The use of synchrotron X-rays to emulate the interaction between heavy ions and electronic devices for next generation space application

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Platform for Advanced
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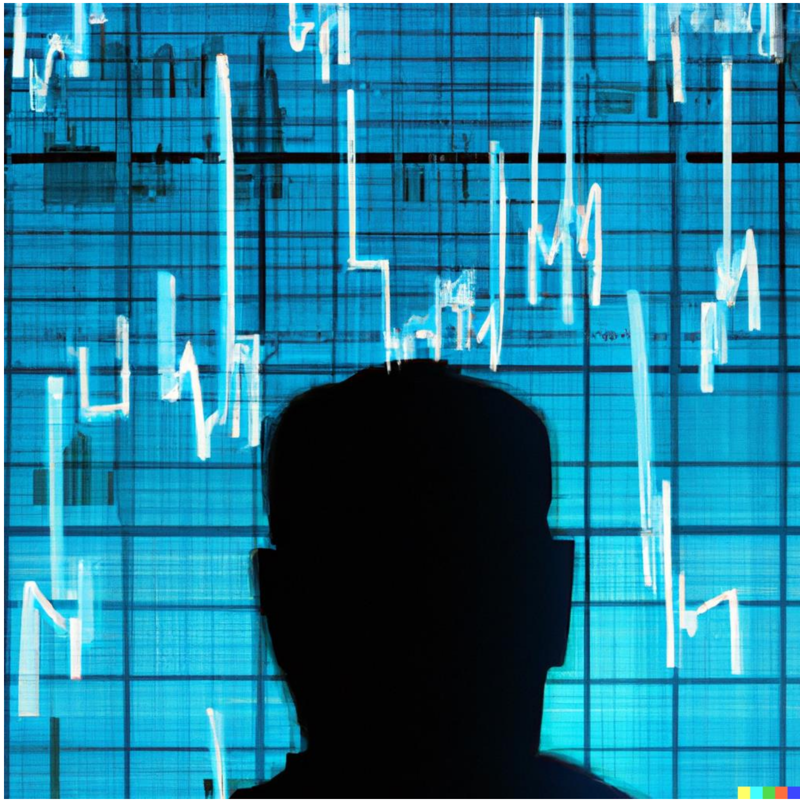
13/06/2024 – GB-RADNEXT

Why pulsed X-rays?

Market trends in aerospace and automotive sectors

- Increase of component demands -> increase in testing demand
- Increase of the use of COTS in RadHard environment -> increase in radiation hardness performaces and qualification of non-RadHard components
- Increase in the complexity of the components -> innovating packaging
- Cost reduction -> always

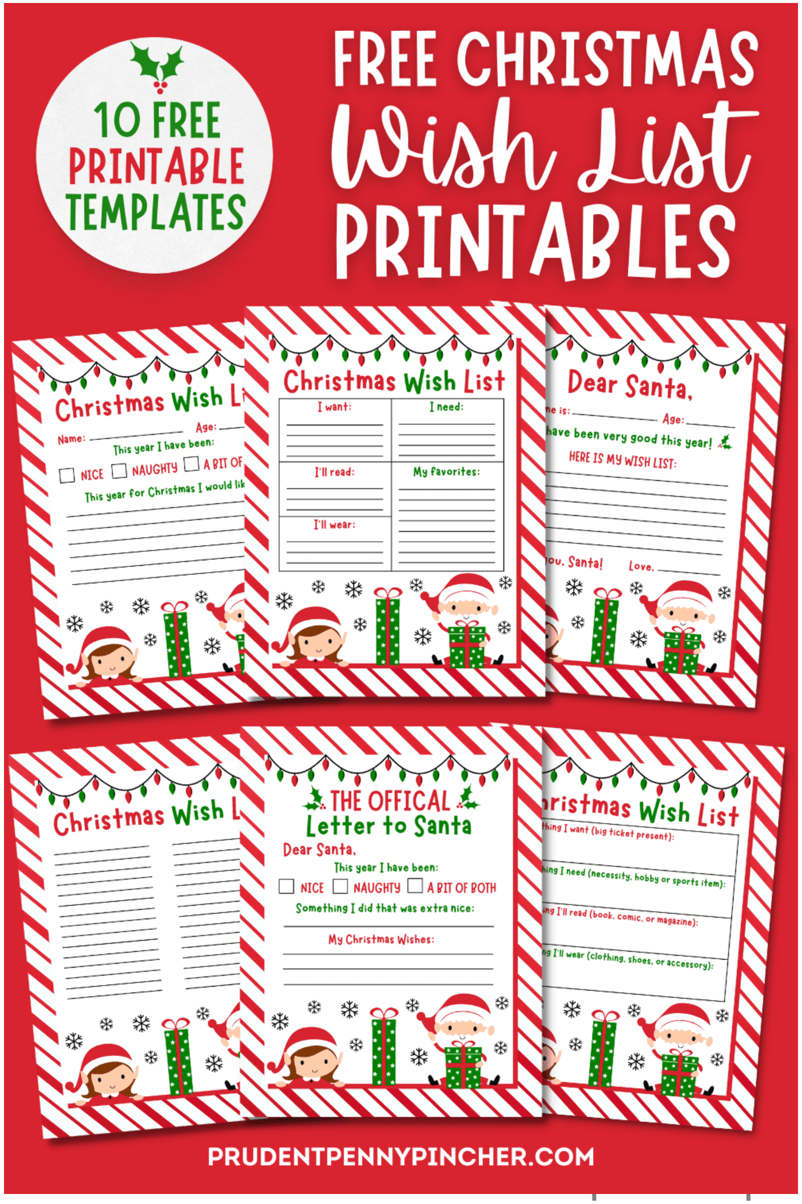


Heavy ions testing… a wish list

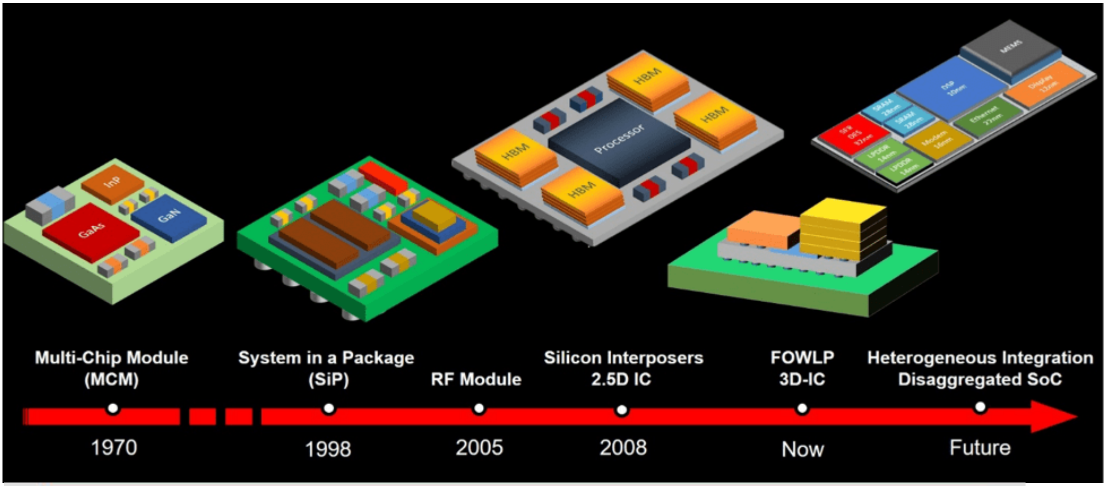
- Larger capacity, instrument availability -> qualification
- Possibility to have focused beams -> debugging
- Higher energy

