

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



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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**

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- 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

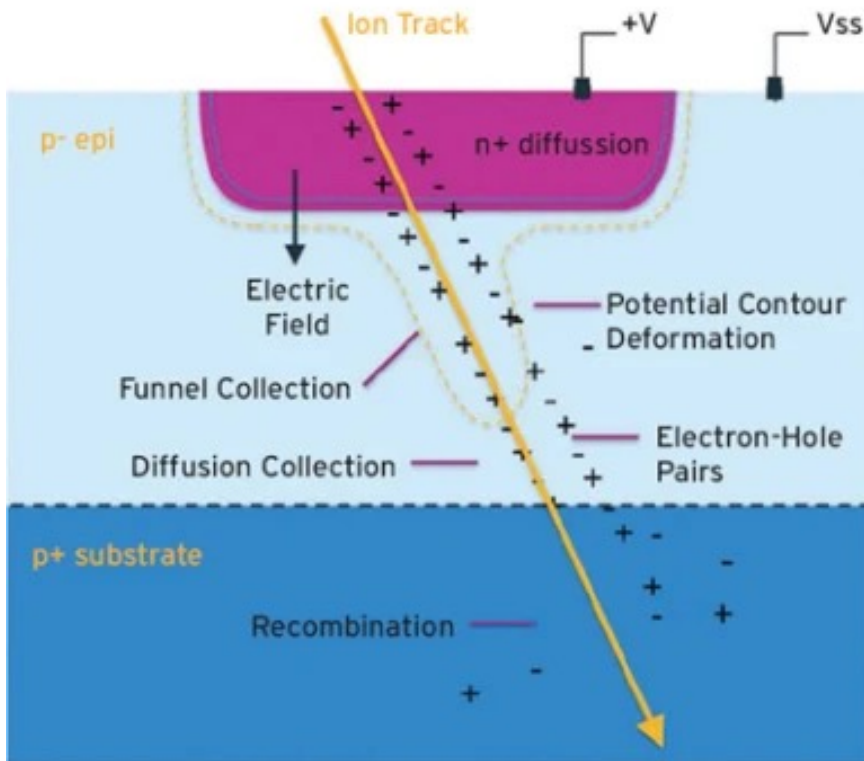
- **Single Event Effects (SEEs)**: includes all the macroscopically observable effects induced by a **single highly energetic particle** that deposits enough energy (**critical energy**) in a sensitive volume (**critical volume**) of the device to trigger an event.

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**.

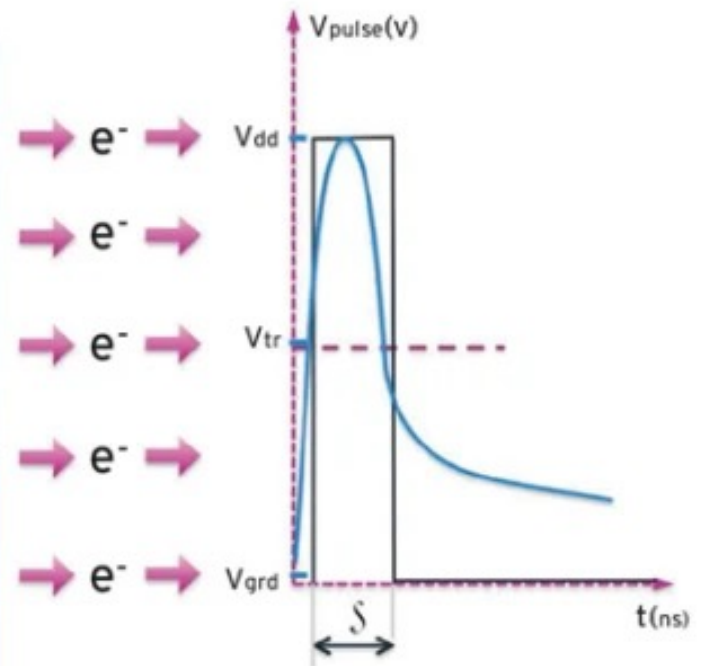
Non-destructive: Switching of logic states, which can be restored to its initial value by rewriting the bit: this type of non-destructive events are called **Single Event Upset (SEUs)**.

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



TRANSIENT PULSE



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.

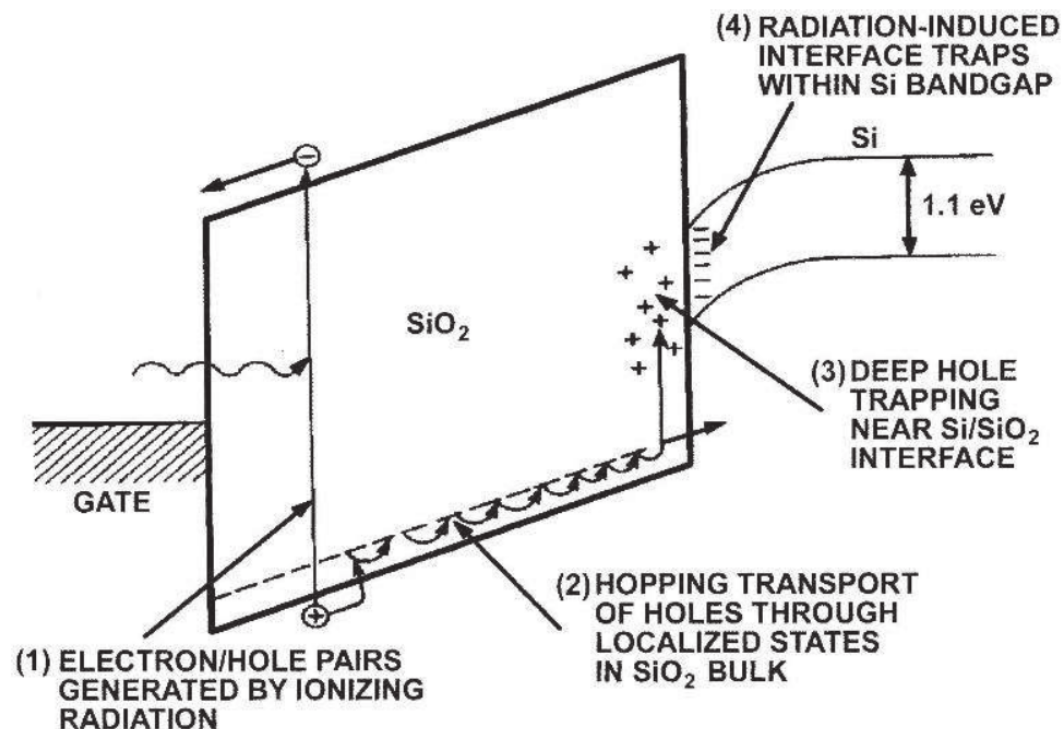


Figure 7. Main processes due to ionizing dose in the MOS insulator layer. (Source: [19])

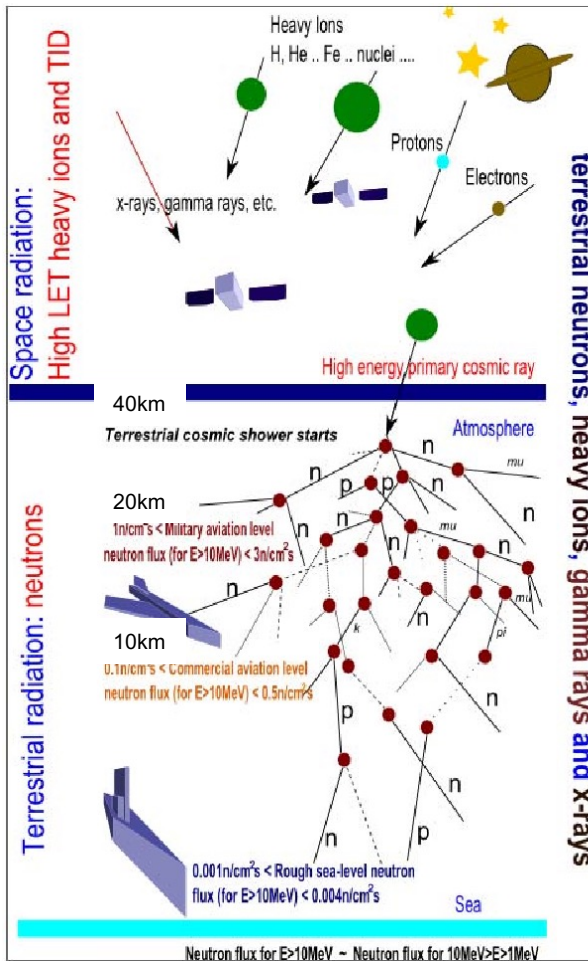
Interaction of cosmic radiations with electronic circuits

- several parameters are affected by ionizing radiation (e.g. transconductance, noise, channel leakage)
- **the shift of the threshold voltage** (shortly ΔV_{th}) is the observed parameter which allows the conversion of absorbed dose into an easily measurable quantity. It is mirrored on the V_{gs} when the transistor works in saturation and the drain current is constant.
- The change in the V_{th} is the result of the **cumulation of charge within the insulator layer** of the metaloxide-semiconductor sandwich, i.e. the silicon dioxide SiO_2 and at the border between the insulator and the semiconductor edge, i.e. Si/SiO_2 interface.

