System level testing in CHARM Facility

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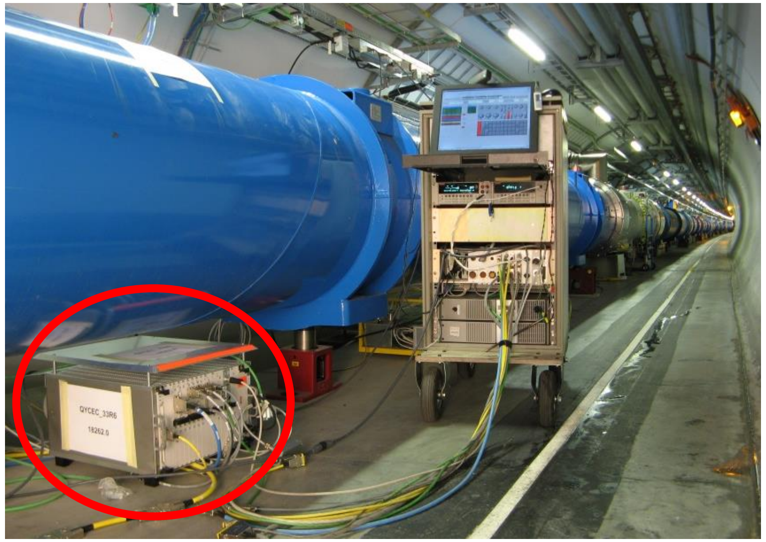
Accelerator’s Challenges

- A large number of **COTS-based** systems are exposed to the LHC radiation environments
- The **reliability** and the **availability** are a main concern for the CERN electronic equipment located in radiation areas
- The **criticality** of the equipment can be very high, the radiation effects can lead to:
  - **Beam Dumps** → Lost time for physics
  - **LHC safety system failures** → Part of the machine can be destroyed
- In the LHC systems are affected by all radiation effects:
  - **TID and DD:**
    - → Affect system lifetime (permanent failure)
    - → Same failure probability for all units
  - **SEE:**
    - → Stochastic system failure rate
    - → **Failure probability depends on number of systems**



@ Courtesy of the TE/MPE Group

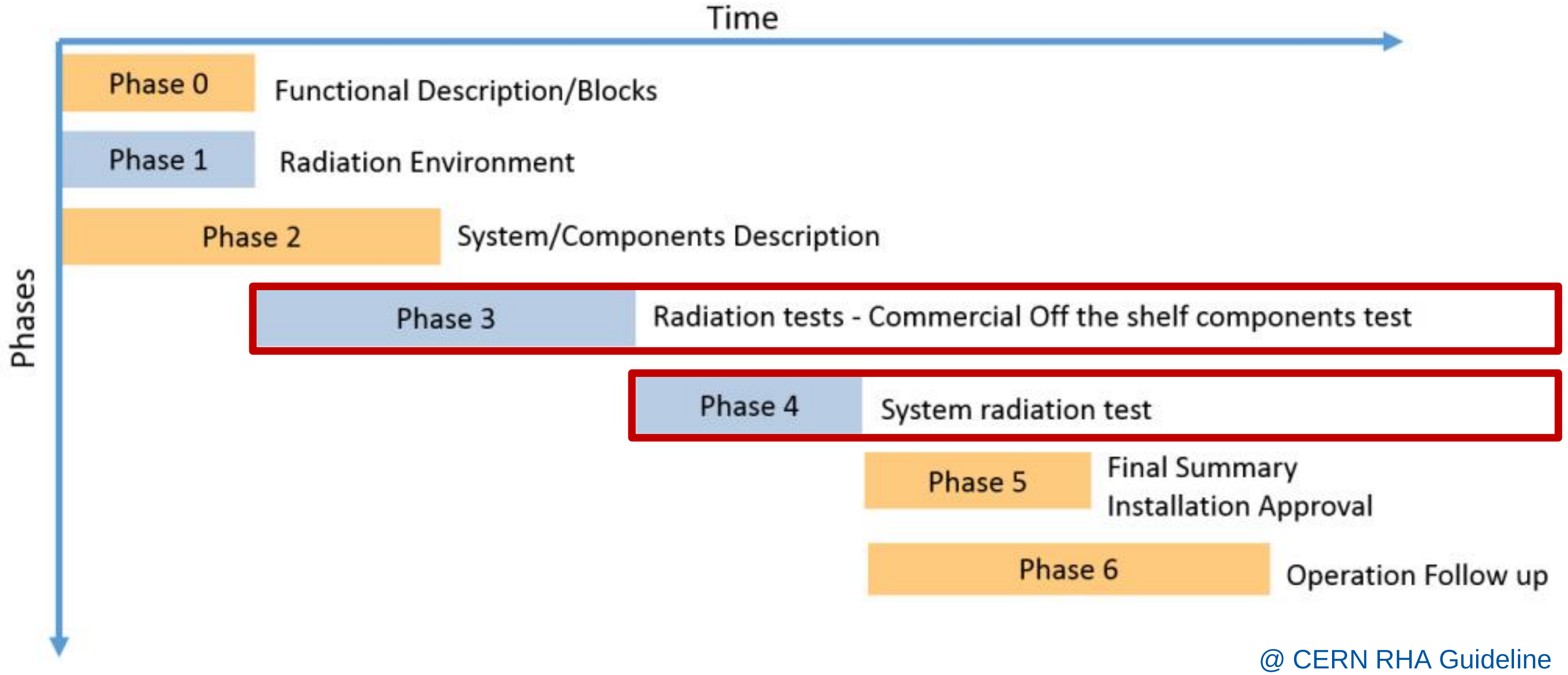
$$N_{SEE\_Failure} = \mathbf{N} * \sigma * fluence$$

Number of systems

Example:
DQLPU = 530 units
(Quench Protection unit system)

CERN RHA Guideline for COTS-based system

From component to system level qualification:



@ CERN RHA Guideline

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

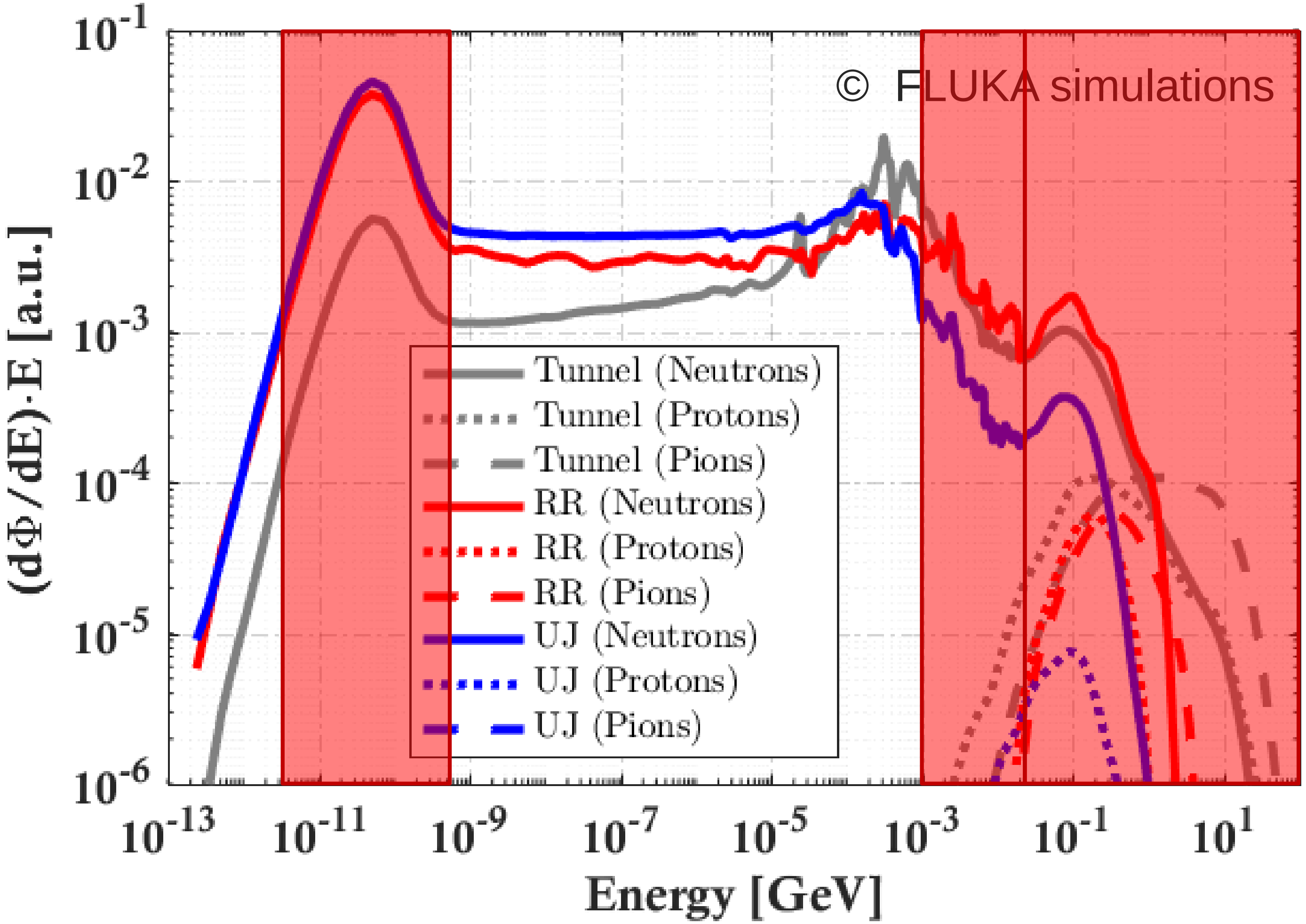
→ System level tests performed at CHARM Facility

