Radiation To Electronics (R2E) Challenges @ the LHC

ASP16 – 4th African School of Fundamental Physics and Applications
University of Rwanda, Kigali, Rwanda
August 17, 2016

Yacine Kadi
CERN Engineering Department
Geneva, Switzerland

The LHC Challenge

LHC is a proton-proton (or ion/ion) collider

- 2 proton beams at 7 TeV of 3×10^{14} p^+ each
- Stored for 10-20 hours in collision
- Total stored energy of **0.7 GJ**
  Sufficient to melt **1 ton of Cu**
- ~5000 cold magnets

- **Tiny fractions** of the stored beam suffice to quench a superconducting LHC magnet or even to destroy parts of the accelerators.
- **Single particles** can impact essential electronics and stop operation

Why do we (at CERN) care about radiation effects?

- **Commercial components** used in systems operating **near the LHC-tunnel** (power converters, cryogenics, QPS system…)

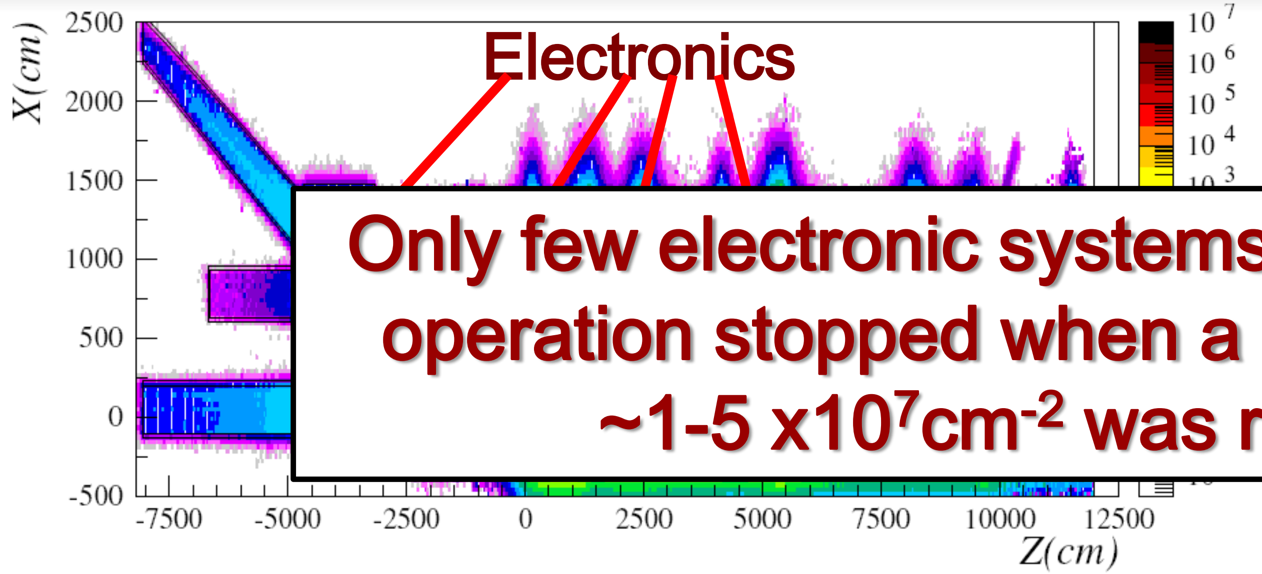
+

- **Intense radiation fields** at the locations of operation

=

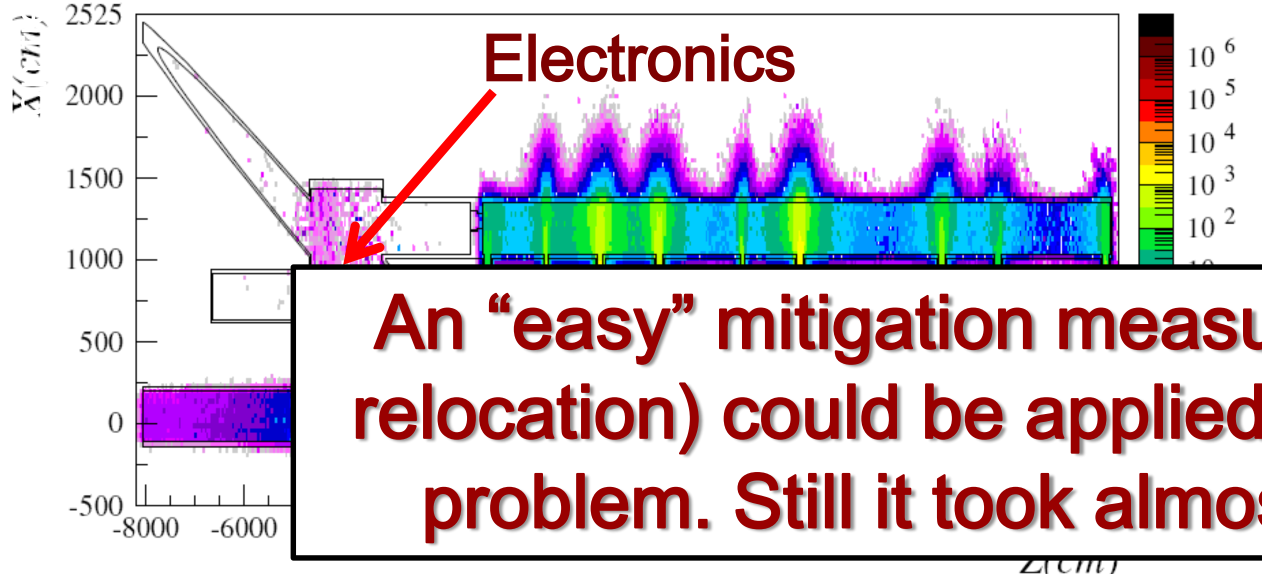
- **SEEs** in components and systems **negatively affecting the operation of the accelerator** (beam dump, etc.)
- Need to **test, monitor, mitigate** and **predict** (R2E project)

Issue: Solved By Heavy Shielding



- 2007 Layout before shielding

Only few electronic systems were exposed, operation stopped when a fluence of only ~1-5 $x10^7 cm^{-2}$ was reached!

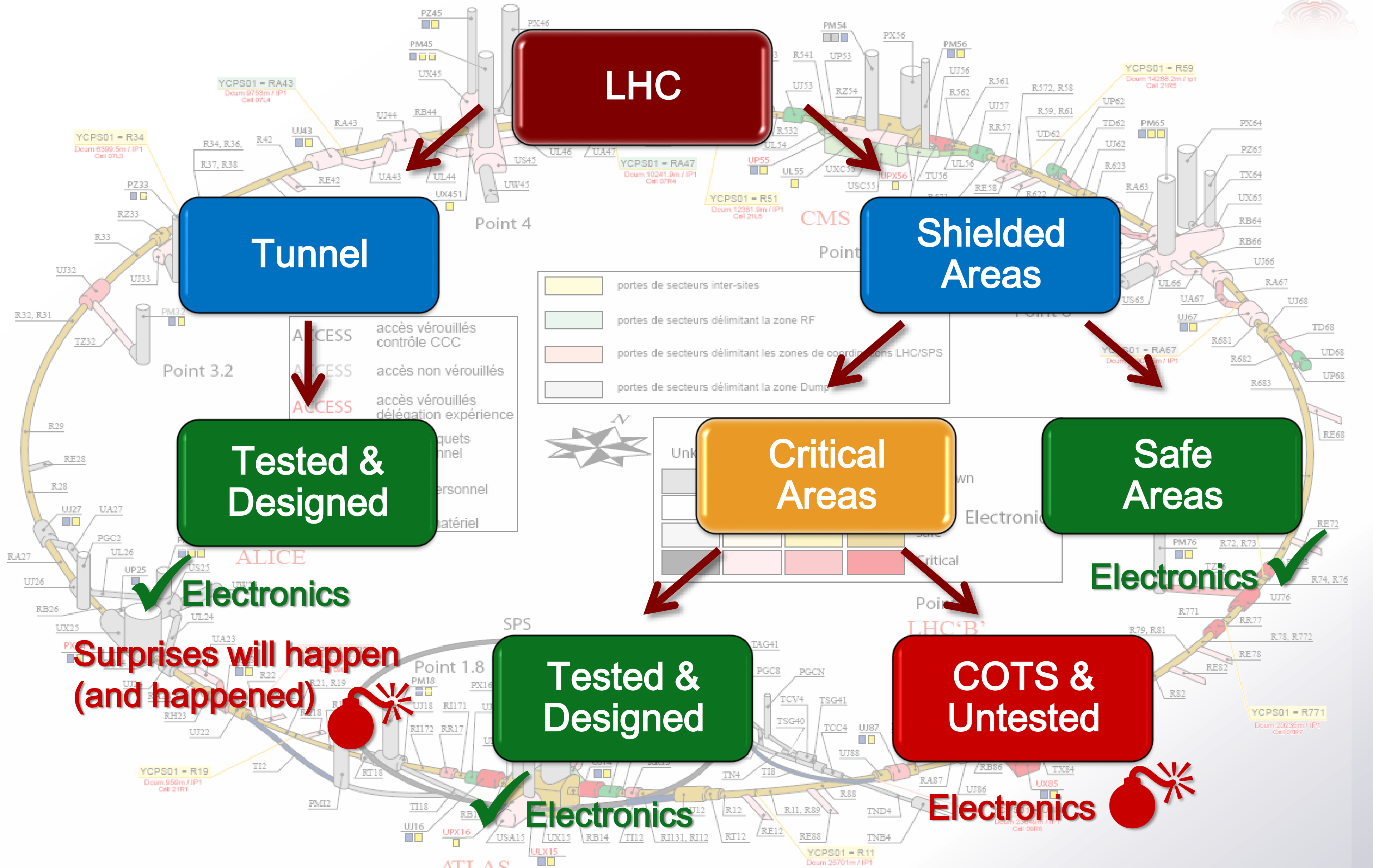


- 2008 Layout – after installation of new shielding

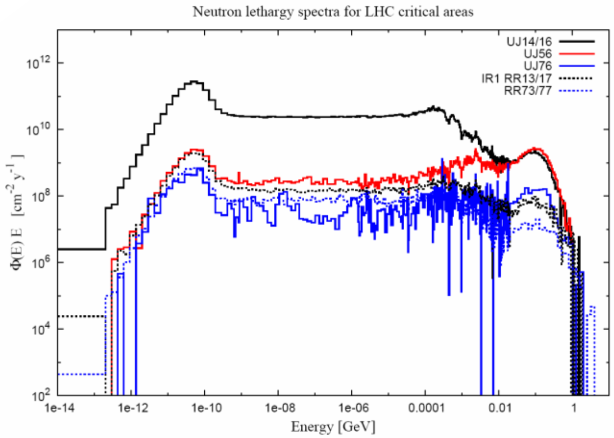
An "easy" mitigation measure (shielding + relocation) could be applied and solved the problem. Still it took almost half a year!

