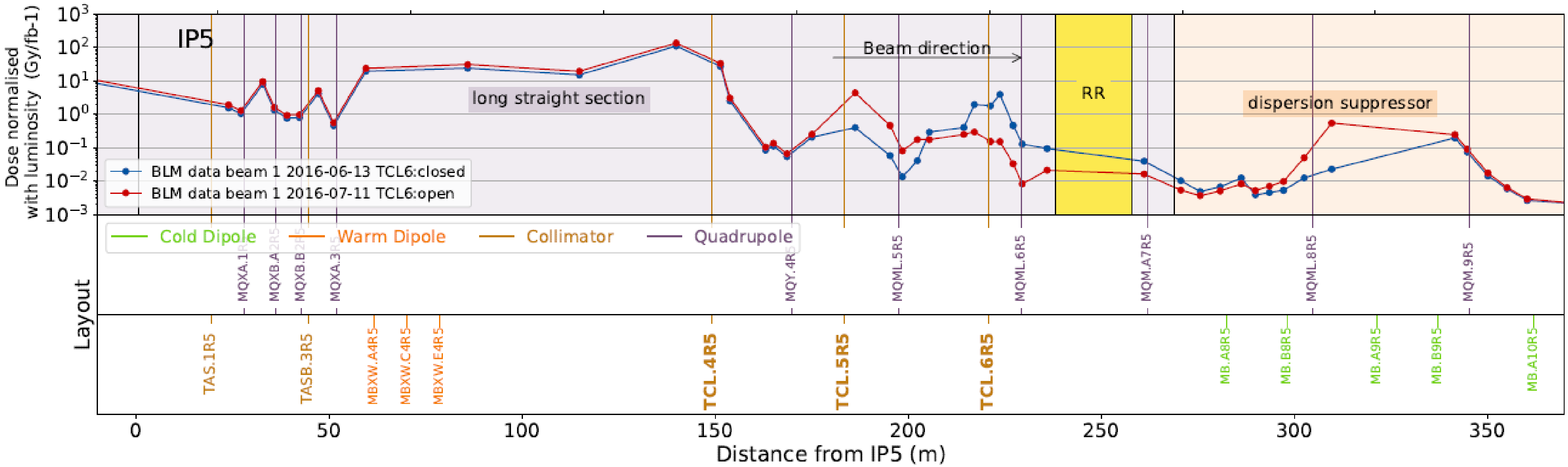
RR position and layout in IP1 and IP5



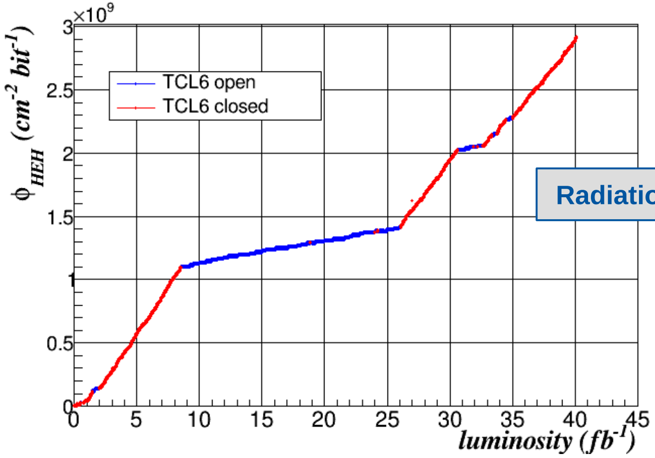
- Alcoves located between half-cells 6 and 7
- Open shielding of 40 cm cast iron
- Hosting large quantities of electronics (notably 120A, 600A and 4-6-8 kA power converters)
- Presently dominating R2E failures in LHC
- Large radiation levels expected for HL-LHC, potentially increasing beyond luminosity scaling

2016 BLM levels as a function of TCL settings



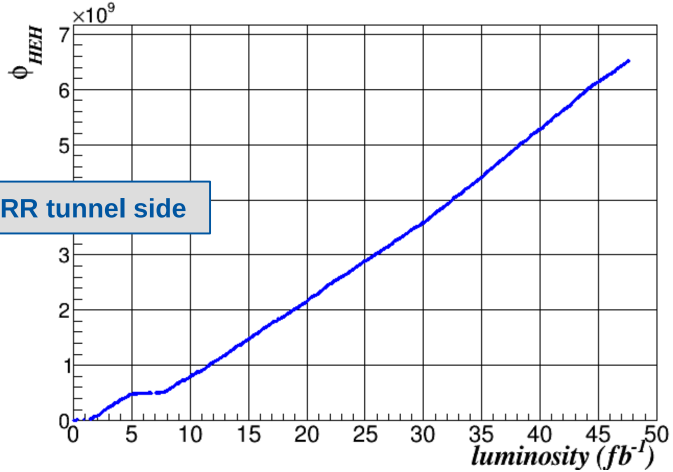
- *Radiation levels in the RR (shielded area, half-cells 6-7) and (to a lesser extent) dispersion suppressor strongly impacted by TCL settings*

RR levels: 2016 vs 2017 (RadMON data)



2016 radiation levels in RR53

Radiation levels in RR tunnel side



2017 radiation levels in RR53 (TCL6 closed)

- *Radiation levels in 2017 larger in IP1 and IP5 RRs due to forward physics operation and TCL requirements*

RR levels: 2016 vs 2017 (RadMON data)

Annual HEH fluences [cm^{-2}]

Location	Tunnel	Shielded
RR13	7.1×10^9 **(5.2)**	2.2×10^8 **(5.2)**
RR17	5.7×10^9 **(5.7)**	3.7×10^8 **(6.9)**
RR53	6.6×10^9 **(2.3)**	3.2×10^8 **(2.7)**
RR57	9.1×10^9 **(2.0)**	3.3×10^8 **(2.1)**

2017 levels (ratio with respect to 2016)

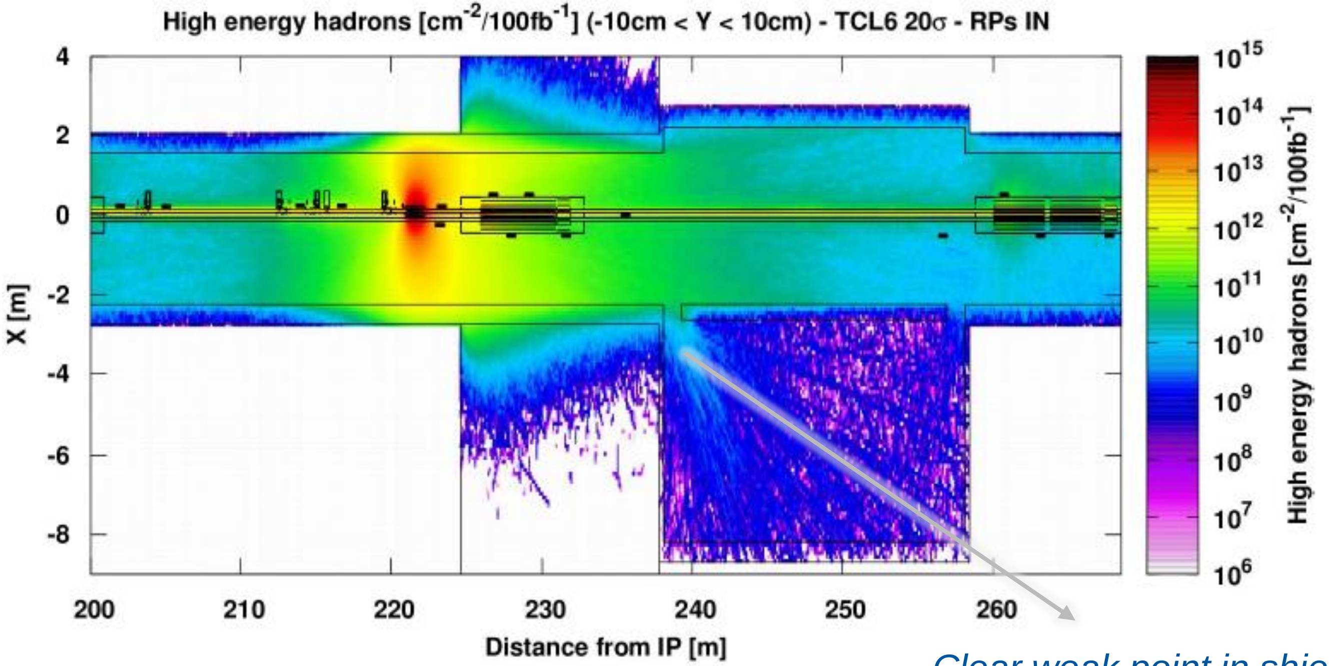
Location	Tunnel	Shielded
RR13	1.36×10^9	4.19×10^7
RR17	1.00×10^9	5.37×10^7
RR53	2.87×10^9	1.17×10^8
RR57	4.55×10^9	1.56×10^8