System level testing challenges

- **Main Cumulative Radiation Effects test challenges (TID+DD):**
  1) **Representativeness of the system degradation scenario(s):**
     → TID/DD Rate(s) similar to operation to reproduce combined TID+DD effects at system/circuit/IC level
  2) **AND representativeness of the DD spectra** (Specially when different semiconductor materials embedded)
     → To avoid NIEL scaling dependency during system level test to keep **(1)** true.
- **Main SEE test challenges:**
  3) **Representativeness of the SEE spectra**
     - **Energy Distribution:** System sensitive to thermal neutrons? Low energy protons? SEL from very energetic particles?
     - **Particle Distribution**: High pions presence could impact the overall cross-section
  4) **Assess very low cross-section** (due to high number of systems in operation)
- **General concerns:**
  5) **Good failure/degradation observability** (measured test points, embedded diagnostic circuits etc…)
     → Failure mode prediction from component level behavior can be a difficult task

LHC: Particle Spectra (SEE)

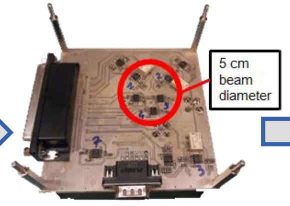
- Intervals of interest:
  - **Thermal Neutrons:** Neutron capture
  - **Intermediate energy neutrons:** Low energy elastic/inelastic products
  - **Low energy Charged hadrons:** direct ionization (relevant for very sensitive technology)
  - **High Energy Hadrons (HEH):** Inelastic interactions

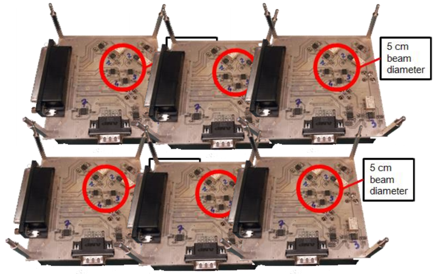


Why CHARM?

CHARM = **C**ERN **H**igh energy **A**ccele**R**ator **M**ixed field facility

Main Mission: Radiation tests of electronic equipment and components in radiation environments similar to the ones of the accelerator





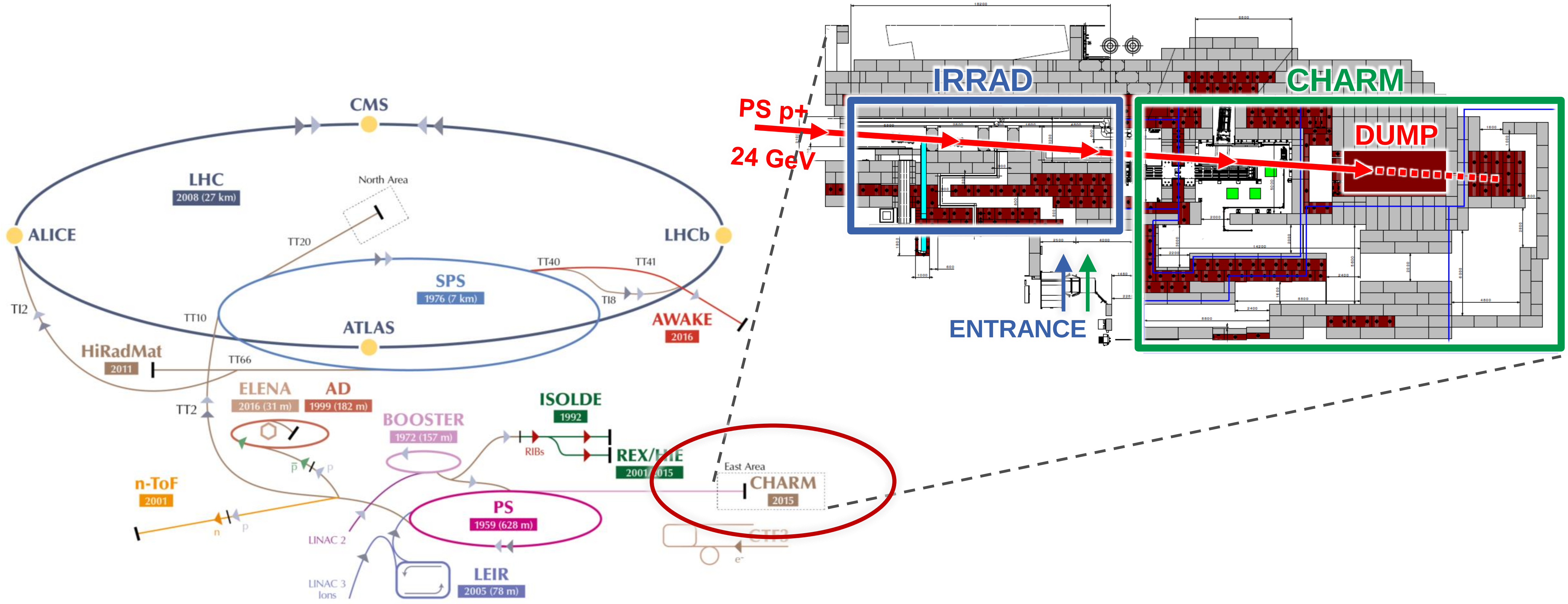
- **Large dimension of the irradiation room:**
  - High number of single components
  - Large volumes electronic equipment
  - High number of system units

- **Numerous representative radiation fields:**
  - Mixed-Particle-Energy: Tunnel & Shielded areas
  - TID, DD, soft and hard SEE testing
  - Direct beam exposure (proton beam 24 GeV or heavy ion beam ~6 GeV/n)

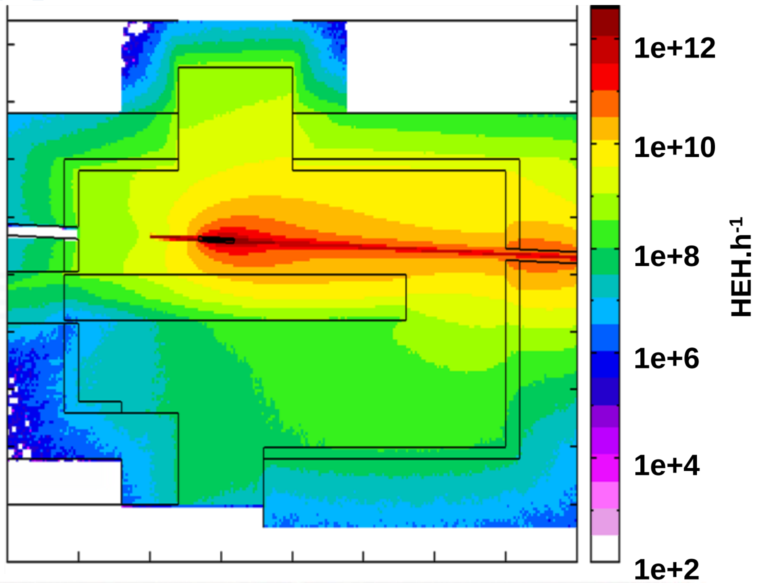
CHARM !

