Hybrid Pixel Detectors

Characterization Process

Leticia Rosa
Silicon Detectors Meeting, 03.12.2024

HELMHOLTZ

DESY.

Outline

Hybrid Pixel Detectors

➔ MEDIPIX & TIMEPIX

Characterization Process

➔ Key measurements

Simulation Tools

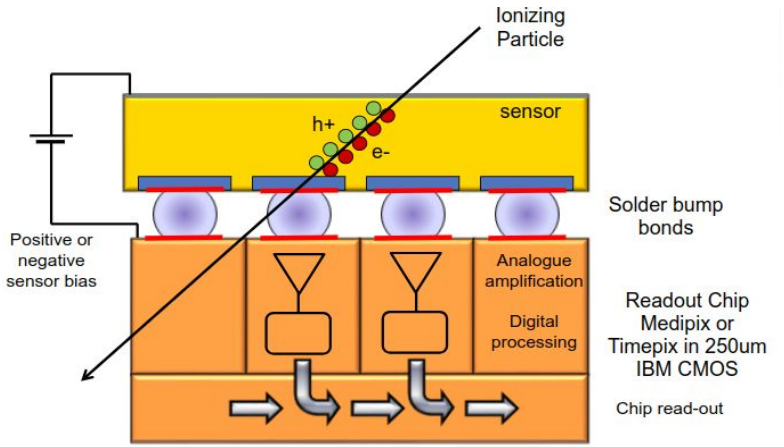
Summary

1. Hybrid Pixel Detectors

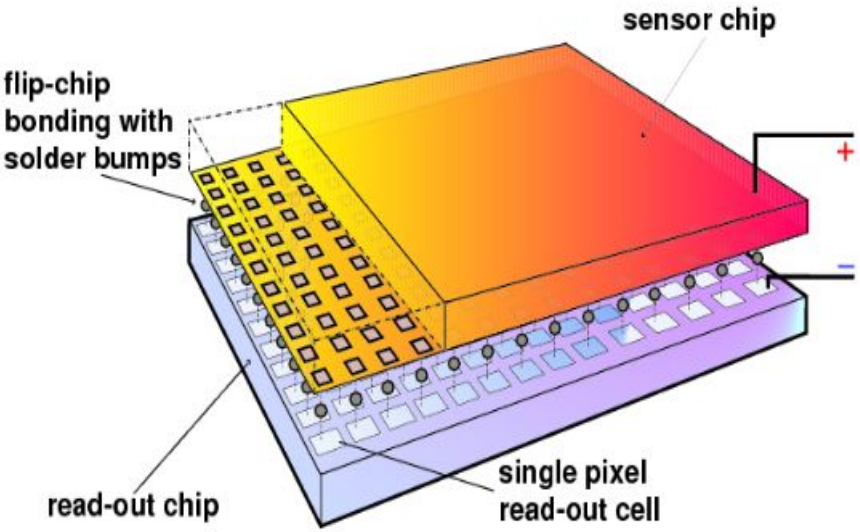
Hybrid Pixel Detectors

Definition

Application-Specific Integrated Circuit (ASIC) readout electronics bonded to a pixelated semiconductor sensor layer.



R. Plackett, "Medipix and Timepix chip developments: Recent Measurements with Timepix as a Particle Tracker," presented at VERTEX 2009, Mooi Veluwe, 16th Sept. 2009.



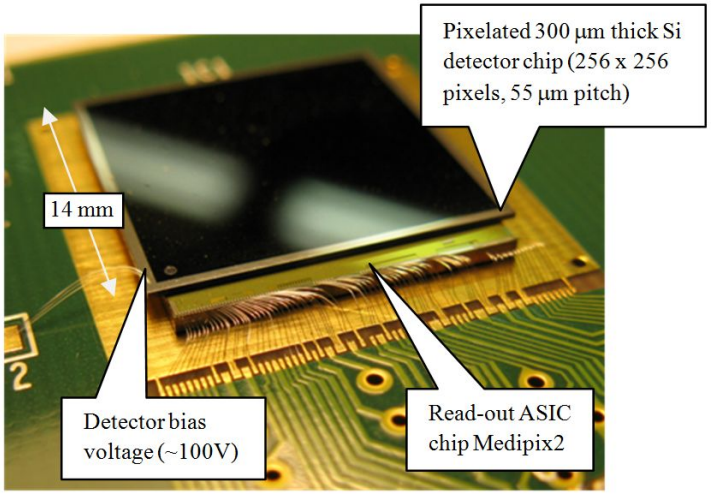
Tlustos, L. Performance and limitations of high granularity single photon processing X-ray imaging detectors, 2005

Sensor Material

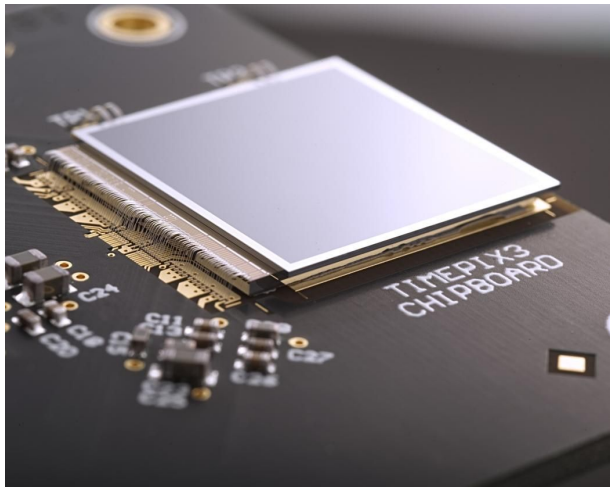
- Si, CdTe, CdZTe, GaAs

Particle Detection ASICS

	Medipix3	Timepix3
Pixel size (µm)	55	
Readout	Frame based	Data driven / Frame based
ToT/ToA	No	Yes
Application	Imaging	Particle Tracking, Imaging



Kraus, V., et al. (2011). FITPix - Fast interface for Timepix pixel detectors. *Journal of Instrumentation*, 6, C01079. https://doi.org/10.1088/1748-0221/6/01/C01079

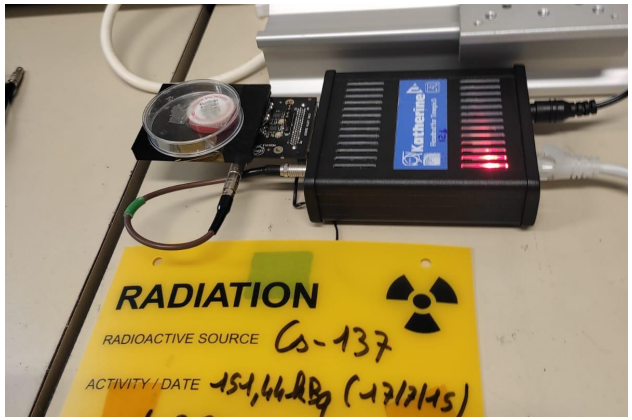


CERN Knowledge Transfer.

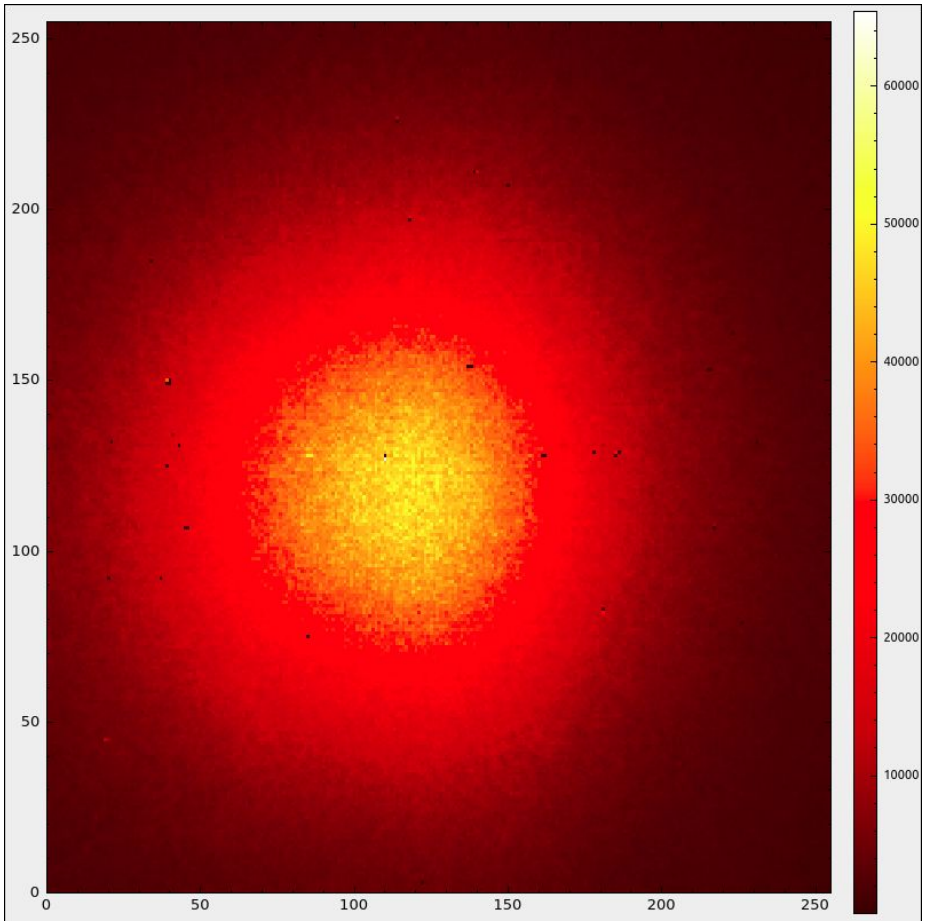
Timepix - Use Case

Source Identification

Objective: Build a portable radiation measurement device to identify type of radioactive source

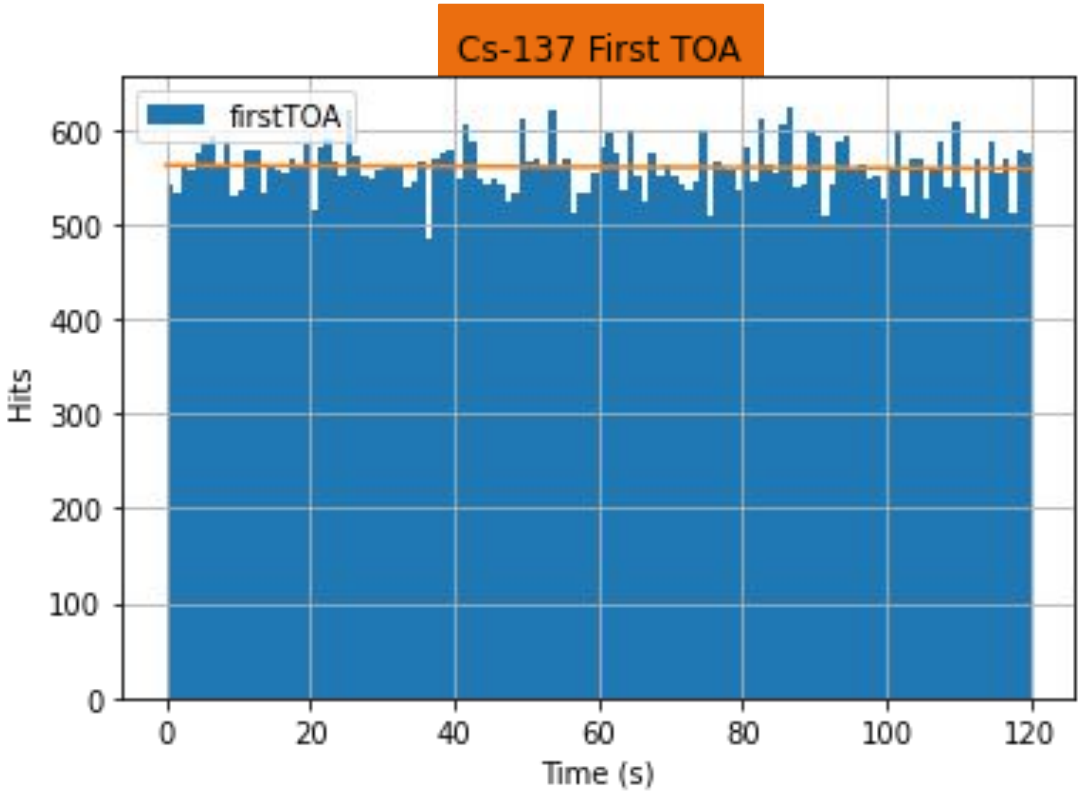


Sr-90 (β^-)



