Use of very intense focused pulsed synchrotron X-rays as a proxy for heavy-ions to test the radiation hardness of complex electronic components

The European Synchrotron

Ennio Capria
Deputy Head of Business Development at the ESRF
Experiment Division

Platform for Advanced Characterisation | PAC-G

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- Effect of ionising radiation on electronic devices.
- The example of aerospace.
- The use of EBS-ESRF to support the R&D of radiation hard electronics -> emulation of heavy ions using pulsed X-rays

- Effect of ionising radiation on electronic devices.
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Interaction of ionising radiations with electronic circuits

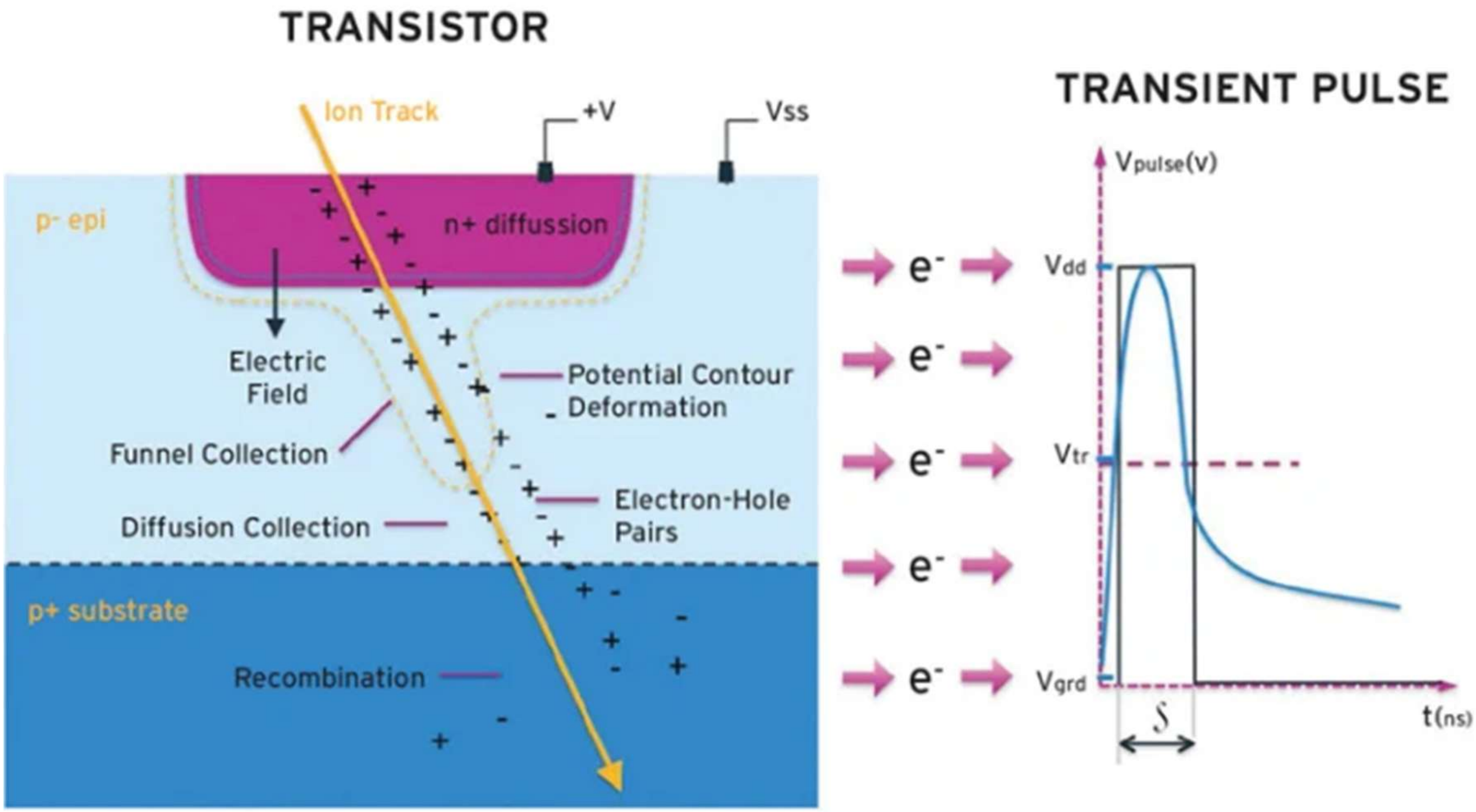
Radiation effects on electronics can be divided in two main categories

- *Single Event Effects* (SEEs): includes all the macroscopically observable effects induced by a single highly energetic particle that deposits enough energy (critical energy) in a sensitive volume (critical volume) of the device to trigger an event.

Being this mechanism stochastic, SEEs are not easily predictable and mitigation techniques must be employed in harsh environments to avoid failures. Single Event Effects include a large variety of radiation damages, which can be further divided into destructive (hard) or non-destructive (soft) events.

Non-destructive: Switching of logic states, which can be restored to its initial value by rewriting the bit: this type of non-destructive events are called Single Event Upset (SEUs).

Destructive: a highly-ionizing particle might activate parasitic structures that trigger latch-up in CMOS devices. This event can be destructive and is named Single Event Latch-up (SEL).


TRANSISTOR
Ion Track
+V
Vss
p- epi
n+ diffusion
Electric
Field
Potential Contour
Deformation
Funnel Collection
Diffusion Collection
Electron-Hole
Pairs
p+ substrate
Recombination
e⁻
TRANSIENT PULSE
Vpulse(v)
Vdd
Vtr
Vgrd
t(ns)

Interaction of ionising radiations with electronic circuits

Radiation effects on electronics can be divided in two main categories

- *cumulative effects* : includes all the effects resulting from the sum of microeffects due to each single penetrating particle; they can be defined as macroscopically, observable variations in the characteristics of an electronic circuit or component due to the gradual degradation of some electronic parameters.

Interaction of cosmic radiations with electronic circuits

TID (Total Cumulated Dose) on CMOS type structures, four major physical processes can be distinguished as follows:

- Holes transport;
- Charge trapping;
- Radiation-induced interface traps build up.

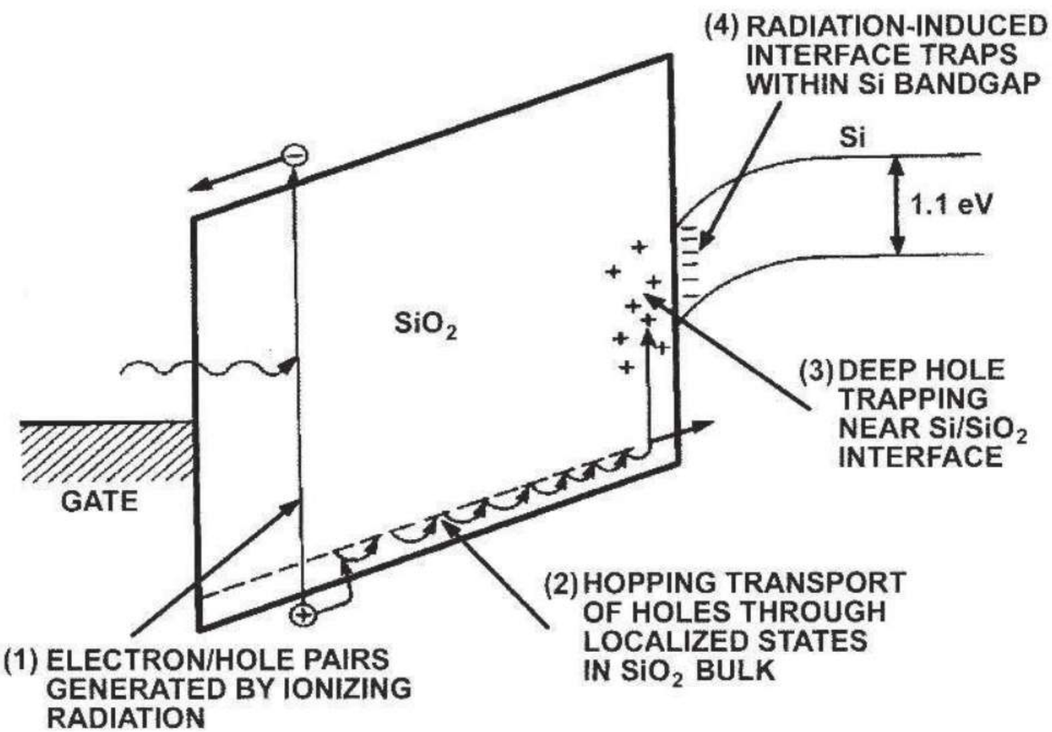


Figure 7. Main processes due to ionizing dose in the MOS insulator layer. (Source: [19])