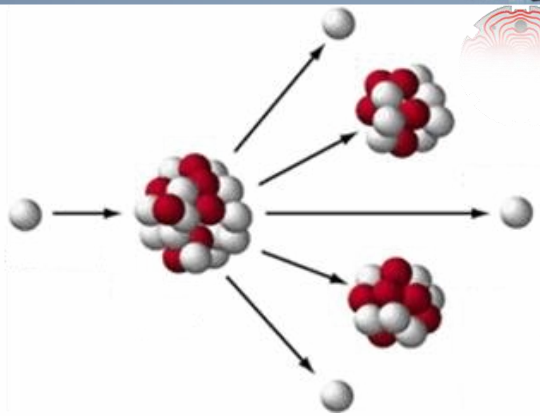
Dose in Gray for a nominal CNGS year ($4.5x10^{19}$ pot)

The LHC Challenge



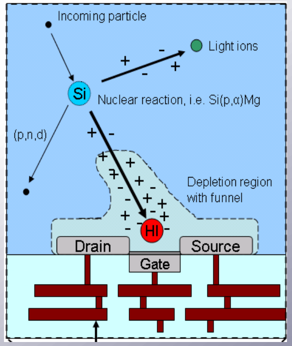
Approach & Requirements





ELECTRONIC COMPONENTS ⟷ RADIATION ENVIRONMENT ⟷ EFFECTS + PHYSICS MODELS

RADIATION EFFECTS
ANALYSIS
TESTS
MITIGATION



Mitigation Strategy

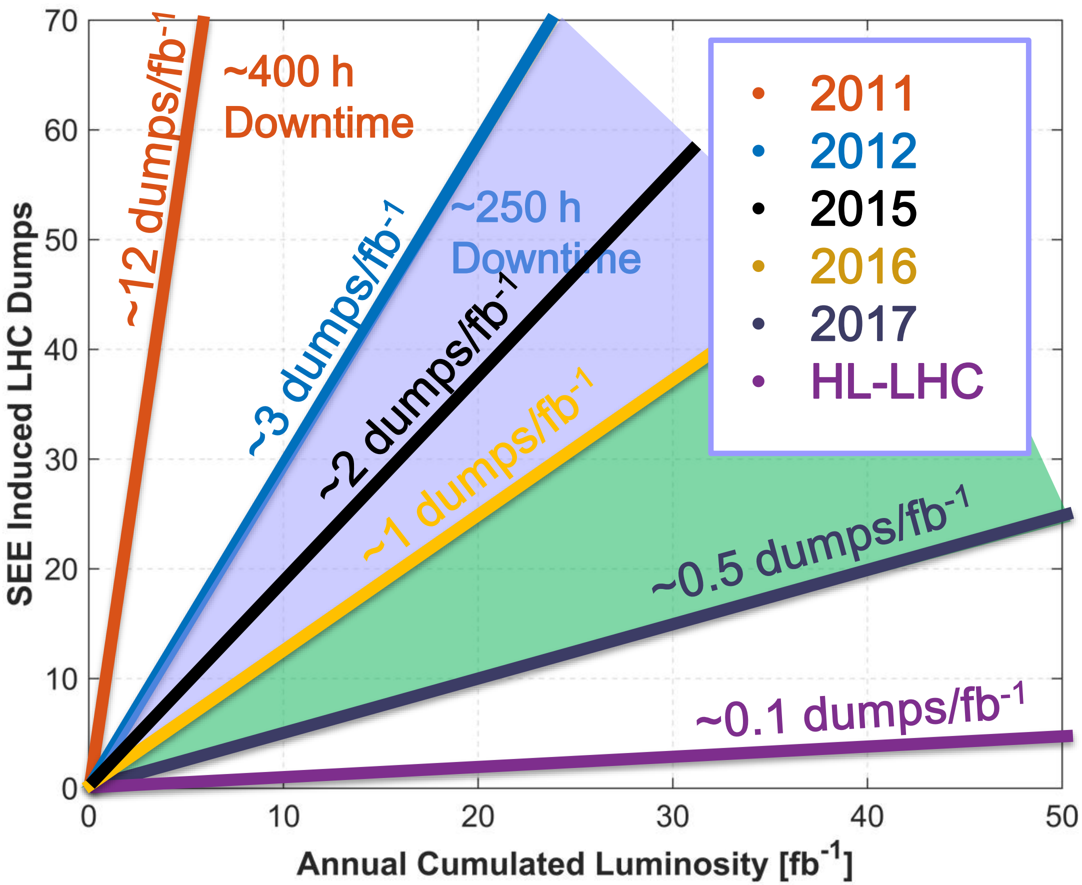
1st Safety Critical → **Immediate Relocation**

2nd Shielding → **"Fast" & Global Improvement**

3rd Most Sensitive → **Highest Impact on Operation:**
(1)Relocation
(2)Shielding
(3)Re-Design

4th Remaining →
(1)Relocation
(2)Shielding
(3)New Design

LHC R2E: Past/Present/Future



Several shielding campaigns prior 2011 + Relocations 'on the fly' + Equipment Upgrades

2011/12 xMasBreak 'Early' Relocation + Additional Shielding + Equipment Upgrades

LS1 (2013/2014) Final relocation and shielding

LS1-LS2 (2015-2018) Tunnel equipment and power converters

LS3-HL-LHC Tunnel Equipment (Injectors + LHC) + RRs

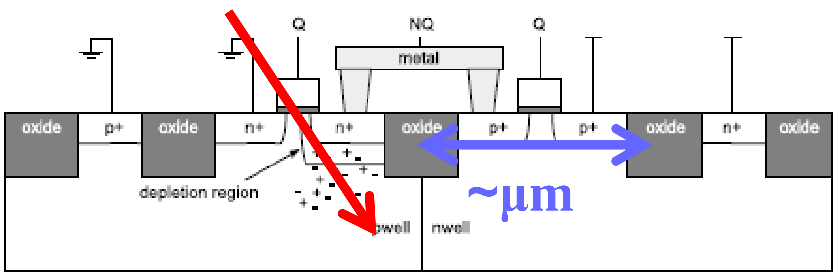
Radiation effects on electronics

- **Total Ionizing Dose Effects (TID):**
  - Cumulative effect, easier to predict
  - LHC absolute values typically not critical (especially in shielded areas)
  - Scaling of components positive for TID (smaller oxides)

- **Single Event Effects (SEEs):**
  - Stochastic events, which can happen “any time” and are therefore harder to predict
  - Absolute levels are high, even in shielded areas (neutrons still make it through!)
  - Most effects are constant with scaling (smaller volumes compensate lower critical charges) but they can also increase (proton direct ionization, etc.)

Typical Single Event Effects

- Example of non-destructive SEE:
  - **Single Event Upset:** unwanted flip in the logical state of a memory bit



- Example of destructive SEE:
  - **Single Event Gate Rupture:** Gate destroyed in a power MOSFET due to the connection between Gate and Drain/Source.

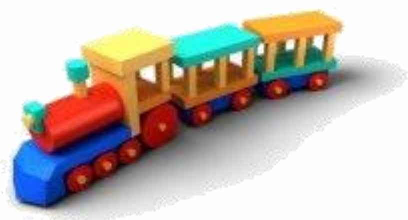
"Everyday"-life Examples

- Toyota Sudden Unintended Acceleration (SUA)

  (from the Safety Record, Volume 7, Issue 1, April 2010)
  *"… **SEU** is one possible explanation for sudden unintended acceleration (SUA) in Toyotas."*

  - loss of customer confidence, negative impact on revenue…
- French rail system

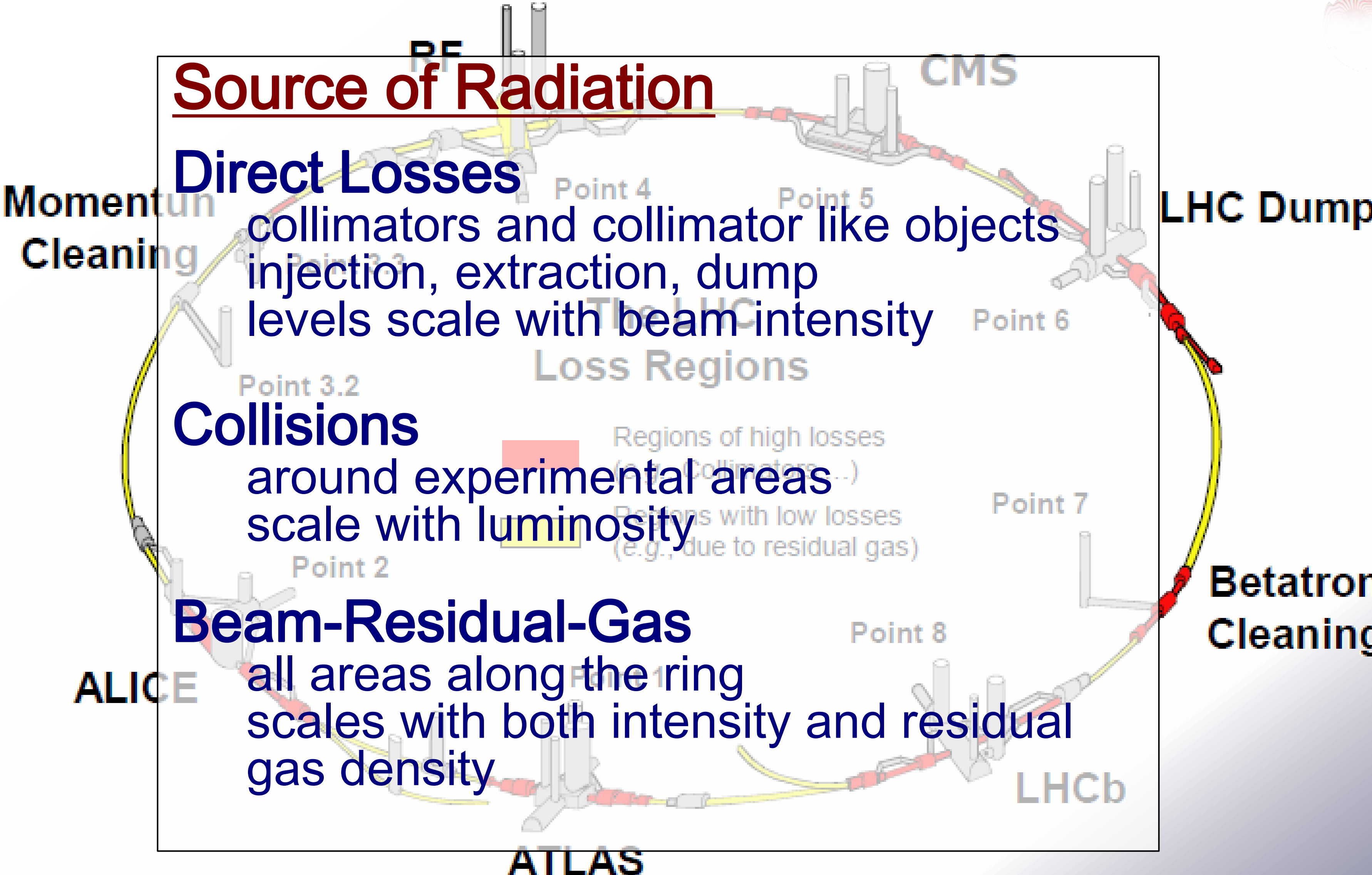
  

  - regular power converter failure in original implementation.
  - SEE cause confirmed, de-ratting applied to solve the problem
- Airborne systems