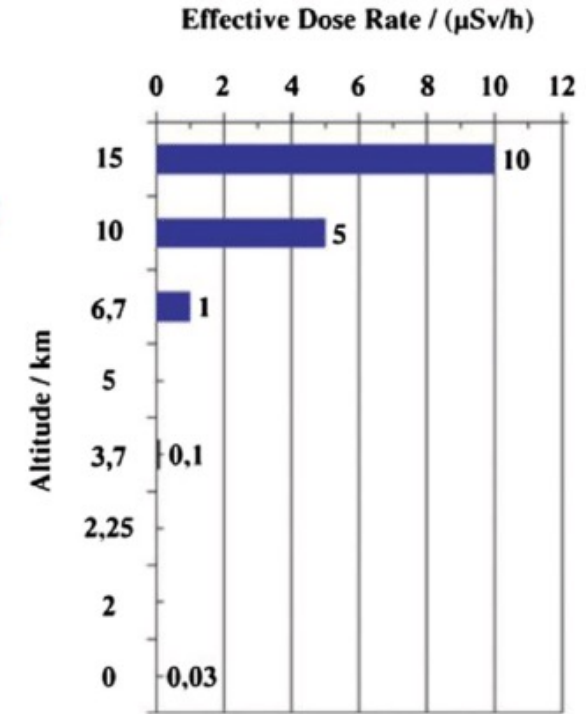
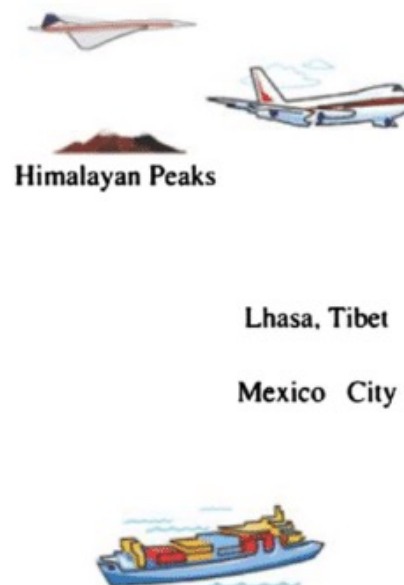
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- Effect of ionising radiation on electronic devices.
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Cosmic radiation distribution

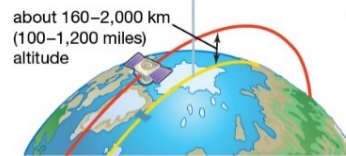
The natural radiation environment on Earth is for the **13%** due to cosmic rays, but the situation is getting much higher increasing the altitude.



terrestrial neutrons, heavy ions, gamma rays and x-rays

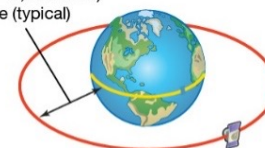


by altitude



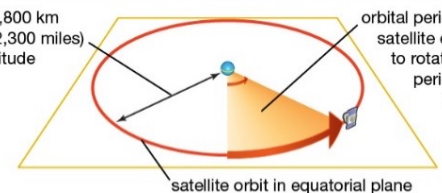
low Earth orbit (LEO)

5,000–10,000 km
(3,100–6,200 miles)
altitude (typical)



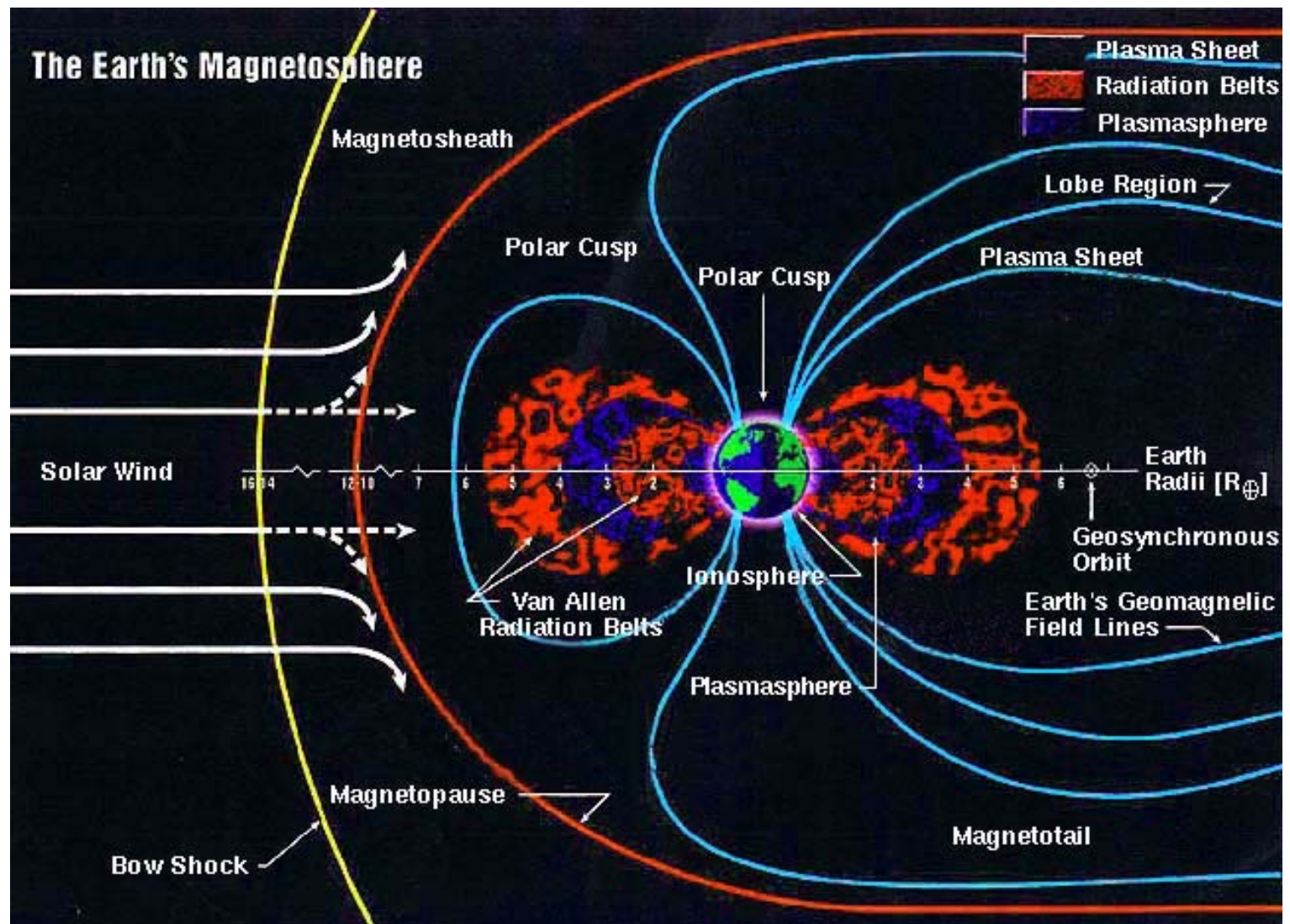
medium Earth orbit (MEO)

35,800 km
(22,300 miles)
altitude



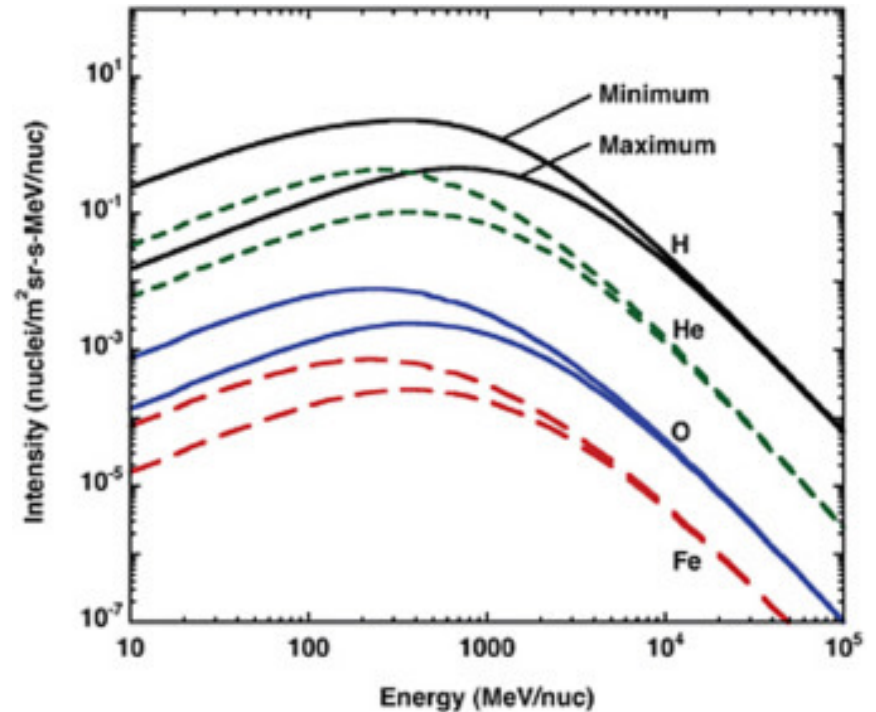
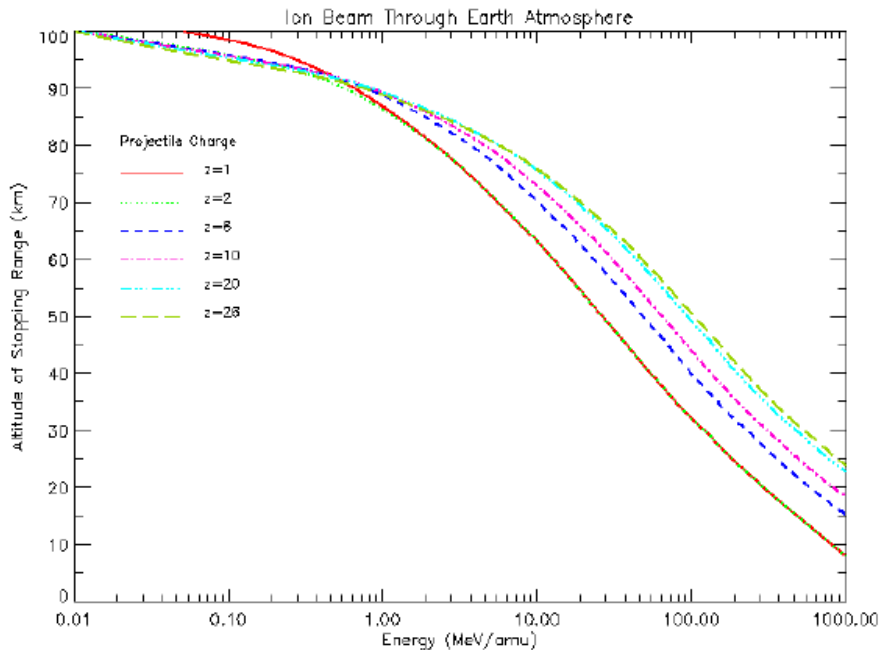
geostationary orbit (GEO)

Cosmic radiation distribution



Earth radius = 6371 km

Cosmic radiation: the heavy ions distribution



- Heavy ions at high energy (above 1 GeV/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.