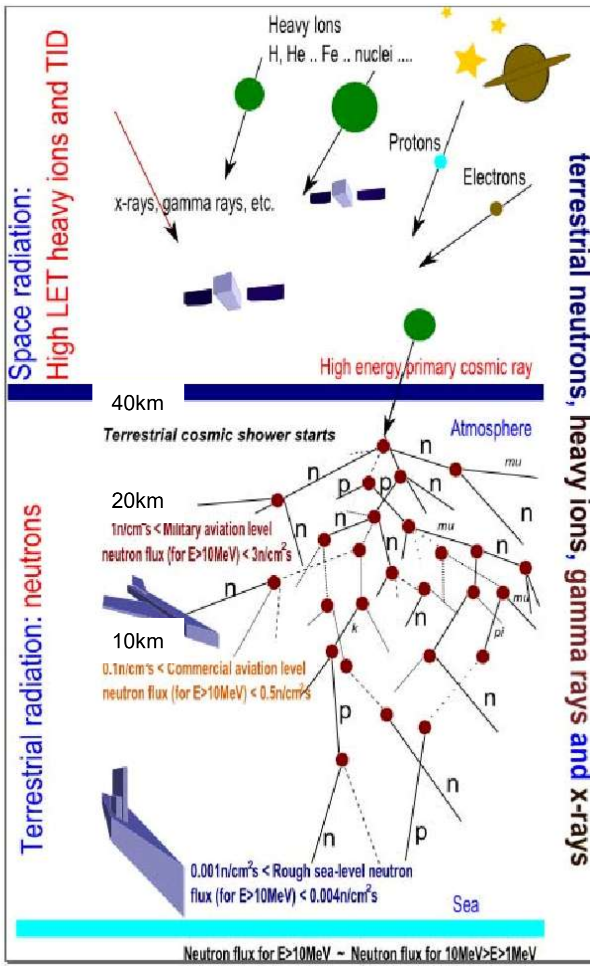
Interaction of cosmic radiations with electronic circuits

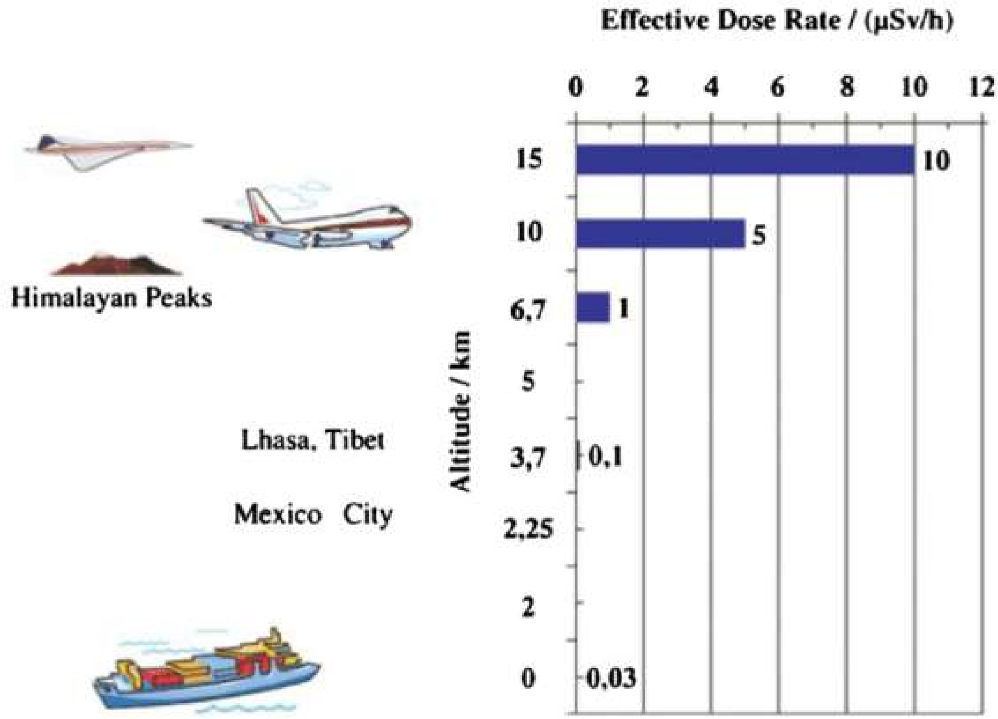
- several parameters are affected by ionizing radiation (e.g. transconductance, noise, channel leakage)
- the shift of the threshold voltage (shortly *ΔVth*) is the observed parameter which allows the conversion of absorbed dose into an easily measurable quantity. It is mirrored on the *Vgs* when the transistor works in saturation and the drain current is constant.
- The change in the *Vth* is the result of the cumulation of charge within the insulator layer of the metaloxide-semiconductor sandwich, i.e. the silicon dioxide *SiO2* and at the border between the insulator and the semiconductor edge, i.e. *Si/ SiO2* interface.

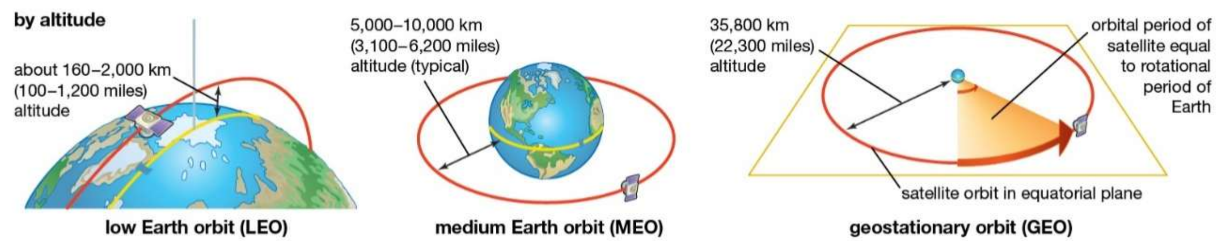
- Effect of ionising radiation on electronic devices.
- The example of aerospace.
- The use of EBS to support the R&D of radiation hard electronics -> emulation of heavy ions using pulsed X-rays

Cosmic radiation distribution

The natural radiation environment on Earth is for the 13% due to cosmic rays, but the situation is getting much higher increasing the altitude.







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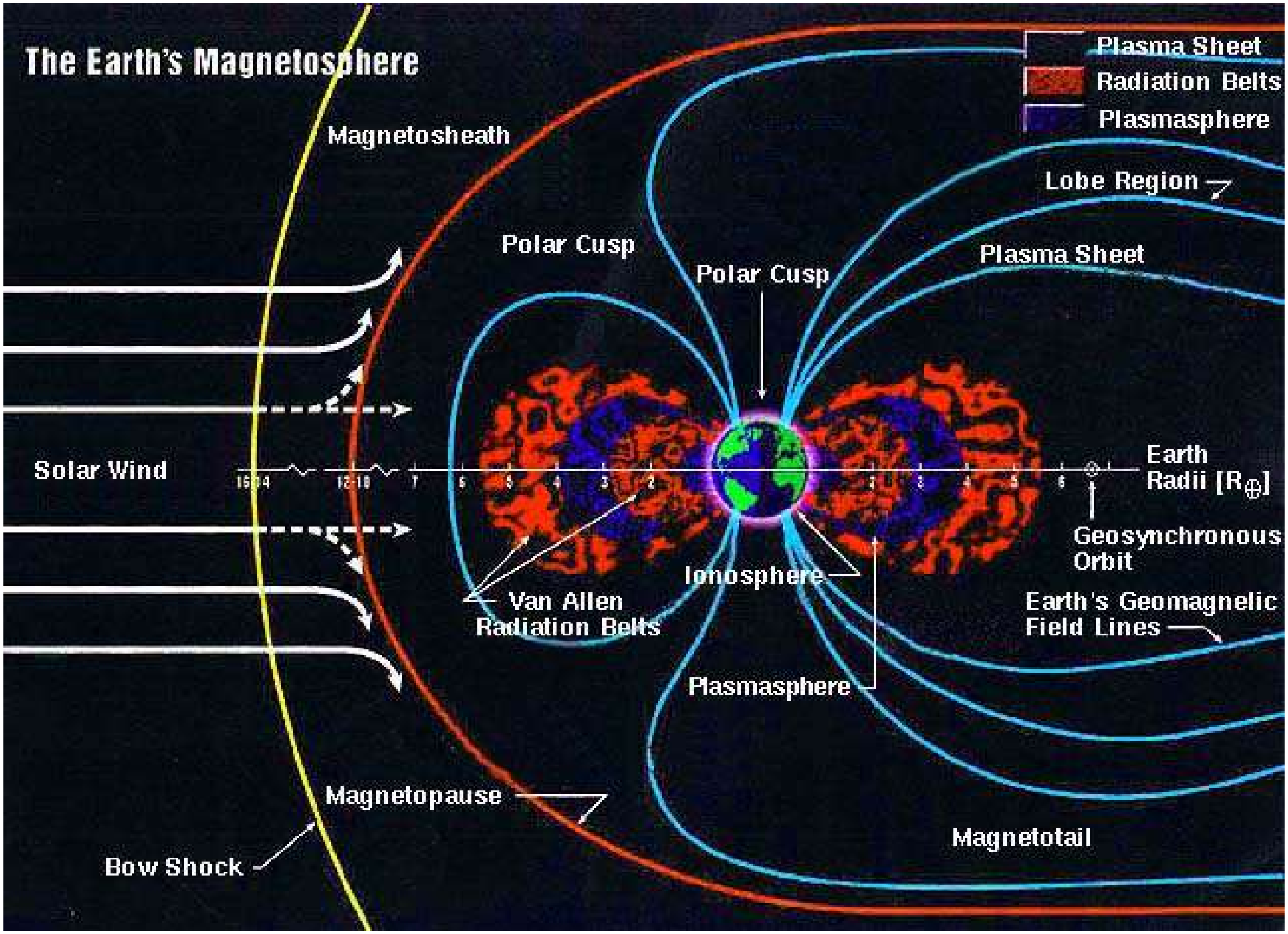
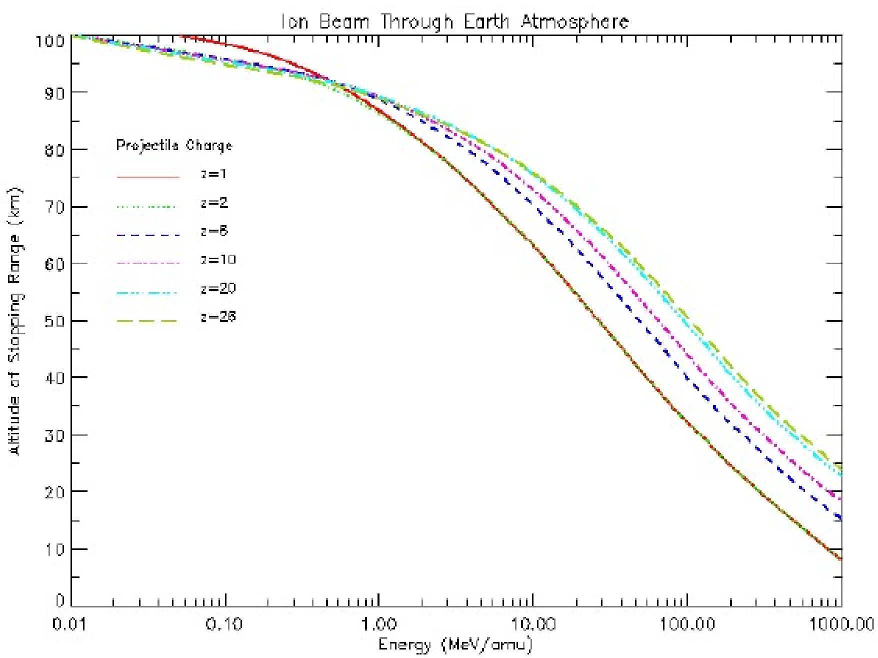
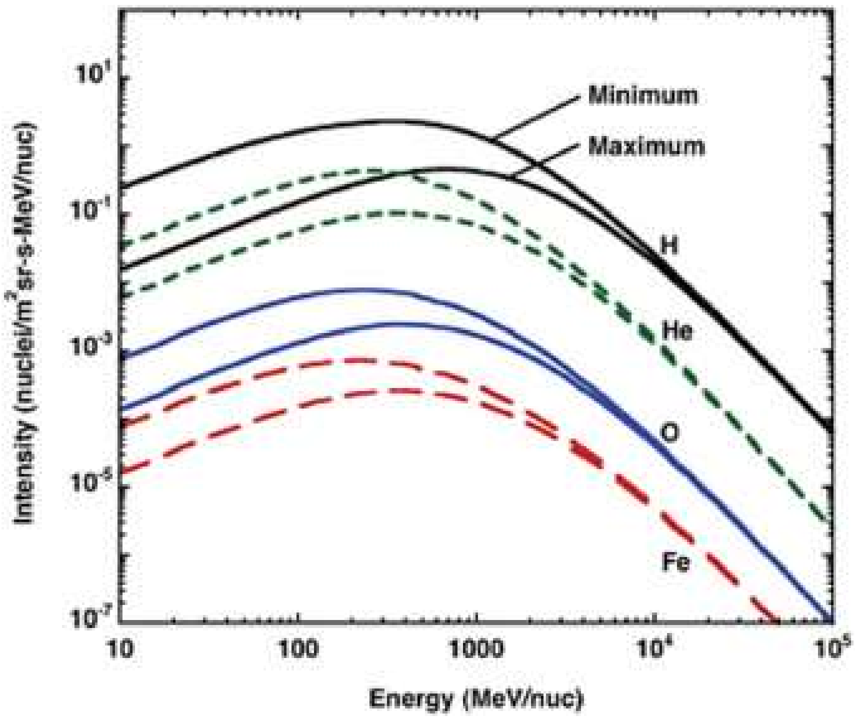
Cosmic radiation distribution