Dose Rate Assessment

First TOA Measurement



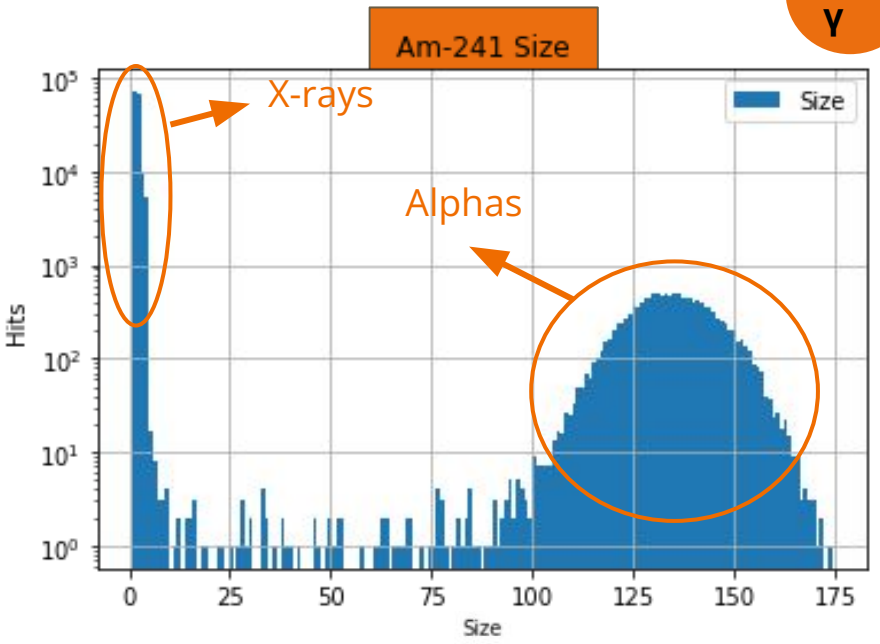
Radiation Flux

Flux: 0.0238 particle/s*mm²

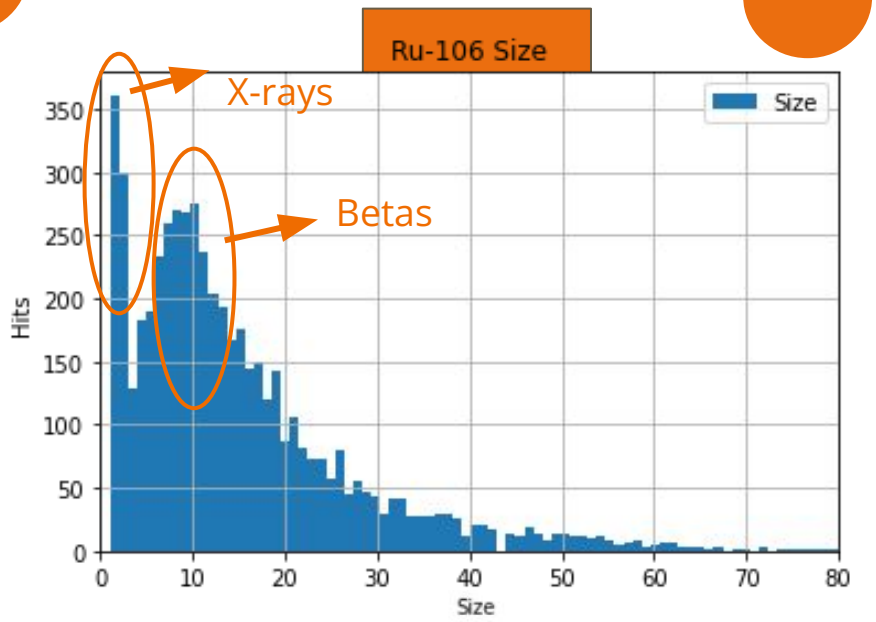
→ **Dose Rate**

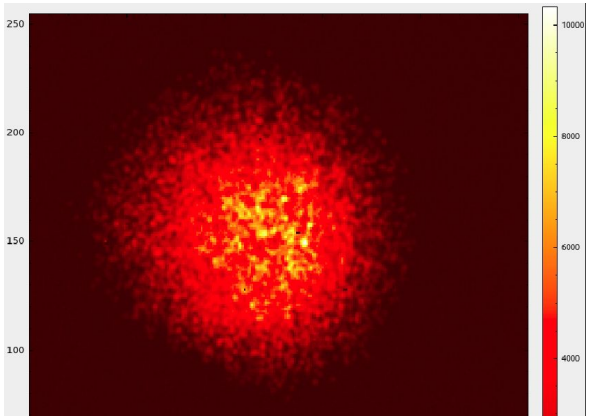
Cluster Size Measurement

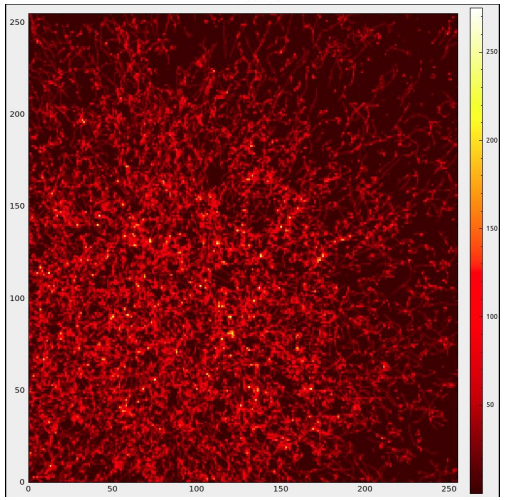
α
γ



β⁻



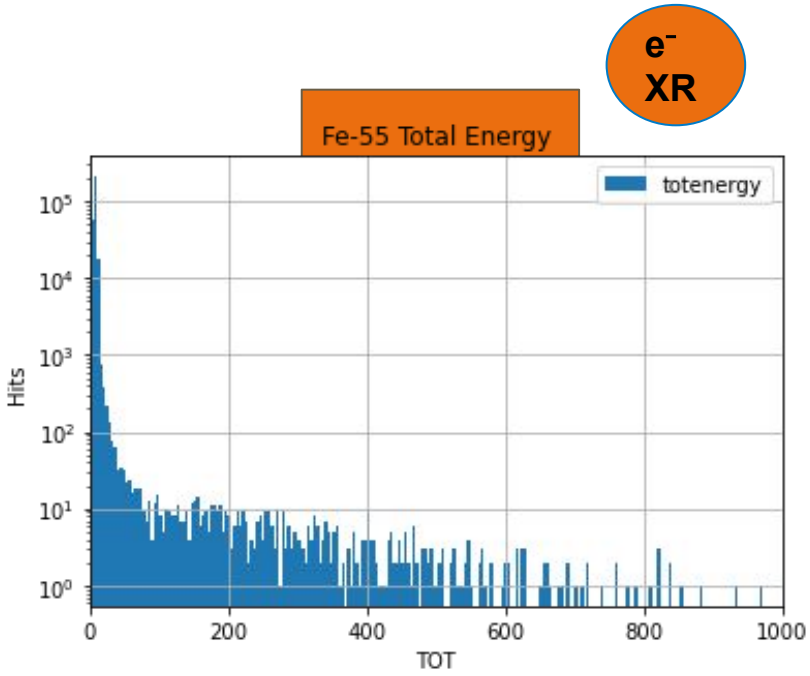




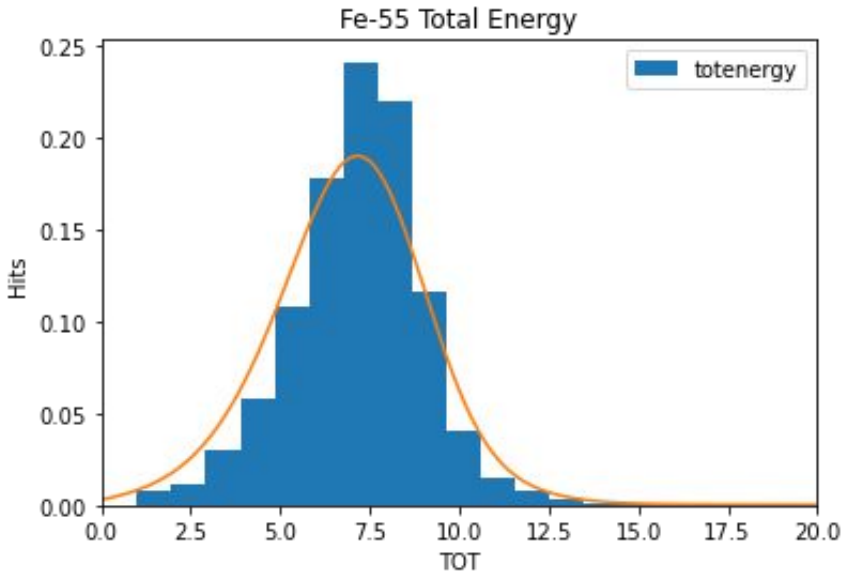
Energy Measurement

TOT

➔ TOT is proportional to the charge released



Cluster size < 3 ➔ Only X-rays



TOT Mean Value: 6.9745
Fe-55 X-ray Emission Peak: 5.899 keV

3. Characterization Process

Characterization Process

Detector Production

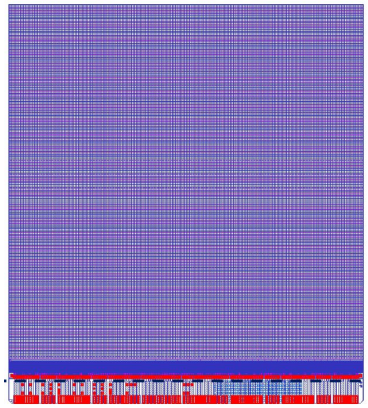
Chip → **Module** → **Large Area**

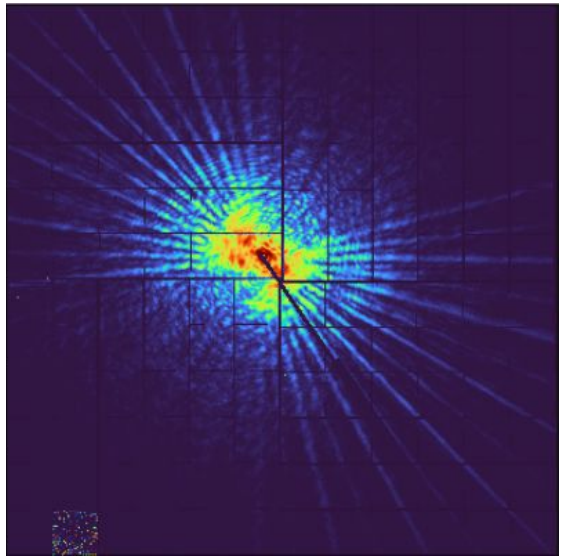
Pixel Response

- Equalization process
- IxV curve

Modules Integration

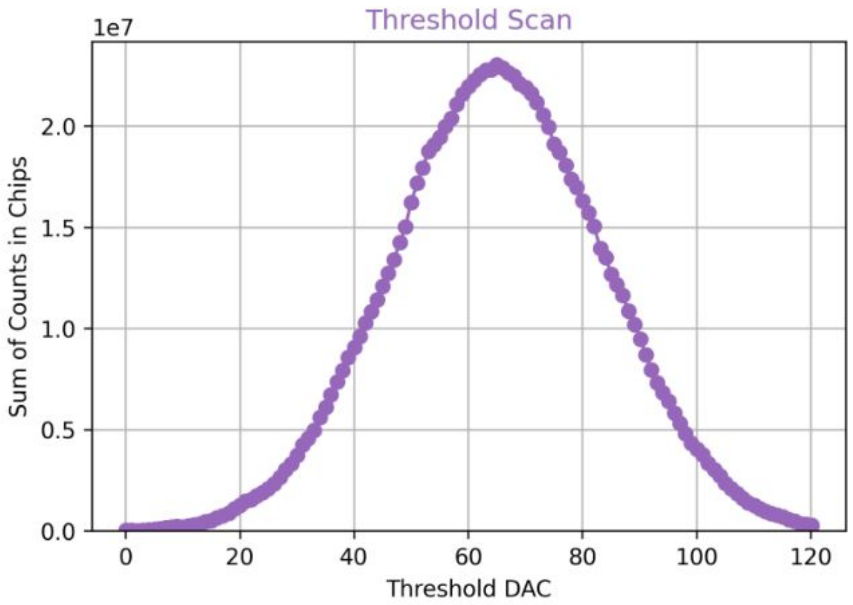
- Energy Calibration & Linearity
- Flatfield Correction & Restoration