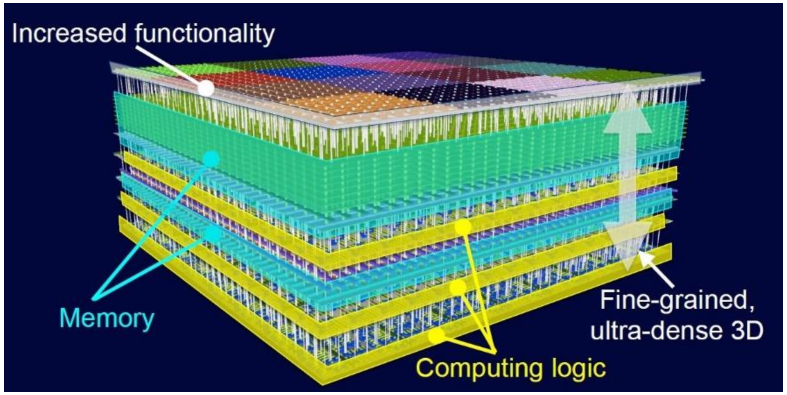
  -> Simplified sample preparation

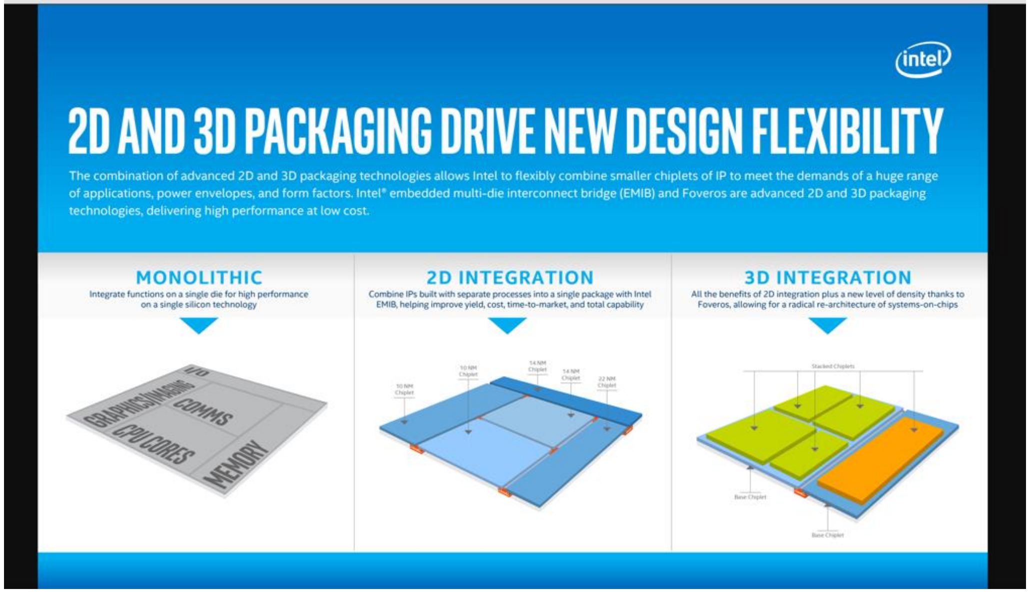
  -> Complex packaging



Trends in microelectronics: 3DIC






intel

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

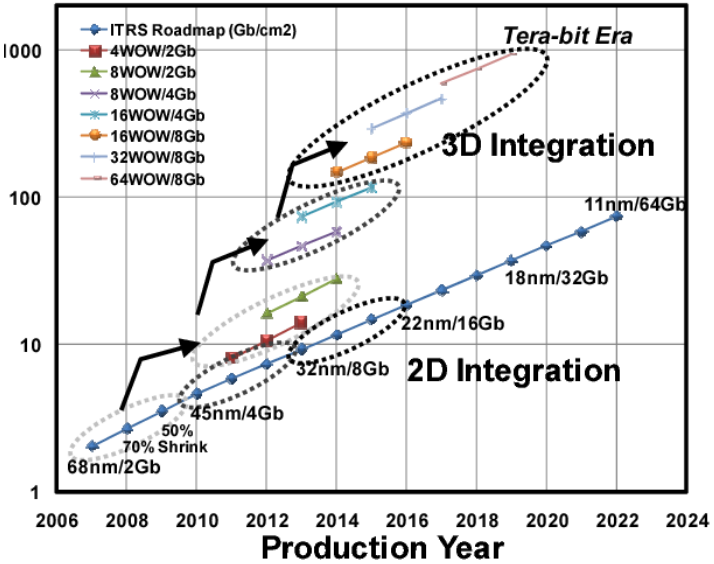
Integrate functions on a single die for high performance on a single silicon technology

2D INTEGRATION

Combine IPs 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



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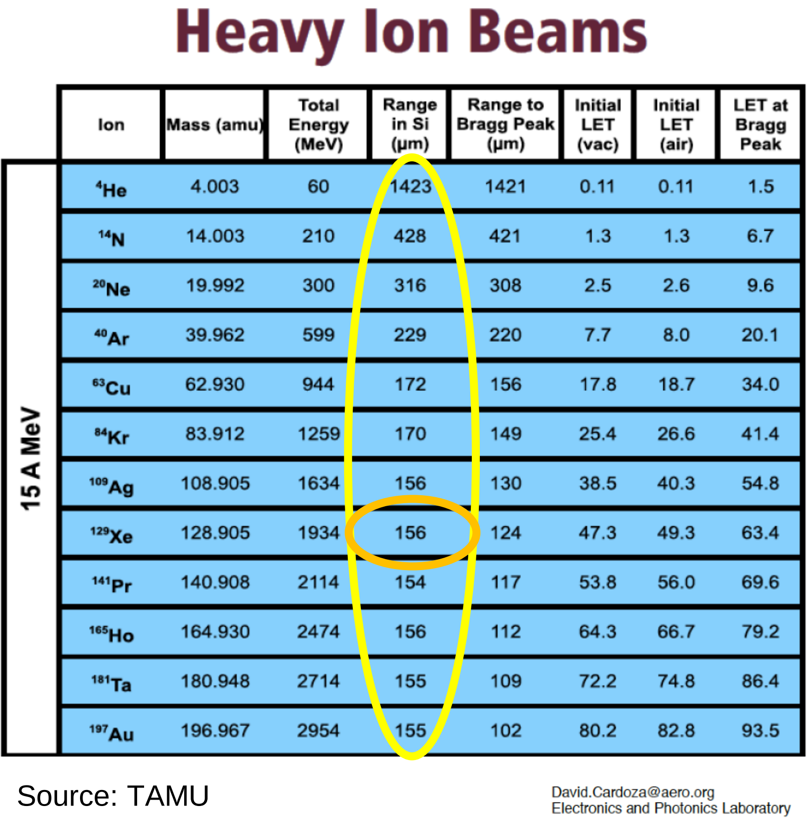
Trends in microelectronics: 3DIC

- Laser is adapted for less integrated components in Silicon but for modern components with several metallisation levels this become critical.
- Moreover when the device complexity is growing also standard heavy ions sources have a serious problem of penetration:
  - Range HI in Silicon:
    - 15 MeV/amu: Xe (2 GeV) = 156 µm
    - 4.6MeV/amu: C (55 MeV) = 72 µm



Heavy Ion Beams

	Ion	Mass (amu)	Total Energy (MeV)	Range in Si (µm)	Range to Bragg Peak (µm)	Initial LET (vac)	Initial LET (air)	LET at Bragg Peak
15 A MeV	^{4}He	4.003	60	1423	1421	0.11	0.11	1.5
	^{14}N	14.003	210	428	421	1.3	1.3	6.7
	^{20}Ne	19.992	300	316	308	2.5	2.6	9.6
	^{40}Ar	39.962	599	229	220	7.7	8.0	20.1
	^{63}Cu	62.930	944	172	156	17.8	18.7	34.0
	^{84}Kr	83.912	1259	170	149	25.4	26.6	41.4
	^{109}Ag	108.905	1634	156	130	38.5	40.3	54.8
	^{129}Xe	128.905	1934	156	124	47.3	49.3	63.4
	^{141}Pr	140.908	2114	154	117	53.8	56.0	69.6
	^{165}Ho	164.930	2474	156	112	64.3	66.7	79.2
	^{181}Ta	180.948	2714	155	109	72.2	74.8	86.4
	^{197}Au	196.967	2954	155	102	80.2	82.8	93.5

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Source: TAMU

Trends in microelectronics: 3DIC

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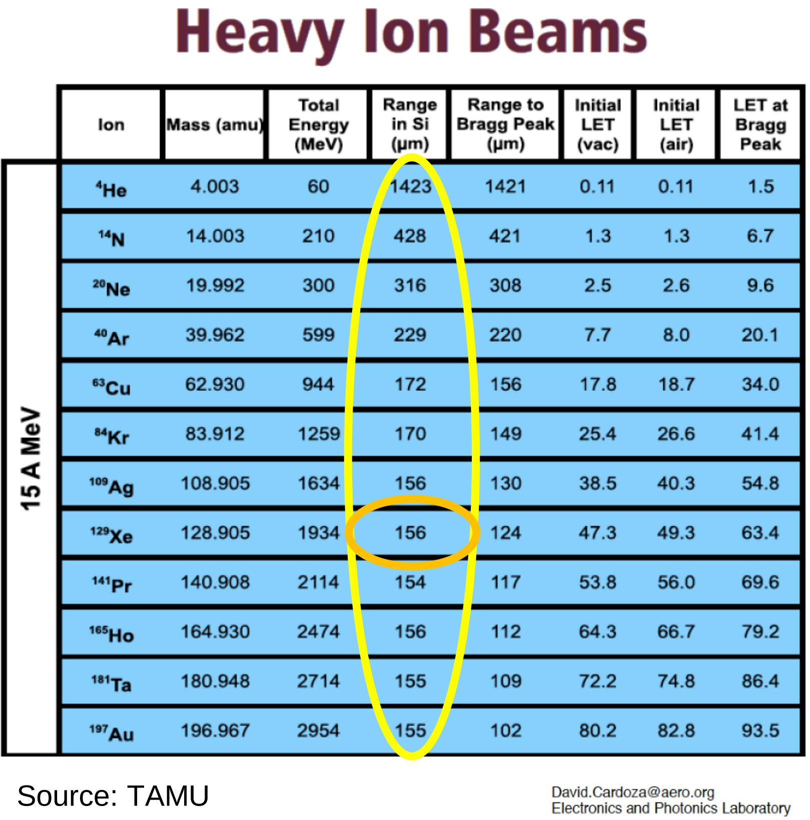

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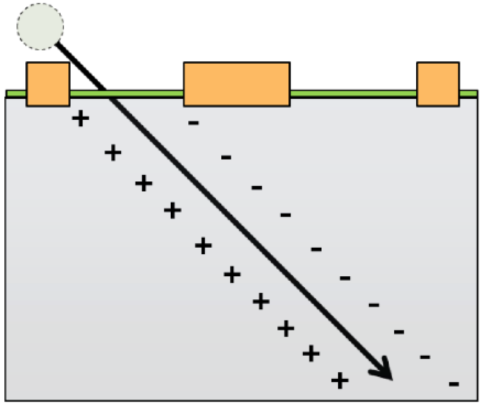
Can **focused X-ray pulses** complement laser testing when circuits become too complex or when a simplified sample preparation procedure is demanded?

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

Addressed by lasers

Non addressed by lasers

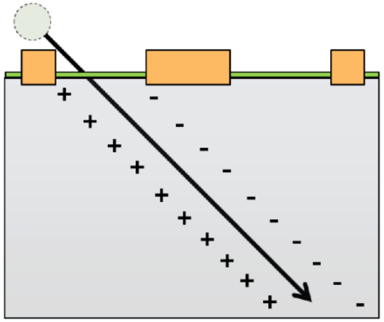
Basic theoretical evaluations?

