Partial charge collection and quantum efficiency of a back-illuminated skipper-CCD

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G. Fernandez-Moroni, J. Tiffenberg

ISPA 2024

March 14, 2024

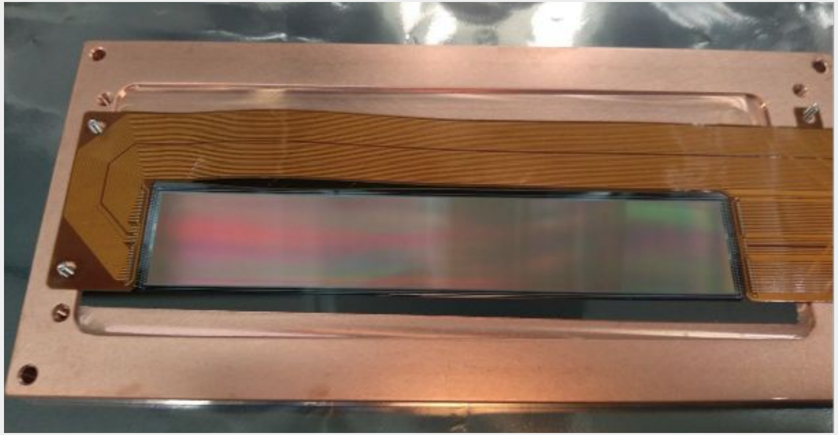

Image: SENSEI sensor

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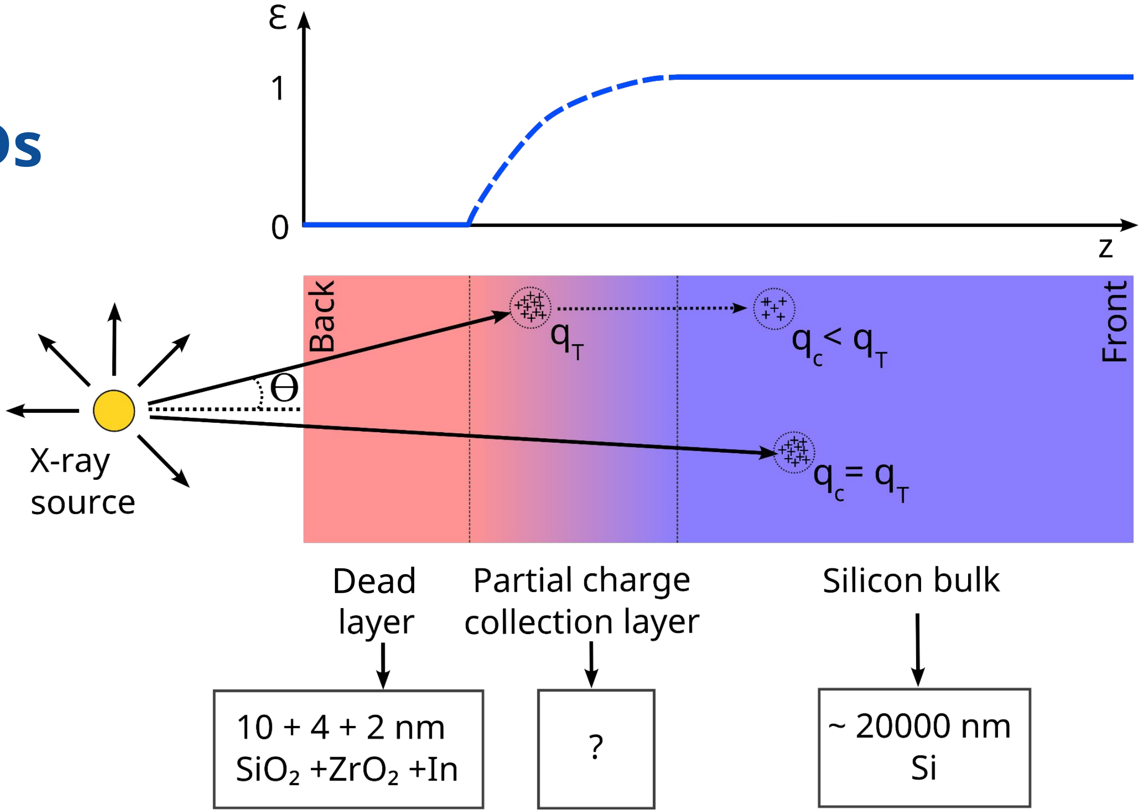
Charge collection efficiency in fully-depleted CCDs