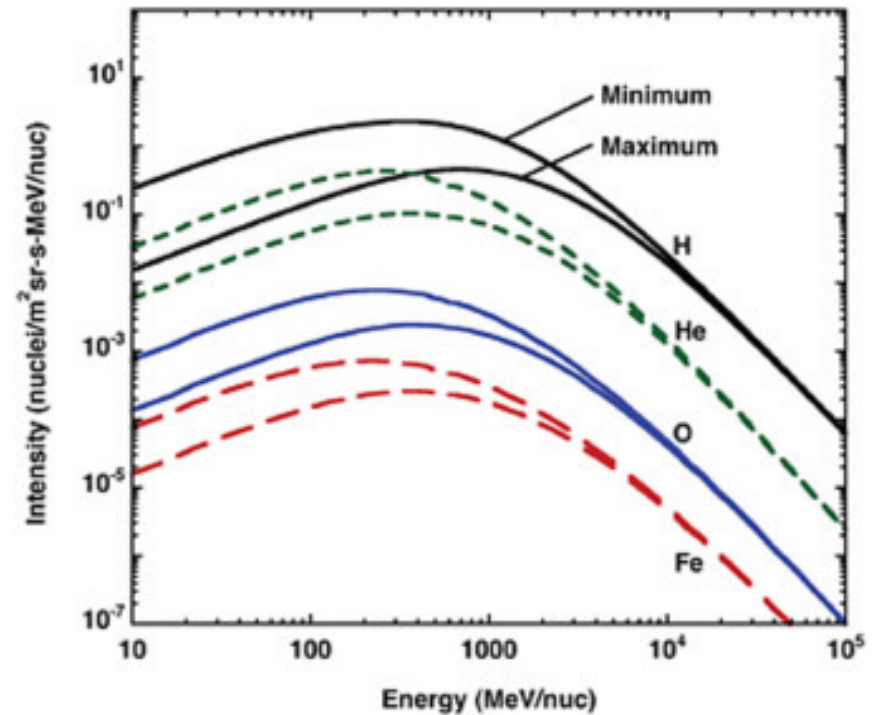
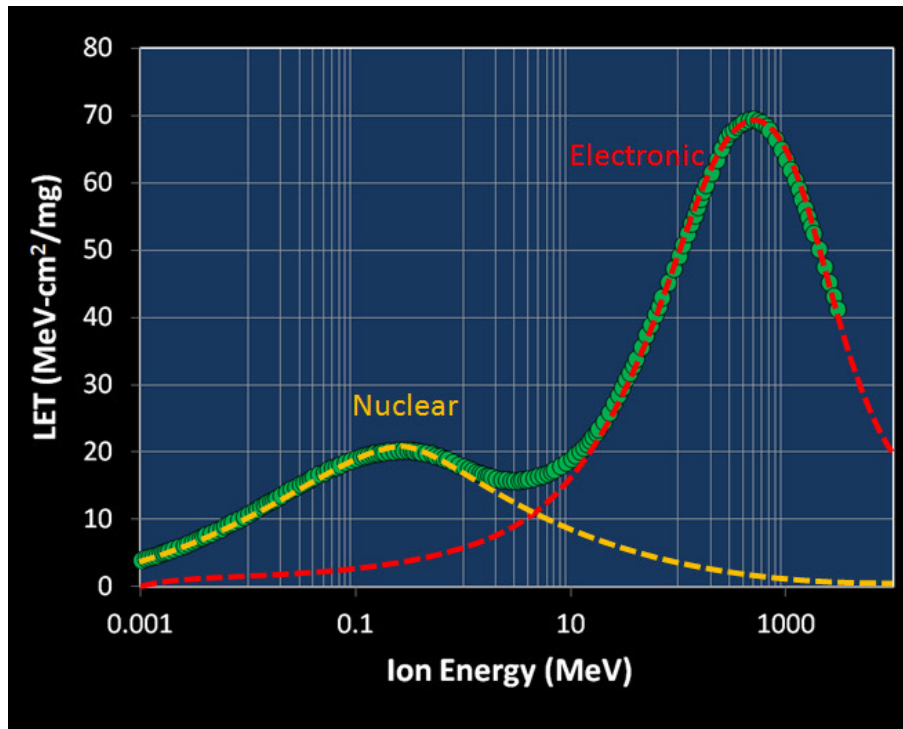
Radiation hardness testing: How do we measure it?

Table 4: Heavy Ions facilities

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

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?

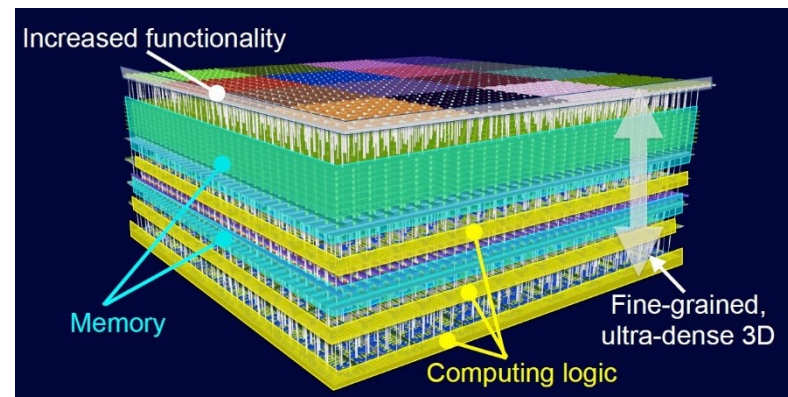
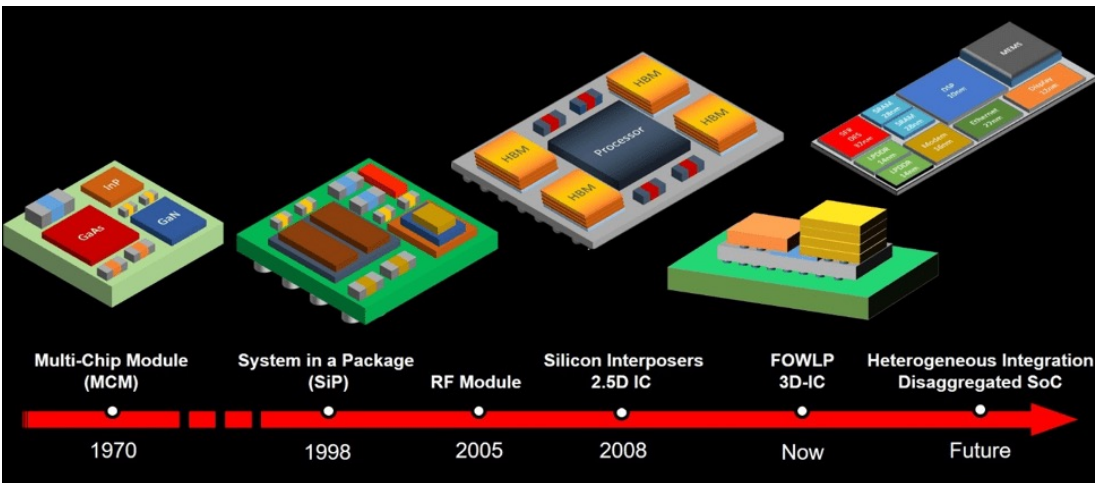
Yes

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



2D AND 3D PACKAGING DRIVE NEW DESIGN FLEXIBILITY

The combination of advanced 2D and 3D packaging technologies allows Intel to flexibly combine smaller chiplets of IP to meet the demands of a huge range of applications, power envelopes, and form factors. Intel® embedded multi-die interconnect bridge (EMIB) and Foveros are advanced 2D and 3D packaging technologies, delivering high performance at low cost.

MONOLITHIC

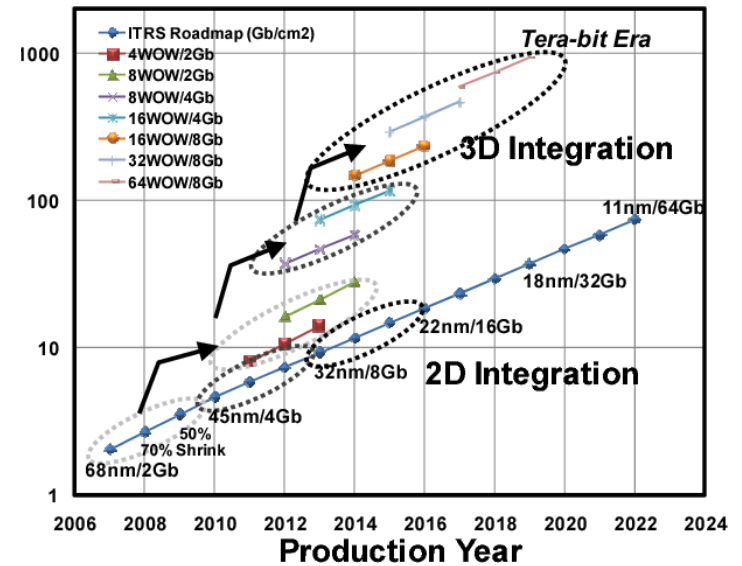
Integrate functions on a single die for high performance on a single silicon technology

2D INTEGRATION

Combine IP's built with separate processes into a single package with Intel EMIB, helping improve yield, cost, time-to-market, and total capability

3D INTEGRATION

All the benefits of 2D integration plus a new level of density thanks to Foveros, allowing for a radical re-architecture of systems-on-chips



