Radiation Hardness of Electronics in the FCC

Rubén García Alía

(On behalf of the Radiation Hardness Assurance sub-WP in the Special Technologies FCC WP)

Outline

- Introduction
- Radiation Environment: Monitoring and Calculations
- Radiation Qualification
- Technological Challenges
- FCC radiation hardness assurance studies
- Summary

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Radiation Hardness Assurance (RHA)

Radiation Environment

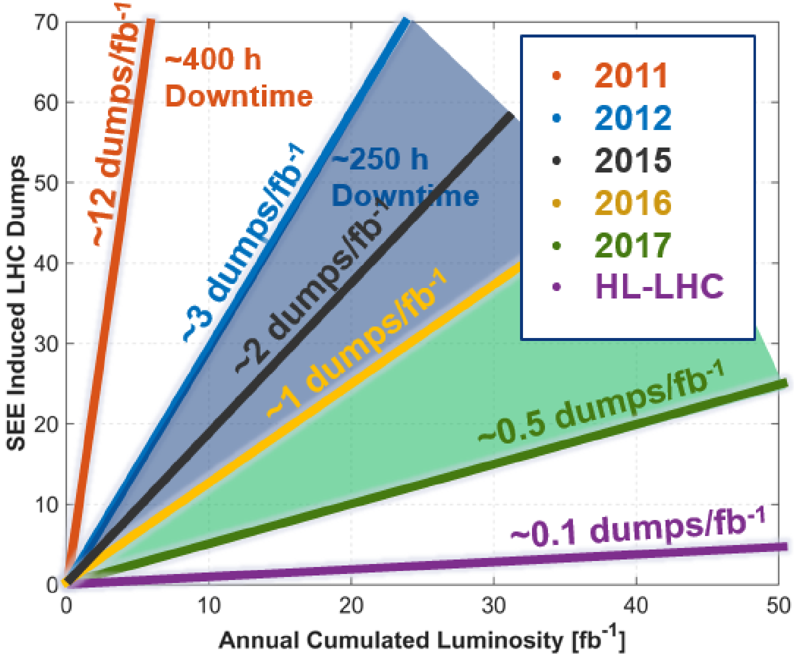
Radiation Testing

Radiation Hardness Assurance

Technological Requirements

Radiation Reliability Constraints

R2E strategy: from mitigation to prevention



2011-2015
Mitigation
(shielding + relocation)

2015-2018
Prevention
(equipment upgrade)

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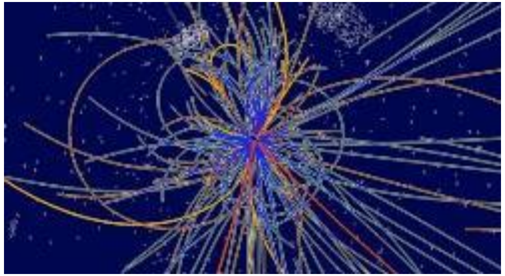
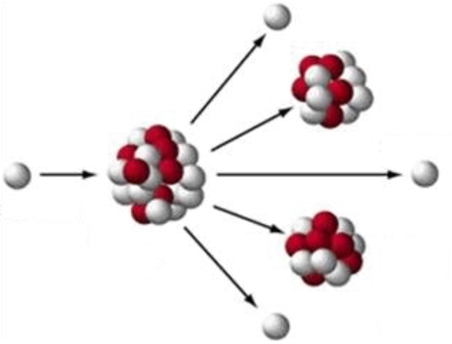
Radiation Environment

