Study of Total Non-Ionizing Dose

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Overview of the Study

Main Goal

- Development of a Total Non-Ionizing Dose (TNID) testing methodology adapted to the different fields of application encountered in the RADNEXT project.

Main approach

- Compare and model the radiation induced **leakage/dark current** of **two reference device types** over **various TNID irradiation conditions.**

- Two devices will be studied simultaneously:

  - **Sub-Task 7.3.1: Silicon PN junction**
    ➔ Gives the average response of silicon over a large silicon volume
  - **Sub-Task 7.3.2 : Silicon detector/image sensor Pixel Array**
    ➔ Gives the statistical distribution of the response of silicon microvolumes

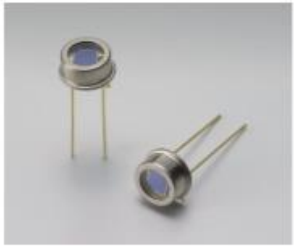
Devices Under Test - Photodiode

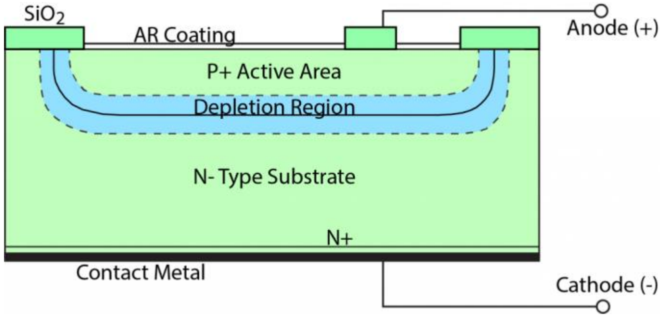
Photodiode Requirements

- Weak TID sensitivity (lowest possible)
- **Large enough to ignore edge effects**
- Weak electric field enhancement (lowest possible)
- Measurable dark current
- **Info available in the literature to estimate the depletion volume**
- Affordable

PIN photodiode 1223 series from Hamamatsu

- Pros
  - Matches all the requirements
- Cons
  - Low reverse current (i.e., pA)





Credit: Hamamatsu / Cross section of a photodiode

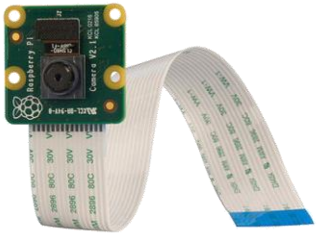
Devices Under Test – CMOS Image Sensor (CIS)

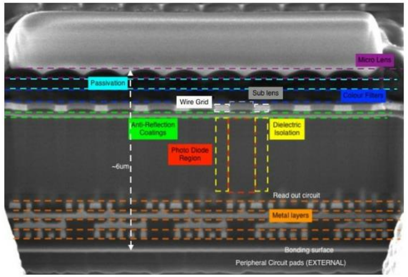
Silicon Pixel Array Requirements

- Weak TID sensitivity (lowest possible)
- Negligible edge effects
- **Weak electric field enhancement (lowest possible)**
- **Very small microvolume (lowest possible)**
- Measurable dark current
- **Affordable**
- Limited test bench development effort
- **Info available in the literature to estimate the depletion volume**

SONY IMX219PQ

- Pros:
  - Matches the requirements
  - **Already tested to TNID in the literature.**
- Cons:
  - **Dark current clamping prevent direct access to the absolute dark current value**





Credit: Sony / Cross section of the IMX219PQ CMOS Image Sensor (CIS)

Starting Hypothesis – Mean Dark Current Increase

- For neutrons/protons with E ∈ [**1-200 MeV**], the TNID induced dark current increase in silicon microvolume is proportional to the total Displacement Damage Dose (D_{dd}) (Srour & Lo UDF*):

