Updated Sensor Response Studies for SVT

Previous report on 2026.06.09 https://indico.bnl.gov/event/33191/

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SVT DST Meeting - 2026.07.07

Introduction

2026.06.09:

- 10um epitaxial+40um substrate planar sensor in TCAD+GEANT4+Allpix^2 simulation
  - Sensor doping profiles tuned to have similar charge collection efficiency as a function of depth to a TZ65 nm CMOS sensor (H2M).
  - Sensor response to high energy charged particles:
    - Hit probability and cluster size from Allpix^2 compatible with pure GEANT4 simulation
    - Incident angle dependence of cluster size distribution from Allpix^2 compatible with ITS3 ER1 sensor measured with 120 GeV protons
  - Sensor response to low energy photons:
    - Hit probability and cluster size distribution from Allpix^2 largely different from GEANT4

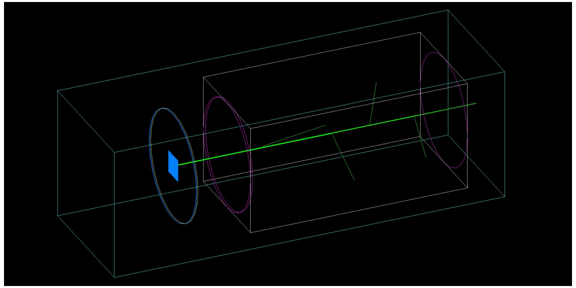
Today:

- Updates on low energy photon studies:
  - Allpix^2 bug fix and comparison of cluster size distribution to ER1 source measurements
  - Impact of Cu layers in the sensor on hit probability and cluster size
  - Eqv. active Si thickness in pure GEANT4 to have compatible hit probability as Allpix^2

Tools Used In This Study - Reminder

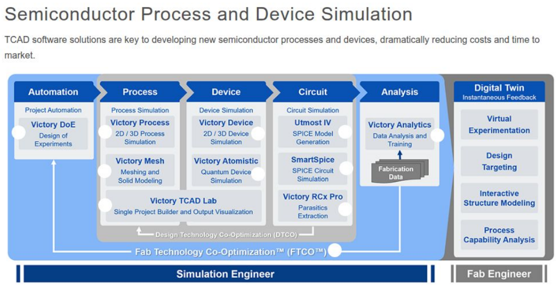
Particles interaction with silicon

40 um inactive + 10 um active Si with 20x20 um^2 pixels



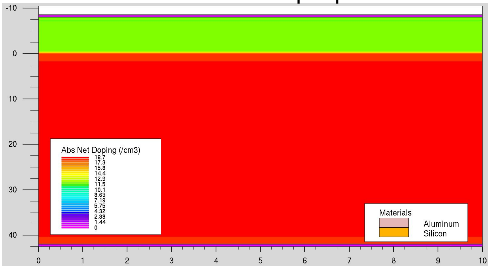
10 E_γ @ 80 keV

Sensor Doping profile and E-field



comprehensive suite of **Technology Computer-Aided Design (TCAD)** software tools to model semiconductor fabrication processes and device behaviors

Simple p-n structure



Transport model + Detector Response

Geometry Definition
Layout, materials

GEANT4 Wrapper
position + E_{dep}

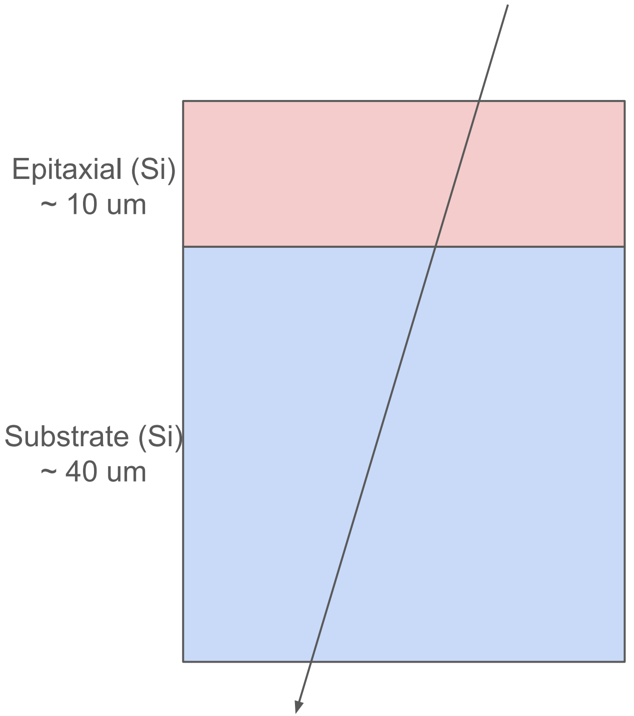
Charge Transport
Drift, diffuse…

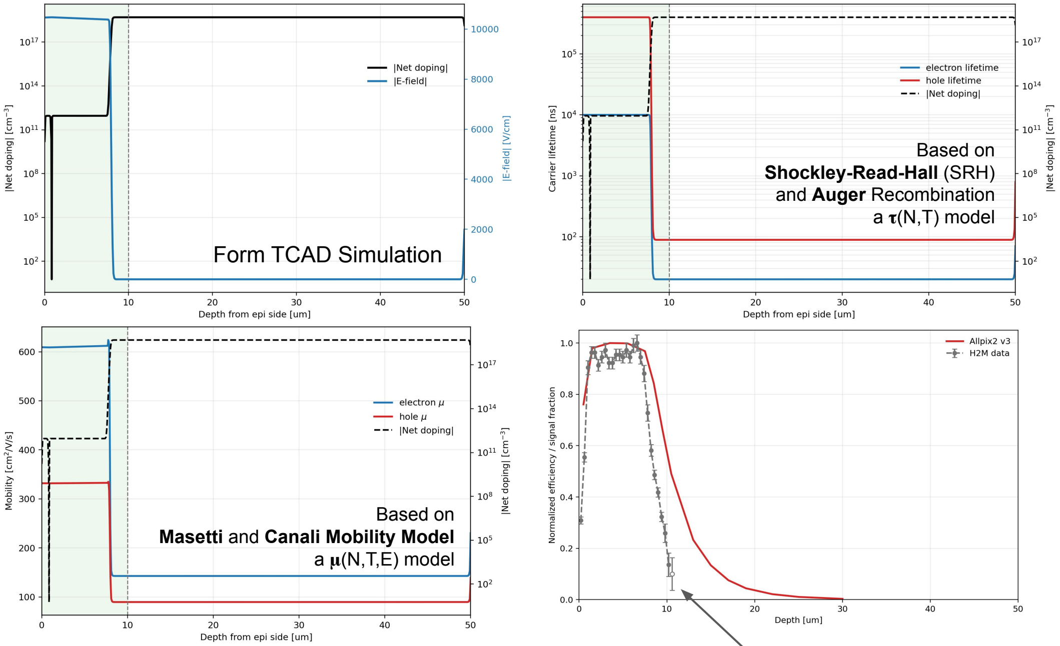
Signal Formation
Charge→electrical signal

