R2E activities at CLEAR

Andrea Coronetti

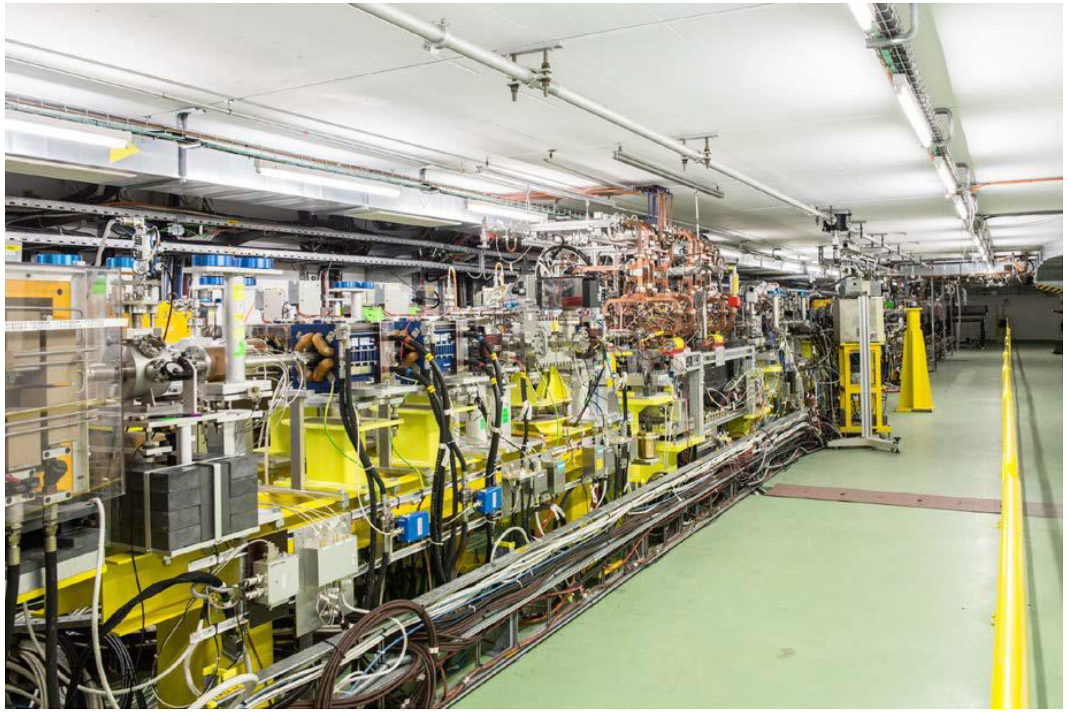
With inputs from Rubén García Alía, Jean Kempf, Giuseppe Lerner, Vanessa Wyrwoll, Daniel Söderström, Florent Castellani

CLEAR Meeting – 16 Mar, 2021

Introduction

- Electron-induced effects in electronics are **not as well explored** as those from ions, protons or neutrons

- CLEAR facility is central to the investigation of these effects:
    - Can allow exploring electron-induced **single-event effects** over a wider range of energy than what can be achived in medical LINACs.
    - Can enable electron-induced **displacement damage** studies and their comparison to proton/neutron irradiations
    - Quite **diverse beam conditions** achievable at VESPER/THz with gun dark current or laser-driven productions
    - Characterization of **electron-on-dump radiative field** to explore further testing opportunities



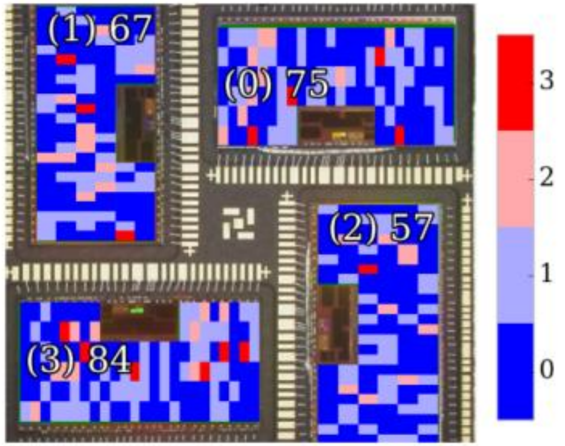
Remarkable results from the past

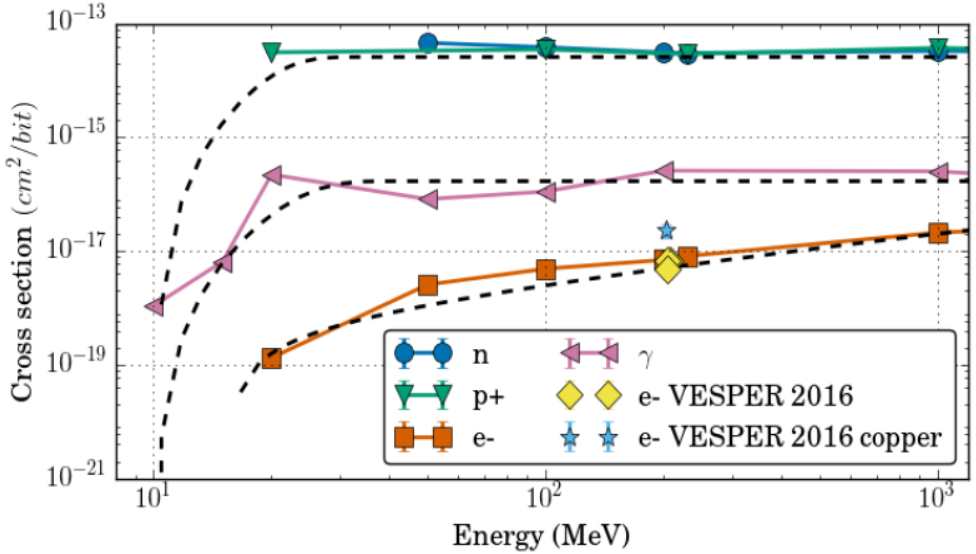
SEU

- First electron-induced SEUs from low-energy electrons
- Medical LINACs limited to 20 MeV
- **CLEAR enabled testing up to 220 MeV**
- Since then several tests:
    - ESA Monitor (reference chip, 250 nm)
    - More integrated technologies (Artix 28 nm)
    - Tests from **industrial** partners (IROC and TRAD)
- Interest for **Jovian environment** space missions (JUICE from ESA)

Main **take-aways** (M. Tali):

- SEUs from high-energy electrons due to **electro- and photo-nuclear** reactions
- Happening in devices with rather **large critical charge**
- **Higher HEE cross-sections wrt HEP cross-sections** in more integrated technologies