Earth radius = 6371 km

Cosmic radiation: the heavy ions distribution





- Heavy ions at high energy (above 1GeV/amu) are part of the cosmic radiation
- These ions mainly affect space applications, but also aeronautic applications can be affected and more recently ground applications.

Radiation hardness testing: How do we measure it?

Table 4: Heavy Ions facilities

Name	Location	Main characteristics	Domain	Availability	Availability	Cost	Accessibility	Constraints
UCL	Louvain (Belgium)	LET : 1.3 -> 62.5 MeV.cm²/mg Range: 73.1 -> 269.3 µm Si	Space	Mid-Feb to mid-July / End of August to mid-December	Set period : Availabilties every 2-3 weeks	750€ / h	30 km from Brussel airport	
KVI	Groningen (Netherlands)	-> 69.3 MeV.cm²/mg	Space	All-year round	Beam time available on request	750€ / h		
RADEF	Jyväskylä (Finland)	LET : 1.83 -> 60.0 MeV.cm²/mg Range: 202 -> 89 µm Si	Space	All-year round	Beam time available on request	750€ / h	25 km from Jyväskyla airport	
GANIL	Caen (France)	-> Pb208 : 98.5 MeV.cm²/mg ; Range 258µm -> Xe136 : 26.4 MeV.cm²/mg ; Range 716µm	Space	Very few availabilty - 2 or 3 slots / year	Set period : Availabilties every 4-6 months	985€ / h	10km from Caen-Carpiquet airport	
GSI	Darmstadt (Germany)	(up to 1GeV/n) LET : 5.8 -> 59.6 MeV.cm²/mg	Space				30 km from Francfort airport	Restricted access to research project
CNA	Seville (Spain)	-> 20 MeV.cm²/mg		few availabilty				
INFN	Legnaro (Italy)	LET : 0.02 -> 81.7 MeV.cm²/mg Range: 23.4 -> 4390 µm Si	Space				45km from airport	
LNS	Catania (Italy)	Energy 0.1 -> 80 MeV/n	Space					
IPN	Orsay (France)	LET : -> 40 MeV.cm²/mg	Space					Range is not sufficient
ILL	Grenoble (France)	LET 0 -> 50 MeV.cm²/mg Range : -> 20 µm Si	Space					

- Various sources of heavy ions around the world, with normalized tests
- HI Energies range is lower than what is requested in space

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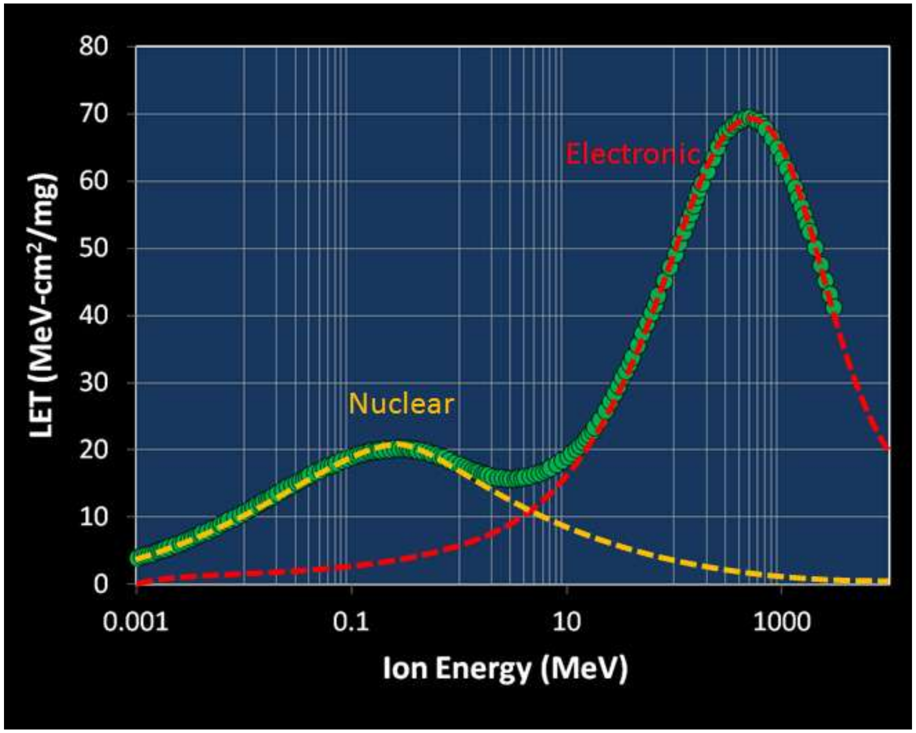
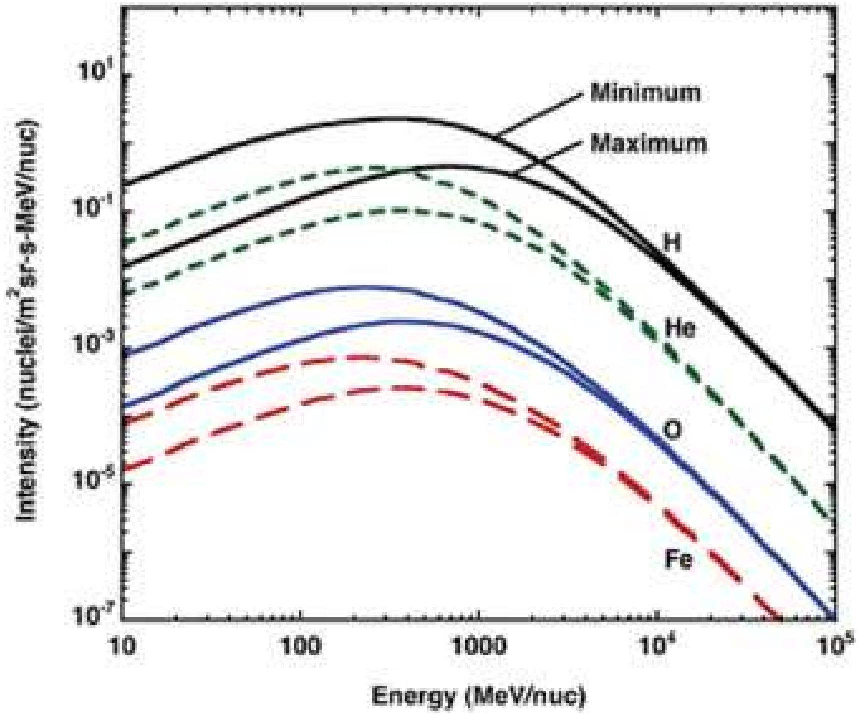
Radiation hardness testing: How do we measure it?