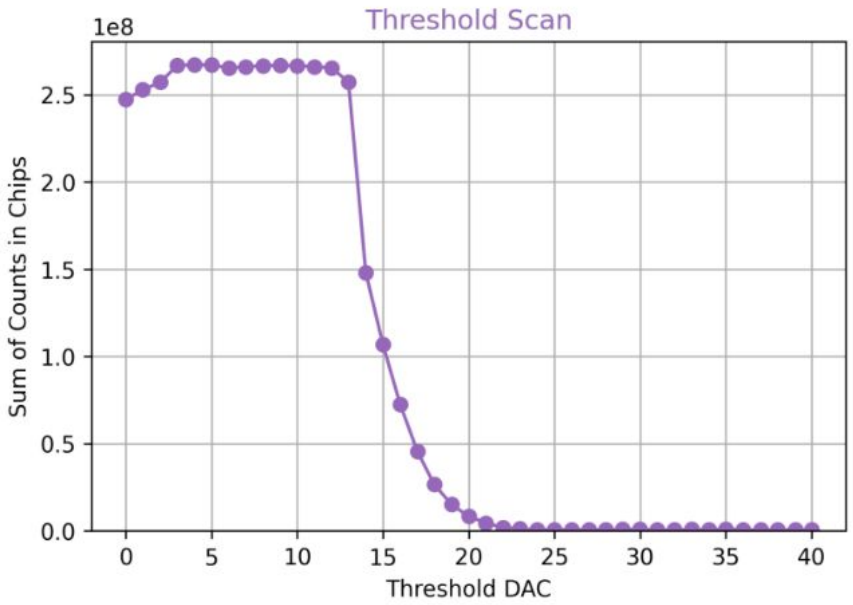


Pixel Response - Equalization Process

Medipix - CdTe 1000 µm



(a) Unequalized.

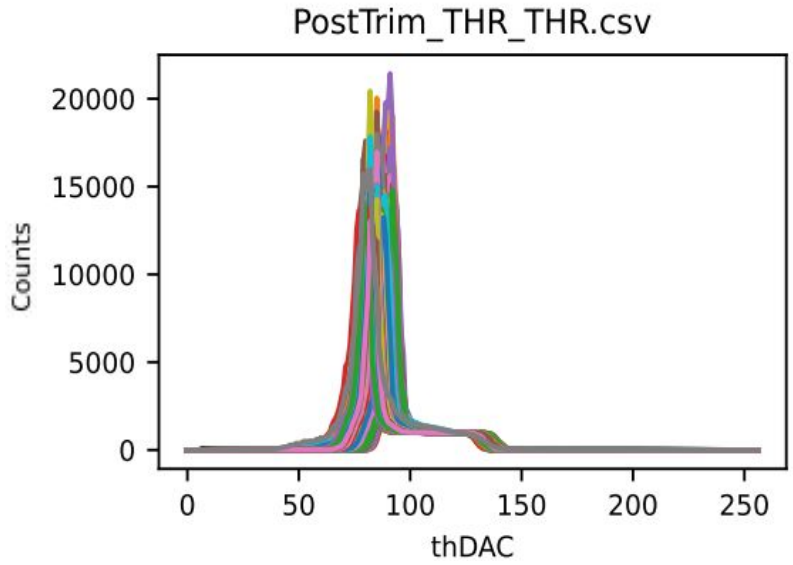


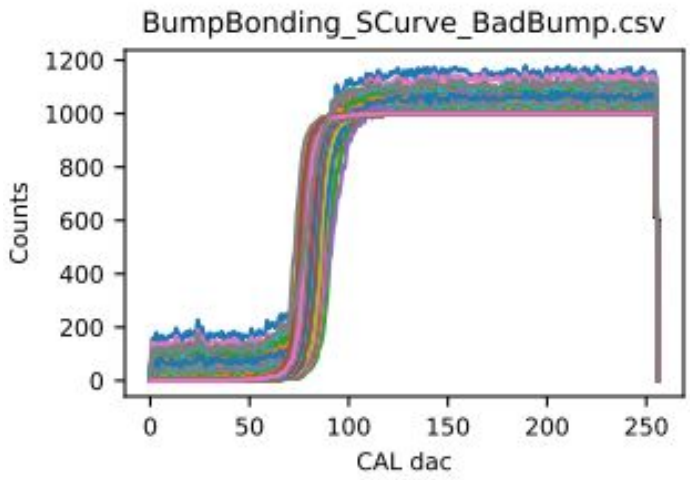
(b) Equalized.

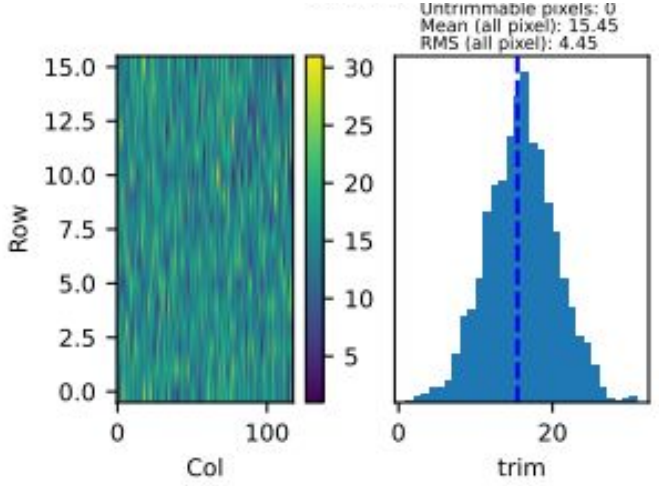
Figure 6: Threshold Scan for a chip.

MaPSA Testing at DESY

Pixel Response - Equalization Process

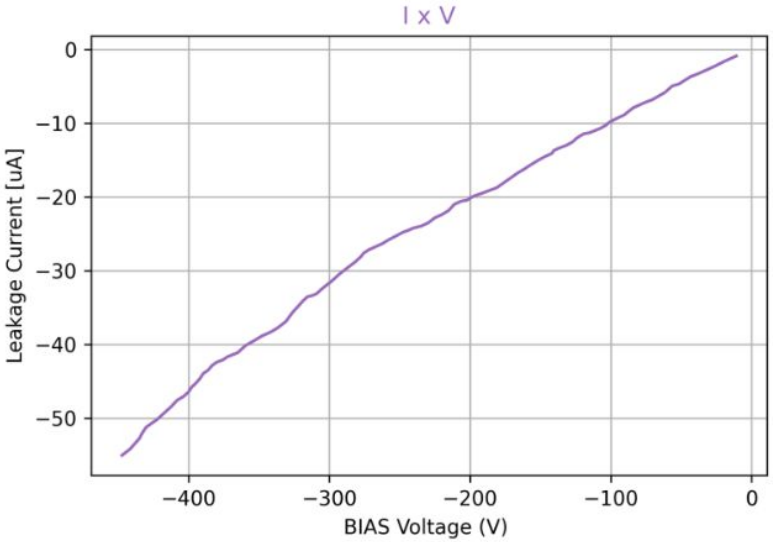


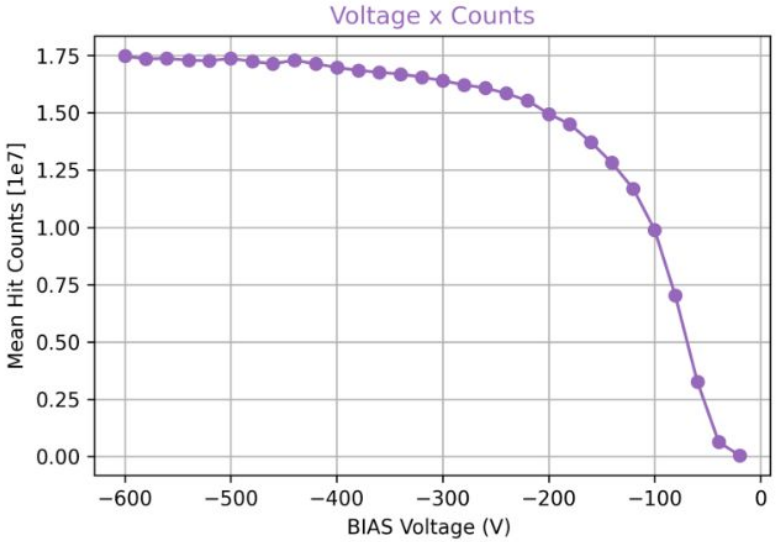




Current and BIAS Measurement

Medipix - CdTe 1000 µm





(a) Leakage current as a function of the applied bias in CdTe sensors in electron collection mode.

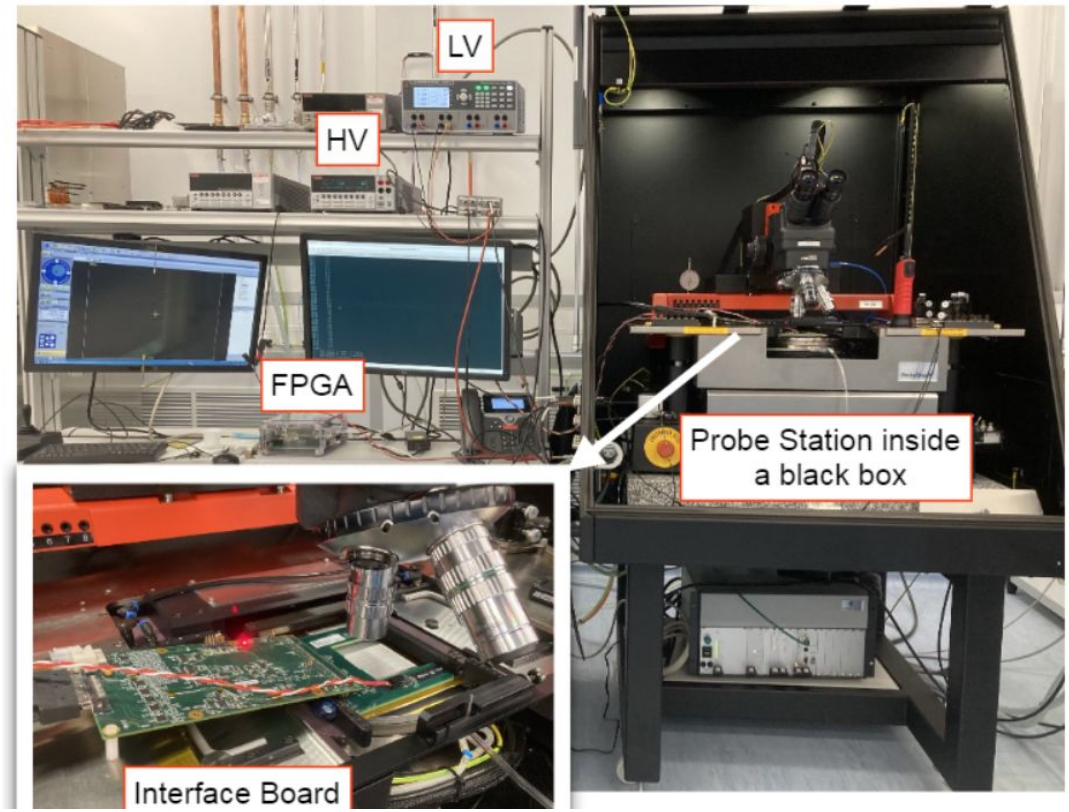
(b) Mean value of hit counts in sensor module sensors versus negative bias voltage applied.