  - Malfunction caused a release of oxygen masks – likely caused be SEE

The LHC & 'Radiation Areas'



Source of Radiation

Direct Losses

- collimators and collimator like objects
- injection, extraction, dump
- levels scale with beam intensity

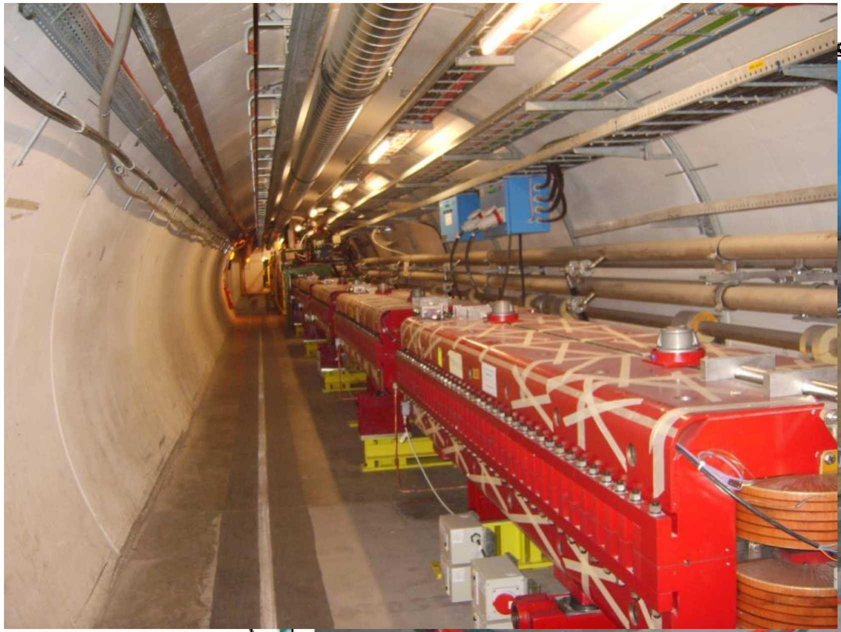
Collisions

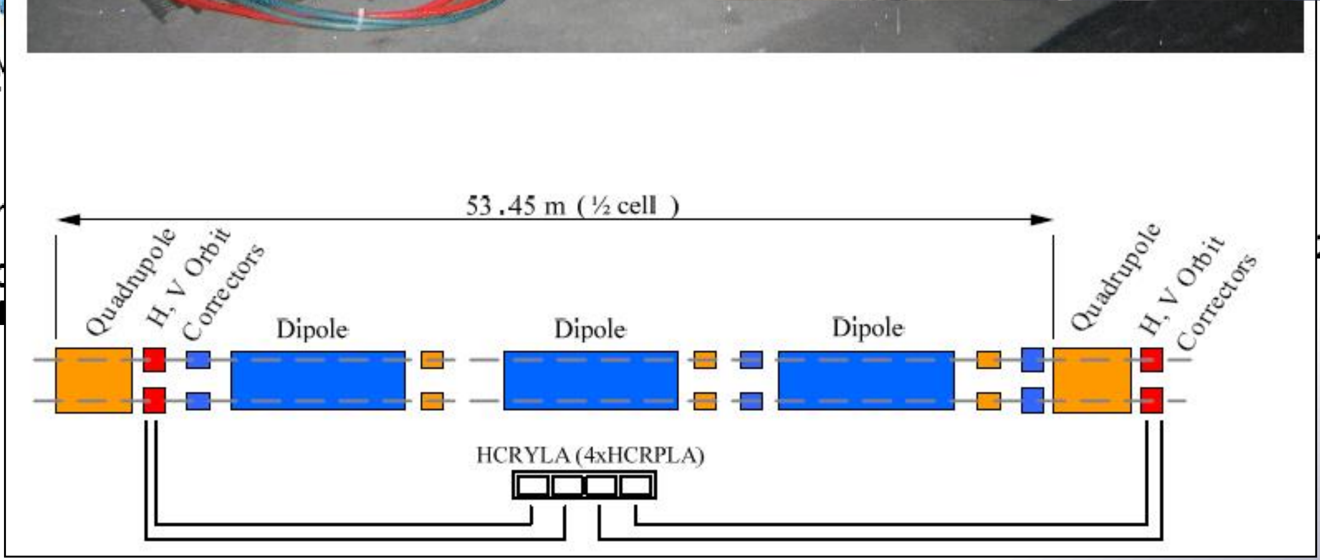
- around experimental areas
- scale with luminosity

Beam-Residual-Gas

- all areas along the ring
- scales with both intensity and residual gas density

Tunnel: LSS/DS/ARC



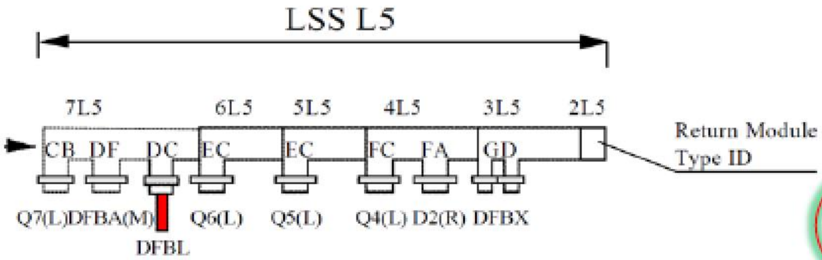


Cellules
12R2-----12

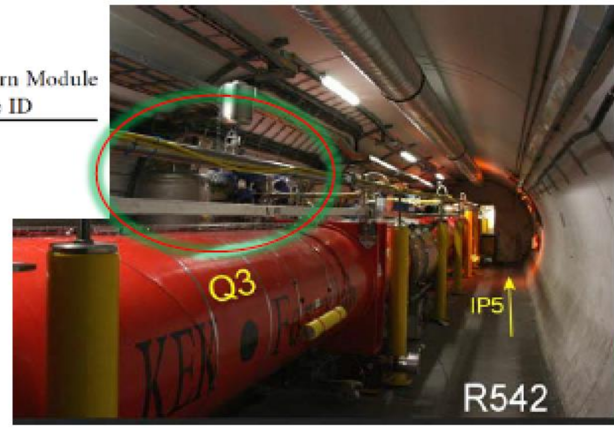
Point 2

2R7

P5 left



QRL module: type ID



DFBX & QRL jumper GD

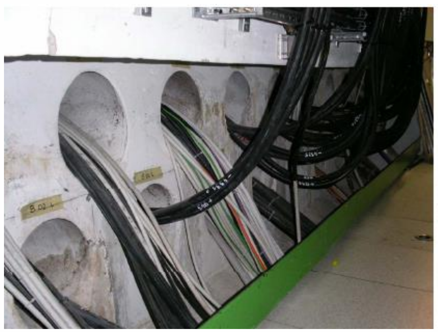
D2 & QRL jumper FA

Q4 & QRL jumper FC

Typical Shielding

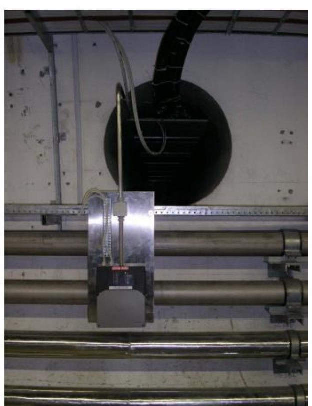
Point 2

Point 3



Point 5

Point 6



Point 7

System example: LHC POWER CONVERTERs

- Minimize the number of converter types:
  - Only the LHC60A-08V was specified for a radioactive environment !
  - 3 other converter types are part now of the radioactive sensitive areas!

LHC120A-10V
4-Quadrant

300 Units

LHC600A-10V
4-Quadrant

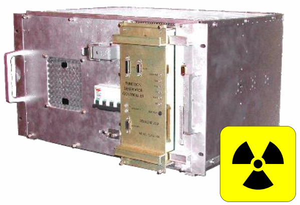
400 Units

LHC4..6kA-08V
1-Quadrant

200 Units

LHC60A-08V
4-Quadrant

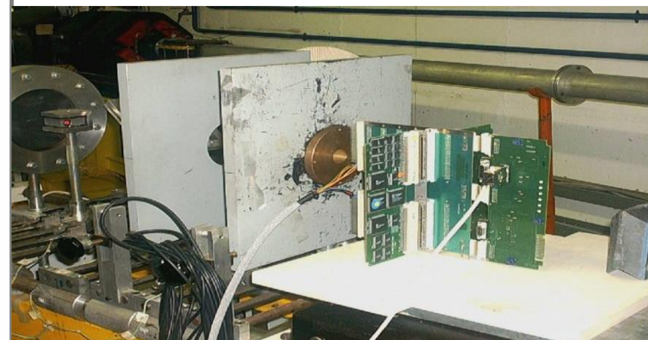
752 Units



Units : Quantity in all machine (UA, RR, UJ, tunnel)

PCs: What was tested and where?

LOUVAIN (2003 - FGCs)

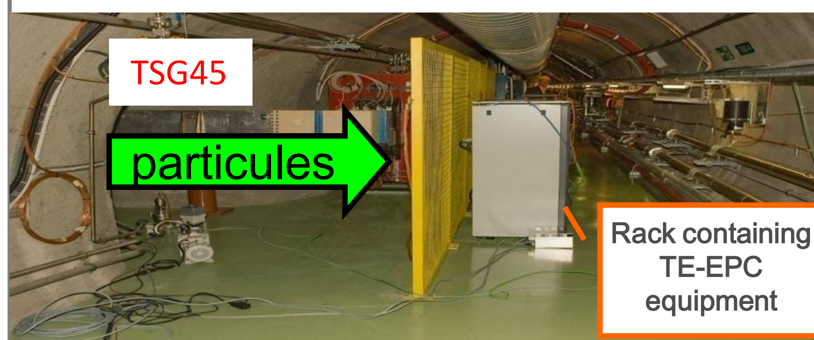


60 MeV proton components tests

PROSPERO (2009 - FGCs)