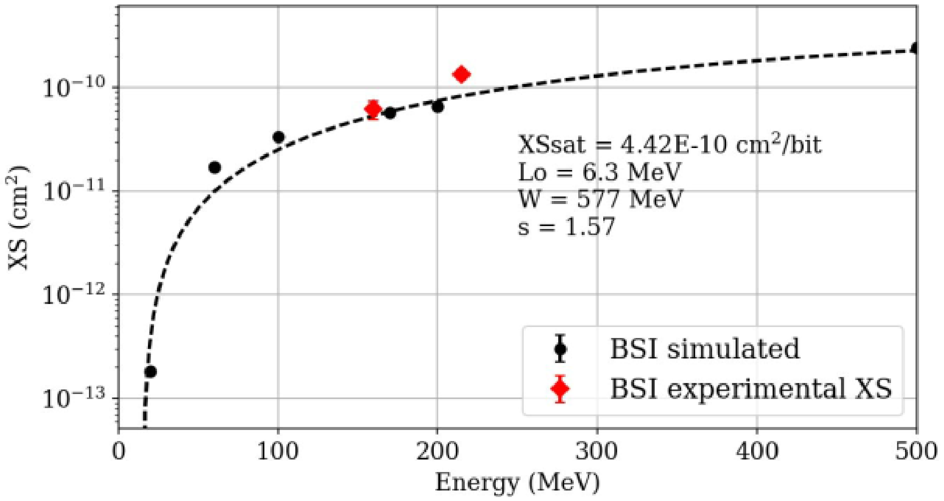


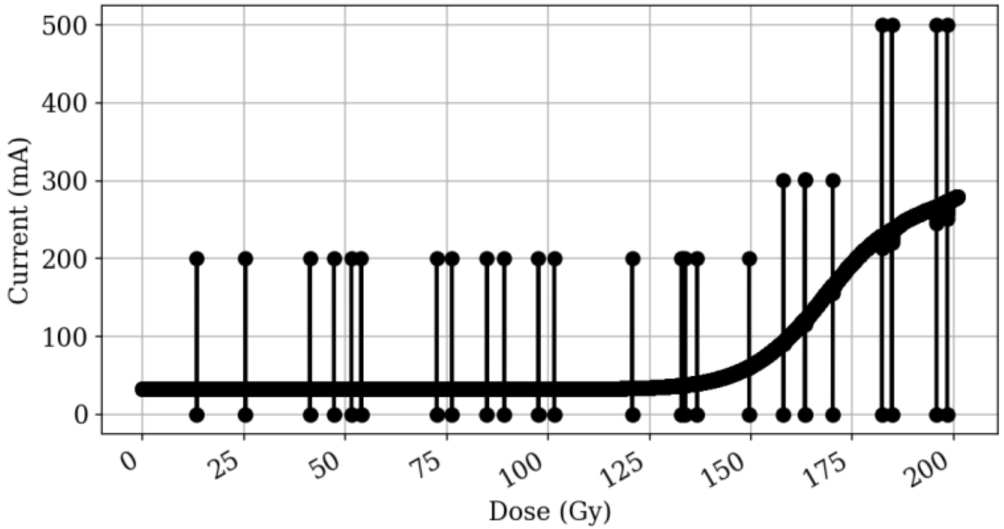


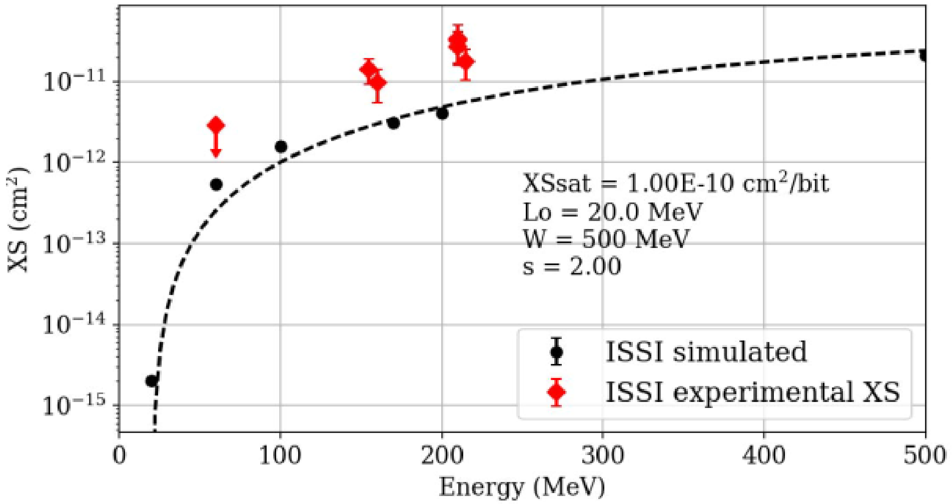
Remarkable results from the past

SEL (M. Tali)

- Potentially destructive effect within a device
- Typically, it requires much higher deposited charge than SEU
- CLEAR enabled **first ever observation and demonstration that HEE can trigger SEL** in SRAM.







Latest R2E activities

SEE studies

- Study of **flash effects** in SRAM (effects caused by very high pulsed fluxes)
- Characterization of **highly integrated SRAMs** (40-90 nm) of the R2E inventory
- **First observations of stuck bits** in DRAM

Displacement damage (and ionizing dose) studies

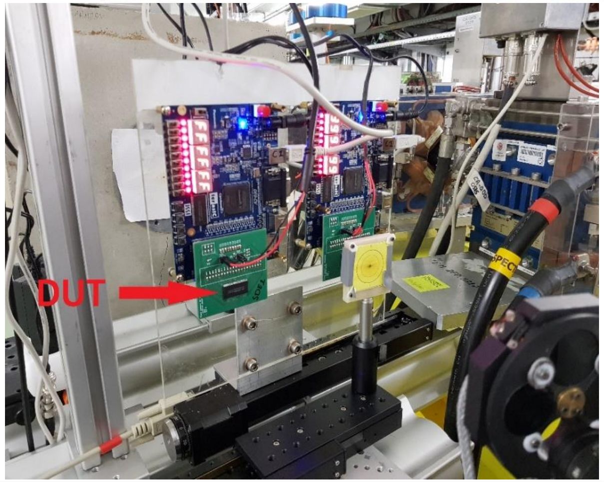
- Determination of the **electron hardness factor** in silicon diodes
- DD and TID Effects on **CMOS image sensors**

Electron-on-dump studies

- Determination of **the photon and HEH radiative field** produced by the dump due to the impinging electron beams

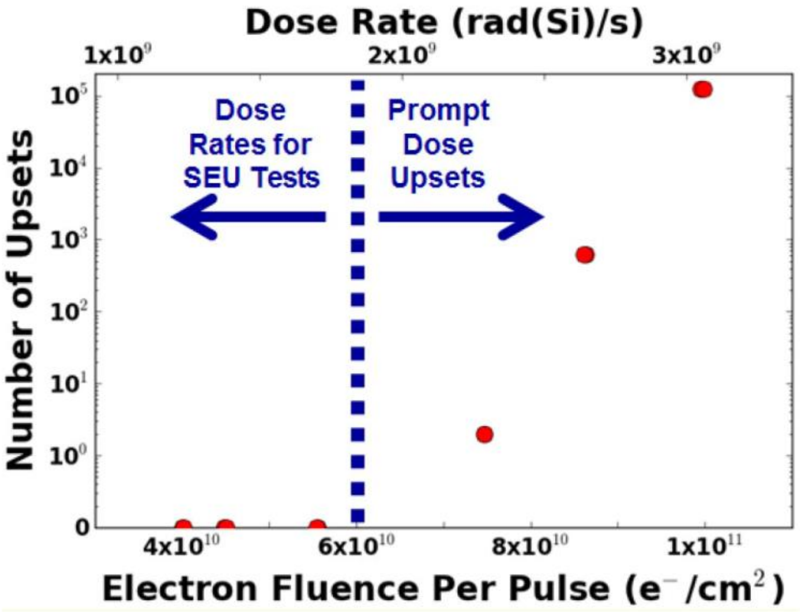
Dosimetry

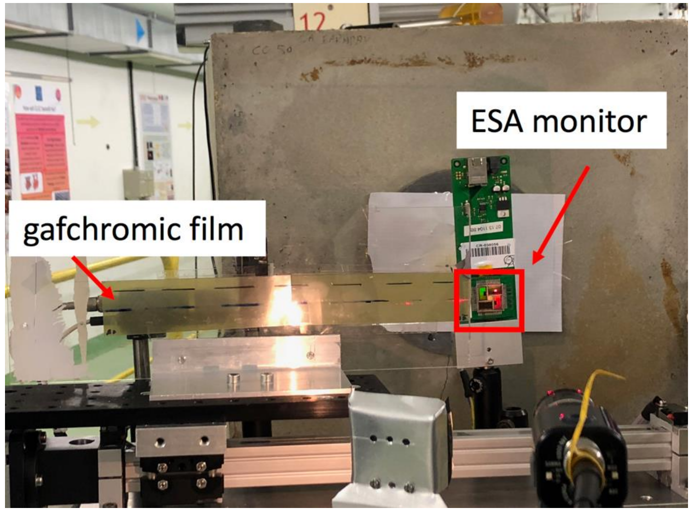
- Liquid ion ionization chamber (not discussed here)

