HiLumi
HL-LHC PROJECT

Status and outlook of specification document for HL-LHC radiation environment for electronics

WP10
Energy Deposition & R2E

CERN

EN STI

R2E

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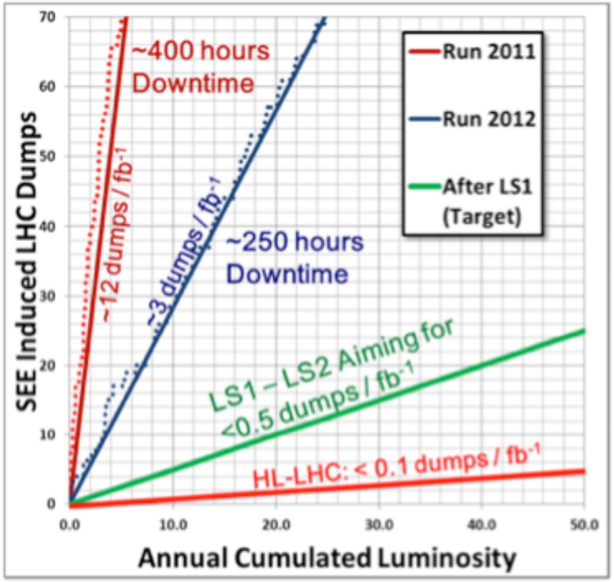
Introduction

- A **radiation level specification document for HL-LHC** is in preparation, covering all areas where COTS-based electronics are employed. Full review planned in ~2 months (tentative date: 12 December).
- Content of the talk:
  - Introduction to R2E at the LHC: radiation induced effects, HL-LHC challenges and Radiation Hardness Assurance procedure.
  - Strategy for the definition of HL-LHC radiation level specifications and scope of the specification document.
  - Preliminary results in a selection of machine locations for proton and (when relevant) ion operation: **DS and shielded areas of IR1-IR5, DS of IR7 with 11T magnets, RRs of IR7, LHCb experimental cavern and nearby shielded alcoves (IP8), LHC arcs**.

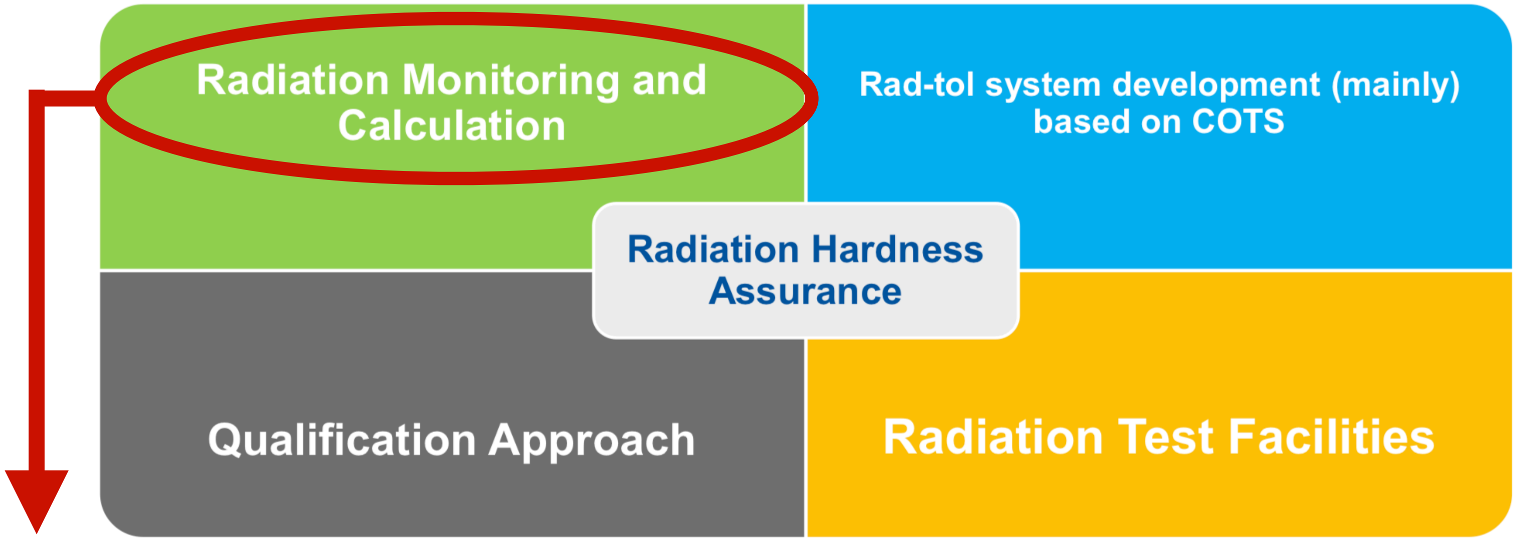
Radiation to Electronics (R2E) and HL-LHC

- Radiation-induced effects on electronics at the LHC:
  - **Cumulative effects**
    - **Total Ionising Dose (TID) [Gy]**.
    - Displacement Damage (DD) driven by **Silicon 1-MeV neutron equivalent fluence (1MeVneq) [cm^{-2}]**.
  - **Single Event Effects (SEEs)**
    - Stochastic events driven by **High Energy Hadron (HEH) and thermal neutron fluence [cm^{-2}]**.



- **HL-LHC:** higher performance → **higher radiation levels**.
- R2E challenges:
  - **Equipment lifetime** constraints.
  - **Reduction of the SEE rate** to improve the machine availability.

RHA procedure and radiation level specifications



- The first step of the **Radiation Hardness Assurance** (RHA) procedure for HL-LHC electronic systems is the **monitoring and calculation of radiation levels**.
- Scope of the specification document: **definition of the radiation levels that the electronic systems at the LHC must be qualified against, in each relevant location of the machine**.

Radiation level specification approach

- The specifications are obtained by combining the data of **radiation monitors** from Run 2 (BLMs, RadMons, etc.) and the predictions of **Monte Carlo simulations** (FLUKA) taking into account:
  - the expected evolution of operational quantities of the LHC.
  - additional safety margins applied according to risk-mitigation principles and expert knowledge.
- By including the specifications in a single document we aim to:
  - **Provide a consistent set of radiation level specifications to all relevant electronic systems,** which remains stable during their development and qualification.
  - **Organise the specifications coherently with the structure of the official HL-LHC documents** (e.g. WP15 integration reports) to facilitate the access to the information.
- A dedicated review is planned (tentative date: 12 December) to ensure that the document meets the requirements of all users.

Preliminary structure of the specification document

Introduction to the different sources of radiation at the LHC

Strategy and tools to derive the R2E specifications

Radiation level specifications presented by location:

- Shielded areas: individual specification for each alcove.
- Tunnel: peak levels below cryostat in each half-cell.

Note: LSS regions not included because the radiation levels are too high for COTS-based electronics: see dedicated talk.

Sources of radiation at the LHC

- Radiation at the LHC is produced with three main mechanisms:
  - **Proton and ion collisions**: inelastic scattering, Bound Free Pair Production (BFPP) and Electromagnetic Dissociation (EMD) for ions.
    → primary source of radiation in **IR1-IR2-IR5-IR8**.
    → radiation levels proportional to **integrated luminosity**.
  - **Interaction of the beam with beamline elements** (e.g. collimators, absorbers, beam screen).
    → primary source of radiation in **IR3-IR7**.
    → always responsible for the **secondary radiation showers** that reach the equipment, even where it is not the primary source.
    → radiation levels influenced by **machine parameters** (optics, collimator settings, shielding elements).
  - **Interaction of the beam with gas remnants** in the pipes:
    → yields lower radiation levels compared to the above effects, and it is typically relevant only in the **arcs**.
    → levels proportional to **beam intensity** and **vacuum pressure**.

Radiation monitoring and calculations: tools and approach

~4000 **BLM detectors** installed along the LHC experimental complex.