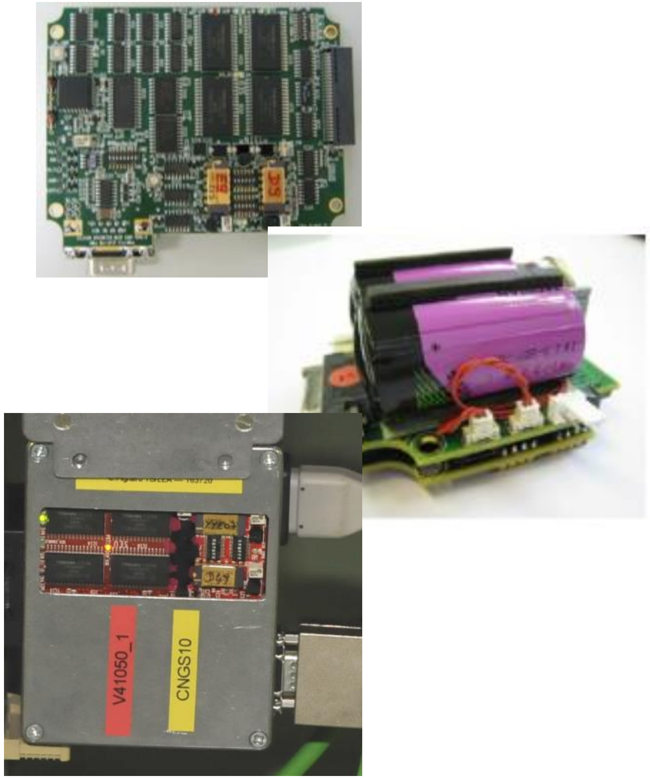
- In the high-energy hadron accelerator context, there are three main sources of radiation:
  I. **Collisions** debris from interaction points
  II. **Losses** in collimator (and collimator-like) elements
  III. **Beam-gas** interactions
- The resulting radiation levels strongly depend on the distance and angle with respect to the interaction point, the involved energies and materials and the shielding present
- The radiation field is quantified through the Total Integrated Dose (**TID**), 1 MeV neutron equivalent fluence (representative of displacement damage, **DD**) and the High Energy Hadron (HEH) fluence (>20 MeV, representative of Single Event Effects, **SEEs**)





Radiation Level Monitoring

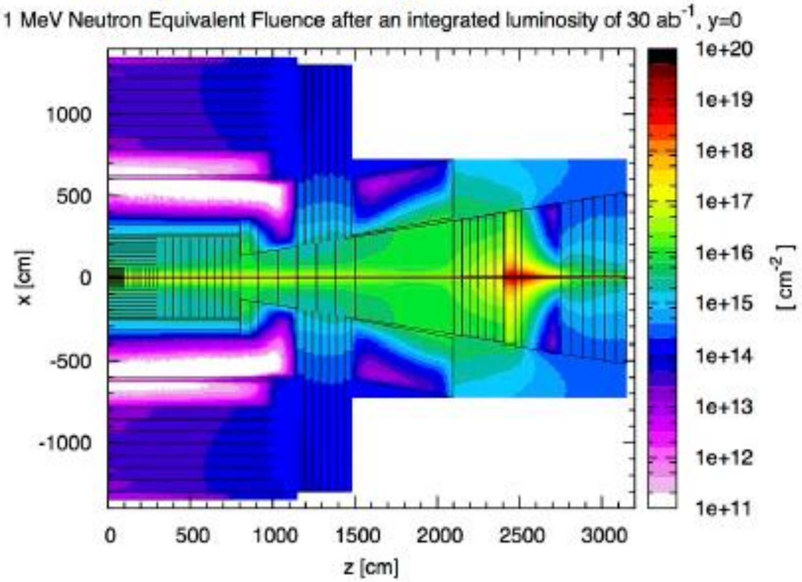
- The **RadMon system** is developed and operated within the R2E project
- It is deployed in the LHC and its injector chain and is capable of measuring TID, HEH fluence and 1 MeV neutron equivalent fluence
- It is based on COTS components Available as deported unit and battery powered
- Continuously under **development** (e.g. HL-LHC and FCC requirements, both in terms of maximum levels and representativeness of technology)
- Possible future complementary LHC dosimetry option: **optical fibre system**



RadMon system responsible: S. Danzeca (EN/STI)

FCC Challenges - MGy Dosimetry

Long term damage:



Simulations by I. Besana

→ Future experiments at FCC will require new dosimetry technologies to go behond the ***MGy range***.