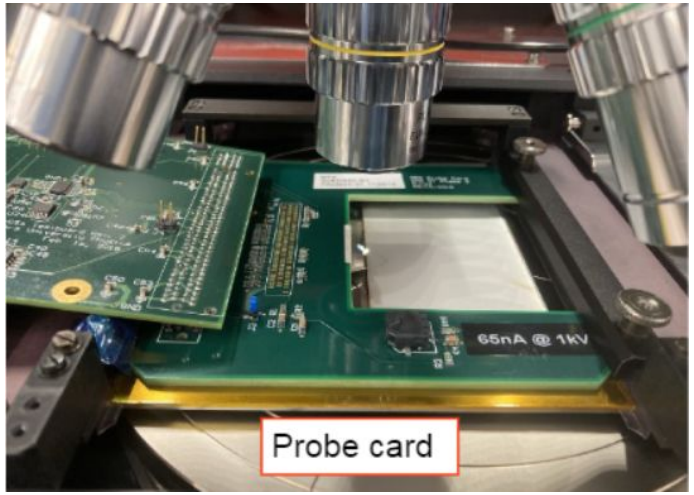
➔ Ensure sensor reaches Full depletion zone (without reaching breakdown)

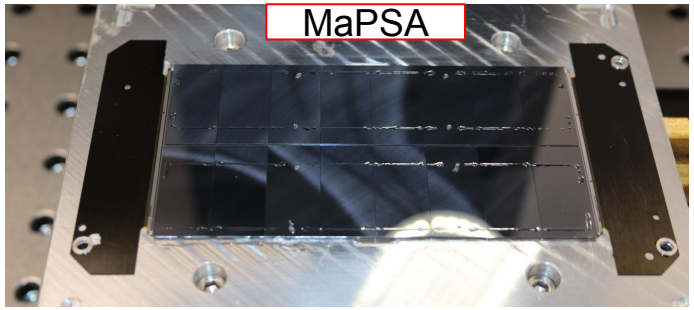
MaPSA Testing at DESY

Probing Tests

- Macro-pixe sub-assembly (MaPSA) for CMS Phase-II Detector Upgrade
- 8 x 2 Si sensors (300 µm)
- Before wire bonding

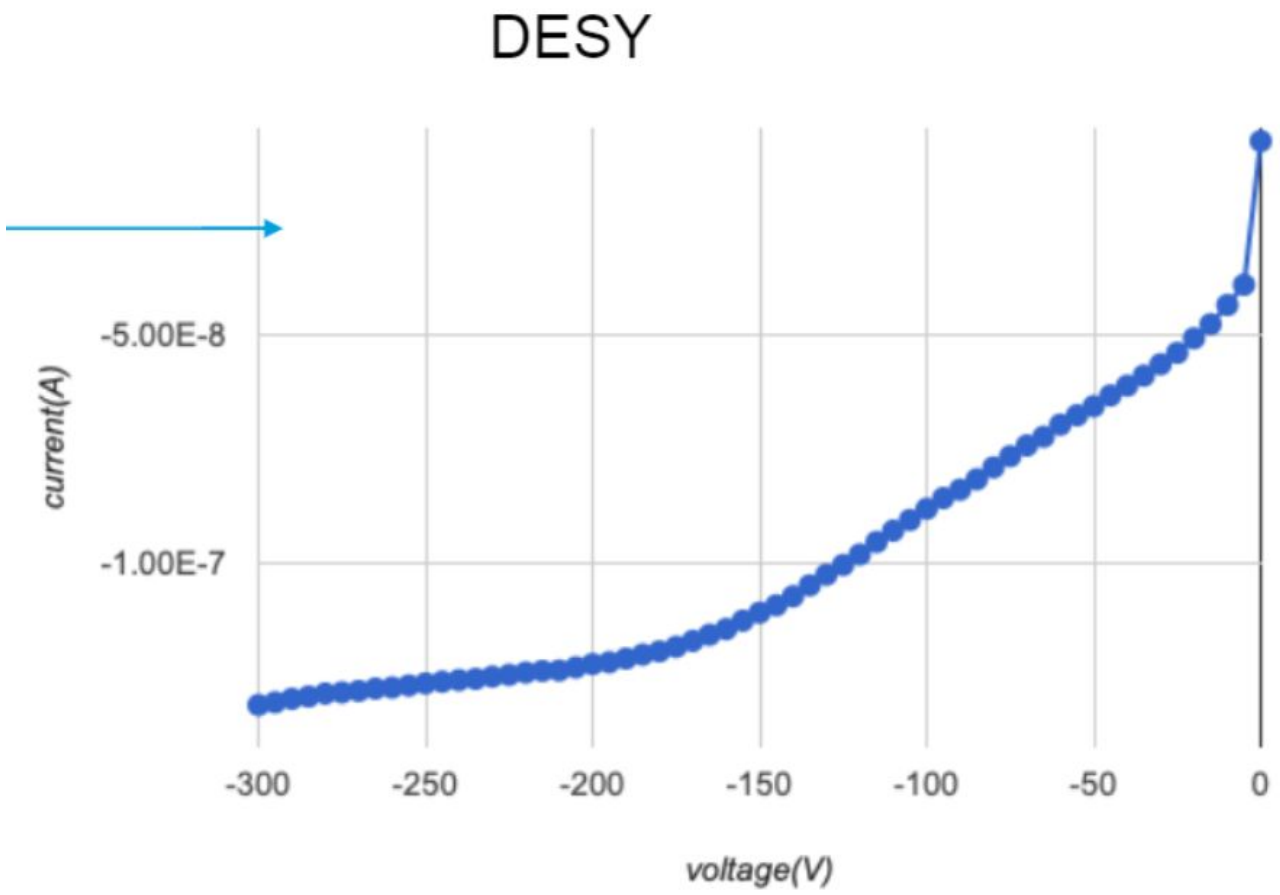






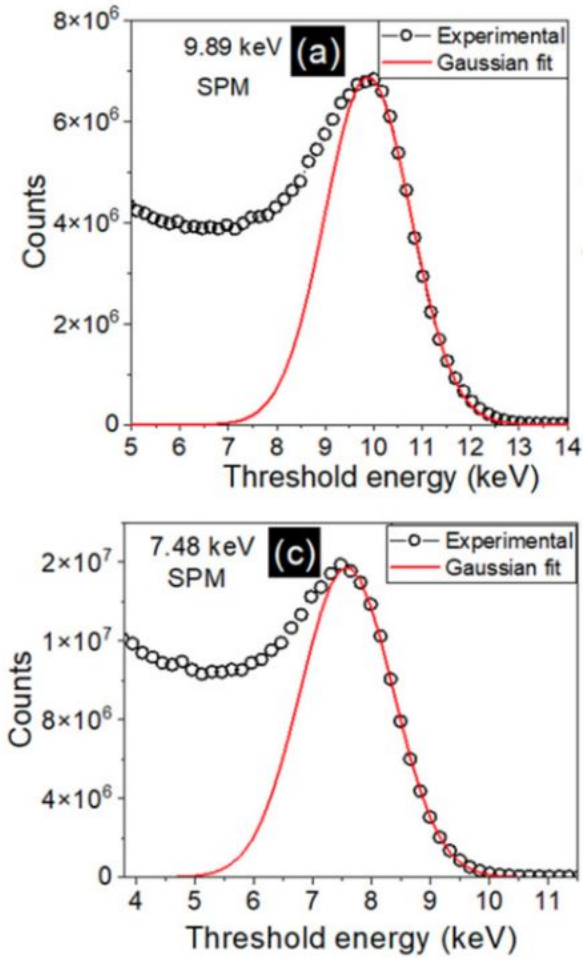
MaPSA Testing at DESY

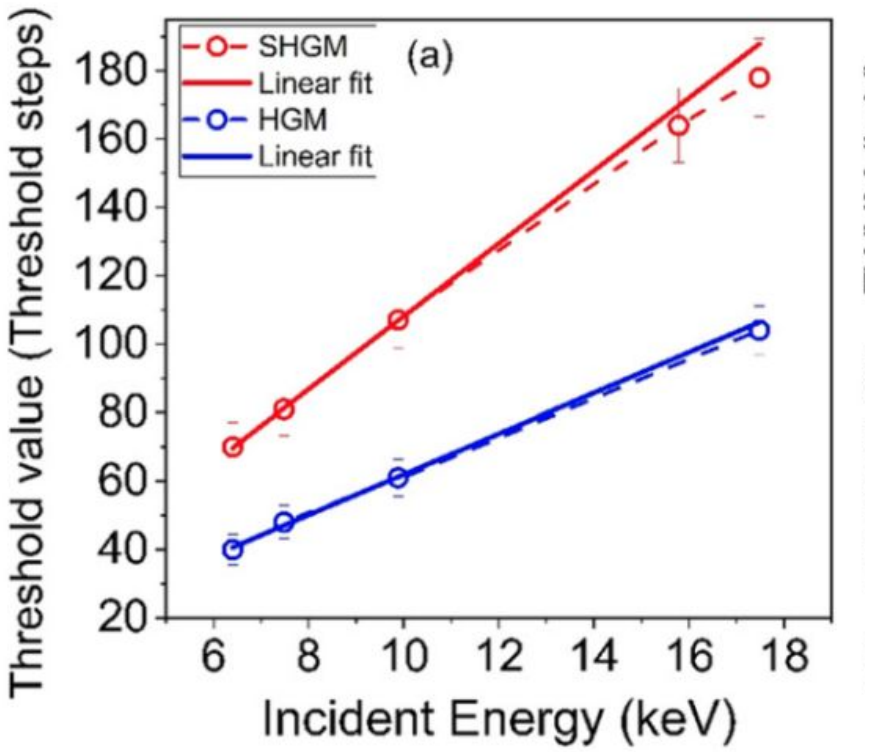
Current and BIAS measurement



Energy Calibration

Medipix - Si 300 µm

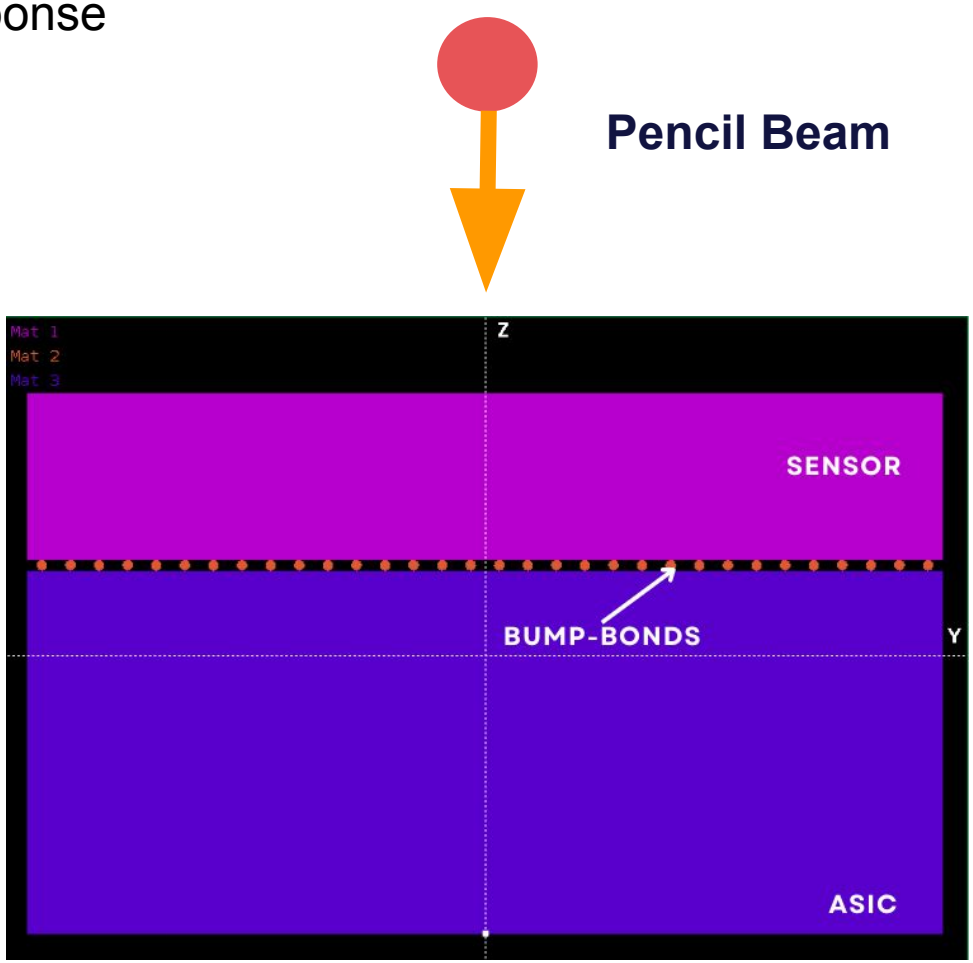




3. Simulation Tools

PENELOPE

- Monte Carlo (Fortran Code - V.2014 + PenEasy V.2015)
- Model the detector response