1MeV neutron displacement damage tests

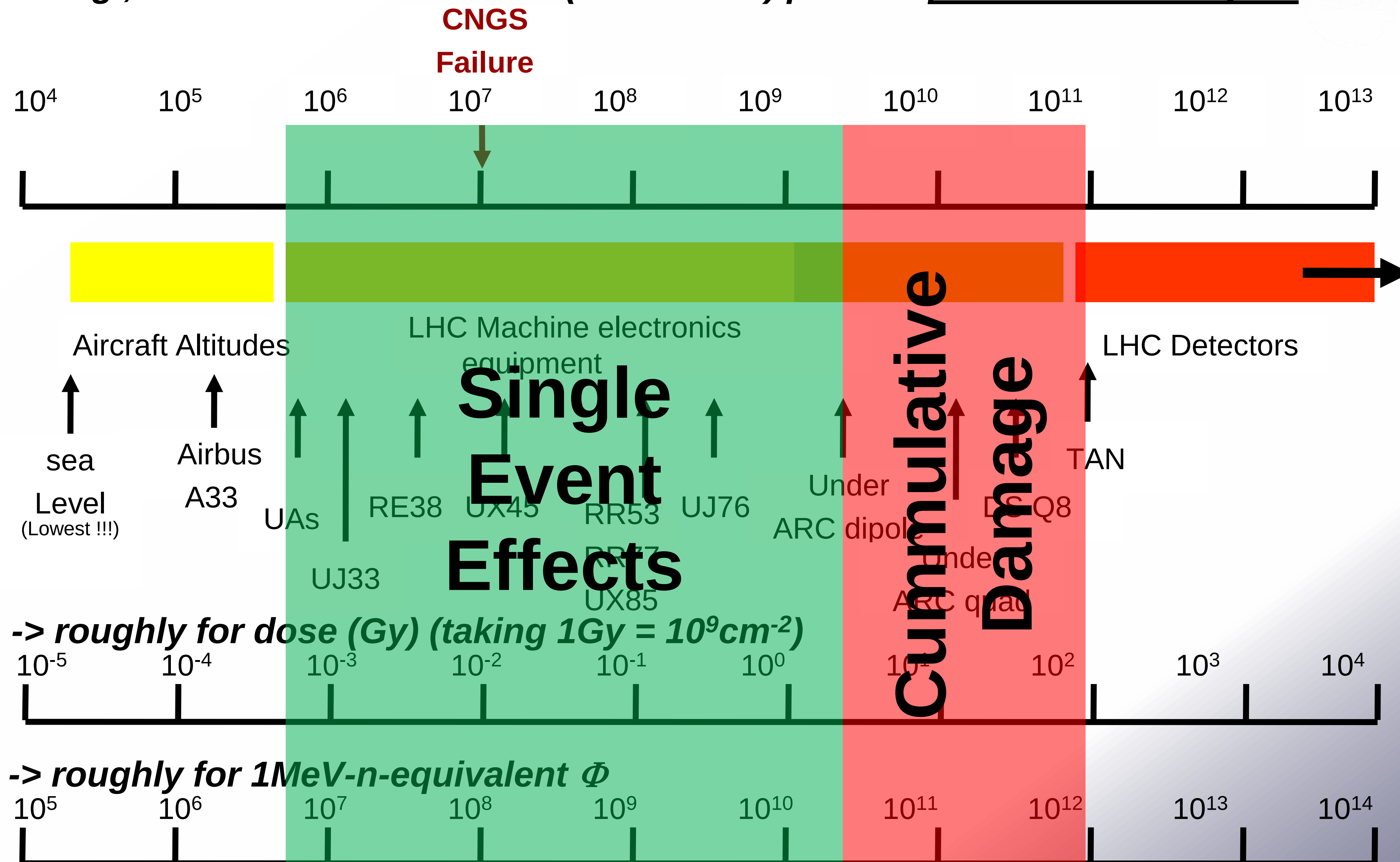
CNGS (2008..2009 – FGCs, 60A, PSUs)



LHC-Environnement System Test

Range of Radiation Levels

e.g., LHC-Levels for Hadrons (E > 20 MeV) per cm² per LHC nominal year



Energy deposition mechanisms

- The **charge collection** leading to the SEE is generated through **ionization**, however, two main different processes can be distinguished:

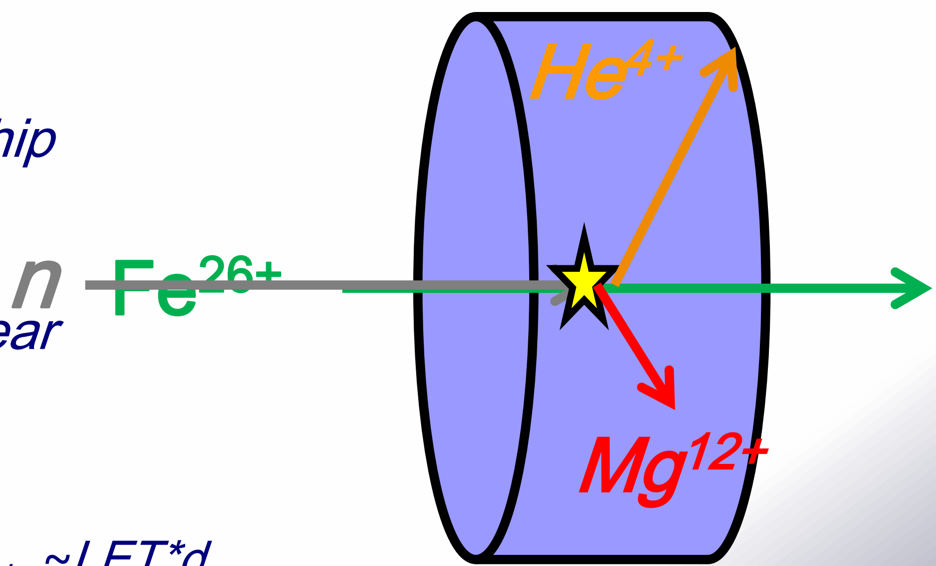
  - **Direct ionization**: the ionizing particle responsible for the energy deposition comes from the **radiation environment**

    - *continuous energy loss*
    - *“deterministic” relationship between ion type and energy and deposited energy through the Linear Energy Transfer (LET)*

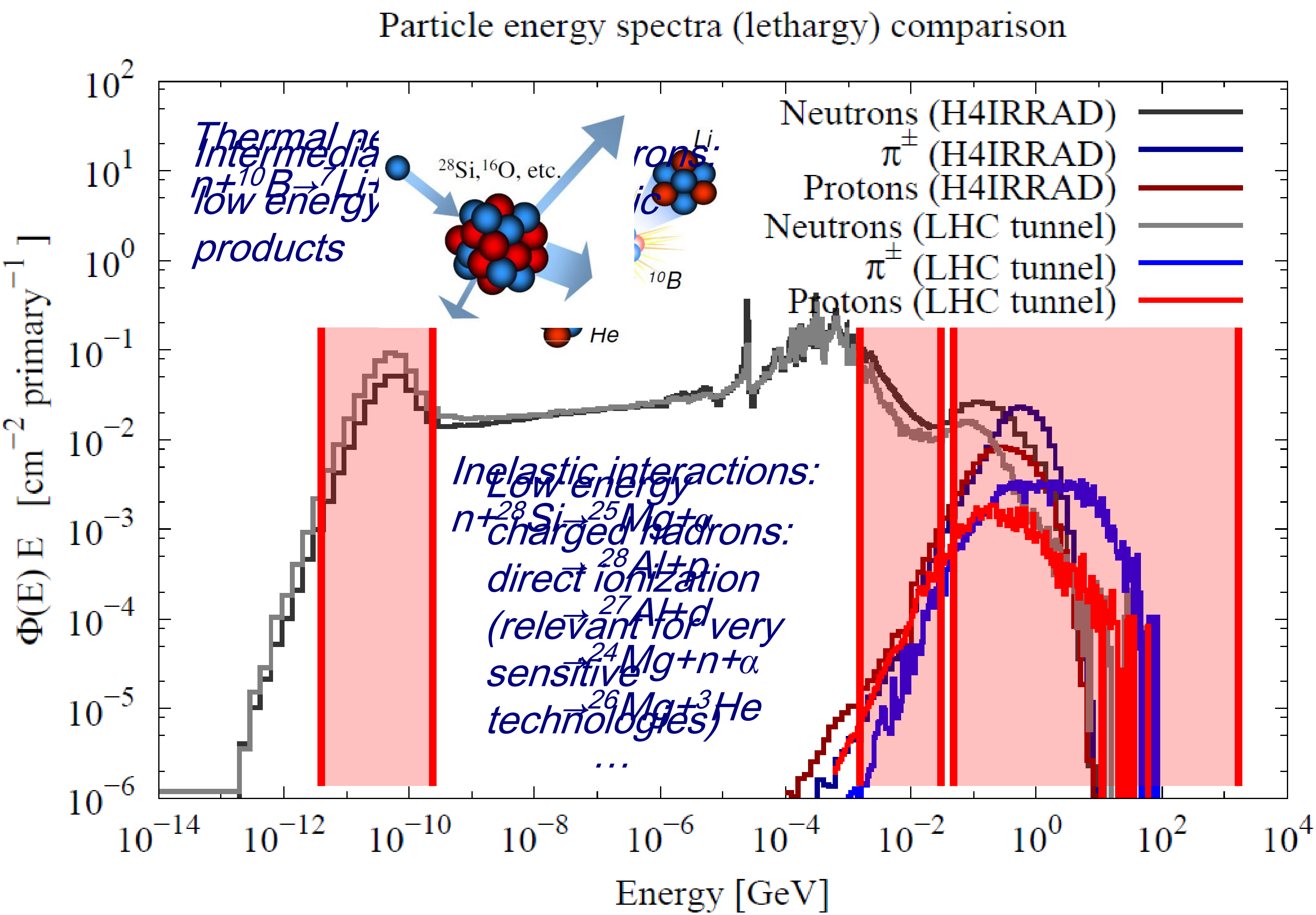
  - **Indirect ionization**: the particle responsible for the energy deposition comes from a secondary particle generated through an inelastic reaction **radiation environment**

    - *mainly induced by energetic hadrons*
    - *complicated relationship between incoming particle and products*
    - *often need to resort to Monte Carlo simulations*

$E_{dep} \sim LET*d$

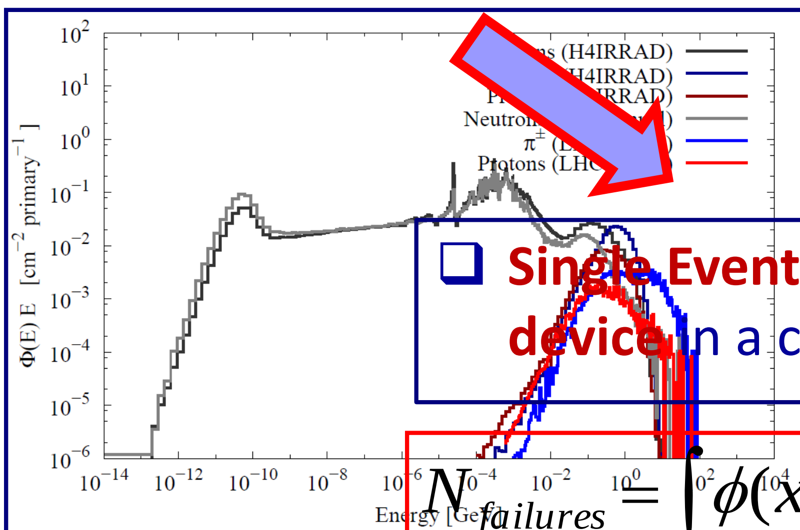


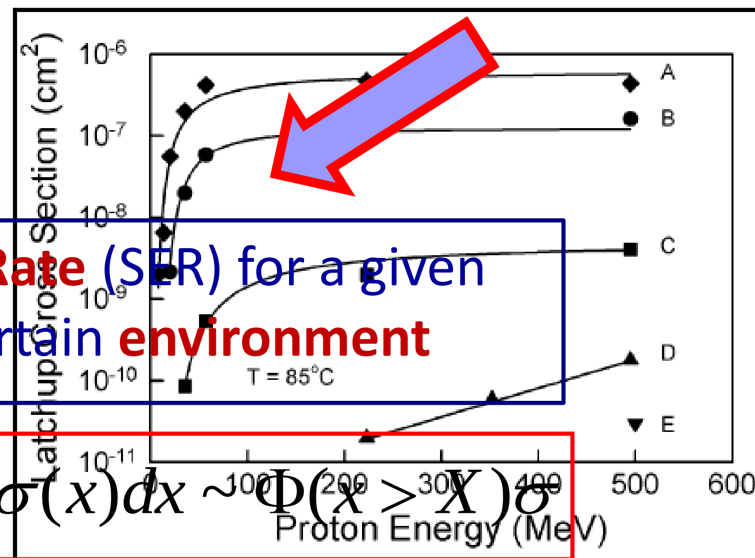
Particle energy spectra: intervals of interest



