Radiation Hardness Assurance and Testing

Rudy Ferraro (BE-CEM-EPR)

R2E Annual Meeting – 1-2 March, 2022

CERN

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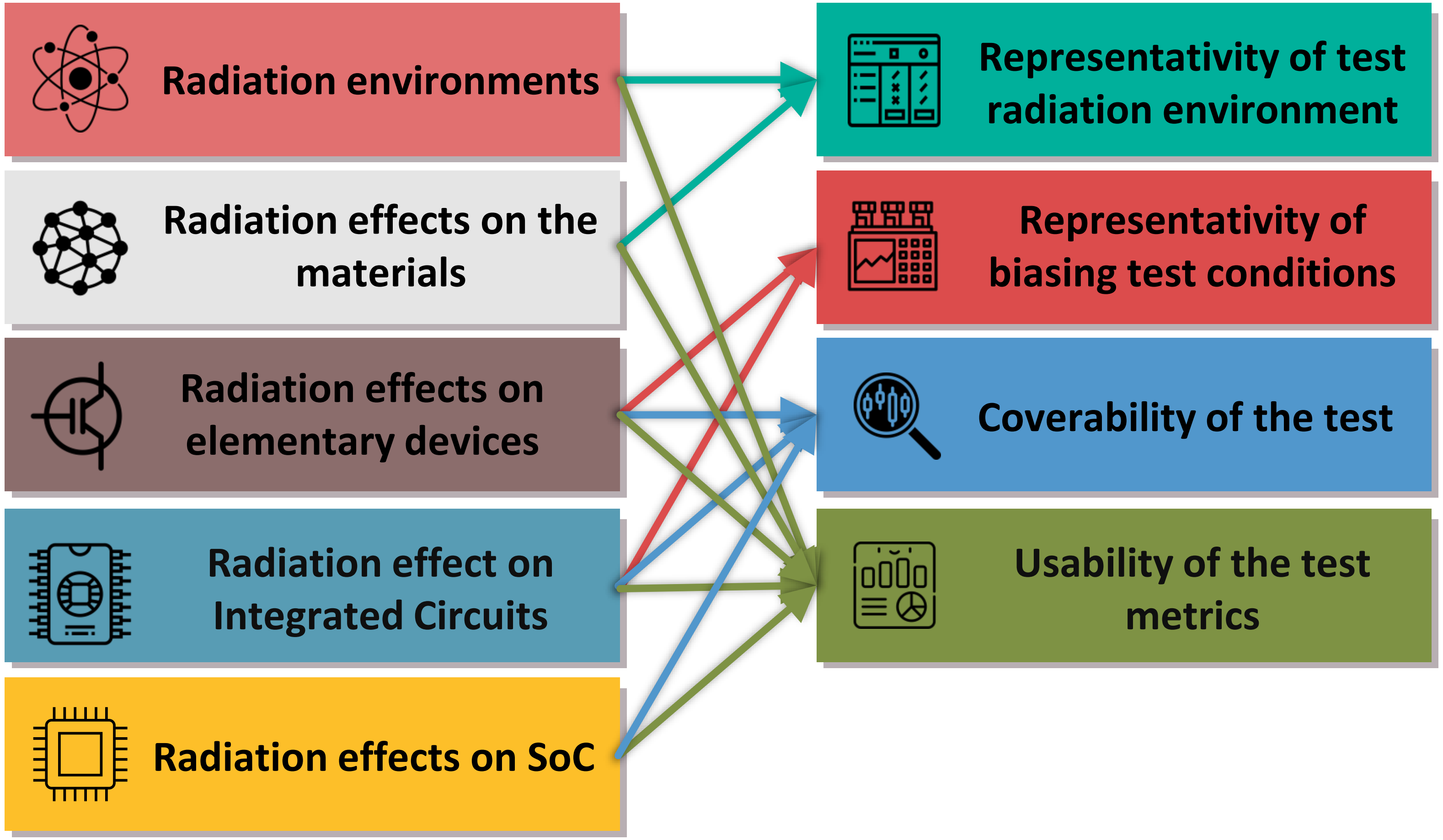
Controls
Electronics &
Mechatronics

CERN RHA & Testing Challenges

Reliable component qualification is obtained through a wide variety of knowledges and activities:



Radiation environments

Radiation effects on the materials

Radiation effects on elementary devices

Radiation effect on Integrated Circuits

Radiation effects on SoC

Representativity of test radiation environment

- Type/Energy of test particle(s)
- Radiation Effect(s)
- Flux, Dose Rate

Representativity of biasing test conditions

- Passive or active irradiation?
- Dynamic or static biasing?

Coverability of the test

- Circuit-level degradation
- Knowledge of failure modes
- Error propagation

Usability of the test metrics

- Should allow a fine estimation in operation

Radiation Effects on Electronics

			SEE	TID	DD
Active Elementary Devices	**Transistor:**	MOSFET	SET, SEB, SEGR, SEL…	ΔV_{TH}	-
		Bipolar…	SET	ΔH_{CE}, ΔI_{CE}, ΔI_{BE} , ΔV_{BE}	ΔH_{CE}, ΔI_{CE}, ΔI_{BE} , ΔV_{BE}
	Diodes:	Zener	SET	$\Delta V_{F,}$ ΔI_L	$\Delta V_{F,}$ ΔI_L
		LED	SET	ΔV_F, ΔP , ΔI_L	ΔV_F, ΔP , ΔI_L
		Schottky…	SET, SEB	ΔV_F , ΔI_L	ΔV_F , ΔI_L
Integrated Circuits	**Digital:**	Memory	SEU, SEFI, SEL, MBU…	ΔI_{CC}	-
		FPGA		$\Delta I_{CC,}$ Δt_{PD}, programmability	-
		µController		ΔI_{CC} , ΔV_{REF} …	-
	Analog:	Opamp	SET, SEL	Δv_{off}, ΔI_{BIAS}, ΔG, $\Delta I_{quiescient}$ …	Δv_{off}, ΔI_{BIAS}, ΔG, $\Delta i_{quiescient}$
		Regulators		ΔI_{CC}, ΔV_{REF}, ΔV_{START} …	ΔI_{CC}, ΔV_{REF}, ΔV_{START} …
	Mixed:	ADC	SEU, SEFI, SEL, MBU,SET	ΔI_{CC}, ΔV_{REF}, Δ_{ENOB} …	-
		DAC		ΔI_{CC}, ΔV_{REF}, Δ_{ENOB} …	-
		Smart Power		ΔI_{CC}, ΔT_P	ΔT_P
	Optronics:	Optocoupler	SET	ΔCTR, ΔI_{TH}	ΔCTR, ΔI_{TH}
		PhotoMOS		$\Delta I_{TH,}$ Switch capability	ΔI_{TH}
SoC Systems	**Can contains all the above**		Destructive events Temporary failures Permanent fault states	Performance degradation Parametric degradation	

Radiation Effects on Electronics

		SEE	TID	DD
Active Elementary Devices	**Transistor:** MOSFET Bipolar… **Diodes:** Zener LED Schottky…	MIL-STD-750, SEB/SEGR ESCC25100	ESCC22900 (ELDR) MIL-STD 883 1019.8 MIL-STD750E 1019.5 ASTM F 1892-06	No standard yet but guidelines
Integrated Circuits	**Digital:** Memory FPGA µController **Analog:** Opamp Regulators **Mixed:** ADC DAC Smart Power **Optronics:** Optocoupler PhotoMOS	Guideline, conference, journal, littérature etc..: *“Guideline for Optocoupler Ground Radiation Testing and Optocoupler Usage in the Space Radiation Environment”*, NASA “*Field Programmable Gate Array (FPGA) Single Event Effect (SEE) Radiation Testing”*, NASA “*SEE Testing of ADC and DAC*”, ESCIES *RADECS* Short courses *NSREC* Short courses		
SoC Subsystem Systems MegaSystems	**Can contains all the above**	No standards for system-level testing but guidelines exist (with a big contribution from CERN/R2E): H. Quinn, "Challenges in Testing Complex Systems,"in IEEE TNS, April 2014 A. Coronetti et al., "Radiation Hardness Assurance Through System-Level Testing: Risk Acceptance, Facility Requirements, Test Methodology, and Data Exploitation,“ IEEE TNS 2021 T. Rajkowski et al., “Comparison of the Total Ionizing Dose Sensitivity of a System in Package Point of Load Converter Using Both Component- and System-Level Test Approaches,” Electronics 2021		

Radiation Effects on Electronics

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Active Elementary Devices	**Transistor:** MOSFET Bipolar… **Diodes:** Zener LED Schottky…	MIL-STD-750, SEB/SEGR ESCC25100	ESCC22900 (ELDR) MIL-STD 883 1019.8 MIL-STD750E 1019.5 **Optoelectronic qualification for CERN Application**	No standard yet but guidelines:
Integrated Circuits	**Digital:** Memory FPGA µController **Analog:** Opamp Regulators **Mixed:** ADC DAC Smart Power **Optronics:** Optocoupler PhotoMOS	Guideline, conference, journal, littérature etc. : see presentation: “Update on FPGA Testing” from A. Scialdone see presentation: “IoT BatMon: Wireless radiation monitoring at CERN”, from A. Zimmaro *“Field Programmable Gate Array (FPGA) Single Event Effect (SEE) Radiation Testing”*, NASA **Combined TID-DD Effects on ICs** *“SEE Testing of ADC and DAC”*, ESCIES **SET Response in Mixed-Field** *RADECS Short courses* *NSREC Short courses* **Optoelectronic qualification for CERN Application**		
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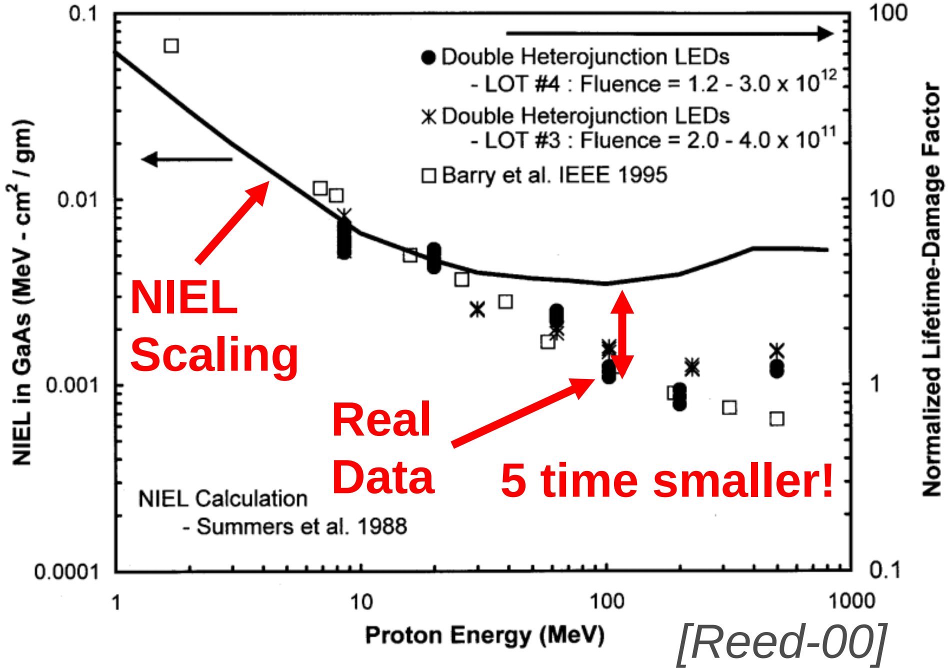
Optoelectronic Qualification: Context

- Optoelectronic components are among **the weakest** part of a system exposed to displacement damage
  - → **Critical LHC systems embed optocouplers**
  - → **It is then crucial to have reliable degradation estimations to avoid premature failures in operation**

- **CERN Component-Level Qualification Process**
  - **TID:** Gamma, **DD:** neutron **DD+TID:** proton sources
  - Displacement Damage in operation are estimated by using NIEL scaling theory

GaAs LED Damage vs protons(E)