Damage Factor

Displacement Damage Dose

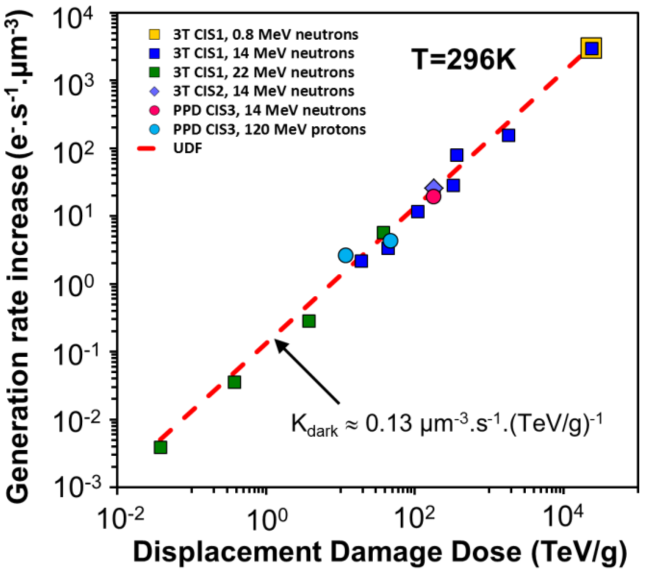
$$\Delta I_{obs} = q \cdot K \cdot V_{dep} \cdot D_{dd}$$

Mean dark current increase

Depletion volume

$$K = 1.4 \pm 0.5 \ \ \mathrm{cm}^{-3} \cdot \mathrm{s}^{-1} \cdot (\mathrm{MeV/g})^{-1}$$

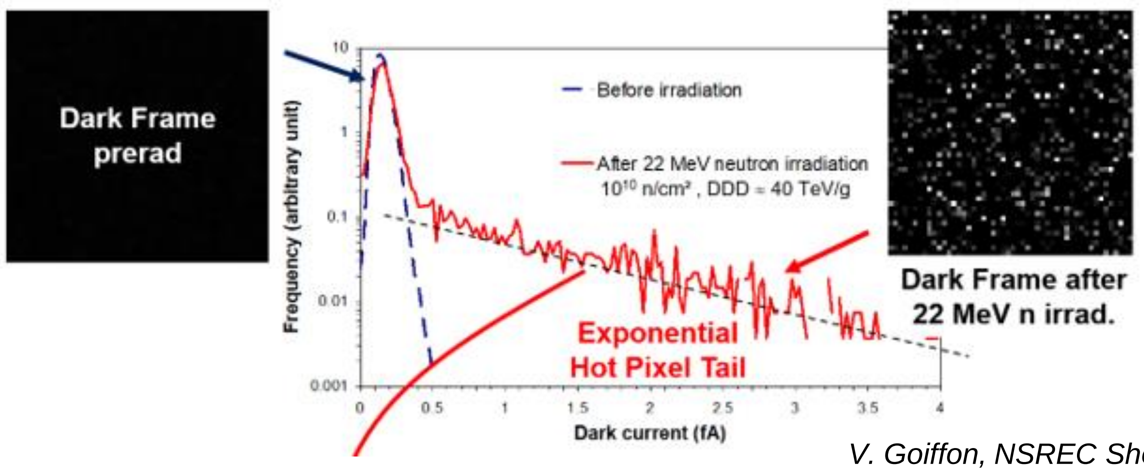
**J.R. Srour and D. H. Lo, IEEE TNS, Dec. 2000.*



C. Virmontois et al., IEEE TNS Aug. 2012

Starting Hypothesis – Dark Current Distribution

Dominated by interface state generation (diffusion dark current)



Dominated by bulk generation (bulk dark current)

V. Goiffon, NSREC Short Course, 2021

"Fixed" Physical Exponential Distribution

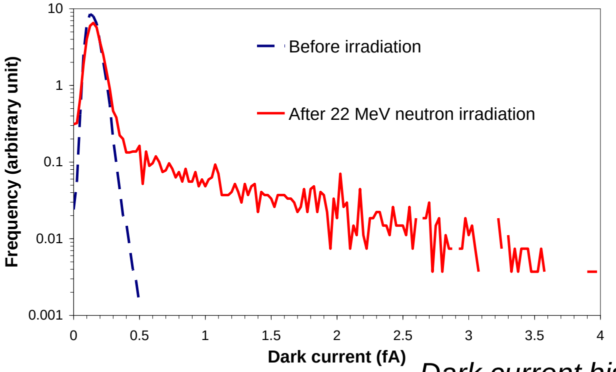
Displacement Damage Dose

$$y \approx K \times \frac{1}{\nu_{dark}} \exp\left(-\frac{x}{\nu_{dark}}\right) \times D_{dd} \times V_{dep}$$