2016 levels

Radiation level increases from 2016 to 17 by factor 2-3 in IP5 and 5-7 in IP1

Updated simulations: TCL6 in, RP in

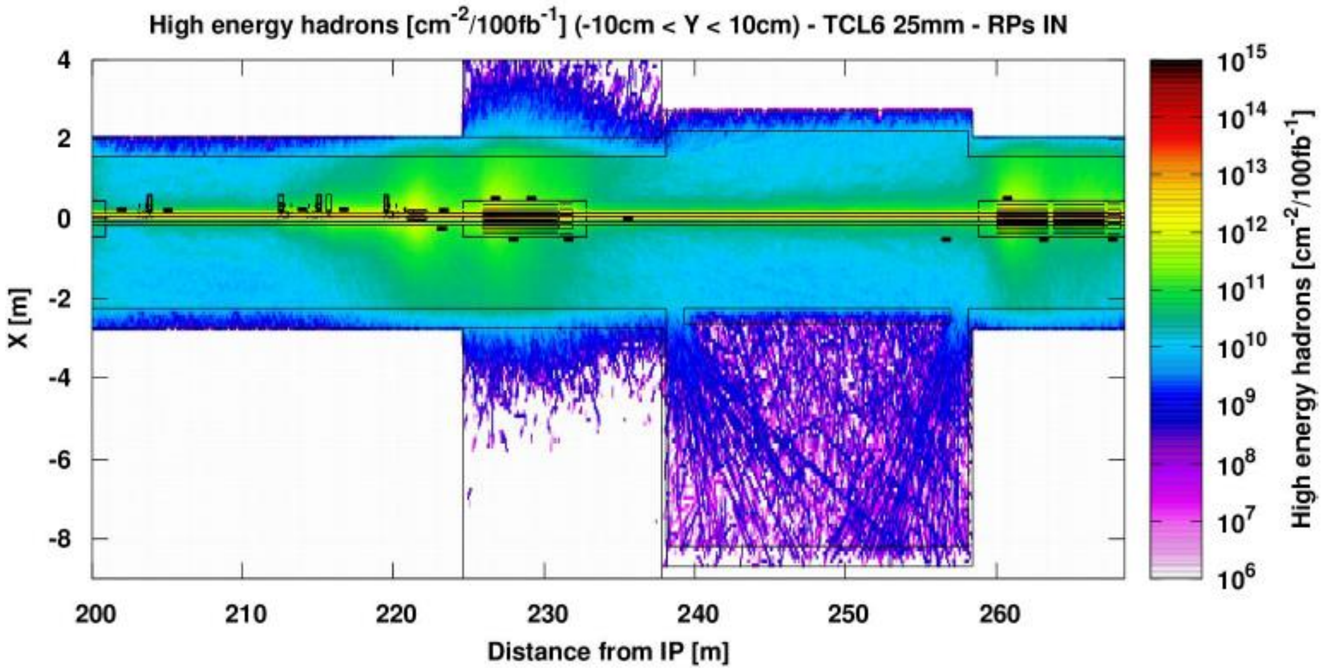
Simulations right of IR5



2017 situation for IP1 and IP5

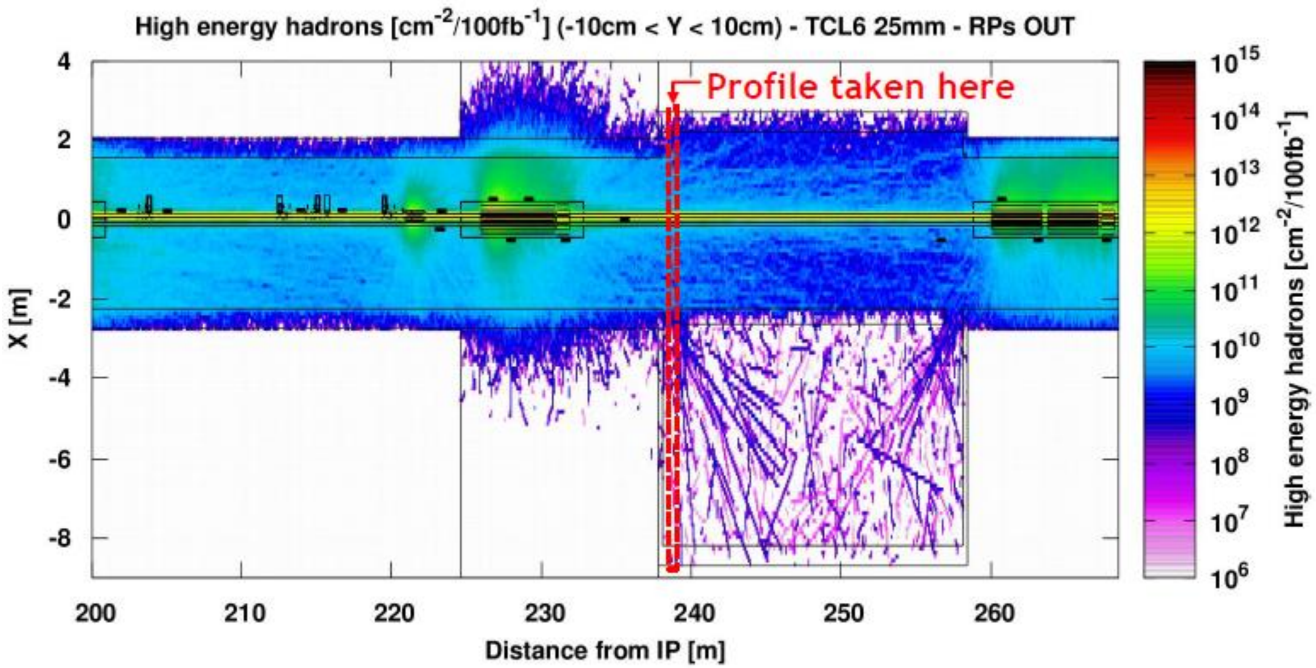
Clear weak point in shielding due to access constraints – possible optimization to be carried out in LS3