- Low energy HI can emulate High energy ones

Should we really care about this?

Not / Maybe / Yes

Should we really care about this?

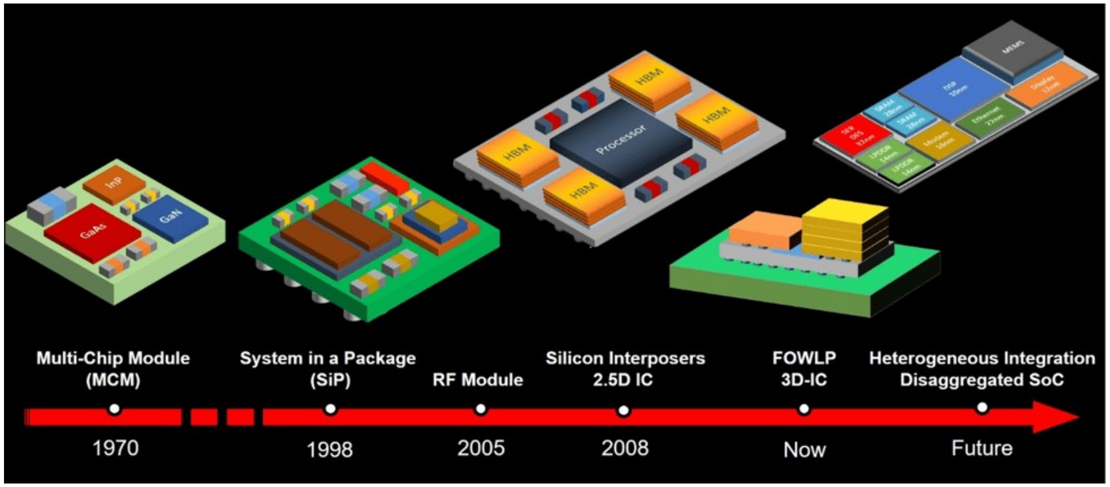
Yes

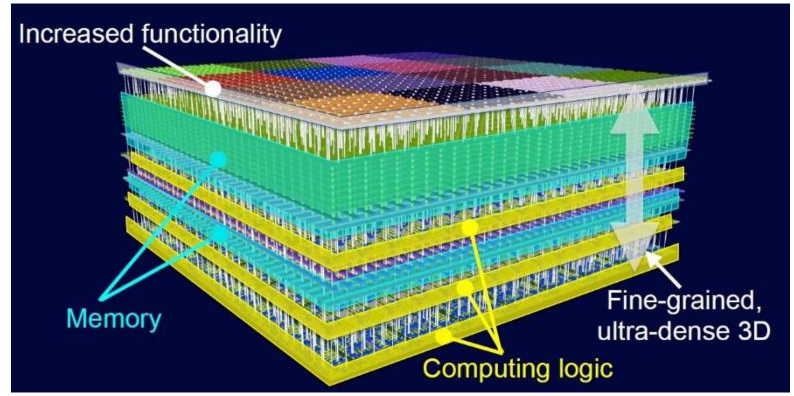
The race for space

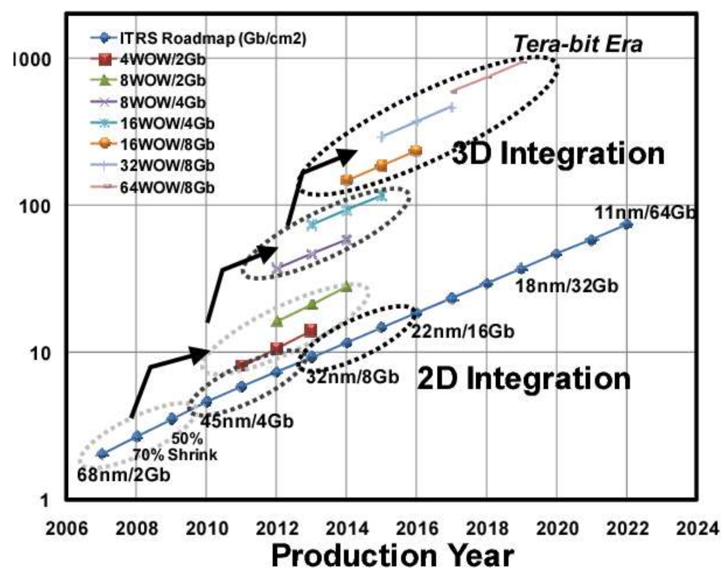
Since the race for space begun:

- Decrease of a factor of 10x of the price for launching
- Satellite as a "commodity"
- Use of COTS (components on the shelf) is becoming a EU priority (ESA)
  - Needs for screening and debugging
- De-risking activity even more strategic
  - because modern circuits are even more sensitive (smaller node)
  - Because future packaging will become inherently more complex

Trends in microelectronics: 3DIC







Critical energy

Node (CMOS / FinFET)	Vdd (typ.)	Qcrit (very approx.)	Vcrit lateral size (x–y)	Vcrit depth (z)	Vcrit volume (order)	Notes
250 nm	2.5–3.3 V	100–300 fC	~2–3 µm × 2–3 µm	~2–3 µm	~10–30 µm³	Early SRAM/logic, large nodes
180 nm	1.8–2.5 V	50–150 fC	~1.5–2 µm × 1.5–2 µm	~1.5–2 µm	~5–10 µm³	Still robust to SEE
130 nm	1.2–1.5 V	20–80 fC	~1–1.5 µm × 1–1.5 µm	~1–1.5 µm	~1–3 µm³	Sensitive to heavy ions
90 nm	~1.0–1.2 V	10–40 fC	~0.5–1 µm × 0.5–1 µm	~0.8–1 µm	~0.2–1 µm³	Beginning of soft error concerns
65 nm	~1.0–1.2 V	5–20 fC	~0.2–0.5 µm × 0.2–0.5 µm	~0.5–0.8 µm	~0.02–0.1 µm³	SEU cross-sections large
45 nm	~0.9–1.0 V	2–10 fC	~0.15–0.3 µm × 0.15–0.3 µm	~0.3–0.6 µm	~0.01–0.03 µm³	Charge collection volumes shrink
28 nm (bulk/FDSOI)	~0.9–1.0 V	0.5–5 fC	~0.05–0.2 µm × 0.05–0.2 µm	~0.2–0.4 µm	~10⁻³–10⁻² µm³	Extremely sensitive
16/14 nm FinFET	0.7–0.9 V	0.2–2 fC	lateral ~ fin width × fin pitch ≈ (10–20 nm) × (50–100 nm)	effective depth ~ fin height + depletion (~50–100 nm)	~10⁻⁴–10⁻³ µm³	FinFETs reduce collection area
7 nm FinFET	0.65–0.75 V	0.05–0.5 fC	~few × 10 nm laterally	~50–80 nm	~10⁻⁵–10⁻⁴ µm³	Approaching “few-electron” regime

The race for space

In technical terms:

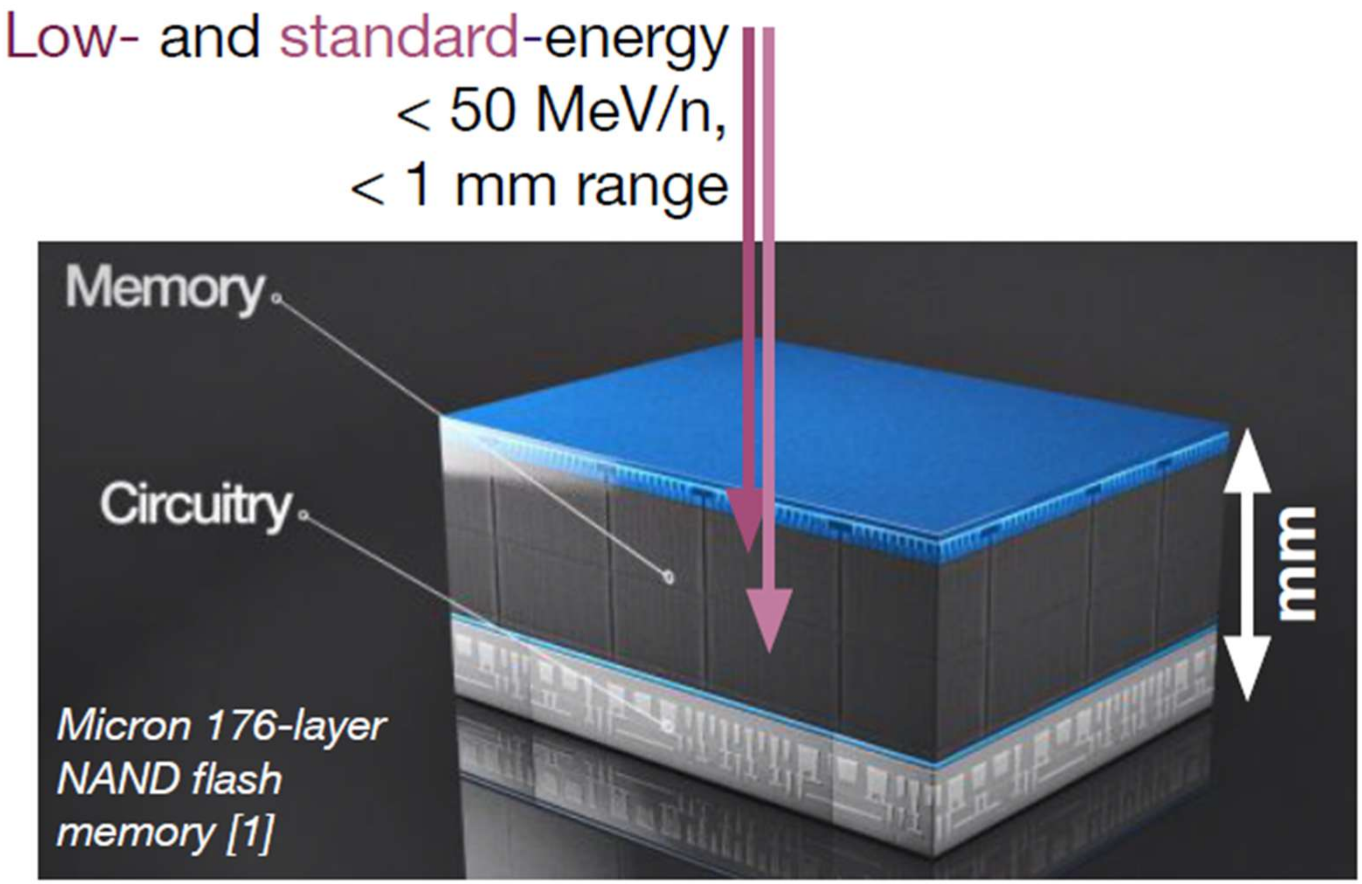
- Need for implementation of the following:

  - Focused sources for mapping excercises
  - Laboratory systems to increase accessibility and flexibility

- For complex electronic device packagings

  - Need to simplify the sample preparation
  - Penetration depth

Trends in microelectronics: 3DIC



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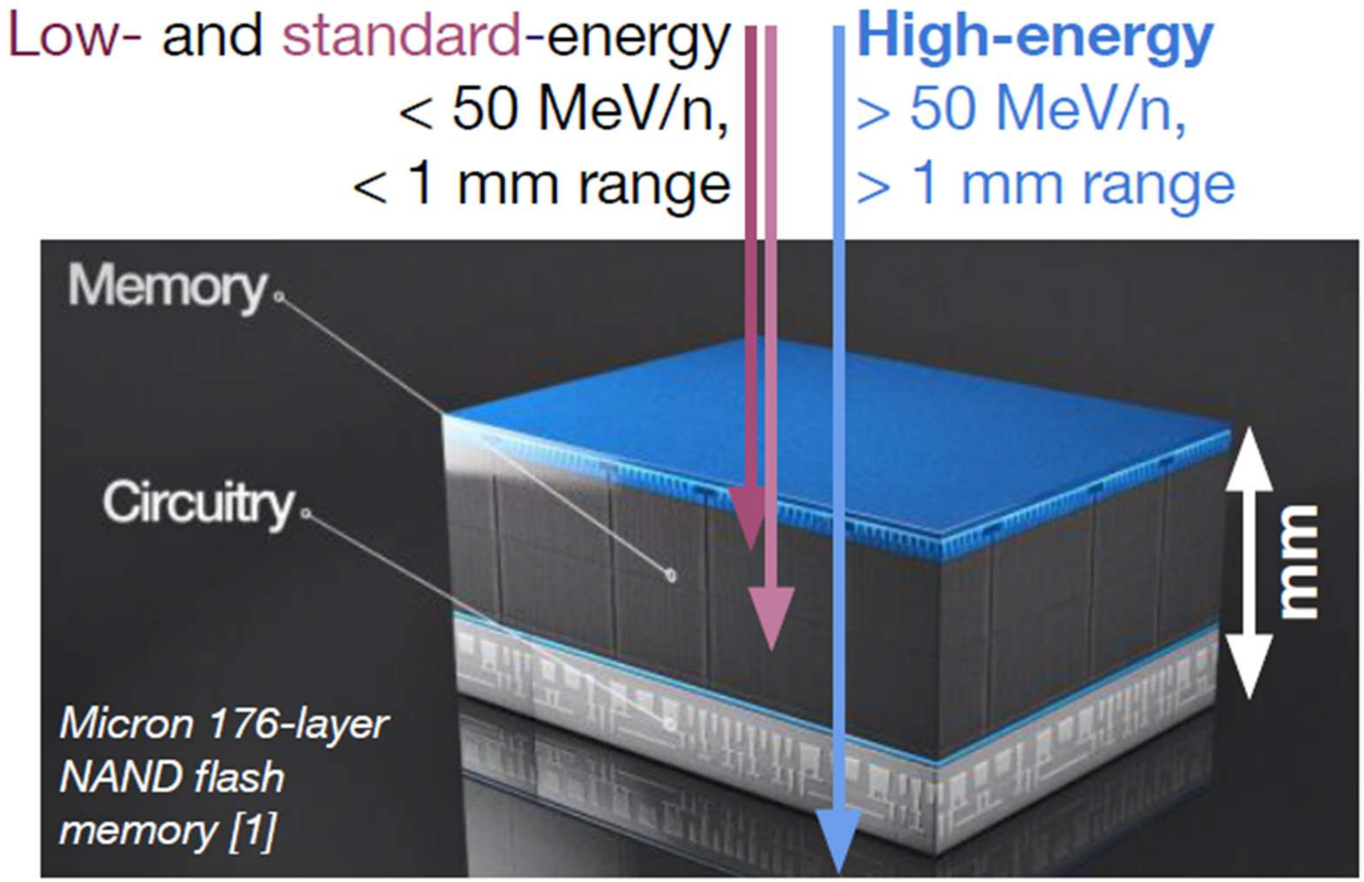
Trends in microelectronics: 3DIC



* Value estimated based on COTS space applications market growth and projected demand in US [2]

Credits Andreas Waets and HEARTS project

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Can photons emulate Heavy Ions?

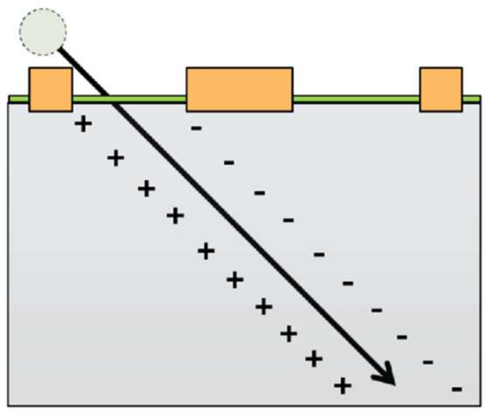
Can photons emulate Heavy Ions?

Yes

Photons vs HI

In both cases the result is the generation of a Ionisation track -> generation of unbound electrons

HI: Coulombian interaction



Photon: Photoelectric absorption

$$n_c = N_{abs} \cdot \frac{E_\gamma}{\Delta E}$$

- E_γ → **Photon energy**
- ΔE → **Carrier creation energy (~ 3-5 eV)**

Source: D. Cardoza, et. al. "single Event Effects Testing with Short Pulsed X-rays" presentation 9.April.2013

In order to obtain a preliminary evaluation of components single events sensitivity, before Heavy Ion qualification, the focused Laser is an alternative which tends to be generalized.

Heavy ions emulation with lasers

- Larger capacity, instrument availability -> qualification
- Possibility to have focused beams -> debugging
- Higher energy -> Simplified sample preparation

  -> Complex packaging, penetration dept

Addressed by lasers

Non addressed by lasers

Heavy ions emulation with X-rays

- Larger capacity, instrument availability -> qualification
- Possibility to have focused beams -> debugging
- Higher energy -> Simplified sample preparation

  -> Complex packaging, penetration dept

Which should be the characteristics of the X-ray beam?

Which should be the characteristics of the X-ray beam?

- Pulse energy? (at a given photon energy)
- Pulse duration?
- Photon energy?
- Beam diameter?

Which should be the characteristics of the X-ray beam?

- Pulse energy? (at a given photon energy)
- Pulse duration?
- Photon energy?
- Beam diameter?