CHARM Facility

- Primary beam line delivered from PS in spills
- CHARM Beam line placed downstream to IRRAD



CHARM: Facility Configuration



- Primary 24 GeV proton beam impinge a target
- Secondary radiation fields similar to the LHC radiation fields.
- Radiation field can be modulated with:

➢ **Target**:

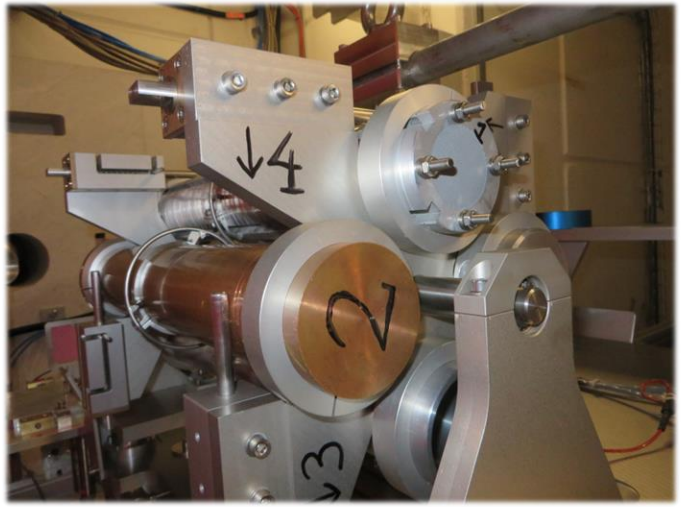
Cu - Copper
AlH - Aluminium Hole
Al - Aluminium

➢ **Shielding**:

C – Concrete (**1,4**)
I – Iron (**2,3**)

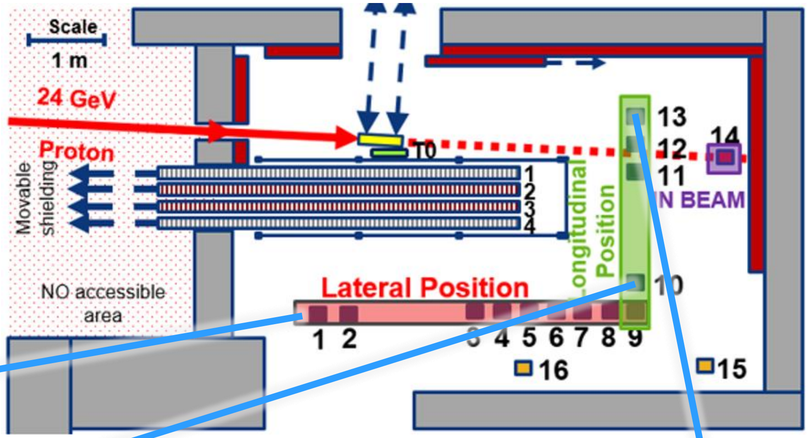
➢ **Positions**:

Lateral **(1:9)**
Longitudinal **(9:13)**



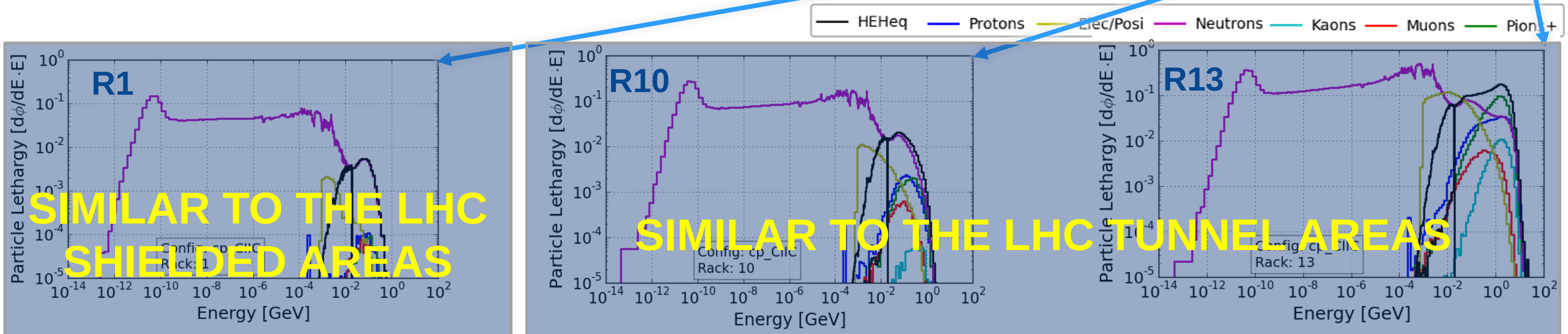
CHARM: Spectra vs positions

- **Target:**
  - **Cu** - Copper
  - **AlH** - Aluminium Hole
  - **Al** - Aluminium
- **Shielding:**
  - **C** – Concrete **(1,4)**
  - **I** – Iron **(2,3)**
- **Positions:**
  - Lateral **(1:9)**
  - Longitudinal **(9:13)**



- **Configuration: Cu CIIC**
  Lethargy spectra from FLUKA Simulations
  HEH/Thermal neutron fluences from RadMONs

$$R = \frac{\Phi_{th}}{\Phi_{HEH}}$$



R1
HEH: 2 x10^{9} cm^{-2}/day
R Factor: 28.1

R10
HEH: 8 x10^{9} cm^{-2}/day
R Factor: 9.93

R13
HEH: 2 x10^{10} cm^{-2}/day
R Factor: 1.03

✓ LHC SEE representativeness

CHARM: DD Spectra characteristics

- **Target**:
  - **AlH** - Aluminium Hole
  - **Al** - Aluminium
  - **Cu** - Copper
- **Shielding**:
  - **C** – Concrete **(1,4)**
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- **Positions**:
  - Lateral **(1:9)**
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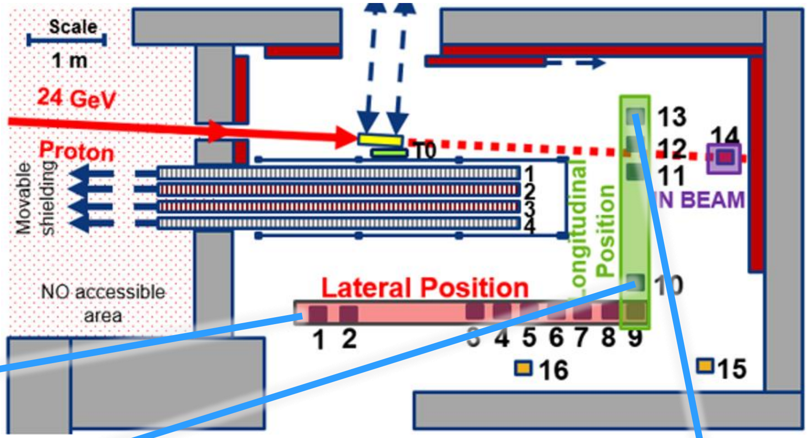
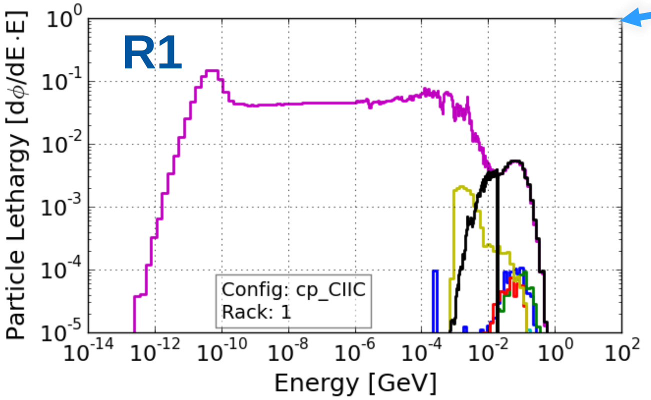
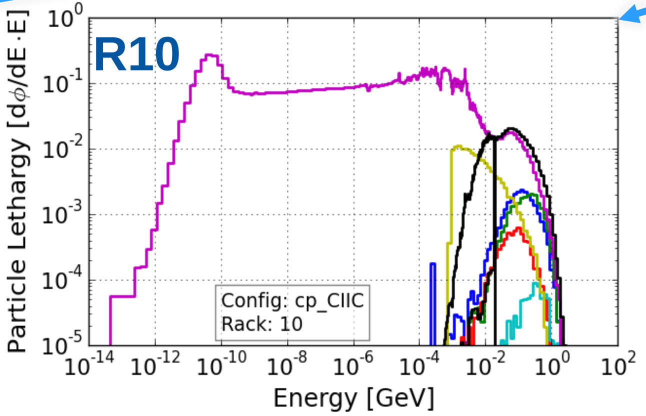