→ Today's semiconductor dosimetry is not capable of dealing with **very high dose** in **mixed-radiation field.**

Sensors study by CERN EP-DT-DD team

Estimated levels of first pixel layers at r = 3.7 cm

- **HL-LHC 3ab^{-1}** (Target for current Irradiation Facilities)
  - 1 MeV neq Fluence = $1.5\text{x}10^{16}$ cm^{-2} , Dose = 5MGy
- **FCC 3ab^{-1}**
  - 1 MeV neq Fluence = $3\text{x}10^{16}$ cm^{-2} , Dose = 10 MGy
- **FCC 30ab^{-1}**
  - 1 MeV neq Fluence = $3\text{x}10^{17}$ cm^{-2} , Dose = 100 MGy

Development of MGy dosimetry for FCC

- CERN Detector Technologies (EP-DT) group is collaborating with EPFL for the design, realization, and characterization of a new dosimetry technology for and above the **MGy** range.
- Studying the impact of radiation (gamma, protons, neutrons) on thin film **nanostructures**.
- Several test structures are being fabricated with different geometrical *(thickness, W, L, shape)* and physical *(material)* properties of the nanolayer.

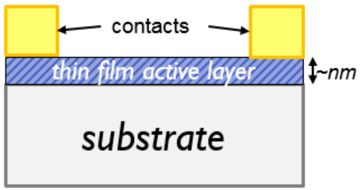
G. Gorine's PhD at CERN/EPFL

CMi EPFL Center of MicroNanoTechnology
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

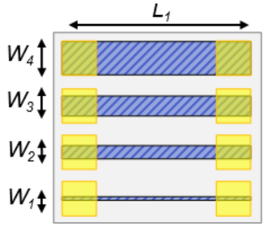
✓ *Design and Microfabrication*

CERN EP DT Irradiation Facilities

✓ *Irradiation and Characterization*



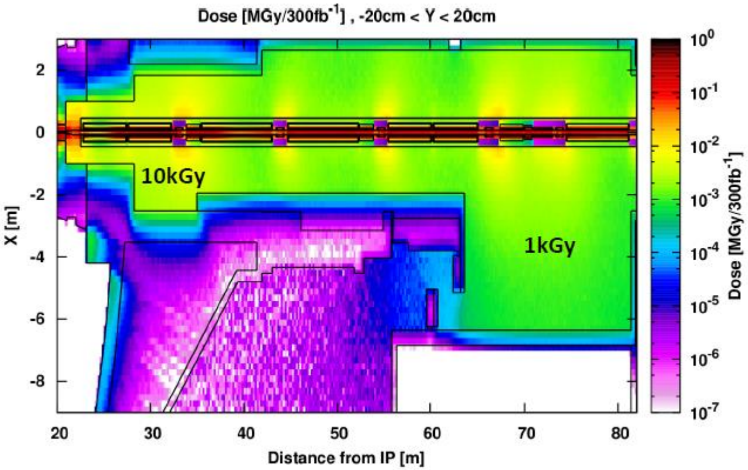
Side view

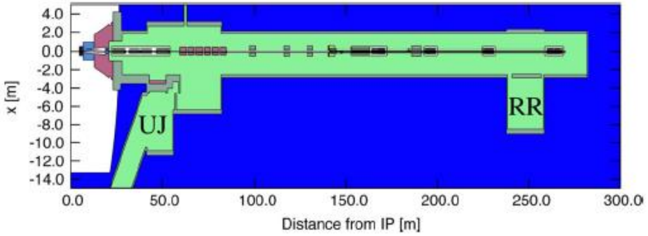


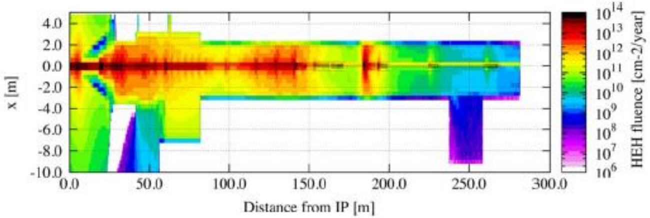
Top view

Radiation Level Calculations

- In the R2E context, radiation level calculations are performed using the **FLUKA** Monte Carlo code
- As an input, it is important to have a detailed information about the concerned geometry and source term
- Radiation level calculations are regularly **benchmarked** with measurements and can be used to **predict** levels in future machines (e.g. HL-LHC, FCC)