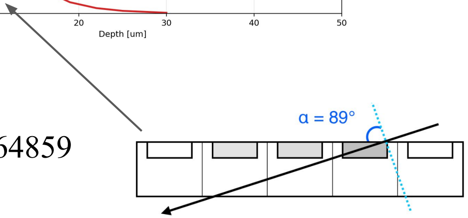
Digitization
Thr. Noise, Elec response

Output
w. ROOT

TCAD+Allpix^2+GEANT4 for Epitaxial and Substrate Silicon



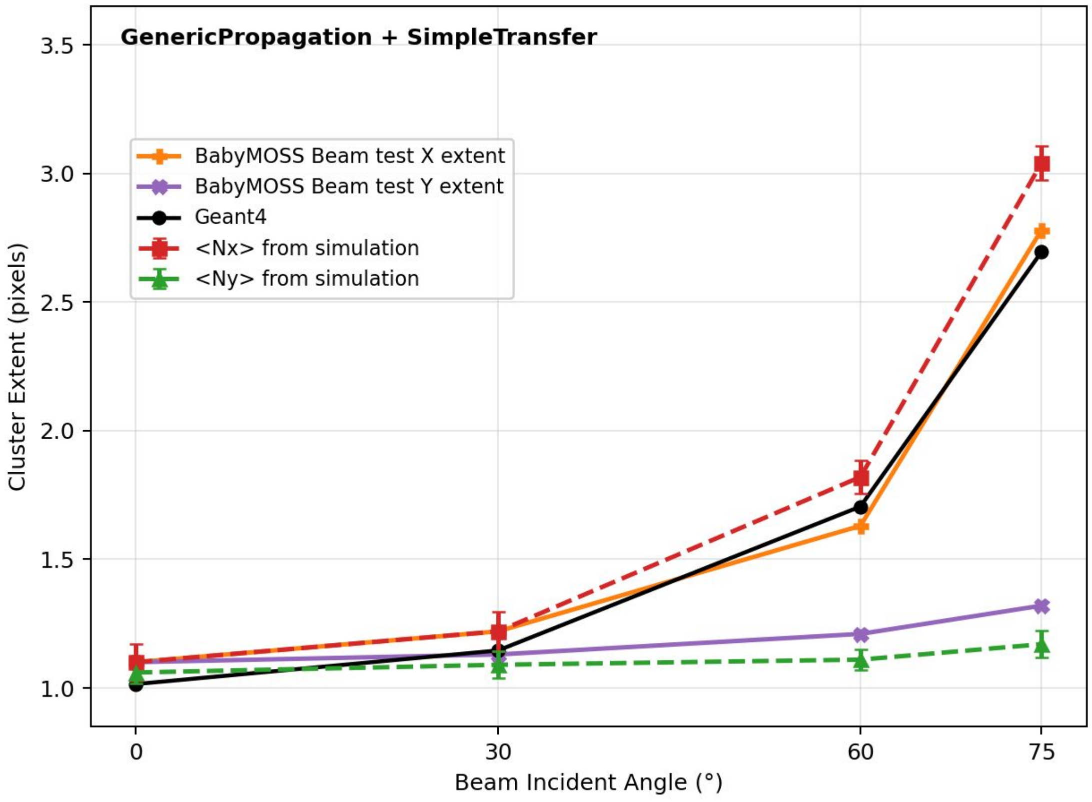


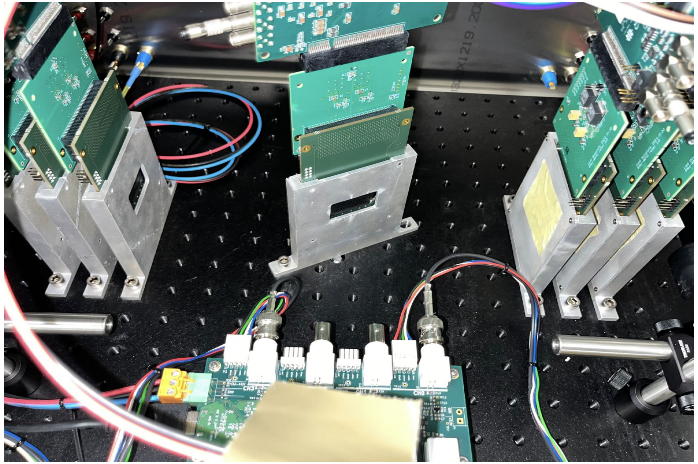


The doping densities are based on ITS2 sensors (TZ180nm): NIMA 950 (2020) 162882, NIMA 988 (2021) 164859

The epitaxial layer thickness is tuned to H2M (TZ65nm) beam test data: doi:10.3204/PUBDB-2025-03980

High Energy Charged Particles (120 GeV protons)



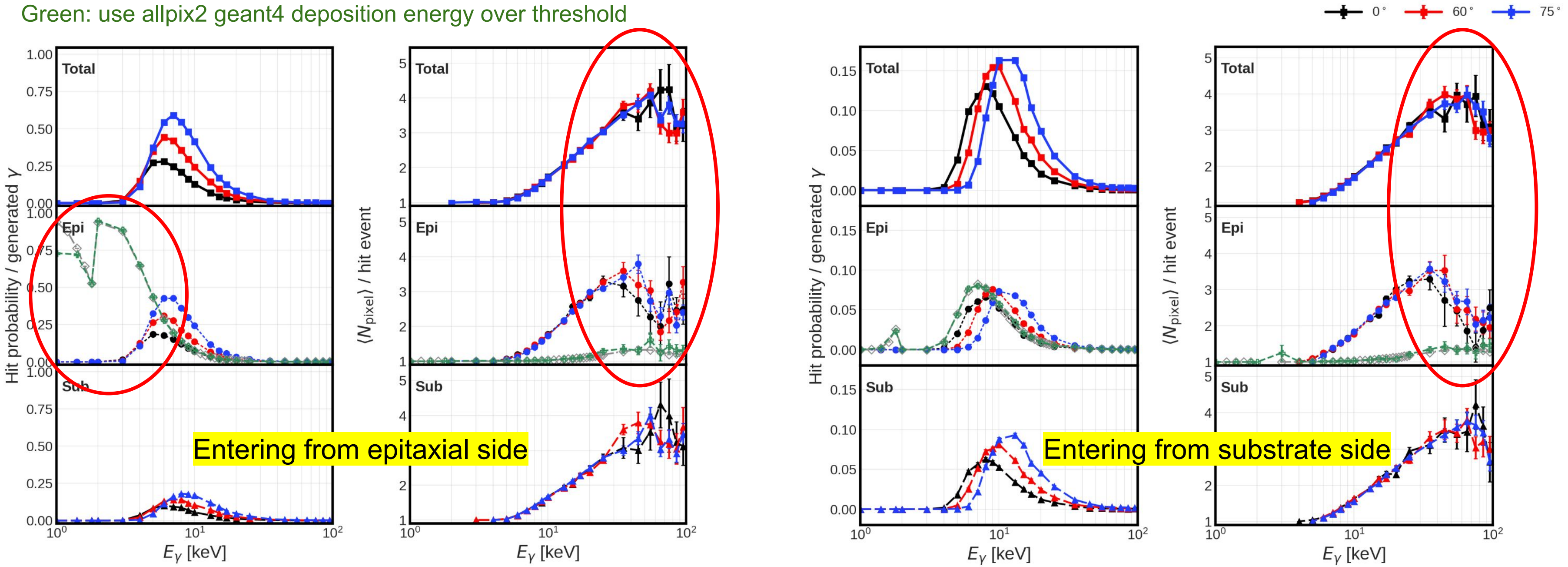


- Allpix^2 compatible with ER1 beam test data with 120 GeV protons, and with pure GEANT4 simulation
- Slightly higher <Nx> and lower <Ny> in simulation than data could partially be due to misalignment of the sensor w.r.t. beam