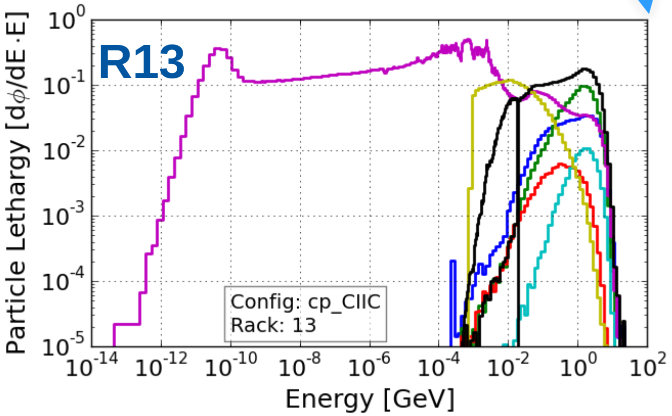
- **Configuration: Cu CIIC**
  Data from FLUKA Simulations
- Particle proportion to total DDEF (DD Equivalent Fluence) or DDD [%]:



Particle contribution (GaAs):
n: 99,5%, p:0,45%, **π:0.05%**



Particle contribution (GaAs):
n: 85,2%, p:7,03%, **π:7,75%**



Particle contribution (GaAs):
n: 54%, p:13%, **π:33%**

CHARM: DD Spectra characteristics

- **Target:**
  - **AlH** - Aluminium Hole
  - **Al** - Aluminium
  - **Cu** - Copper
- **Shielding:**
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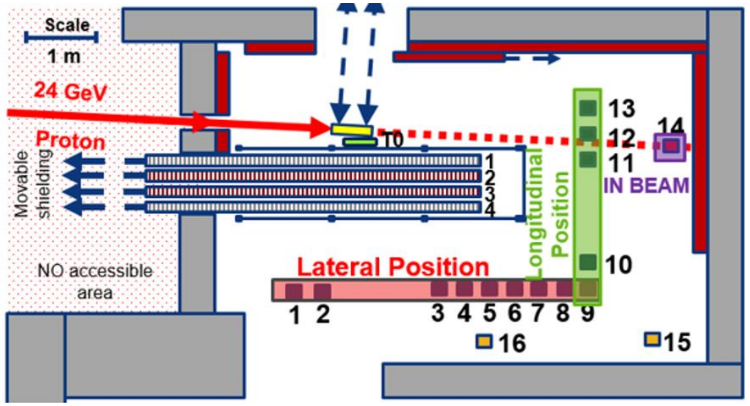
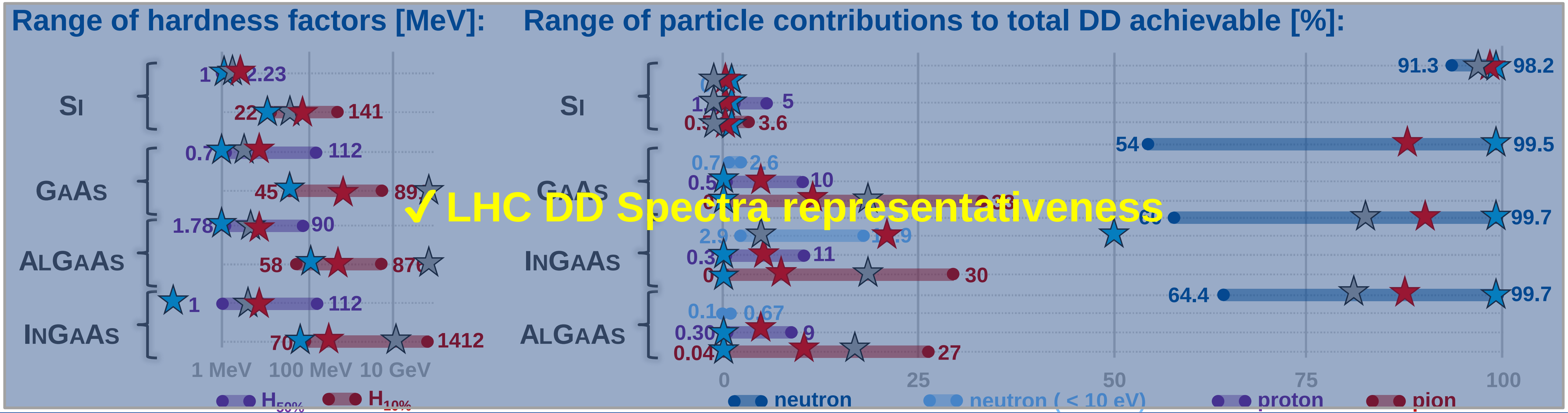
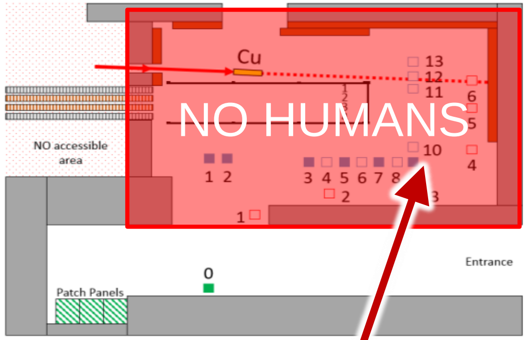