X-Ray pulse to emulate His: carrier generation

Energy_keV	Attenuation length (mm)	Electrons/photon	LET/electron (keV/um)	N.photons LET=1	N.photons LET=30	N.photons LET=60
1	2.73E-03	278	3.66E-01	6.37E+02	1.91E+04	3.82E+04
2	1.55E-03	556	1.29E+00	1.80E+02	5.40E+03	1.08E+04
5	1.75E-02	1389	2.85E-01	8.16E+02	2.45E+04	4.90E+04
10	1.27E-01	2778	7.90E-02	2.95E+03	8.85E+04	1.77E+05
15	4.15E-01	4167	3.61E-02	6.45E+03	1.93E+05	3.87E+05
18	7.07E-01	5000	2.55E-02	9.15E+03	2.74E+05	5.49E+05
20	9.61E-01	5556	2.08E-02	1.12E+04	3.36E+05	6.72E+05
25	1.79E+00	6944	1.39E-02	1.67E+04	5.02E+05	1.00E+06
30	2.99E+00	8333	1.00E-02	2.32E+04	6.96E+05	1.39E+06
50	9.79E+00	13889	5.11E-03	4.56E+04	1.37E+06	2.74E+06
100	2.34E+01	27778	4.28E-03	5.45E+04	1.63E+06	3.27E+06

Photon Energy up -> Attenuation length up
Photon Energy up -> E/photon up
Photon Energy up -> LET/electron down -> more photons for same LET

Correlation: ion energy -> photon energy
ion Z -> pulse energy energy
Pulse energy linearly dependent from photon energy

LET 1 to 60 -> photons/pulse -> 6E2 to 3.27E6 -> the value depend from the top layer
E=500MeV/n -> photon energy -> 100keV