$\nu_{dark} \approx$ 4500 e-/s @ 23°C (≈ 0.7 fA @ 23°C)

Starting Hypothesis – Dark Current Distribution

- In a pixel array, the hot pixel tail of the dark current increase distribution is given by the following exponential distribution which **solely depends on Ddd**:



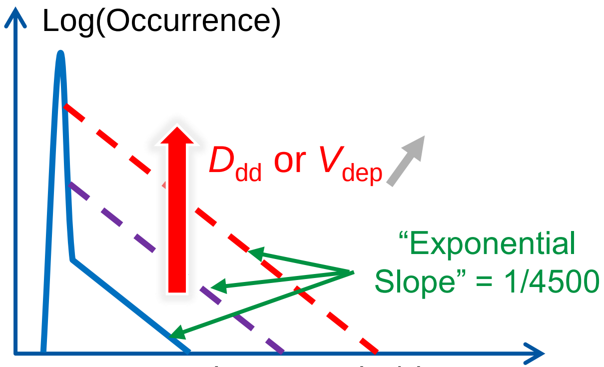
Dark current histogram

"Fixed" Physical Exponential Distribution

Displacement Damage Dose

$$y \approx K \times \frac{1}{\nu_{\text{dark}}} \exp\left(-\frac{x}{\nu_{\text{dark}}}\right) \times D_{\text{dd}} \times V_{\text{dep}}$$

$\upsilon_{dark} \approx$ 4500 e-/s @ 23°C (≈ 0.7 fA @ 23°C)



Model of the dark current distribution

Purpose of the TNID test campaign

- Validate further (or not) these hypothesis
- Explore the possibility to use photodiodes (PDs) and/or CMOS Image Sensor as **Ddd dosimeters** to compare facilities
- Explore the limit of these hypotheses
  - By using **particles/energies** that change the dominant defect structure (point defect vs clusters)
  - By using a rich **mixed environment** (CHARM)
  - By following closely, the **annealing behavior**
  - By comparing the behavior of **grounded and biased devices**

Targeted Irradiation Parameters

- Constraints:
  - High enough to ensure a **measurable signal** and **enough statistics** (e.g.,CIS)
  - Low enough to **limit activation** and to reduce the beam time
- **Proposed target: 400 TeV/g ⇔ $1\text{x}10^{11}$ 1-MeV-n_{equ}/cm^2** ⇔ $\approx 1.2\ \text{x}10^{11}$ 60-MeV-H/cm^2

	Proton	Neutron	Flux	Fluence	Date	Conditions	Dose (TeV/g)
TRIUMPH	480 MeV		N/A	1.27E11	17-juil	GND @RT	400
	355 MeV			1.06E11			
UCL		23 MeV	1.00E+07	1.00E+10	14-sept	GND & Biased @ RT	40-800
				1.50E+10			
				2.50E+10			
				5.00E+10			
				1.00E+11			
NPI CAS		3MeV - 33MeV	1.00E+09		22-janv	GND & Biased @ RT	150-20000