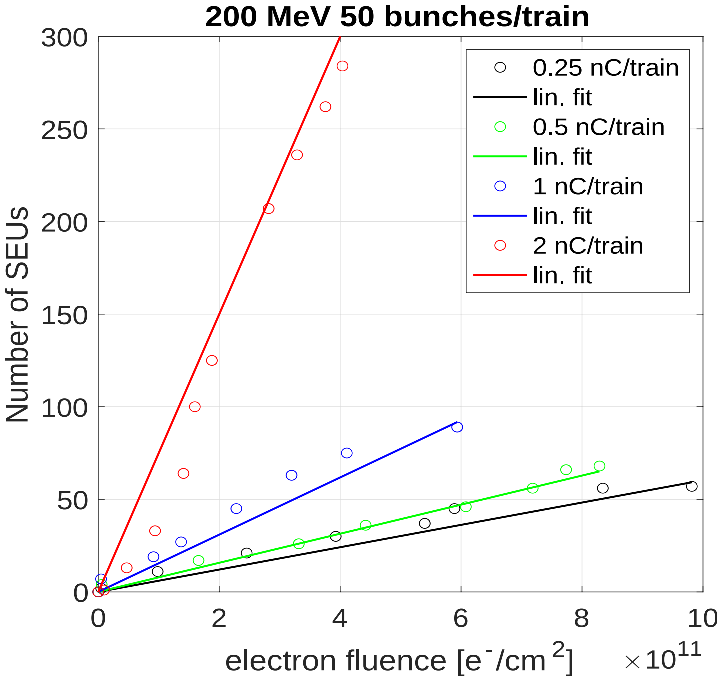


Flash effects (V. Wyrwoll)

Gadlage 2015, IEEE TNS

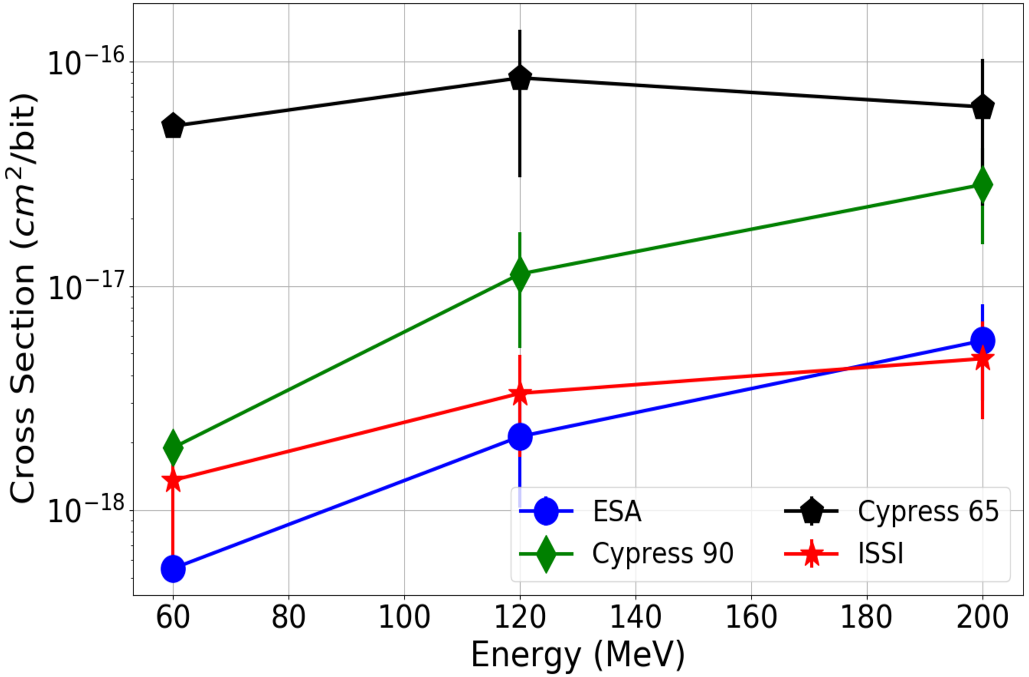


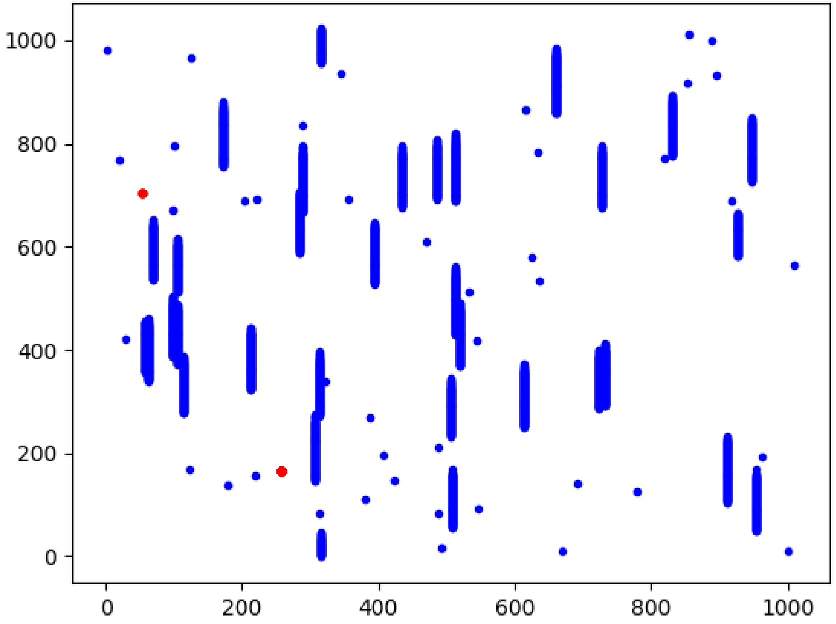




- SEE testing is performed at an accelerated rate; however, one has to **make sure that each SEE is due to the interaction of a single electron**
- Tests with ESA monitor show that **for the same fluence the number of SEUs may differ** for diverse beam conditions (e.g., bunch charge), which require further investigations.

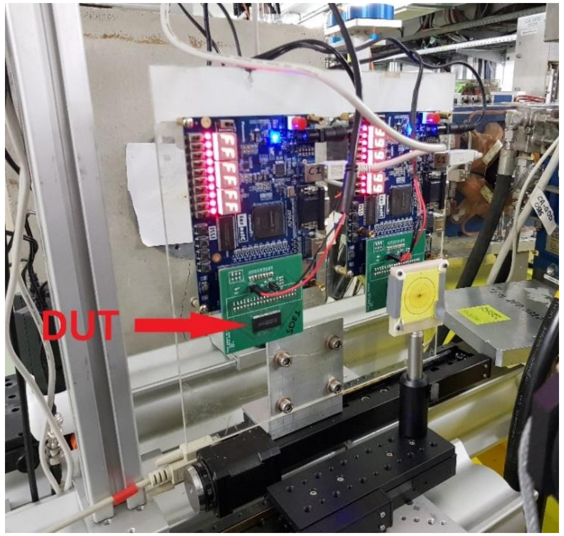
SEUs in highly-integrated SRAMs (F. Castellani)