Essential tool for online TID monitoring during operation.

~400 **RadMons** installed in the tunnel (DS and first part of the arcs) and shielded areas.

They measure HEH fluence with SRAMs (v6 RadMons), TID with RadFETs and 1MeVneq fluence with PIN diodes.

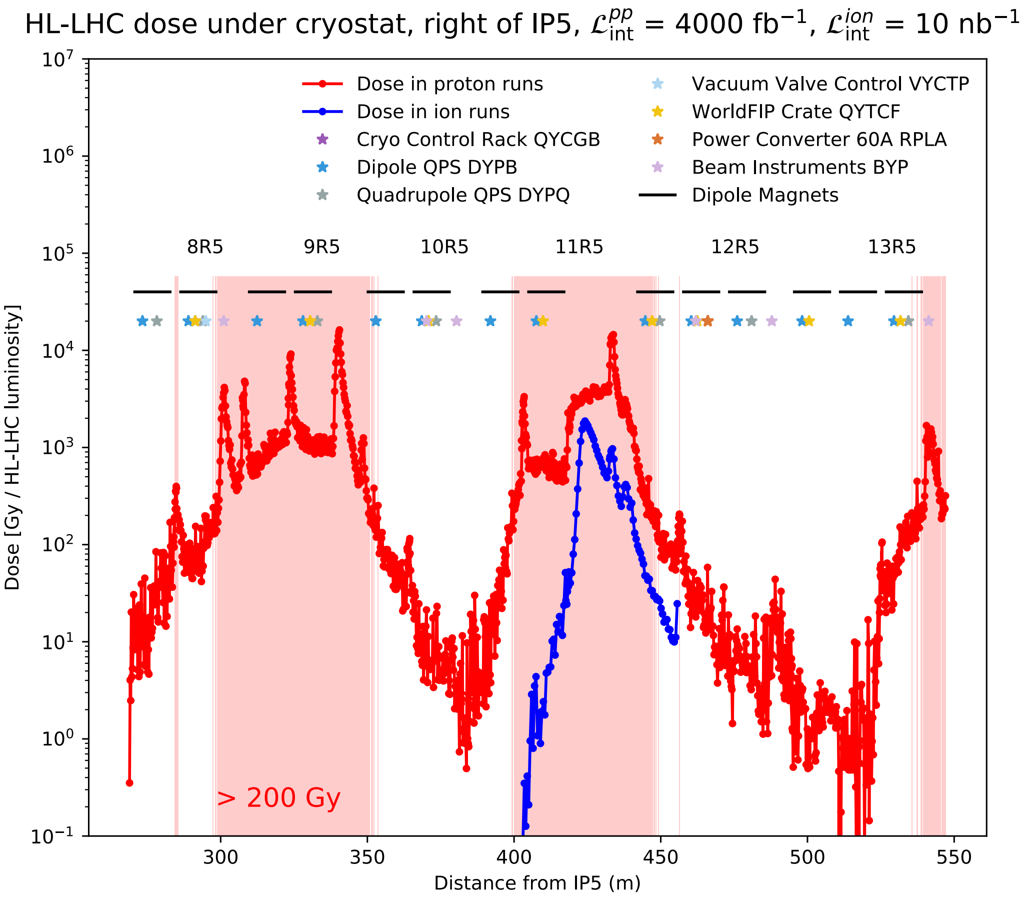
FLUKA

Additional information from **FLUKA simulations**, essential to define HL-LHC specifications.

- Data and simulations studied for R2E purposes within the **Monitoring and Calculation Working Group (MCWG)** - link to regular meeting on indico.
- Another promising tool for radiation monitoring is **optical fibre dosimetry** (see review by D.Di Francesca).

TID below the cryostats in the IR1-IR5 DS

- **Red:** TID below the cryostats (electronic rack position) for proton operation (**4000 fb^{-1}**) from FLUKA simulation by A.Tsinganis with HL-LHC optics v1.3 and TCL4-TCL5-TCL6 closed (14σ).
- **Blue:** TID for ion operation (**10 nb^{-1}**) from a FLUKA simulation of Bound Free Pair Production (BFPP).
- Note: a relevant portion of the ion luminosity is expected in Run 3, so for the next few years ion losses will be the dominant source of radiation in cell 11.
- Significant TID spikes in cell 9 → not trivial to define a single TID specification per half-cell.

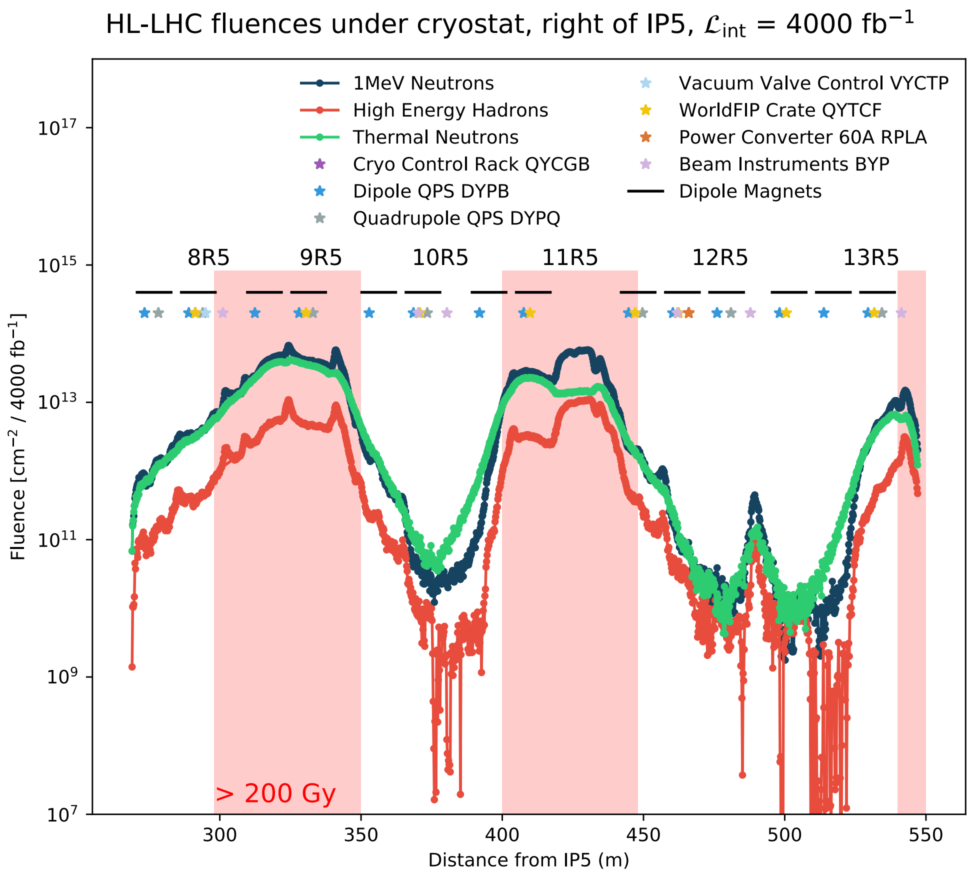


Fluences below the cryostats in the IR1-IR5 DS

- High Energy Hadron (HEH), 1 MeV neutron equivalent and thermal neutron fluences below the cryostats in the IR1-IR5 DS for the ultimate HL-LHC scenario (**4000 fb^{-1}**).