X-Ray pulse to emulate His: carrier generation

X-ray what is available today on ID09 @ ESRF

4E9 ph/pulse@18keV

100ps < commuting time

Diam 25um

Penetration depth 700um

5000 electrons/photon

2E13 electrons/pulse

2.85E10 electrons/pulse/um

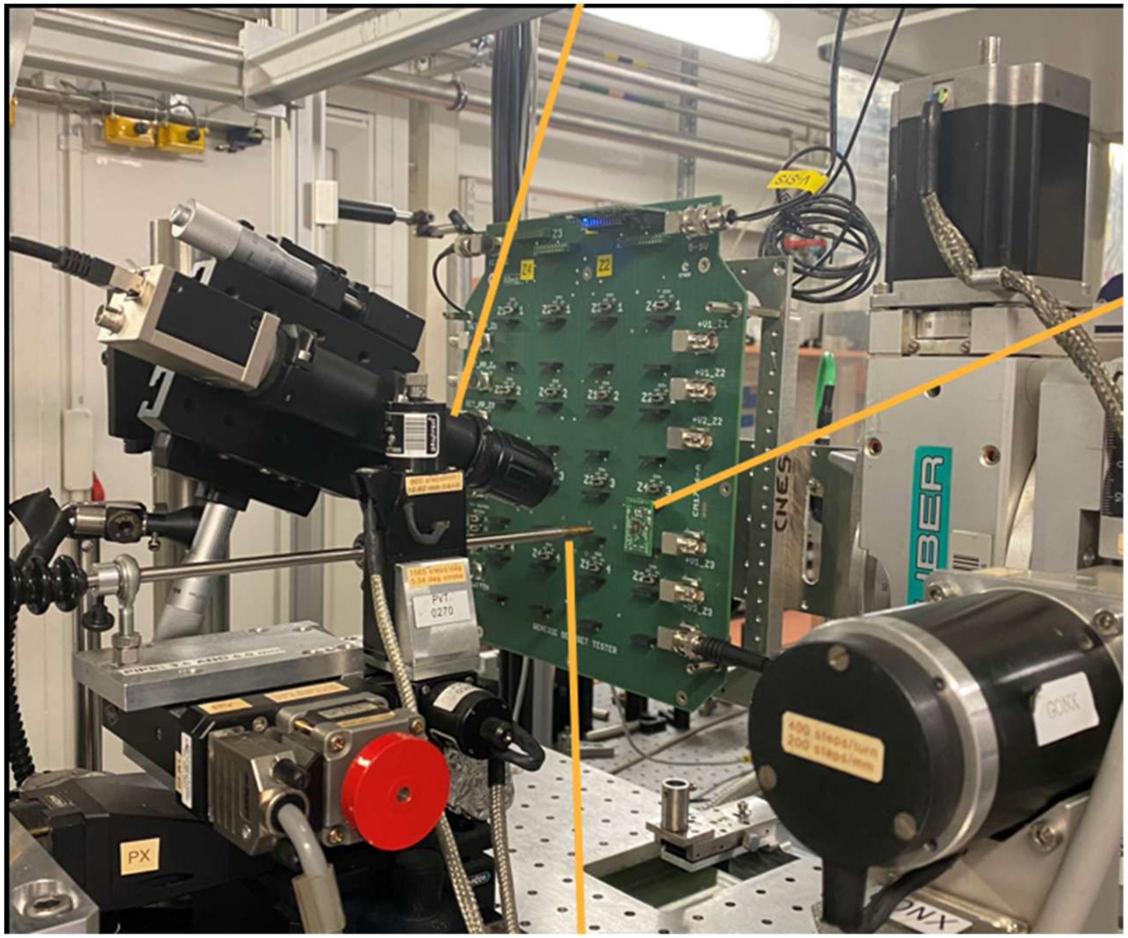
2.3uC = 3.3nC/um

Energy pulse = 11.5 uJ

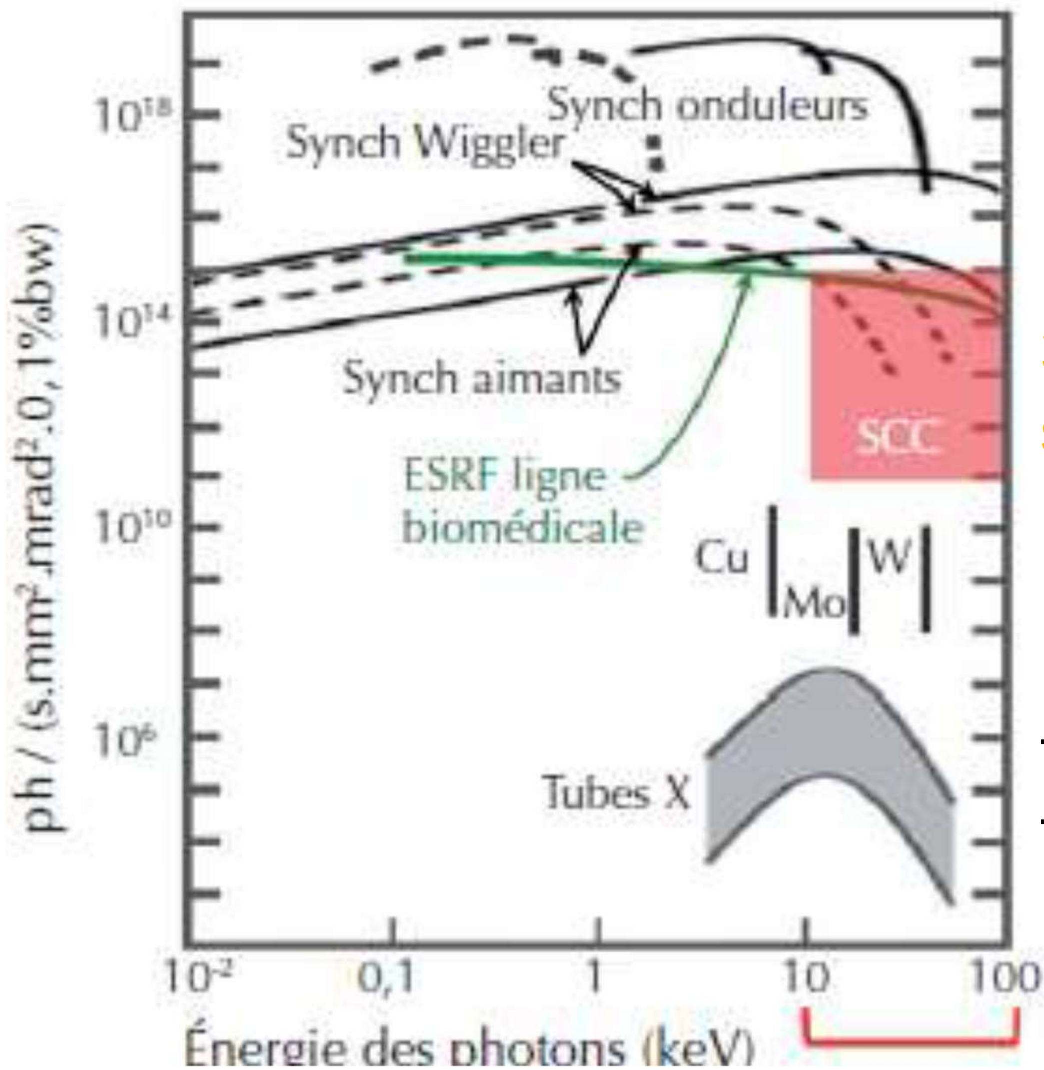
Diam 5um

1.6E8 ph/pulse

1.14E9 electrons/pulse/um

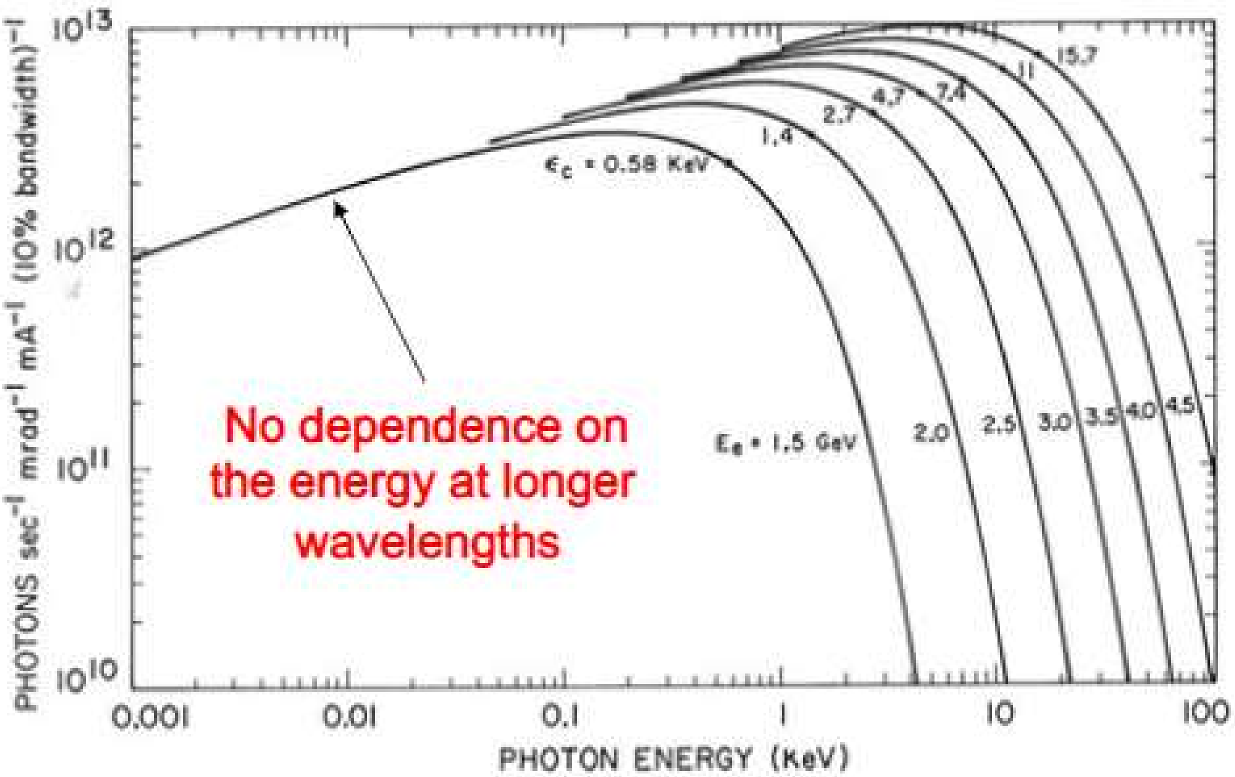


X-Ray pulse to emulate His: sources



3rd and 4th gen synchrotrons. Free Electrons Lasers and Extreme Light Installations seems the only candidates with the right brilliance

X-Ray pulse to emulate His: sources



Medium energy synchrotron (storage ring energy <3GeV) can be promising up to 10keV

Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, the adequate fluence is available.
- Pulse duration?
- Photon energy?
- Beam diameter?

Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration?
- Photon energy?
- Beam diameter?

Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration? An HI deposit his energy in ~100fs, nonetheless, any pulse duration < clock commuting time (ns) is acceptable
- Photon energy?
- Beam diameter?

Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration? 150ps would be enough; 10-100fs pulses are available at FELs and ELIs -> characterization are running
- Photon energy?
- Beam diameter?

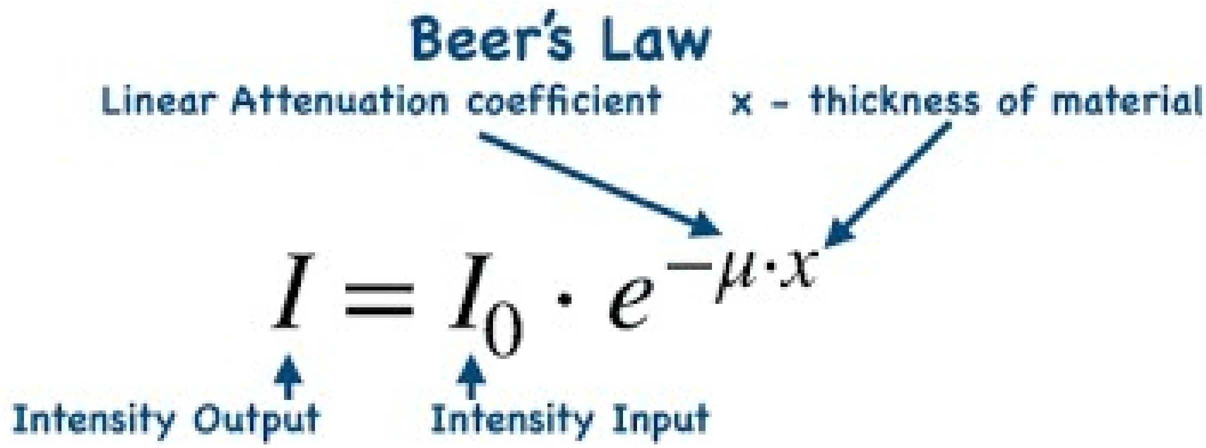
Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration? 150ps would be enough
- Photon energy?
- Beam diameter?

Which should be the characteristics of the X-ray beam?

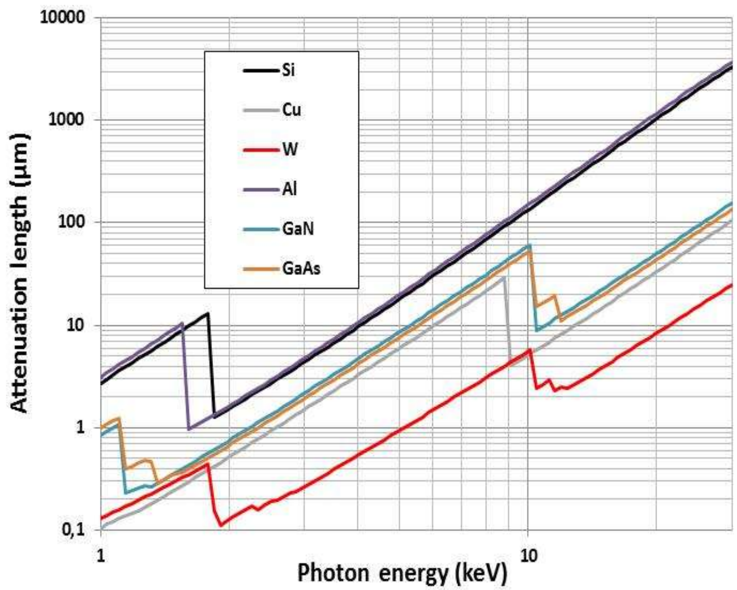
- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration? 150ps would be enough
- Photon energy? Would it be possible to cross 3DIC packaging?
- Beam diameter?

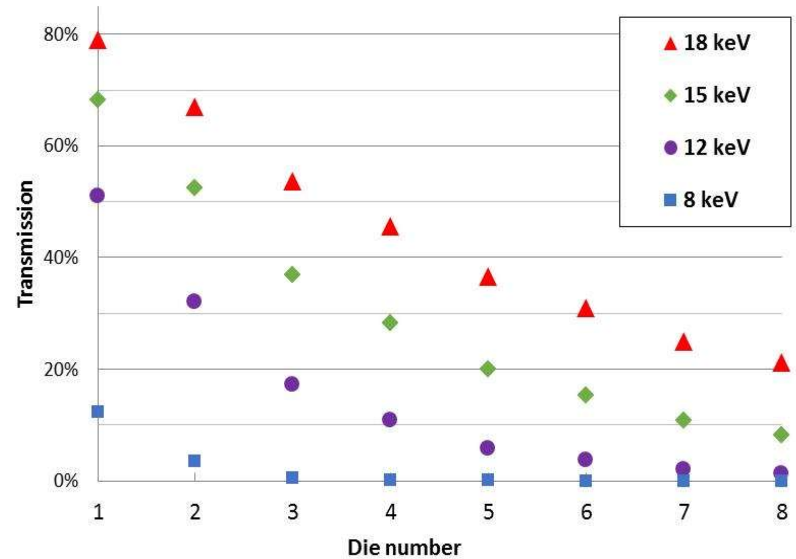
X-Ray pulse to emulate His: energy transfer



- By using the linear attenuation coefficients, it is possible to evaluate the portion of incoming energy absorbed by a material and transferred to the devices
- This can be used to calculate the sensible charge deposed in a certain active area or the dose.

X-Ray pulse to emulate His: penetration





X-ray attenuation lengths of materials commonly used in IC manufacturing [7]. For comparison purpose, a 1064 nm laser beam in silicon having a doping level of 2.1018cm has an attenuation depth of 330 µm

X-ray transmission as a function of die number

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Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration? 150ps would be enough
- Photon energy? At 30keV we already have enough energy to cross 8 stacked dies. For more complex structure it is necessary to increase to 100keV at least.
- Beam diameter?

Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration? 150ps would be enough
- Photon energy? At 30keV we already have enough energy to cross 8 stacked dies.
- Beam diameter?

Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration? 150ps would be enough
- Photon energy? At 30keV we already have enough energy to cross 8 stacked dies.
- Beam diameter? The ionization track of an HI is considered to be equal to few nm. This assumption does not consider the mean free path of secondary electrons. This means that the concept of mapping of single components on the IC could be questionable

Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
- Pulse duration? 150ps would be enough
- Photon energy? At 30keV we already have enough energy to cross 8 stacked dies.
- Beam diameter? A setup providing a 1um pin-hole solution would be enough to start (specific modelling actions are needed). The problem is to have enough photons -> better to focus

Does the correlation under consideration has a physical meaning?

X-Ray pulse to emulate His: SET

- X-rays can generate SEU
- An equivalent LET for X-rays can be calculated if ph E < 10keV, with a precise correlation with the heavy ions probe
- Some R&D is still necessary to understand the correlation when ph E > 10keV

Figure 12 and Figure 13 show the observed SET transients (voltage versus time) and normalized to compare their shapes. It can be noted that the three types of particles give comparable transients for this PIN diode.