Low Energy Photons - Buggy Results

Grey: pure GEANT4 simulation

Green: use allpix2 geant4 deposition energy over threshold

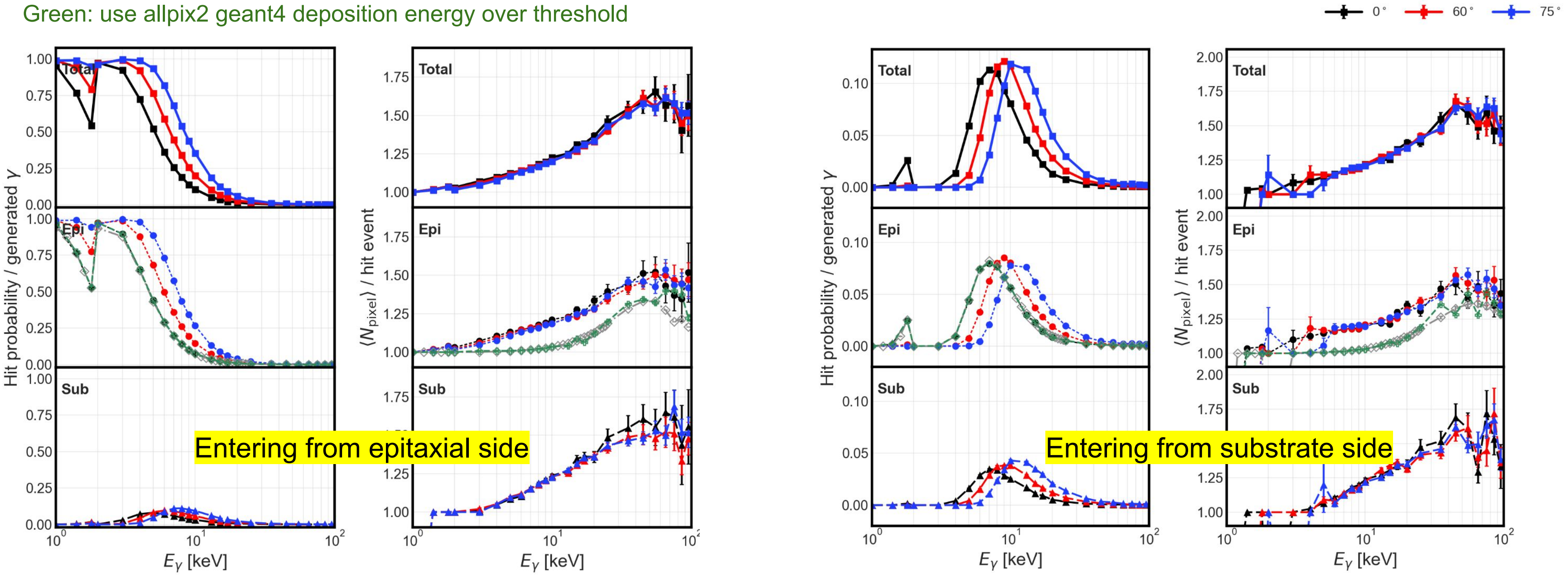


A bug found in the previous Allpix^2 simulation for low energy photons (charged particle simulation is not affected) where the E-field configuration was incorrect

Low Energy Photons - Corrected Results

Grey: pure GEANT4 simulation

Green: use allpix2 geant4 deposition energy over threshold

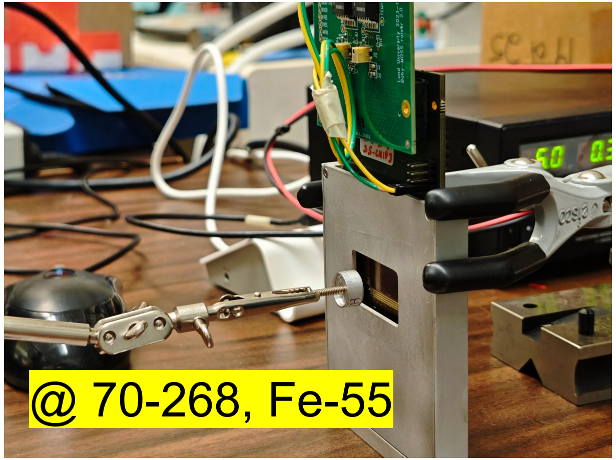


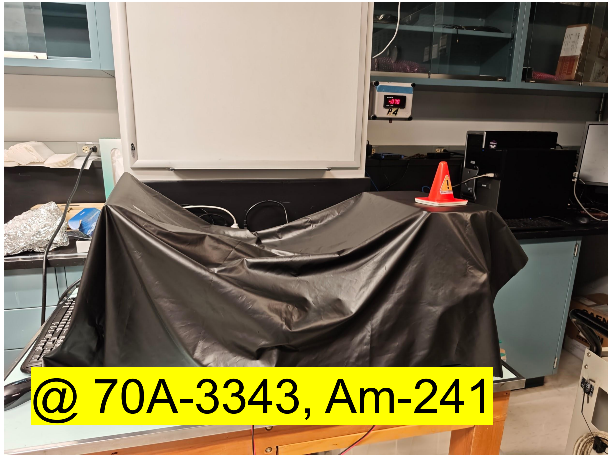
Significant dependence of cluster size on photon energy

Negligible dependence of cluster size on incident angle

Fe-55 & Am-241 Source Measurements with ER1 Sensor

- Chip & Boards: W21D4 S5-CHIP3 + 22 + RNC22
- **Bias: 0V** at room temperature
- DACS: IBIAS 62; IBIASN 100, IBD 50, IRESET 10; **VCASB 15**, VCASN 104; VS 145 - same as cern configuration
- Fe-55: γ ~5.9 keV;
- Am-241: γ ~ 59.54 keV, 17.75keV, etc



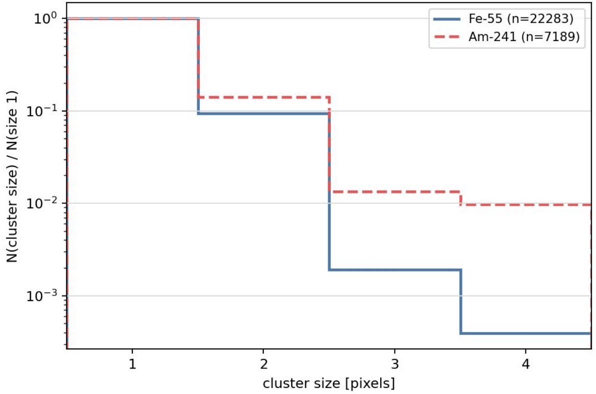


*The THR scan is not done for this sensor, so threshold might be different from 0.54 keV as in simulation

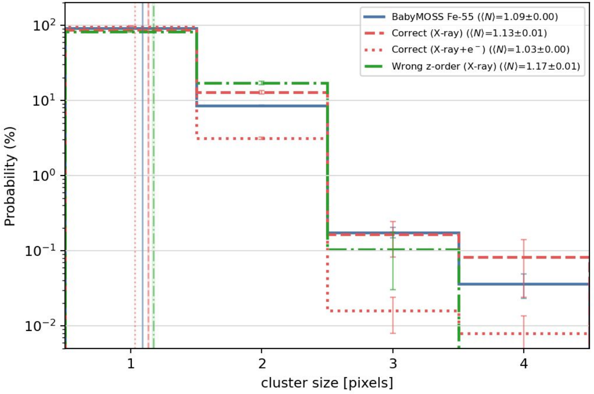
Fe-55 & Am-241 Source Measurements with ER1 Sensor