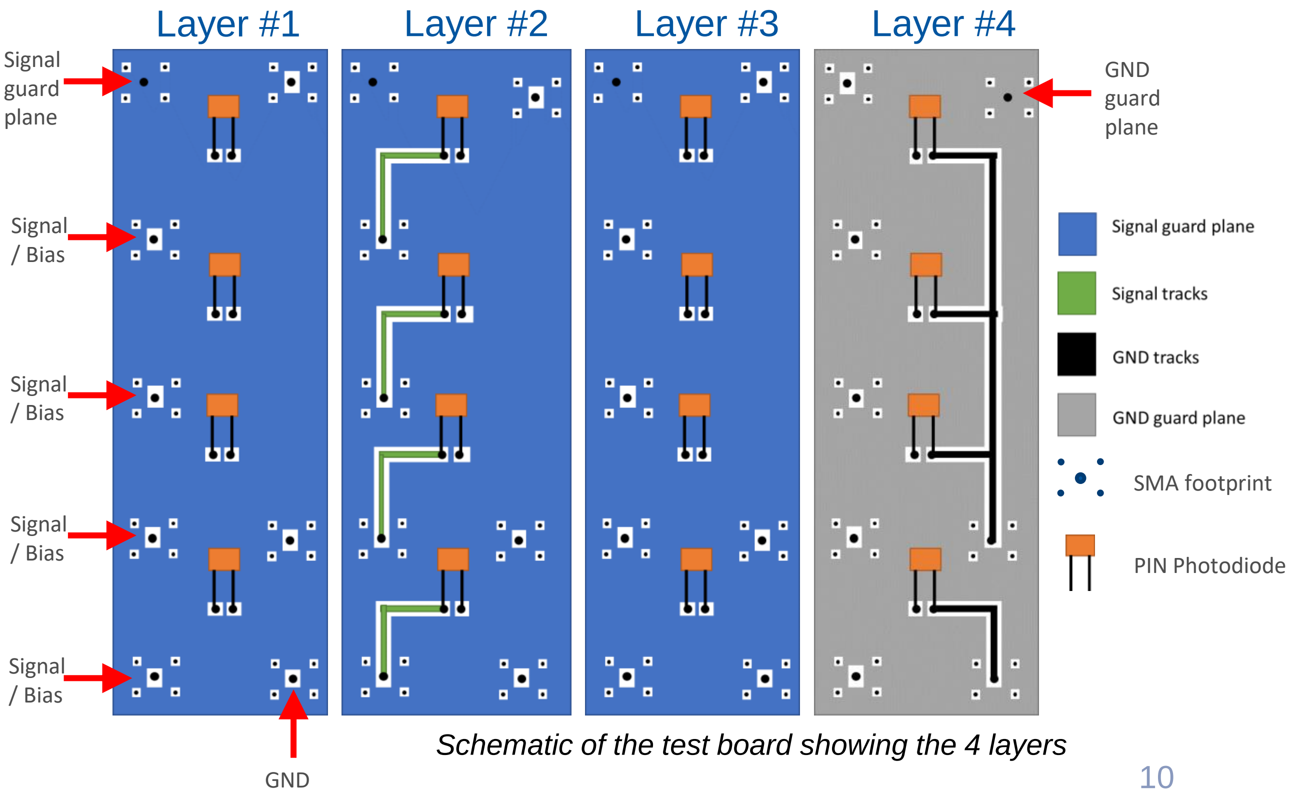
Radiation Test Setup

Custom test board

- IV measurement [pA]
- 12 PIN PDs with different biased

A 4-layer PCB is used:

1. Signal guard plane
2. Signal layer
   - signal tracks
   - signal guard plane
3. Signal guard plane
4. GND signal layer
   - GND signal tracks
   - GND guard plane



Schematic of the test board showing the 4 layers

Radiation Test Setup

Custom test board

- IV measurement [pA]
- 1 PIN PDs with different biased

A 4-layer PCB is used:

1. Signal guard plane
2. Signal layer
   - signal tracks
   - signal guard plane
3. Signal guard plane
4. GND signal layer
   - GND signal tracks
   - GND guard plane

Schematic of the cross section of the test board showing the 4 layers

Working principle:

- Guarded planes prevents leakage current by canceling the potential difference between the signal tracks and the planes