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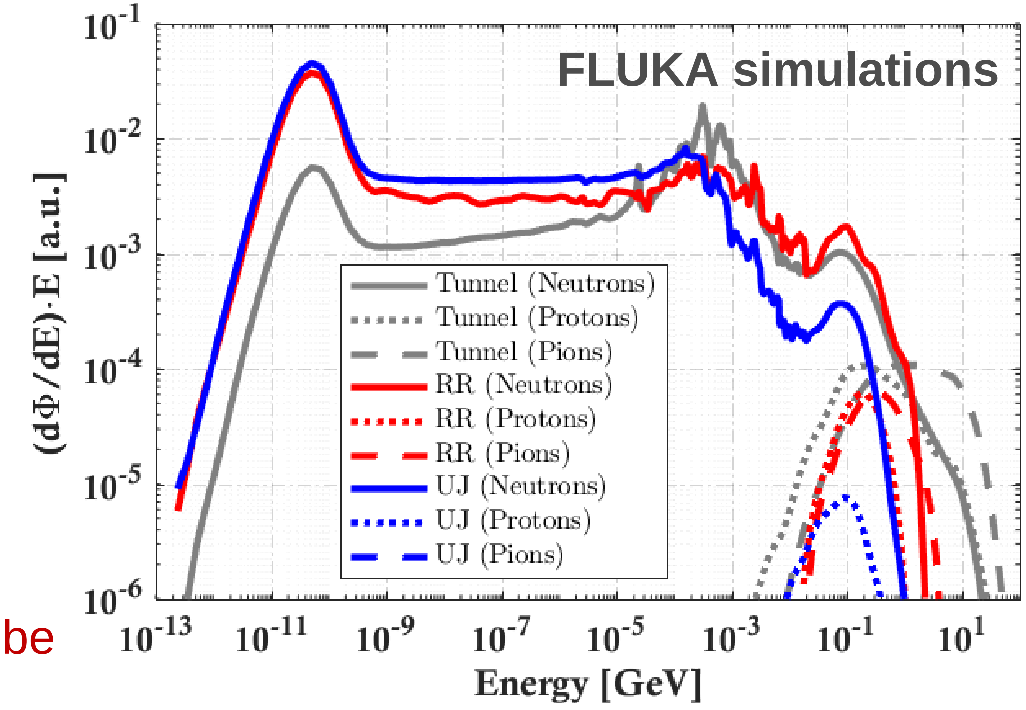
- **Problem: Systematic NIEL scaling violations for optoelectronic semiconductor materials have been reported in many studies**
- **Objectives of this study:** Investigate the use of application-specific radiation environments for displacement damage qualification for LHC applications

Optoelectronic Qualification: LHC Spectra Analysis

COTS-based systems are installed in three main LHC areas:

- **Tunnel**: Dispersion Suppression (DS) areas
  - High Energy (up to tens of GeV)
  - High pions and proton contributions
- **Shielded Areas:**
  - **RR (Lightly Shielded)**
    - High energies relatively attenuated
    - Pion and proton contributions attenuated
  - **UJ (Heavily Shielded)**
    - High energies strongly attenuated
    - Negligible pion and proton contributions

Proton, pion and neutron Normalized Lethargy Spectra:



→ **Objective:** Quantify the LHC DD spectra characteristics to be reproduced during radiation tests

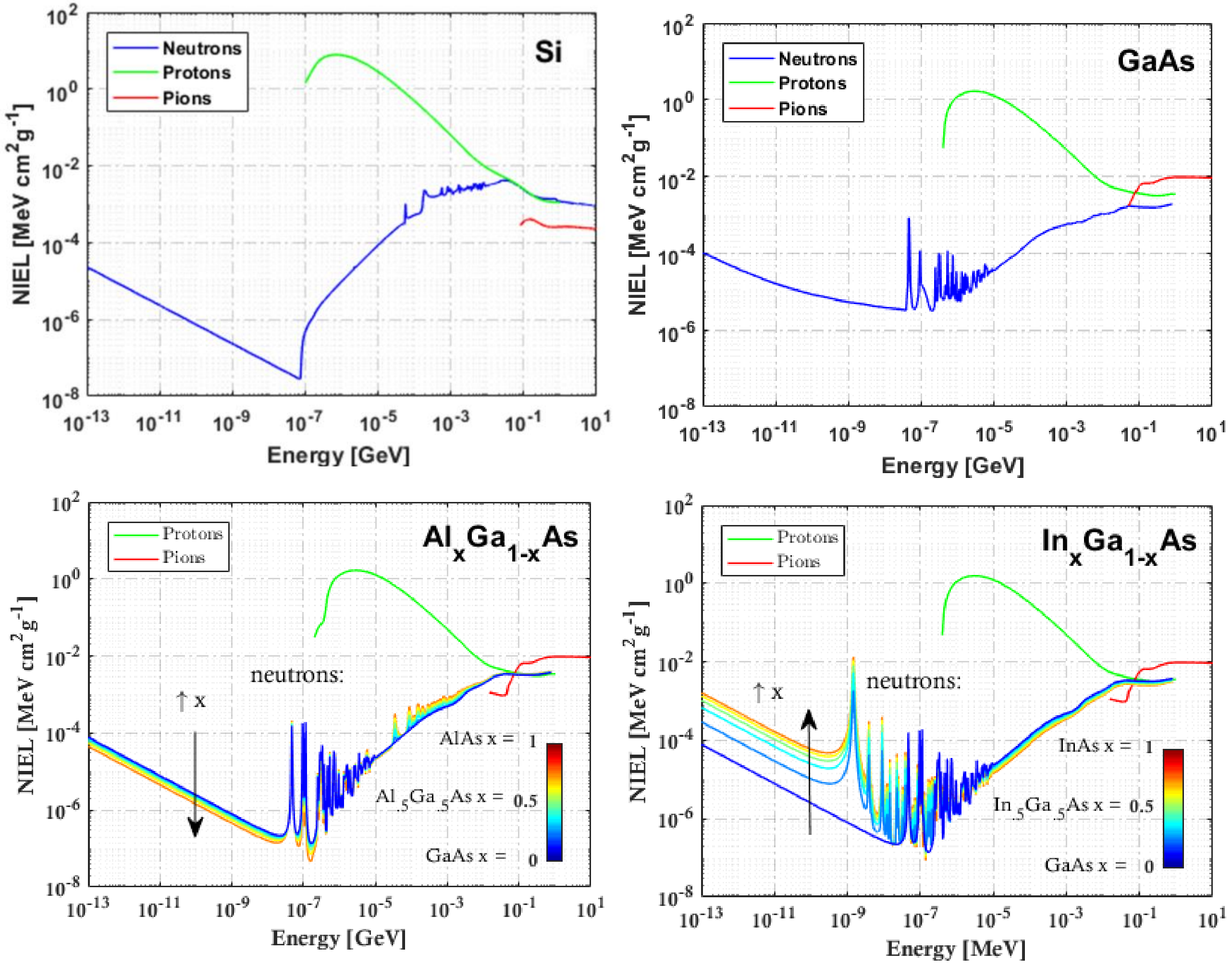
Optoelectronic Qualification: LHC Spectra Analysis

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

Considered Materials: GaAs, AlGaAs, InGaAs

GaAs-like materials specific challenges:

- More sensitive to pion than Silicon
- Pion NIEL mostly theoretical



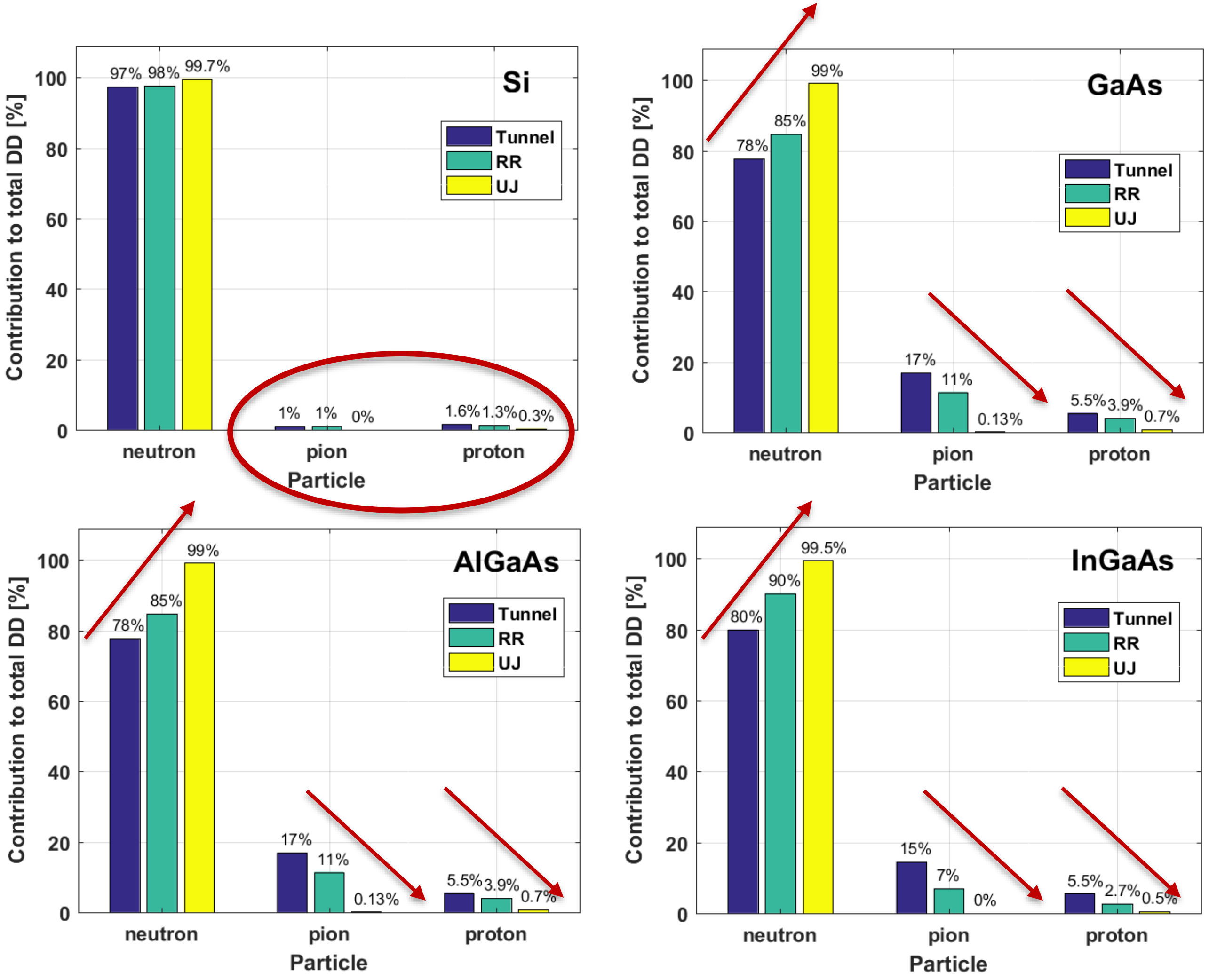
Optoelectronic Qualification: LHC Spectra Analysis

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

Considered Materials: GaAs, AlGaAs, InGaAs

Typical Spectra DD characteristics:

- **Particle contribution to total DD:**
  - **Si:** Negligible proton/pion contributions
  - **GaAs/InGaAs/AlGaAs:**
    - **Proton / pion contributions decrease while shielding increase**