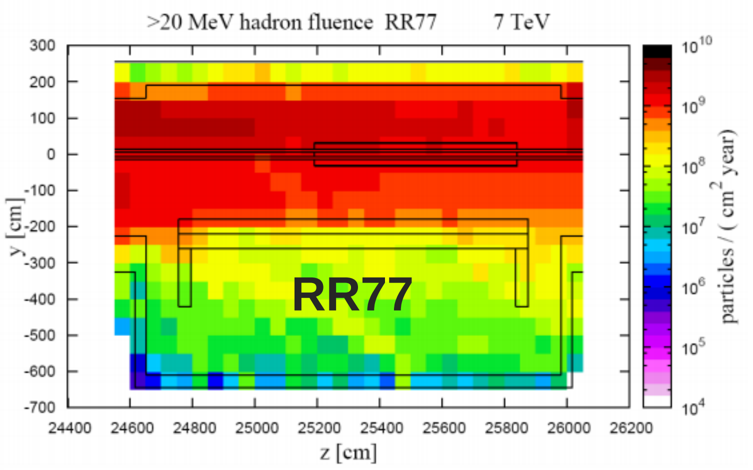


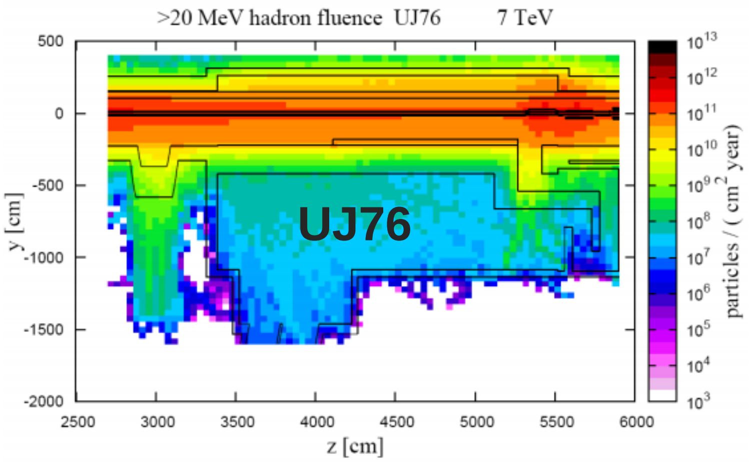
Simulations by FLUKA team

Shielded Areas

- Shielding is efficient in reducing the radiation levels, however **neutrons** will still contribute even after typical shielding thicknesses (e.g. 200 cm concrete for UJ76 or 40 cm concrete + 40 cm iron for RR77)
- Annual radiation levels after the shielding for LHC nominal conditions are still **high** for commercial electronic components (~10^7-10^9 HEH/cm^2 – at ground level, ~10^5 HEH/cm^2)

Simulations by K. Roed





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Radiation qualification

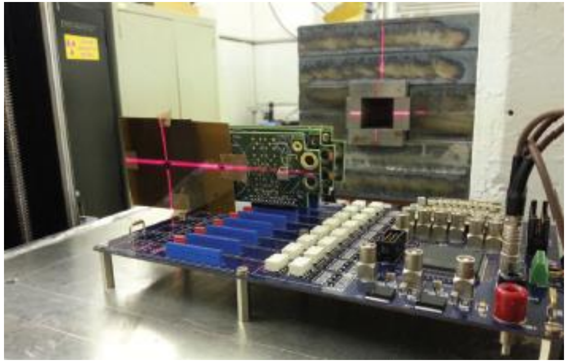
Constraints	Short project time frame, budget restrictions, necessity of mass production, use of COTS
Radiation Requirements	Design lifetime (e.g. TID limit), maximum number of LHC dumps per year (e.g. SEE failure cross section limit)
Radiation Qualification	Component selection, radiation risk classification, type testing, batch testing, system testing…

Use of COTS components

- LHC systems are generally based on commercial-of-the-shelf (**COTS**) due to cost and performance
- Their use is also driven by the very large number of components per unit and units per system (e.g. more than 1000 power converters in LHC with more than 40 type of electronic components each)
- The use of COTS components is increasing even for space applications, where criticality is extreme
- Low cost, state-of-the-art performance, but parts need to be **qualified**
- COTS performance in radiation varies significantly, even for components with very similar electrical performance