Critical charge in critical volume

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

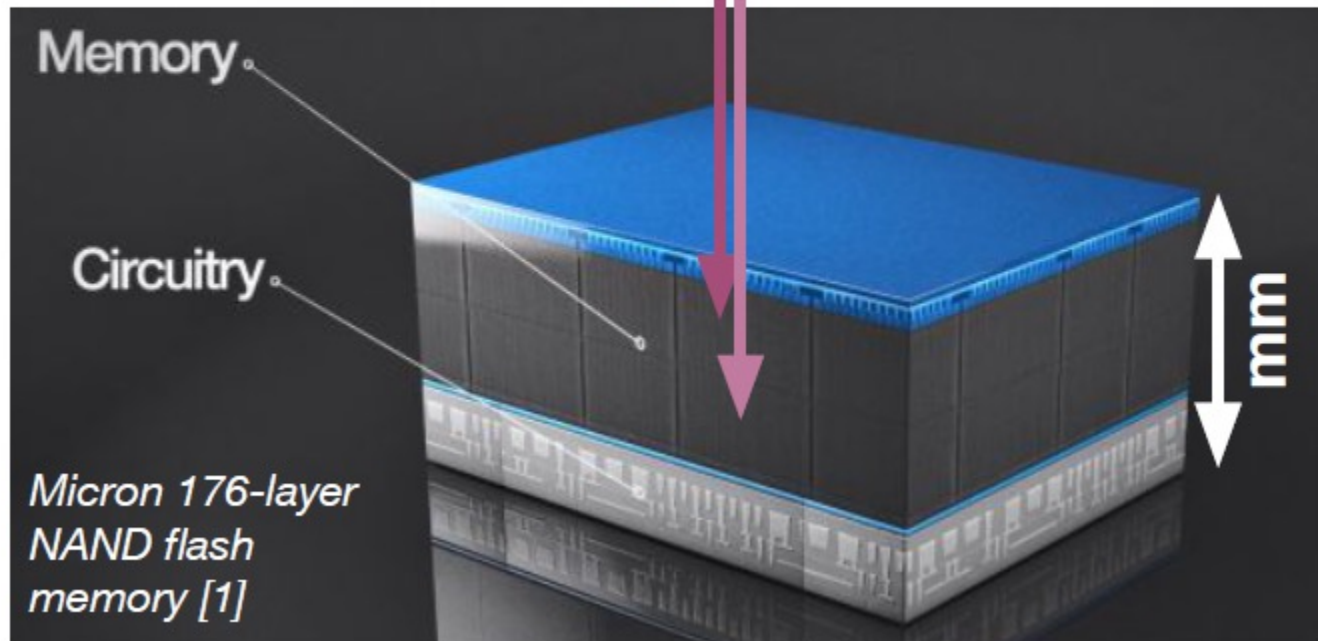
The race for space

In technical terms:

- Need for implementation of the following:
 - Focused sources for mapping exercises
 - Laboratory systems to increase accessibility and flexibility
- **For complex electronic device packagings**
 - **Need to simplify the sample preparation**
 - **Penetration depth**

Trends in microelectronics: 3DIC

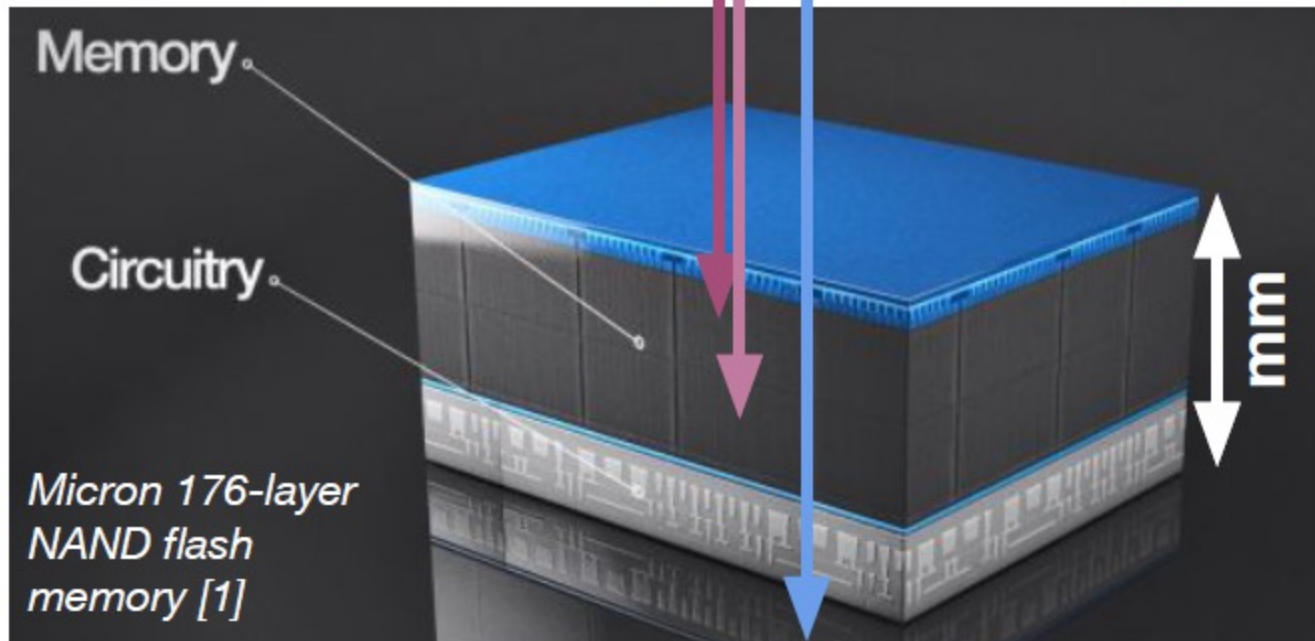
Low- and standard-energy
< 50 MeV/n,
< 1 mm range