SEE Rate Prediction

- **Environment:**
  - typically particle LET or energy spectra
  - from measurements, simulations, models, etc.
  - atmospheric-like, outer space, Earth radiation belts, high energy accelerators…
- **Device response:**
  - typically an error cross section as a function of particle LET or energy
  - from SEE measurements, models, simulations, etc.
  - Can be very different even for “electronically identical” devices



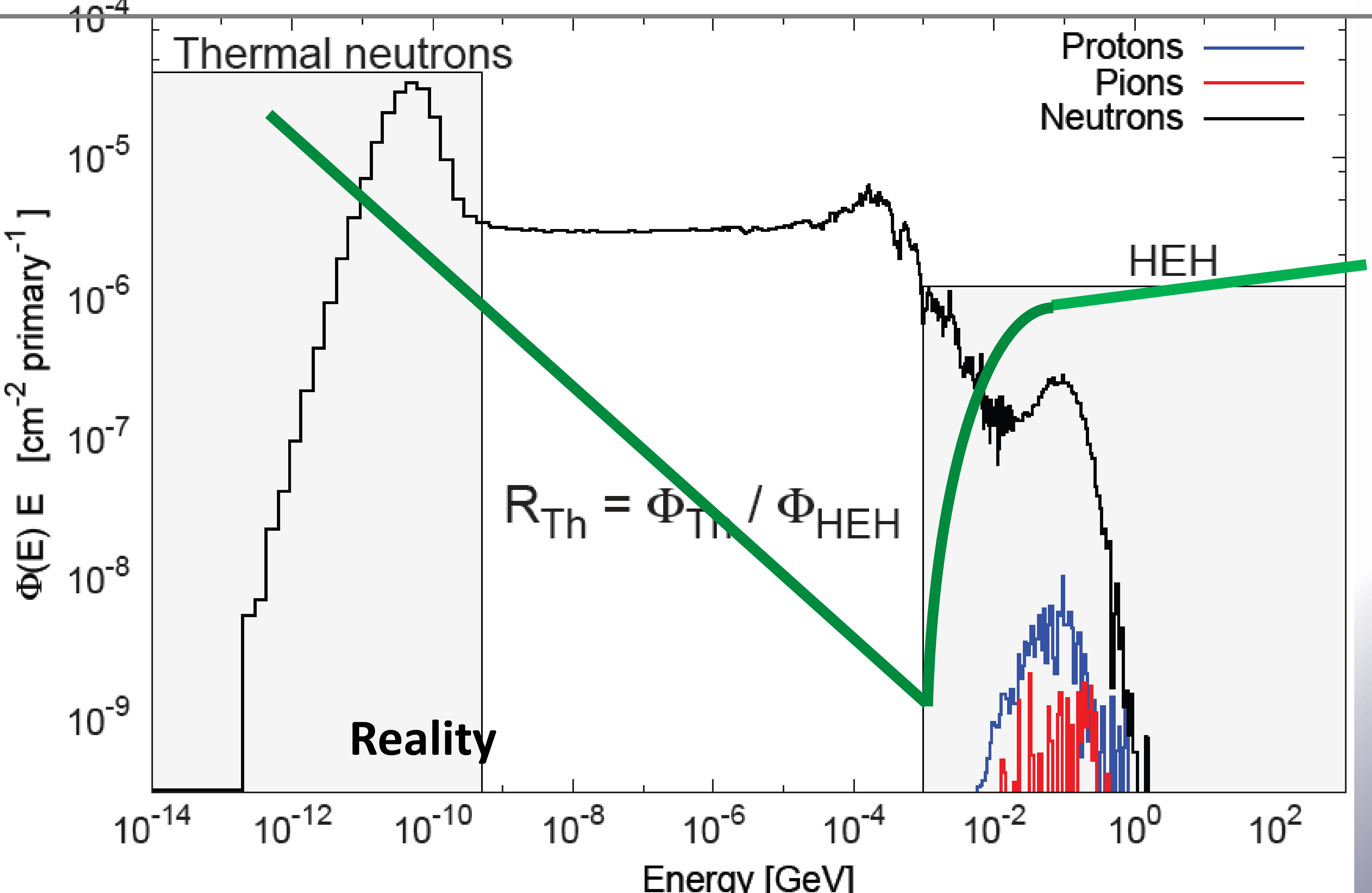


- **Single Event Rate** (SER) for a given **device** in a certain **environment**

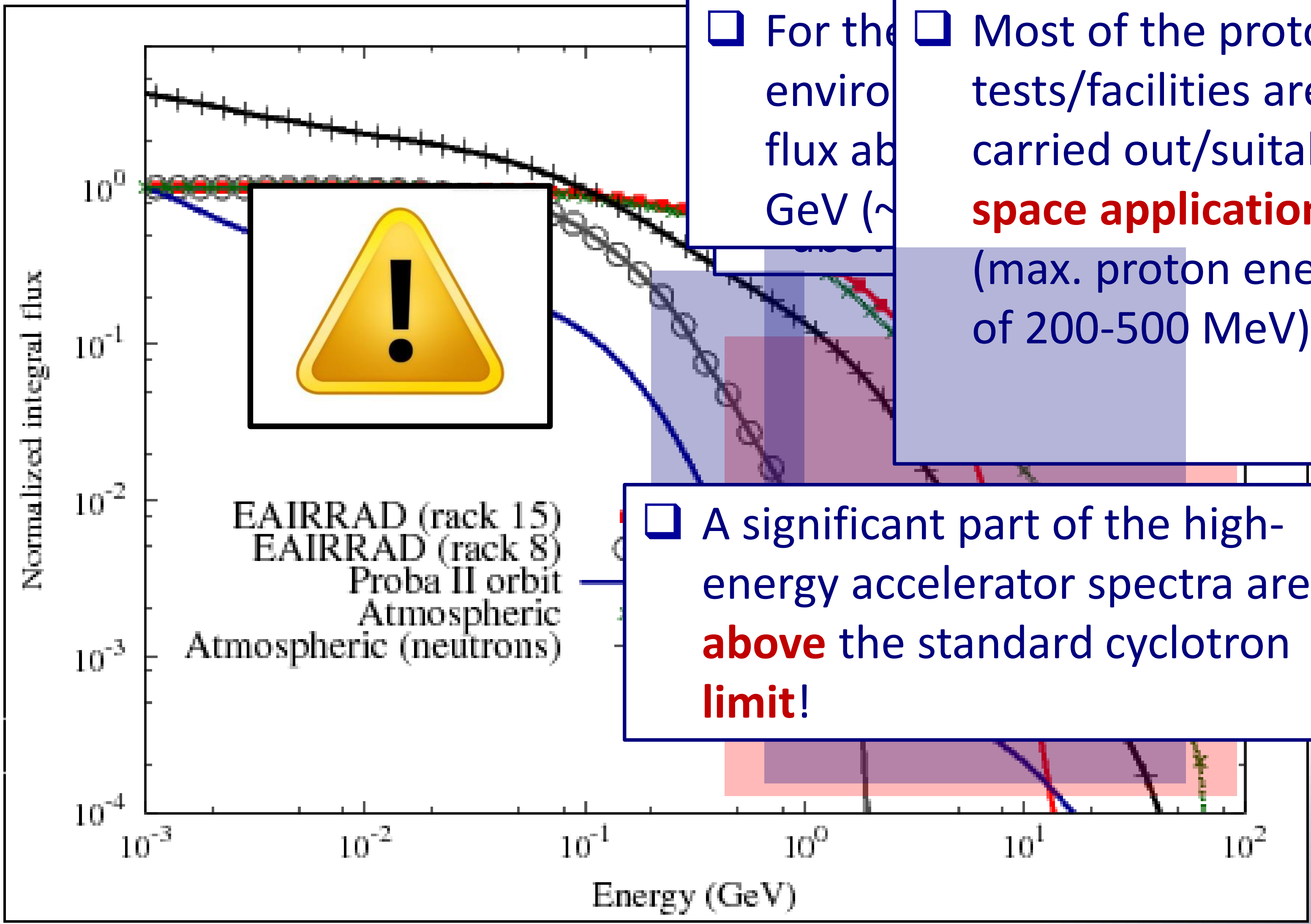
$$N_{failures} = \int \phi(x)\sigma(x)dx \sim \Phi(x > X)\sigma$$

Radiation field and device sensitivity

$$\#SEE = \sum(\sigma_{Th.n.} \cdot \Phi_{Th.n.}) + \sum(\sigma_{5-20MeV\,n} \cdot \Phi_{5-20MeV\,n}) + \sum(\sigma_{HEH} \cdot \Phi_{HEH})$$



Particle Energy Spectra *hardness*

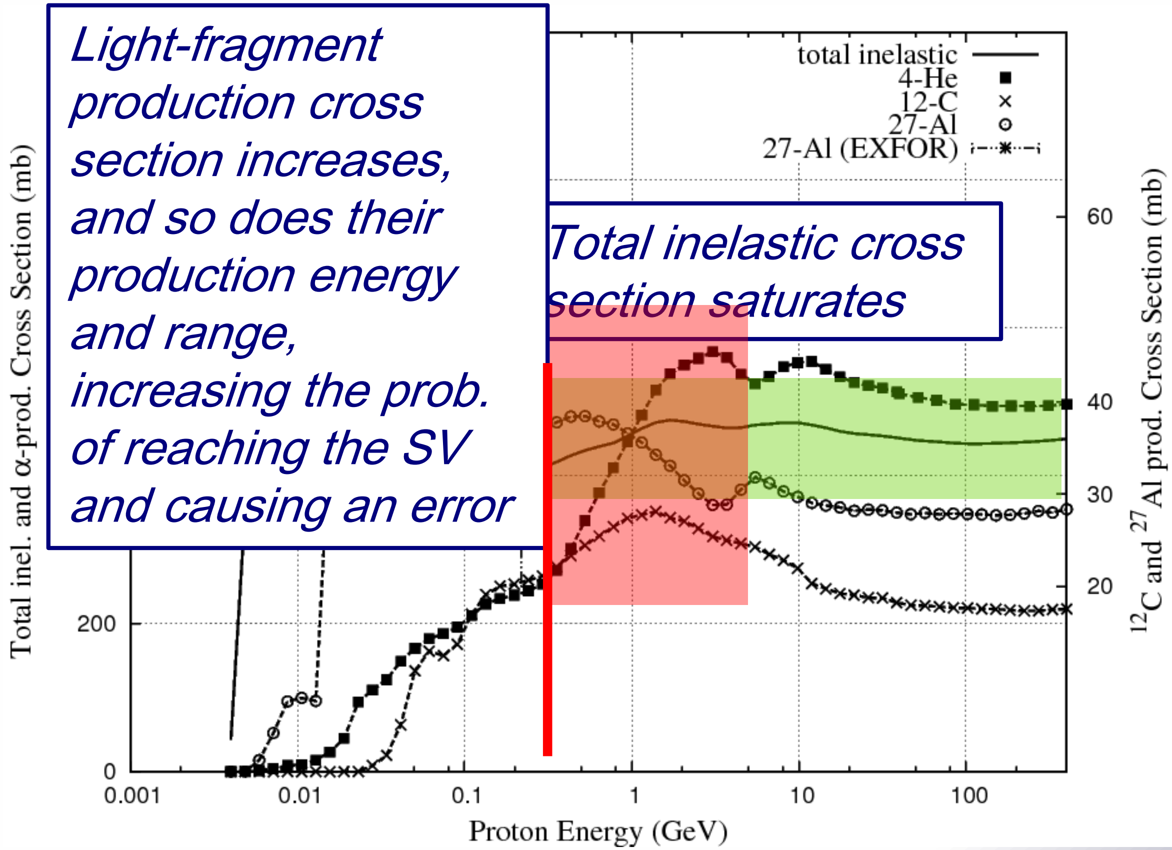


- For the enviro flux ab GeV (~
- Most of the proton tests/facilities are carried out/suitable for **space applications** (max. proton energies of 200-500 MeV)
- A significant part of the high-energy accelerator spectra are **above** the standard cyclotron **limit**!