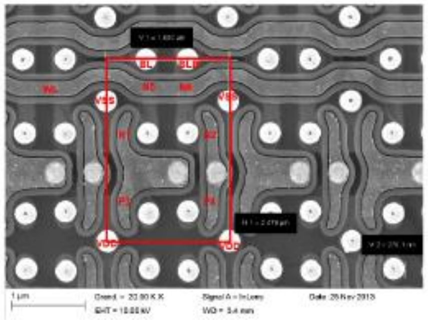
Radiation testing

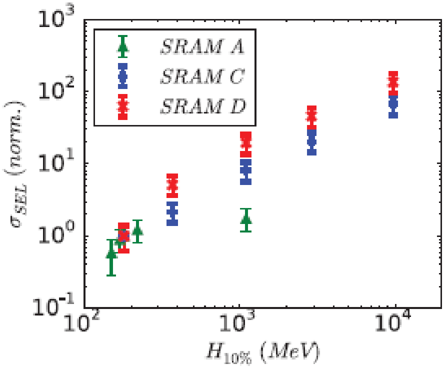
- Need to carefully define the **target levels** (HEH fluence, TID…) and select a ***representative*** radiation test environment
- Need to carefully select the number of components to be tested in order to determine the intra-lot and inter-lot sensitivity **variability**
- Test parameters such as temperature, bias conditions, frequency, etc. should be similar enough to **worst-case application**



Example: SEE cross section energy dependence

- Typically, SEE cross sections induced by silicon nuclear fragments and triggered by a small energy deposition (LET_{th}<5 $MeVcm^2$/mg) have a fairly constant value above several 10s of MeVs
- However, SEE cross sections dominated by **high-Z fragments** and with a relatively large LET threshold have a strong energy dependence up to the GeV range
- Therefore, testing at typical proton cyclotron energies (30-200 MeV) might lead to a **significant underestimation of the high-energy accelerator failure rate** (e.g. factor ~100 for tests at 60 MeV applied to the LHC tunnel)

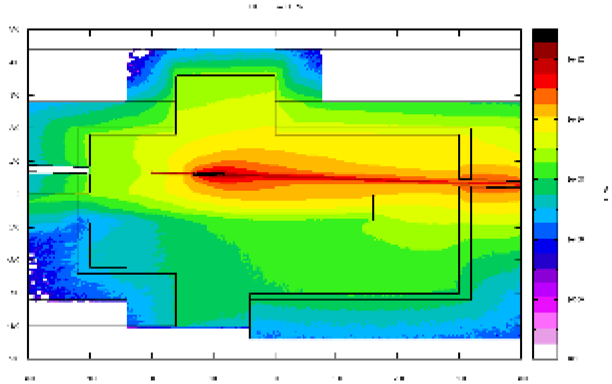




R. Garcia Alia et al, IEEE TNS 62.6 (2015)

CHARM facility

- Cern High-energy AcceleratoR Mixed-field facility
- Generates a radiation environment similar to that present in the **LHC** through the interaction of a 24 GeV PS proton beam with a 50 cm metallic target
- Radiation environment can be adapted (e.g. alcoves, tunnel, terrestrial and space applications) by varying the test location, shielding configuration and target
- Radiation environment calculated using FLUKA and **benchmarked** with RadMon measurements
- Crucial advantages for LHC equipment groups: in-house (availability, distance), reproducing a very similar environment to applications, possibility to perform system and batch tests…



IRRAD facility

- Radiation damage studies on:
  - materials used around accelerators/experiments, electronic components
  - equipment sitting in the inner/middle layers of HEP experiments
- IRRAD proton facility in 2015:
  - 341 objects at RT, -25ºC and 1.9K
  - 348 dosimetry measurements
  - 25 teams of users from 20 institutes
  - >10^{17} p/cm^2 delivered, >30 MGy/year (HL-LHC ready and FCC adaptable)

IRRAD Facility responsible: F. Ravotti (EP-DT)

- ❑ Beam momentum:
  24 GeV/c
- ❑ Beam spot:
  12×12 mm^2 (FWHM)
- ❑ Proton flux:
  ~10^{16} p/cm^2 in 5 days
- ❑ Several optics possible variants.