DETECTOR GEOMETRY

Simulation Parameters

Semiconductor Transport Properties

Parameters	Si		CdTe	GaAs
Thickness [µm]	300	675	1000	
BIAS [V]	80	120	-300	
Electric Field [V/cm]	2666	1777	-3000	
Fano Factor	0.115		0.10	
Pair Creation E (W±) [eV]	3.62		4.43	4.2
$\mu\tau$ Electron [cm^2V^{-1}]	2		3×10^{-3}	8×10^{-5}
$\mu\tau$ Hole [cm^2V^{-1}]	1		2×10^{-4}	4×10^{-6}
Charge Carrier Collected	Holes		Electrons	

THOR

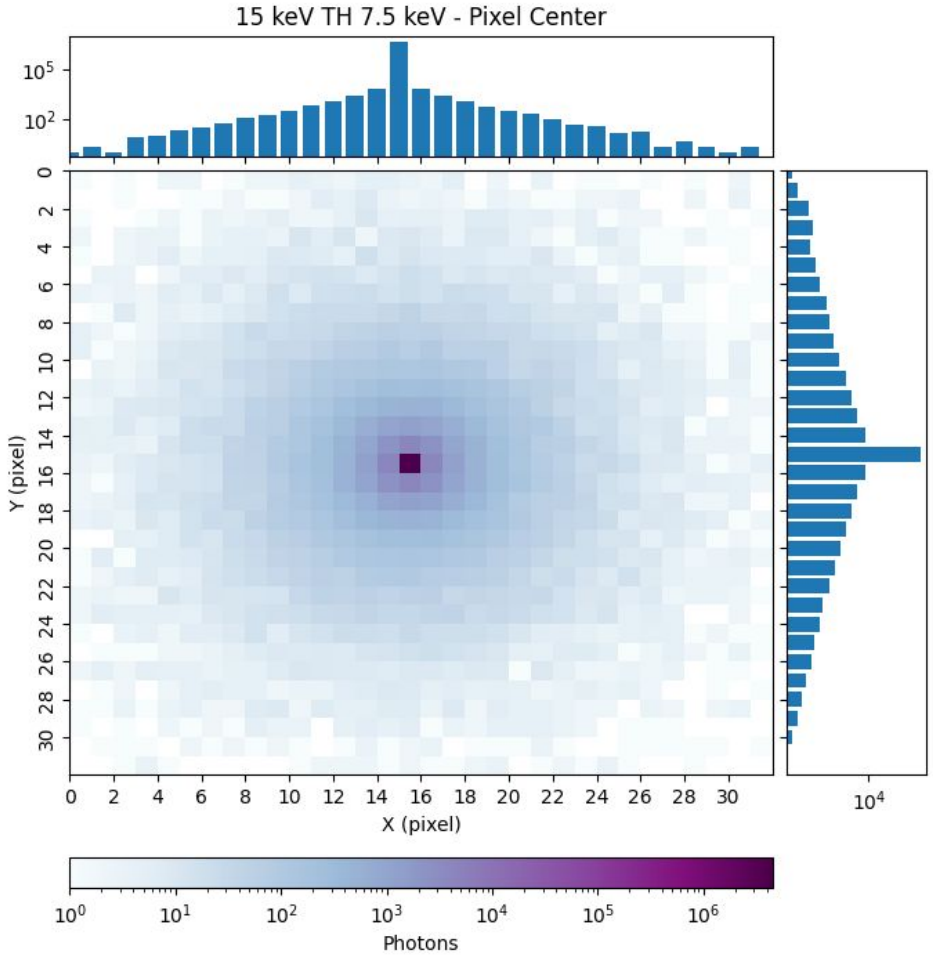
Transport of electrons and **HO**les in semiconducto**R**s

- Modified version of PenEasy code
- Extends functionalities of PENELOPE
- Improve simulation of electrons and holes transport dynamics in semiconductors