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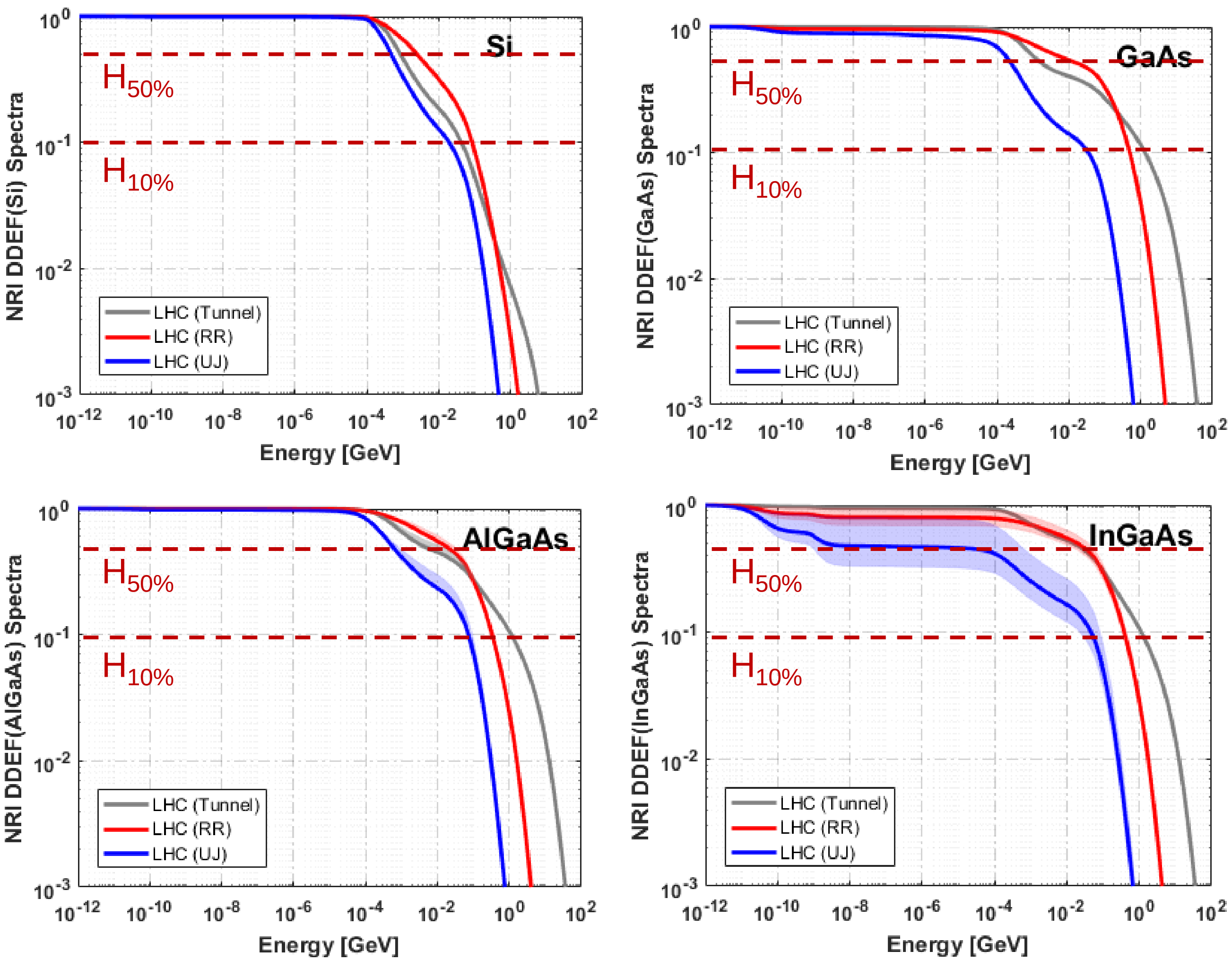
  - **GaAs/InGaAs/AlGaAs:**
    - **Proton / pion contributions decrease while shielding increase**
- **Energy Distribution:**
  - DD Normalized Reverse Integral (NRI)
  - **$H_{50\%}$, $H_{10\%}$:** Energy values for which the DD fluences contributes to 50% and 90% of the total displacement damages.

These characteristics has to be reproduced in test environments.



Optoelectronic qualification: Solution

- **Target:** 🟨

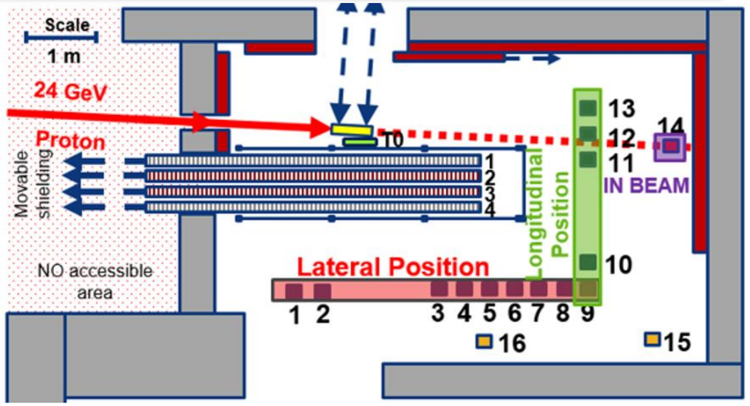
  Cu - Copper
  Al - Aluminium
  AlH - Aluminium Hole

- **Shielding:**

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

- **Positions:**

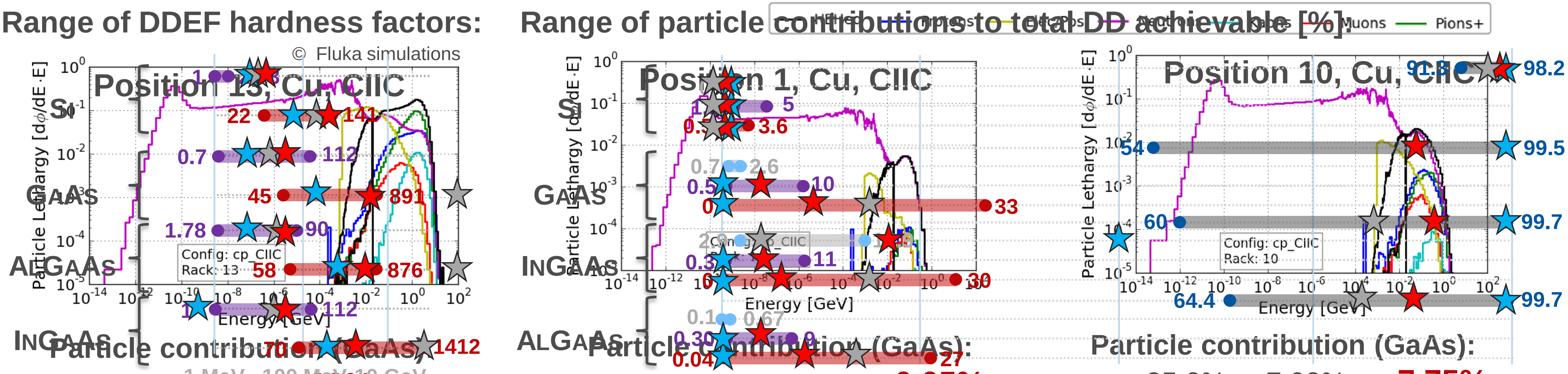
  Lateral (**1:9**) 🟥
  Longitudinal (**9:13**) 🟩



☆ Tunnel ★ RR ★ UJ

Range of DDEF hardness factors:

Range of particle contributions to total DD achievable [%]:



Particle contribution (GaAs):

n: 54%, p:13%, π:33%

● $H_{50\%}$ ● $H_{10\%}$

Particle contribution (GaAs):

n: 99,5%, p:0,45%, π:0,05%

Particle contribution (GaAs):

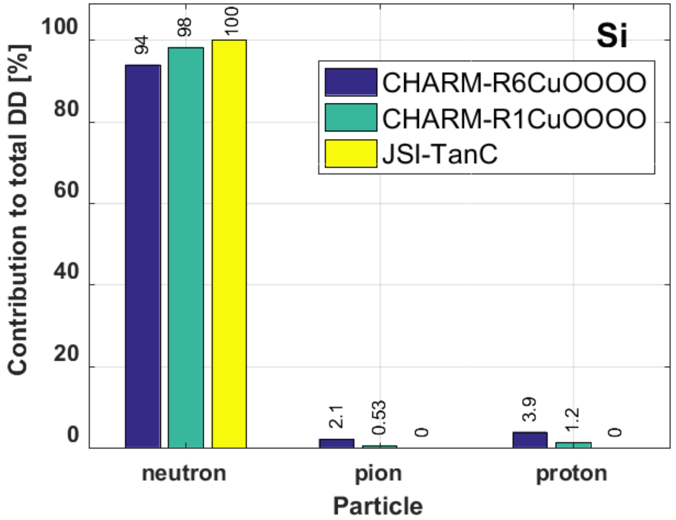
n: 85,2%, p:7,03%, π:7,75%

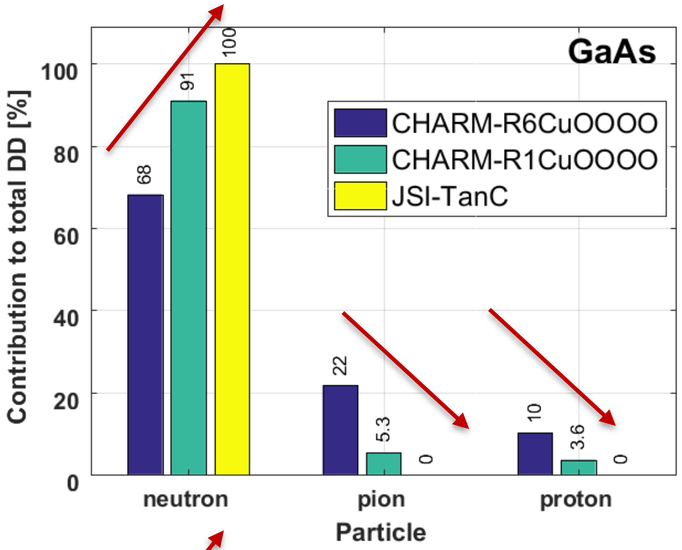
● neutron ● neutron (< 10 eV) ● proton ● pion

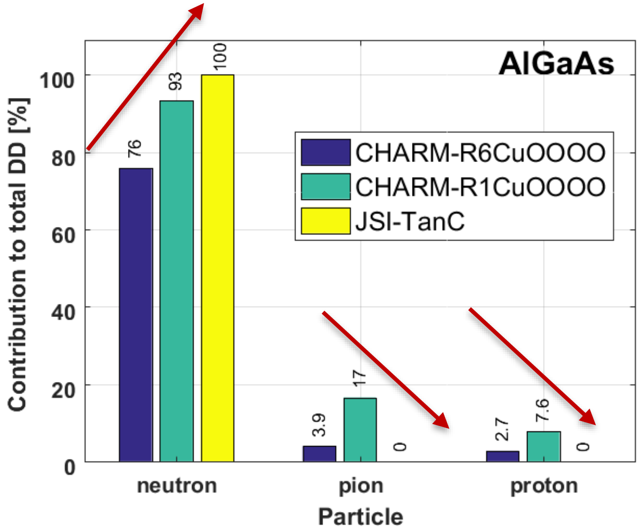
Optoelectronic Qualification: Example

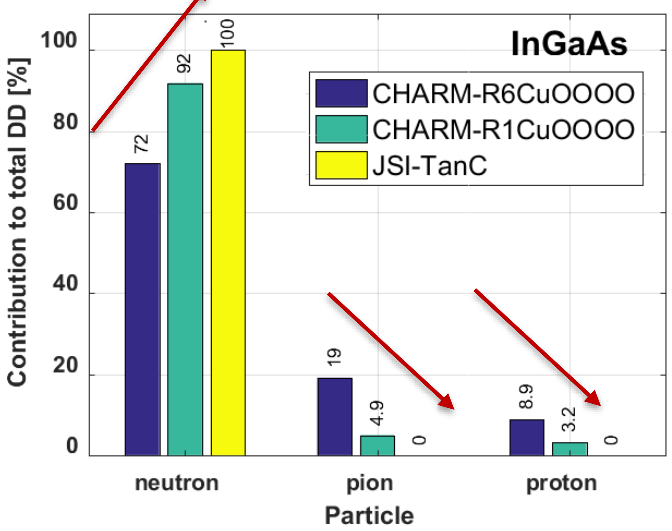
Test radiation fields characteristics:

- **CHARM (CERN):**
  - R6CuOOOO
    - → Energies similar to RR
    - → Contributions similar to tunnel
  - R1CuOOOO
    - → Energies between RR & UJ
    - → Contributions similar to RR
- **JSI (Jozef Stefan Institute) :**
  - Nuclear reactor → neutron only
  - Softer energy spectra than UJ
  - Same particle contributions as UJ
- **PSI (Paul Scherrer Institute):**
  - 200 MeV proton beam