Updated simulations: TCL6 out, RP in



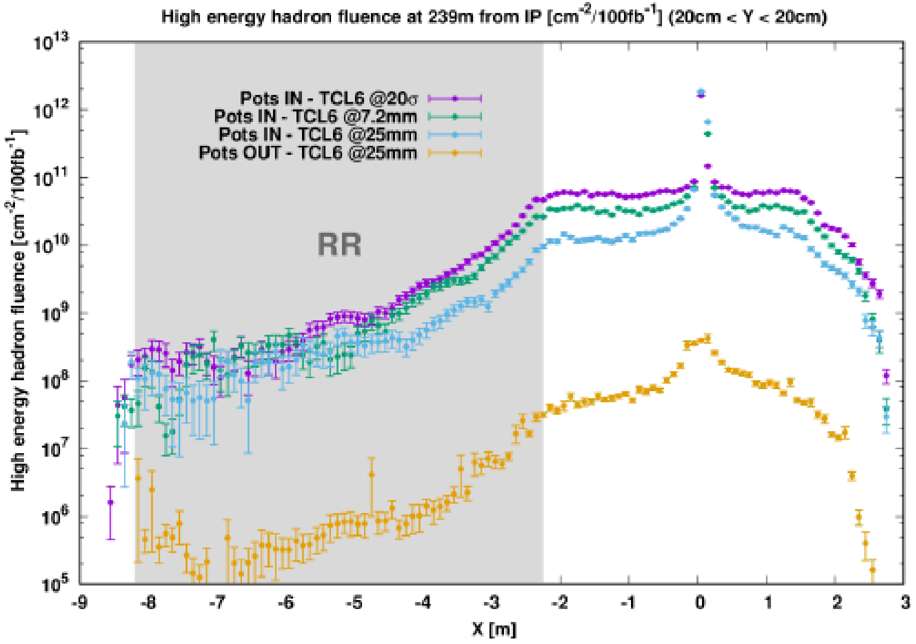
Benchmarked during 2017 end-of-fill TCL scans (collimation team)

Updated simulations: TCL6 out, RP out



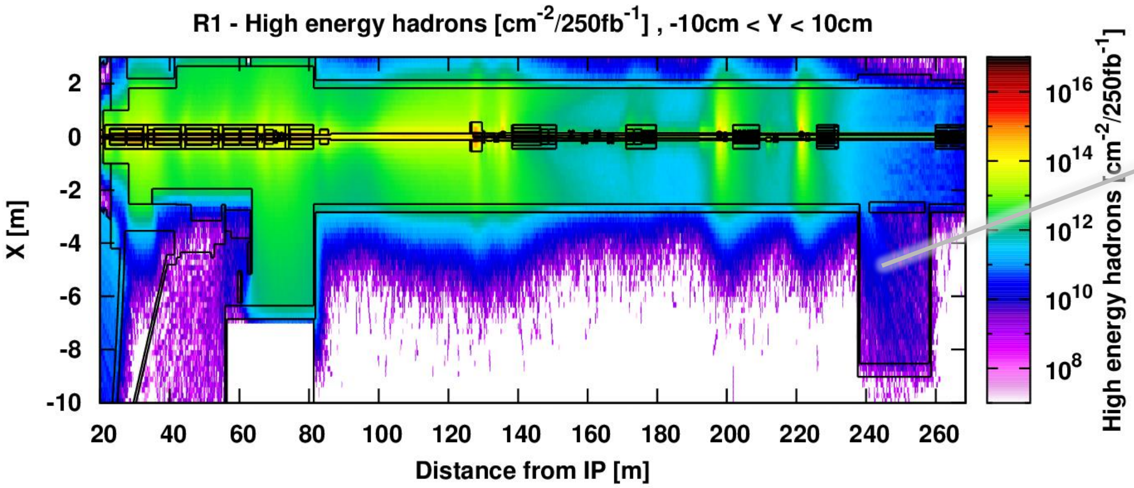
2016 situation for IP1

Updated simulations: impact of RPs



- For present LHC machine, R2E failures dominated by power converters in IP1 and IP5 RRs
- For TCL6 closed settings, 10-15 R2E failures per year (50 fb^{-1}) are expected
- Failure rate acceptable for LHC operation, but if scaled with radiation levels, could become a threat for HL-LHC operation → rad-tol converters in LS2
- For present machine and as derived by end-of-fill scans/FLUKA studies, reducing the RR radiation levels by opening TCL6 does not provide significant reduction margin due to RP impact
- For HL-LHC, TCL settings will be determined by magnet protection needs

FLUKA simulations for HL-LHC RRs



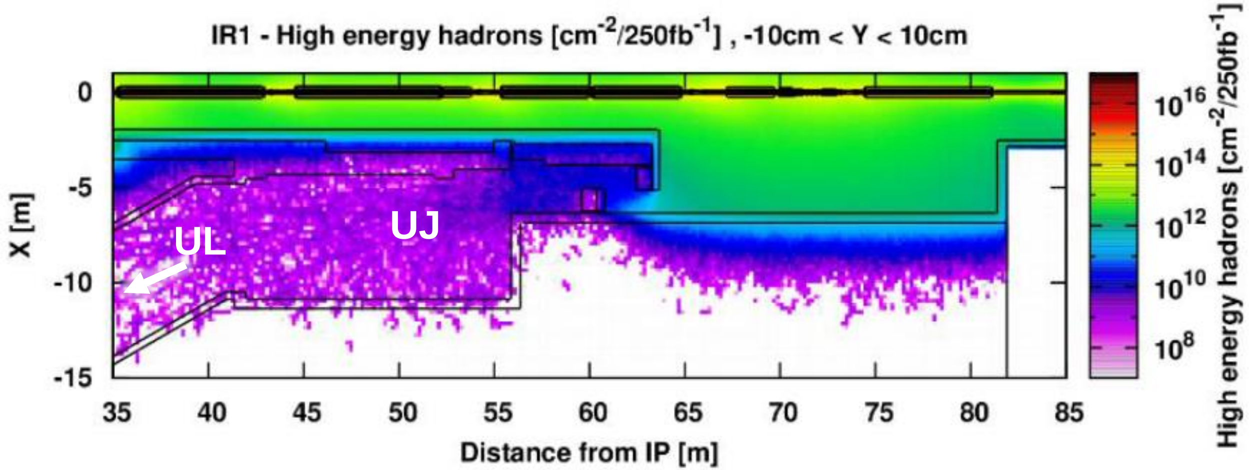
Expected RR radiation levels for HL-LHC

Quantity	Expected Value
ϕ_{HEH} (cm^{-2}yr^{-1})	~3×10^{9}
ϕ_{neq} (cm^{-2})	~3×10^{11}
TID (Gy)	~60

Annual fluence (250 fb^{-1}) for HEH, total cumulative (3000 fb^{-1}) for displacement damage (ϕ_{neq}) and TID

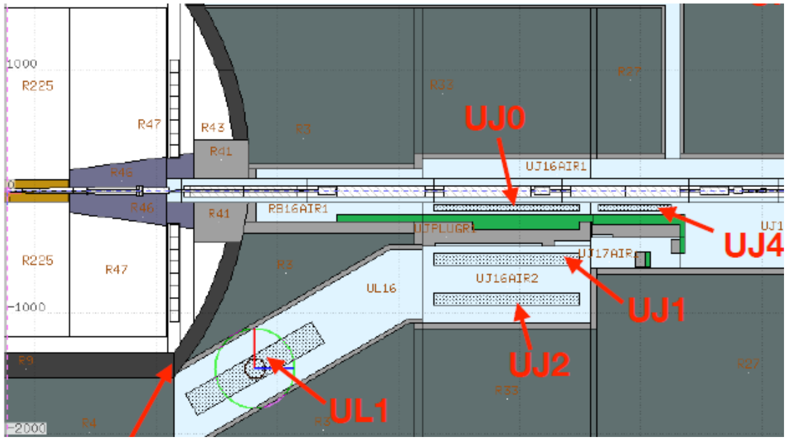
- *Highly challenging ϕ_{HEH} annual levels [example: 100 systems and 1 failure per system upper limit implies upper limit for* ***SEE cross section*** *of 3×10^{-12} cm^2/system → 2-3 systems tested during 2-3 weeks at CHARM (i.e. operating facility to its limit)]*
- *Even in shielded areas, cumulative expected values can imply* ***lifetime threat*** *for sensitive COTS (e.g. displacement damage in opto-couplers)*