Are the beam characteristics appropriate?

X-Ray pulse to emulate HIs: carrier generation

Heavy ions have high LET

=>1 ion creates high density of electron/hole-pairs along the path (Ø 100 nm), along a release time of 100fs.



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- 55 MeV Carbon: LET of 500 keV/µm

=> ≈ 1E5 electrons per µm = 7E6 electrons (assuming 70um penetration depth)

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

E_γ → **Photon energy (~ 1000s eV)**

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

$\frac{E_\gamma}{\Delta E}$ → **Factor on the order of 10^3 - Large**

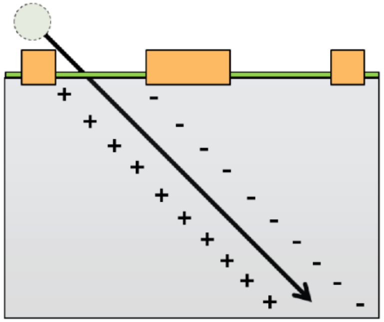
- 2000 MeV Xenon: LET of 11.000 keV/µm

=> ≈ 2E6 electrons per µm = 3E8 electrons (assuming 150um penetration depth)

X-Ray pulse to emulate His: carrier generation

X-ray

A 10 keV photon X-ray absorbed in Si produces photo electron leading to carrier creation ≈ 2000 pairs



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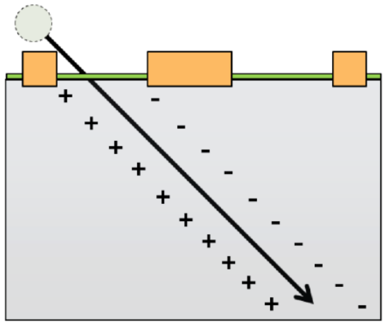
X-Ray pulse to emulate His: carrier generation

X-ray what is needed (ideal case)

3.5E4 - 1.5E5 ph/pulse fully absorbed in the active area

100fs

Diam. < few nm



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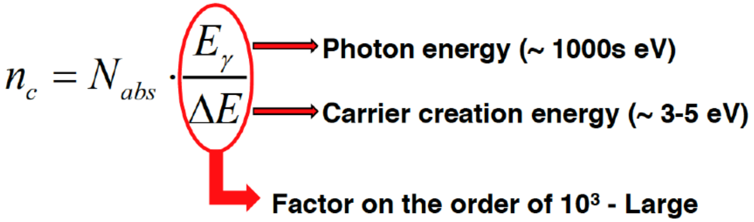

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X-Ray pulse to emulate His: carrier generation

X-ray what needed (ideal case)

3.5E4 - 1.5E5 ph/pulse fully absorbed in the active area

100fs < pulse duration < commuting time

Diam. < few nm

X-ray available on ID09 @ ESRF

4E9 ph/pulse

150ps < commuting time

Diam 35um

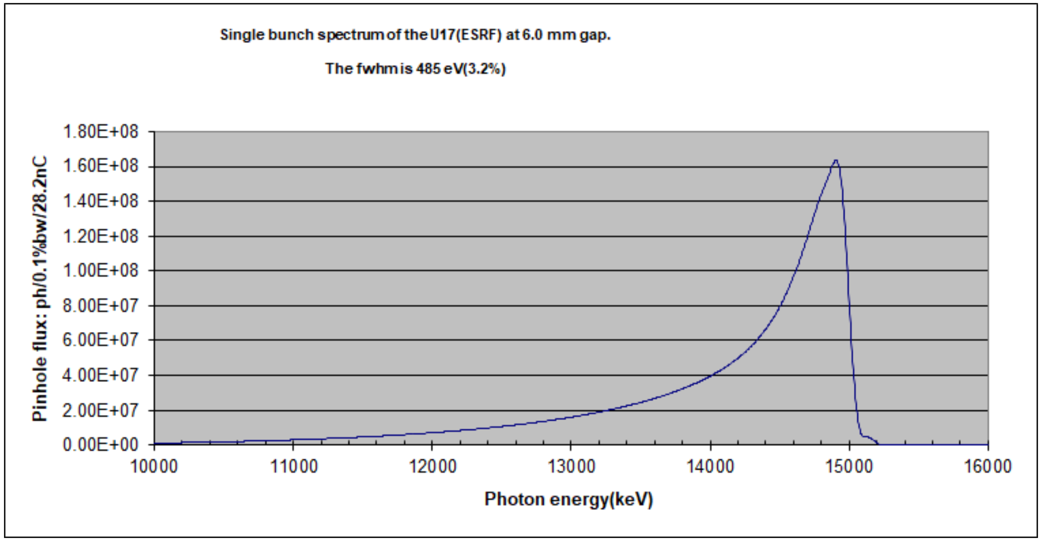
or (with a pinhole)

8E7 ph/pulse

150ps < commuting time

Diam 5um

- The energy of the pulse is 9.6 uJ
- The energy spectrum is half Lorentian with a bandwidth of 3.2% around 15keV



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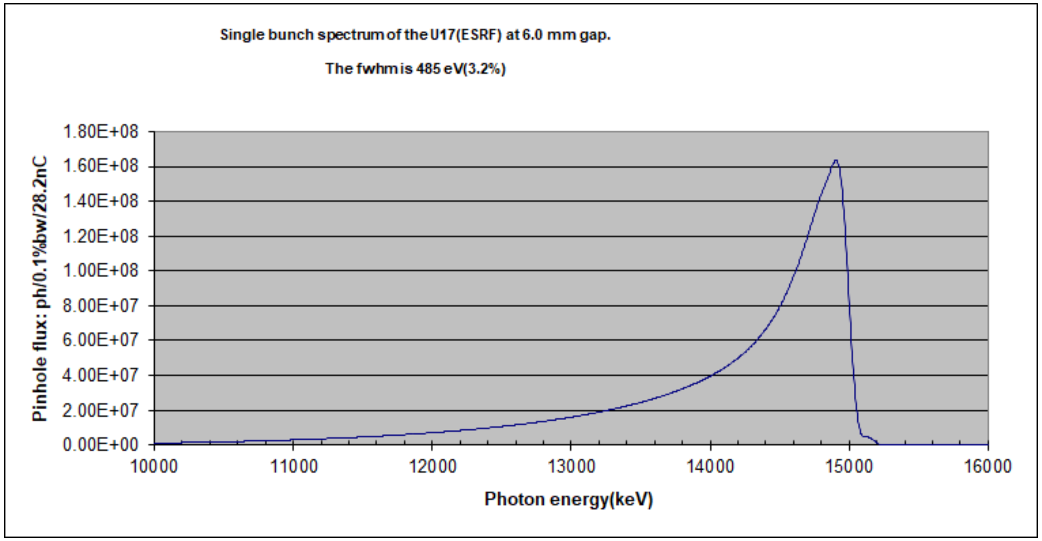
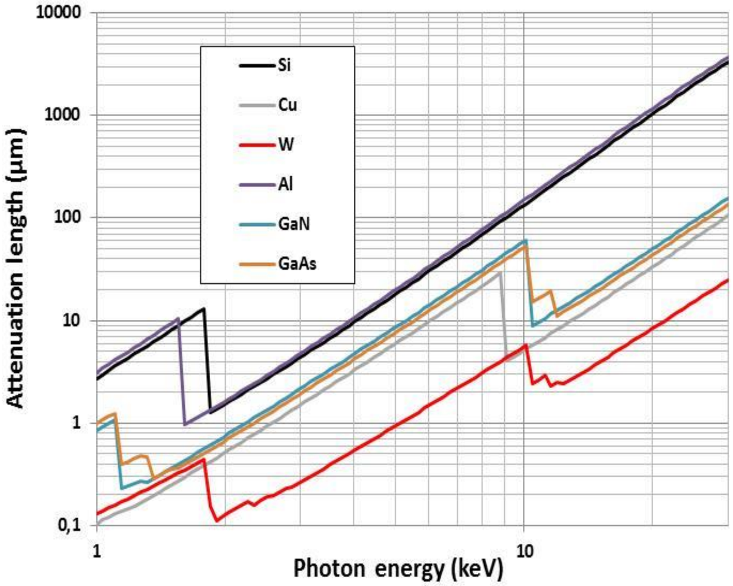
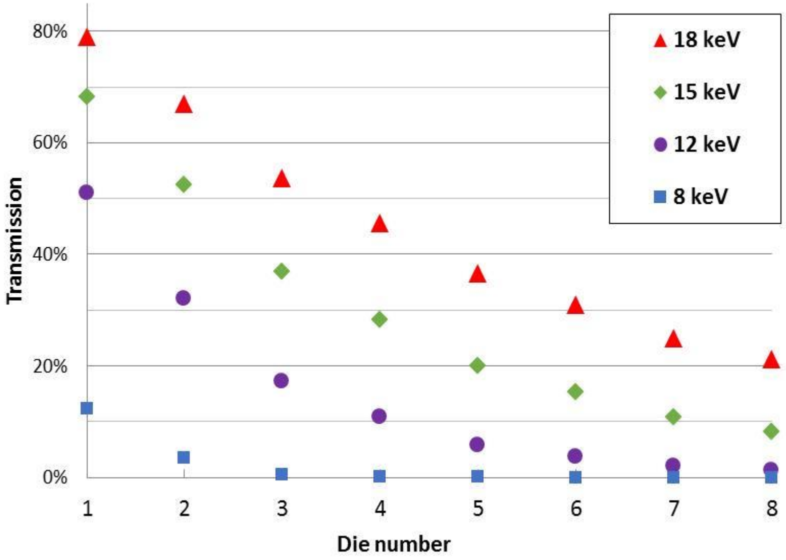