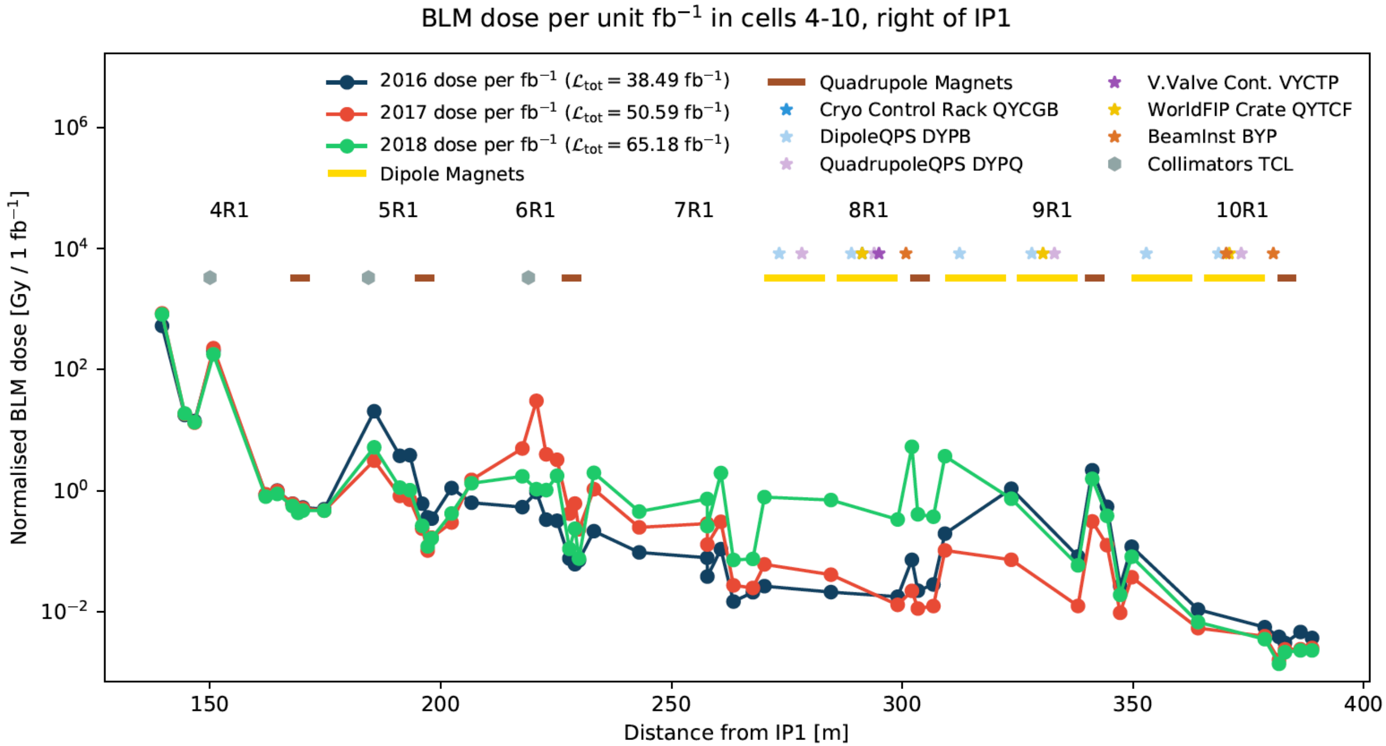
- Results for proton operation only, based on the FLUKA simulation by A.Tsinganis with HL-LHC optics v1.3. The areas with TID > 200 Gy are highlighted.

- Similar pattern as for TID but less local fluctuations, as expected for hadron-dominated quantities.



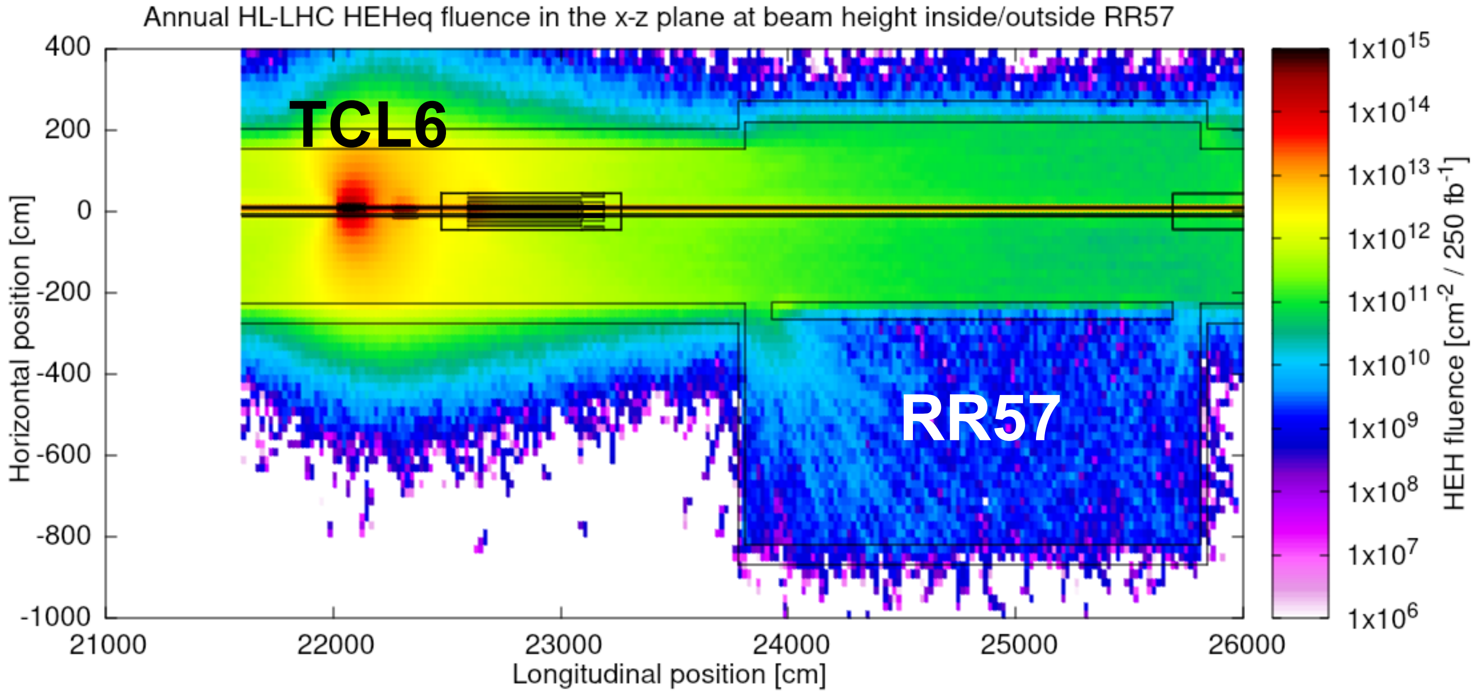
Impact of collimator settings on IR1-IR5 DS levels

- In Run 2 the LHC operated with **different TCL5, TCL6 and Roman Pot (RP) settings**, with **impact on the radiation levels in the DS**.
- The 2018 configuration with TCL5 and TCL6 out and RP in reduced the RR levels but increased the levels in the tunnel in cell 8 → **impact on equipment, particularly QPS** (see LMC talk by R.García Alía).
- HL-LHC: TCL5-TCL6 closed, RP out (as in FLUKA simulations).



HL-LHC radiation levels in the IR1-IR5 RRs

- Annual (**250 fb^{-1}**) HEH fluence in RR57 (representative of all IR1-IR5 RRs) at Level 0 (beam height) from FLUKA with optics v1.3.
- TCL6 is the dominant source of radiation in the RR
  → radiation levels sensitive to the collimator settings: higher levels with TCL6 closed, lower levels with TCL6 open (as seen in Run 2).
- Relevant leakage of radiation from the RR entrance on the IP side.