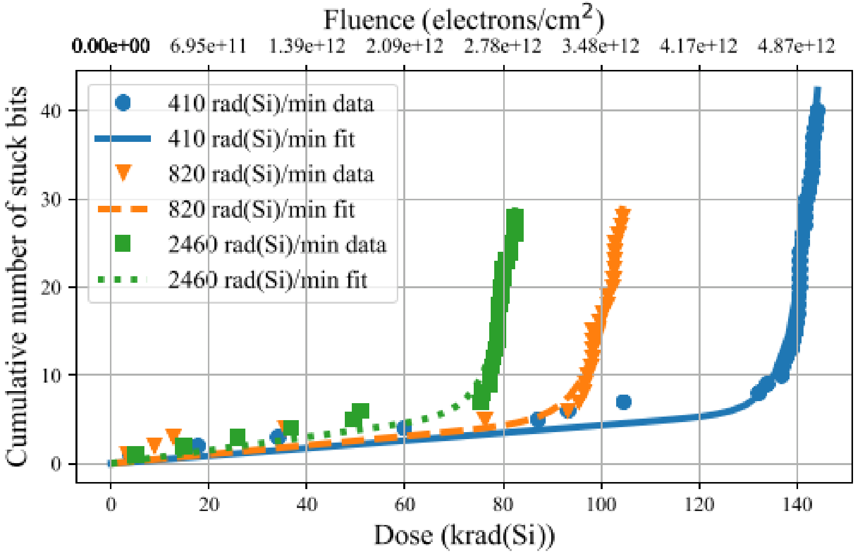


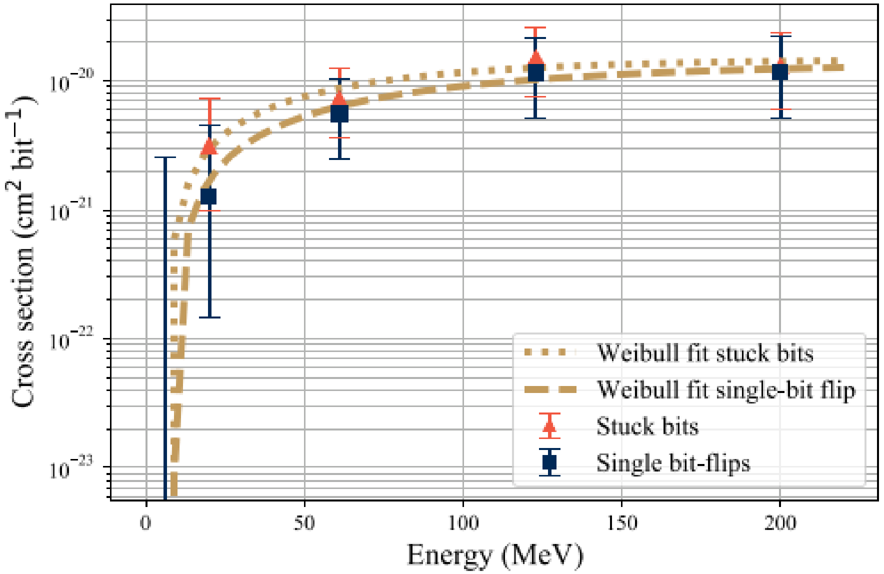


- **Different behaviors** observed (ISSI 40 nm XS very similar to ESA monitor X vs. Higher cross-sections for Cypress 65 and 90 nm)
- Large collected data helps claiming that typically **3-4 orders of magnitude differences wrt to HEP** are to be expected (though not proportional behavior with scaling)
- Beam conditions can generate **unwanted row or column SEFIs**

Stuck bits in DRAM (D. Söderström)

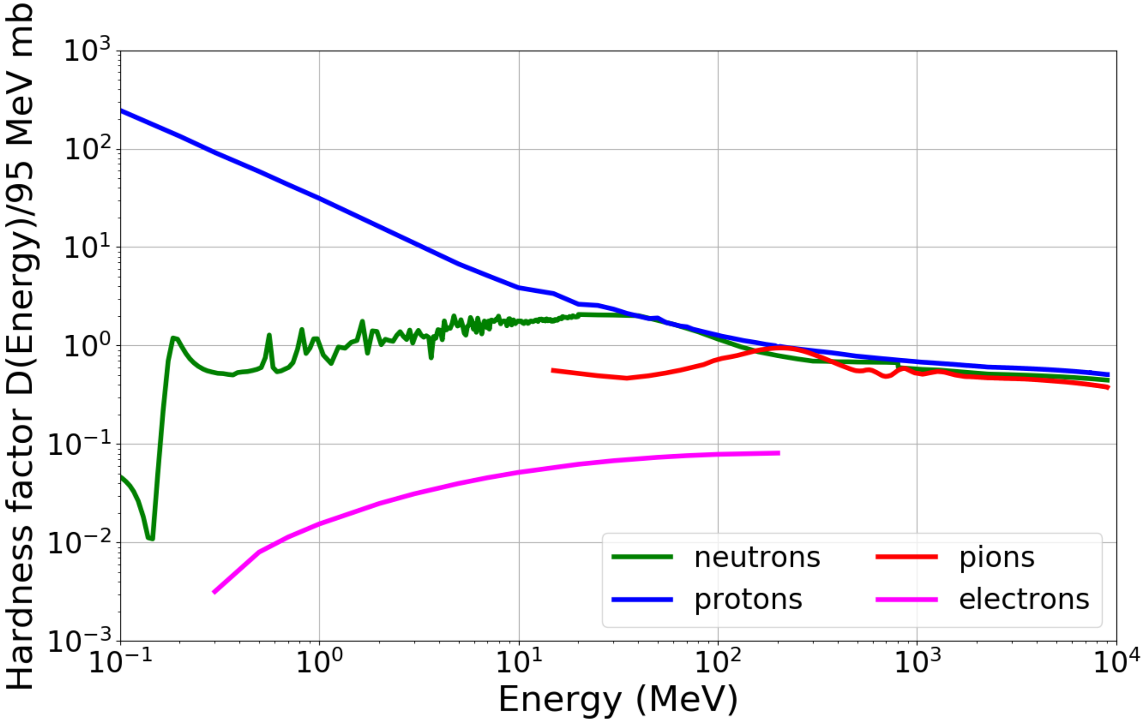




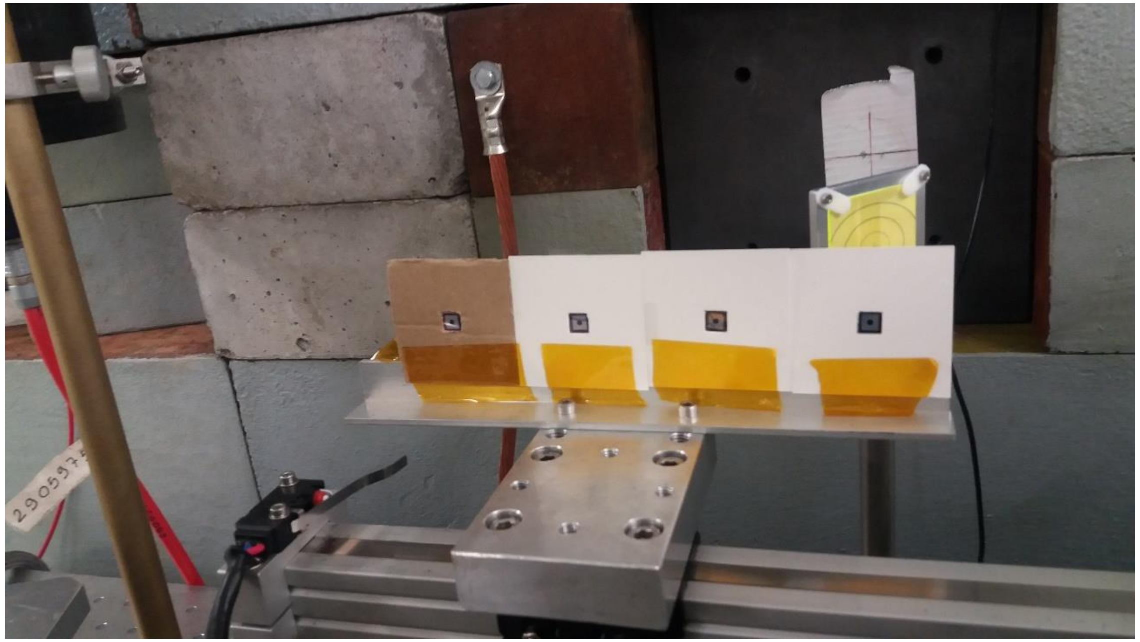


- Stuck bit is a **hard SEE** caused by a **single particle strike** (it is no longer possible to rewrite a different value to the bit); it can be **permanent or intermittent** (latter related to DD effects)
- Typically not many statistics until device fails due to TID (but no dose rate dependence)
- **Cross-sections similar to those of SEUs**
- Study complemented with experiments in medical LINAC