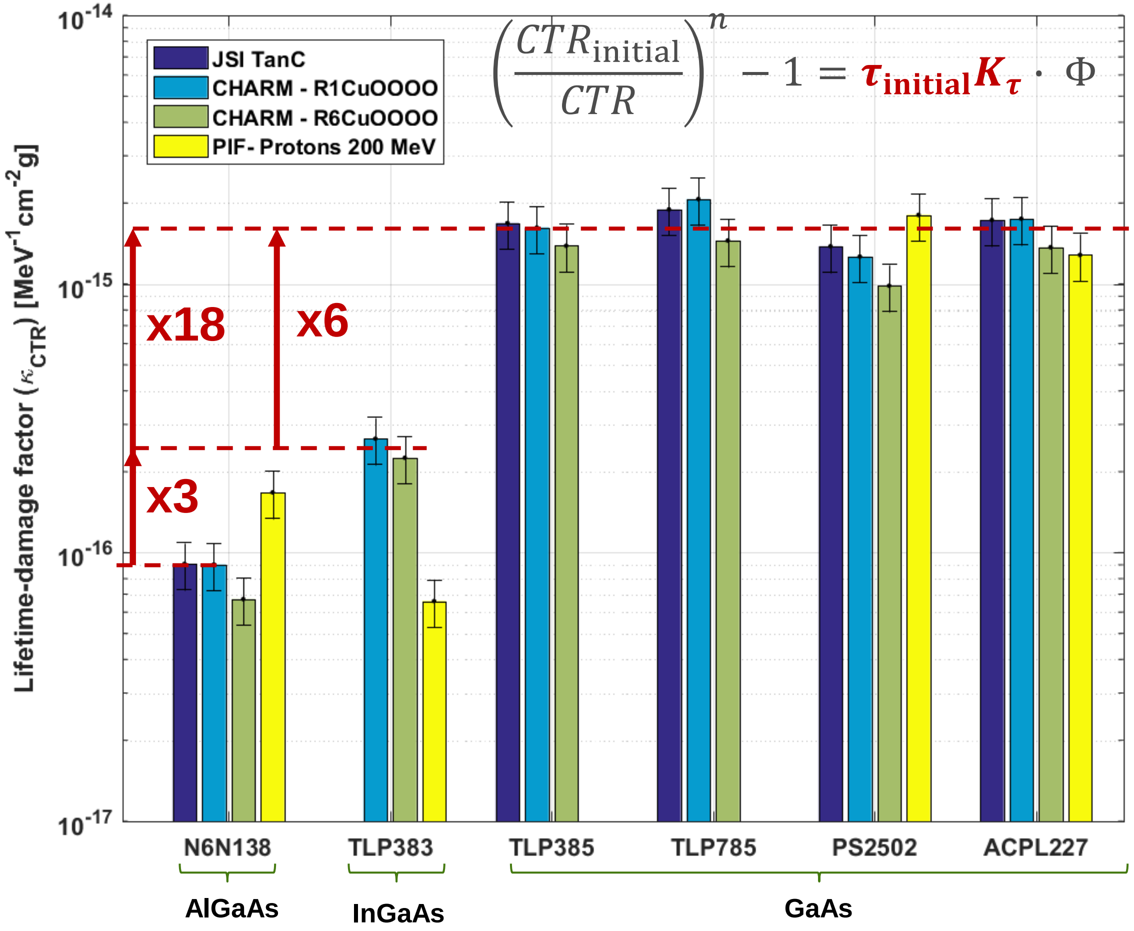


Optoelectronic Qualification: Example

- **Clear difference between the different materials**
  - AlGaAs factors three times lower than InGaAs
  - … and 18 times than GaAs

→ InGaAs and AlGaAs are better candidates for radiation environments

CTR = **C**urent **T**ransfer **R**atio

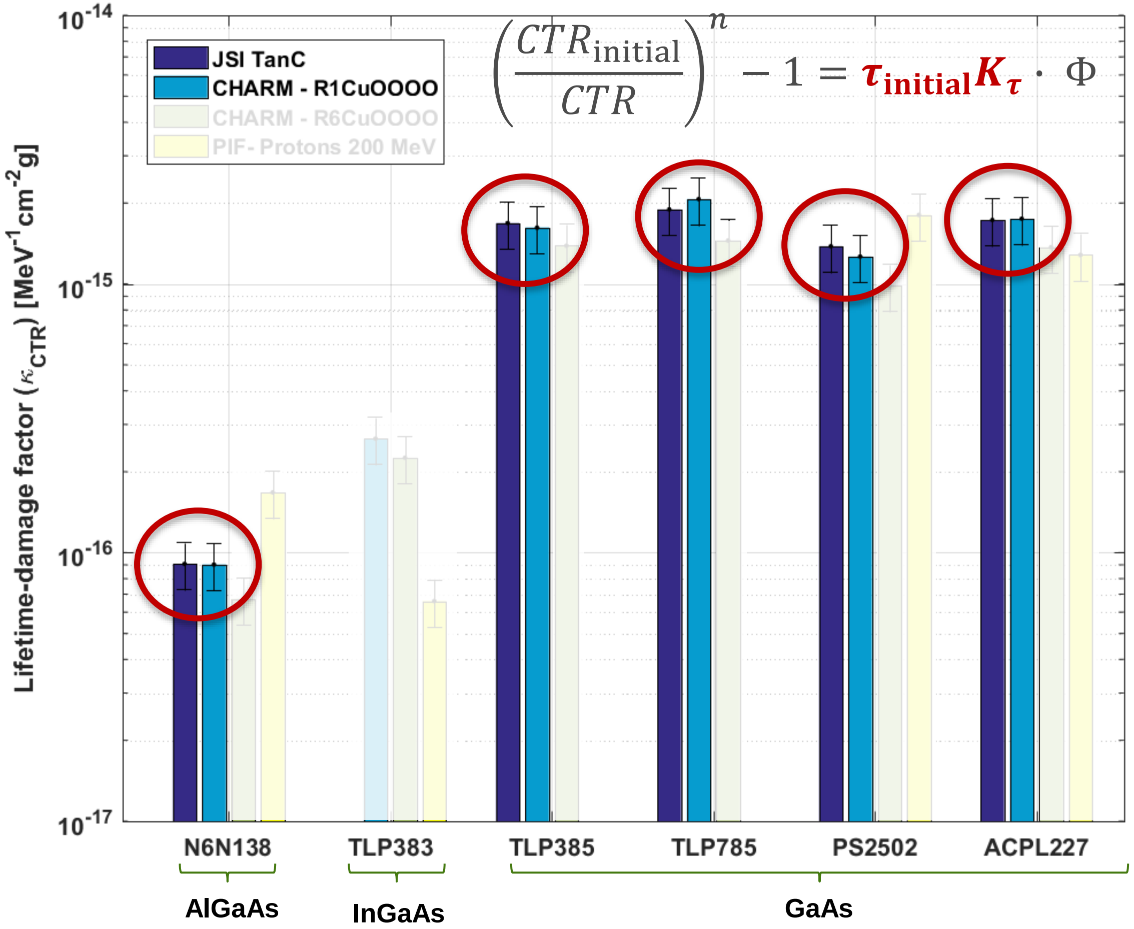


$$\left(\frac{CTR_{\text{initial}}}{CTR}\right)^{n} - 1 = \boldsymbol{\tau}_{\textbf{initial}}\boldsymbol{K}_{\boldsymbol{\tau}} \cdot \Phi$$

Optoelectronic Qualification: Example

- Clear difference between the materials
- **Very Good agreement JSI/CHARM-R1**
  - Negligible proton/pion contributions in position 1
  - Very different energy spectra
  - **→ No Neutron NIEL violations**

CTR = **C**urent **T**ransfer **R**atio

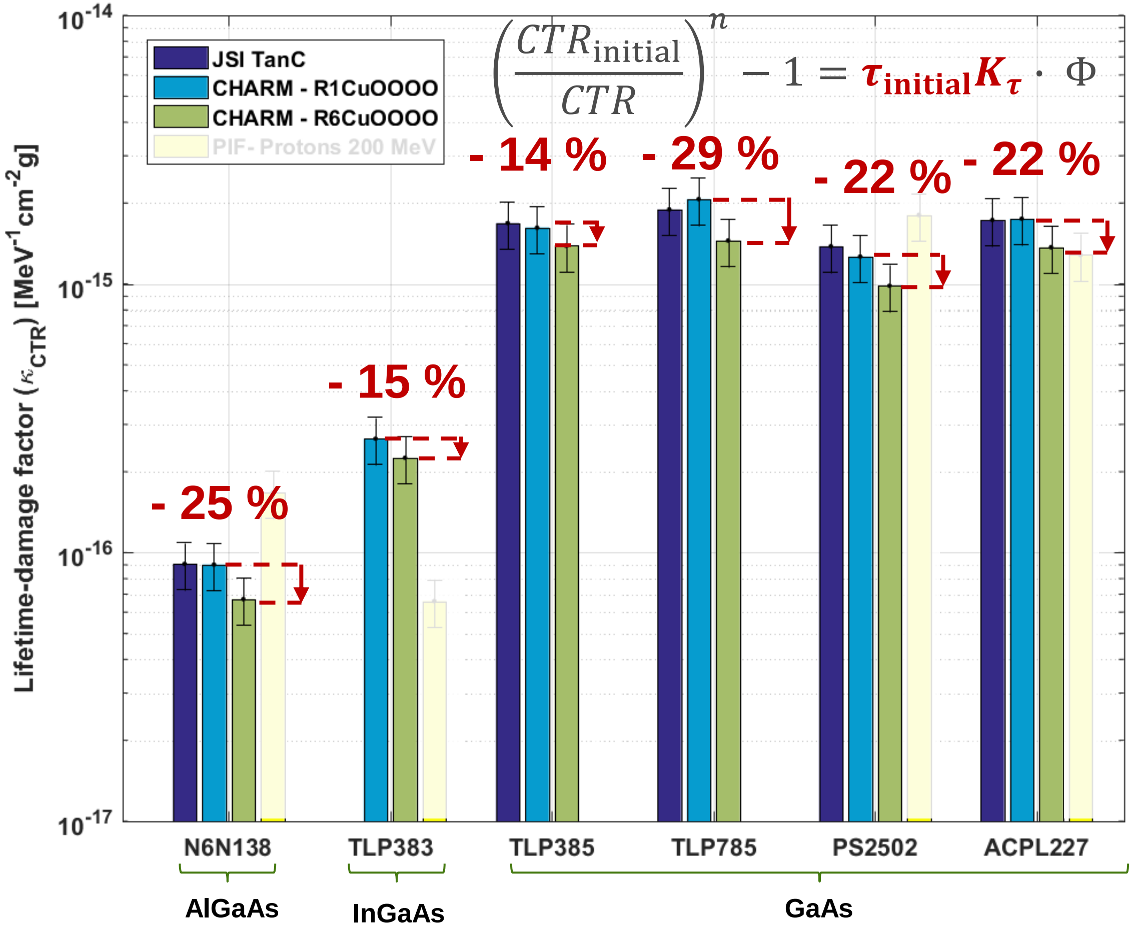


$$\left(\frac{CTR_{\mathrm{initial}}}{CTR}\right)^{n} - 1 = \boldsymbol{\tau_{\mathrm{initial}} K_{\tau}} \cdot \Phi$$

Optoelectronic Qualification: Example

- Clear difference between the materials
- Good agreement JSI/CHARM-R1
- **Systematic diff CHARMR1 → CHARMR6**
  - Factors in position 6 about -20% lower for all materials
  - ~25% of proton and of pion contributions
  - **→ Overestimation of the pion/proton damages?**
    - NIEL overestimation (→ NIEL model issue)
    - Flux overestimation (→ FLUKA simulation issue)

CTR = **C**urent **T**ransfer **R**atio



$$\left(\frac{CTR_{\text{initial}}}{CTR}\right)^{n} - 1 = \tau_{\text{initial}} K_{\tau} \cdot \Phi$$

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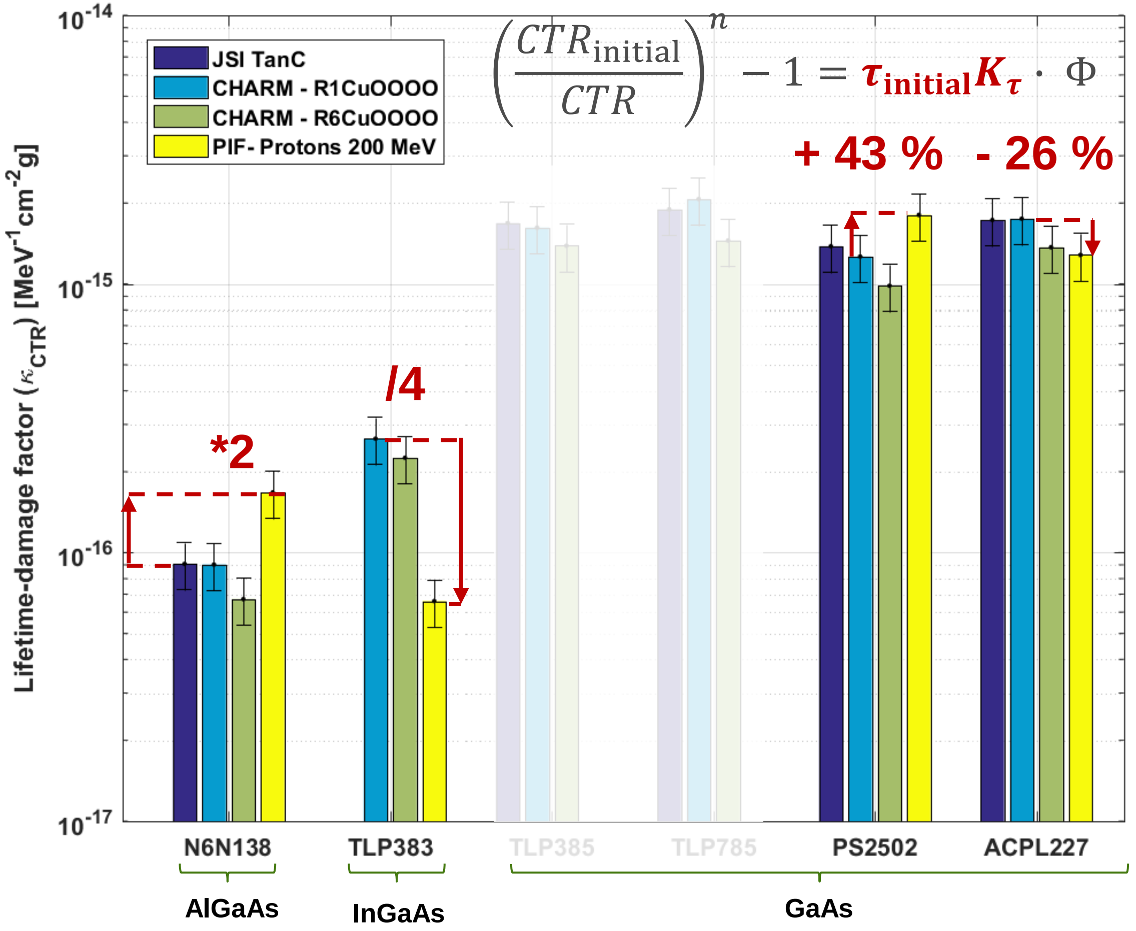
Lifetime-damage factors comparison