Trends in microelectronics: 3DIC

Low- and standard-energy
< 50 MeV/n,
< 1 mm range

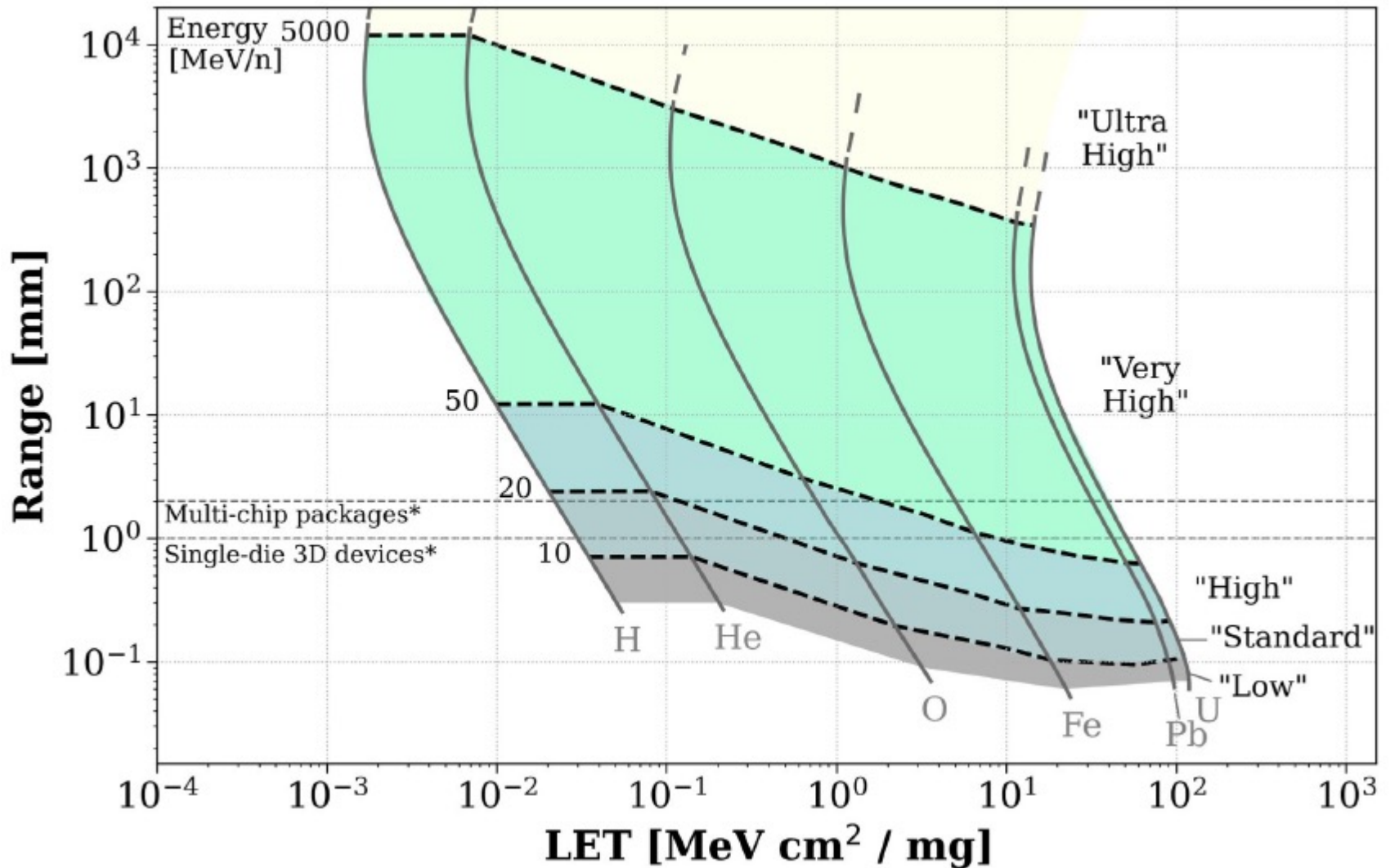
High-energy
> 50 MeV/n,
> 1 mm range



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

Considerations on penetration depth

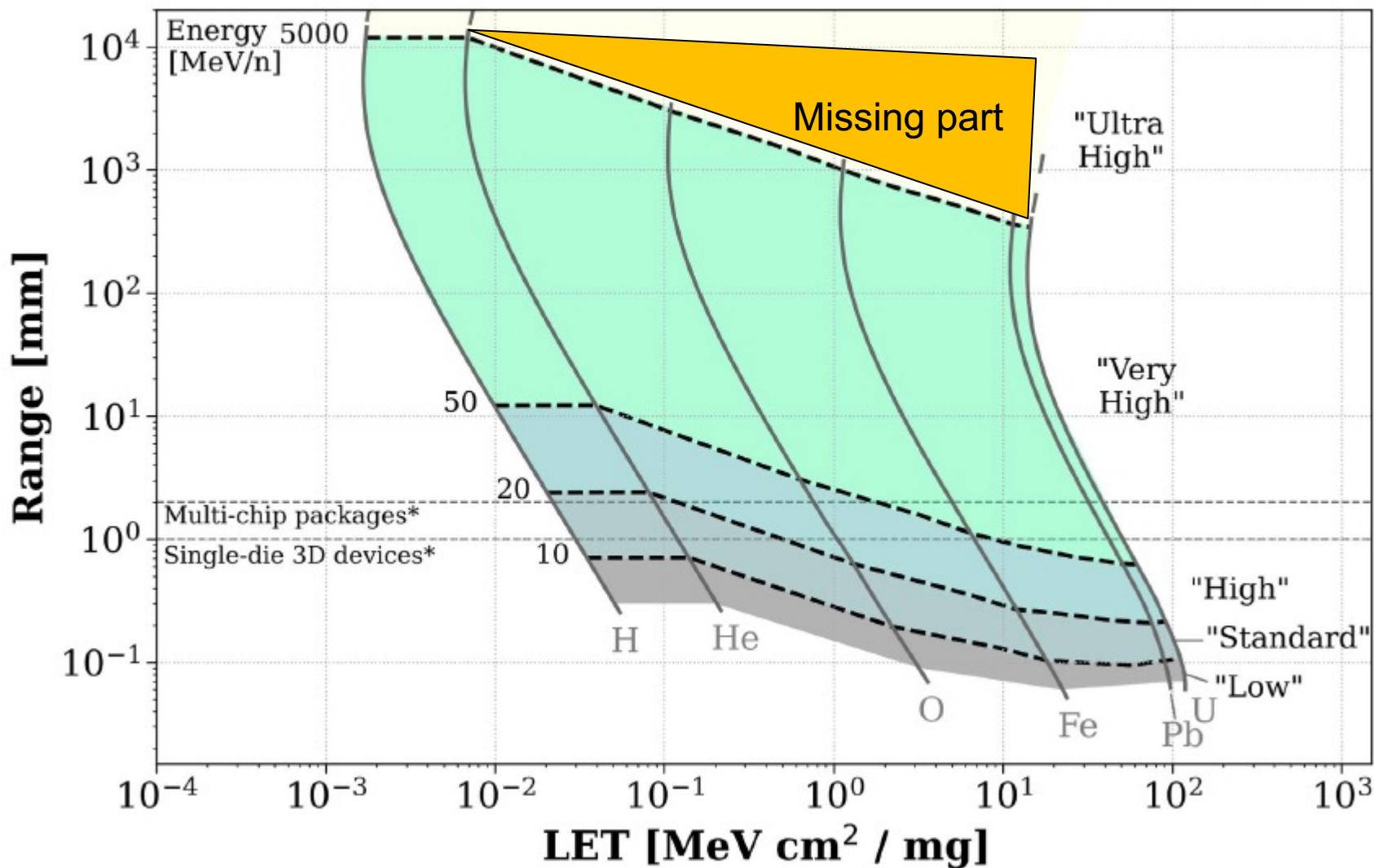
Credits Andreas Waets and HEARTS project



- Various sources of heavy ions around the world, with normalized tests
- **HI Energies range in standard facilities**

Considerations on penetration depth

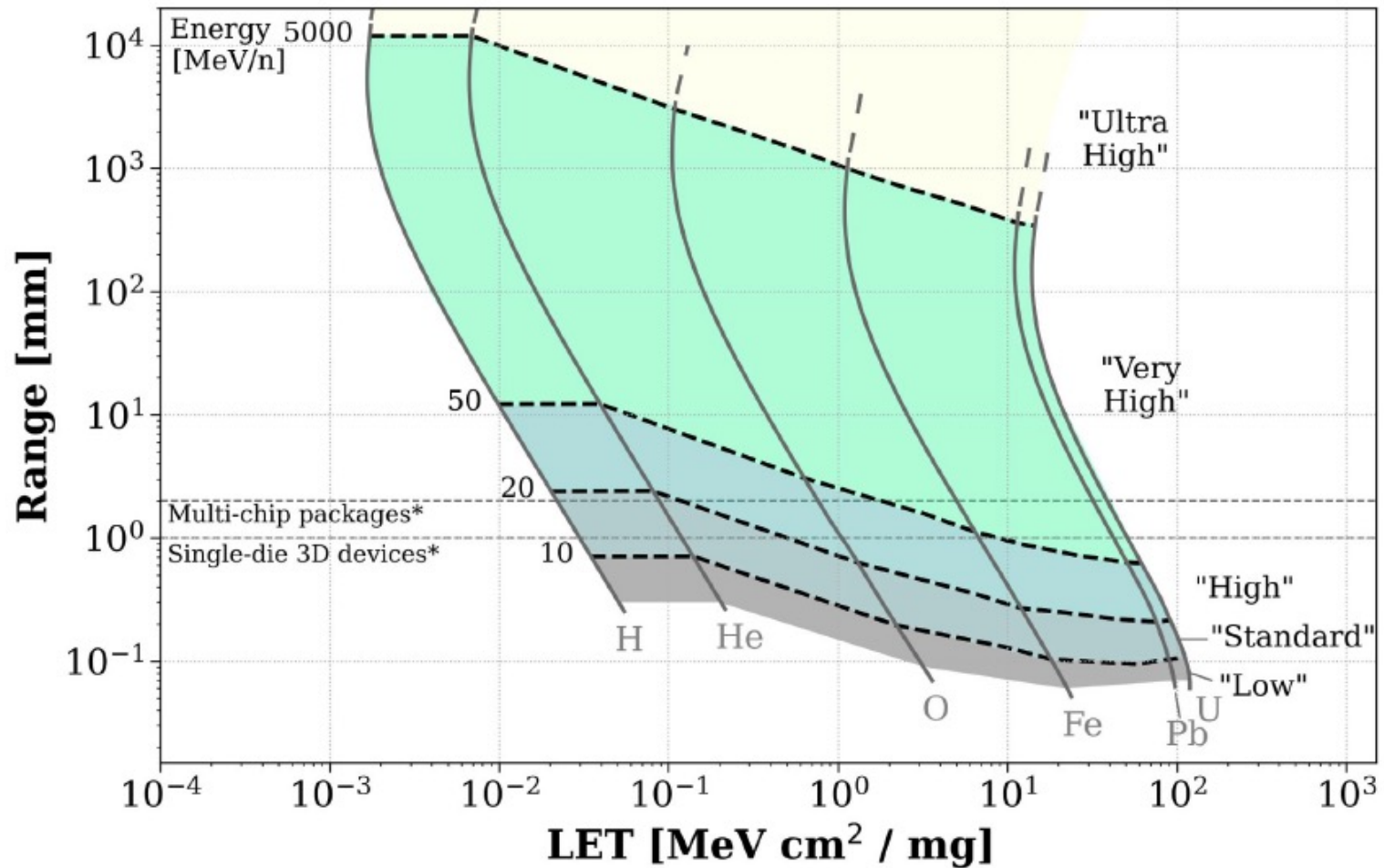
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- Various sources of heavy ions around the world, with normalized tests
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Considerations on penetration depth

Credits Andreas Waets and HEARTS project



Can **focused X-ray pulses** complement laser testing when circuits become too complex or when a simplified sample preparation procedure is demanded?

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- The example of aerospace.
- The use of ESRFs to support the R&D of radiation hard electronics -> **emulation of heavy ions using pulsed X-rays**

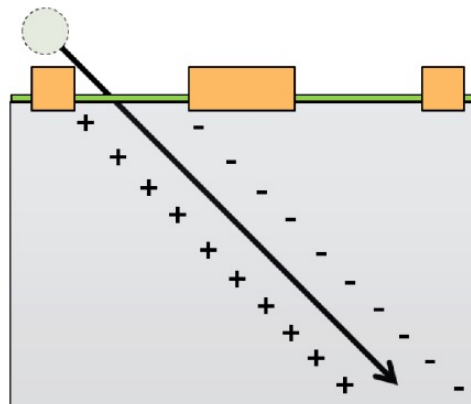
Can photons emulate Heavy Ions?