Simulation Measurements

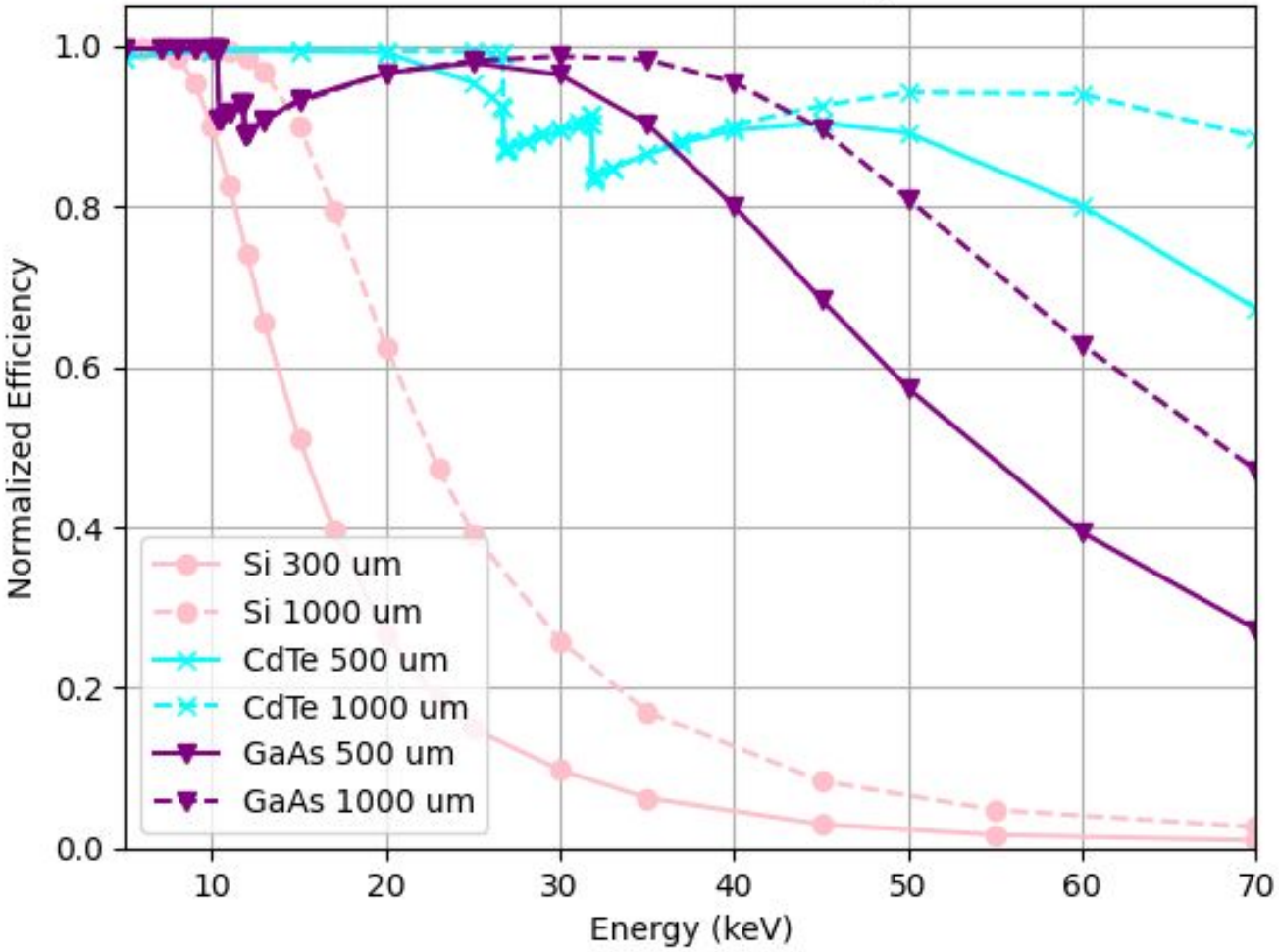
Energy Deposition

Si 675 um - 15 keV



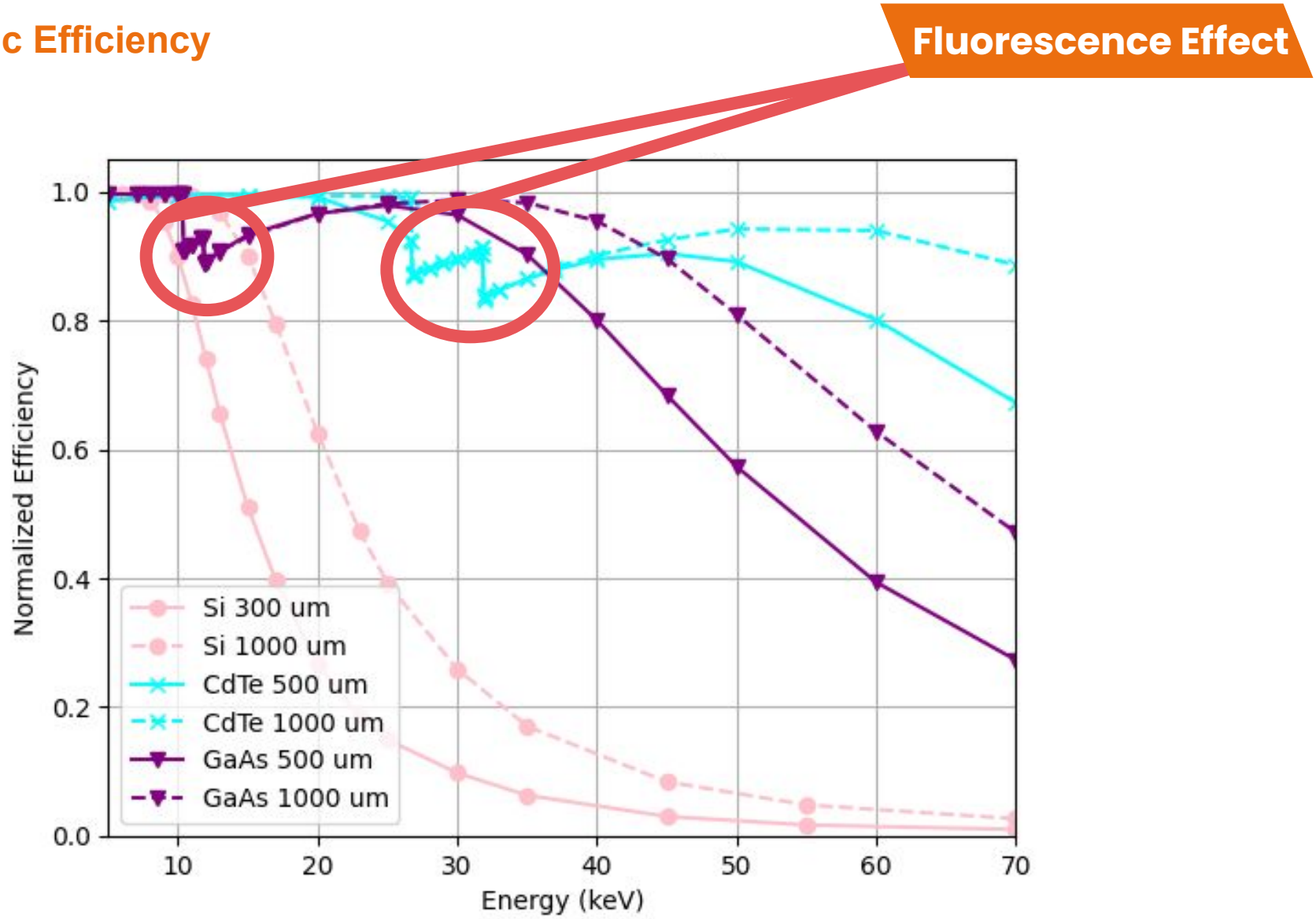
Simulation Measurements

Intrinsic Efficiency



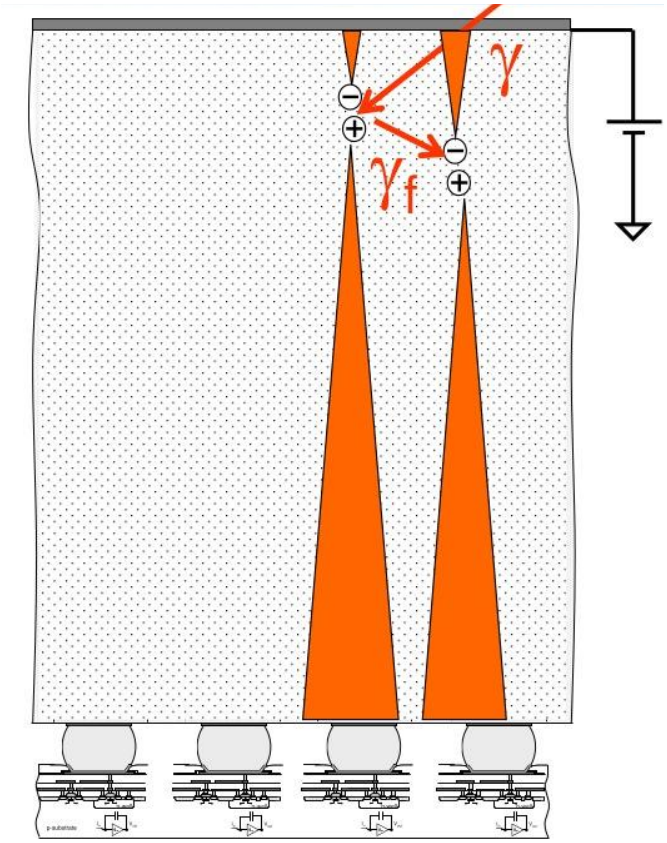
Simulation Measurements

Intrinsic Efficiency



Fluorescence

In High-Z Materials



	N	k-edge (keV)	Kα energy (keV)	dα (μm)	η [%]
Si	14	1.84	1.74	12	5
Ge	32	11.11	9.89	51	55
GaAs:					
Ga	31	10.38	9.25	42	51
As	33	11.87	10.54	16	57
CdTe:					
Cd	48	26.73	23.17	128	84
Te	52	31.82	27.47	64	87

Journal of Instrumentation Volume 6 June 2011
D Pennicard and H Graafsma 2011 *JINST* **6** P06007
doi:10.1088/1748-0221/6/06/P06007

M. Campbell.Single Particle Detection for Spectroscopy CT and Tracking in Hadron Therapy Using Medipix Chips.2016

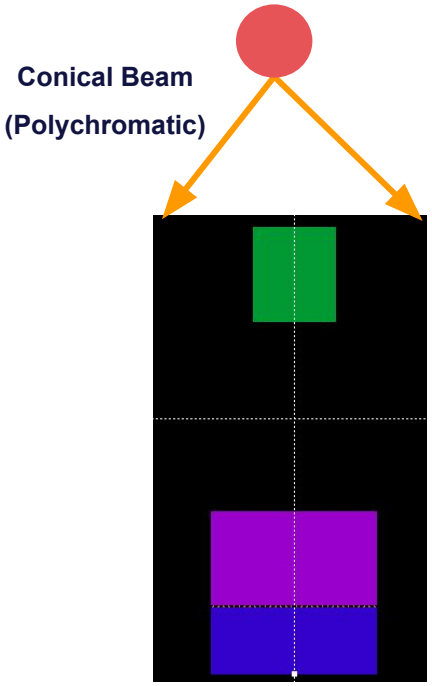
Simulation Measurements

Modulation Tansfer Function

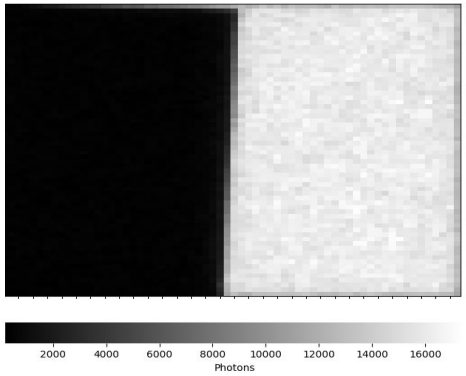
➔ Quantifies the system spatial resolution across the frequency domain

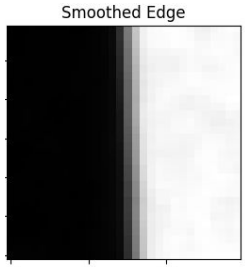
- Medipix3RX
- Si 300 µm and CdTe 1000 µm
- Tungsten sharp edge object (2º)
- X-ray tube (70 kV)

Simulation Model

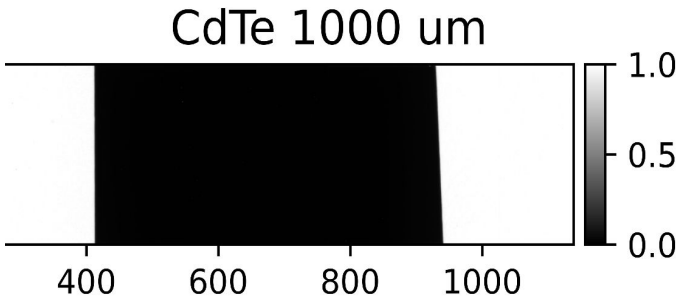


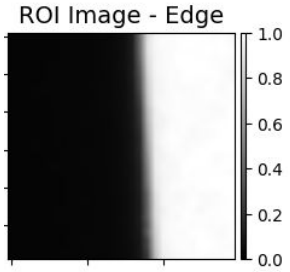
Simulated Edge





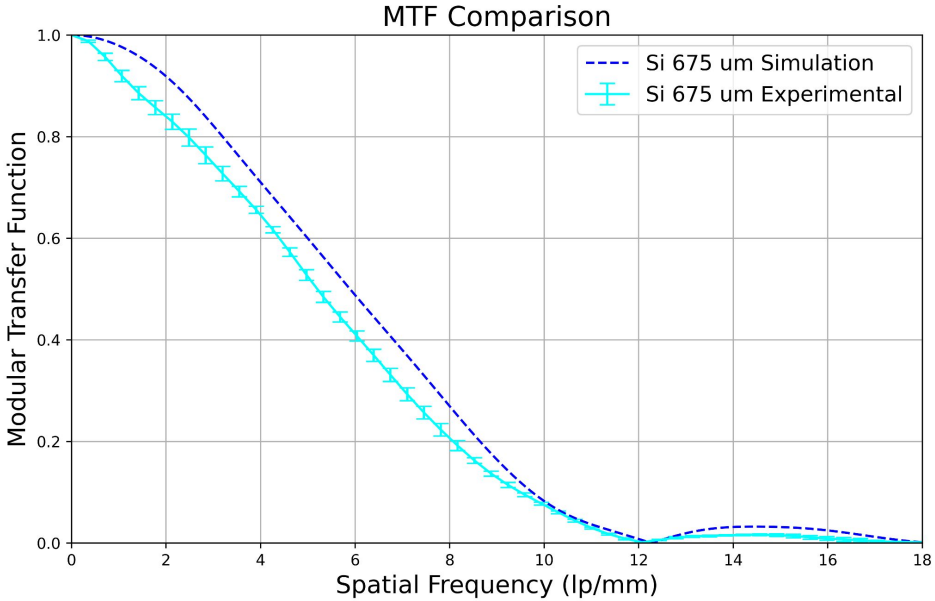
Experimental Edge

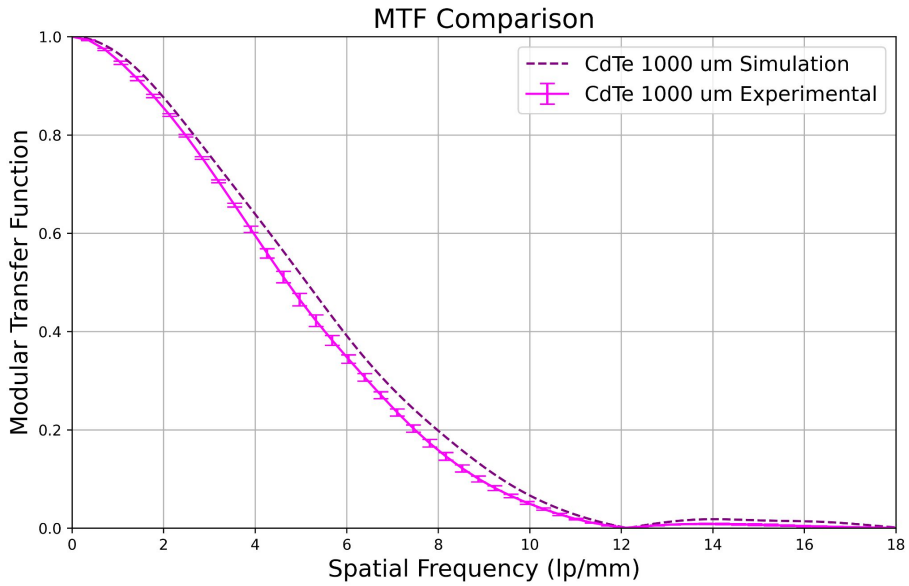




Simulation x Experimental Data

MTF Assessment





	Experimental	Simulation	
MTF 50%	5.19	5.89	lp/mm
MTF 10%	9.49	9.74	lp/mm

	Experimental	Simulation	
MTF 50%	4.69	5.12	lp/mm
MTF 10%	8.88	9.37	lp/mm

Summary

Characterization Process:

- ➔ Key measurements define detector state and aim to optimize operation conditions
- ➔ Is an essential part of detector development and production
- ➔ Can be used for different applications, such as High Energy Physics, Photon Science, and Medical

Simulations:

- ➔ Simulations enable modeling the detector’s behavior in detail
- ➔ Insights on future applications and detector design

Thank you!

Contact

Deutsches Elektronen-
Synchrotron DESY

www.desy.de

Leticia Rosa
FH - CMS
leticia.braga.da.rosa@desy.de
+ 49 0 40 8998 2407

Backup

Specifications

Medipix3

Pixel matrix	**256 x 256**
Pixel size	55 x 55 µm² or 110 x 110 µm²
Technology	CMOS 130 nm
Measurement modes	• Single pixel (SPM) • Charge summing (CSM)
Gain modes	• Super low gain mode • Low gain mode • High gain mode • Super high gain mode
# thresholds	• 2 per 55 µm pixel • 8 per 110 µm pixel
Programmable counter depths	• 2 x 1-bit • 2 x 6-bit • 2 x 12-bit • 1 x 24-bit
Readout type	Frame based • Sequential R/W • Simultaneous R/W
Readout Time	Depends on counter depth used
Minimum threshold	~ 500 e-

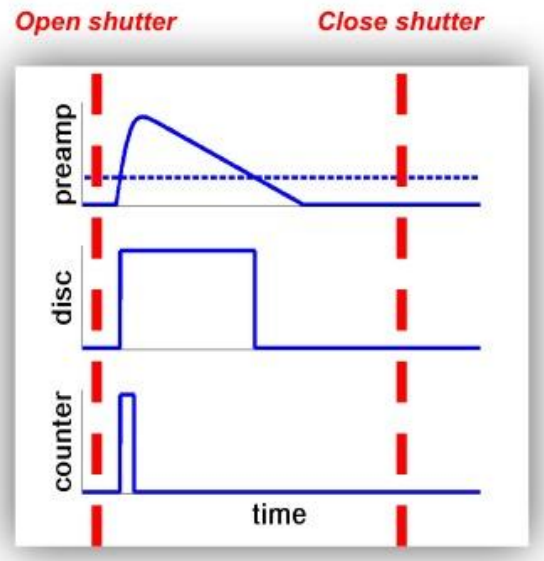
Timepix3

Pixel matrix	256 x 256
Pixel size	55 x 55 µm²
Technology	CMOS 130 nm
Measurement modes	• Simultaneous 10 bit TOT and 14 + 4 bit TOA • 14 + 4 bit TOA only • 10 bit PC and 14 bit integral TOT
Readout type	• Data driven • Frame based (both modes with zero suppression)
Dead time (pixel, data driven)	>475 ns (pulse processing + packet transfer)
Output bandwidth	40 Mbits/s – 5.12 Gbits/s
Maximum count rate	0.4 Mhits/mm²/s (data driven mode)
TOA Precision	1.56 ns
Front end noise	60e- RMS
Minimum threshold	~500 e-