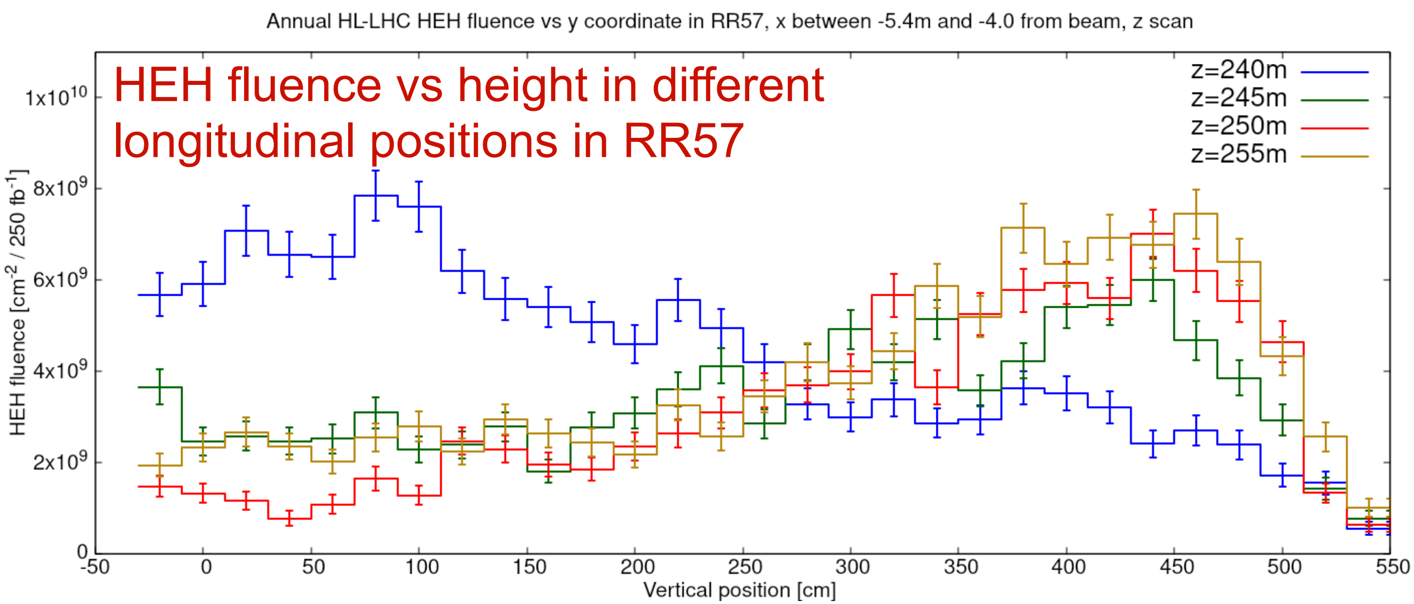


Radiation levels specifications in the IR1-IR5 RRs

- Non-uniform levels in the RRs due to the leakage from the IP-side entrance and to the limited height of the RR wall (~2.8m) that does not fully shield Level 1.
- Similar non-uniformities occur in most areas of the LHC → the specifications must consider them.

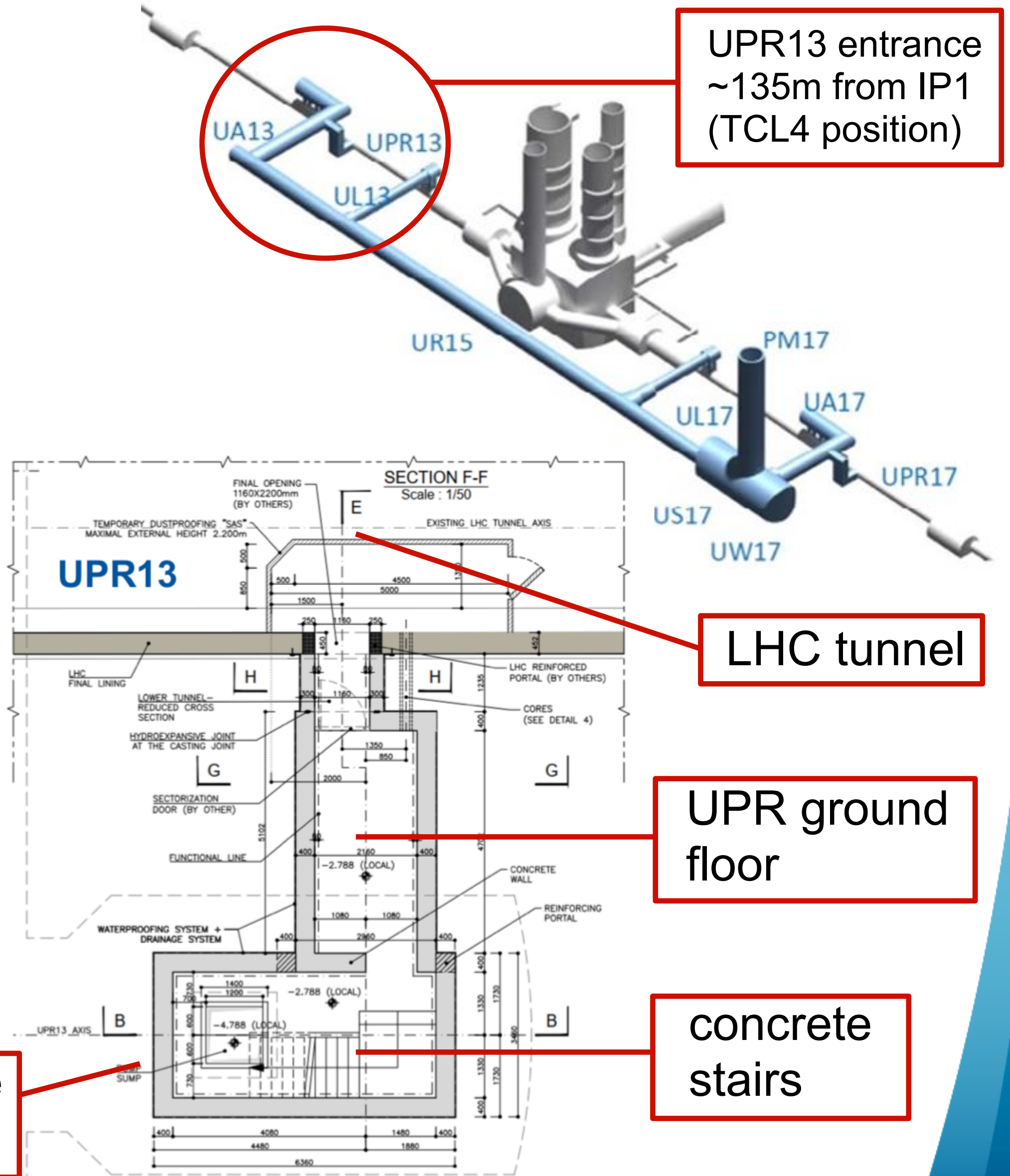
		Annual (250 fb^{-1}) HL-LHC radiation levels		
		Minimum	Maximum peak	Average
TID	[Gy]	2	12	6
Φ_{HEH}	[cm^{-2}]	$1.5 \cdot 10^9$	$8 \cdot 10^9$	$3 \cdot 10^9$
Φ_{th-n}	[cm^{-2}]	$3 \cdot 10^{10}$	$6 \cdot 10^{10}$	$4 \cdot 10^{10}$
$\Phi_{1MeV-neq}$	[cm^{-2}]	$1 \cdot 10^{10}$	$3.5 \cdot 10^{10}$	$2 \cdot 10^{10}$