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

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

Photon energy
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

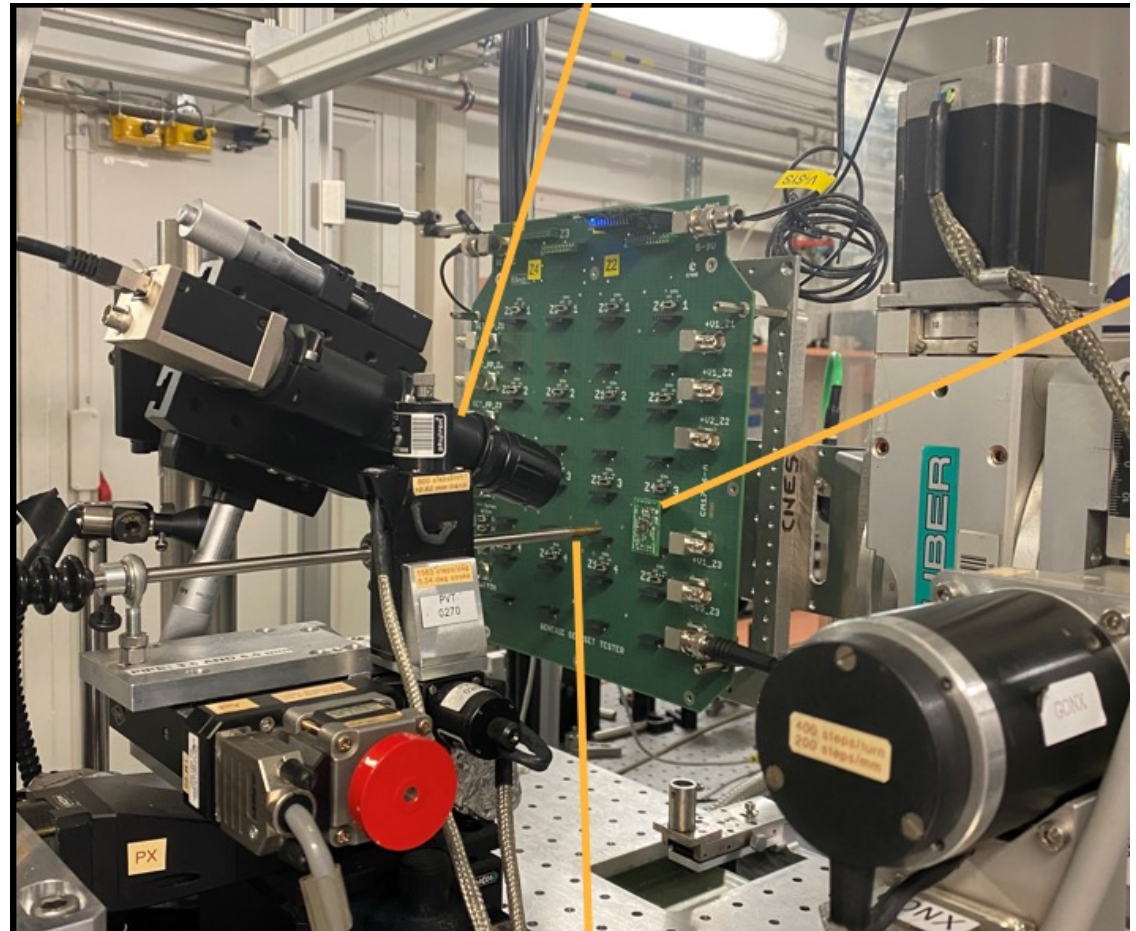
2.3uC = 3.3nC/um

Energy pulse = 11.5 uJ

Diam 5um

1.6E8 ph/pulse

1.14E9 electrons/pulse/um



X-Ray pulse to emulate His: carrier generation

X-ray what may be available in the future

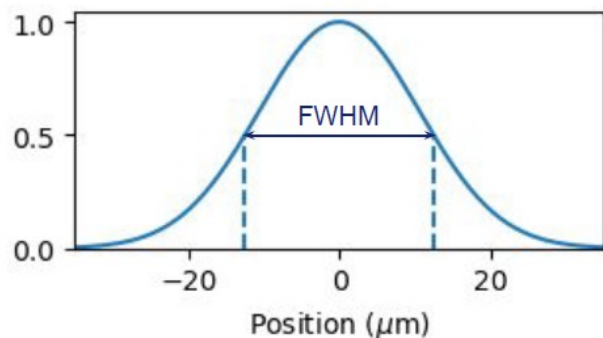
3E6 ph/pulse

150ps

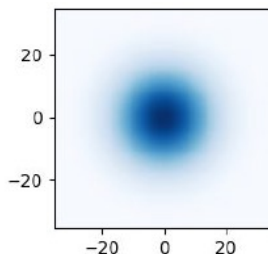
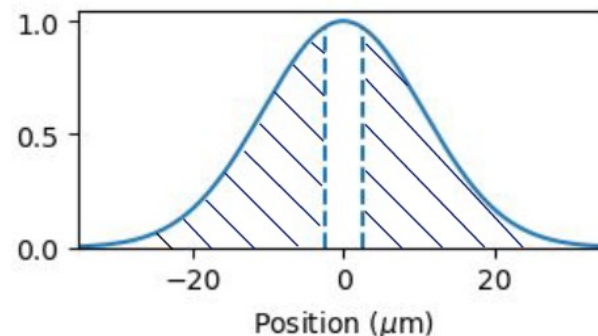
Diam 1 μ m

1.6E7 electrons/pulse/ μ m

For a Gaussian beam of 25 μ m :



+ pinhole



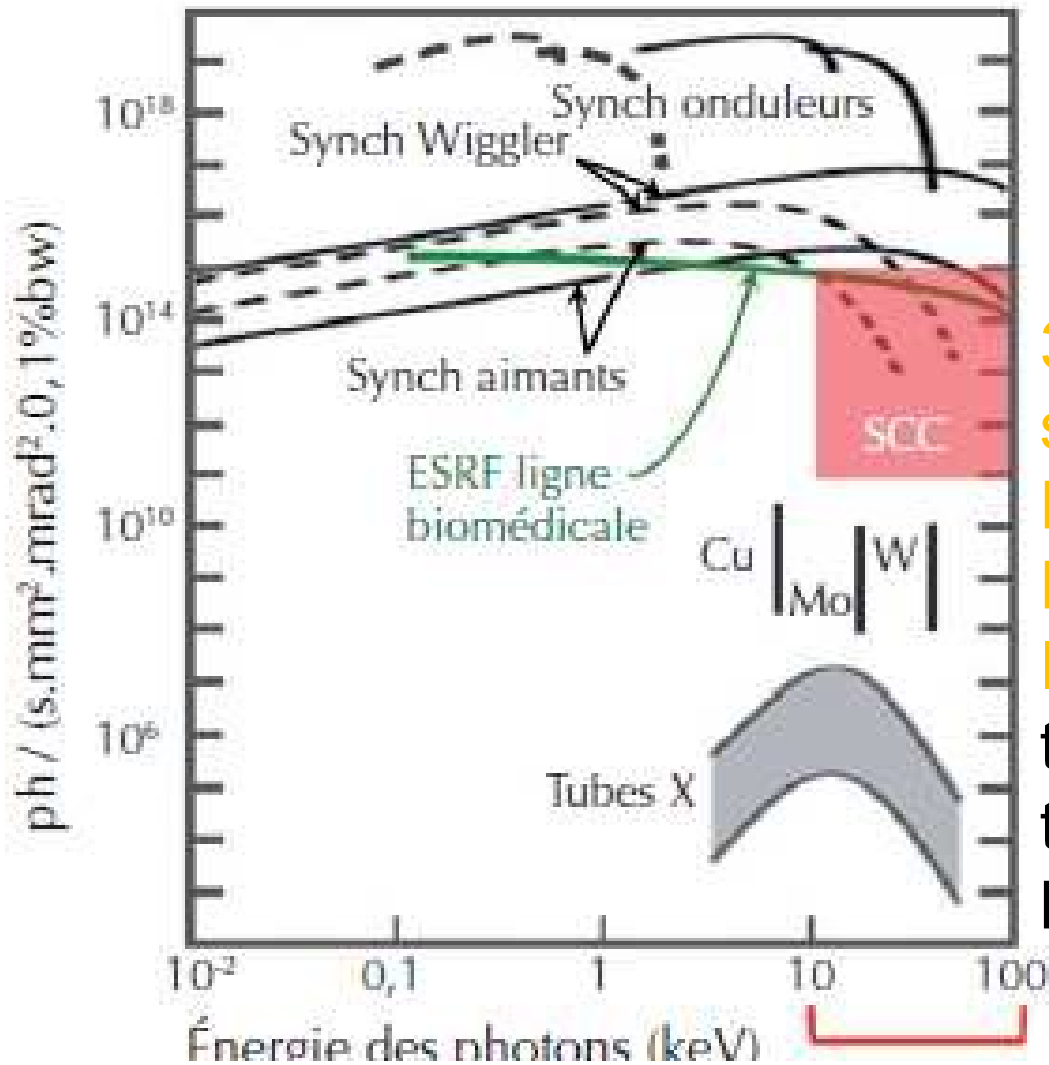
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less than 20% transmission

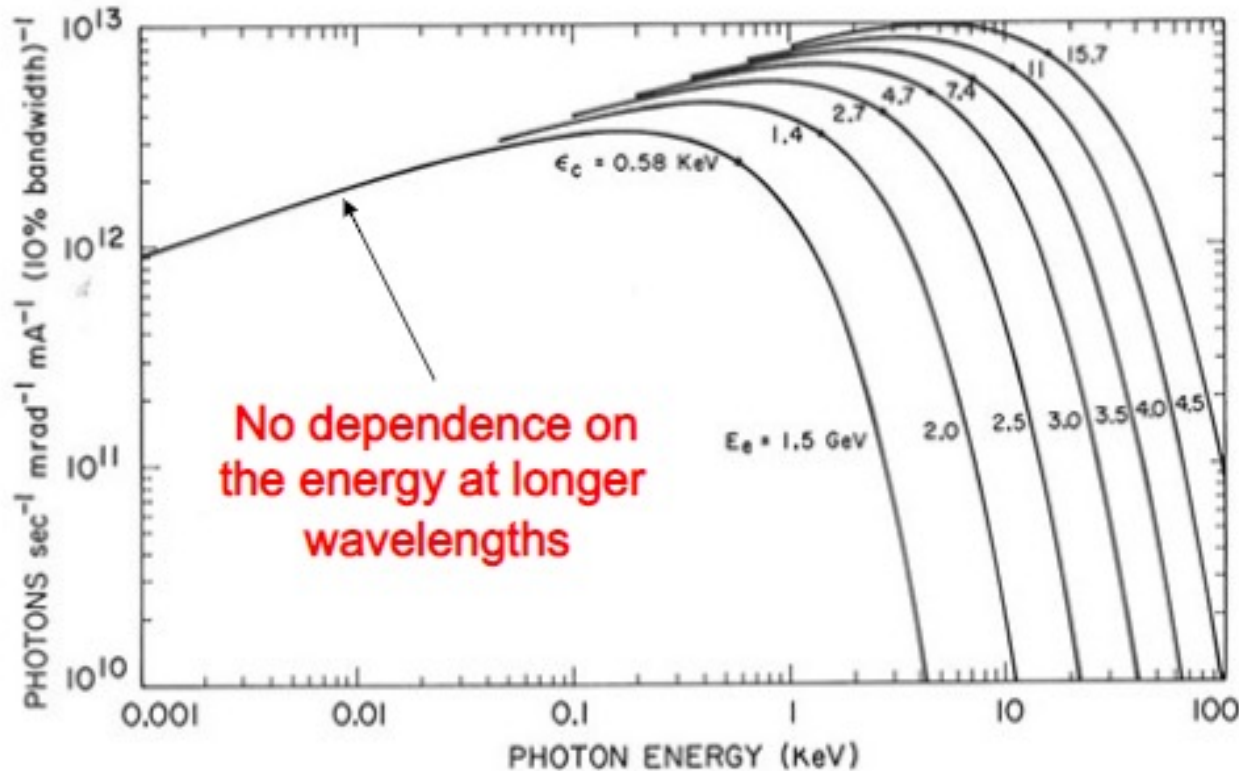
transmitted intensity very sensitive to
beam vs. pinhole misalignment

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 $\sim 100\text{fs}$, 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?