X-Ray pulse to emulate HI: penetration

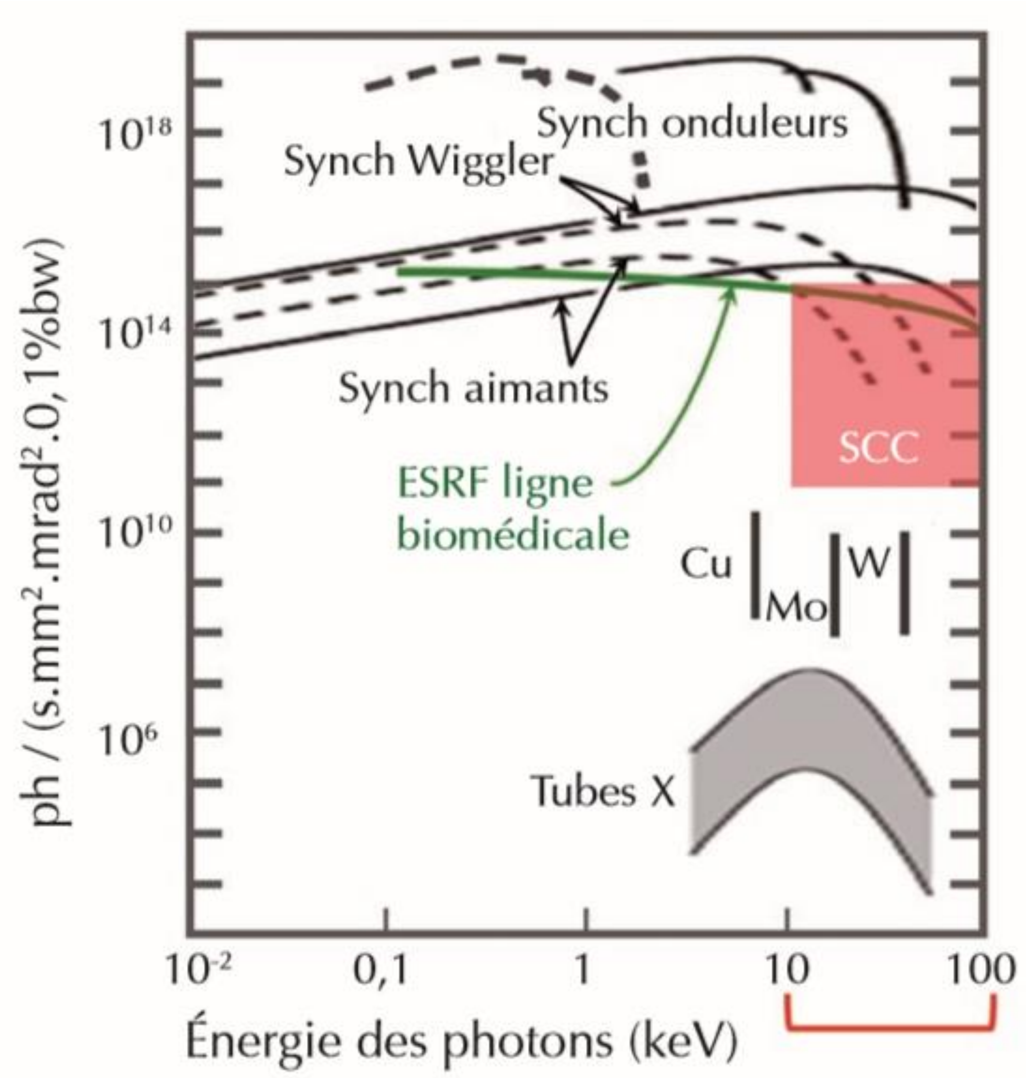


X-ray attenuation lengths of materials commonly used in IC manufacturing [7]. For comparison purpose, a 1064 nm laser beam in silicon having a doping level of 2.1018cm has an attenuation depth of 330 µm



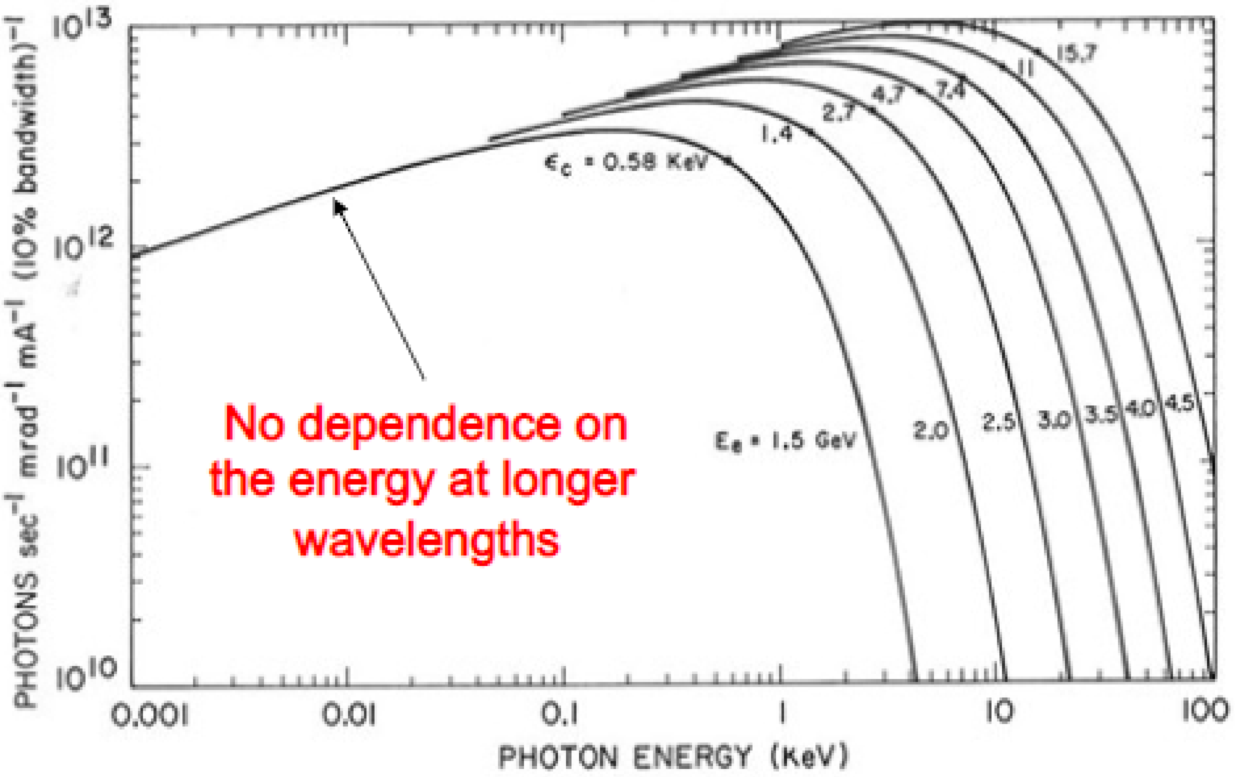
X-ray transmission as a function of die number (hypothesis dice thickness 200um)

X-Ray pulse to emulate HI: sources



3rd gen synchrotrons seems
the only candidates with
the right
brilliance

X-Ray pulse to emulate HI: sources



No dependence on the energy at longer wavelengths

- Medium energy synchrotron can be promising only up to 10keV
- For larger energies high energy synchrotrons are needed

X-Ray pulse to emulate His: localized dose (TID)