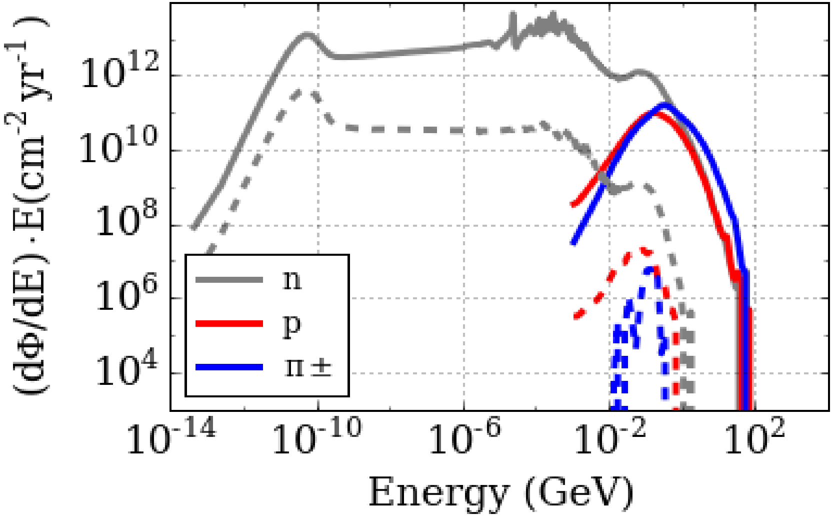
FLUKA simulations for HL-LHC UJs and ULs



- *UJ levels compatible with integrated luminosity scaling from present machine → for HL-LHC,* ***~5×10^{9}*** *HEH/cm^{2}/year*
- *UL expected levels of* ***~1×10^{8}*** *HEH/cm^{2}/year [i.e. high risk of SEEs for distributed system]; strong gradients and complex location dependence [two sources: leak from UJ and directly from experimental cavern]*

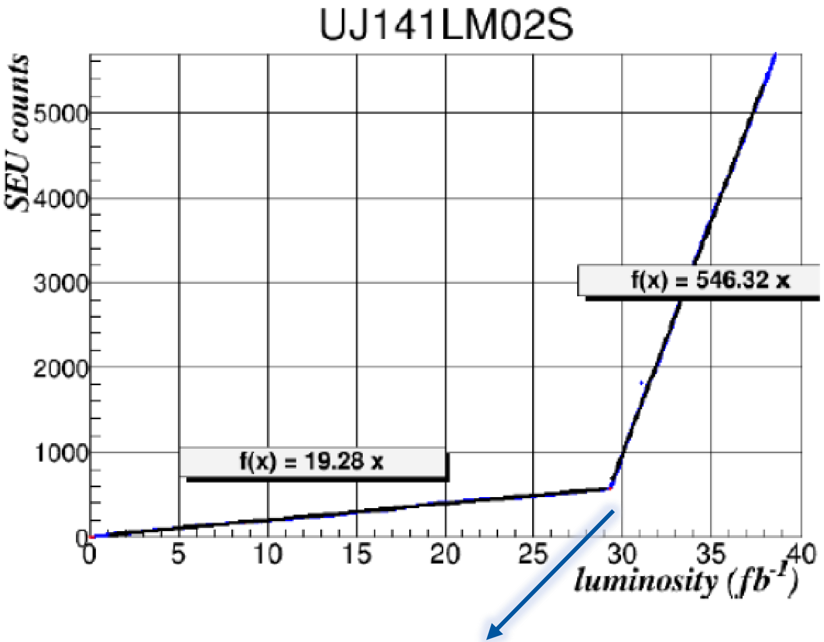
Brief particle energy spectra consideration





- *Tunnel location (UJ0, full lines) versus shielded location (UJ1, dashed lines)*
- *Relative neutron contribution increases significantly with shielding, notably the relative thermal neutron flux*

UJ thermal neutron flux measurement



Reduction in supply voltage for enhanced thermal neutron sensitivity

- Thermal neutron flux can be measured by varying RadMON supply voltage
- Quantified through **R-factor** as ratio between thermal and high-energy hadron fluxes
- 2016 measurements in UJ show R-factors of **10-15** (i.e. prominent thermal neutron flux as expected for shielded areas)
- Sensitivity to thermal neutrons not considered in HEH flux values, and becoming (again) relevant for SEUs in deep sub-micron technologies (e.g. **SRAM based FPGAs**)

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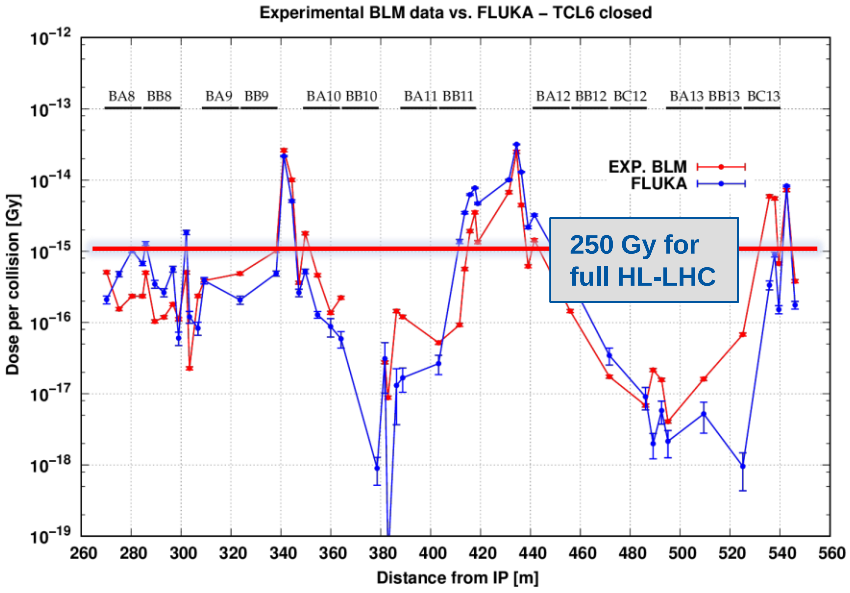
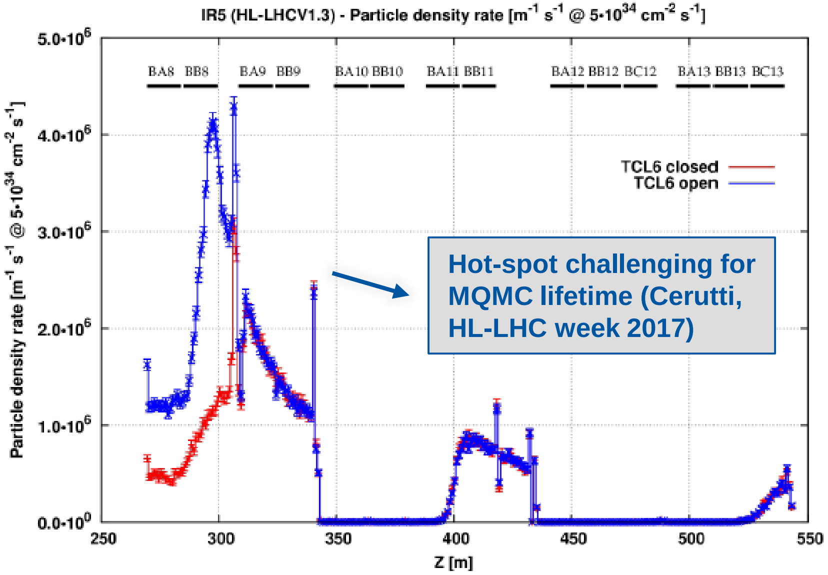
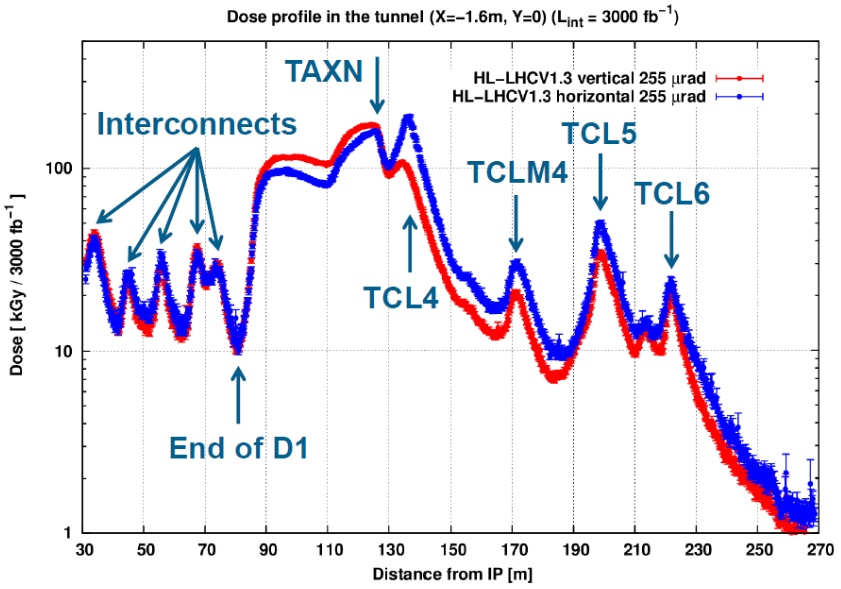
FLUKA simulations for HL-LHC DS