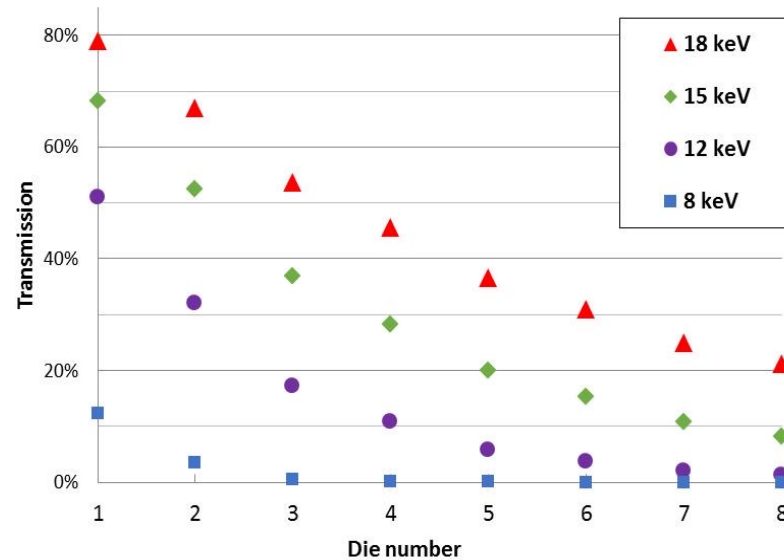
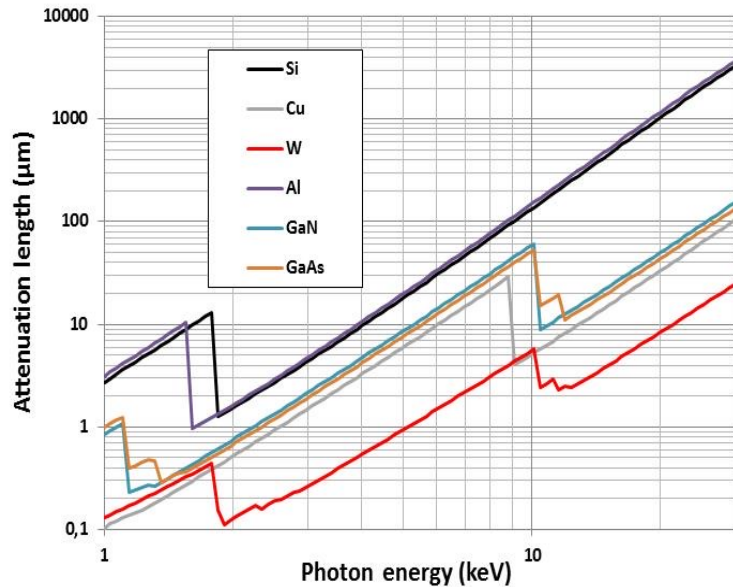
Which should be the characteristics of the X-ray beam?

- Pulse energy? At synchrotrons, we have enough photons
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- **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: 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 $2 \cdot 10^{18} \text{cm}^{-3}$ has an attenuation depth of $330 \mu\text{m}$

X-ray transmission as a function of die number

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 (delta electrons halo). This means that the concept of mapping of single components on the IC could be questionable**

X-Ray pulse to emulate HIs: ionization track diameter

High energy X-ray may offer the possibility to reach deep layers, but the ionization track will enlarge.

This trend is the same existing for HIs

Radiation Type	Track Length (μm)	δ-ray Region Diameter (nm)
Heavy ions < 50 MeV/u	20–1500	800–2000
Heavy ions > 50 MeV/u	1000–20000	>1200
10 keV X-ray	127	140
15 keV X-ray	415	180
30 keV X-ray	3000	300
100 keV X-ray	23000	900

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 1 μ m 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?

Does the correlation under consideration has a physical meaning?

How? NO

The structure of the ionization track? Completely different

What? YES

The deposition of the critical energy in the critical volume? Ok

Does the correlation under consideration has a physical meaning?

- Does the collected charge varies linearly with the pulse energy?
- Does the deposited dose is comparable with the one deposited by an HI?
- Is it possible to define a correlation to calculate an equivalent LET correspondent to a given pulse energy?

Does the correlation under consideration has a physical meaning?

- Does the collected charge varies linearly with the pulse energy?
- Does the deposited dose is comparable with the one deposited by an HI?
- Is it possible to define a correlation to calculate an equivalent LET correspondent to a given pulse energy?

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.

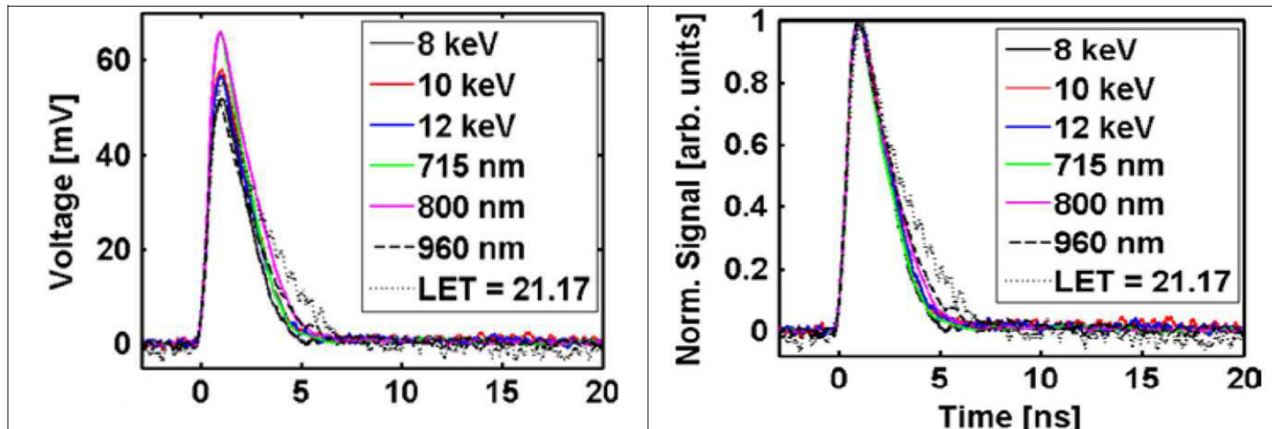


Figure 12: SET observed with laser photons, X-photons and heavy ions

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

X-Ray pulse to emulate His: : Photodiode

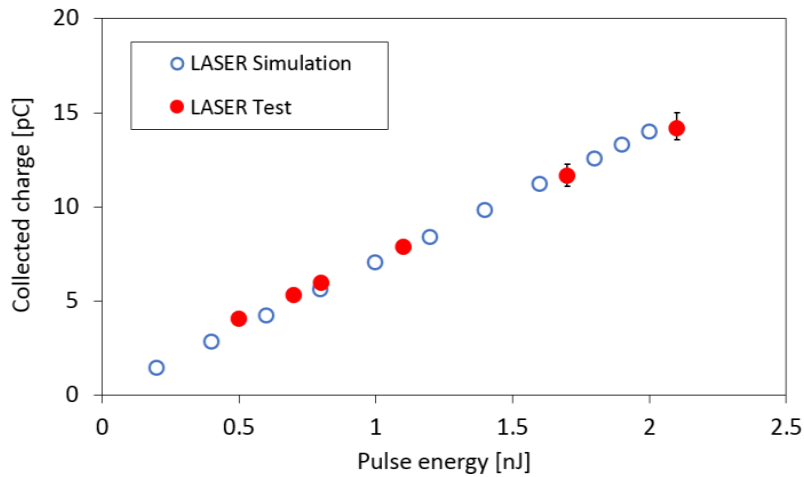
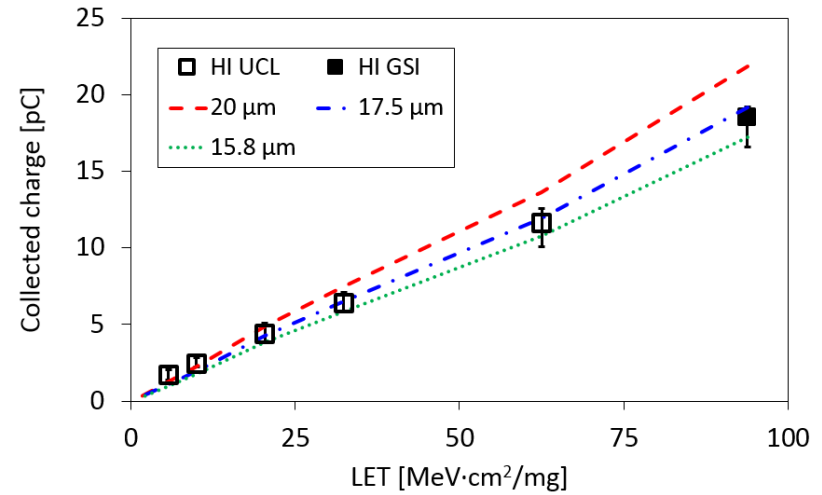
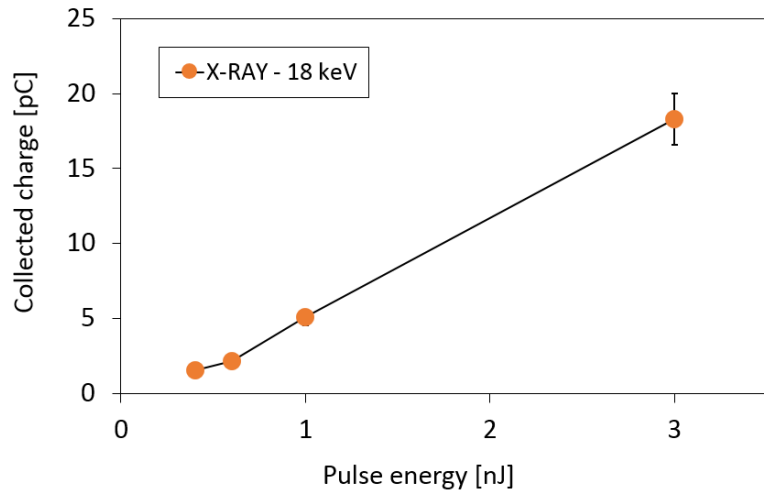


TABLE V
CORRELATION TABLE

Heavy ions LET (MeV.cm ² /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

Does the correlation under consideration has a physical meaning?