Minimum, maximum and average annual radiation levels in RR57



Radiation levels in the IR1-IR5 UPRs-UAs

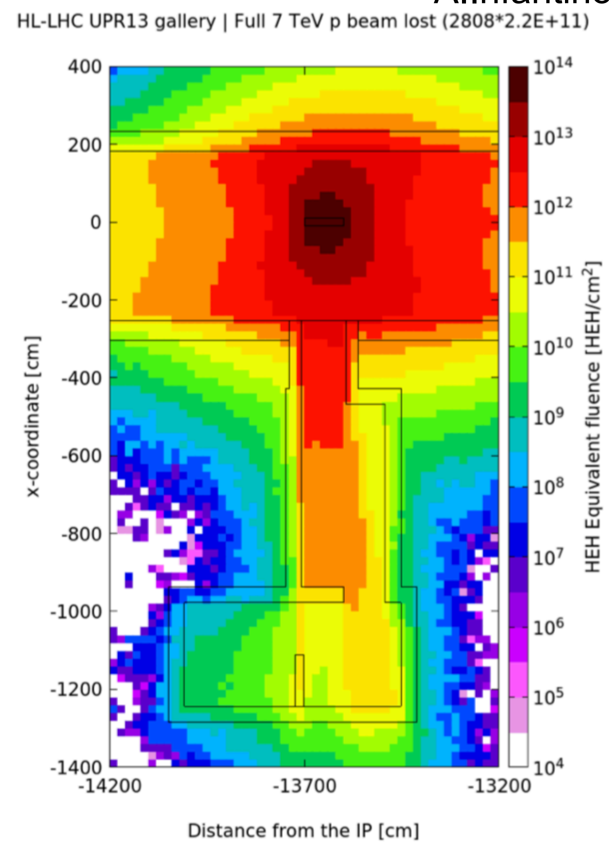
- Radiation Protection (RP) and preliminary R2E results for the new **UPR-UA galleries** in IR1-IR5 discussed in A.Infantino's 39th MCWG talk.
- The levels in the UAs (~10m above the tunnel) are obtained with FLUKA simulations of radiation leakage from the tunnel through the UPR.
- **UPR13** is the worst-case scenario due to the "single-chicane" ground floor layout and the proximity of the entrance to the TCL4 collimator.

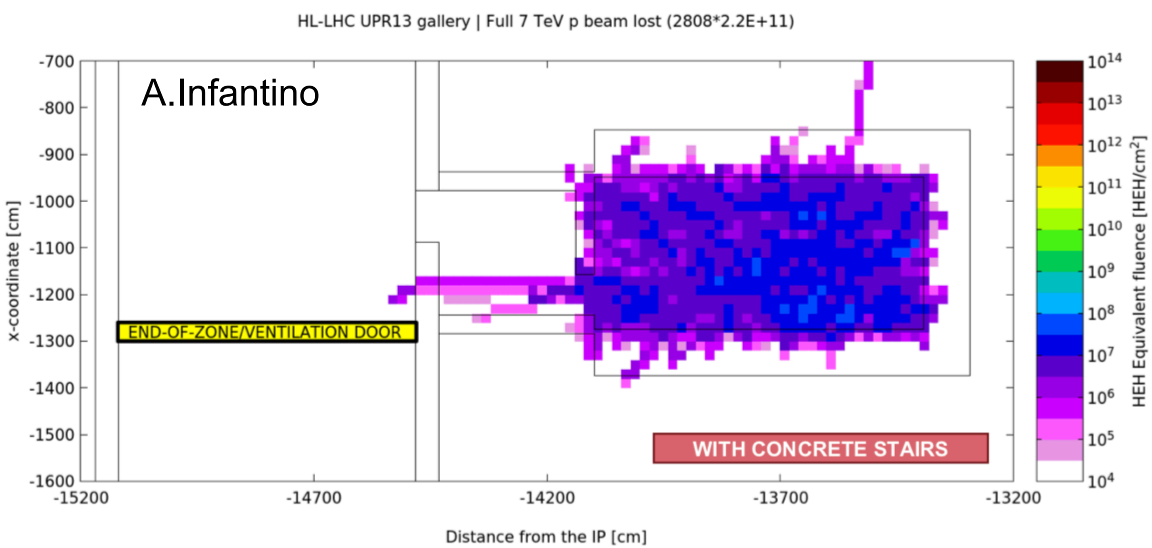


Radiation levels in UPR13-UA13

- FLUKA results by A.Infantino normalised to a full 7TeV proton beam lost in front of UPR13 → transmission factors from the tunnel to the UA entrance are extracted:
  - HEH transmission $<5 \cdot 10^{-7}$ (low stats). Realistic value 10^{-8}-10^{-9}.
  - Thermal neutron transmission $\sim 6 \cdot 10^{-8}$ (plots in backup).
- Next step: normalise R2E predictions to tunnel levels and derive HL-LHC specifications.

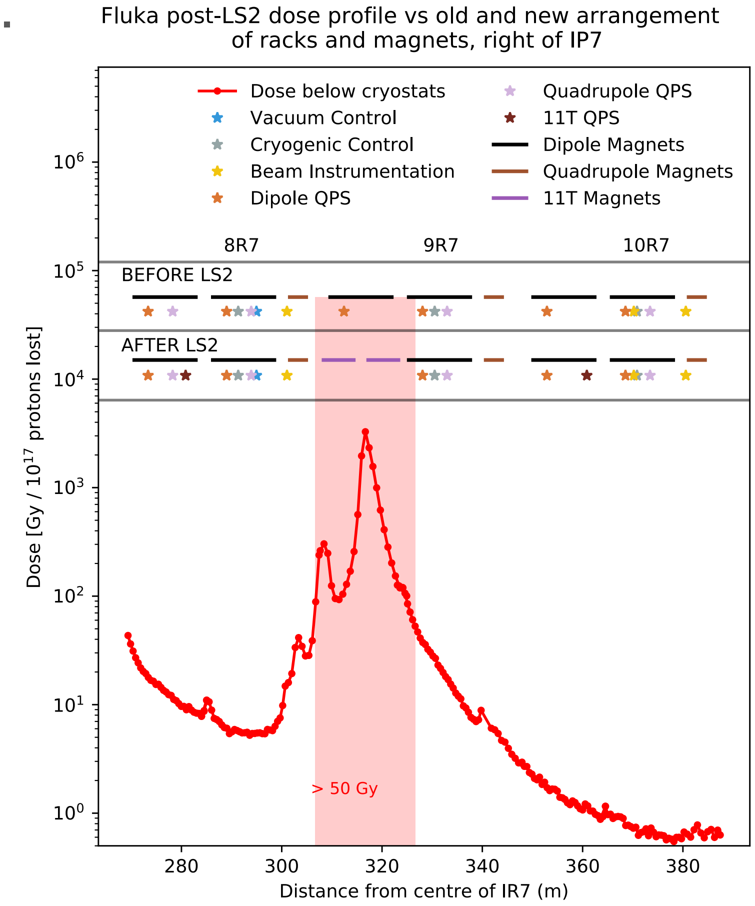
A.Infantino





Radiation levels in the DS of IR7 after LS2

- TID below cryostats in IR7 with 11T magnet and TCLD collimator in cell 9 from a FLUKA simulation by C.Bahamonde Castro, normalised to **10^{17} lost protons** in the primary IR7 collimators (full HL-LHC lifetime).
- Significant TID peak in due to the TCLD collimator → rack relocations already foreseen (see [Integration Report for Installation, EDMS 1904620]).
- Important: the number of lost protons in IR7 is strongly affected by the optics configuration of the LHC (see [talk at the 77th TCC meeting]).