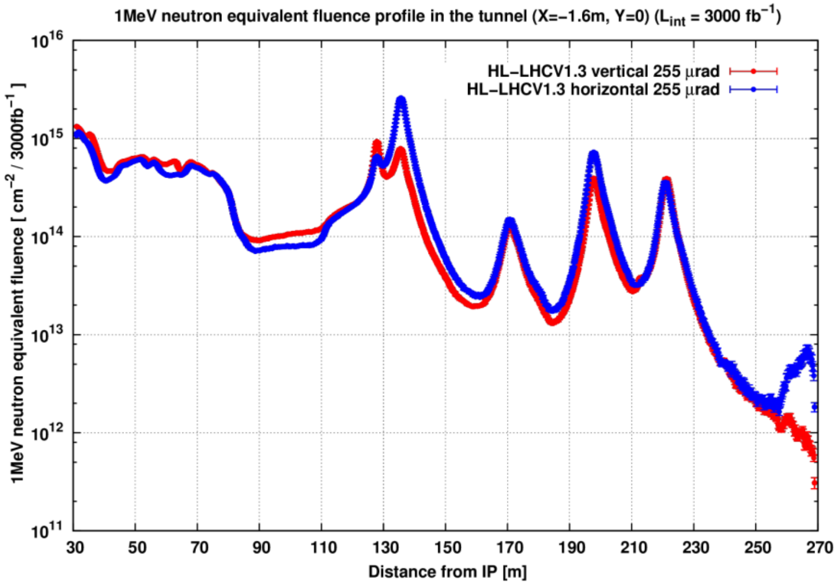




- *DS areas host broad variety of COTS based critical systems, notably QPS*
- *Present machine levels expected to increase with integrated luminosity, yielding **annual TID levels below 10 Gy** for majority of areas below dipole magnets → strong gradients: importance of distributed monitoring and possible relocaton*

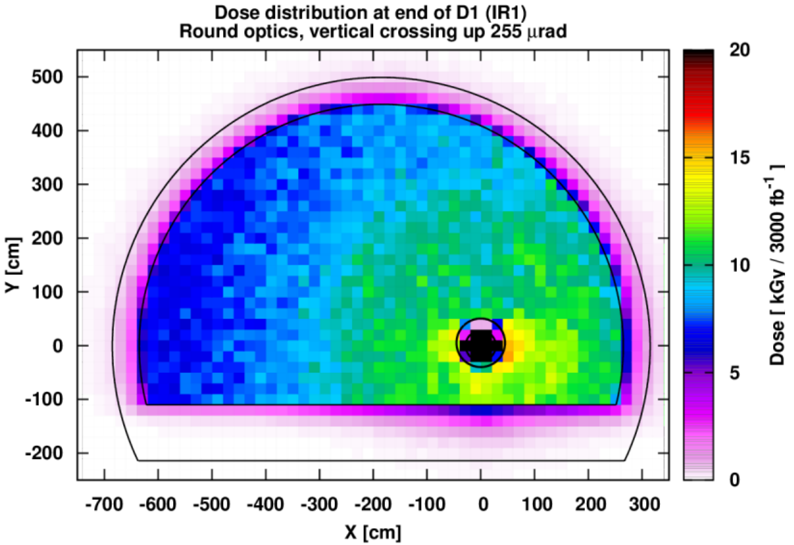
FLUKA simulations for HL-LHC LSS

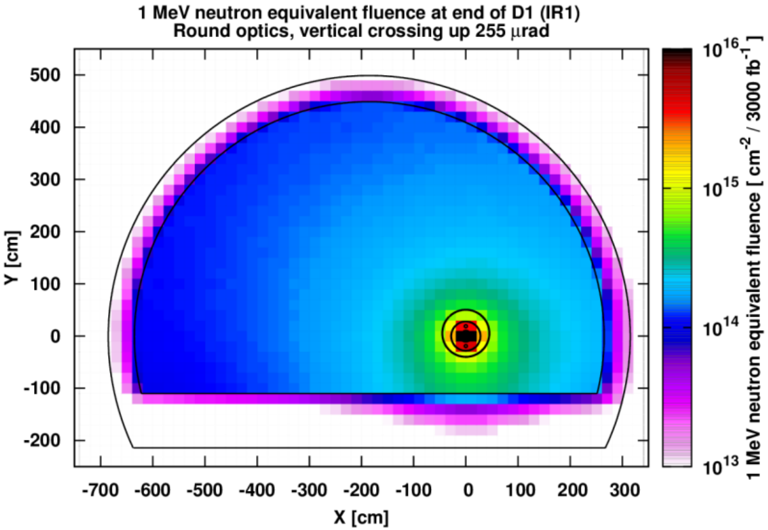




- *The LSS tunnel will in general not host active COTS based systems; however radiation levels around the machine are still highly relevant for e.g. passive electronics (gauges, cables, etc.)*
- *FLUKA/R2E study carried out to evaluate radiation levels and respective qualification options for by-pass cold diodes for HL-LHC to be placed in DFX (D1 extension)*

Transversal cut at end of D1





- *Expected cumulative radiation levels at DFX area (possible location for by-pass diodes) are* ***~15 kGy*** *and* ***~5·10^{14} n$_{eq}$/cm^2***
- *Test programmed at* ***CHARM*** *for 2018 with main objective of reproducing previous results on diffusion diodes (tested up to ~2 kGy and ~3×10^{13} n$_{eq}$/cm^2); however qualification of new diodes with enhanced radiation tolerance will need to be carried out in* ***external facility*** *(LS2 CHARM shutdown, limitation on achievable radiation levels)*