Displacement damage



Hardness Factor: $k = \frac{\alpha(e, 200\ MeV)}{\alpha(n, 1\ MeV)}$

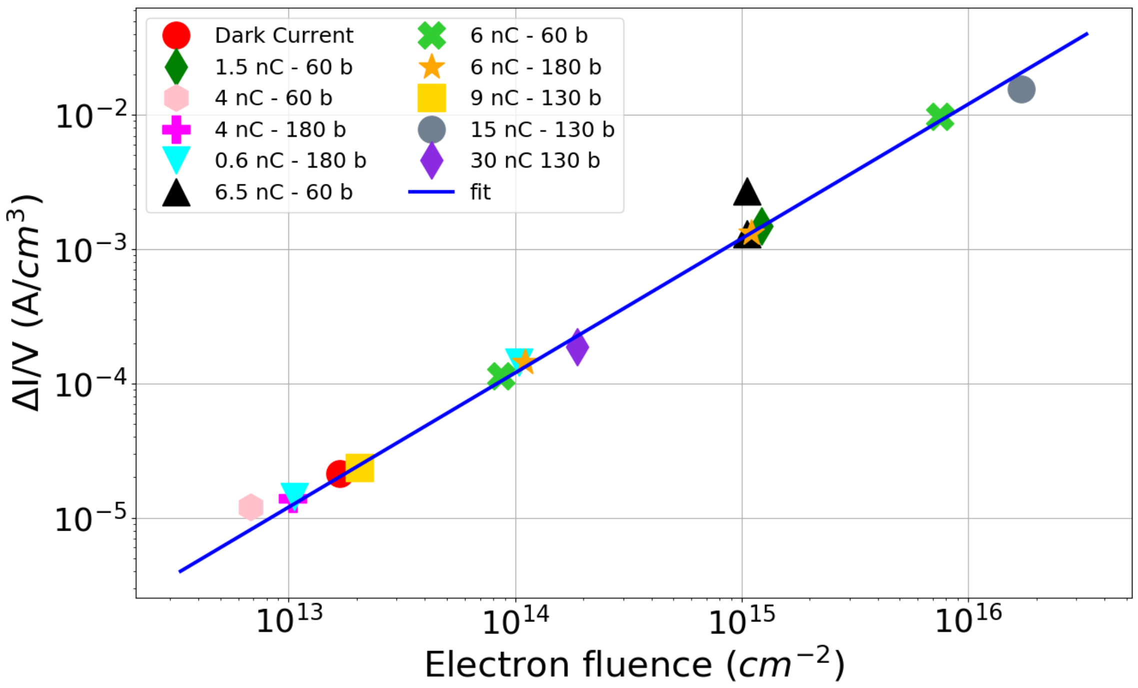


- Measurement of eletron hardness factor were made in the past. For **200 MeV electrons** it was determined to be **0.08**
- First study performed measuring **leakage current on EP diodes**

Displacement Damage

- CLEAR enables displacement damage testing:
  - It is possible to reach **fluences of 10^{16} e/cm^2 in half a day**.
- Similar levels with protons can be reached in IRRAD (long shutdown)
  - However, **proton irradiation activates** devices much more than electron irradiation

- Several diodes were irradiated in different beam conditions (**test linearity**)
- Measurements of **leakage current** and correlation with fluence
- Calibration done solely on **facility log data**
- Possible further (i) **TCT** and (ii) **TSC** measurements to determine (i) depleted voltage and (ii) defects concetration

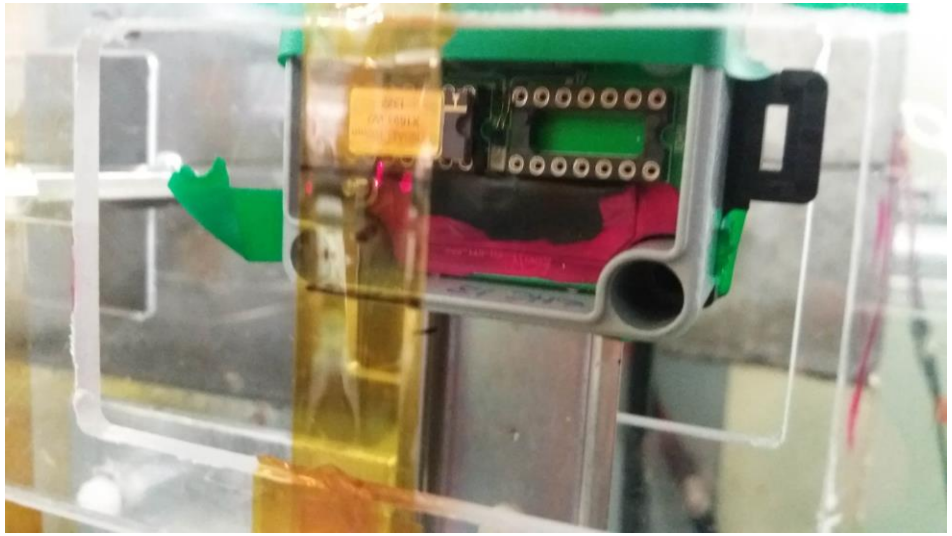


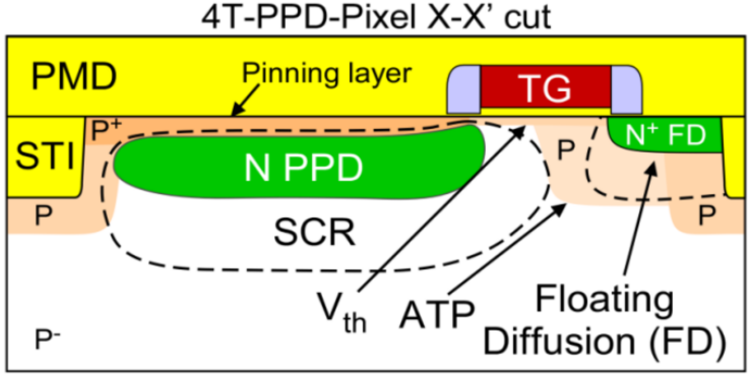
Main take-aways

Hardness factor of **0.038**

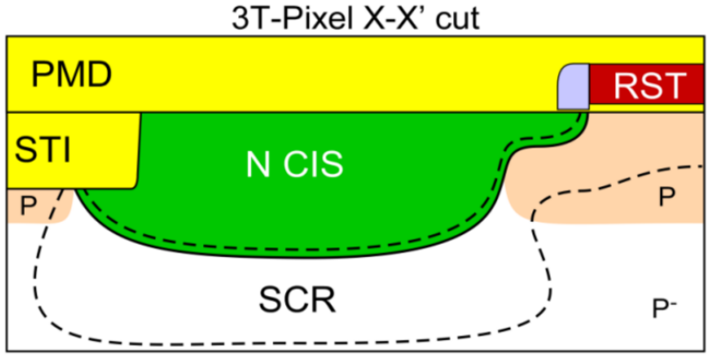
Linearity allows using these diodes for **cross-calibration purposes**

Displacement Damage (J. Kempf)





Pinned (buried) PhotoDiode (PPD)