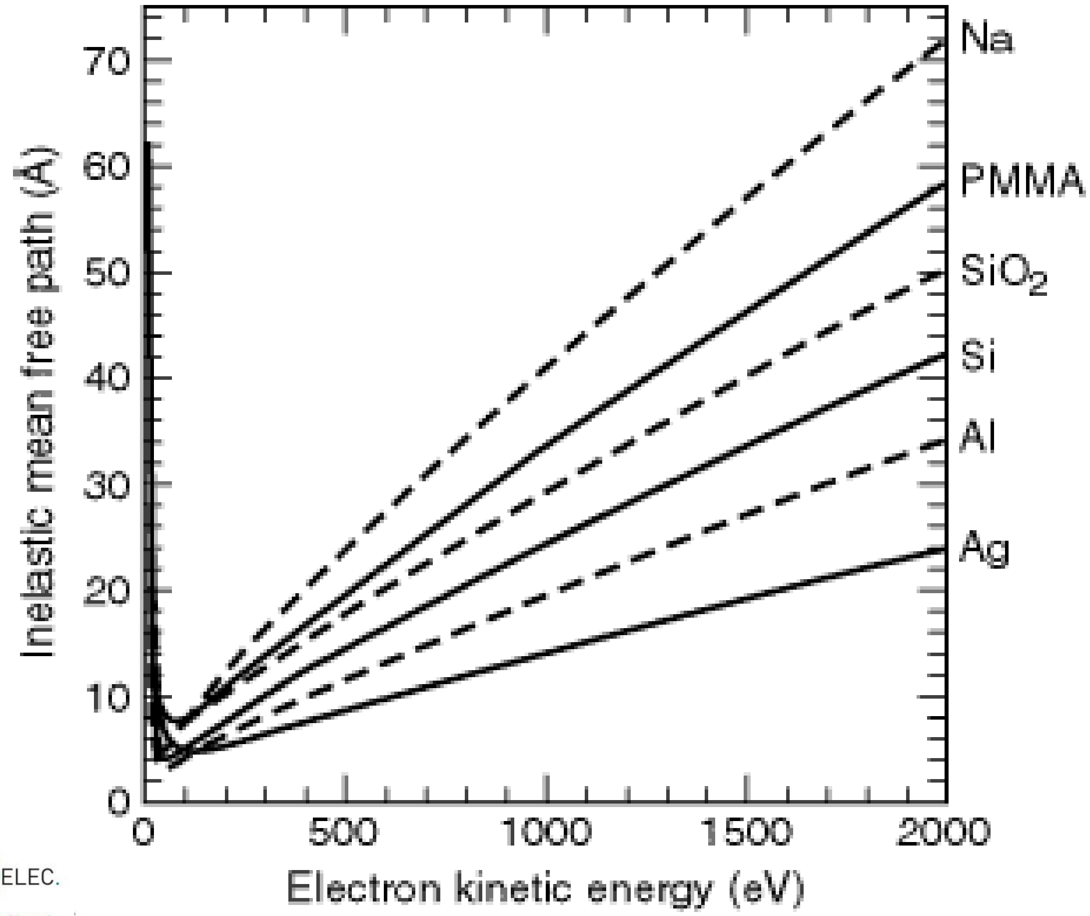
Dose calculation

- Energy of the pulse: 9.6E-6 J/pulse
- Spot size: 35um
- Photon energy: 15keV
- Pulse duration: 100ps
- Oxide thickness: 3nm
- The **localised** dose is 2335 Gy/pulse = 234 krad/pulse

https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

X-Ray pulse to emulate His: ionization track diametre

High energy X-ray may offer the possibility to reach deep layers, but would the ionization track diameter still be meaningful?



Ionisation cloud for the punctual impact of one photon can be estimated:

- 10keV: 7-20 nm
- 100keV: 140-400nm

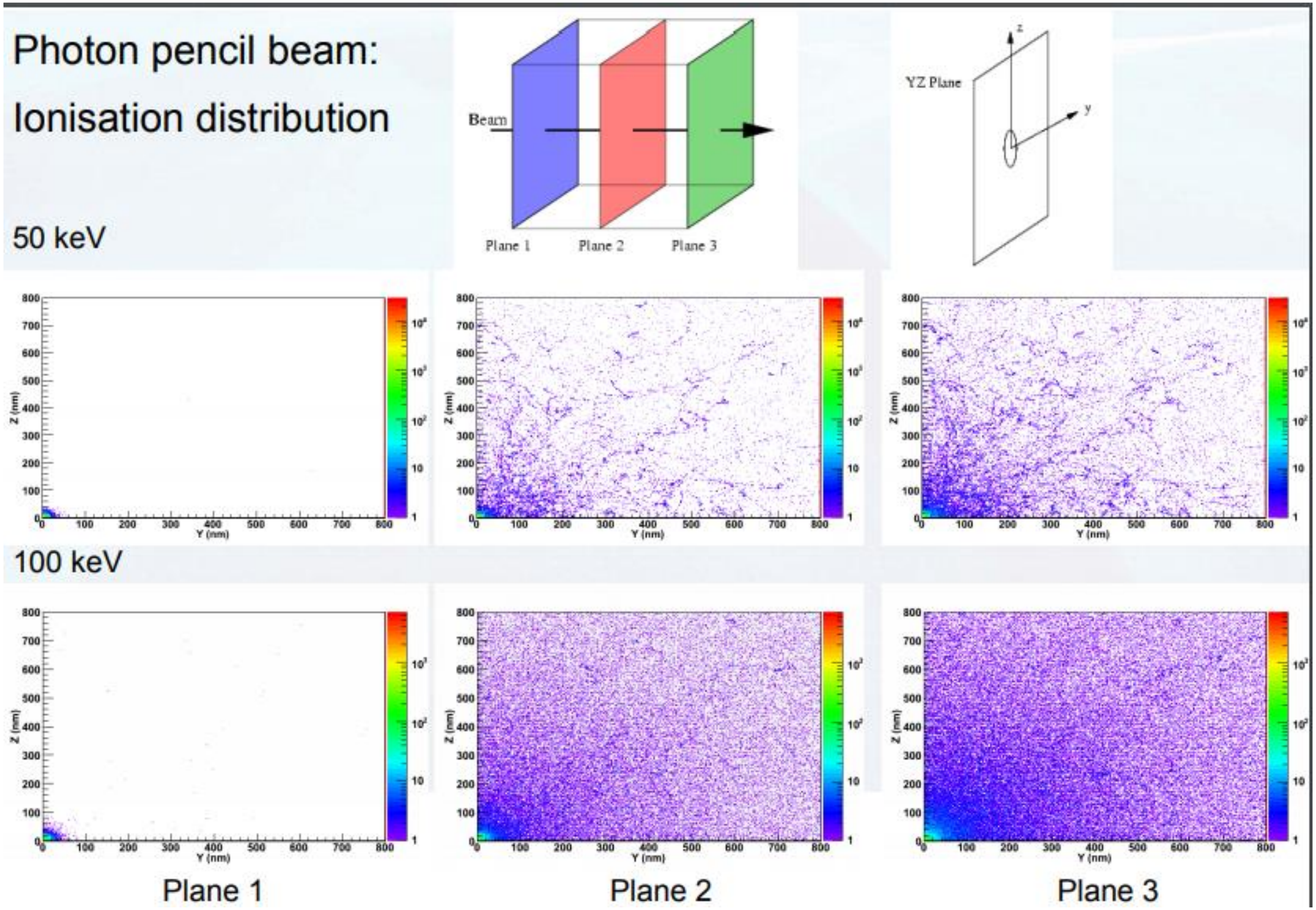
With a 100nm large beam, this means having a ionization track of:

- 10keV: 115-140 nm
- 100keV: 380-900nm

X-Ray pulse to emulate His: ionization track diametre

With a certain spread in deeper layers

Simulation of the behavior
on a 400um thick block of ice



Photon pencil beam:

Ionisation distribution

50 keV

100 keV

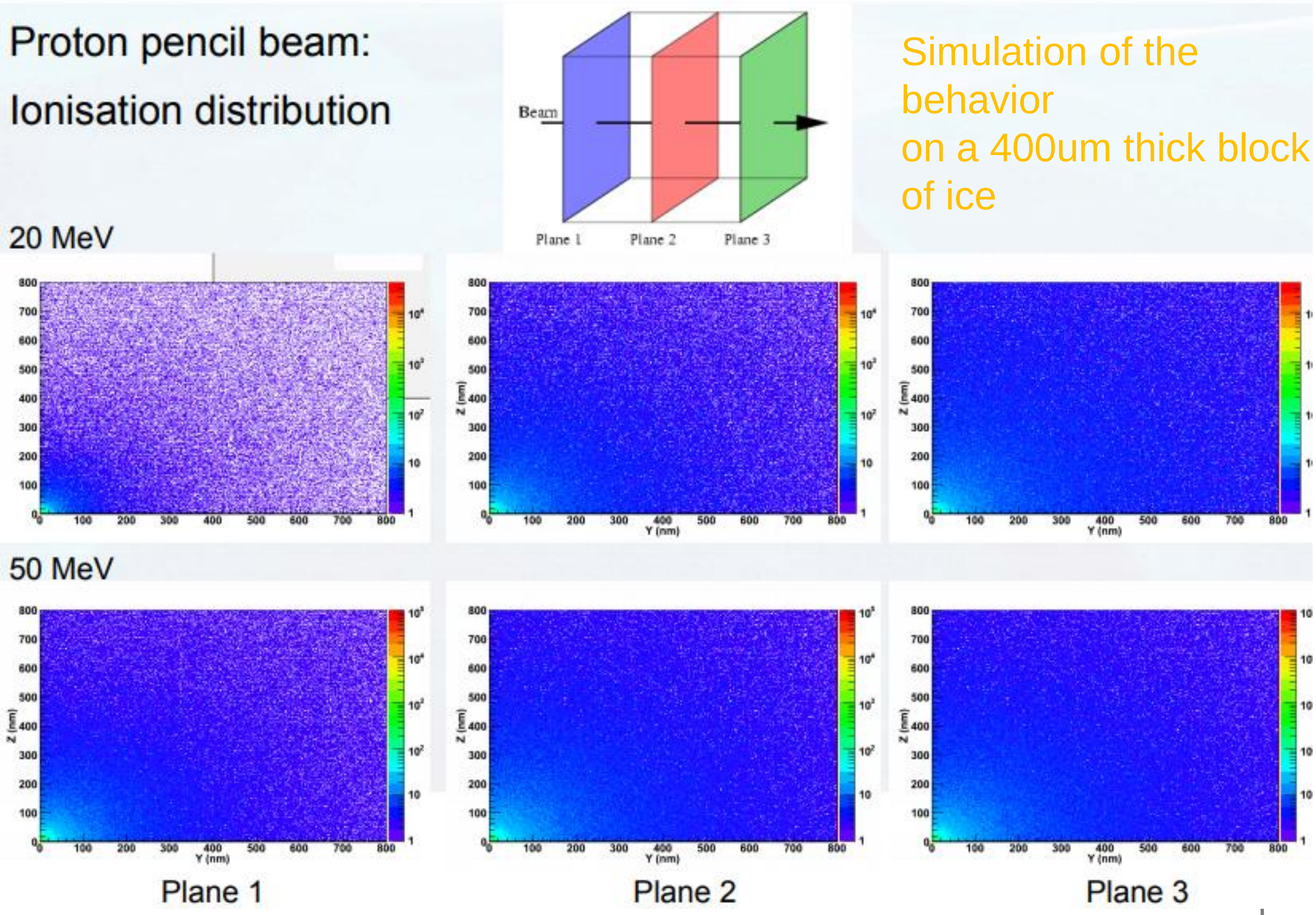
Plane 1

Plane 2

Plane 3

X-Ray pulse to emulate His: ionization track diametre

Comparable with the proton ionisation profile



Proton pencil beam:

Ionisation distribution

Simulation of the behavior
on a 400um thick block
of ice

20 MeV

50 MeV

Plane 1

Plane 2

Plane 3

Preliminary results

X-Ray pulse to emulate His: State of the art

- 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.