bias=0 V, Vcasb=15, background-subtracted

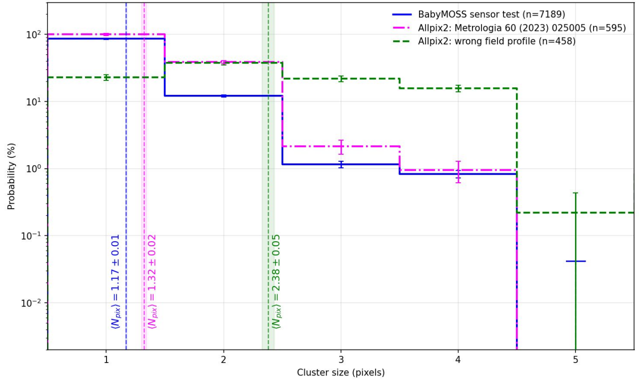
Source measurements



Fe-55 source



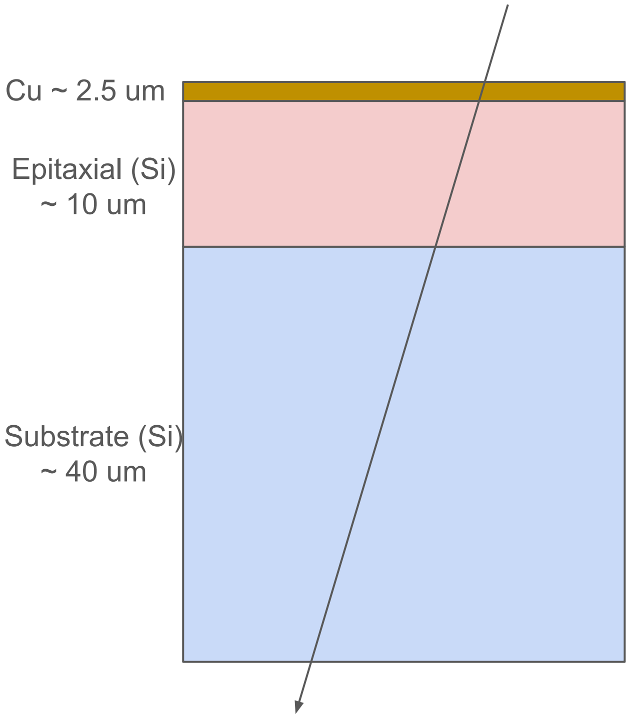
Am-241 source

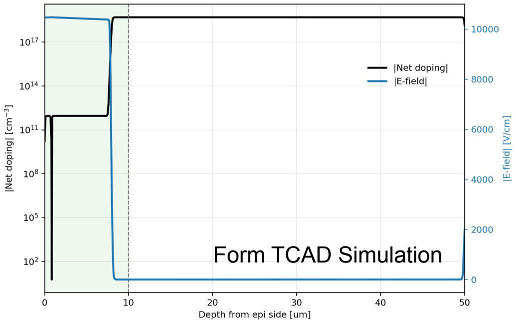


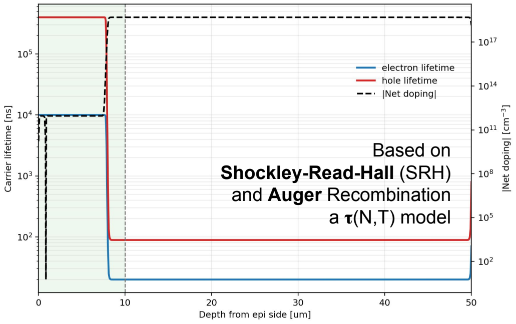
- Cluster size distributions measured with Fe-55 and Am-241 are compatible with those from the corrected Allpix^2 simulation

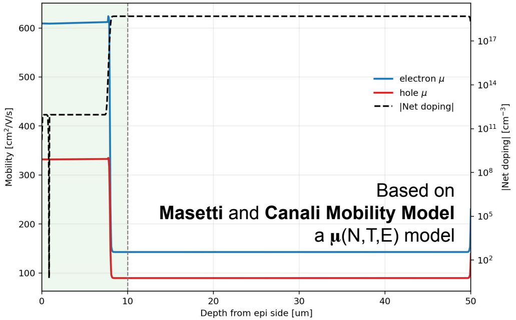
*The THR scan is not done for this sensor, so threshold might be different from 0.54 keV as in simulation

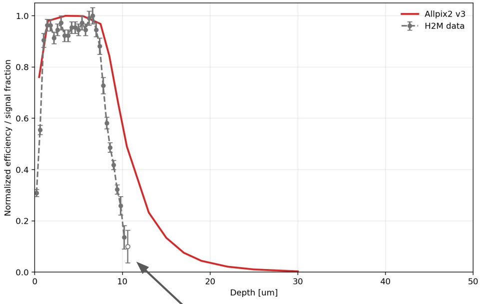
TCAD+Allpix^2+GEANT4 Simulation w. 2.5 um Cu

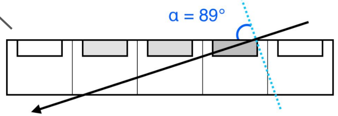












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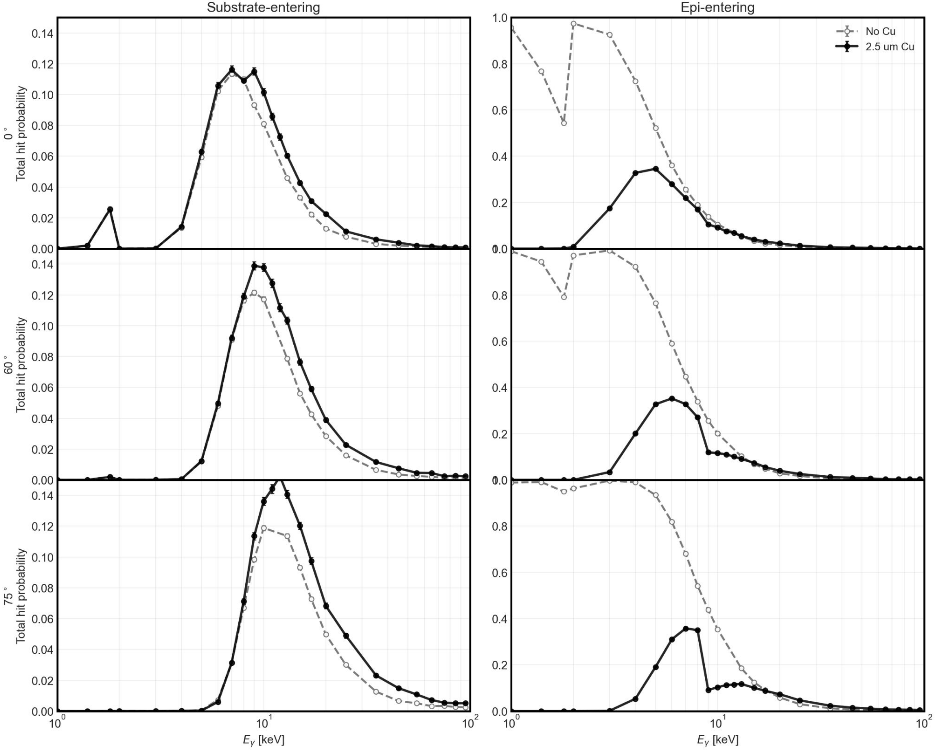
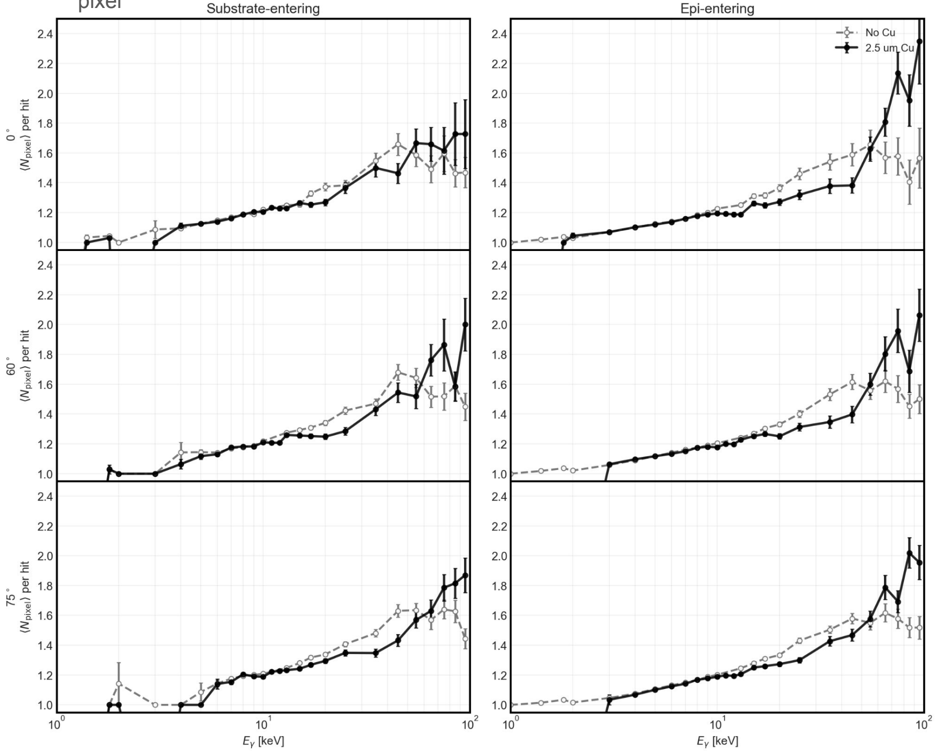
Low Energy Photons in Allpix^2 - w./w.o. 2.5um Cu layer