Partial charge collection layer

Region at the back of the CCD:

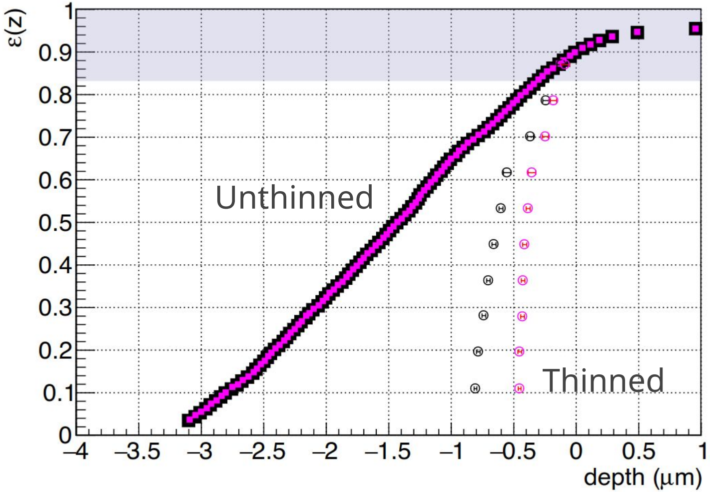
- Transition between dead layer and Silicon bulk
- High recombination probability
- Only charges escaping to Silicon bulk are collected

Why do we care about PCC?

- Possible background in neutrino and dark matter experiments
- **Quantum efficiency** of visible light in back-illuminated CCDs

Summary of previous work

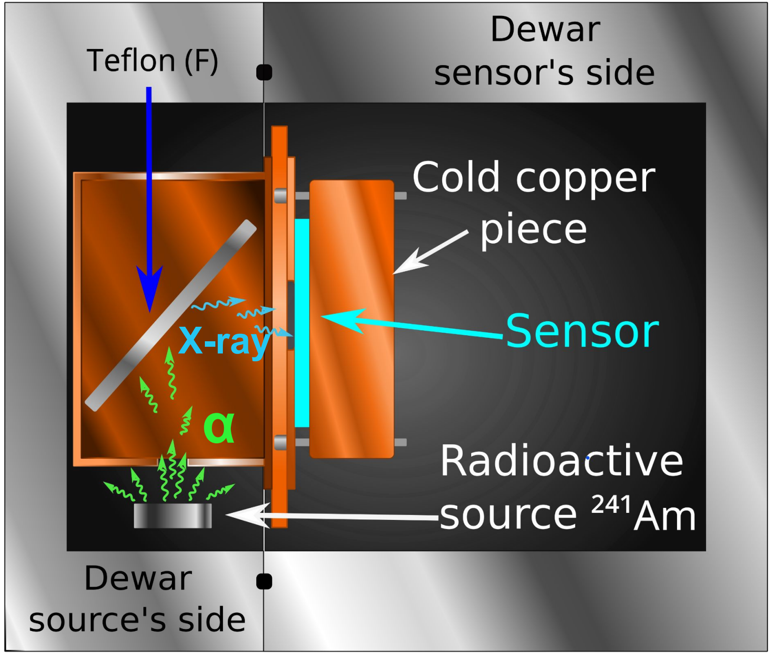
- Comparison between thinned and unthinned CCDs
- 55Fe X-ray source (5.9 and 6.4 keV)
- Attenuation length ~ 15 um
- Low statistics for thinned CCD
- New work: leverage data from Fano noise measurement



Charge-Collection Efficiency in Back-Illuminated Charge-Coupled Devices. G. Fernandez Moroni, et al. Phys. Rev. Applied 15, 064026 (2021)