SEU: Energy Dependence

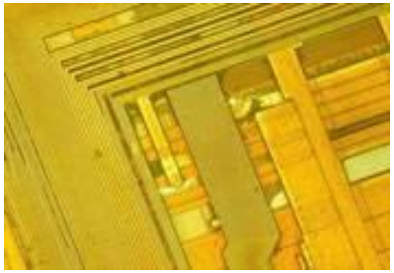
Above ~100 MeV, the total hadron-Silicon inelastic cross section is saturated, however:

- more light, long-ranged fragments are produced
- and they are produced with larger energies (and therefore ranges)



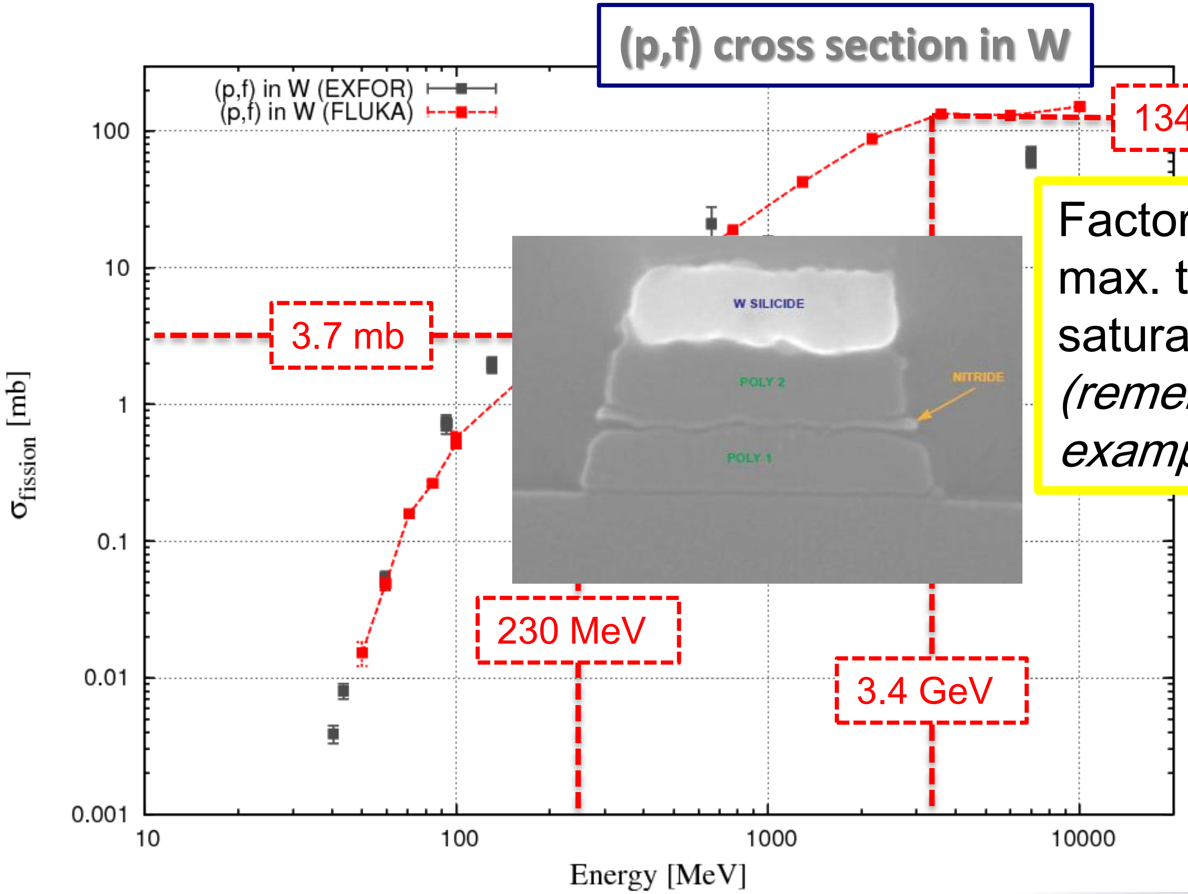
"LHC"-life example: SEL on CPLD

- A Complex Programmable Logic Controller (CPLD) was tested using **60 MeV protons**
- **No SEEs** were **observed** for the **three devices** tested before these started failing due to total ionizing dose effects (cumulative) after 120 Gy.
- The component was then exposed to high energy particle radiation at an **LHC-environment**. **Permanent destruction** of the part occurred in the **early stage** of the test.
- Importance of **testing** in the actual **operation environment** (not always feasible in a systematic way) and of being able to **model/predict** the **error rate** (energy dependence knowledge, for example)



Fission: Energy Dependence

- **High-Z materials** (namely **tungsten**) are often used in the interconnection layers of the memories, **near the sensitive volumes**
- Energetic hadrons can induce **fission** in these materials, producing very **high-LET fragments** that can **dominate the SEE cross section**



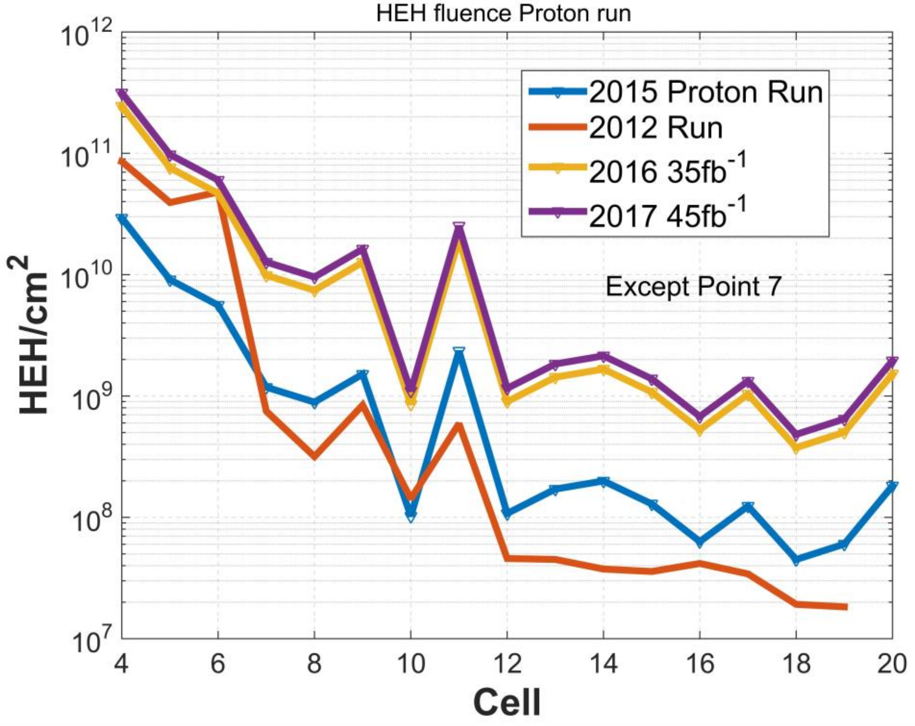
Factor ~35 between max. test energy and saturation *(remember, CPLD example!)*

How to reach the nominal performances

- Failures tracking and Radiation monitoring
- Needs of tolerant hardware for LS2 and beyond
- Radiation Hardness Assurance – RHA

Radiation Levels – Tunnel Areas

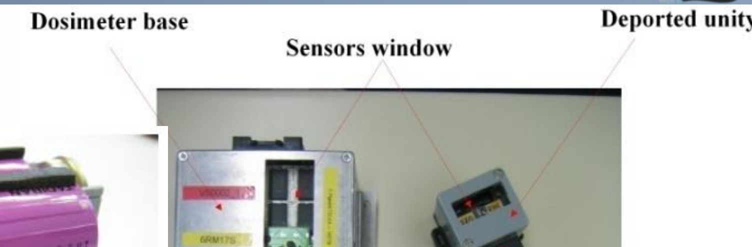
- Failure rates are proportional to the radiation levels
- Tunnel areas – several equipment installed: QPS, EPC, Cryo



- Analysis based on the RadMon measurements up to end November
- 2012 vs 2015 highlights the predicted impact of the 25ns operation
- 2015 HEH fluence higher than 2012 in cells >8 due to the higher beam-gas interaction
- 2015 low luminosity impacts the cell <8 with less fluence
- expected radiation level for 2016 and 2017 are ~8x and ~10x higher than the 2015 (scaling with the integrated luminosity)

RadMon Detection System

- **Online (through WorldFIP)** and **Standalone version**
- **Deported unit** (for TID/1MeV)
- 3 types of sensors:
  - **RadFets** (NMRC) for TID
  - **PIN diodes** (Siemens) for 1MeV n eq.
  - **SRAMs** for high-E hadron fluence (SEEs)
- System of ~400 online radiation moni
- **Several detailed calibration campaigns**
  - thermal neutron response and intermediate energy (few MeV) neutrons
  - additional RadFet calibration (& batch) tests
  - Additional 1MeV verifications