Hit probability



$<N_{pixel}>$/Hit



X-ray Absorption Edges

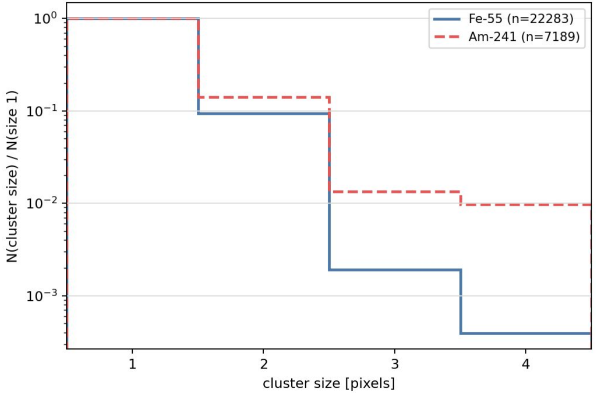
Element 29: Cu   Atomic mass: 63.5460

Edge	keV	A
K	8.9789	1.3808
L-I	1.0961	11.3114

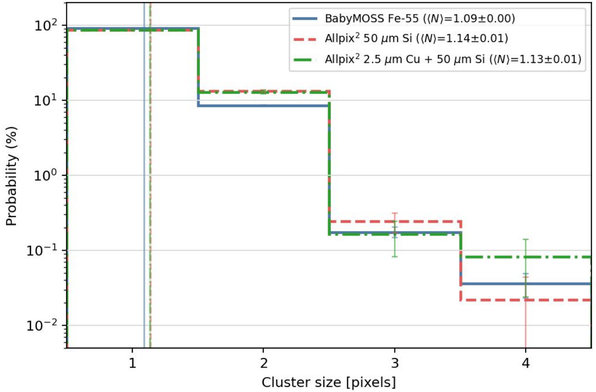
http://skuld.bmsc.washington.edu/scatter/data/Cu.html

Low Energy Photons in Allpix^2 - w. 2.5um Cu

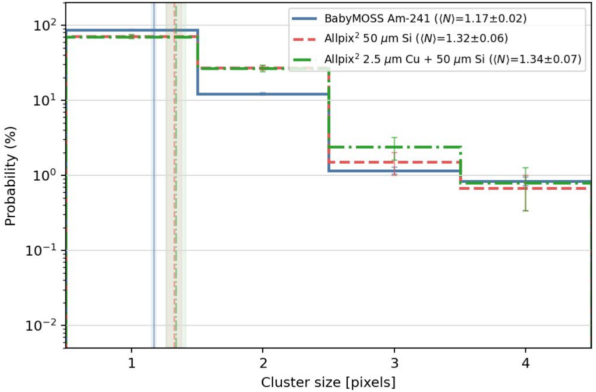
Source measurements



Fe-55 source



Am-241 source



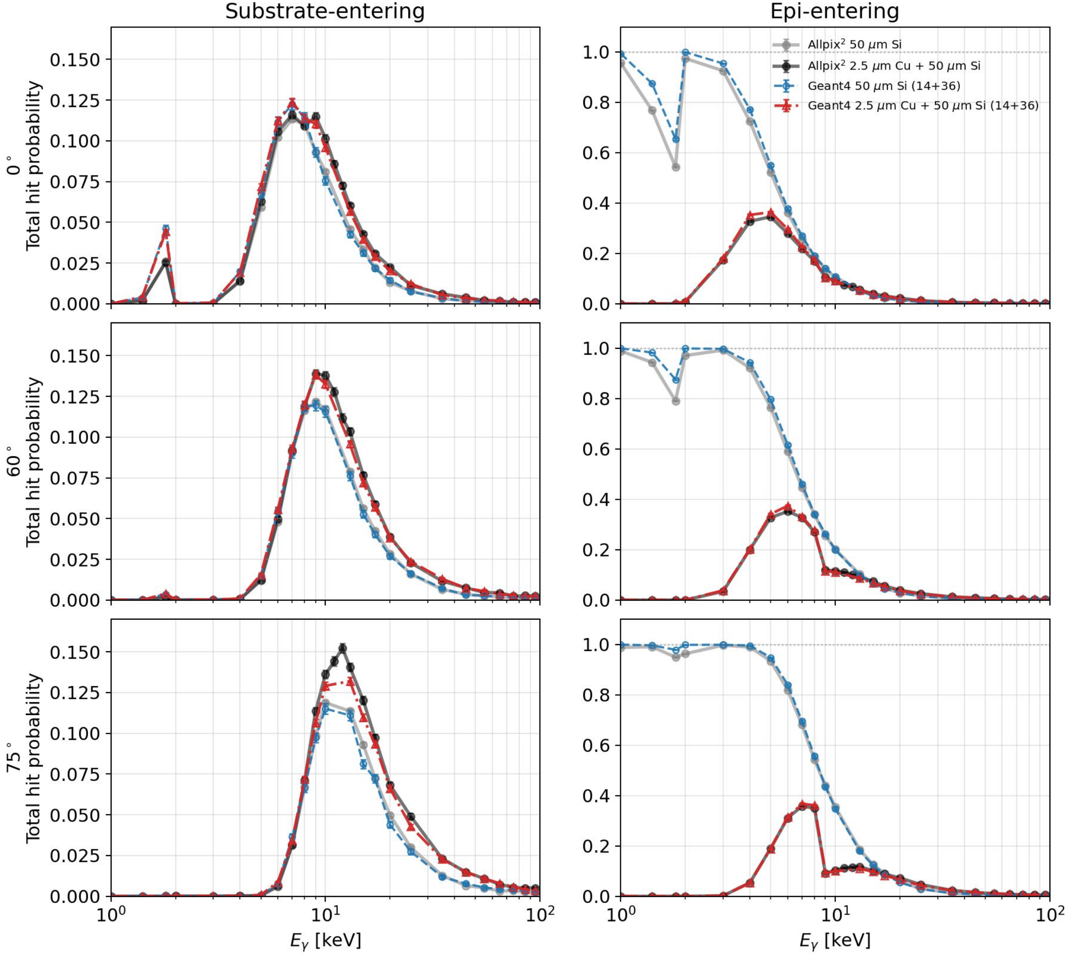
- Little change in cluster size distribution after adding the Cu layer in Allpix^2. Results from Allpix^2 are still compatible with ER1 source measurements

*The THR scan is not done for this sensor, so threshold might be different from 0.54 keV as in simulation

Summary and Outlook

- It is important to get SVT sensor response correct in simulation for SVT data rate estimation, as the latter strongly depend on hit probability and cluster size
- We have attempted to use TCAD+GEANT4+Allpix2 to understand sensor responses to high energy charged particles and low energy photons
    - Initial results on cluster size compatible with high energy charged particles (120 GeV protons) and low energy X-ray source (Fe-55, Am-241) measurements. We have not checked hit probability for low energy photons - difficult to do with radiative sources
    - To have an accurate accounting of hit probability and cluster sizes and thus data rates, we should measure them on ER2/Final sensors in SVT running conditions with charged particle beam and synchrotron light source, and improve the simulation with realistic sensor structure when we have access to foundry doping profiles
- Impractical to adopt TCAD+GEANT4+AllPix2 for ePIC simulation - rely on DD4Hep GEANT4
    - A sensor structure with 2.5um Cu + 14um active Si + 36um inactive Si in pure GEANT4 simulation gives compatible hit probabilities as full Allpix2 simulation (see next page)
    - More involved to describe cluster size - 3D sensor charge collection efficiency map, or particle specie+energy+incident angle dependent parameterization?