- Clear difference between the materials
- Good agreement JSI/CHARM-R1
- Systematic diff CHARMR1 → CHARMR6
- **Proton results not consistent with neutrons/mixed field**
  - No consistent trend observed within the devices
  - **AlGaAs:** proton damage two times higher
    → Overestimation of the damage in operation
  - **InGaAs: proton damages 4 times lower**
    → Underestimation of the damage in operation
    → Can lead to premature failure in operation

CTR = **C**urent **T**ransfer **R**atio


$$\left(\frac{CTR_{\text{initial}}}{CTR}\right)^n - 1 = \tau_{\text{initial}} K_\tau \cdot \Phi$$

Optoelectronic Qualification: Resources

R. Ferraro et al., ***"COTS Optocoupler Radiation Qualification Process for LHC Applications Based on Mixed-Field Irradiations,"*** in IEEE Transactions on Nuclear Science, vol. 67, no. 7, pp. 1395-1403, July 2020, doi: 10.1109/TNS.2020.2972777.

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 67, NO. 7, JULY 2020 1395

COTS Optocoupler Radiation Qualification Process for LHC Applications Based on Mixed-Field Irradiations

Rudy Ferraro, Gilles Foucard, Angelo Infantino, Luigi Dilillo, Markus Brugger,
Alessandro Masi, Rubén García Alía, and Salvatore Danzeca

***Abstract*—Optoelectronic components are the most sensitive devices of systems exposed to radiation environments. Displacement damage (DD) effects can severely degrade the performances of such devices, which are extensively used in critical electronic systems installed in particle accelerators or nuclear power plants. This work investigates the use of application-specific radiation spectra for damage estimations in operation instead of mono-energetic proton or neutron irradiations. An analysis of the characteristics of the Large Hadron Collider (LHC) radiation environment in terms of DD is presented in this work along with the demonstration of the ability of the CERN High Energy Accelerator Mixed Field (CHARM) facility of CERN to reproduce them. Then, a set of optocouplers made of gallium arsenide (GaAs), indium gallium arsenide (InGaAs), and aluminum gallium arsenide (AlGaAs) are tested under these environments, and the results are compared to proton and neutron irradiations.**

***Index Terms*—Displacement damage (DD), nonionizing energy loss (NIEL), particle accelerator, radiation hardness assurance (RHA), total ionizing dose (TID).**

I. INTRODUCTION

At CERN, the Large Hadron Collider (LHC) requires a vast quantity of electronic systems to operate. For this reason and due to requirements in terms of performance, availability, and cost constraints, most of the systems are based on commercial off-the-shelf (COTS) components rather than radiation-hardened ones. Consequently and in addition to single-event effects (SEEs), these parts can be affected by both displacement damage (DD) and total ionizing dose (TID) effects induced by the LHC radiation environments. Critical LHC systems embed optoelectronic components such as the quench protection system (QPS) and the electronic power converters (EPCs). Optoelectronic components, especially the commercial ones, are very sensitive to the DD effect. Thus, for such systems exposed to radiation environments inducing high total nonionizing dose (TNID), like in the LHC, optoelectronic components are often the weakest devices in systems.

As opposed to standard radiation hardness assurances (RHAs), mostly dedicated to space applications and focusing on device-level qualification, CERN's RHA includes system-level radiation tests in representative radiation environments [1]. However, the part selection and qualification process against DDs are usually performed with proton beams and neutron sources. The part response in the LHC is estimated according to the nonionizing energy loss (NIEL) scaling hypothesis. According to this hypothesis, the DD damage induced by different kinds of particles at different energies can be scaled to their NIEL [2].

However, while the NIEL scaling hypothesis has been verified with many components for silicon semiconductors, systematic scaling violations have been observed between high and intermediary energy protons on different optoelectronic devices with various semiconductor materials such as Si charge-coupled devices (CCDs) [3], AlGaAs LEDs [4], SiC LEDs [5], and GaAs [6]. Those studies and many other NIEL studies are mainly focused on proton responses since most of them target space applications, where the environment is mostly dominated by protons.

In most of the LHC's areas where COTS-based systems are installed, the radiation environments are dominated by neutrons and the TID/DD qualification tests currently performed with protons could lead to a dramatic degradation underestimation in operation for some semiconductor materials. In addition, as it is the case for protons, NIEL scaling violation within different neutron energies could occur; therefore, there is no guarantee that neutron tests performed at fixed energy will provide a response representative of the behavior in the LHC environment.

As a solution to this issue, the National Aeronautics and Space Administration (NASA) has proposed in its optocoupler test guideline [2] to perform tests at multiple proton energies to scan the effective damage factor energy dependency of the part instead of using NIEL scaling from experiments performed at single energy.

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Rudy Ferraro is with the European Organization for Nuclear Research (CERN), CH-1211 Genève, Switzerland, and also with the Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier (LIRMM), Centre National de la Recherche Scientifique (CNRS), Université de Montpellier, 34095 Montpellier, France (e-mail: rudy.ferraro@cern.ch).

Gilles Foucard, Angelo Infantino, Markus Brugger, Alessandro Masi, Rubén García Alía, and Salvatore Danzeca are with the European Organization for Nuclear Research (CERN), CH-1211 Genève, Switzerland.

Luigi Dilillo is with the Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier (LIRMM), Centre National de la Recherche Scientifique (CNRS), Université de Montpellier, 34095 Montpellier, France.

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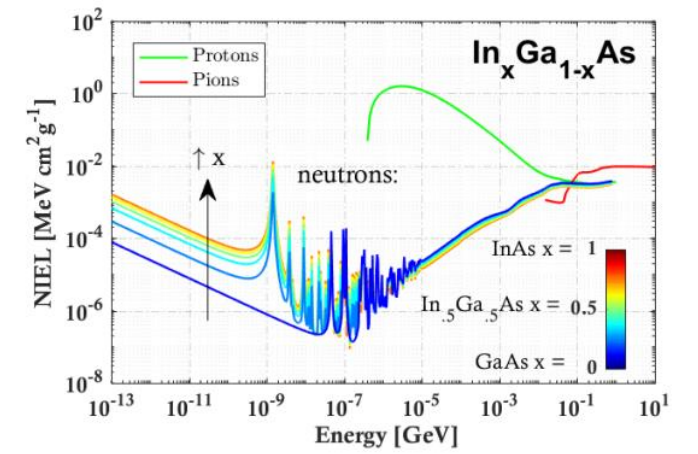


Fig. 2. NIEL of neutrons, protons, and pions for AlGaAs and InGaAs for different indium and aluminum contributions.

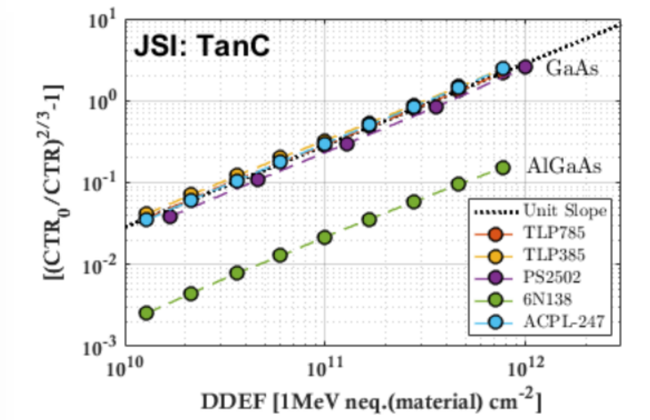
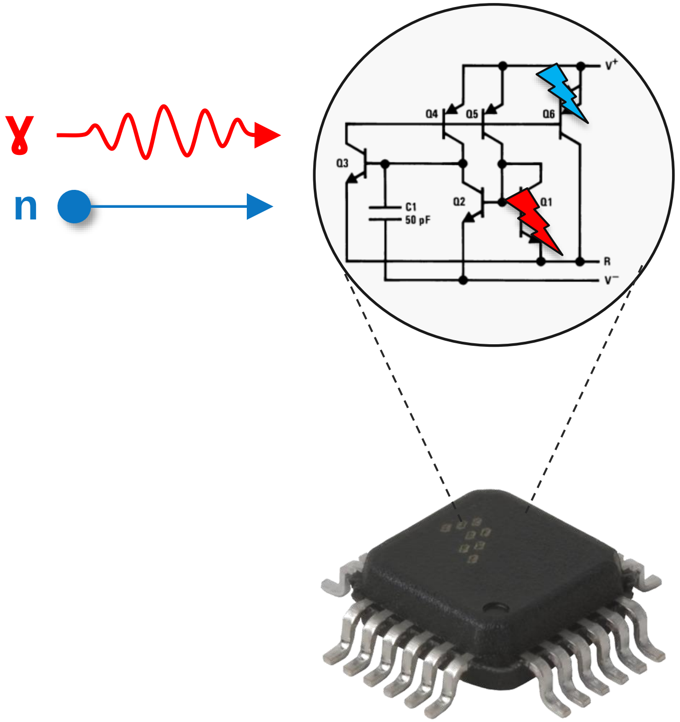


Fig. 4. Evolution of the relative lifetime damages of the different tested optocouplers as a function of the DDEF for their own material composition (GaAs, AlGaAs, or InGaAs) obtained in the CHARM and JSI facilities.

Combined TID-DD effects on ICs: Context

- At CERN, systems can be highly distributed and exposed to a **wide variety of ionizing and non-ionizing dose levels**.
- Integrated Circuits (ICs) are made of several transistors that can exhibit different sensitivities to TID and DD effects
- In operation different DD/TID rate ratios could lead to complete different component degradation profiles
- Impossible to estimate from individual TID and DD irradiations for most of the components
- **No standards or test methodology exist for combined TID-DD qualification**



- **Objectives of this Study:**
  - Investigate the impact of the LHC radiation environments on the qualification process of component sensitive to combined TID-DD effects and propose a qualification methodology against this effect

Combined TID-DD effects on ICs: Solution

Study of the Impact of the LHC Radiation Environments on the Synergistic Displacement Damage and Ionizing Dose Effect on Electronic Components

Rudy Ferraro, Salvatore Danzeca, Chiara Cangialosi, Rubén García Alía, Francesco Cerutti,
Andrea Tsinganis, Luigi Dilillo, Markus Brugger, and Alessandro Masi

***Abstract*—Bipolar-based components can exhibit a higher (or lower) degradation when exposed to both total ionizing dose (TID) and displacement damage (DD) effects simultaneously than the sum of the two separated effects. This paper investigates the implications of this synergistic effect on the radiation qualification process of large hadron collider's (LHC's) electronic equipment. More specifically, the impact of the wide range of DD/TID rate ratios of the LHC's areas on the synergistic degradation rates is investigated. An analysis of the ratios of a crucial part of the accelerator is performed. A demonstration of the ability of the CHARM mixed-field facility of CERN to perform radiation tests in representative LHC's ratios is also presented as well as radiation test results of a bipolar integrated circuit exposed to these different ratios are presented. Finally, the impact of this effect on the CERN radiation hardness assurance process is discussed and a simple method is proposed to qualify component against such effects.**

***Index Terms*—Displacement damage (DD), particle accelerator, radiation hardness assurance (RHA), synergistic effects, total ionizing dose (TID).**

I. INTRODUCTION

AT CERN, a large amount of electronic systems mostly based on commercial off the shelf (COTS) components are exposed to the harsh mixed-field radiation environments induced by the large hadron collider (LHC) accelerator and its injection lines. The lifetime and the performances of these systems are, thus, affected simultaneously by both displacement damage (DD) and total ionizing dose (TID) effects. In the past, it was assumed that these two effects were independent in radiation damage and their combined effects on component were the simple sum of their degradation. Therefore, the two effects were characterized separately with gamma sources for TID and neutrons sources for DD [1], [2]. However, in the past decade, researchers have pointed out that these two combined effects have a nonlinear impact on bipolar and optoelectronic components and their synergistic effects cannot be decoupled [2]–[10].