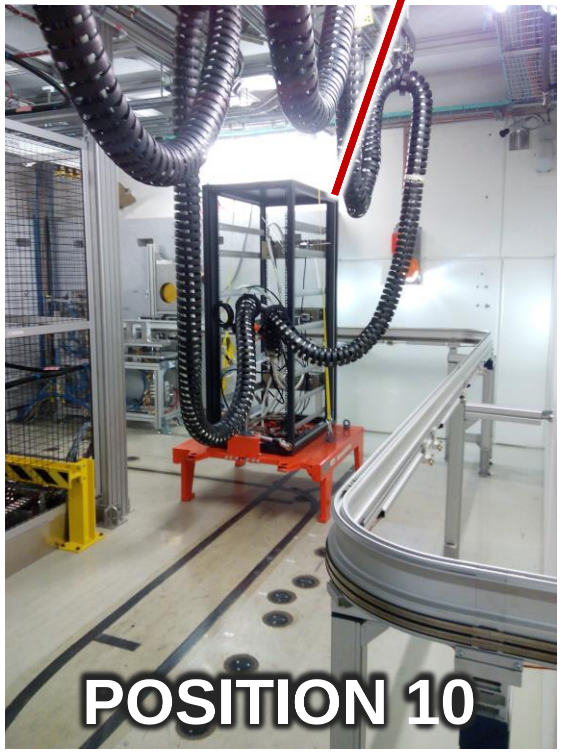
Tunnel RR UJ



CHARM: Operation

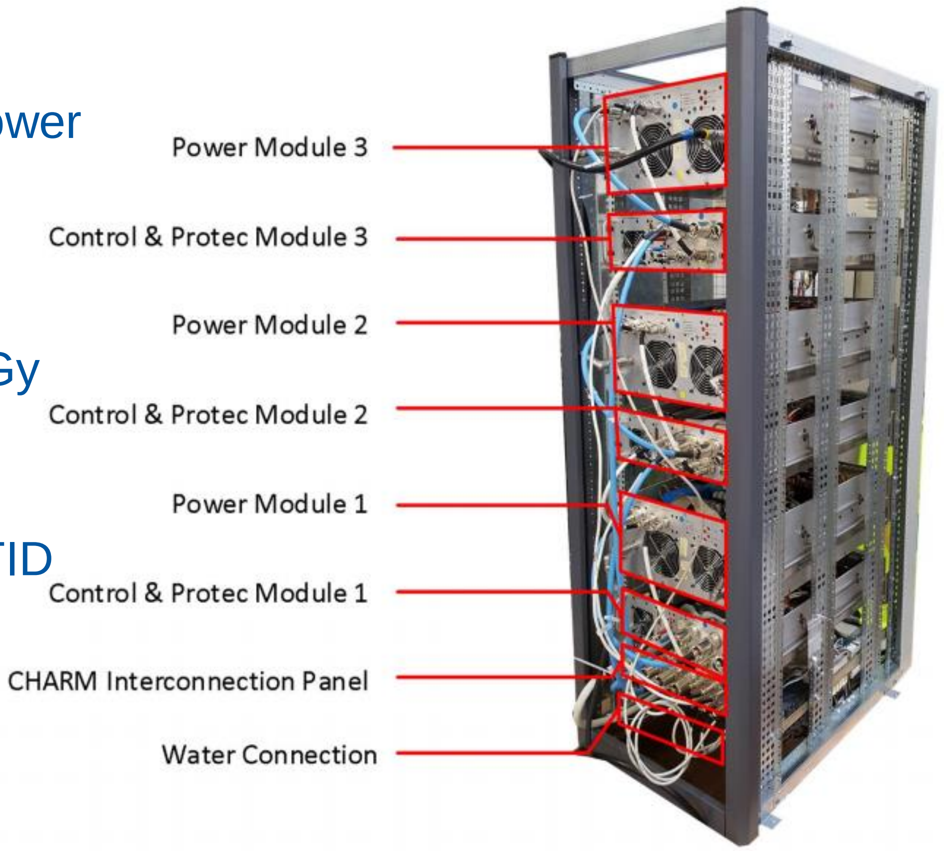
- The access is every Wednesday → An user run last minimum one week
- Up to **two racks** can be placed in the facility
- A single rack can fit **several users**
- The racks are brought inside by a **robotic conveyer**
- It automatically leaves the rack in position
- It reduces the **time of exposure** of the working people in the activated area
- An overhead conveyer allow testing small systems or sets of components in parallel of the main user
- The radiation levels (TID+DD+HEH+Th. Neutrons) are monitored on the rack on several positions by means of the CERN Radiation MONitoring (RadMON) systems.





An example of system level testing: EPC

- **System**: R2E LHC Electronic Power Converter (EPC)
- **Function:** Supply and control the current in all four power quadrants, for superconductive magnets
- **Location:** Shielded RR (Shielded) Areas
- **Expected annual dose (HL-LHC):** ~3 Gy/y **Target Dose:** 200 Gy
- **Objective of the campaign:**
  1) Validate the 20 years of lifetime operation against DD and TID
  2) Identify Power Converter failure modes



- **Test Protocol:**

Rack Assembly → Pre-irradiation Tests → CHARM Dry Run → CHARM Irradiation → Cool Down → Post-irradiation Tests → Long-term Storage

@ From EDMS: 1851356

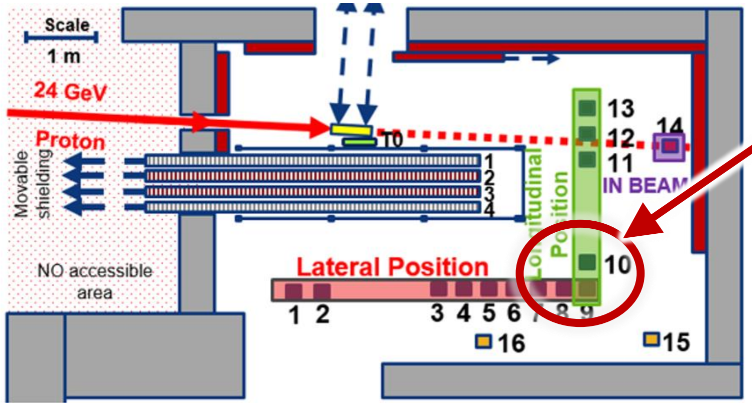
An example of system level testing: EPC

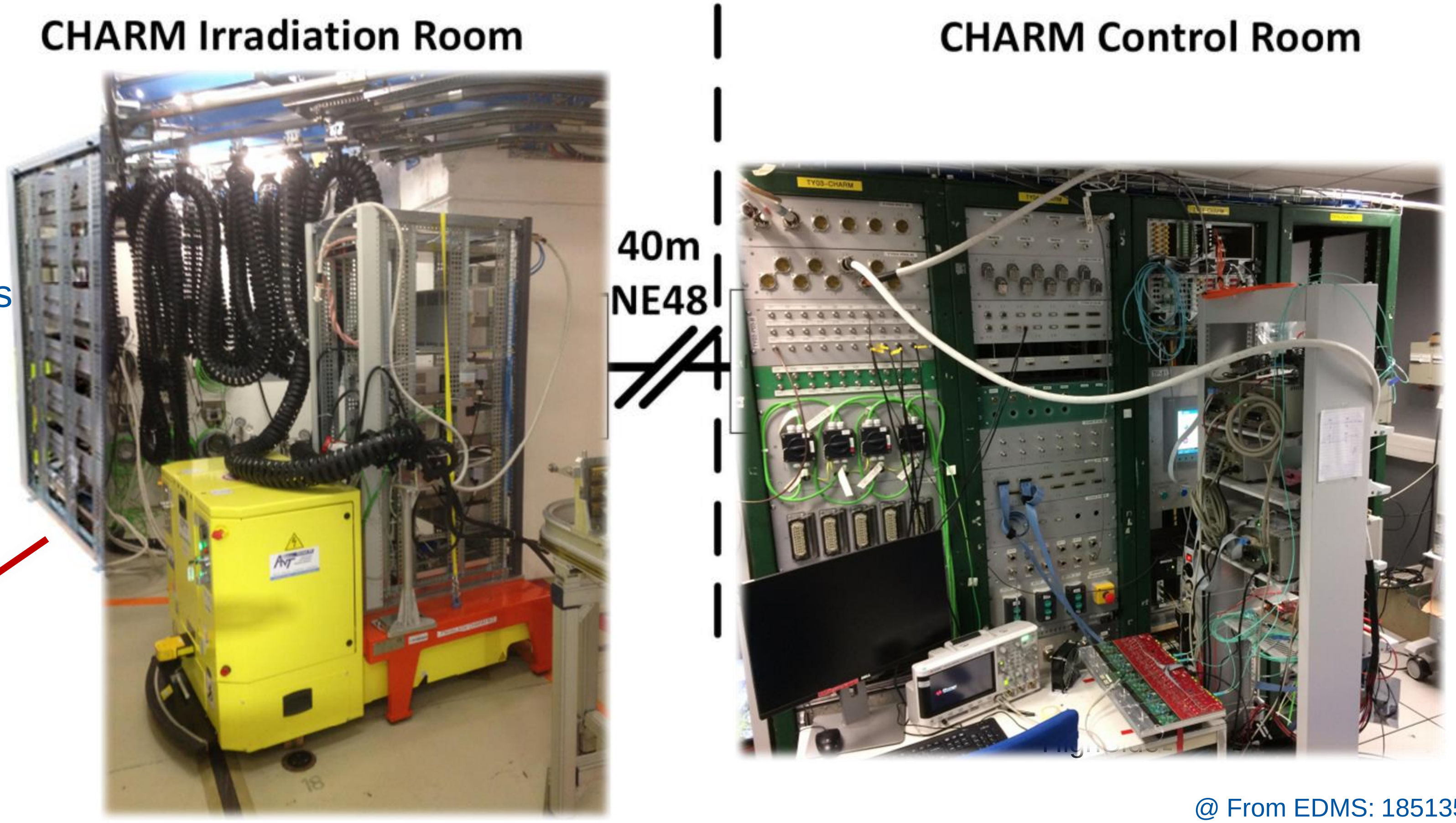
- **Test plan:**
  - **Configuration:** CuOOOO
  - **Position:** 10
  - **#Irradiations:**