Match Hit Probability in GEANT4 withe Allpix2 Simulation

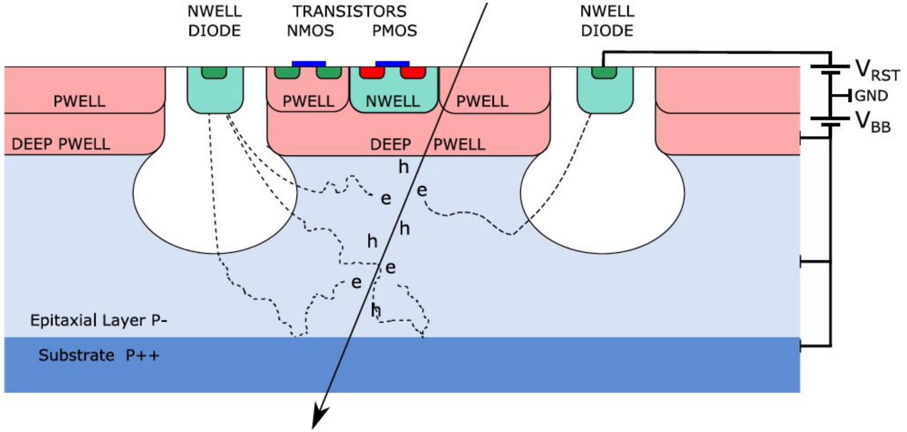


Compare **black** with **red**

Pure GEANT4 simulation with 2.5 um Cu + 14 um active Si + 36 um inactive Si

matches with Allpix2 hit probability (w. Simple p-n structure) relatively well

Introduction



- P/N-well: high doping, electrical circuit
- Epitaxial: low doping, sensor active volume
- Substrate: high doping, mechanical handling

1. Particles interact with sensor and generate signal charges [1]
2. Signal charges collected through drifting and diffusion [2-7]
3. Collected charges are processed by integrated readout electronics

- **References**

[1] Passage of Particles Through Matter, S. Navas et al. (Particle Data Group), Phys. Rev. D110, 030001 (2024)

[2] Simulation and measurements of charge collection in monolithic active pixel sensors, Grzegorz Deptuch et al., NIMA 465 (2001) 92–100

[3] New Generation of Monolithic Active Pixel Sensors for Charged Particle Detection, Grzegorz Deptuch (2002).

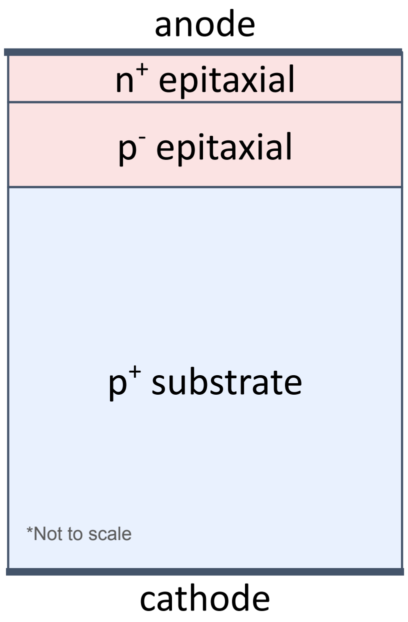
[4] Study of Monolithic Active Pixel Sensors for the Upgrade of the ALICE Inner Tracking System, Miljenko Šuljić, CERN-THESIS-2017-304

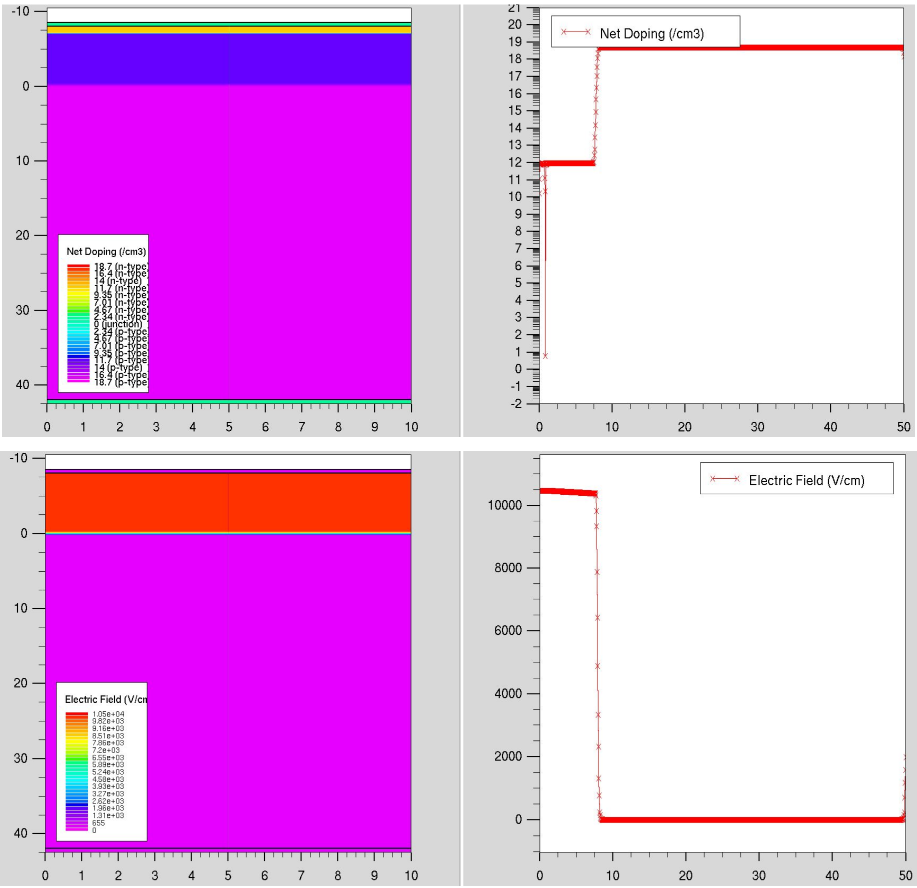
[5] MC simulation of charge collection processes in Monolithic Active Pixel Sensors for the ALICE ITS upgrade, Miljenko Šuljić, NIMA 950 (2020) 162882

[6] Development and performance study for the ALICE ITS3: the first truly cylindrical inner tracker, Isabella Sanna, CERN-THESIS-2024-359

[7] TCAD and charge transport simulations of MAPS in 65nm for the ALICE ITS3, Isabella Sanna et al., JINST 20 (2025) C06032

Doping and E-field from Silcavo TCAD Simulation





We don’t know the manufacture process and doping profiles for ITS3 sensors made from TowerJazz 65 nm process

The following study uses a simple p-n structure to get carrier drifting, diffusion, and recombination parameters.