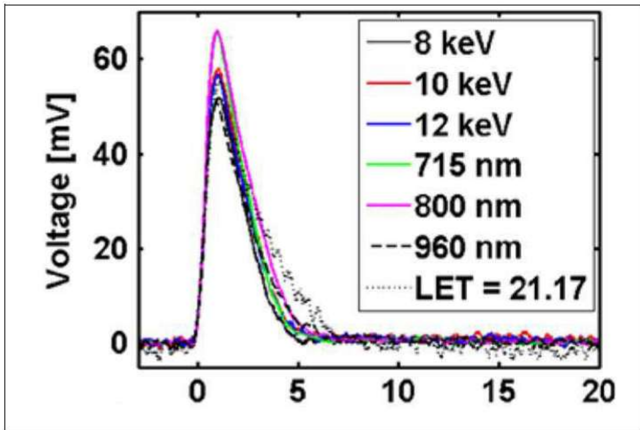


Figure 12: SET observed with laser photons, X-photons and heavy ions

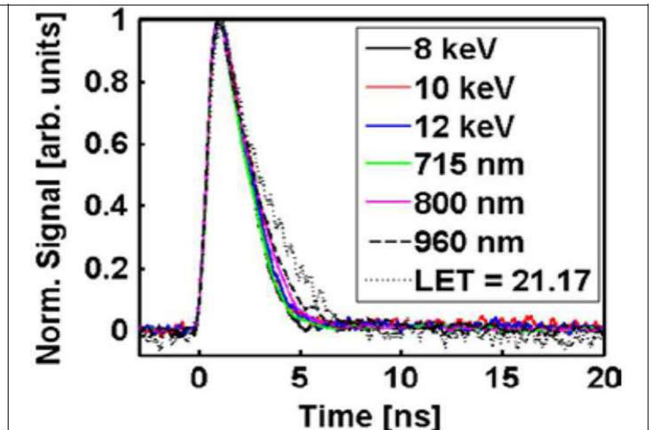
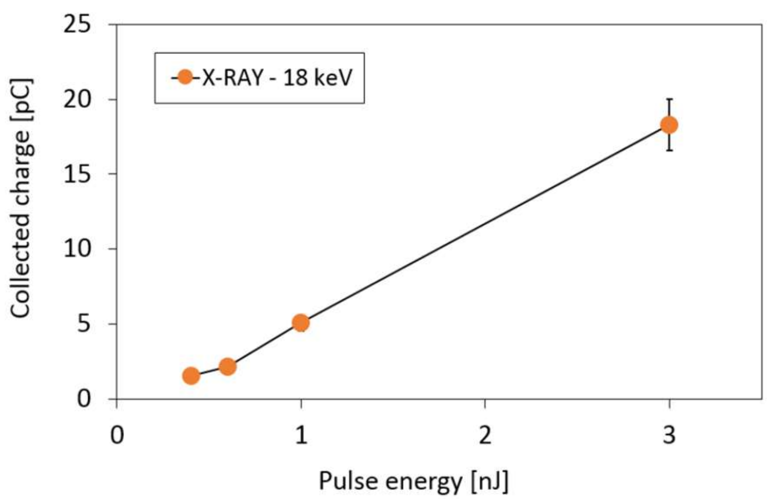
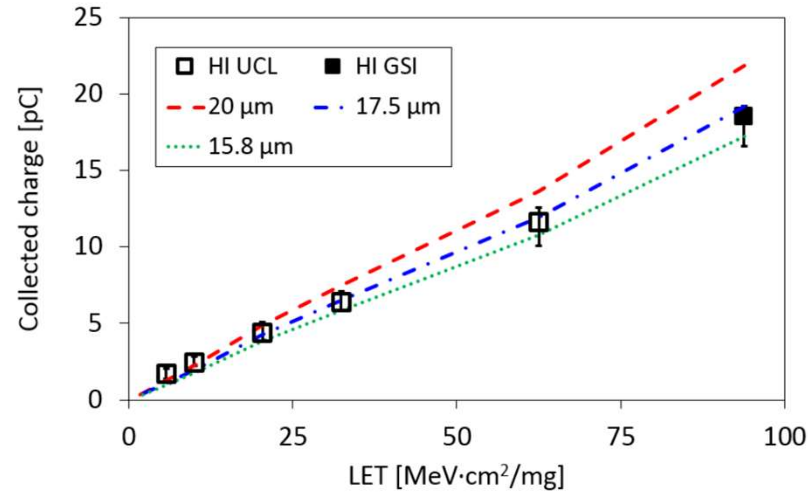


Figure 13: Standardized SETs obtained with laser photons, X-photons and heavy ions

X-Ray pulse to emulate His: : Photodiode





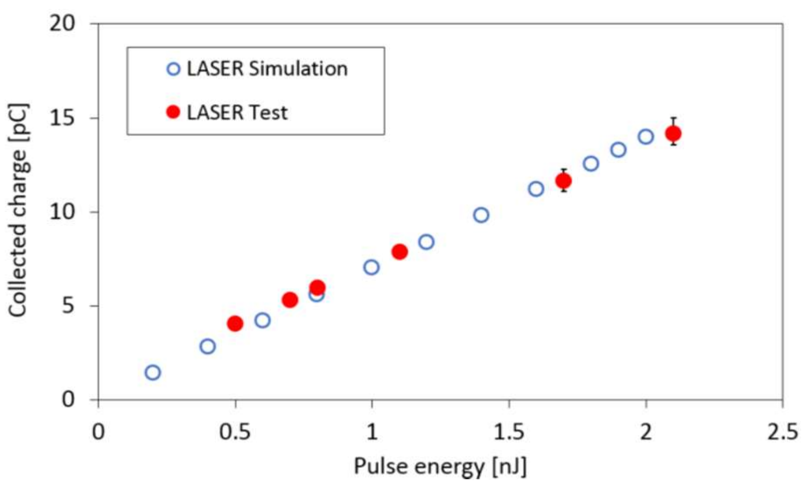


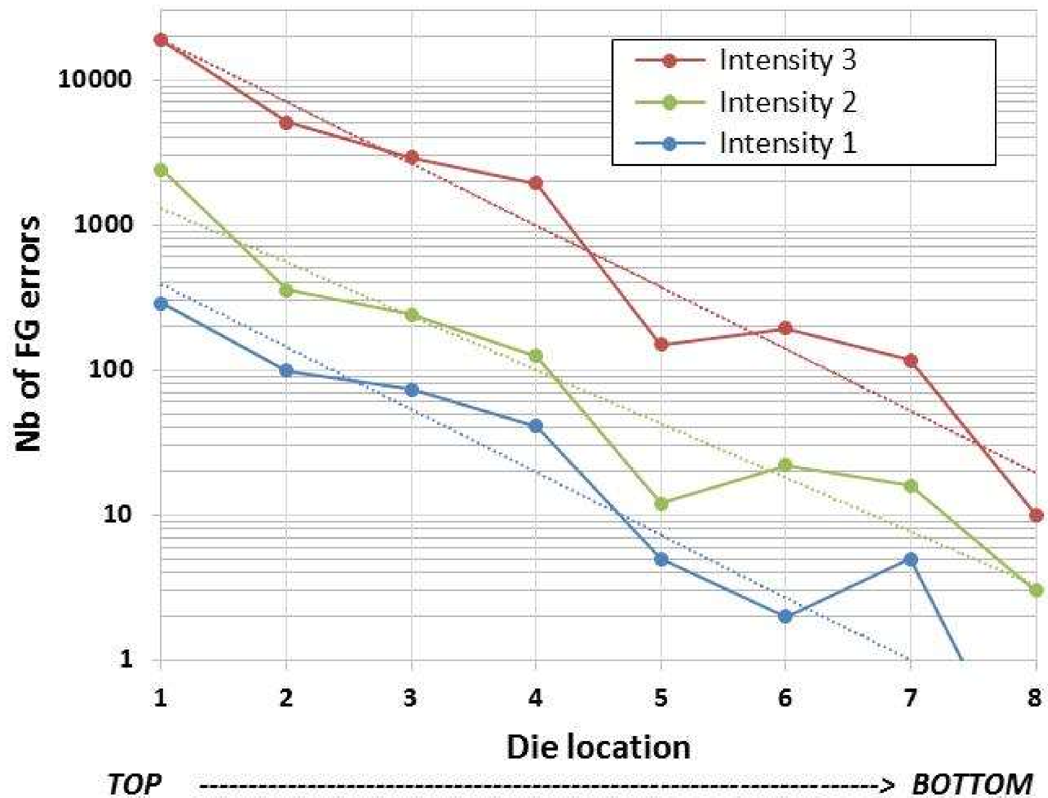
TABLE V
CORRELATION TABLE

Heavy ions LET (MeV.cm²/mg)	X-rays Energy 18 keV (nJ)	Laser Energy 1064 nm (nJ)	Collected charges (pC)
1.3	0.32	0.16	0.7
3.3	0.38	0.22	1.1
5.7	0.45	0.29	1.5
10.0	0.57	0.42	2.3
16.0	0.75	0.60	3.5
20.4	0.87	0.73	4.3
32.4	1.22	1.09	6.6
45.8	1.60	1.49	9.1
62.5	2.08	1.98	12.2
93.8	2.97	2.91	18.1

Credit TRAD

Preliminary studies at the ESRF

CASE 1: 3D integrated circuit



Number of FG errors (SEU) vs die number for
3 different energies per pulse

Cécile Weulersse, Christian Binois, Hagen Schmidt, Mathias Sander and Ennio Capria – *unpublished results*

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