Radiation Test Setup

Custom test board

- IV measurement [pA]
- 12 PIN PD with different biased

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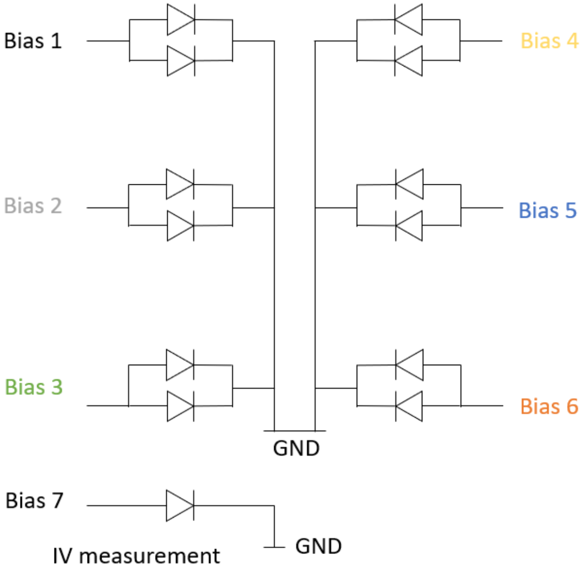
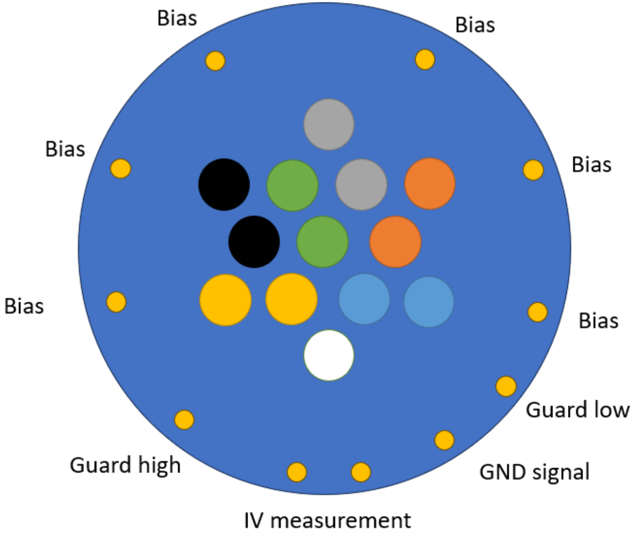
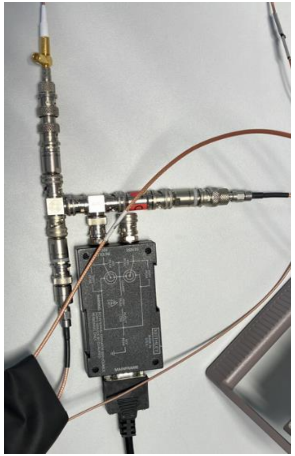




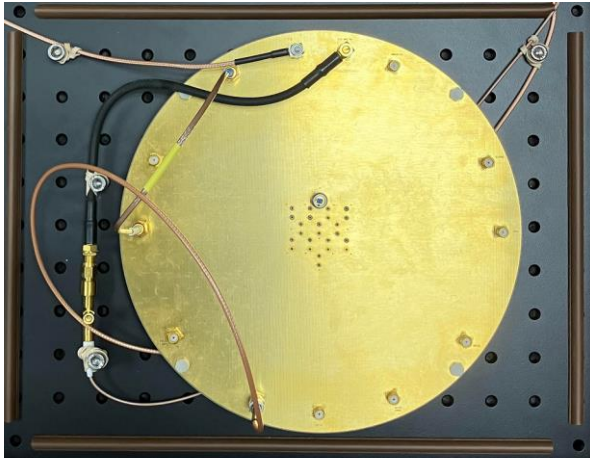
Top view of the test board showing the 12 + 1 slots