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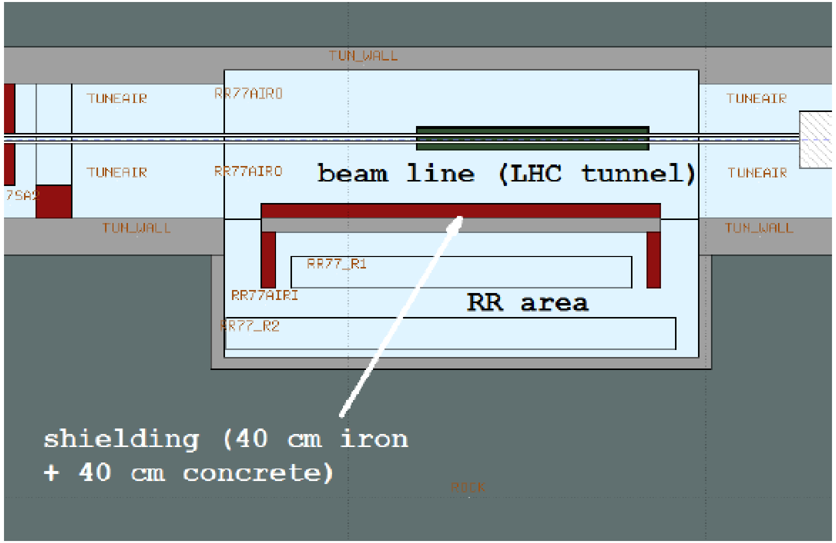
IP7: RRs

- *RR radiation levels in IP7 similar to those in IP1/5 on tunnel side*
- *Inside the RR shielded (i.e. relevant for equipment) levels are a factor 5-10 lower than shielded areas in IP1/5 due to enhanced shielding*
- *In addition, scaling in IP7 for HL-LHC (intensity driven) will be less than for IP1/5 (luminosity driven)*



Present machine

Point	Tunnel	Shielded
1	10^9	$3\text{-}5\times10^7$
5	$3\text{-}5\times10^9$	$0.5\text{-}1\times10^8$
7	$1\text{-}2\times10^9$	10^7