    - Session 1: 1 Week, 1 system

    - Session 2: 1 Week, 1 system

    - Session 3: 2 weeks, 2 systems





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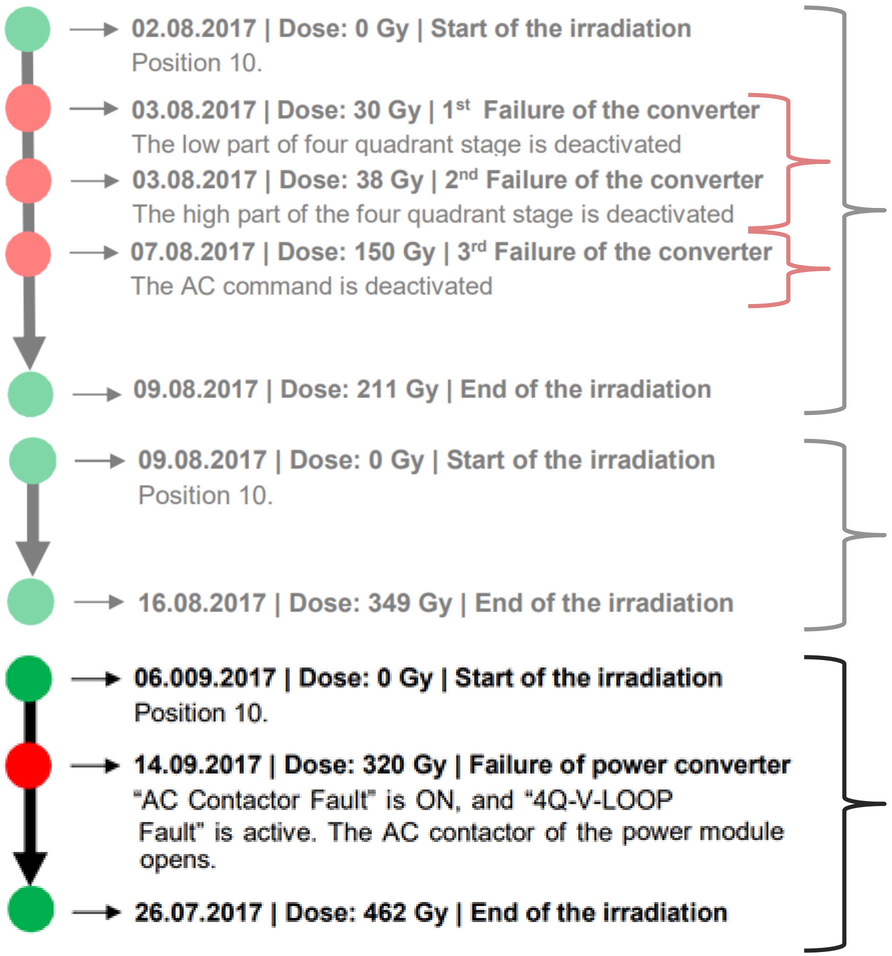
An example of system level testing: EPC



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**

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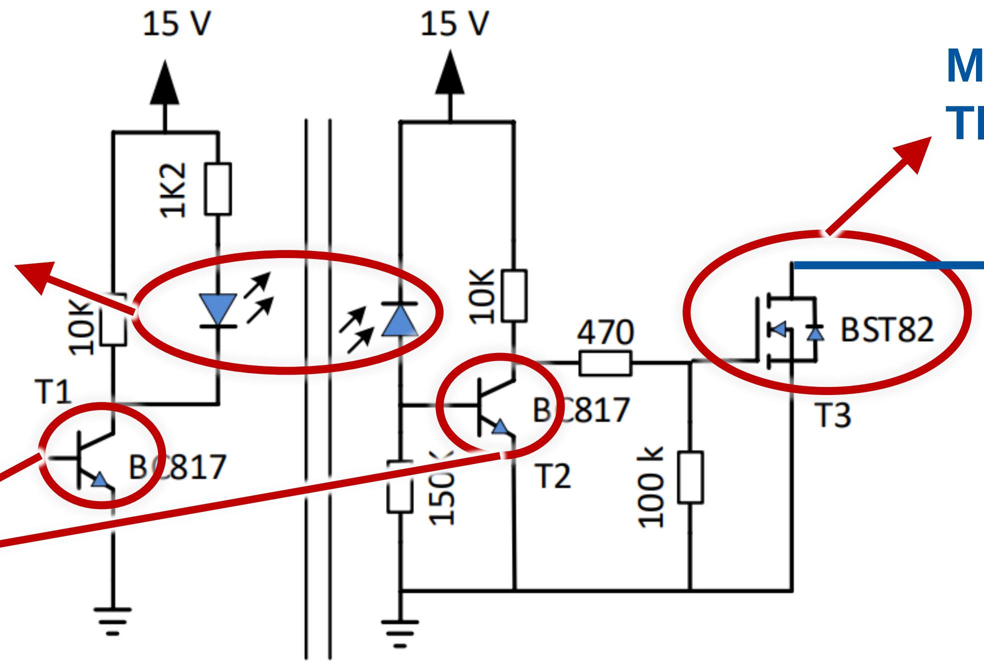
An example of system level testing: EPC

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.

Optocoupler:
TID+DD(AlGaAs): ↓CTR

BJT:
TID+DD(Si): ↓β



MOSFET:
TID: ↓Vth

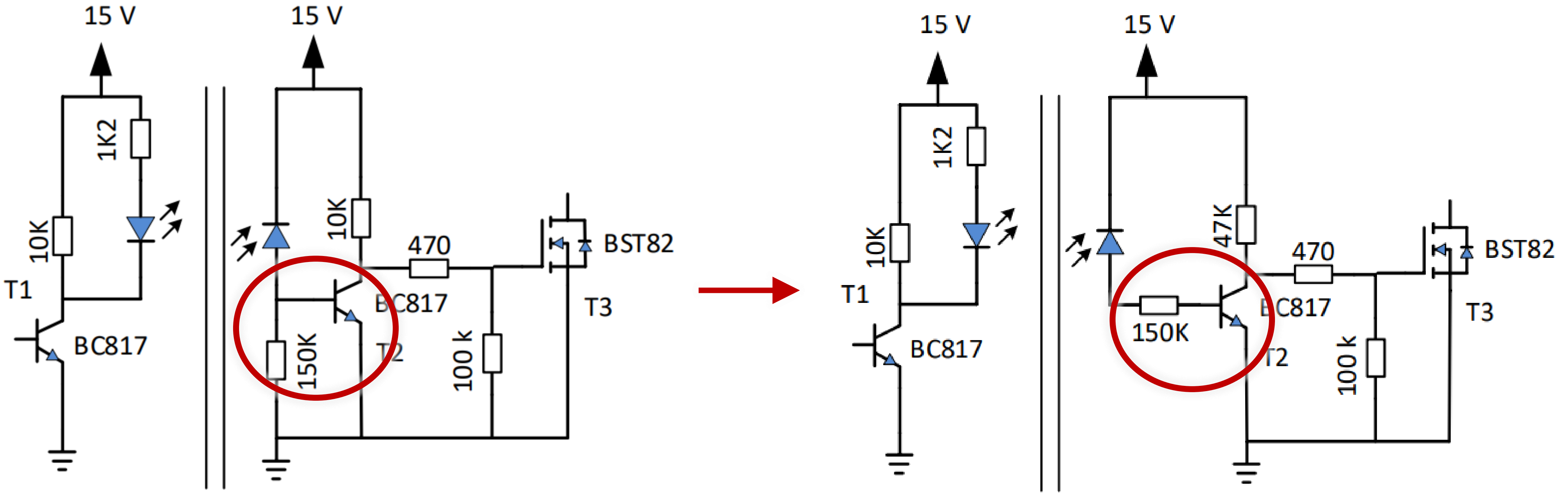
Fault Signal Detection:
- 5V → No Faults detected.
- 0V → Faults detected.

@ From EDMS: 1851356

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

An example of system level testing: EPC

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



Initial Design Re-Design

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Conclusion

- LHC radiation environments present specific challenges in terms of radiation qualification
- These challenges impact the way the system level tests have to be performed:
  - Representative TID/DD rate and DD spectra required to ensure realistic system degradation responses
  - Representative particle spectra required to assess realistic SEE response (to thermal, intermediate hadron, high energy hadrons)
- The CHARM facility allows testing high number of components and systems in representative LHC environments
- A careful selection of the CHARM facility configuration allows dealing with most of the environmental challenges / requirements
- An example of system test performed at CHARM showed how system failure modes can be identified and mitigate thanks to system level test in realistic conditions

Thank you all for your attention!

Questions?