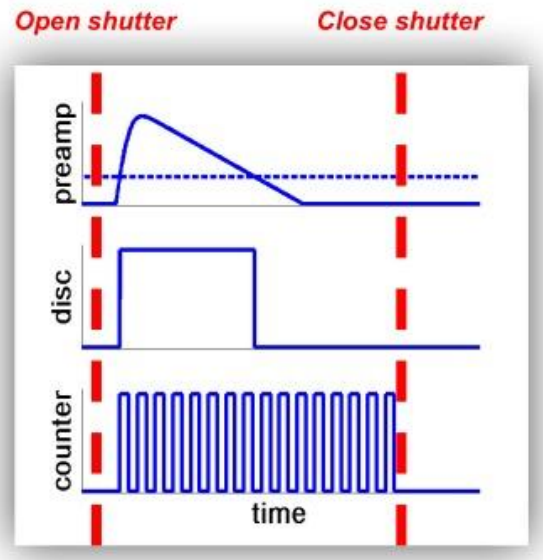
M. Campbell.Single Particle Detection for Spectroscopy CT and Tracking in Hadron Therapy Using Medipix Chips.2016

Timepix Operation Modes

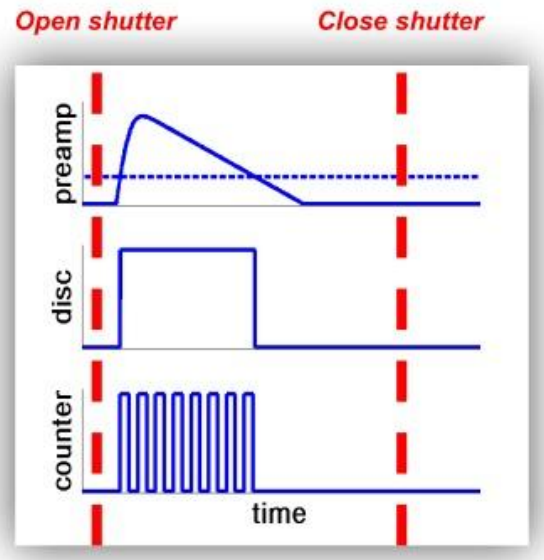
Particle Counting



Time of Arrival (ToA)



Time over threshold (ToT)



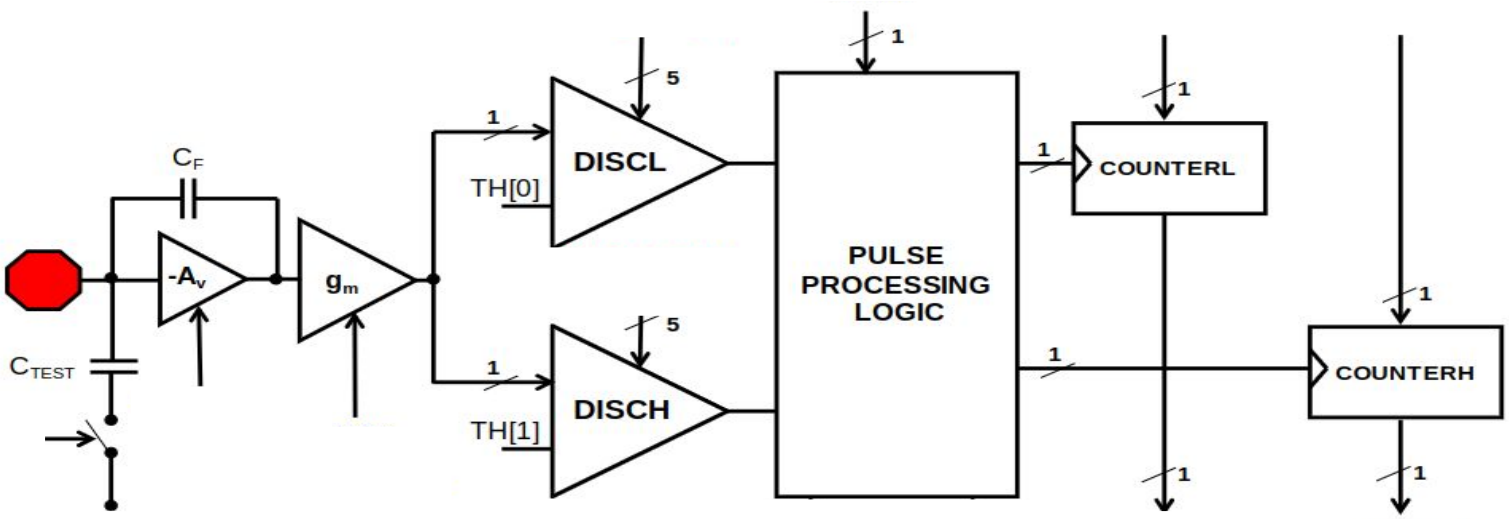
M. Campbell. Particle Detection and Imaging Using the Medipix and Timepix Chips.2018

Medipix

Measure the arrival time when particles are detected.

Measure of the energy deposited by the particle

Medipix Overview



Adapted from Ballabriga, R. & Llopart, X. Medipix3RX manual v1.4, 2012

2. Characterization Process

Count-rate Linearity

Medipix - Si 300 µm

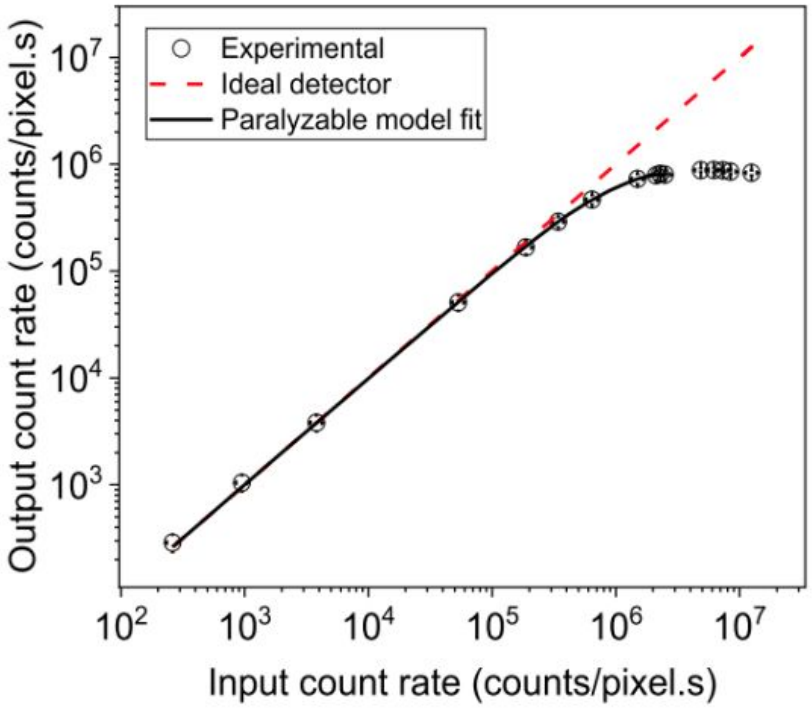


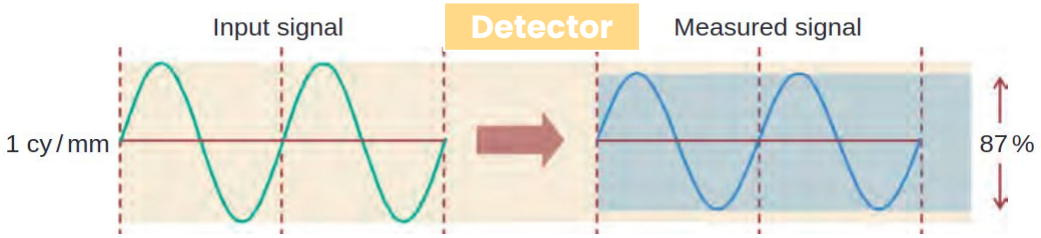
Figure 4. Count-rate linearity measurement fitted to the paralyzable model. The ideal detector's response is depicted in the red dashed line.

MTF Measurement

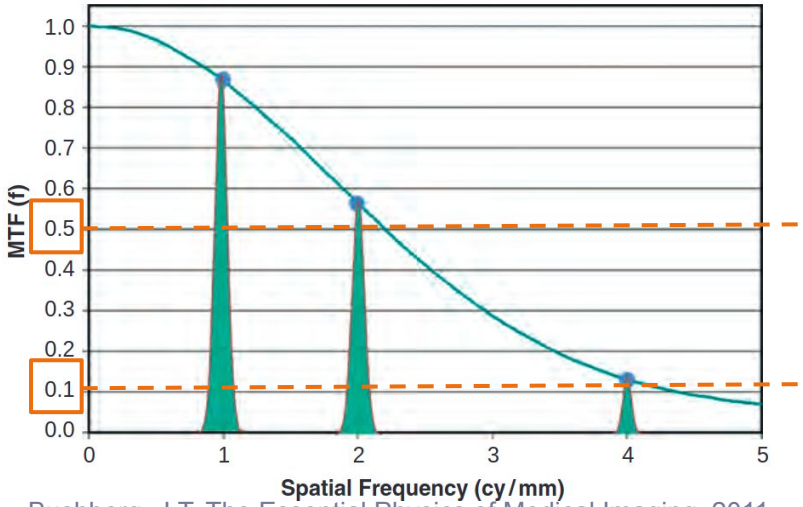
Slanted Edge Method

➔ **M**odulation **T**ransfer **F**unction

➔ Quantifies the system spatial resolution across the frequency domain



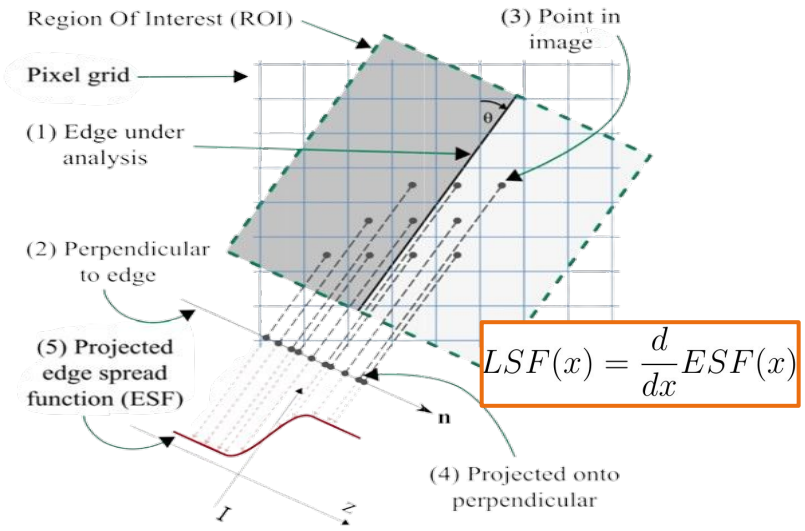
Bushberg, J.T. The Essential Physics of Medical Imaging, 2011