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Technological challenges

- The semiconductor component industry is **rapidly evolving** due to the strong customer demand (e.g. computer electronics: higher IC density, greater functionality, lower power consumption)
- Very hard to predict what the market will look like in 10+ years!
- The strong dependence of the radiation response to the specific technology requires a continuous qualification and **understanding of new effects**
- Though also starting to play a role, radiation tolerance requirements for applications driving the COTS market are far more relaxed than high-energy accelerator or space applications
- Requirements driving the technological progress (e.g. scaling, power consumption) can have very different impacts on **sensitivity to radiation**

Technological challenges: wide bandgap materials

- Wide bandgap semiconductor materials (SiC, GaN) are a **promising technology** for high frequency and voltage power applications (e.g. considered for near future electric vehicle applications)
- However, **sensitivity to destructive SEEs** such as SEB or SEGR generally increases with respect to current Si technology
- In addition, **new effects** such as “Heavy Ion Driven Leakage Current” have been identified and need to be carefully studied

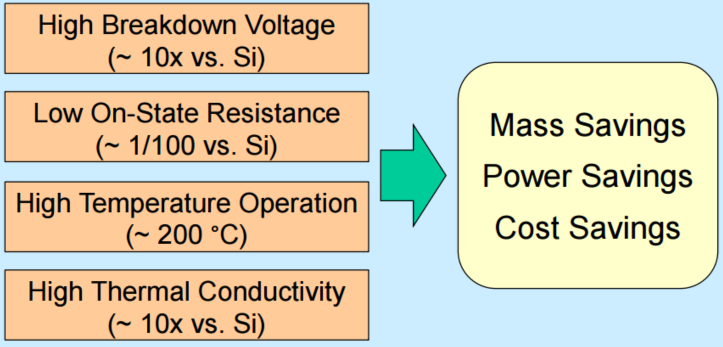


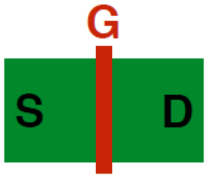
Fig. 1. Benefits of SiC power technology as compared to silicon.

J. M. Lauenstein, NSREC (2015)

Technological challenges: 65 nm

- 65 nm technology: strong dependence of radiation response on transistor size – responsible mechanisms taking place in parasitic structures

Narrow Channel Transistor (**L**)



Short Channel Transistor (**W**)

Research by F. Facio (EP-ESE-ME)

Technological challenges: 65 nm

- Radiation damage is severe in short and narrow channel transistors, where it depends on the bias and the temperature applied both during and after irradiation

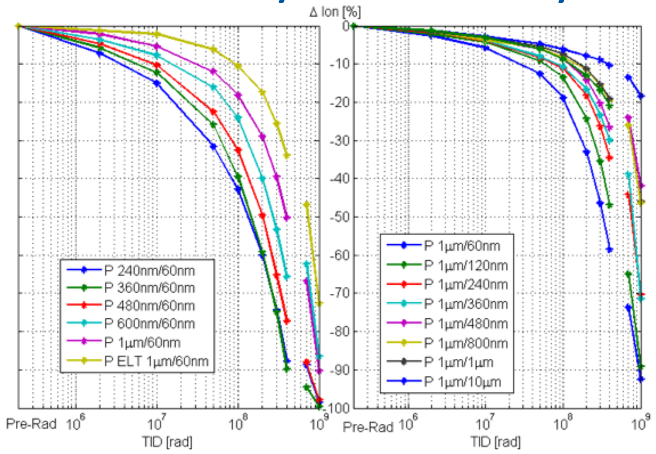
T = 25°C

Bias: |Vgs|=|Vds|=1.2V

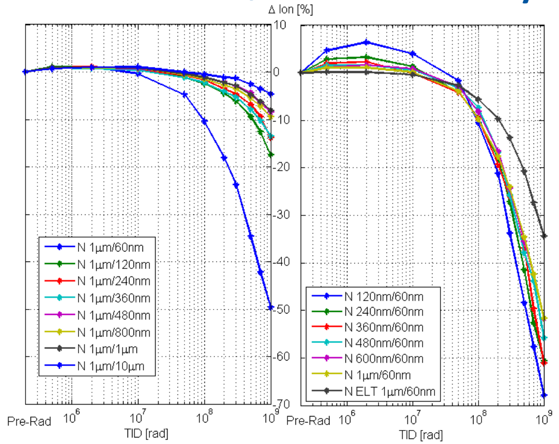
Radiation-Induced Narrow Channel Effect (RINCE)