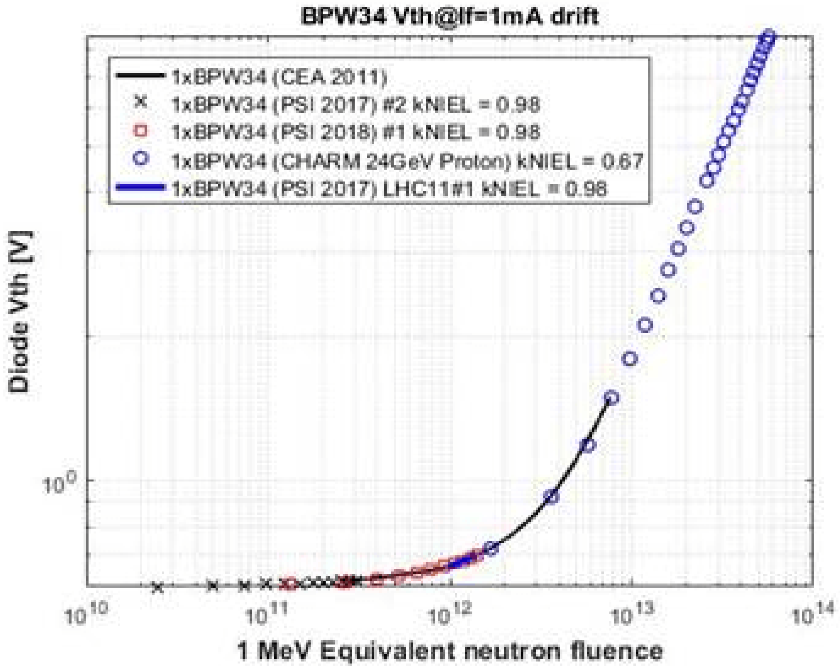


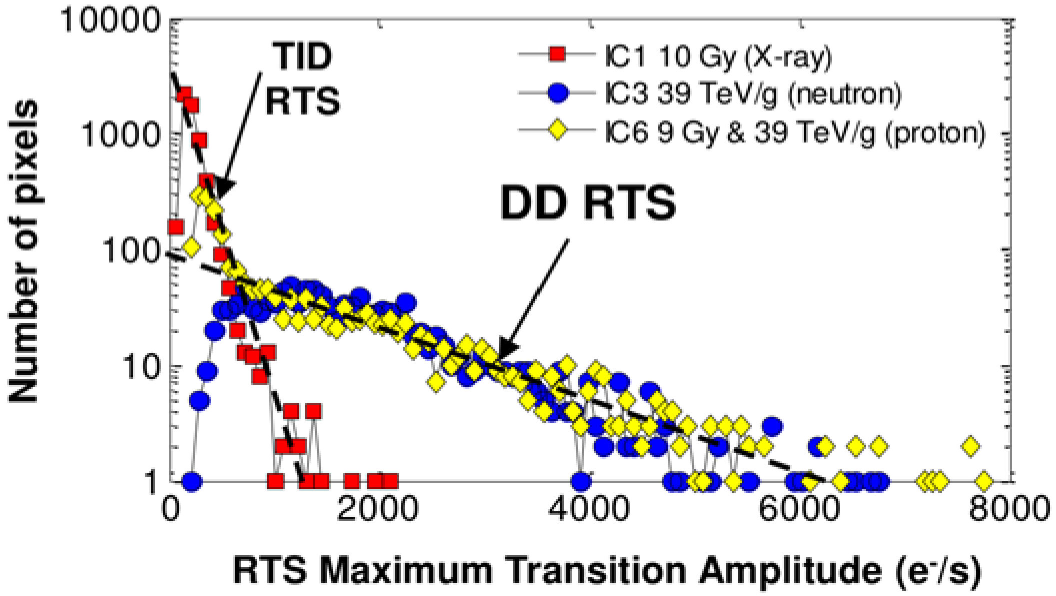
Conventional photodiode

Thorougher study of DD in electronics by means of additional devices:

- **RadMon diode**
- **CMOS Image sensors** from ISAE Supaero (also TID study for Jovian environment)

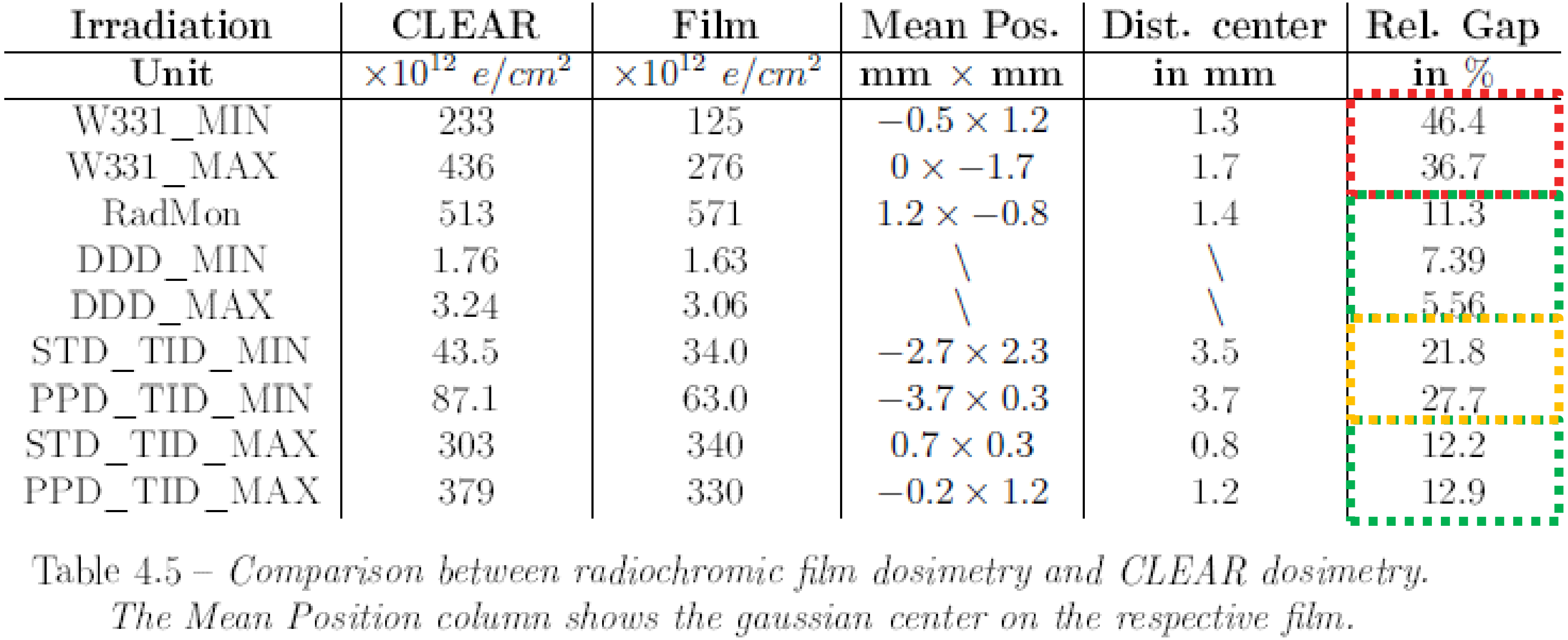
Displacement Damage (J. Kempf)





- RadMon is a **well calibrated** device in HEH environments used for radiation monitoring purposes at CERN
- **CMOS image sensors** effects:
  - Dark current
  - Random Telegraph Signal (RTS)

Displacement Damage (J. Kempf)

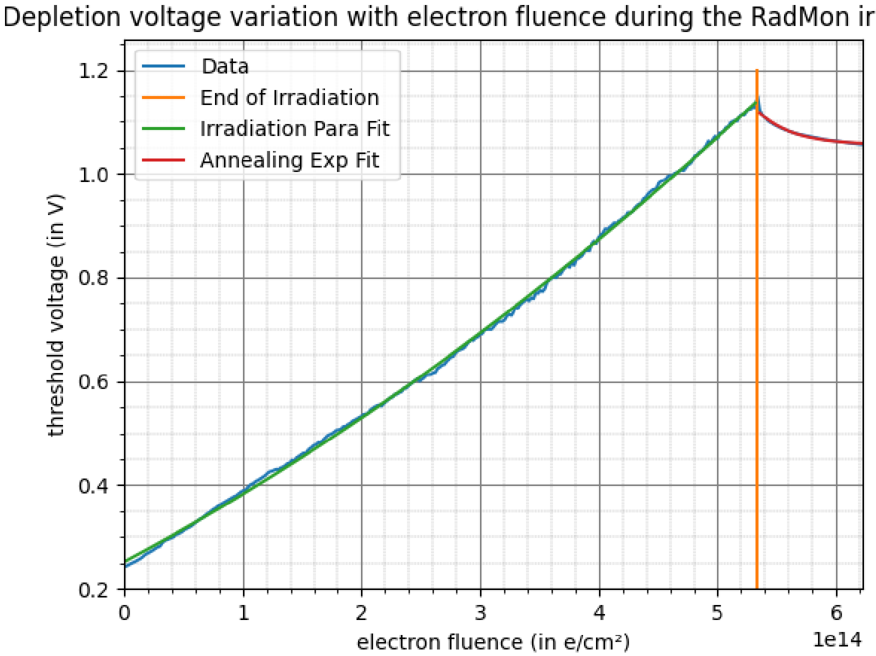


Irradiation	CLEAR	Film	Mean Pos.	Dist. center	Rel. Gap
Unit	$\times 10^{12}\ e/cm^2$	$\times 10^{12}\ e/cm^2$	mm × mm	in mm	in %
W331_MIN	233	125	-0.5×1.2	1.3	46.4
W331_MAX	436	276	0×-1.7	1.7	36.7
RadMon	513	571	1.2×-0.8	1.4	11.3
DDD_MIN	1.76	1.63	\	\	7.39
DDD_MAX	3.24	3.06	\	\	5.56
STD_TID_MIN	43.5	34.0	-2.7×2.3	3.5	21.8
PPD_TID_MIN	87.1	63.0	-3.7×0.3	3.7	27.7
STD_TID_MAX	303	340	0.7×0.3	0.8	12.2
PPD_TID_MAX	379	330	-0.2×1.2	1.2	12.9