2016 HEH fluences (cm^{-2}) in RR tunnel and shielded areas

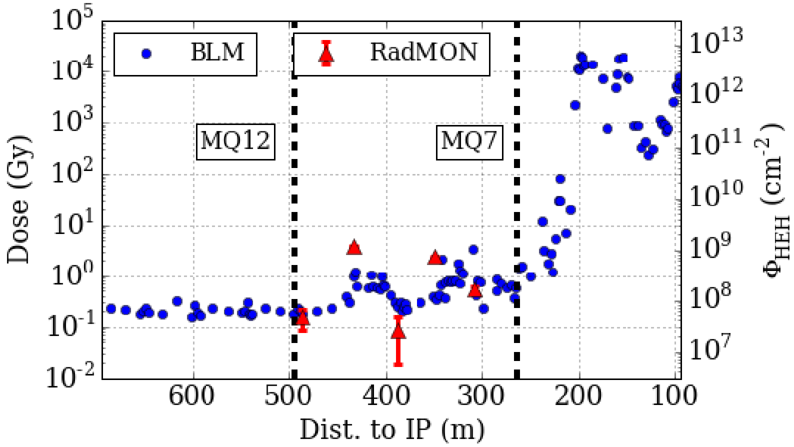
HL-LHC

→ *3×10^9* *SEE and lifetime threat*

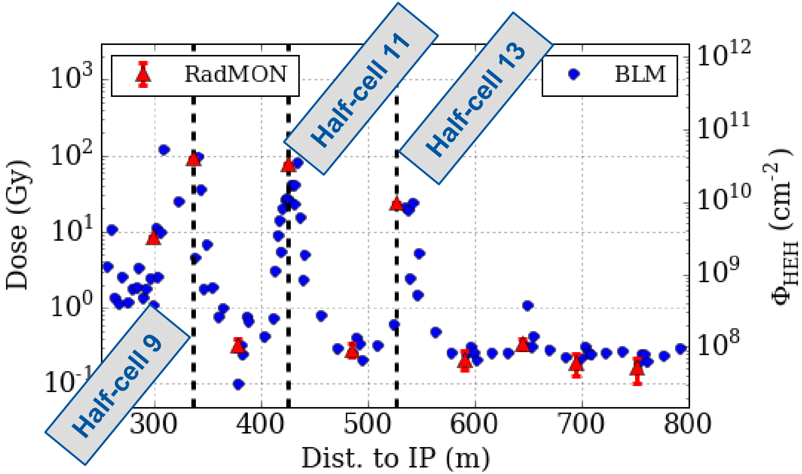
→ *2×10^8* *Mainly SEE threat*

IP7 vs IP1/5: Dispersion Suppressor

2016, L7



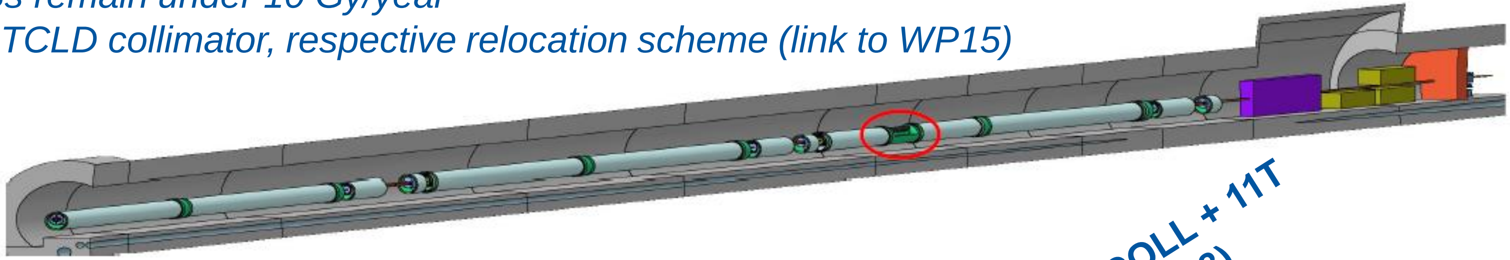
2016, R5

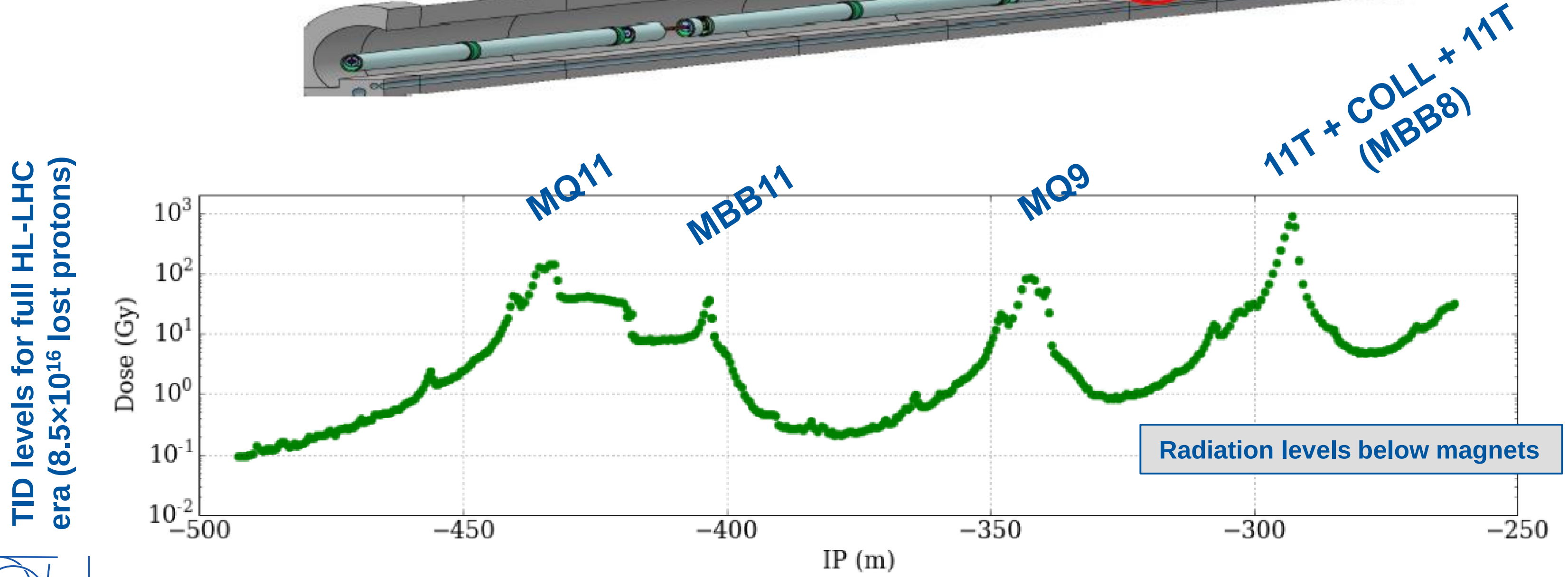


- *Levels in IP7 DS are over an order of magnitude lower than those in IP1/5 for present machine*
- *In addition, levels for HL-LHC IP7 are expected to increase with integrated intensity, whereas levels in IP1/5 will scale with integrated luminosity*

HL-LHC IP7 DS levels: 11T/TCLD configuration

- *FLUKA calculations for HL-LHC radiation levels in DS, driven by 11T/TCLD configuration*
- *Levels below MBs remain under 10 Gy/year*
- *Hot-spot around TCLD collimator, respective relocation scheme (link to WP15)*





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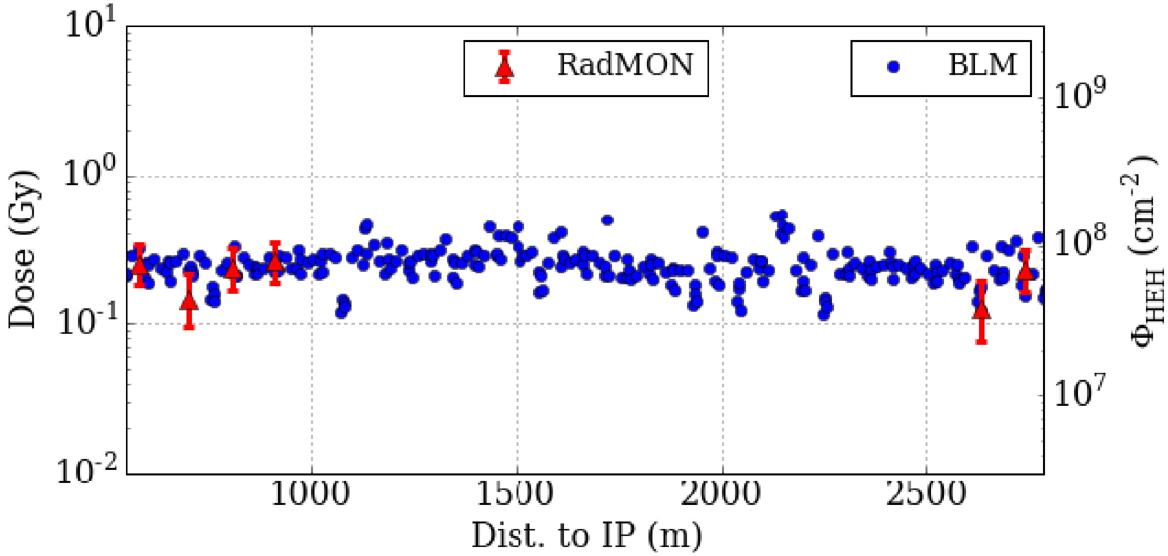
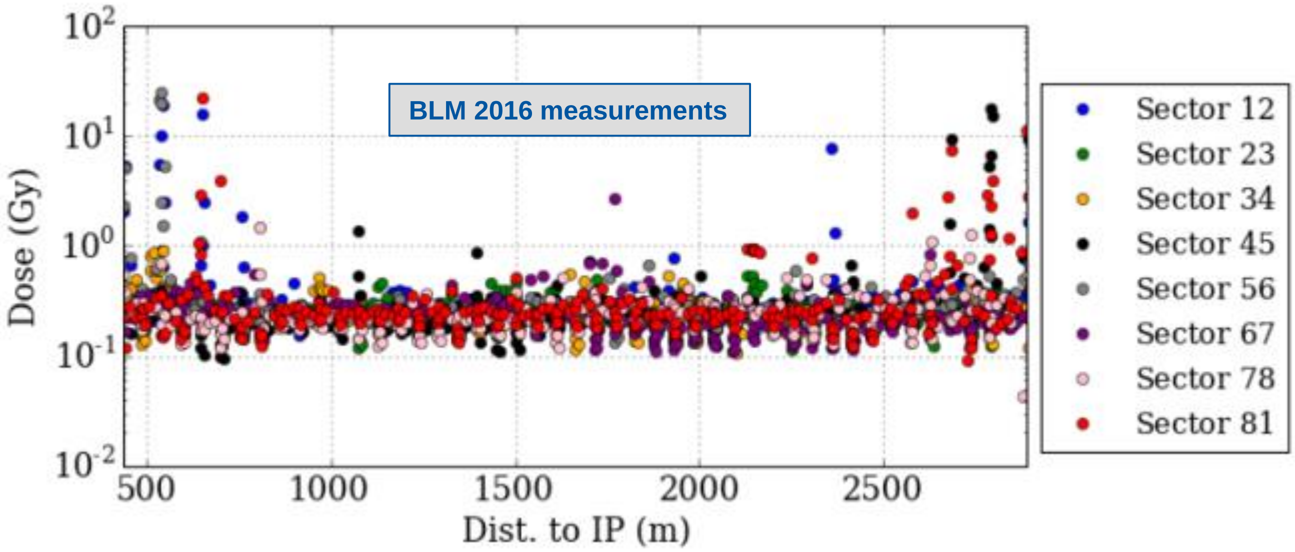
LHC ARC

2016 radiation levels in LHC ARC – Sector 23



*BLM annual doses of **less than 1 Gy**, HEH annual fluences of **~5×10^7 HEH/cm^2** → can be considered as baseline due to beam-gas interactions in the ARC*