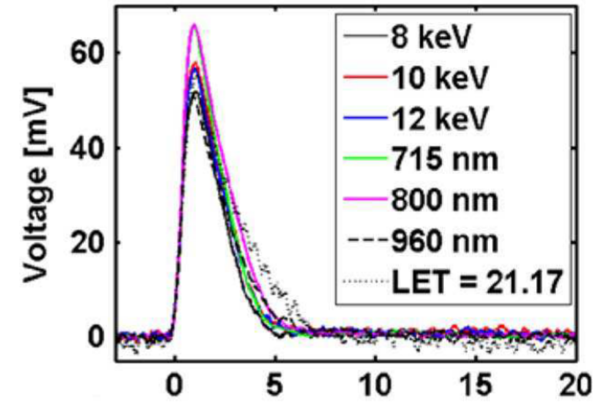


Figure 12: SET observed with laser photons, X-photons and heavy ions

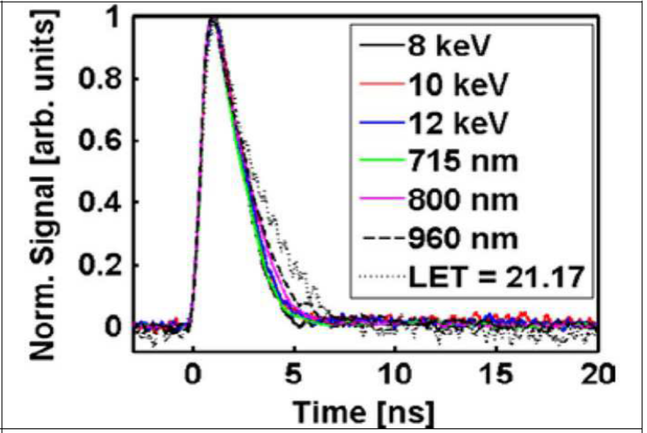
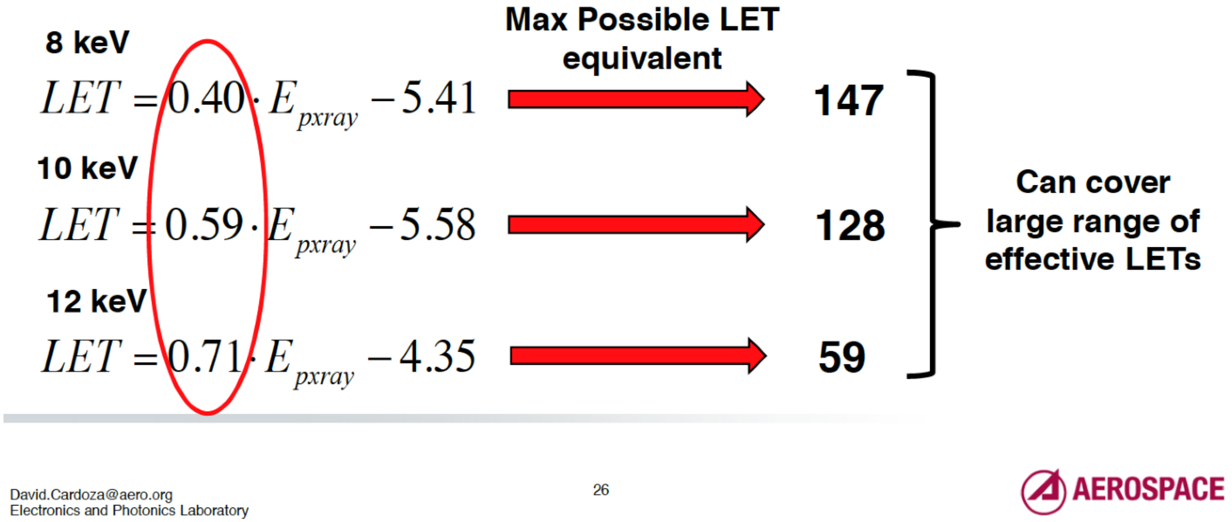


Figure 13: Standardized SETs obtained with laser photons, X-photons and heavy ions

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

X-Ray pulse to emulate His: State of the art

SET Experiments with Si PIN diode at APS:



Max Possible LET equivalent

8 keV

$$LET = 0.40 \cdot E_{pxray} - 5.41$$

147

10 keV

$$LET = 0.59 \cdot E_{pxray} - 5.58$$

128

12 keV

$$LET = 0.71 \cdot E_{pxray} - 4.35$$

59

Can cover large range of effective LETs

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AEROSPACE

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

Devices on which SET/SEE have been observed

Logic and analog

- SET in Si, analog and digital,components photodiodes, bipolar systems
- SET in SiGe
- SET in AlGaN/GaN HEMT
- SET in GaAs transistors

Power devices

- SET SiC in power devices
- SET GaN in power devices

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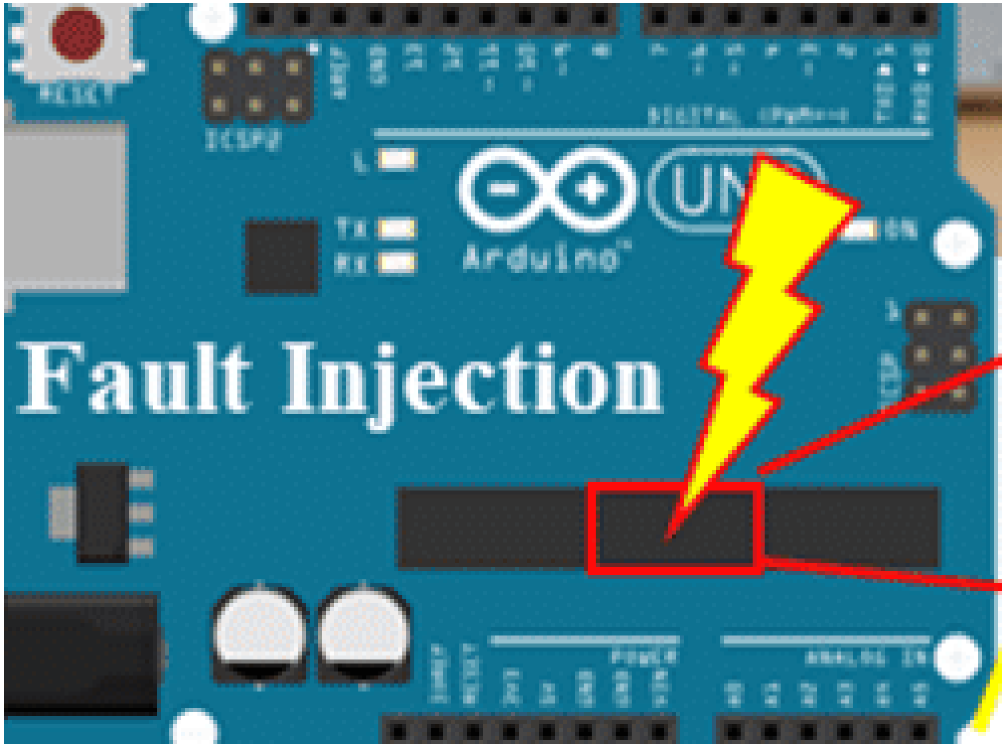
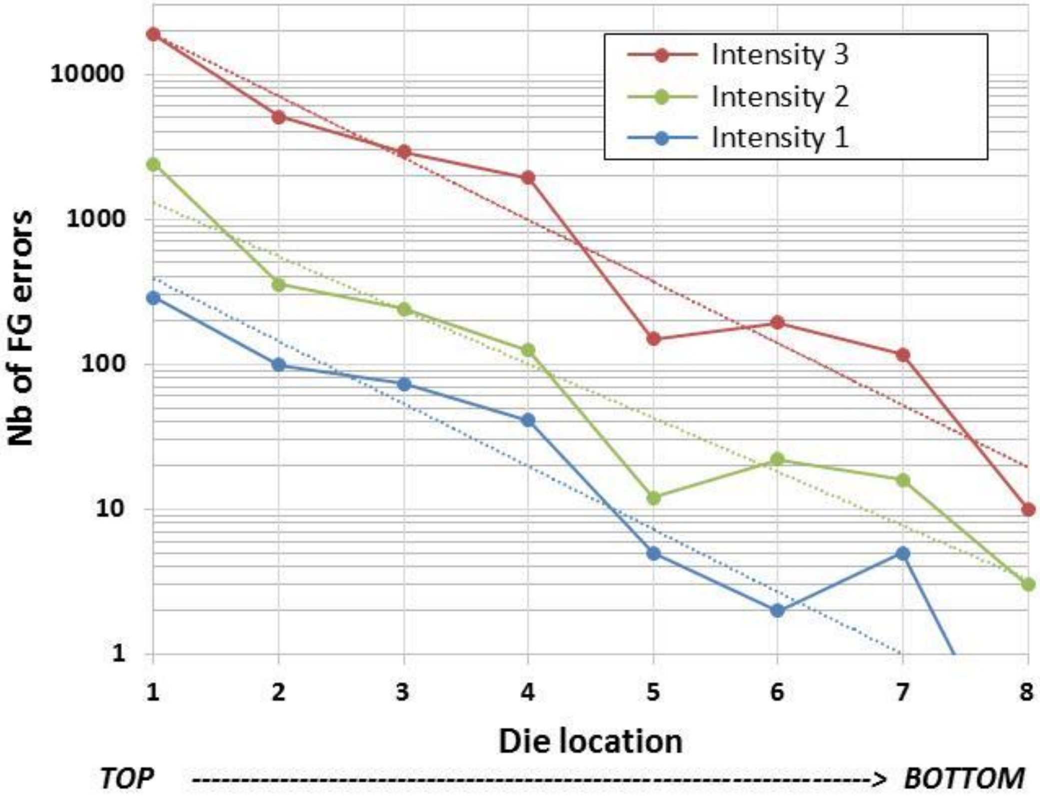
Fault injection