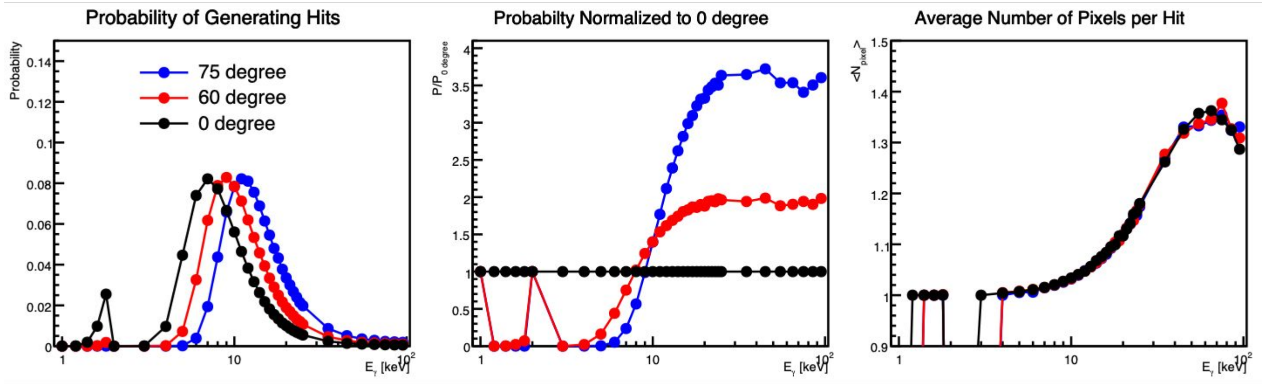
The doping densities are based on MAPS sensors made from TZ180nm process:

NIMA 950 (2020) 162882

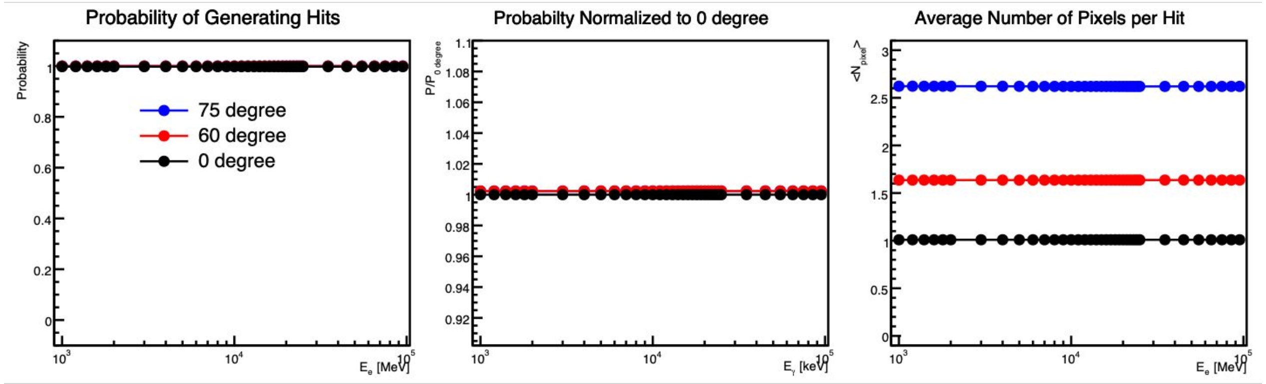
NIMA 988 (2021) 164859

Particle Interaction with Silicon (GEANT4)

Low-Energy Photon

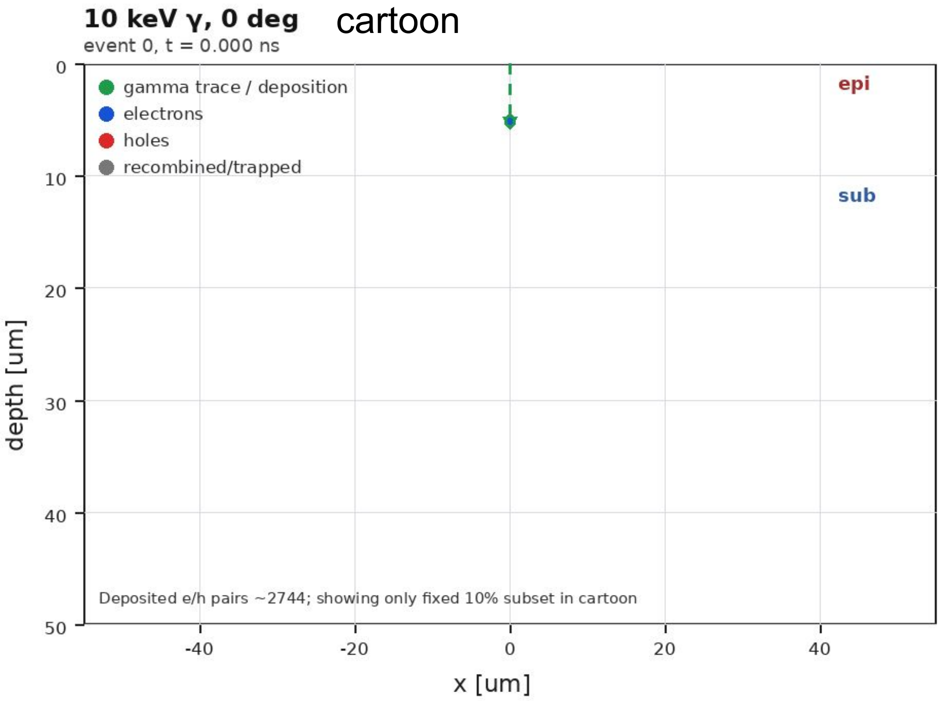


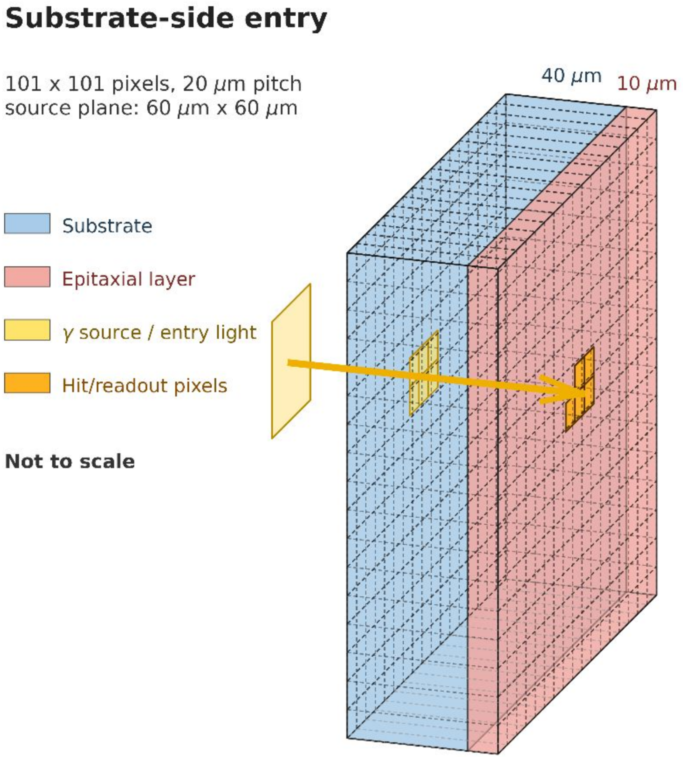
High-Energy Electron



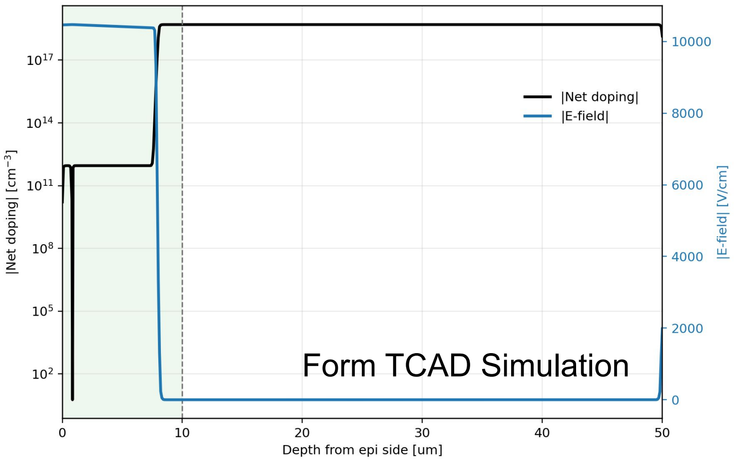
Interaction with Particle and Charge Transport via AllPix2