Bushberg, J.T. The Essential Physics of Medical Imaging, 2011

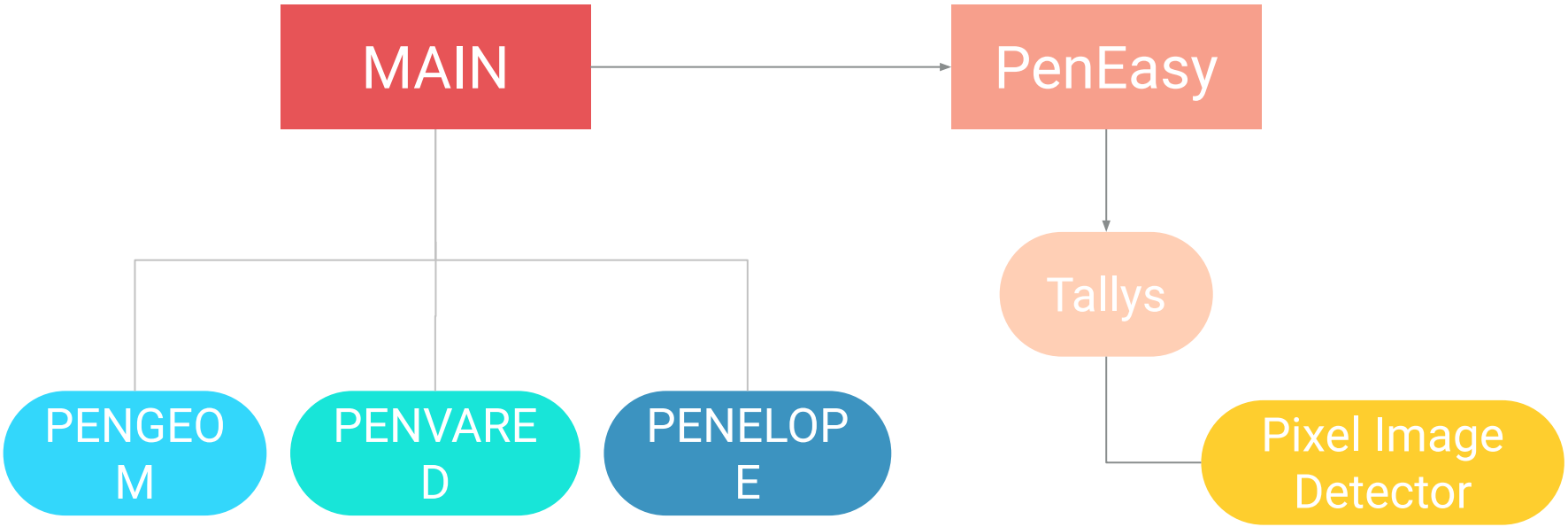
DEFINITION

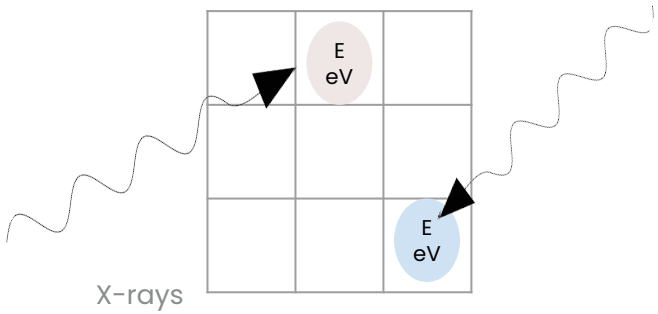
$$MTF = |F[LSF(x)]|$$



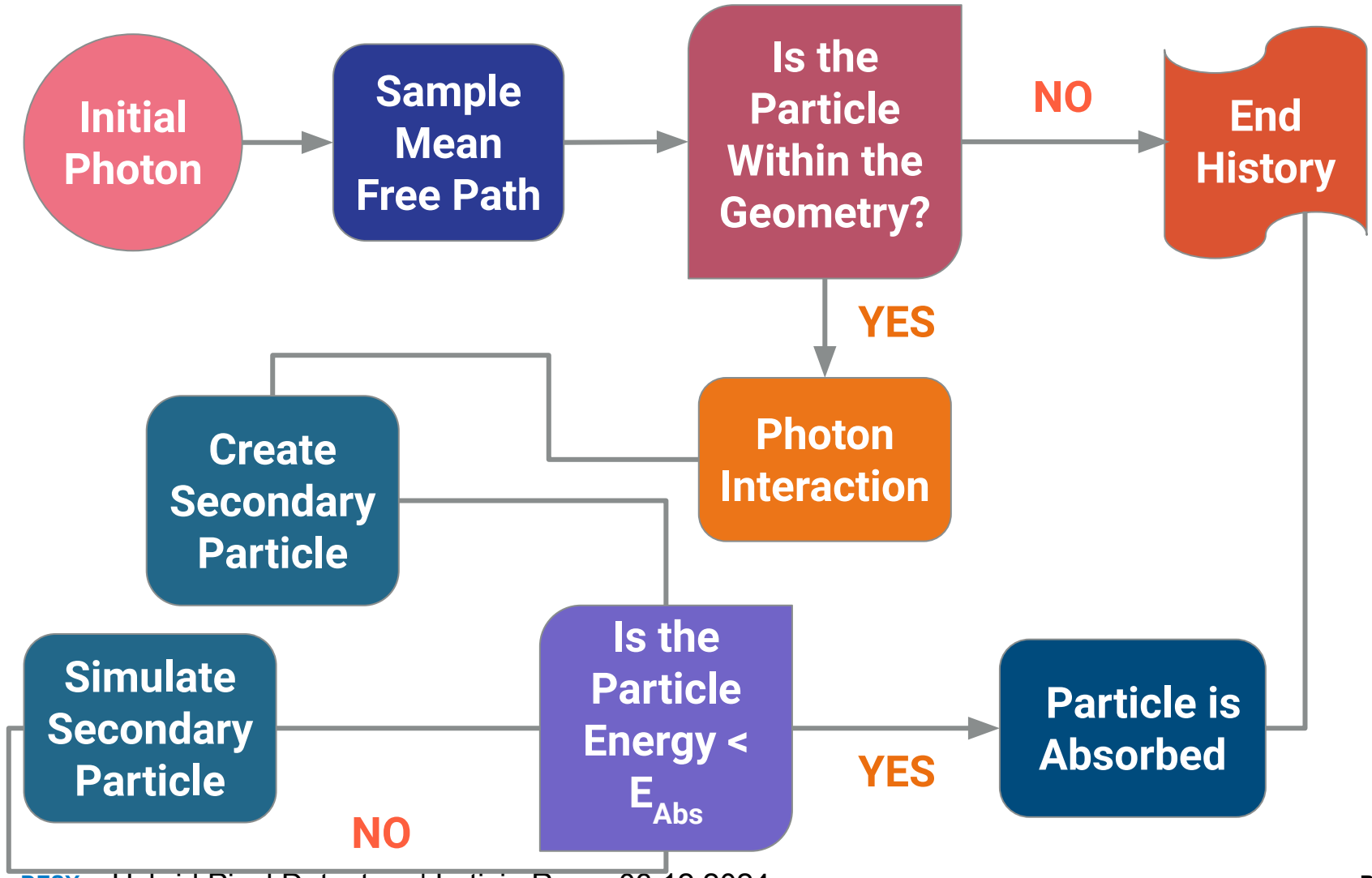
Viallefont-Robinet, F. et al. Comparison of MTF measurements using edge method: towards reference data set, 2018

PENELOPE Code Structure

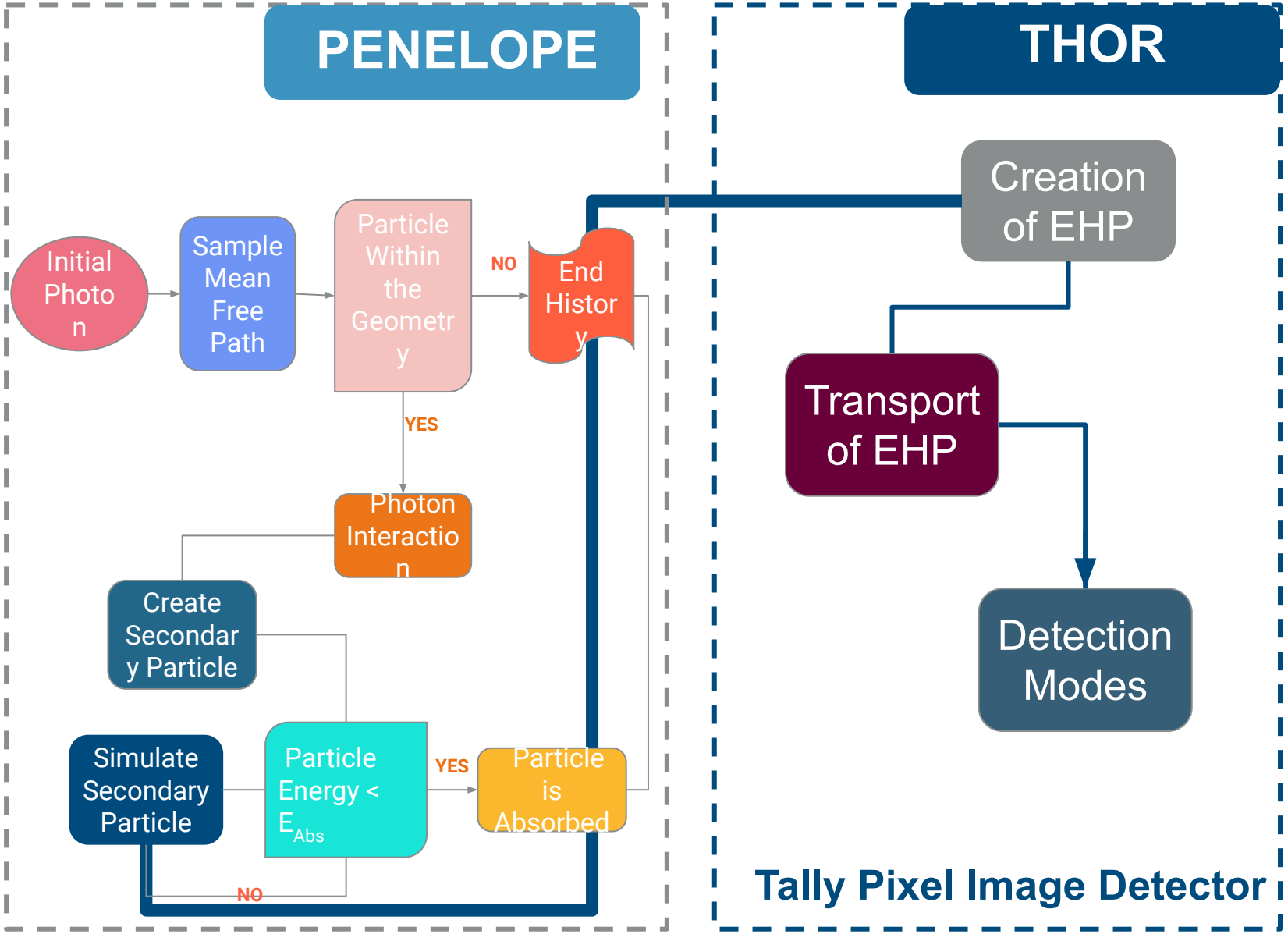




PENELOPE Simulation Process



Simulation Workflow



THOR Code

Creation of EHP

If particle is electron

$E_{dep} > W_{\pm}$

Energy to create an EHP

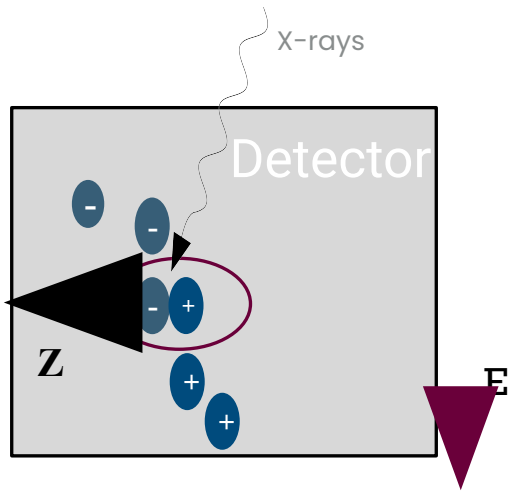
EHP:

Poisson ($\frac{E_{dep}}{W}$, F)

Fano Factor

Transport of EHP

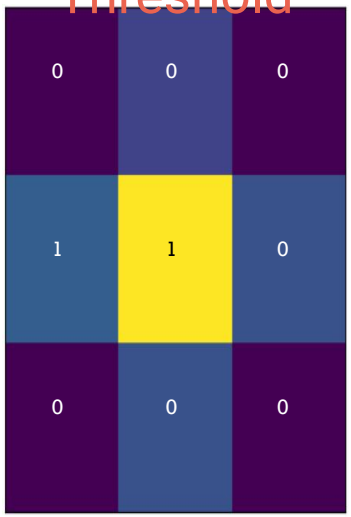
$$\sigma = \sqrt{\frac{2k_bTZ}{eE}}$$



Detection Modes

Photon Counting

Energy Threshold



Error Calculation

MTF

➔ Randomic ROIs selection along the edge

➔ ESF calculation for each ROI