- Localised fault injection has been demonstrated for:
  - Functional safety investigation
  - Cybersecurity resistance evaluations

3 case studies at the ESRF

CASE 1: 3D integrated circuit

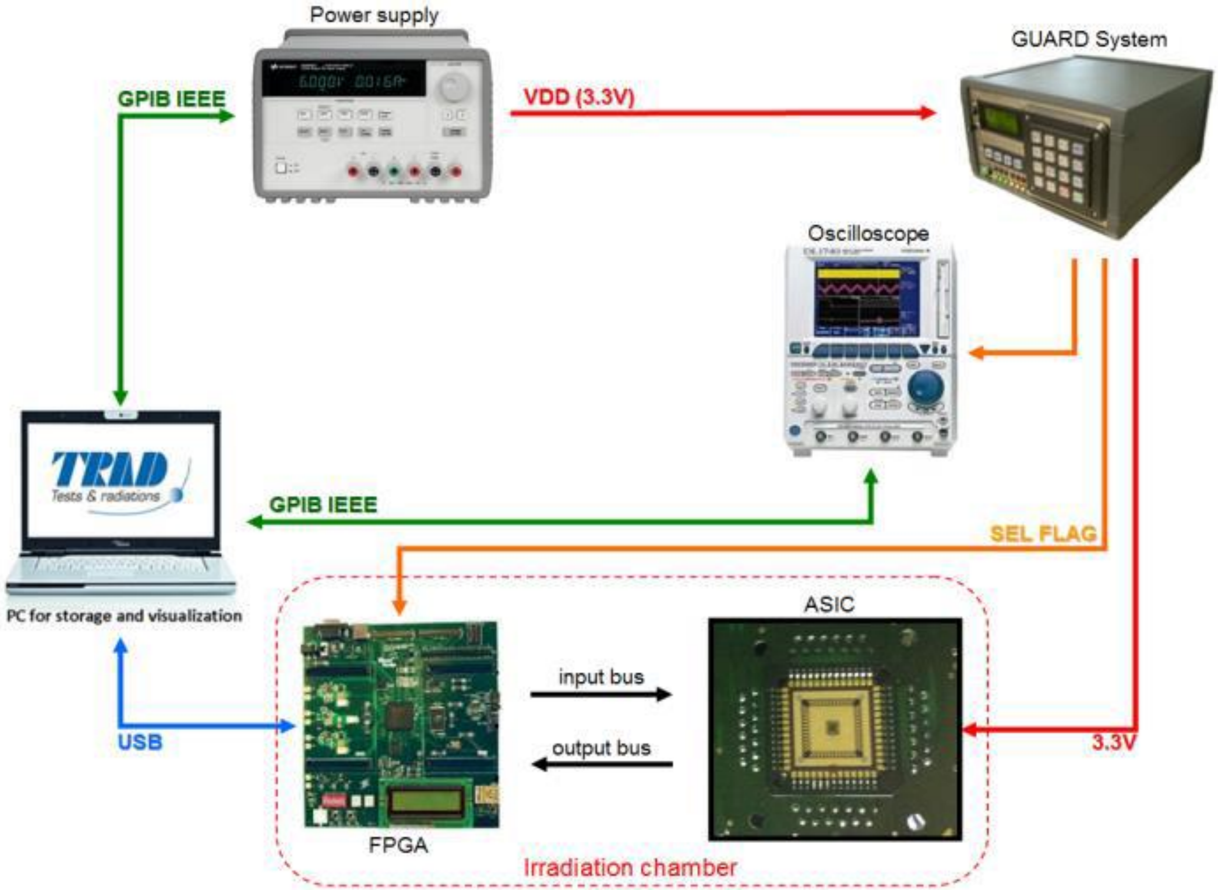


AIRBUS

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*

CASE 2: Photodiode



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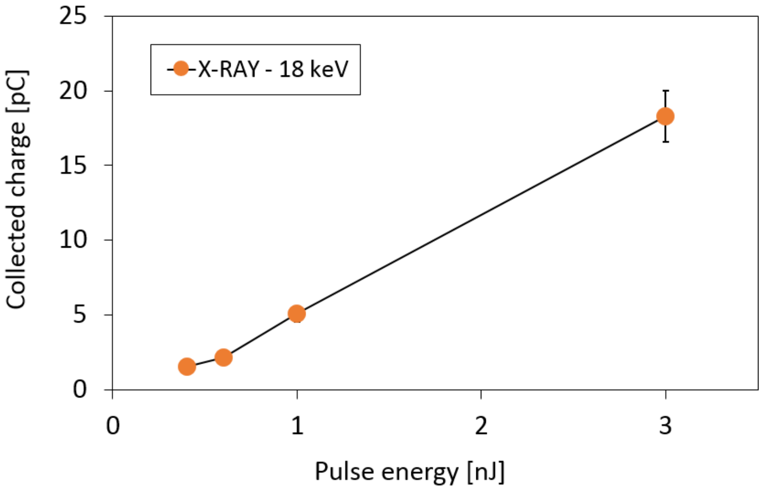
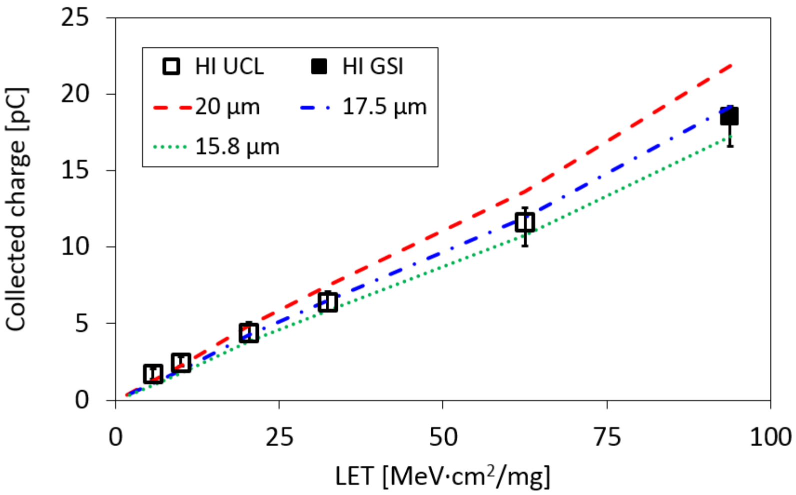
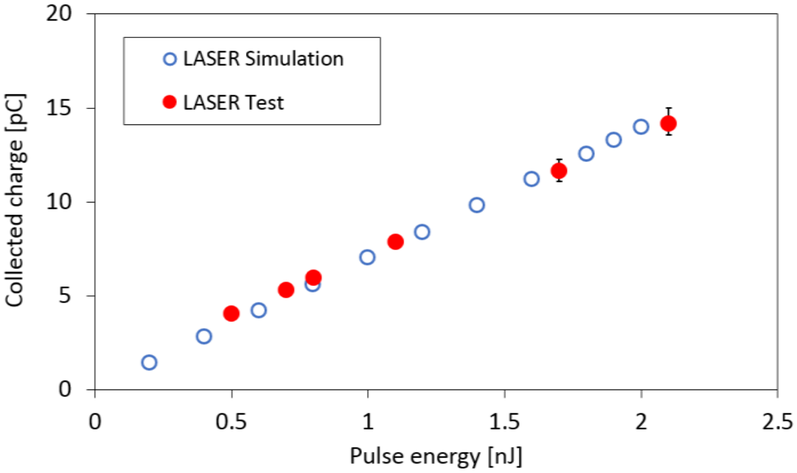