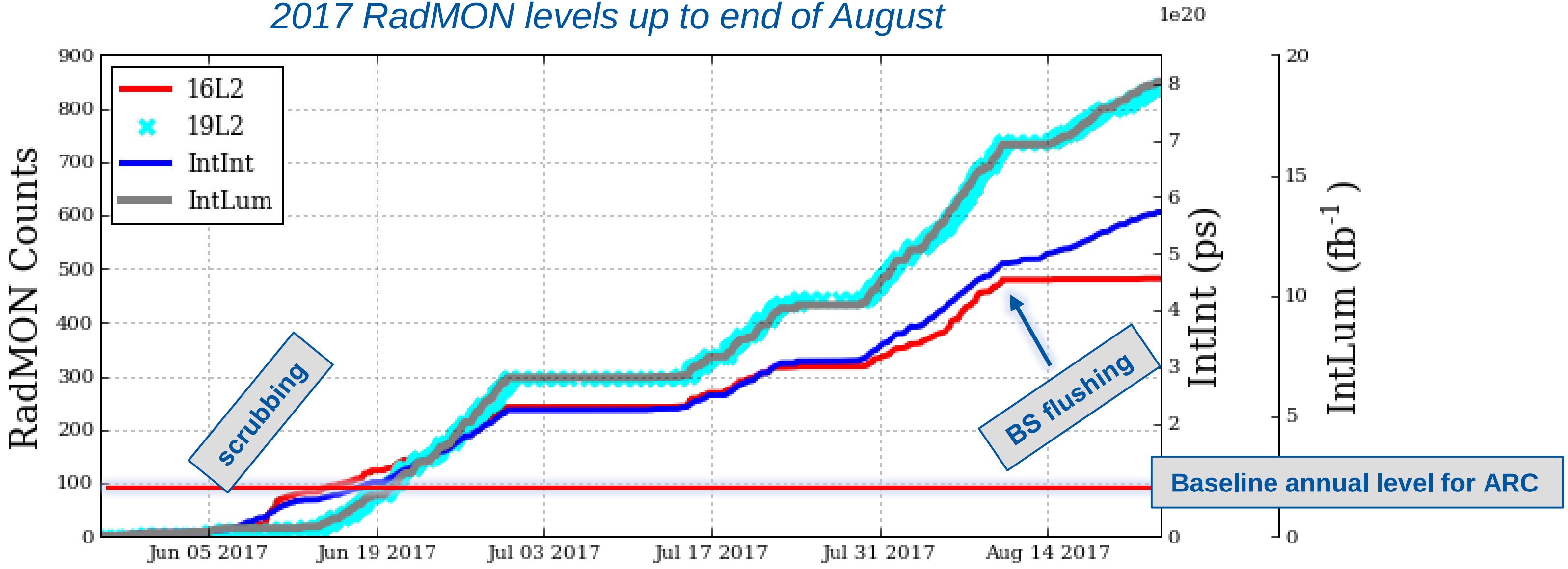
LHC ARC



- *"DS like" peaks of up to few 10s of Gy per year observed locally in the ARC*
- *Important to monitor their evolution: if driven by luminosity, they could become a threat for equipment lifetime in HL-LHC (or before, e.g. 60A power converter ~50 Gy TID lifetime estimation)*

LHC ARC: 16L2 and 19L2

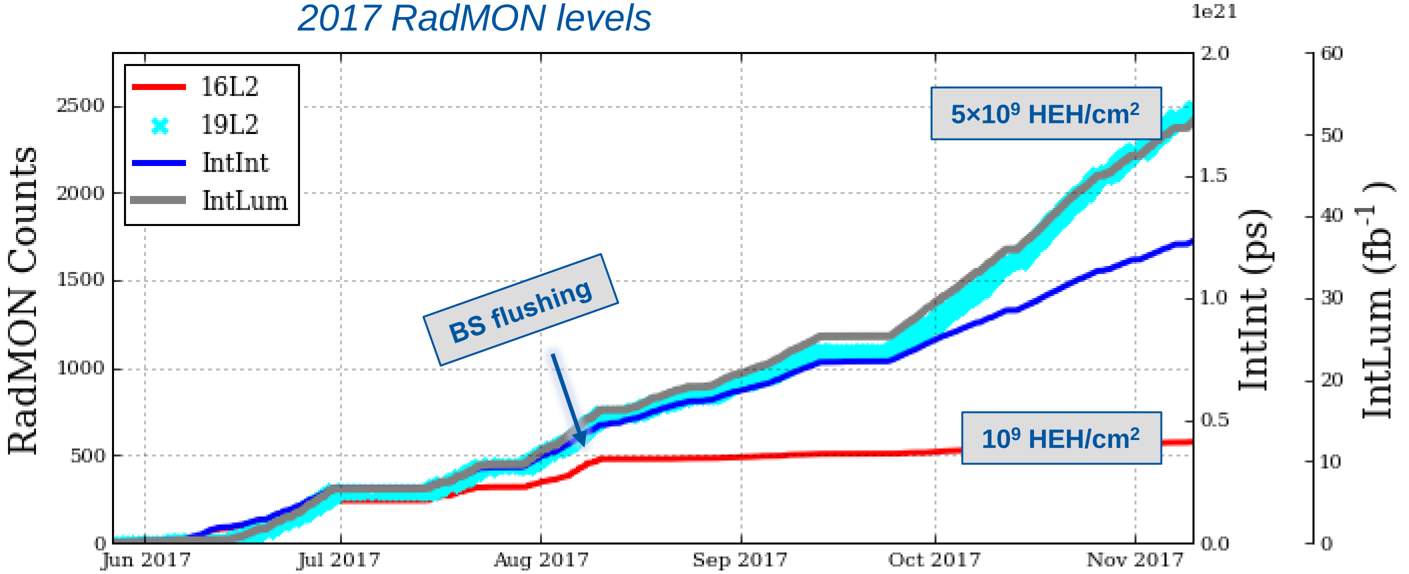
2017 RadMON levels up to end of August



- *Two examples of ARC radiation level peaks: 16L2 (intensity driven) and 19L2 (luminosity driven)*
- *16L2 losses already significant during scrubbing; steady-state losses disappeared (i.e. compatible with baseline level) after BS flushing (compatible with BLM observation)*

LHC ARC: 16L2 and 19L2

2017 RadMON levels



- *Radiation levels in 16L2 (19L2) in 2017 were a factor 20 (100) larger than baseline value*
- *Just two examples of arc peaks → currently under investigation with focus on equipment impact*

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HL-LHC radiation level summary

Location	Expected radiation level			
	HL-LHC Annual		HL-LHC Lifetime	
	HEH ($cm^{-2}yr^{-1}$)	SEU rate (yr^{-1}) (*)	TID (Gy)	1 MeV n_{eq} (cm^{-2})
LHC arc (**)	1×10^9	500	20	1×10^{10}
Dispersion Suppressor (below dipoles)	1×10^{10}	5×10^3	200	1×10^{11}
UJ (IP1 and IP5)	5×10^9	5×10^3	100	5×10^{11}
UL (IP1 and IP5)	1×10^8	100	2	5×10^{10}
RR (IP1 and IP5)	3×10^9	2×10^3	60	3×10^{11}
RR (IP7) (***)	2×10^8	150	5	2×10^{10}

(*) SEU rate for component with sensitive surface of ~4 cm^2 and LET threshold of ~3 $MeVcm^2/mg$
(**) Scaled with intensity, safety margin of 5 (i.e. peaks not considered)
(***) Scaled with intensity, safety margin of 3

Not directly covered in overview

- But still carefully considered:
  - Radiation levels in **injectors**: new electronics (e.g. BPM system), possible LIU impact, increasing impact on LHC availability
  - LHC **ion losses** and respective radiation levels → can locally dominate overall levels
  - Correlation between operational and **test facility** environments/radiation effects, and implications on qualification approach

Conclusions & Outlook

- Highly **valuable experience from Run 2** radiation levels and correlation with operational conditions; crucially complemented by dedicated FLUKA calculations
- HL-LHC: significantly more stringent overall reliability requirements on critical systems, plus increased radiation levels (in some critical locations, scaling above integrated luminosity)
  - Aiming at **"SEE-free" COTS based systems** (upper limit of one R2E failure per system-year, compatible [but near the limit] of CHARM qualification capabilities)
  - **Cumulative levels** start becoming a serious threat for COTS based systems, even in partially shielded areas
- Outlook: focus on further LHC analysis will be on **ARC levels**, including peaks and dependence with operational parameters