Barnaby *et al.* [3] have performed X-rays, protons, and neutrons experiments on bipolar operational amplifiers, and the experimental results have revealed a nonlinear mechanism between the TID and DD. The proton-induced degradation was lower than the sum of X-rays and neutron-induced degradations. From these data, an analytical model has been made, demonstrating that for p-n-p transistors, the net positive charge caused by ionization in the oxide can suppress the bulk recombination and, thus, moderate the effect of displacement damage (i.e, bulk lifetime degradation) [4]. On the other hand, for n-p-n transistors, the positive oxide charges can enhance the bulk recombination and, thus, the DD effects. It is shown that the level of nonlinearity between the mechanisms depends on several factors such as the doping, the base depth, or the transistor architecture.

Li *et al.* [5], [6] have also demonstrated synergistic effects on n-p-n and p-n-p transistors, showing through simultaneously and sequential proton and electron irradiations how the TID can enhance or reduce the DD effects on the current gain degradation. They also showed through proton irradiations at different energies in [7] and [8] that the level of synergistic effects depends also on the ratio between the number of interface traps generated in the oxide by ionization and the number of defects induced in the bulk by DD.

Gorelick *et al.* [9] have exposed 12 different linear integrated circuits (ICs) to sequential neutron and gamma-rays irradiations. Half of the components have exhibited different degrees of nonlinear interactions between the two mechanisms. Another simulation of the phenomenon has been performed by Wang *et al.* [10] validating the principles proposed in [4] with a good agreement with experimental results [11].

To summarize, the TID effect can enhance or reduce the DD effect on n-p-n and p-n-p transistors, respectively, depending

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R. Ferraro is with the European Organization for Nuclear Research (CERN), CH-1211 Geneva, Switzerland, and also with the Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier, Centre National de la Recherche Scientifique, Université de Montpellier, 34095 Montpellier, France (e-mail: rudy.ferraro@cern.ch).

S. Danzeca, C. Cangialosi, R. G. Alía, F. Cerutti, A. Tsinganis, M. Brugger, and A. Masi are with the European Organization for Nuclear Research, CH-1211 Geneva, Switzerland.

L. Dilillo is with the Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier, Centre National de la Recherche Scientifique, Université de Montpellier, 34095 Montpellier, France.

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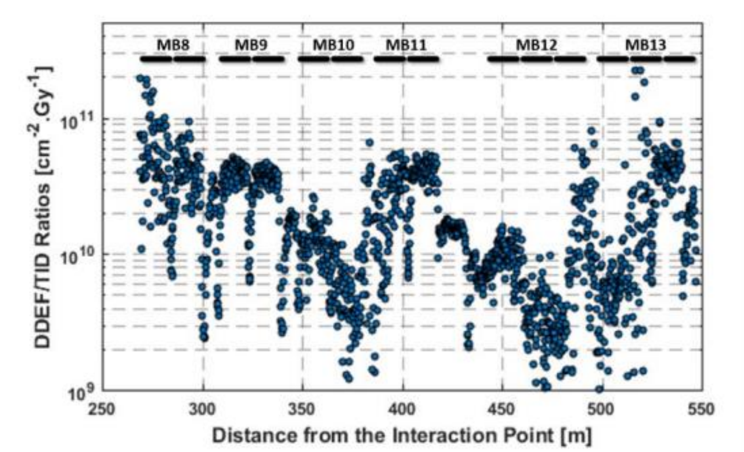


Fig. 4. Ratio between DDEF and TID in LHC's DS area of point 5 at equipment level.

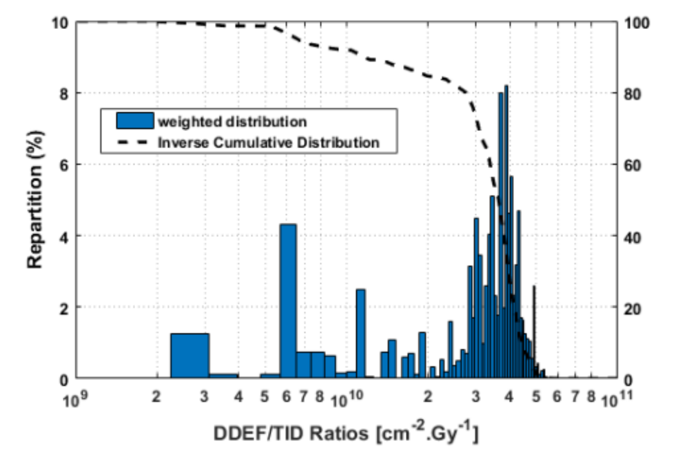
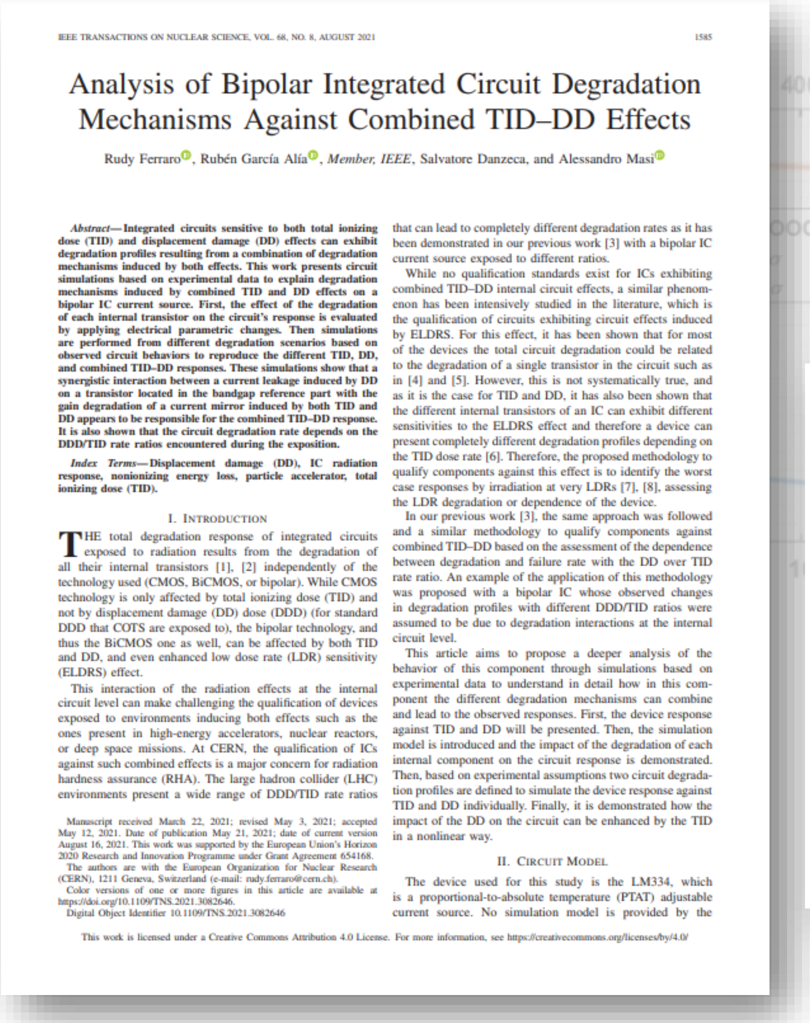


Fig. 5. Probability and inverse cumulative weighted distribution of the DS area's DDEF/TID rate ratios weighted to the annual amount of TID and DDEF.

Combined TID-DD effects on ICs: Examples



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Analysis of Bipolar Integrated Circuit Degradation Mechanisms Against Combined TID–DD Effects

Rudy Ferraro, Rubén García Alía, *Member, IEEE*, Salvatore Danzeca, and Alessandro Masi

***Abstract*—Integrated circuits sensitive to both total ionizing dose (TID) and displacement damage (DD) effects can exhibit degradation profiles resulting from a combination of degradation mechanisms induced by both effects. This work presents circuit simulations based on experimental data to explain degradation mechanisms induced by combined TID and DD effects on a bipolar IC current source. First, the effect of the degradation of each internal transistor on the circuit's response is evaluated by applying electrical parametric changes. Then simulations are performed from different degradation scenarios based on observed circuit behaviors to reproduce the different TID, DD, and combined TID–DD responses. These simulations show that a synergistic interaction between a current leakage induced by DD on a transistor located in the bandgap reference part with the gain degradation of a current mirror induced by both TID and DD appears to be responsible for the combined TID–DD response. It is also shown that the circuit degradation rate depends on the DDD/TID rate ratios encountered during the exposition.**

***Index Terms*—Displacement damage (DD), IC radiation response, nonionizing energy loss, particle accelerator, total ionizing dose (TID).**

I. INTRODUCTION

THE total degradation response of integrated circuits exposed to radiation results from the degradation of all their internal transistors [1], [2] independently of the technology used (CMOS, BiCMOS, or bipolar). While CMOS technology is only affected by total ionizing dose (TID) and not by displacement damage (DD) dose (DDD) (for standard DDD that COTS are exposed to), the bipolar technology, and thus the BiCMOS one as well, can be affected by both TID and DD, and even enhanced low dose rate (LDR) sensitivity (ELDRS) effect.

This interaction of the radiation effects at the internal circuit level can make challenging the qualification of devices exposed to environments inducing both effects such as the ones present in high-energy accelerators, nuclear reactors, or deep space missions. At CERN, the qualification of ICs against such combined effects is a major concern for radiation hardness assurance (RHA). The large hadron collider (LHC) environments present a wide range of DDD/TID rate ratios that can lead to completely different degradation rates as it has been demonstrated in our previous work [3] with a bipolar IC current source exposed to different ratios.

While no qualification standards exist for ICs exhibiting combined TID–DD internal circuit effects, a similar phenomenon has been intensively studied in the literature, which is the qualification of circuits exhibiting circuit effects induced by ELDRS. For this effect, it has been shown that for most of the devices the total circuit degradation could be related to the degradation of a single transistor in the circuit such as in [4] and [5]. However, this is not systematically true, and as it is the case for TID and DD, it has also been shown that the different internal transistors of an IC can exhibit different sensitivities to the ELDRS effect and therefore a device can present completely different degradation profiles depending on the TID dose rate [6]. Therefore, the proposed methodology to qualify components against this effect is to identify the worst case responses by irradiation at very LDRs [7], [8], assessing the LDR degradation or dependence of the device.

In our previous work [3], the same approach was followed and a similar methodology to qualify components against combined TID–DD based on the assessment of the dependence between degradation and failure rate with the DD over TID rate ratio. An example of the application of this methodology was proposed with a bipolar IC whose observed changes in degradation profiles with different DDD/TID ratios were assumed to be due to degradation interactions at the internal circuit level.

This article aims to propose a deeper analysis of the behavior of this component through simulations based on experimental data to understand in detail how in this component the different degradation mechanisms can combine and lead to the observed responses. First, the device response against TID and DD will be presented. Then, the simulation model is introduced and the impact of the degradation of each internal component on the circuit response is demonstrated. Then, based on experimental assumptions two circuit degradation profiles are defined to simulate the device response against TID and DD individually. Finally, it is demonstrated how the impact of the DD on the circuit can be enhanced by the TID in a nonlinear way.

II. CIRCUIT MODEL

The device used for this study is the LM334, which is a proportional-to-absolute temperature (PTAT) adjustable current source. No simulation model is provided by the

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The authors are with the European Organization for Nuclear Research (CERN), 1211 Geneva, Switzerland (e-mail: rudy.ferraro@cern.ch).

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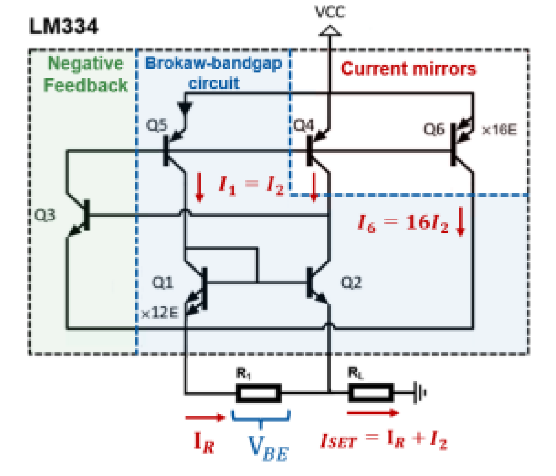

Fig. 1. Simplified internal circuit of LM334 with the different parts underlined.