LHC: TID & DD levels distribution

LHC is divided in three main areas:

- **ARCs** → low radiation levels (< 2Gy per year expected HL-LHC)
- **Long Straight Section (LSS)**
  - ➢ High radiation levels (up to 10kGy per year expected)
  - ➢ Radhard systems only
- **Dispersion Area (DS)**
  - ➢ TID from **10 mGy** up to **1kGy** per year
  - ➢ DDEF from **10^8** up to **10^{13}** 1 MeV neq.$cm^{-2}y^{-1}$

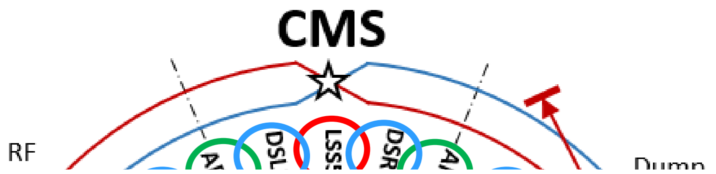
➢ **Below MB10 per year:**

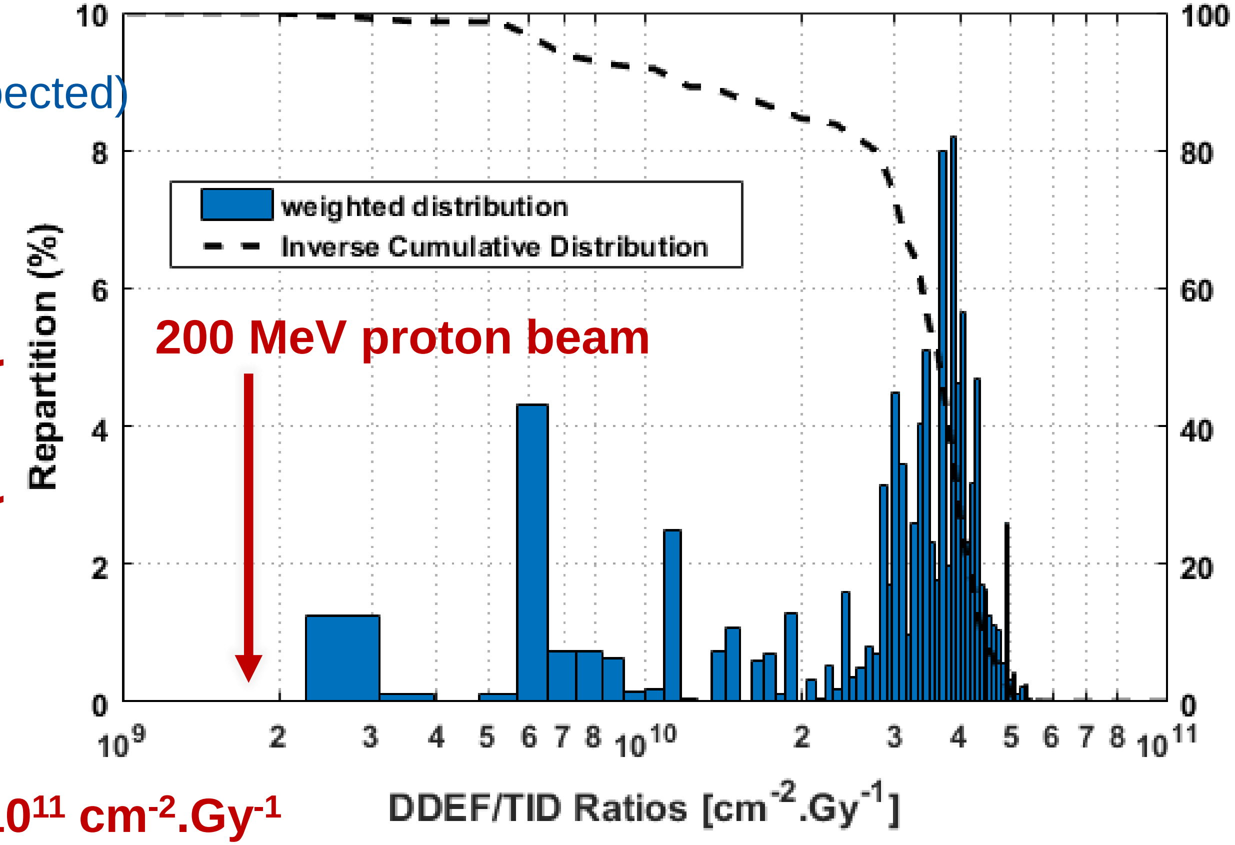
- TID: 50 Gy
- DDEF: 3 x10^{11} neq. cm^{-2}

x7

➢ **Below MB11 per year:**

- TID: 50 Gy
- DDEF: 2x10^{12} neq. cm^{-2}





➢ Wide variety of **DDEF/TID Ratio**: From **10^9** up to **10^{11} $cm^{-2}.Gy^{-1}$**

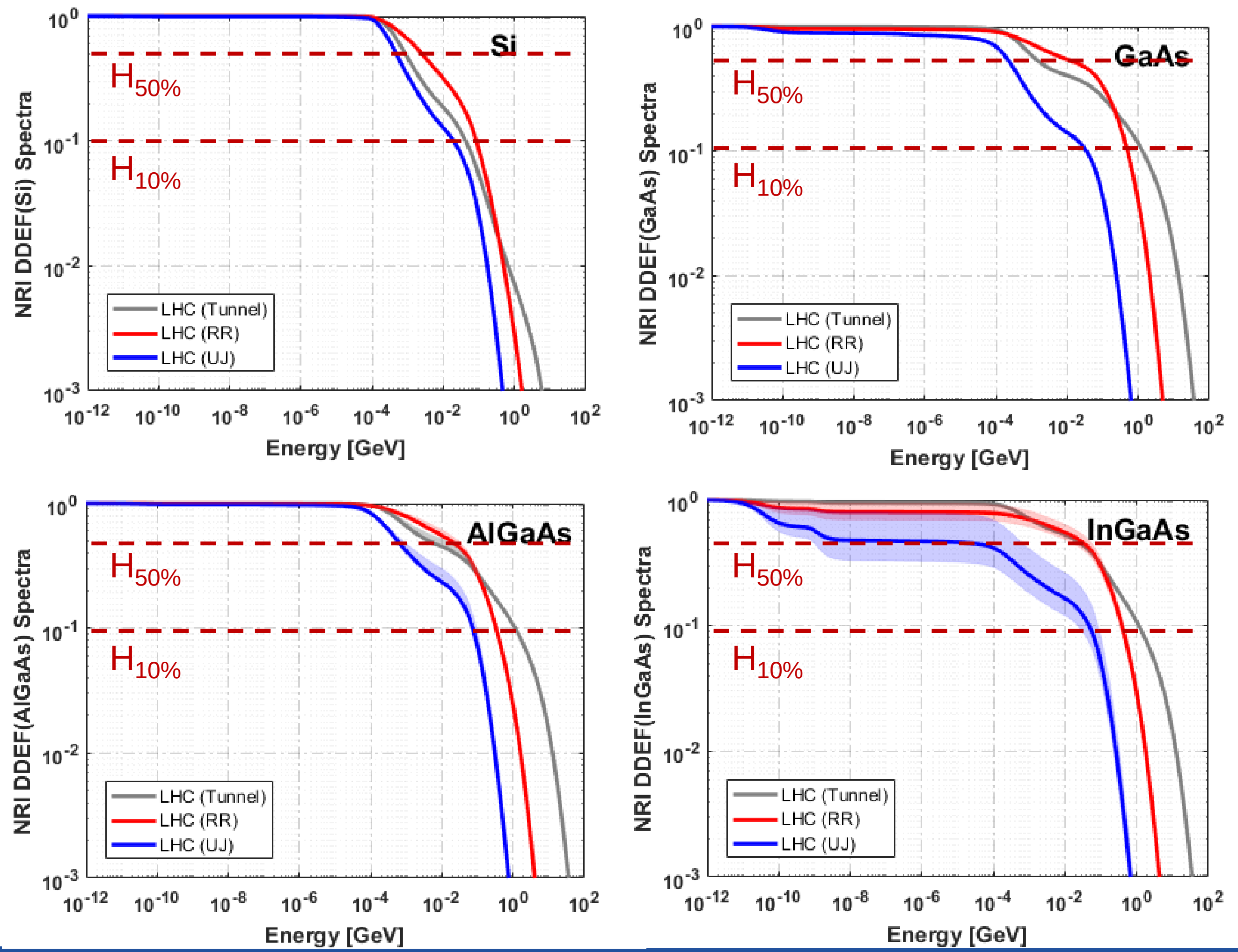
LHC Spectra DD Characteristics

LHC Spectra DD characteristics obtained by combining LHC Spectra with particle NIELs

Considered Materials: GaAs, AlGaAs, InGaAs

Typical Spectra DD characteristics:

- **Energy Distribution:**
  - DD Normalized Reverse Integral (NRI)
  - **$DDH_{50\%}$, $DDH_{10\%}$:** Energy values for which the DD fluences contributes to 50% and 90% of the total DD.