Table 4.5 – *Comparison between radiochromic film dosimetry and CLEAR dosimetry. The Mean Position column shows the gaussian center on the respective film.*

- Very strong efforts on **dosimetry** (comparison of CLEAR facility logs wrt radiochromic film measurements)
- Mixed results (sources of discrepancy not always clear)
  - Typical **goal** would be to have difference of **±10%**

Displacement Damage (J. Kempf)


Depletion voltage variation with electron fluence during the RadMon irradiati

Irradiation	CLEAR Flu.	Film Flu.	DV	LC	LC Flu.
Unit	$\times 10^{12}\ e/cm^2$	$\times 10^{12}\ e/cm^2$	in V	in µA	$\times 10^{12}\ e/cm^2$
W331_MIN	233	125	\	1.35 ± 0.05	131 ± 5
W331_MAX	436	276	200	2.55 ± 0.03	247 ± 3

Table 5.1 – *Results for W331 irradiations. The diode volume is 0.075* cm^{-3} *and the damage factor for this technology is* $\alpha = 1.38 \times 10^{-18} A/(e \cdot cm)$

No data yet on CMOS Image Sensors

- RadMon only **live measurement** of damage (threshold voltage variation)
- Hardness factor for RadMon is **0.034** (good agreement with previous measurements on diodes)
- EP diodes used for cross-calibration have **better agreement with film measurements**
- Plenty of data yet to analyze (Defect spectroscopy, CMOS image sensor dark current and RTS)

Electrons-on-dump (G. Lerner)

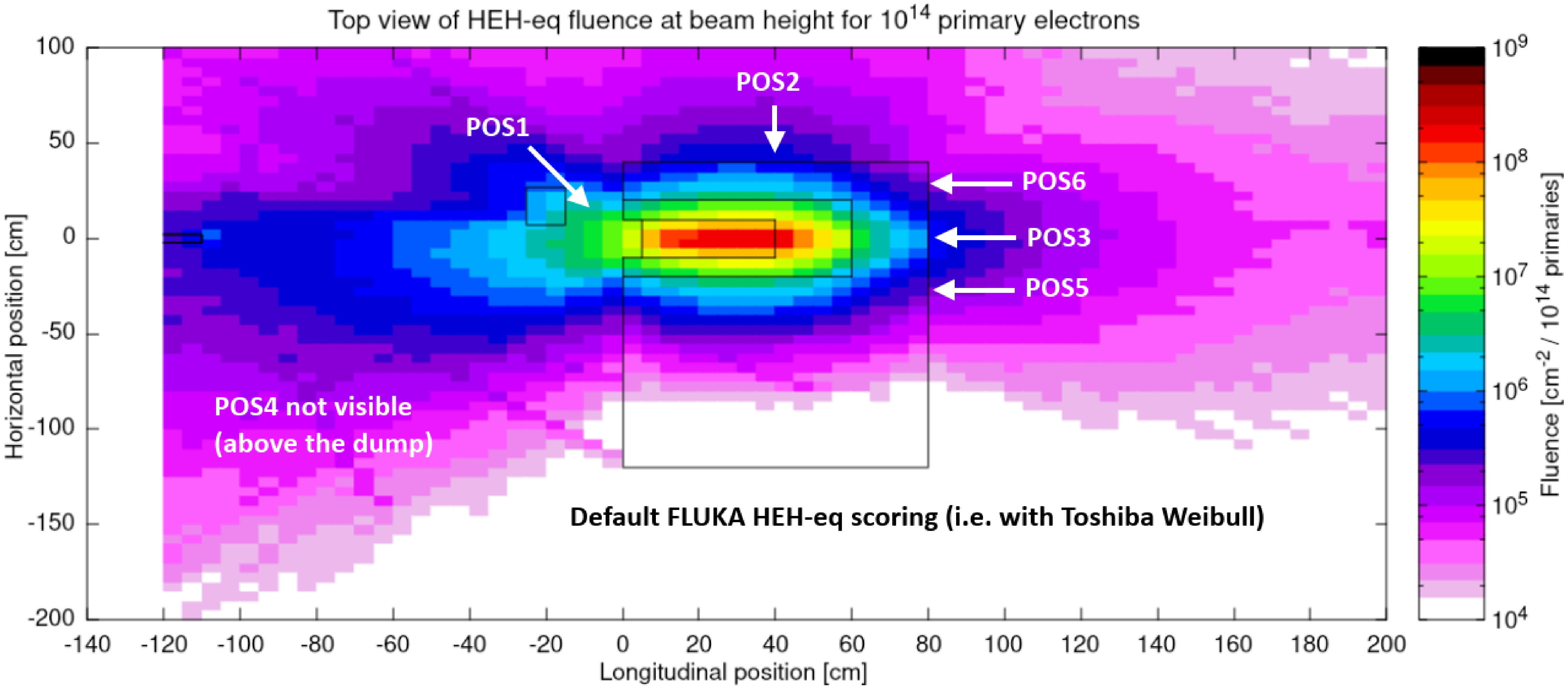
The experiment

- Determination of the radiative field generated by the **interaction of a high-intensity electron beam with the dump**.
- Characterization done by **measuring SEUs in SRAMs** placed all around the dump
- Accomplished by directing high-intensity, small beams **directly on the dump** without material in the beamline
- Effect of thermal neutron studied thanks to B_4C shielding
- Comparison with **FLUKA simulations** thanks to the detailed description of the dump