Radiation-Induced Short Channel Effect (RISCE)

PMOS W array **PMOS L array**



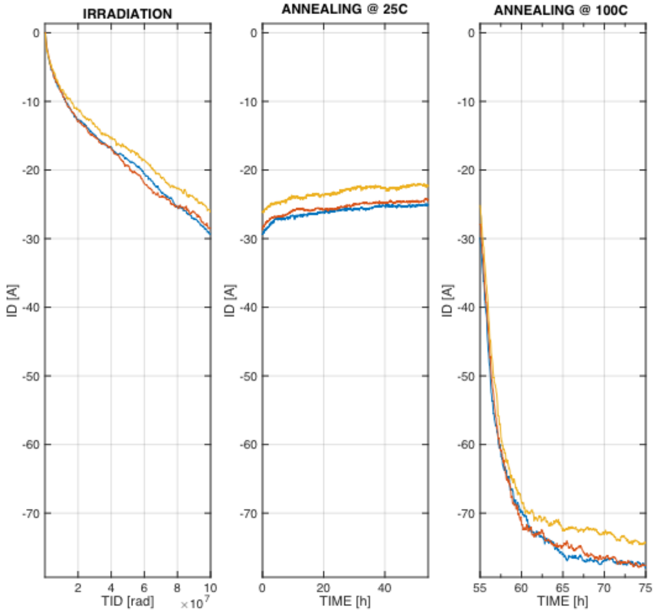
NMOS W array **NMOS L array**



Technological challenges: 65 nm

- The qualification procedures for CMOS foresee a 1-week annealing period post-irradiation at 100ºC. This considerably worsens the performance of PMOS transistors.

Delta Id (%)



Transistors' size: W=0.6um, L=60nm
Irradiation conditions:
* Bias:
"Diode" => |Vgs|=|Vds|=1.2V

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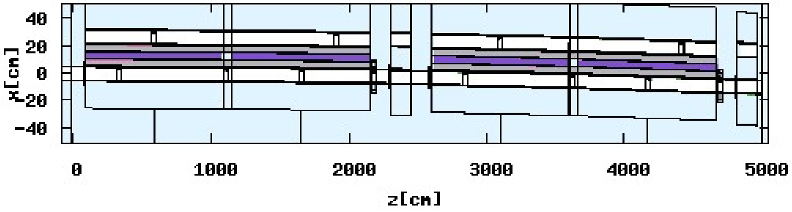
FCC RHA studies

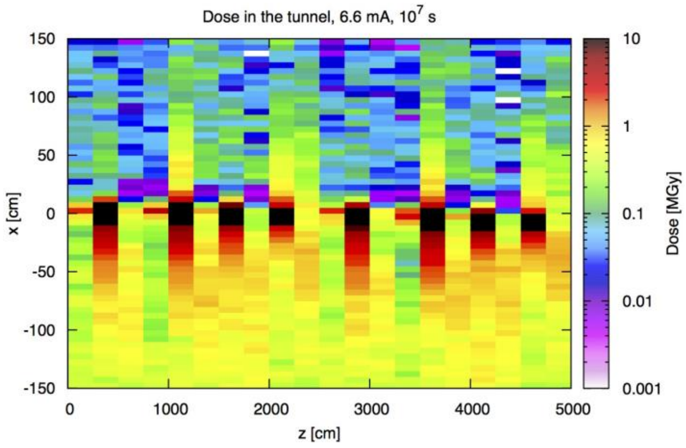
- Presently focused on the prediction of **radiation levels** for different scenarios and machine locations and research and development of required electrical component and system **technologies**
- Close collaboration with **FLUKA team** for implementation and running of radiation level calculations
- Close collaboration with **civil engineering** and **equipment groups** to iterate over design affecting radiation levels
- Close collaboration with external institutes for **technological development** (e.g. University of Erlagen for radiation tolerant high speed communication link)
- Increased radiation levels, larger number of components and units per system and tighter reliability requirements will certainly require **innovative radiation hardness assurance solutions**