HEH fluence in the IR7 RRs

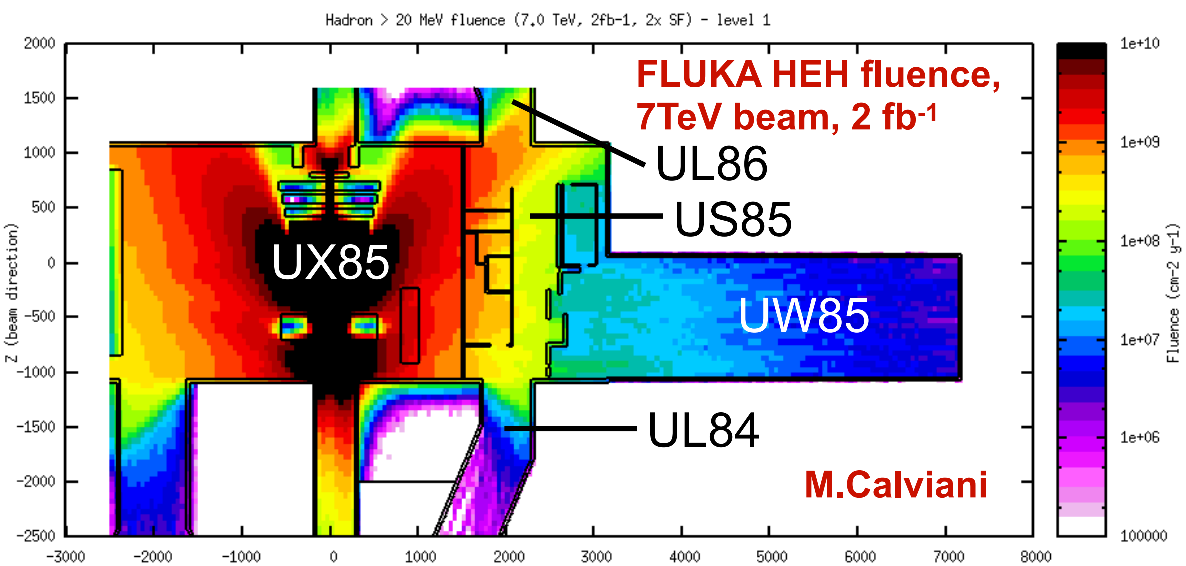
- HL-LHC HEH fluence in the IR7 RRs obtained from by 2018 RadMon data at L0 and L1 scaled with integrated beam intensity.
- Observations:
  - Large L1/L0 HEH fluence ratio (RR wall only shields L0).
  - The HEH fluence increased by a factor 3 from 2017 to 2018 in RR73 (as the total IR7 losses, see TCC talk) but not in RR77.
- RR73-77 HL-LHC HEH fluence specifications for L0 (with safety margins): **$2 \cdot 10^8$ cm^{-2}/y**, ~10 times lower than the IR1-IR5 RRs.

		Annual HEH fluence at RadMON location (cm^{-2}/y)				
		2016	**2017**	**2018**	**Run 3**	**HL-LHC**
RR73	L0	$1.6 \cdot 10^7$	$1.8 \cdot 10^7$	$6.6 \cdot 10^7$	$9.9 \cdot 10^7$	$1.3 \cdot 10^8$
	L1	n.a.	$1.9 \cdot 10^8$	$6.3 \cdot 10^8$	$9.5 \cdot 10^8$	$1.3 \cdot 10^9$
RR77	L0	$1.2 \cdot 10^7$	$1.4 \cdot 10^7$	$1.6 \cdot 10^7$	$2.4 \cdot 10^7$	$3.2 \cdot 10^7$
	L1	n.a.	$3.0 \cdot 10^8$	$4.9 \cdot 10^8$	$7.4 \cdot 10^8$	$9.8 \cdot 10^8$

*Run 3 and HL-LHC annual HEH fluences are obtained by scaling the 2018 values with integrated beam intensity

Radiation levels in the shielded areas in IR8

- In IR8 the levels scale with **LHCb luminosity**. Planned upgrades:
  - **Upgrade I** (ongoing) → from ~6.5 fb^{-1} in Run 2 (annual max **~2.6 fb^{-1}/y** in 2018) to ~50 fb^{-1} in Runs 3+4 (average **~7fb^{-1}/y**, factor **~3** increase).
  - **Upgrade II** (LS4, under discussion) → 50 fb-1/y (extra factor **~7** increase, factor **~20** from Run 2).
- HEH fluence (from RadMon data and 2010 FLUKA simulation by M.Calviani, see details in talk at 39th MCWG meeting) already in 10^7-10^8 range in US85, UW85, UL84-86 → high post-upgrade levels, especially for Upgrade II.

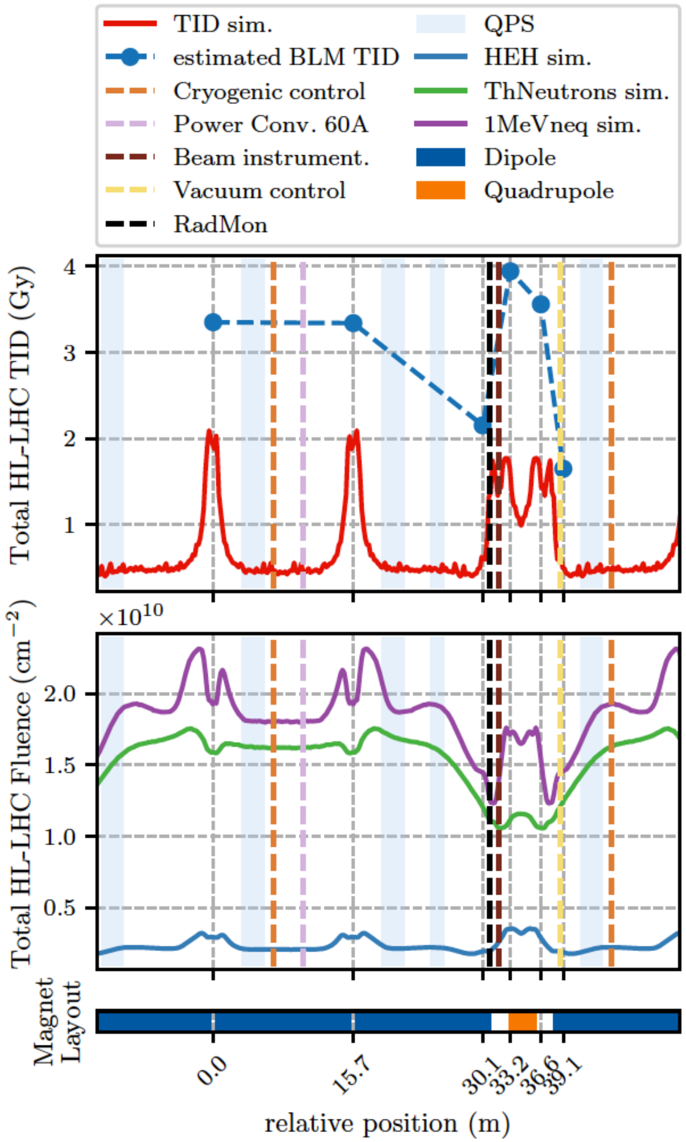


- Significant impact on electronics (e.g. cryogenic racks: ongoing iterations with equipment owners).
- Work is in progress to improve the accuracy of the FLUKA model with input from LHCb members (M. Karacson).

Radiation levels in the arcs

- Arc radiation level analysis by K.Bilko using Run 2 **BLM-RadMon** data and a FLUKA simulation by C.Bahamonde Castro scaled to unit beam intensity and gas pressure.
- **Typical Run 2 levels: TID <100 mGy/y, HEH fluence ~5·10^{7} cm^{-2}/y.**
- In addition, **local spikes up to many Gys** are seen → to be monitored in operation, impact on equipment can be critical.
- **HL-LHC** predictions from Run 2 scaling:
  - Integrated beam intensity from 3·10^{21} ps/y to 8·10^{21} ps/y.
  - Conservative assumption on gas pressure: factor 4 increase.
- **Full HL-LHC TID <5 Gy, annual HEH fluence at floor level ~2.5·10^{8} cm^{-2}/y (excluding spikes).**