- Does the collected charge varies linearly with the pulse energy? Yes!.
- Does the deposited dose is comparable with the one deposited by an HI?
- Is it possible to define a correlation to calculate an equivalent LET correspondent to a given pulse energy?

Does the correlation under consideration has a physical meaning?

- Does the collected charge varies linearly with the pulse energy? Yes! Demonstrated in literature.
- Does the deposited dose is comparable with the one deposited by an HI? Similar to the one deposited by an ion, if similar LET and penetration depth (important to define an appropriated grid, $1\text{E}6/\text{cm}^2 = 10\mu\text{m}$ step)
- Is it possible to define a correlation to calculate an equivalent LET correspondent to a given pulse energy?

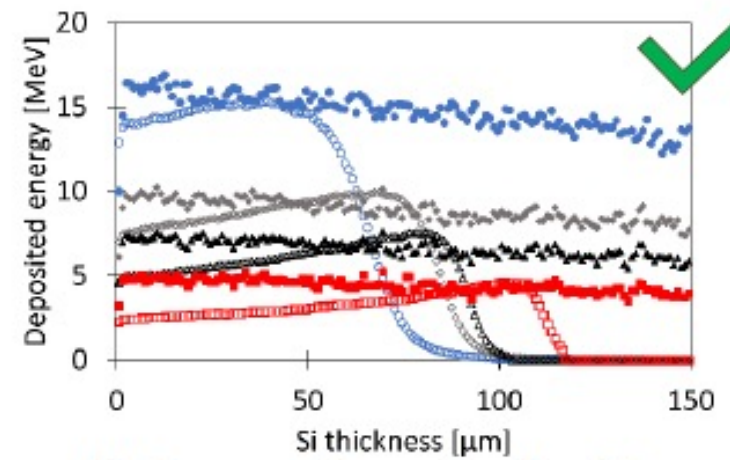
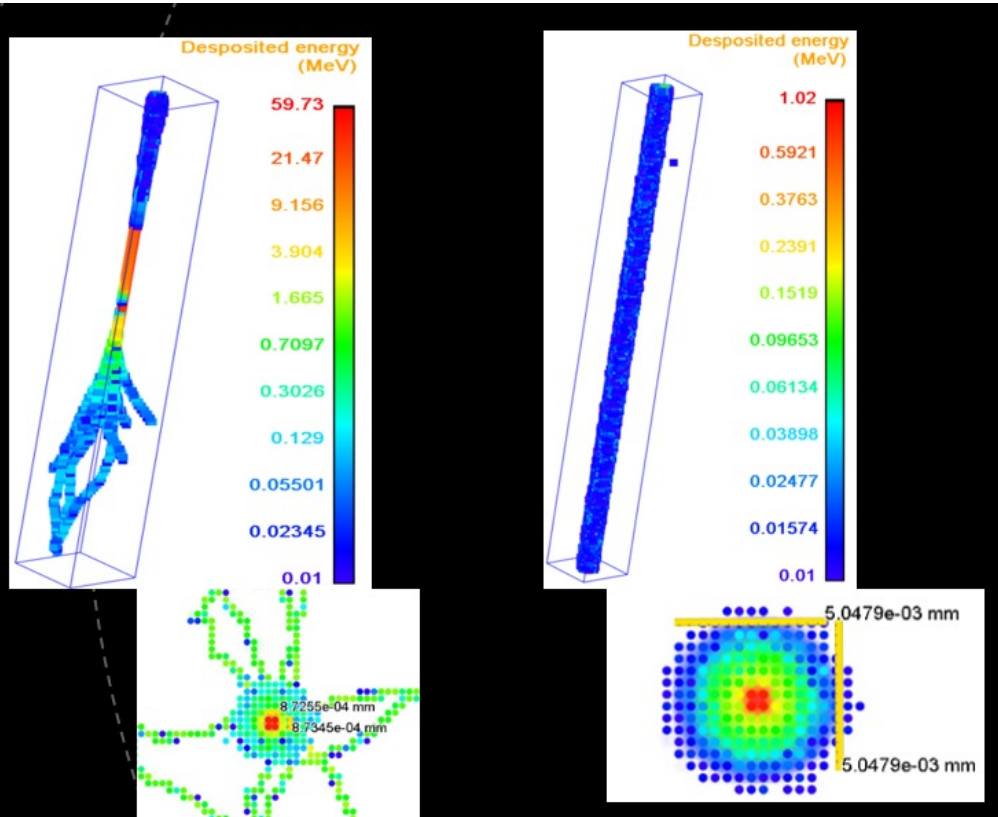
Does the correlation under consideration has a physical meaning?

- Does the collected charge varies linearly with the pulse energy? Yes! Demonstrated in literature.
- Does the deposited dose is comparable with the one deposited by an HI? The same of the equivalent HI
- Is it possible to define a correlation to calculate an equivalent LET correspondent to a given pulse energy?

Does the correlation under consideration has a physical meaning?

- Does the collected charge varies linearly with the pulse energy? Yes! Demonstrated in literature.
- Does the deposited dose is comparable with the one deposited by an HI? Is it lower than the max dose supported by the circuit? After a rough estimate the value of dose is quite high. Further modeling activity is needed.
- **Is it possible to define a correlation to calculate an equivalent LET correspondent to a given pulse energy? Yes, but you need to know the layout of the circuit. Otherwise only qualitative informations.**

X-Ray pulse to emulate His: dose release mechanisms



- Xe 995 MeV
- ◇ Kr 769 MeV
- △ Ni 582 MeV
- Ar 379 MeV
- 18 keV-2 nJ
- ◊ 18 keV-1.2 nJ
- ▲ 18 keV-0.9 nJ
- 18 keV-0.6 nJ

Credit L. Coic TRAD

Does the correlation under consideration has a physical meaning?

- Does the collected charge varies linearly with the pulse energy? Yes! Demonstrated in literature.
- Does the deposited dose is comparable with the one deposited by an HI? Is it lower than the max dose supported by the circuit? After a rough estimate the value of dose is quite high. Further modeling activity is needed.
- Is it possible to define a correlation to calculate an equivalent LET correspondent to a given pulse energy? Further modeling activity and an appropriate layout of the component is needed for quantitative data.

Does the correlation under consideration has a physical meaning?

- Does the collected charge varies linearly with the pulse energy? **Yes! Demonstrated in literature.**
- Does the deposited dose is comparable with the one deposited by an HI? Is it lower than the max dose supported by the circuit? After a rough estimate the value of dose is quite high. **Further modeling activity is needed.**
- Is it possible to define a correlation to calculate an equivalent LET correspondent to a given pulse energy?
Layout to be needed

What do we know

Logic and analog

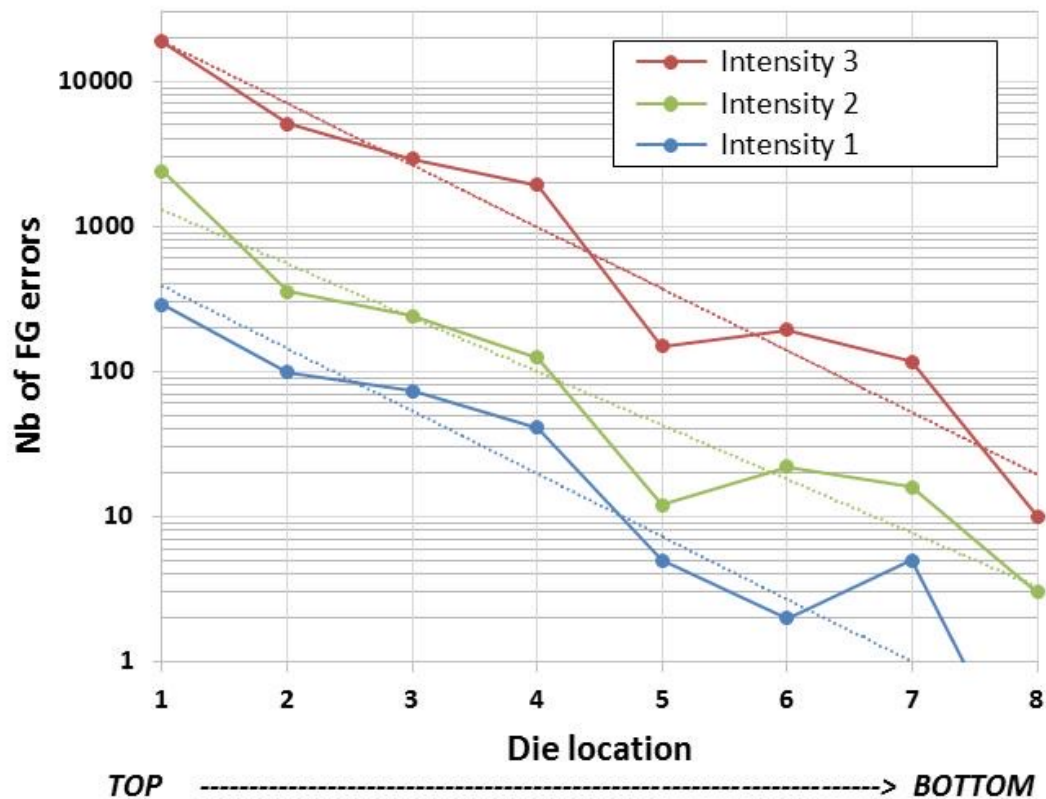
- SEE in Si, analog and digital, photodiodes, bipolar systems
- SEE in SiGe
- SEE in AlGaIn/GaN HEMT
- SEE in GaAs transistors

Power devices

- SEE SiC in power devices
- SEE GaN in power devices

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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