FCC RHA studies: ee synchrotron radiation

- Simulation of full cell, 175 GeV electrons, 6.6 mA current, 10^7 seconds and 55.6 mT B field
- Annual doses larger in inner part of the tunnel (~600 kGy) due to reflection off the absorbers and the absence of material
- Radiation levels orders of magnitude larger than present LHC tunnel case



Simulations by I. Besana and F. Cerutti (EN-STI-FDA)



FCC RHA studies: hh ARC scaling

Energy Scaling

$$S = \left(\frac{E_{FCC}}{E_{LHC}}\right)^{0.8}$$

Beam Intensity Scaling

$$I = \frac{(NB \times BP)_{FCC}}{(NB \times BP)_{LHC}}$$

Scaling Factors

Note: Data from FCC-ACC-SPC-0001

Energy

LHC	7	TeV
FCC	50	TeV
S	**4.8**	

Fluence to Dose F2D

2.00E-09 $Gy*cm^2$

Note: From the "Radiation Level Assumption" Table

Hp: 1 Gy y^{-1} /5e8 cm^{-2} y^{-1}

Intensity

Number of bunches NB (25 ns)	
LHC	2808
FCC	10600
Bunch population BP [1E11]	
LHC	1.15
FCC	1.00
I	**3.28**
S*I	**15.82**

- Dose and HEH fluence values expected to increase by a factor ~16 for the ARC region (source term: beam gas interaction)
- This factor does not include the increase in the number of units!
- Detailed FLUKA simulations will be implemented for this and other study cases (e.g. extraction area)

Calculations by A. Infantino (EN-EA)

Next steps to be taken

- FCC sub-WP: Radiation Hardness Assurance of Electronics
- **Task 1**: Radiation levels at FCC
- **Task 2**: FCC radiation qualification requirements, evaluation of radiation facilities
- **Task 3**: Equipment needs for the accelerator, identification of technologies
- **Task 4**: State-of-the-art development for rad-hard components and systems, common versus specific developments with HL-LHC
- **Task 5**: Define the needed developments linked to technology

Summary

- Challenging radiation environment, reliability requirements and technological performance objectives
- Important to consider radiation effects at very early stage of accelerator conception (e.g. iteration with civil engineering)
- Present studies focused on:
  - radiation level calculations based on expected optics and layout
  - Identification of electronic technological requirements and R&D of radiation tolerant solutions
- Innovative radiation hardness approaches will certainly be needed!

FCC RHA sub-WP contacts

- **EN department**: Markus Brugger, Francesco Cerutti, Anton Lechner, Ilaria Besana, Angelo Infantino, Rubén García Alía
- **EP department**: Mar Capeans, Federico Faccio, Federico Ravotti, Michael Moll, Georgi Gorine

Some R2E references

"FLUKA Simulations for SEE Studies of Critical LHC Underground Areas", K. Roed et al, IEEE TNS, 58(3), 2011

"LHC RadMon SRAM Detectors Used at Different Voltages to Determine the Thermal Neutron to High Energy Hadron Fluence Ratio", IEEE TNS, D. Kramer et al, IEEE TNS 58(3), 2011

"Method for Measuring Mixed Field Radiation Levels Relevant for SEEs at the LHC", K. Roed et al, IEEE TNS 59(4), 2012

"SEU Measurements and Simulations in a Mixed Field Environment", R. G. Alia et al, IEEE TNS 60(4), 2013

"Qualification and Characterization of SRAM Memories Used as Radiation Sensors in the LHC", S. Danzeca et al, IEEE TNS 61(6), 2014

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"Preliminary design of CERN Future Circular Collider tunnel: first evaluation of the radiation environment in critical areas for electronics", A. Infantino et al, submitted to ICRS13 conference