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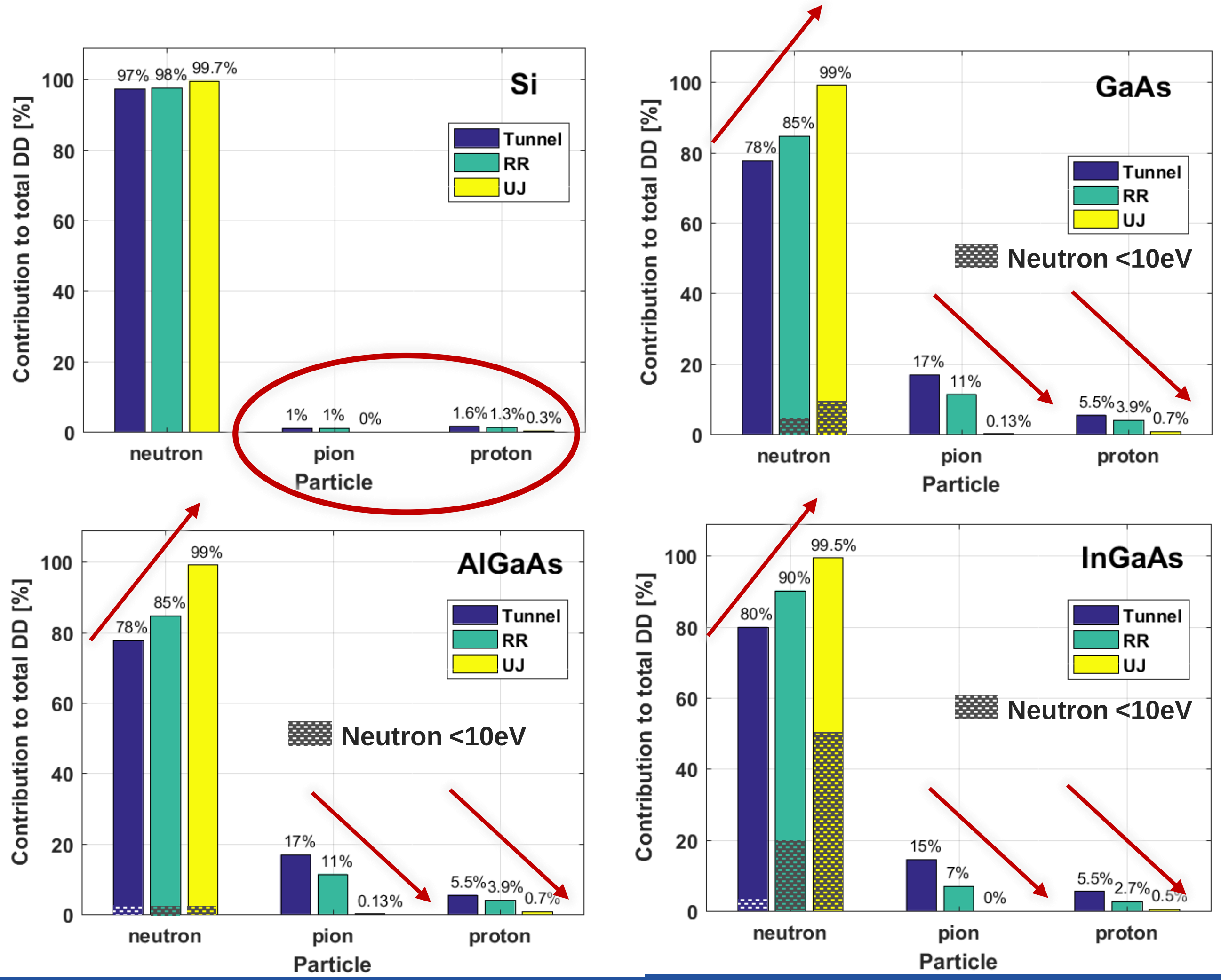
  - **$DDH_{50\%}$, $DDH_{10\%}$:** Energy values for which the DD fluences contributes to 50% and 90% of the total DD.
- **Particle contribution to total DD:**
  - **Si:** Negligible proton/pion contributions
  - **GaAs/InGaAs/AlGaAs:**
    - **Proton / pion contributions decrease while shielding increase**

→ characteristics to be reproduced during system level tests.



CHARM: TID-DD levels distribution

- **Target:**
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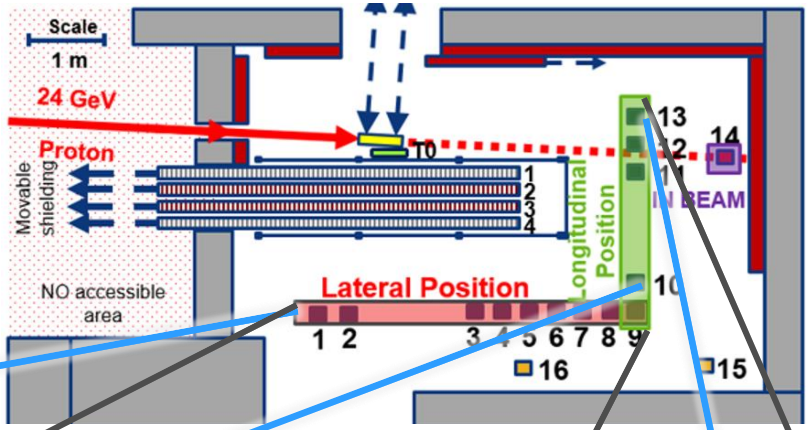
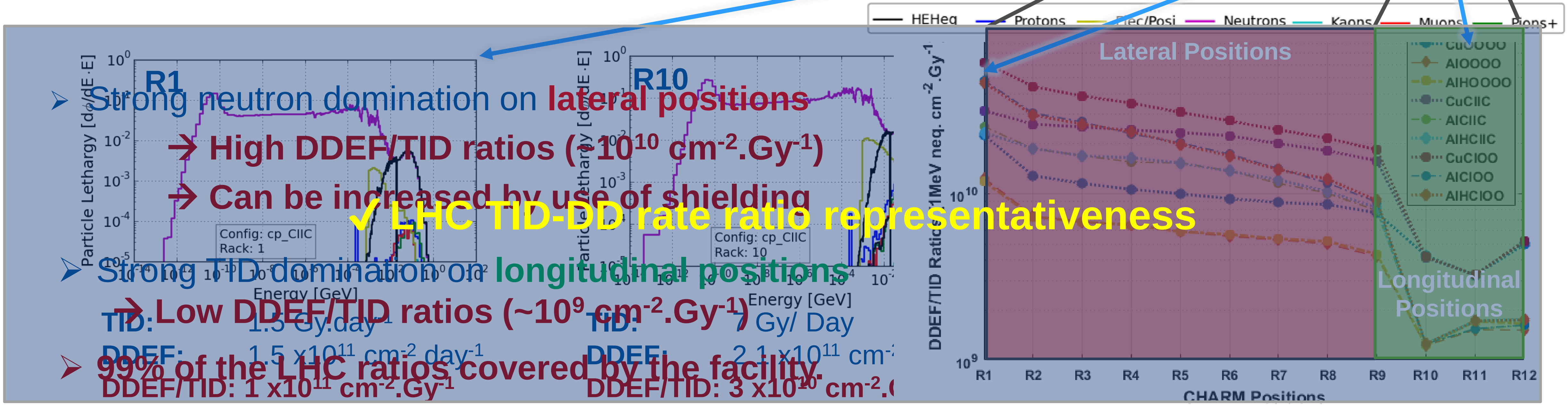
  - **Al** - Aluminium
  - **Cu** - Copper
- **Shielding:**
  - **C** – Concrete (**1,4**)
  - **I** – Iron (**2,3**)
- **Positions:**
  - **1-16**
- **Configuration: Cu CIIC**
  Data from FLUKA Simulations





- Strong neutron domination on **lateral positions**
  - → **High DDEF/TID ratios (~10^{10} cm^{-2}.Gy^{-1})**
  - → **Can be increased by use of shielding**
- Strong TID domination on **longitudinal positions**
  - → **Low DDEF/TID ratios (~10^{9} cm^{-2}.Gy^{-1})**
- **99% of the LHC ratios covered by the facility**

✓ LHC TID-DD rate ratio representativeness