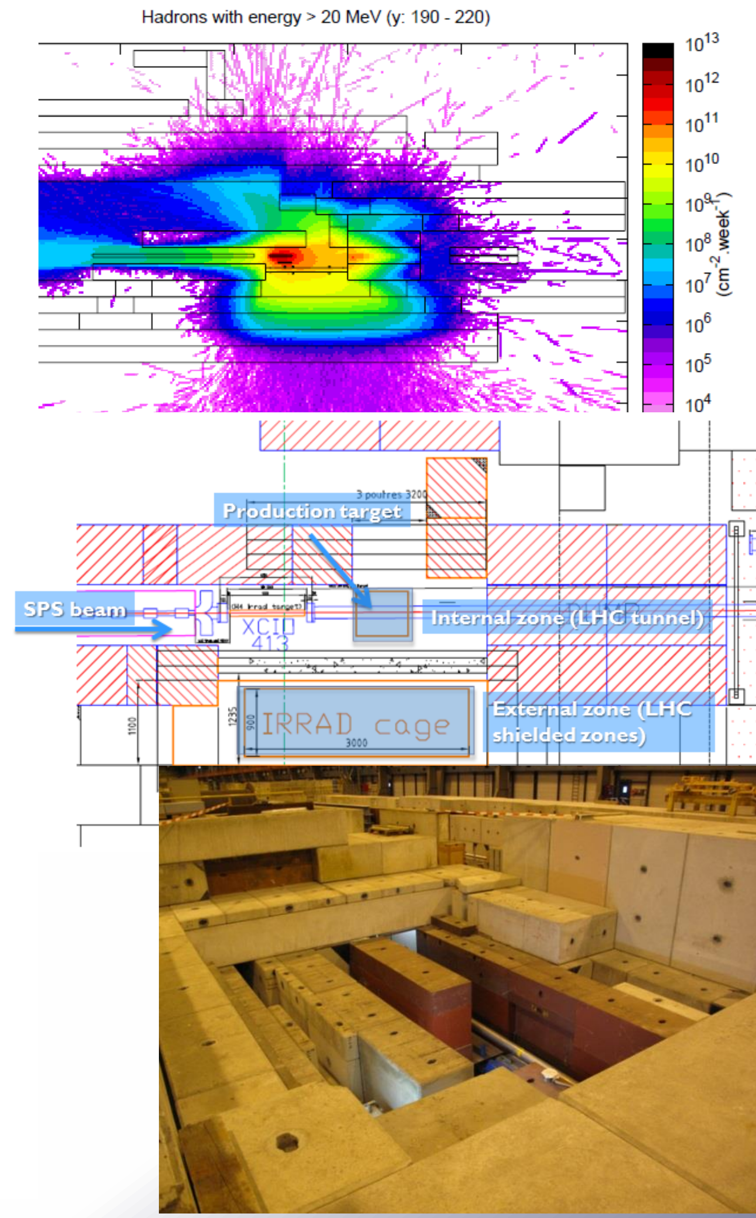


Where do we test (so far)

- **CERN**
  - **CNRAD (mixed-beam)**
  - **H4IRRAD (mixed-beam)**
- **PSI (protons)**
- **CEA Reactor (neutrons)**
- **Heavy-Ion Facilities (LET)**
- **Thermal neutron facilities (neutrons)** (Prague, Oslo, Rome)
- **Fraunhofer (TID)**
- **Others (mainly for calibration, e.g, PTB)**

H4IRRAD Test Area

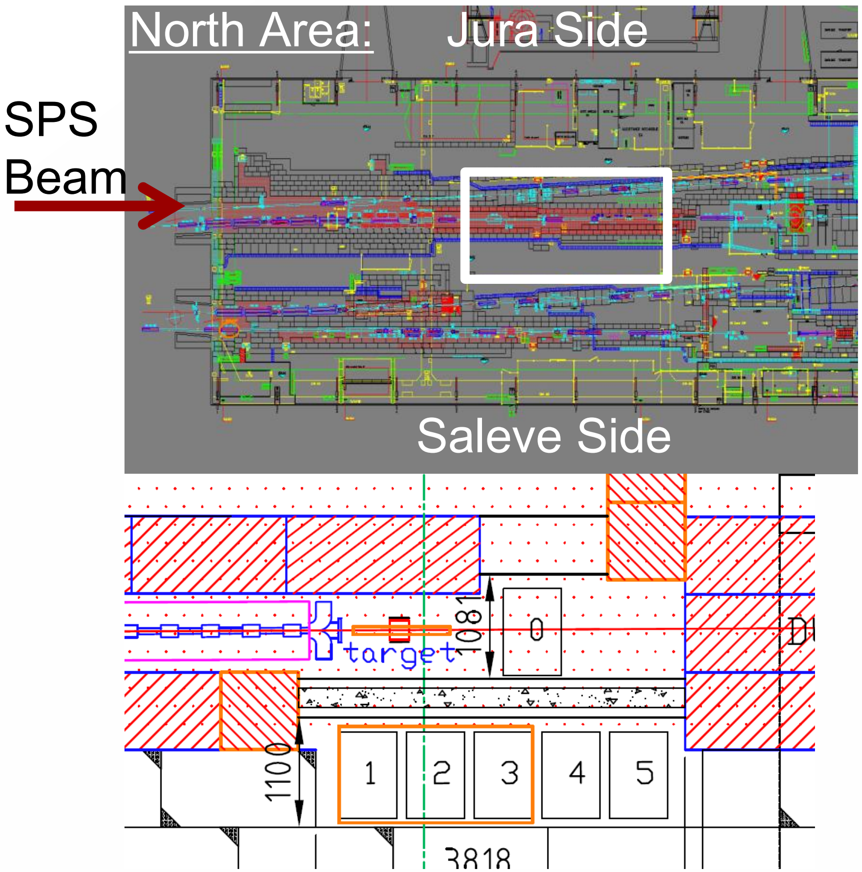
- **Mixed-Particle Test Area -> LHC**
- Secondary beam from the SPS – 280 GeV –> 1m Cu-target
- **Internal/External radiation zones**
- For **“small” to “bulky”** equipment
- Pulse intensity ~10^9 p/spill, ~1.5×10^{12}p/day **(~5×10^5 HEH/cm^2/min)**
- Typical rad levels:
  - Internal: ~2×10^9 HEH/cm^2/day, **~1 Gy/day**
  - External: ~4×10^8 HEH/cm^2/day **~200 mGy/day**



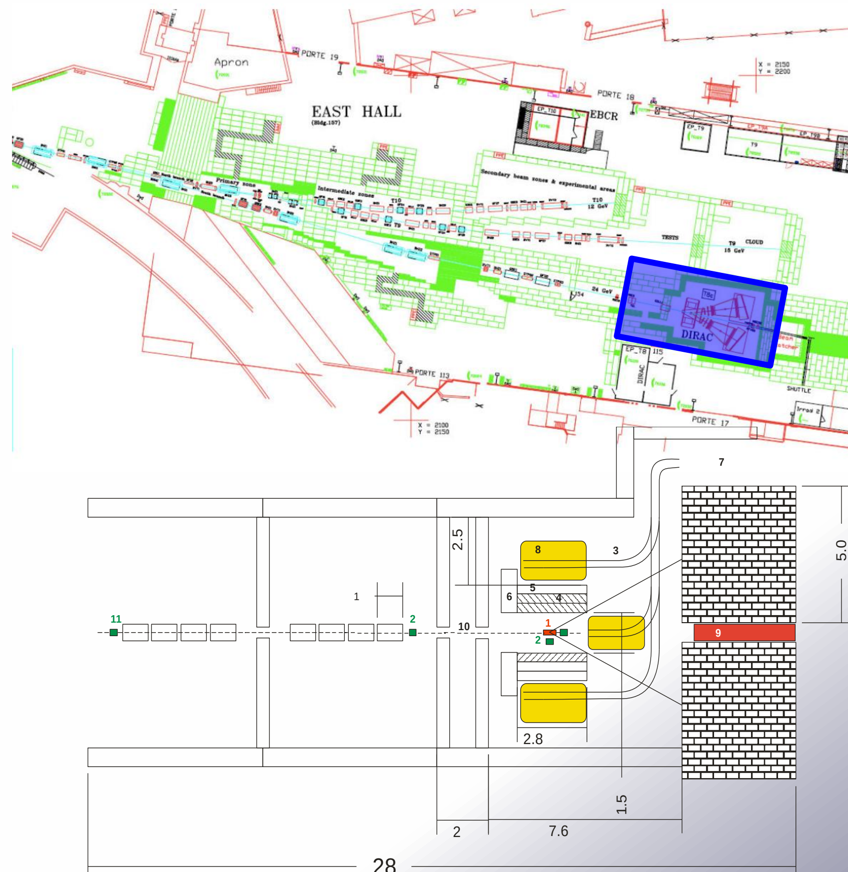
New Facility: CHARM

Extensive and **complex radiation test campaigns** exceed our current test possibilities (CNRAD, PSI) – Important to think ahead!