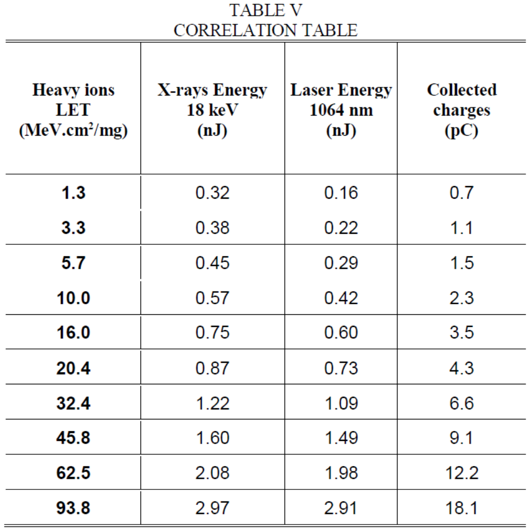
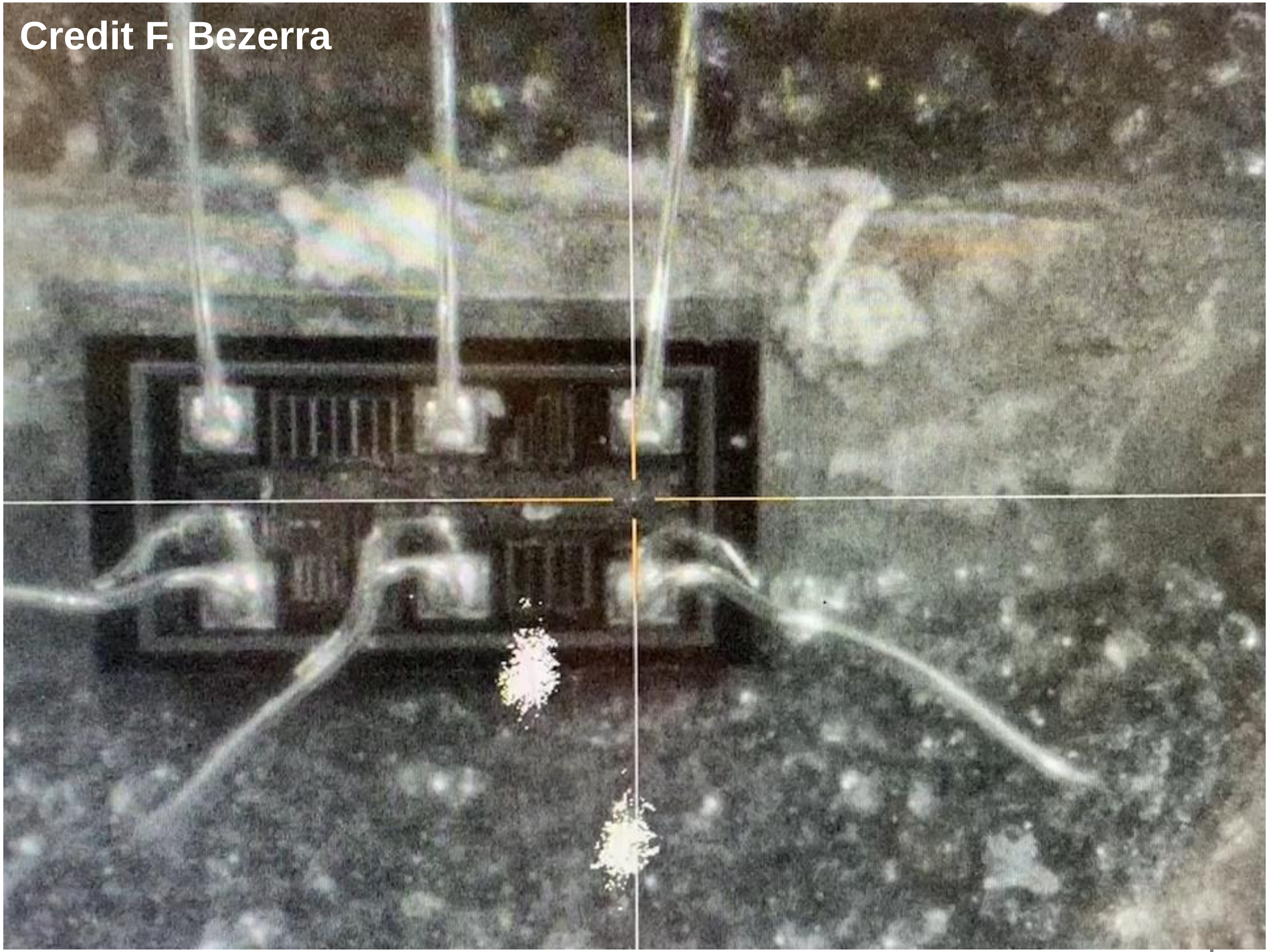


TABLE V
CORRELATION TABLE

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

G. Augustin, M. Mauguet, N. Andrianjohany, N. Chatry, F. Bezerra, E. Capria, M. Sander and K-O. Voss, Proceedings of RADECS 2019

CASE 3: Latchup



What do we miss?

Modelling of the SEE

- High fidelity models are needed in order to predict SEE and understand the interaction of X-ray pulses and correlate with NI LET.
- This model should take into account the characteristics of the material , the quantum confinement effects of nanostructures and the stress.
- Dedicated experiments need to be designed, in case involving pulsed/nanofocus beams

Understand TID

- Predict TID deposited; the complication is due to the extreme time and space localisation condition of the energy deposited which could likely trigger some non linear phenomena.

Take away messages

- The capability of synchrotron pulsed X-rays to deposit critical charges on electronic components has been demonstrated
- This can be used for:
  - Fault injection
  - Pre-screening (latchup or other)
  - LET/sensitivity characterisation
- Possibility to analyse non-decapsulated components and stacked/complex components has been demonstrated; the experiment should be carefully designed
- The possibility to focus beams can allow mapping experiments to allow the identification of critical areas
- Dose can be a problem
- For high photon energies, the spatial localisation has to take into consideration the mean free path of secondary electrons
- If you are interested to try…RADNEXT!

WHICH WOULD BE THE NEXT COMPONENT WE WANT TO MEASURE?

Further take away message

- The capacity is there
- Huge range of instruments capabilities and energy
- Time structure is rare
- Irradiation is not a strategic mission
- **A community effort is needed**

Do not miss the bonus…

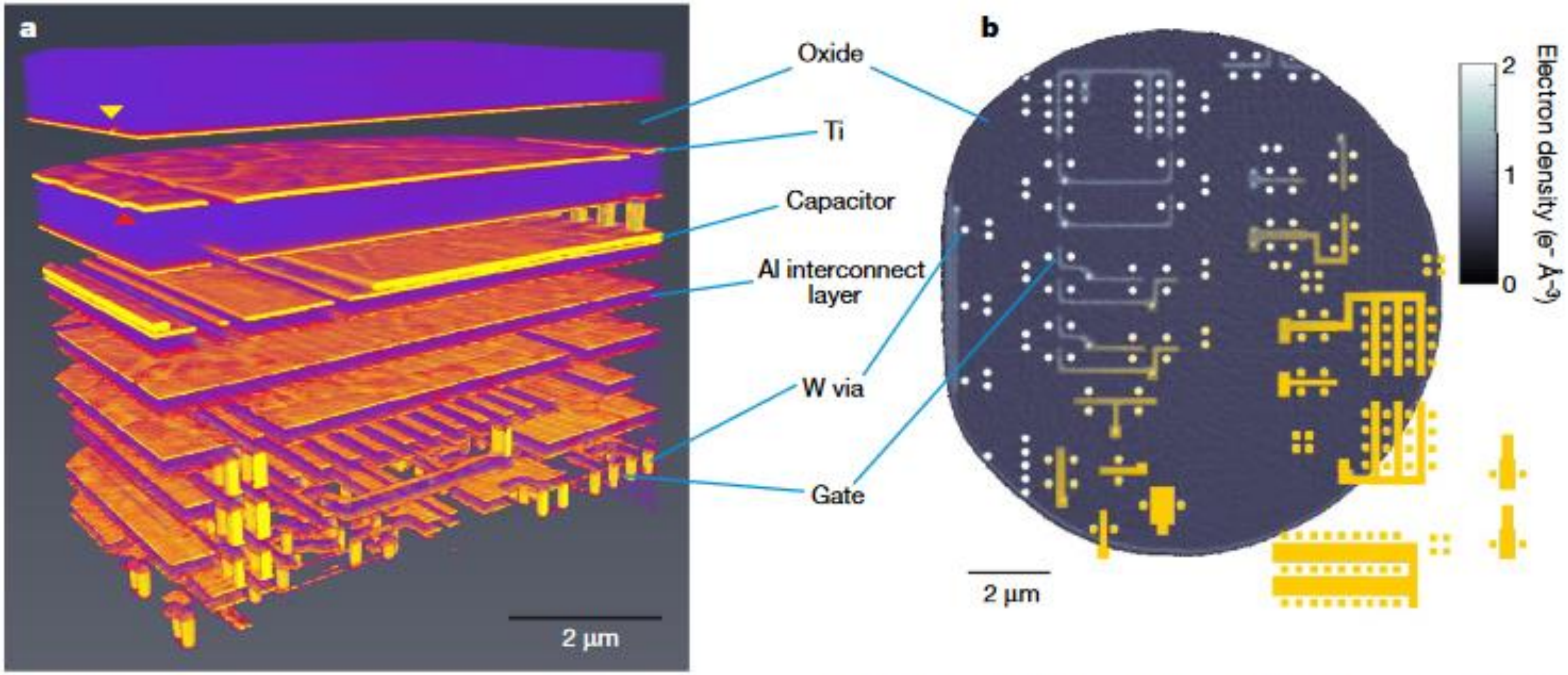


Figure 2 | PXCT of detector ASIC chip. a, 3D rendering of the PCXT tomogram with identified elements. The yellow triangle indicates a manufacturing fault in the Ti layer. The Al layer in the region of the red triangle shows variances in thickness causing a waviness of the Ti layer on top. Via, through-layer connector. **b,** Axial section across the second lowest layer, which contains the transistor gates; the grey scale (top right) represents electron density (in e^{-} $Å^{-3}$). The corresponding layer from the design file is shown as the partial overlay in yellow.

Possibility to run high resolution 3D imaging non-destructive failure analysis

M. Holler *et al*., "Three-dimensional imaging of integrated circuits with macro- to nanoscale zoom" in *Nature Electronics*, vol. 2, pp. 464-470, 2019

M. Holler *et al*., "High-resolution non-destructive three-dimensional imaging of integrated circuits" in *Nature*, vol. 543, pp. 402-406, 2017

ESRF
The European Synchrotron

Many thanks to:

The ID09 team
Michael Wulff
Matteo Levantino
Mathias Sanders

The AIRBUS team
Cécile Weulersse
Christian Binois
Hagen Schmidt

The TRAD team
G. Augustin
M. Mauguet
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