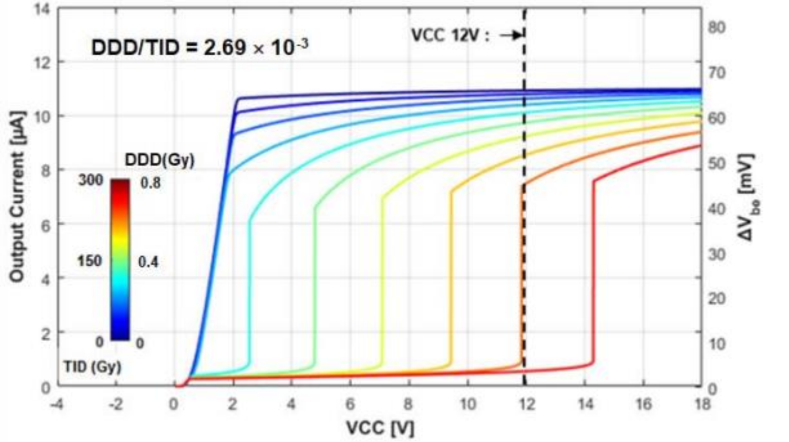

Fig. 13. Simulated characteristic output current evolution observed against TID–DD irradiation.

Conclusions

- Reliable component qualification requires knowledge of radiation effects from the lowest level, the material, to the highest level like ICs or System-On-Chip
- Testing standards and guidelines inherited from the space field provide a valuable starting point for our community
- Many of these standards does not apply to particle accelerator spectra and a constant work is being done to develop qualification methods dedicated to CERN
- We have identified weaknesses in the traditional testing methodologies, especially for the qualification of optoelectronics and combined TID-DD effects on ICs
- Then qualification methodologies dedicated to the LHC environments were developed for these two topics
- It was shown the huge impact on the qualification of having unreliable qualification procedure
- Numerous studies are still been carried out to evaluate methodologies and guidelines for other types of effects

Thank you for your attention!

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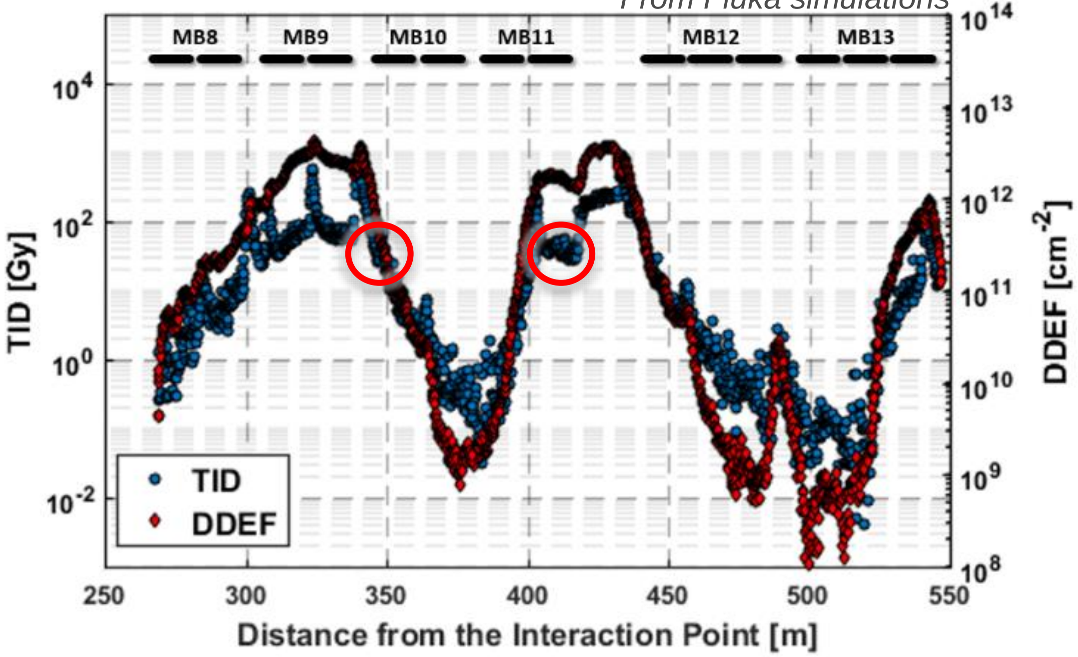
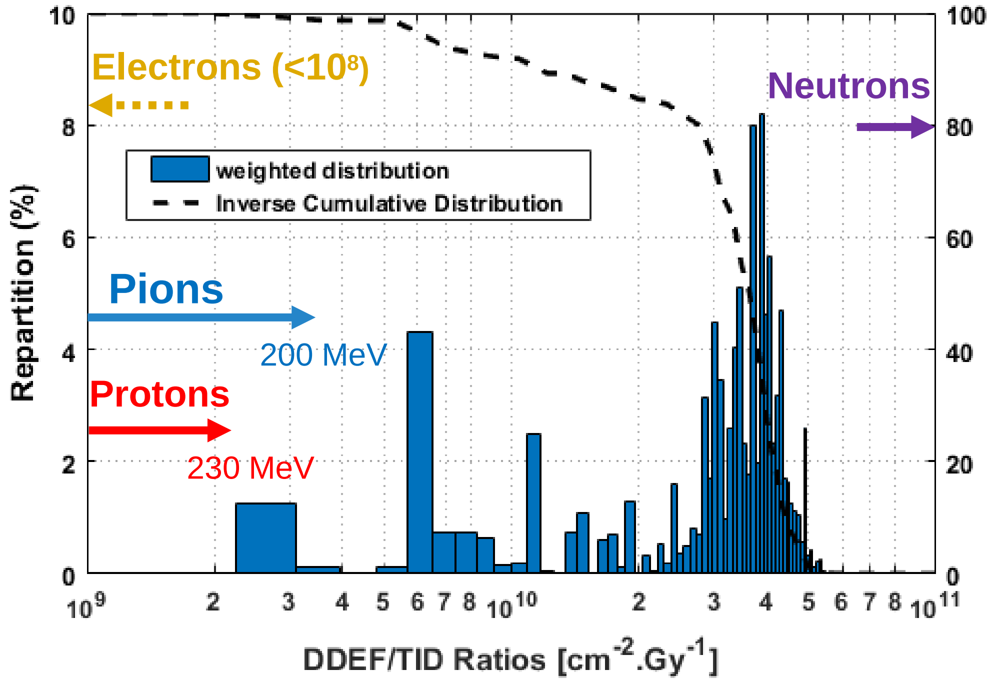
Combined TID-DD effects on ICs: LHC levels Analysis

- Taking the DS area as example:

From Fluka simulations



- DDEF/TID Ratio weighted Distribution:



10 years radiation levels:

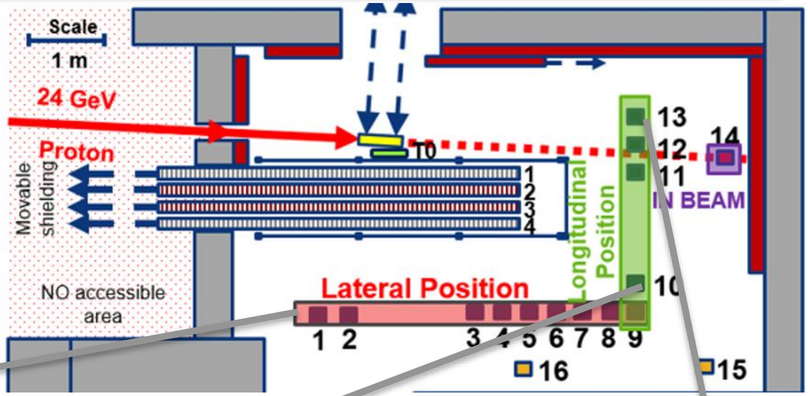
- **Below MB10:** TID: 700 Gy
  DDEF: 1 x10^{12} neq. cm^{-2}
- **Below MB11:** TID: 700 Gy
  DDEF: 2x10^{13} neq. cm^{-2}

x20

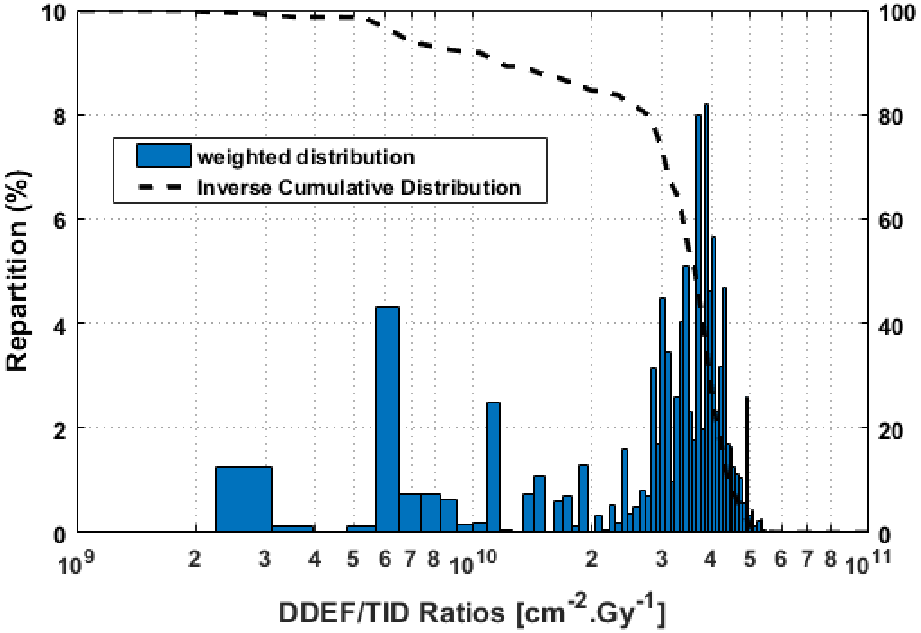
- Wide variety of **DDEF/TID Ratio**: From **10^9** up to **10^{11} cm^{-2}.Gy^{-1}**

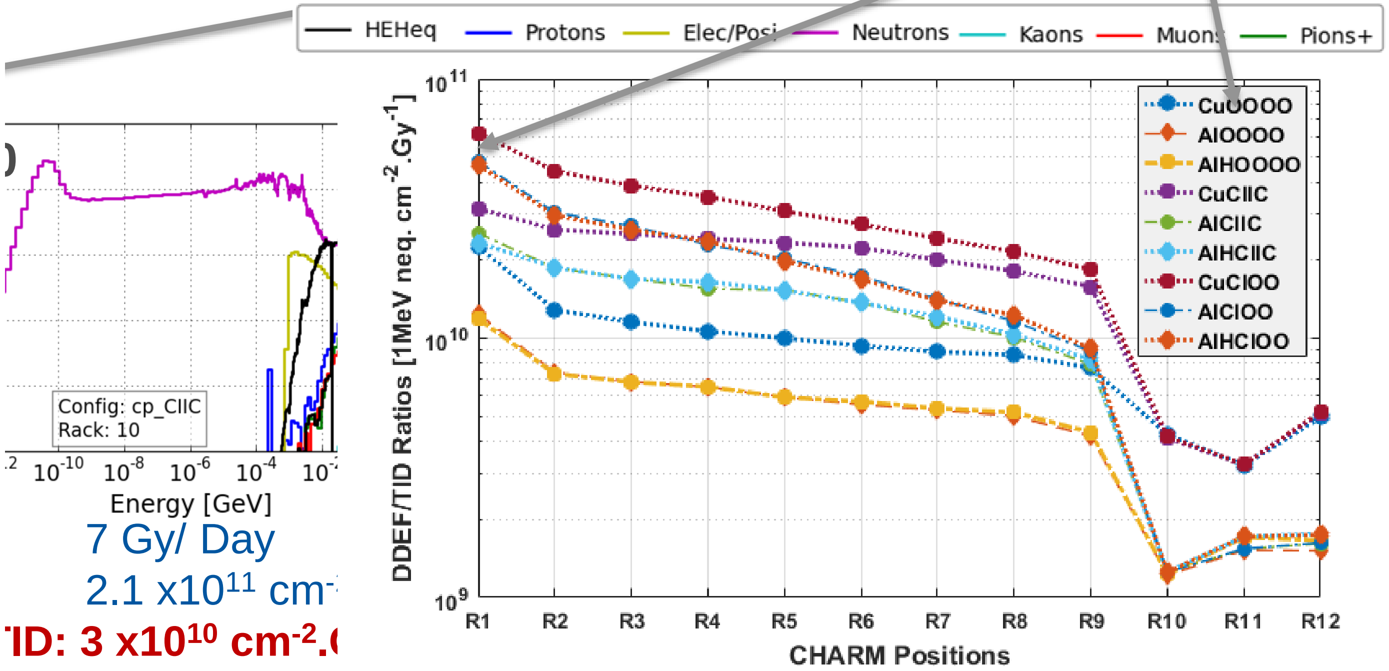
Combined TID-DD effects on ICs: Solution