K.Bilko, RADECS 2019



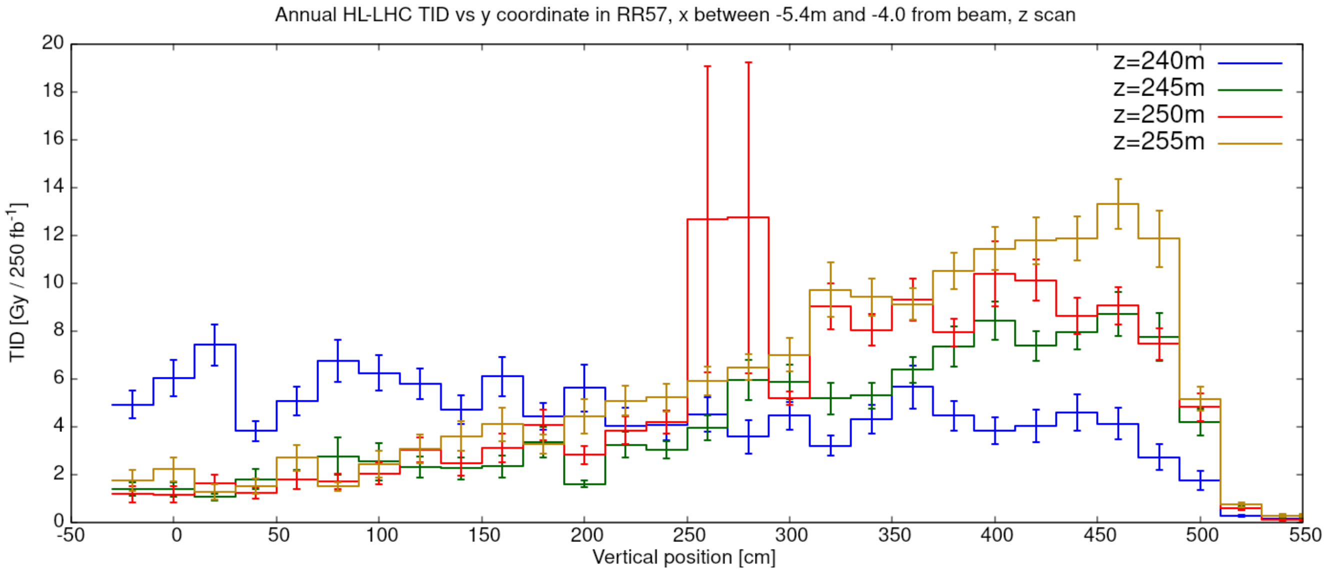
Conclusions and next steps

- I described the **status of the preparation of a radiation level specification document for HL-LHC**, covering all areas where COTS-based electronics are used (DS, arcs, shielded areas).
- The specifications are obtained with radiation level data from Run 2 (BLMs, RadMons) and FLUKA simulations, considering the expected evolution of the relevant LHC operational parameters and applying safety margins based on the uncertainties in the extrapolation and on general arguments.
- **Preliminary results** of R2E specifications in various machine locations are presented.
- Not covered in this talk: IR1-IR5-IR7 UJs, IR4-IR6, REs (arc alcoves, generally radiation-safe), injection lines.
- A **review** of the specification document is tentatively planned for the **12 December** - the concerned users (i.e. equipment groups) are encouraged to attend to ensure that their needs are covered.

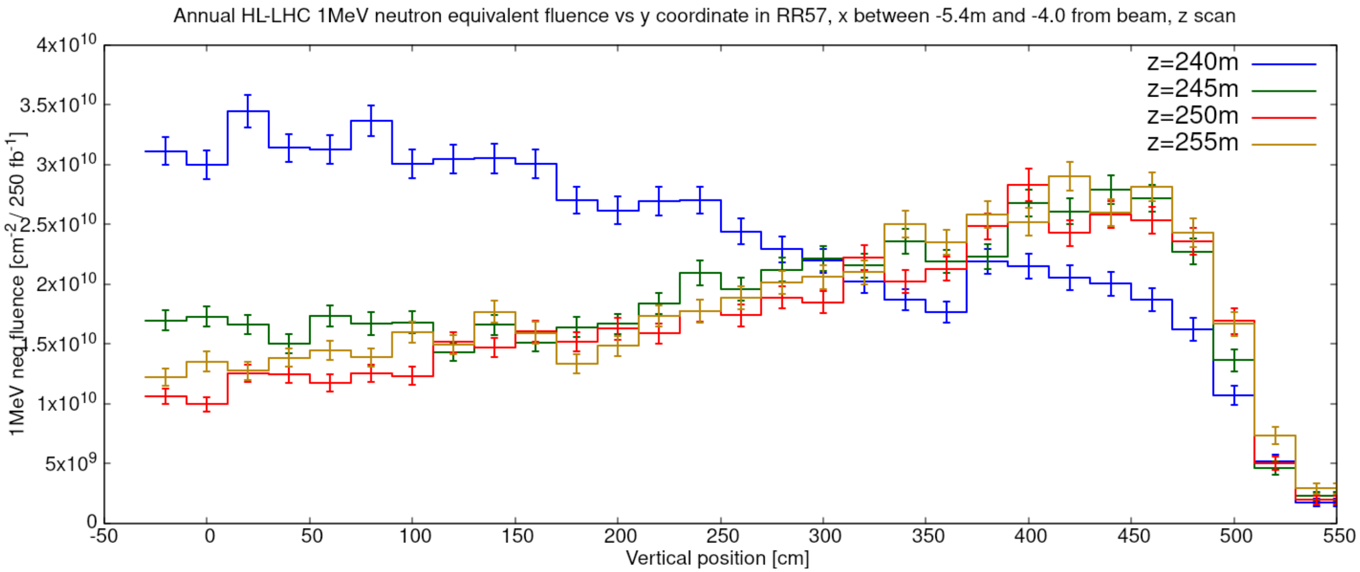
BACKUP

y scans of FLUKA levels for different z in RR57 (1)