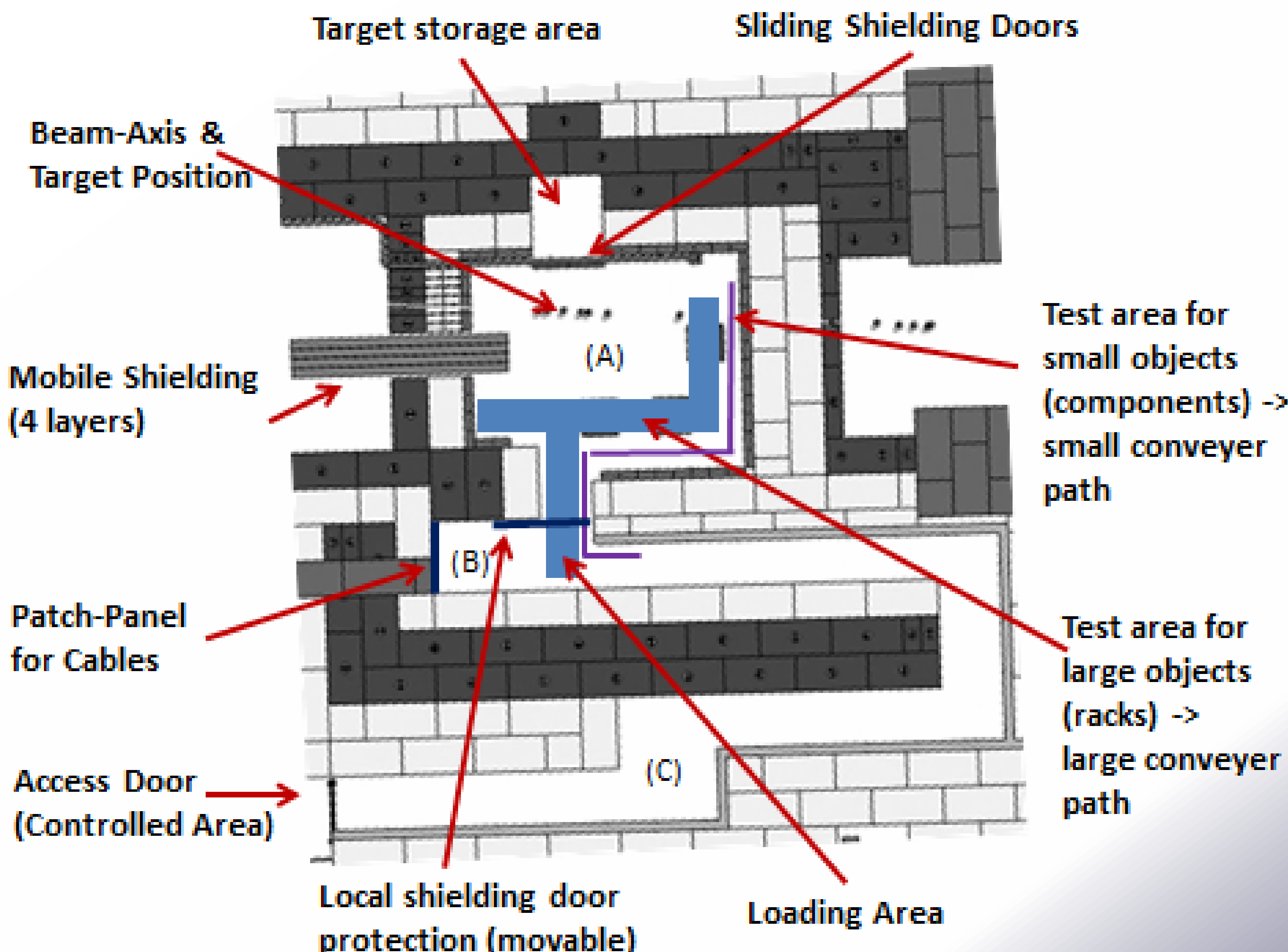
- **H4IRRAD (2011)**



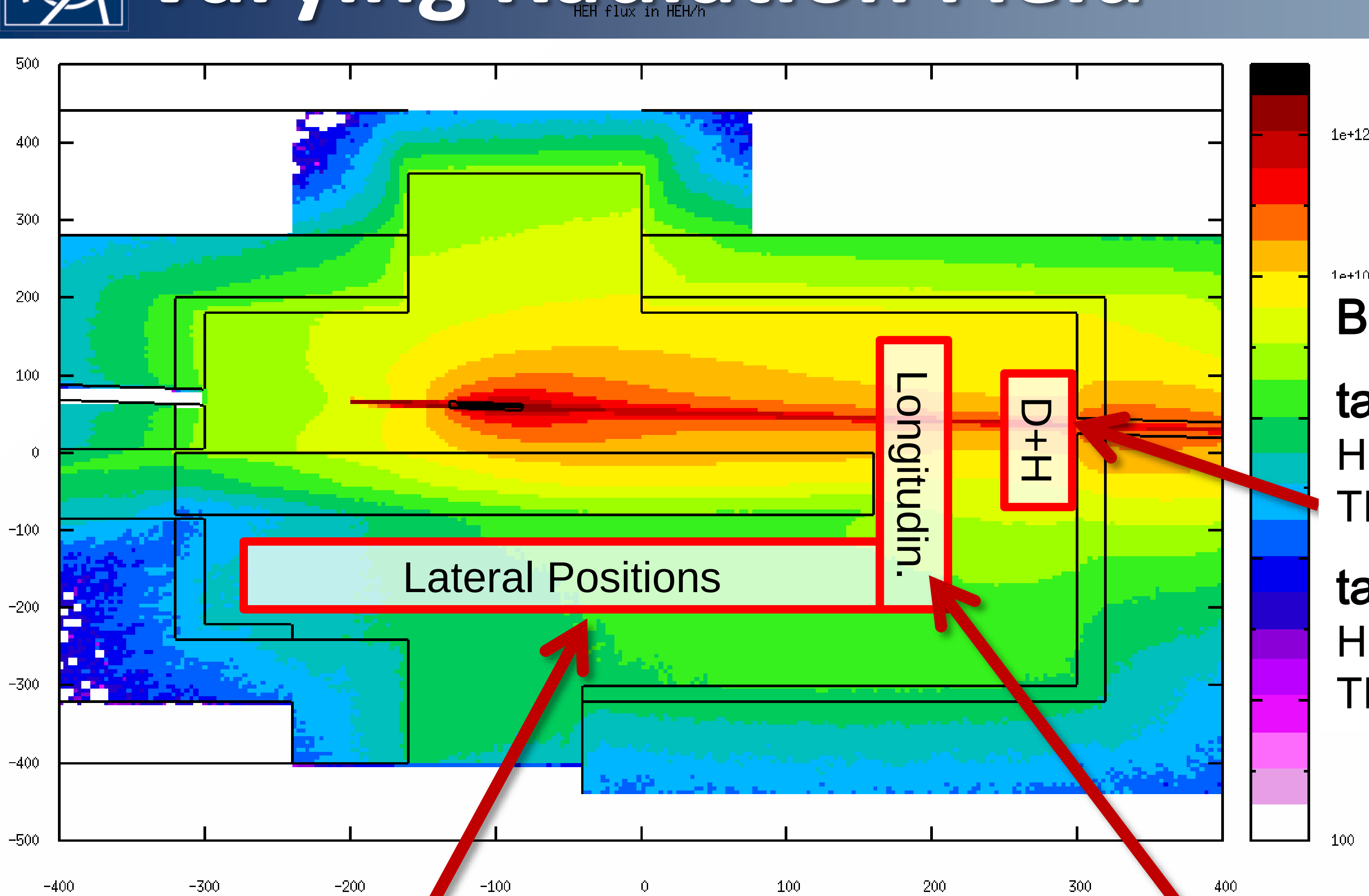
- **PS-EastArea (2014)**



Main Elements



Varying Radiation Field



Beam Position

target in:

HEH: $>10^{11} cm^{-2}h^{-1}$

TID: >100 Gyh^{-1}

target out:

HEH: $>10^{13} cm^{-2}h^{-1}$

TID: >10 $kGyh^{-1}$

HEH: $10^{8} cm^{-2}h^{-1} – 10^{11} cm^{-2}h^{-1}$

TID: $0.1 Gyh^{-1} – 100 Gyh^{-1}$

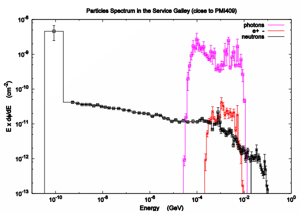
(gradients to be considered)

Full racks, crates, set of cards, components

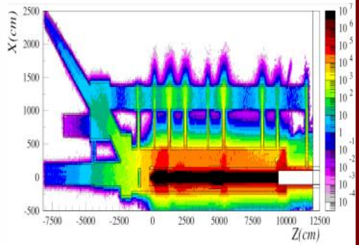
HEH: $10^{7} cm^{-2}h^{-1} – 10^{10} cm^{-2}h^{-1}$, TID: $10 mGyh^{-1} – 10 Gyh^{-1}$

Summary: Radiation Physics/Effects/Monitoring

nuclear cascade



h > 20 MeV



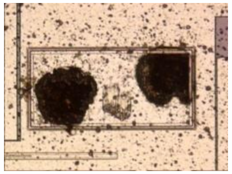
Radiation Field

h, e,.. > 100 KeV

EM cascade

radiation damage in semiconductors

Single Events



Effect in the Device

Displacement

Dose

Radiation Monitor

SEU counter (HEH, thermals)

Measurement

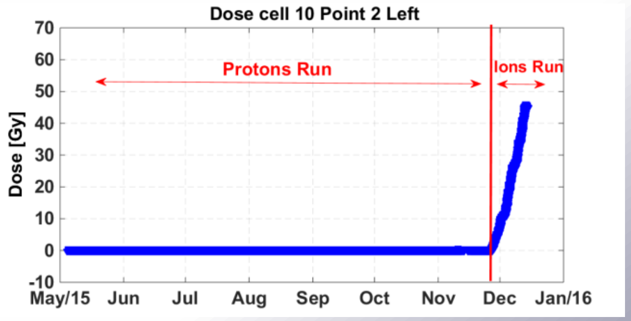
Radfet (TID)

PIN Diodes (1 MeV n eq)

The long term total ionizing dose TID problem

LHC Era	Machine Energy	Integrated Luminosity	Radiation Dose in Arc	Radiation Dose in DS
	[GeV]	[fb-1]	[Gy/year]	[Gy/year]
Run 1	3.5/4.0	~30	<<1	~10
Run 2	6.5/7.0	~100	~1	~20
Run 3	7	~300	~2-4	~40
HL-LHC	7	~3000	~4-8	~80-160

- We should **not forget the Ions runs**
  - Due to the Bound-Free Pair Production (BFPP), even for short runs, radiation levels can be up to 50 times those of a proton run (Very localized)
- The solution before the HL is rotate/substitute the equipment where the level are too high (DS)



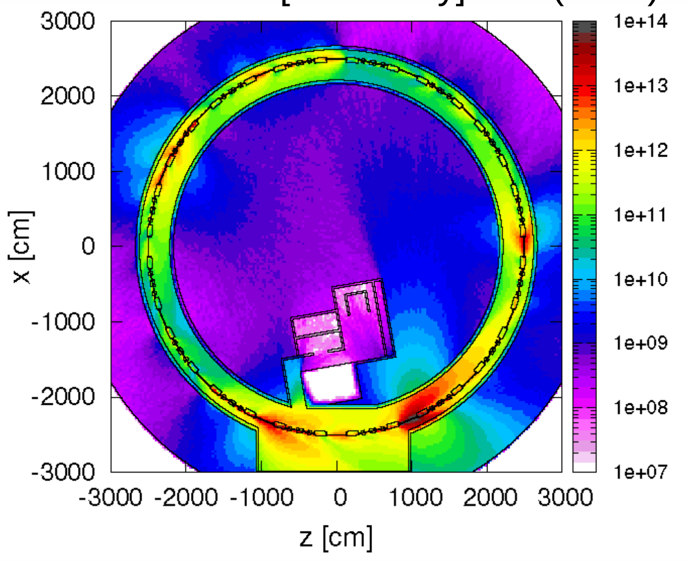
The long term total ionizing dose TID problem

Assess the evolution in the coming years of radiation levels in the Injector Chain according to operation, machine developments, etc.

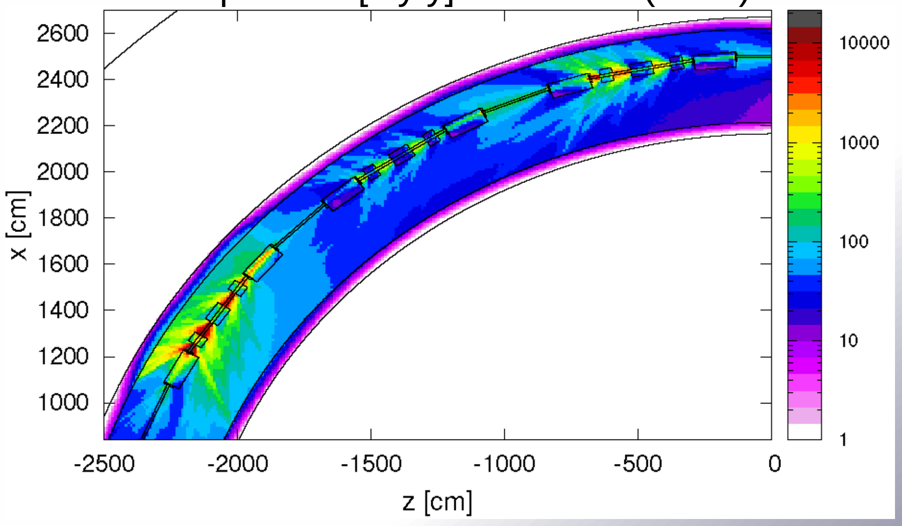
Follow-up of Beam intensities & Losses:

- **LINAC 2 -> LINAC 4**, inj. 50 -> 160 MeV
- **PSB**, magnet realignment; ext. 1.4 -> 2.0 GeV
- **PS**, e.g. CT -> MT Extraction
- **SPS**, e.g. SBDS LSS1 -> LSS5

HEH fluence [heh/cm^2/y] 16P (2014)



Prompt Dose [Gy/y] P08->P10 (2014)



THANK YOU
FOR YOUR ATTENTION