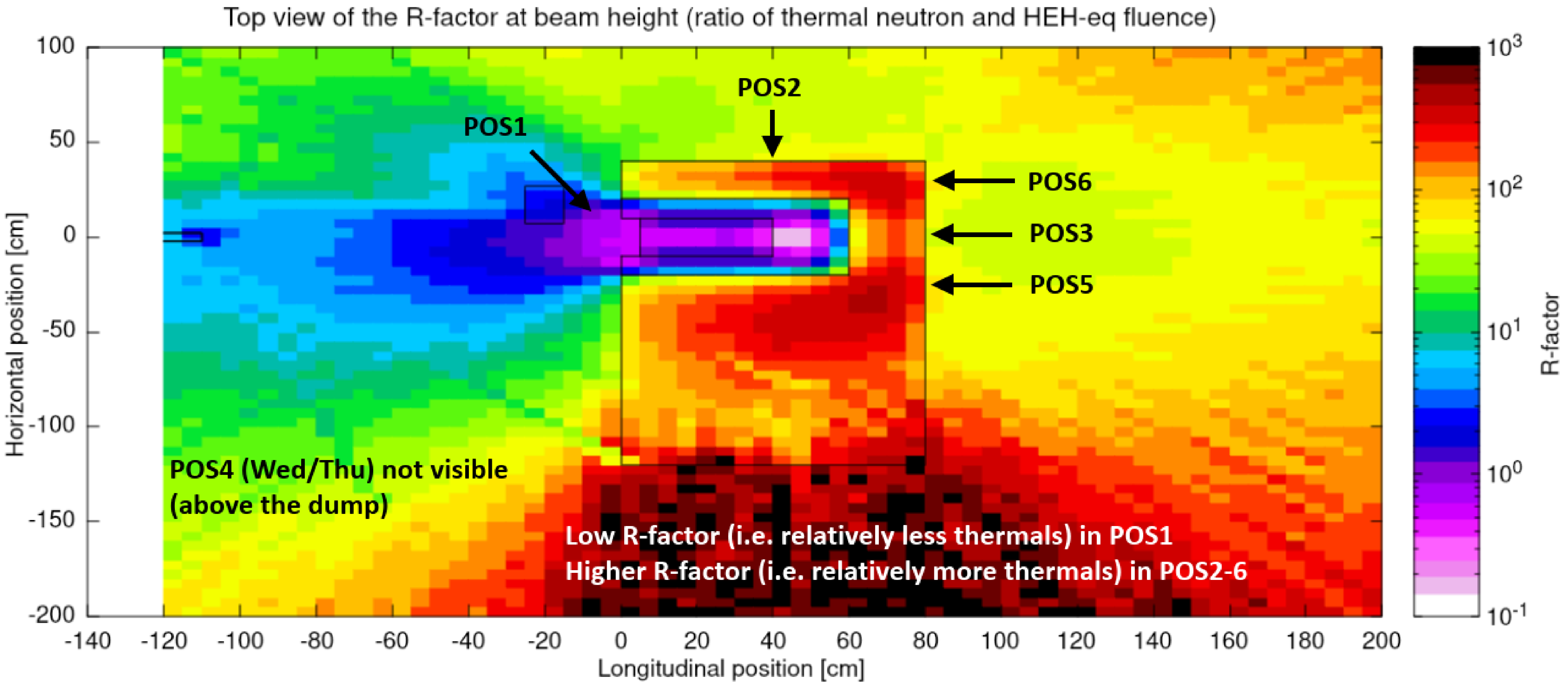
Scope

- Determining **influence** of the dump **neutrons and photons** on in-beam **electron SEU** measurements
- **In-house source** of thermal and intermediate energy neutrons for testing (higher fluxes than Am-Be)
- Evaluation of possible R2E effects for equipment around dump

Electrons-on-dump (G. Lerner)



Electrons-on-dump (G. Lerner)

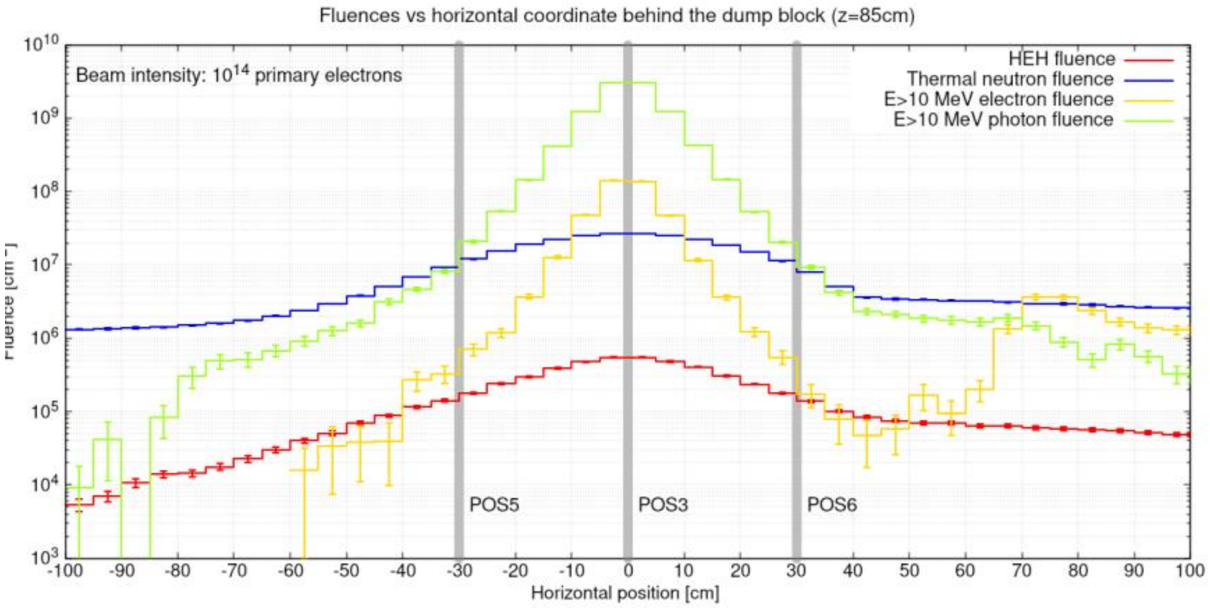


POS4 (Wed/Thu) not visible (above the dump)

Low R-factor (i.e. relatively less thermals) in POS1
Higher R-factor (i.e. relatively more thermals) in POS2-6

Electrons-on-dump (G. Lerner)

- Thanks to radiative field predictions from FLUKA one can **predict the number of SEUs in the SRAM** because the thermal, intermediate and high-energy neutron experimental cross-sections are known
- Photon cross-sections, however, are **not known**, but photon fluxes are very high



Main take-aways

- Dump front-side: relatively **high** and not so stable **SEU rate** (low thermal neutron contribution) and strong dependency with the material in the beam
- Dump top-side: **lower** and more stable **SEU rate** (more contribution from **thermal neutrons**)
- Dump back-side in the center: relatively **high** and stable **SEU rate, possible contribution of photons** (considering FLUKA predictions on neutron response)
- Dump back-side off-centered: similar to top-side.

Publications

- M. Tali et al., "High-Energy Electron-Induced SEUs and Jovian Environment Impact," in IEEE Transactions on Nuclear Science, vol. 64, no. 8, pp. 2016-2022, Aug. 2017.
- M. Tali et al., "Mechanisms of Electron-Induced Single-Event Upsets in Medical and Experimental Linacs," in IEEE Transactions on Nuclear Science, vol. 65, no. 8, pp. 1715-1723, Aug. 2018.
- M. Tali et al., "Mechanisms of Electron-Induced Single-Event Latchup," in IEEE Transactions on Nuclear Science, vol. 66, no. 1, pp. 437-443, Jan. 2019.
- M. Tali, " Single-Event Radiation Effects in Hardened and State-of-the-art Components for Space
- and High-Energy Accelerator Applications”, PhD Thesis, University of Jyväskylä, Finland, 2019.
- A. Coronetti et al., “SEU Characterization of Commercial and Custom-designed SRAMs manufactured in 90 nm technology and below”, in IEEE Radiation Effects Data Workshop, Santa Fe, NM, USA, 2020.
- D. Söderström et al., “Electron-induced Single Event Upsets and Stuck Bits in SDRAMs in the Jovian Environment”, accepted for publication in IEEE Transactions on Nuclear Science, 2021.
- D. Poppinga et al., “VHEE beam dosimetry at CERN Linear Electron Accelerator for Research under ultra-high dose rate conditions”, Biomedical Physics Express, vol. 7, no. 1, 2021.

And more are coming...

Conclusions

- CLEAR has been central to R2E activities over the last 5 years
  - It enabled studying key radiation effects that it was not possible to study elsewhere
    - HEE SEU, SEL, stuck bits
  - It enabled studying displacement damage effects in a short time and with low level of activation
    - Determination of hardness factor
    - Defect spectroscopy
    - Appliactions to CMOS image sensors
  - New uses derived from electron-on-dump measurements

- Dosimetry remains challenging
  - Film calibrations could help

- Several collaborations with academic and industrial partners
  - Slowed-down by contingent pandemic situation

Outlook

- Electronics testing/qualification
  - Displacement damage
    - Most of the R&D completed
    - Synergistic TID effects on top of DD to be investigated (one drawback with respect to proton irradiation is the larger TID for same DD)
  - Mixed-field generated from electrons-on-dump:
    - Part of the R&D completed
    - Further measurements with more sensitive devices (to measure energy deposition) are foreseen to determine HEHeq flux and thermal neutron flux

- Radiation effects R&D
  - Effects of pulsed electron/photon beams on electronics can be achieved at CLEAR
    - FCC-ee R&D

Thank you for your attention!

CERN SY STI R2E RADSAGA