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



- **99% of the LHC ratios covered by the facility.**





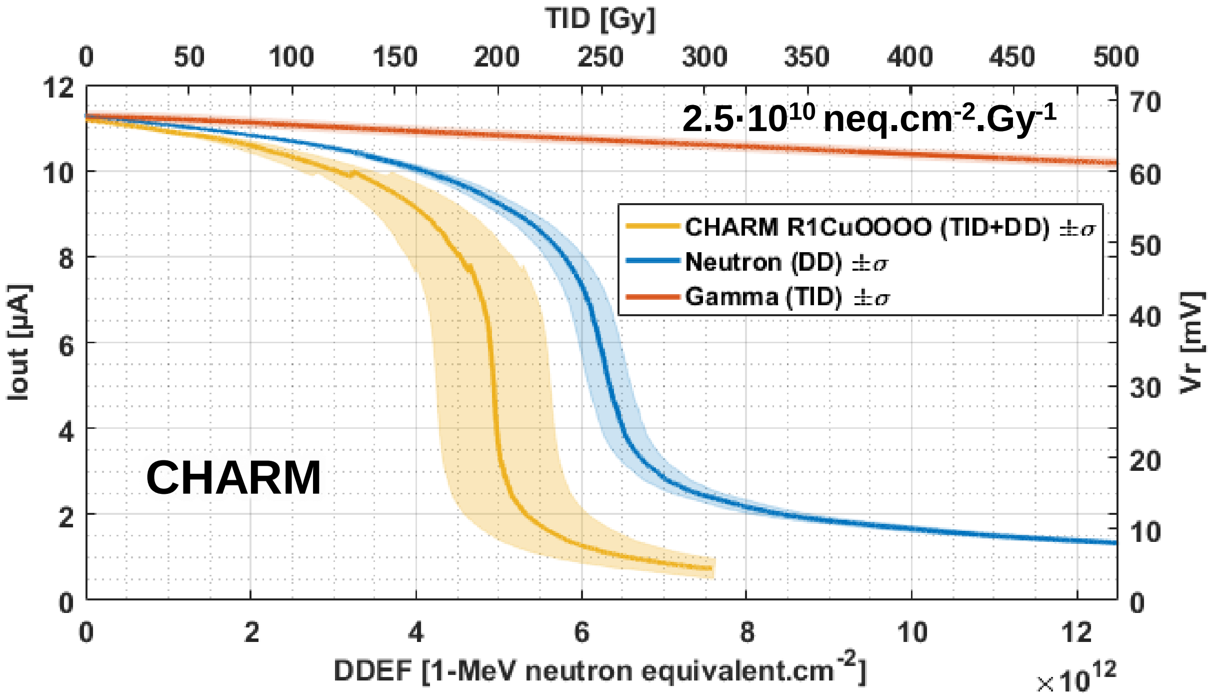
7 Gy/ Day

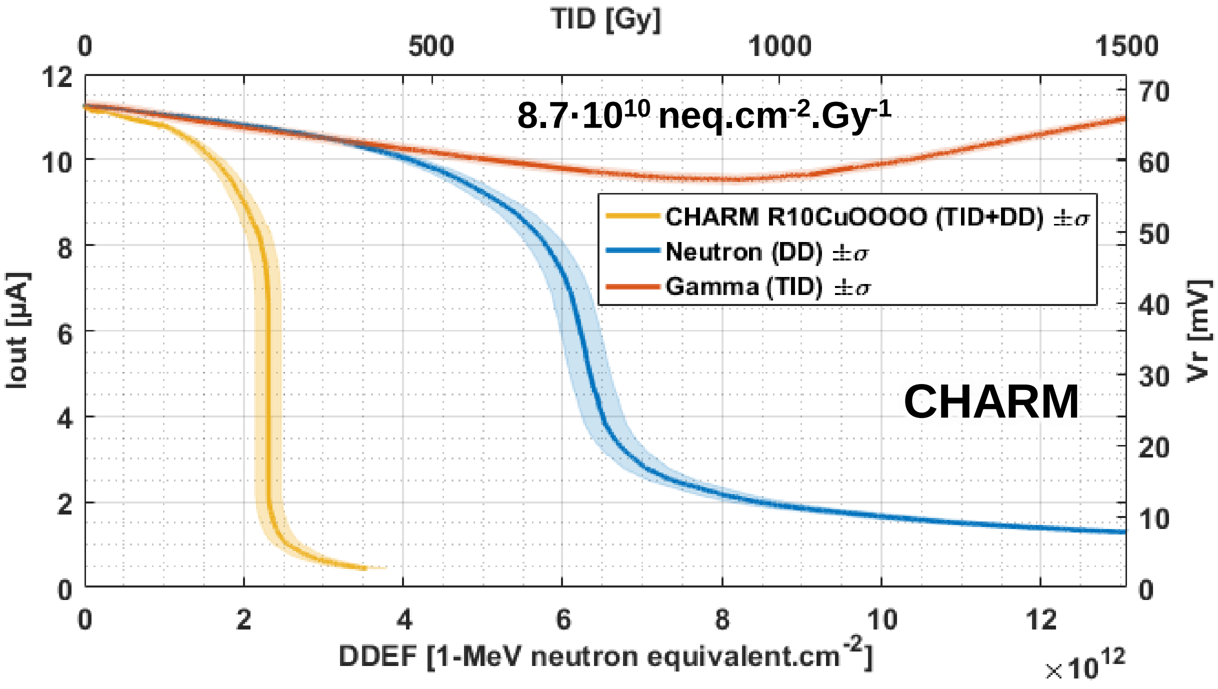
2.1 x10^{11} cm

ID: 3 x10^{10} cm^{-2}.

Combined TID-DD effects on ICs: Examples

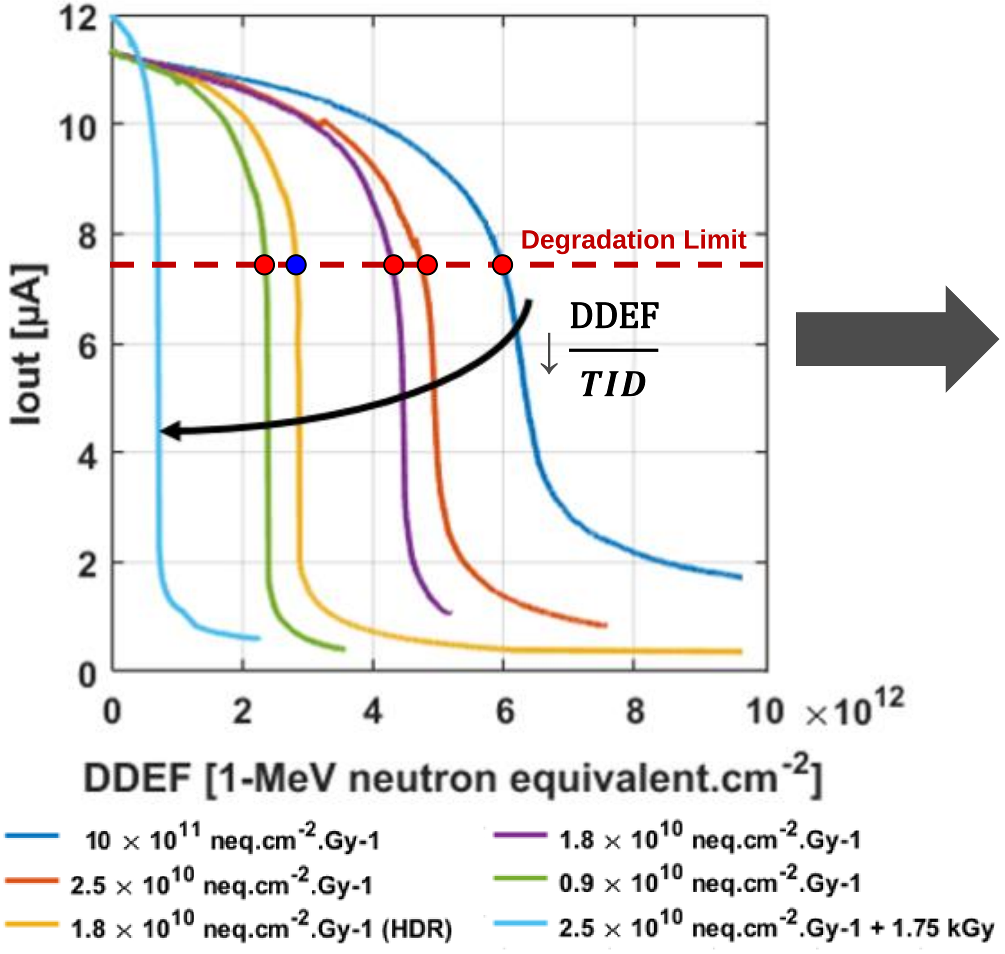
- **Current Source (LM334):**
  - Same degradations profile as DD one
  - Different degradation mechanism than TID
  - Degradation rate increase with TID contribution
  - **Combined TID+DD response unpredictable from individual TID & DD responses**

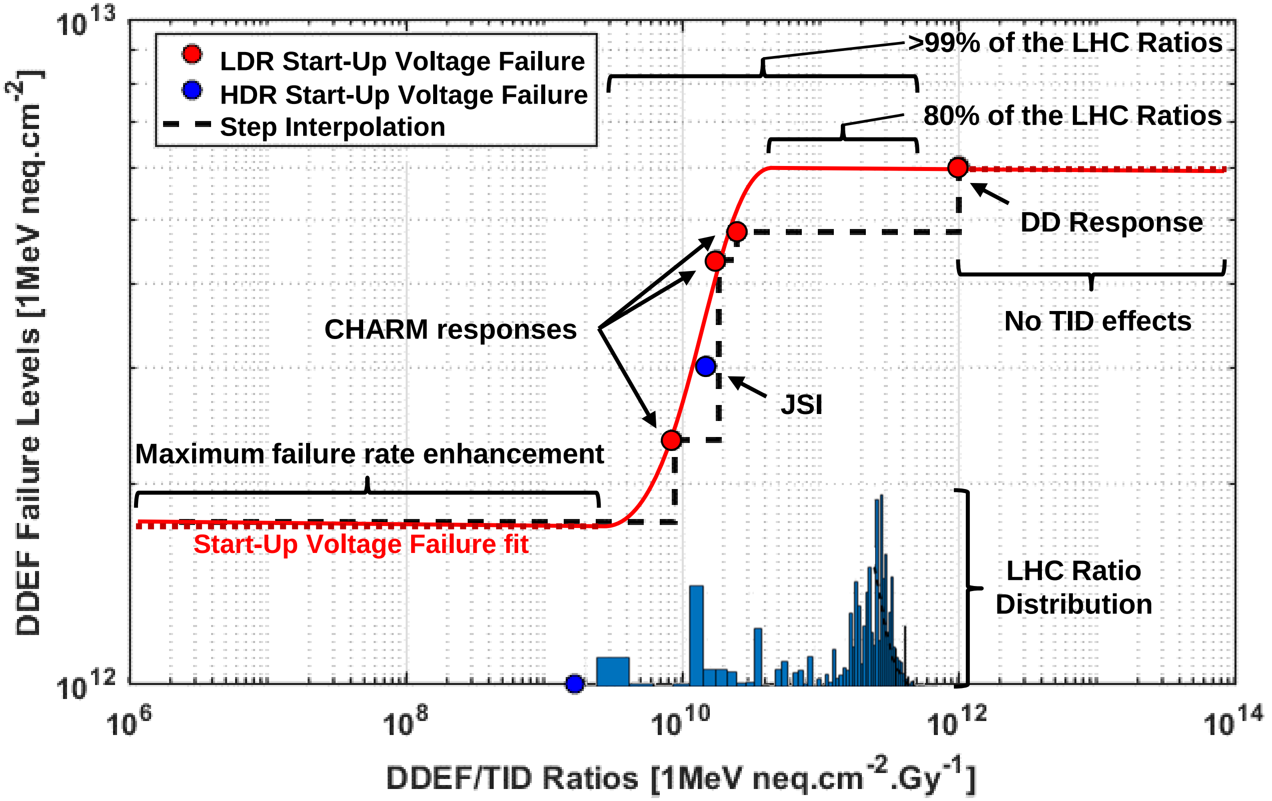




Combined TID-DD effects on ICs: Solution

- Applied on LM334 Current Source:





- How can we quantify the device response against all LHC ratios?
  - extract failure levels as a function of DDEF/TID ratios
  - Interpolate response between ratios