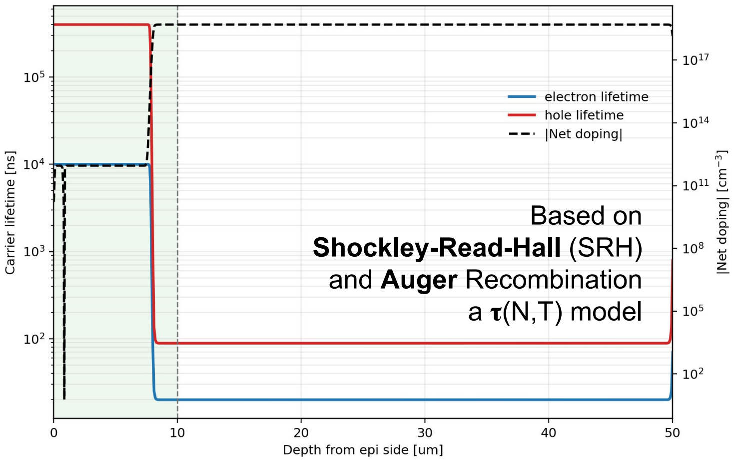
cartoon

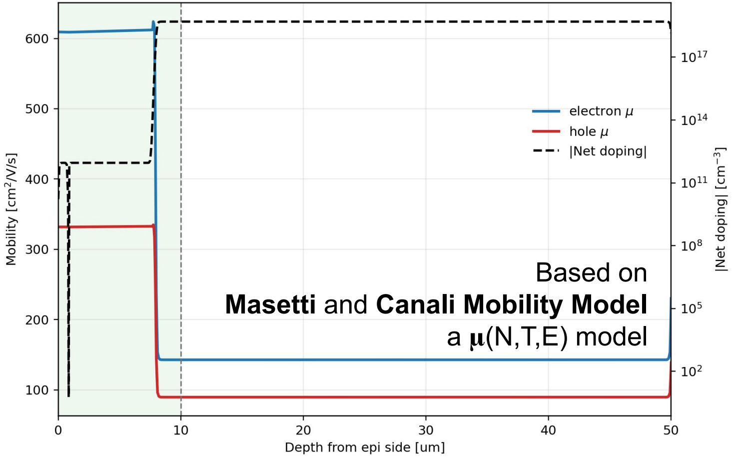


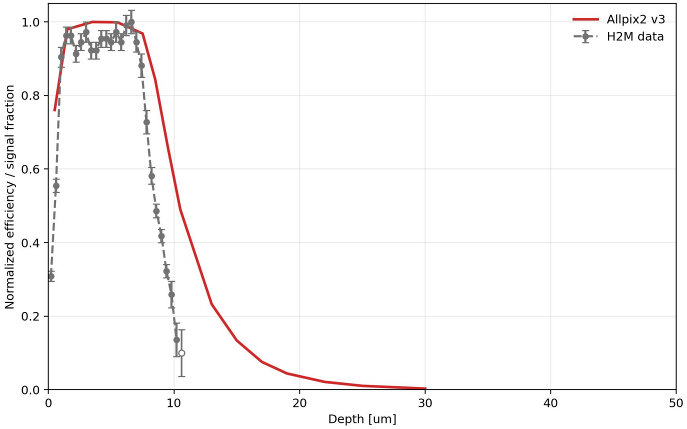


Doping profile, E-fields, and Carrier Mobility in AllPix2

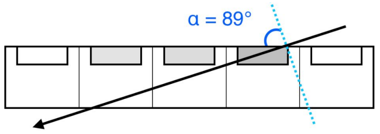








H2M (TZ65nm) beam test data:
doi:10.3204/PUBDB-2025-03980



Fe-55 & Am-241 Sources

Fe-55

Dataset #1:

Author: Huo Junde   Citation:Nuclear Data Sheets 109, 787 (2008)

Parent Nucleus	Parent E(level)	Parent Jπ	Parent $T_{1/2}$	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	Decay Scheme	ENSDF file
$^{55}_{26}$Fe	0.0	3/2-	2.744 y *9*	ε: 100 %	231.21 *18*	$^{55}_{25}$Mn		

Electrons:

	Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
Auger L	0.61	139.9 % *14*	8.53E-4 *8*
Auger K	5.19	60.1 % *8*	0.00312 *4*

Gamma and X-ray radiation:

	Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
XR l	0.64	0.66 % *10*	4.2E-6 *6*
XR kα2	5.888	8.2 % *4*	4.85E-4 *21*
XR kα1	5.899	16.2 % *7*	9.6E-4 *4*
XR kβ1	6.49	1.89 % *9*	1.23E-4 *6*
XR kβ3	6.49	0.96 % *5*	6.3E-5 *3*
	126.0 *1*	1.280E-7 % *20*	1.61E-10 *3*

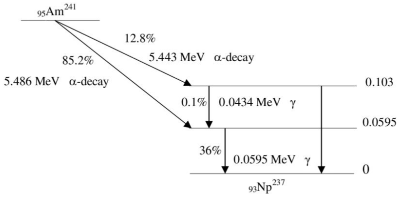
Am-241

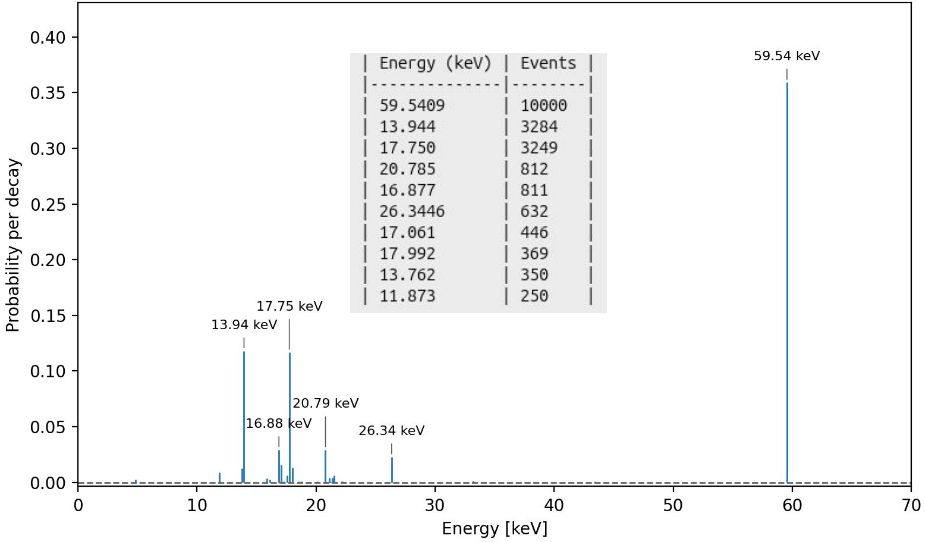
IOP Publishing | Bureau International des Poids et Mesures   Metrologia
Metrologia 60 (2023) 025005 (18pp)   https://doi.org/10.1088/1681-7575/acb99

Determination of absolute Np L x-ray emission intensities from ^{241}Am decay using a metallic magnetic calorimeter

Matias Rodrigues*, Martin Loidl and Sylvie Pierre

Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), F-91120 Palaiseau, France





https://www.nndc.bnl.gov/nudat3/