Radiation Test Setup



Separating the 3 channels
- Signal
- Guard
- GND

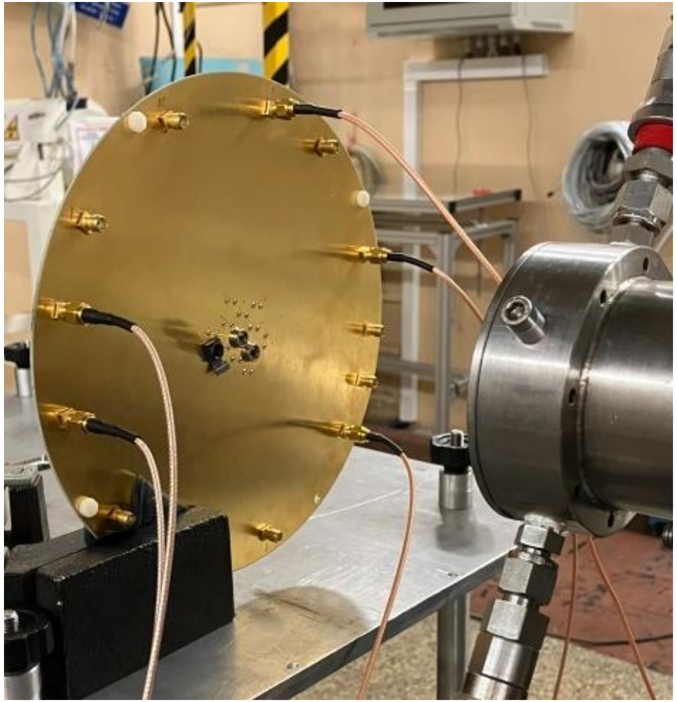
from the triaxe Keithley 6430

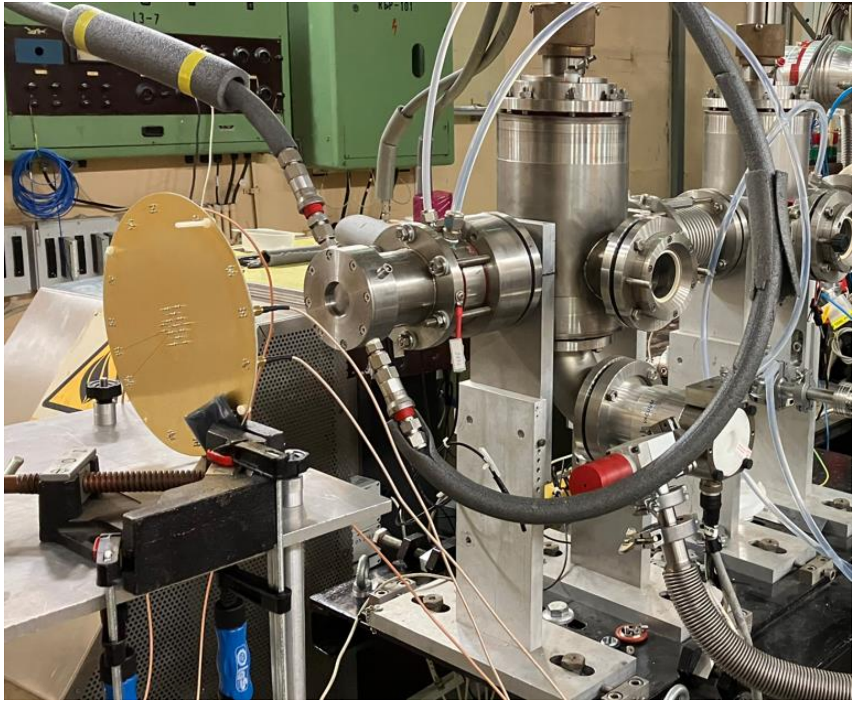


Custom test board
- 1 for irradiation + 1 for measurement
- Circular design to accommodate beam uniformity
- 12 PIN PD slots
- 6 different bias conditions

Flexible IV measurement setup
- Optically black environment
- Temperature probe
- pA sensitivity
- Dedicated software
- Allows annealing decay measurements

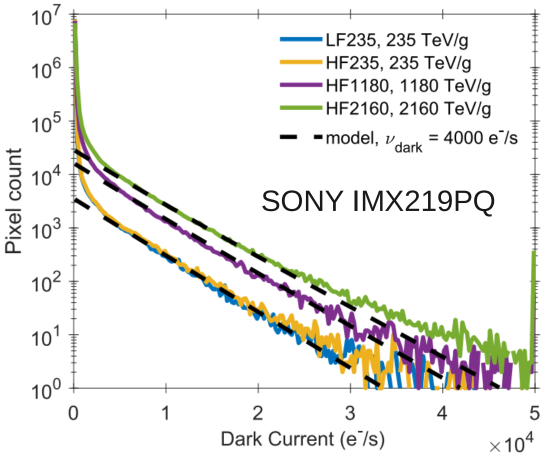
Radiation Test Setup



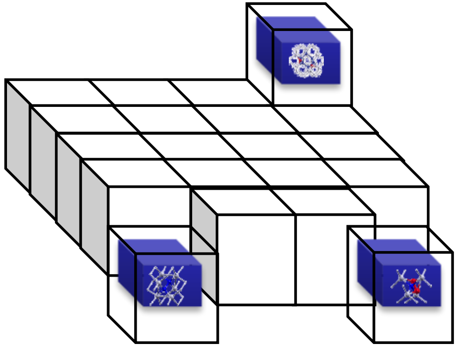


Next steps

- Data analysis and modeling on the data gather during the irradiations at TRIUMPH, UCL, NPI-CAS
- Electrons irradiations ?
  - ~ a few MeV
  - Beyond the point defect/cluster threshold
  - Above the point defect/cluster threshold
  - Facilities ?
    - RADNEXT offer: CSL Beta source
    - 0-3.5 MeV mono-energetic
- Gamma-rays relevant for point defect displacement damage?



Dark current distribution after proton irradiation



Schematic showing microvolume sampling of radiation-induced defects by a pixel array

THANKS FOR YOUR ATTENTION

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