Total Ionising Dose

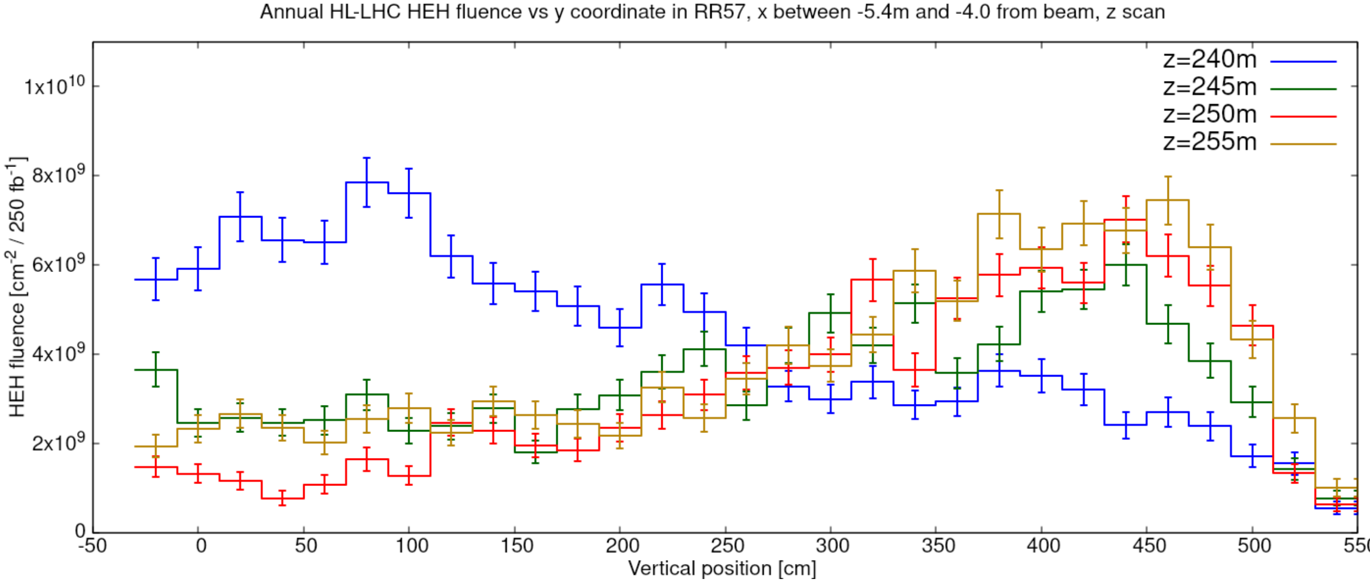


1-MeV neutron equivalent fluence

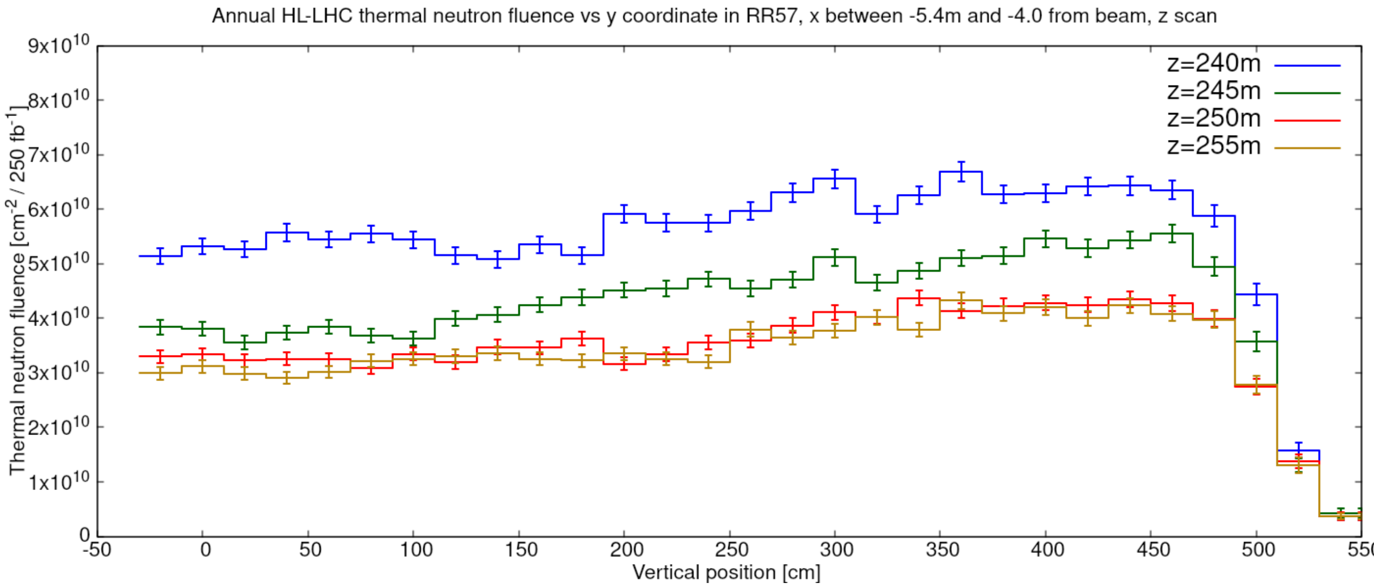


y scans of FLUKA levels for different z in RR57 (2)

HEH fluence



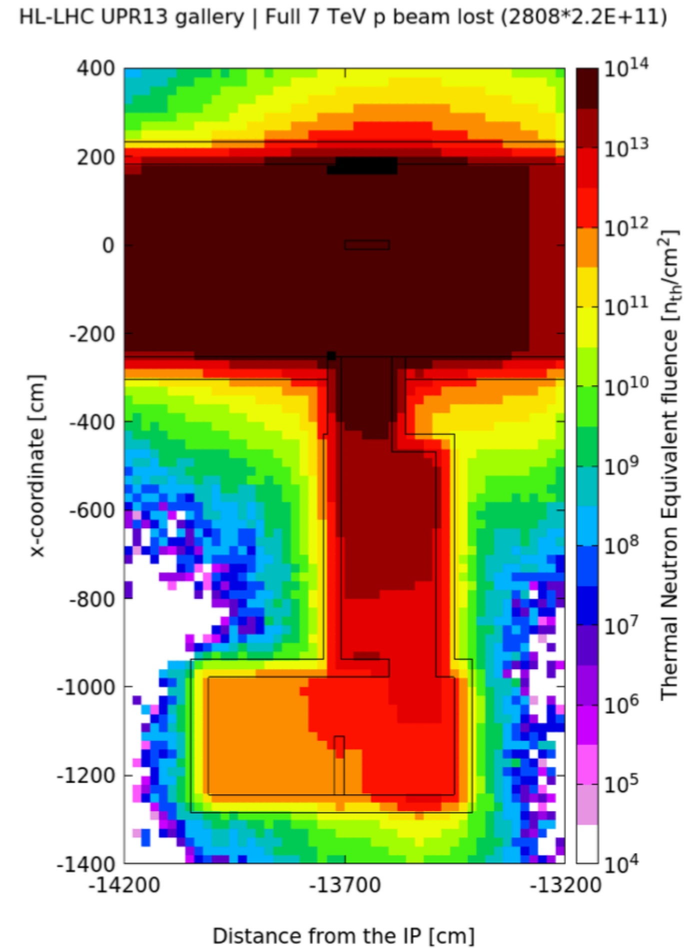
thermal neutron fluence

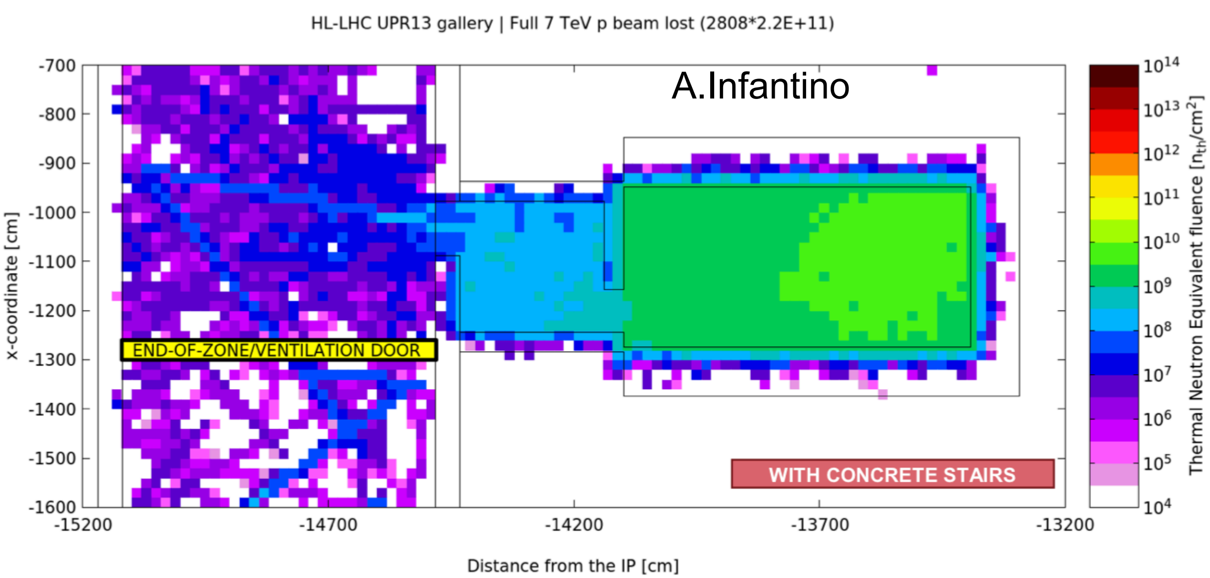


Thermal neutron fluence in UPR13-UA13

- FLUKA results by A.Infantino normalised to a full 7TeV proton beam lost in front of the UPR13.
  - Transmission coefficient of thermal neutron fluence from the main LHC tunnel to the entrance of UA13: **~6·10^{-8}**.

A.Infantino





Dose levels in the DS of IR8

- 2018 BLM dose rescaled to 100 fb^{-1} for protons and 1.5 nb^{-1} for ions, in the DS of IR8.
- The dose is lower than in IR1-IR5, but the levels in cell 8-9 and the ion BFPP peak can be significant.
- Note: levels may be a factor 2-3 lower under the cryostats.