Experimental setup

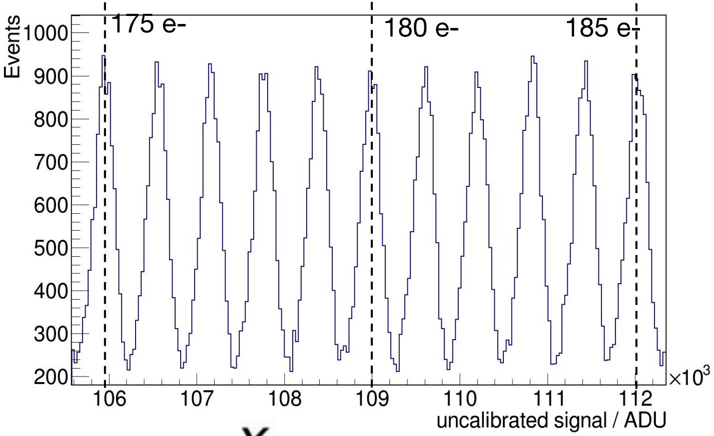
- S. Holland skipper-CCD design
- Vacuum vessel at <10^{-4} torr
- CCD Temperature 123 K
- 3.7 Mpix of 15 μm
- Read-out electronics: low-threshold acquisition board
- 300 skipper samples ⇒ 0.2 e- noise
- Continuous readout
- 677 eV fluorescence x-rays (F)

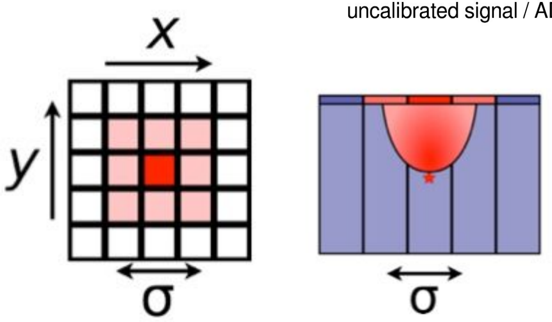


Unraveling Fano noise and the partial-charge-collection effect in x-ray spectra below 1 keV. D. Rodrigues et al. Phys. Rev. Applied 20, 054014 – Published 7 November 2023

Reconstruction and quality cuts

- Calibration from deep sub-electron resolution
- Cluster reconstruction (join neighboring pixels with charge > 0.6 e-)
- Remove hot columns and edges
- Compute charge variance in cluster
- Remove (very) asymmetric events
- No other cut





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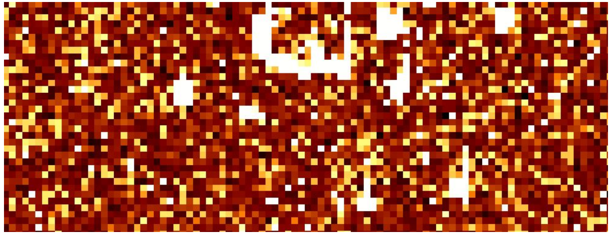
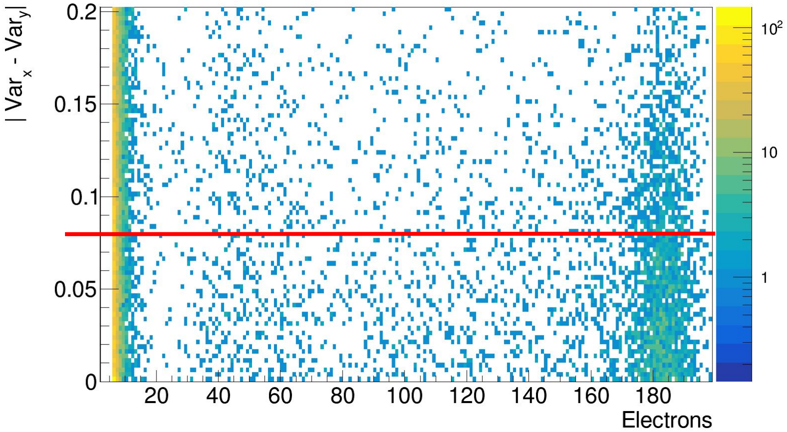
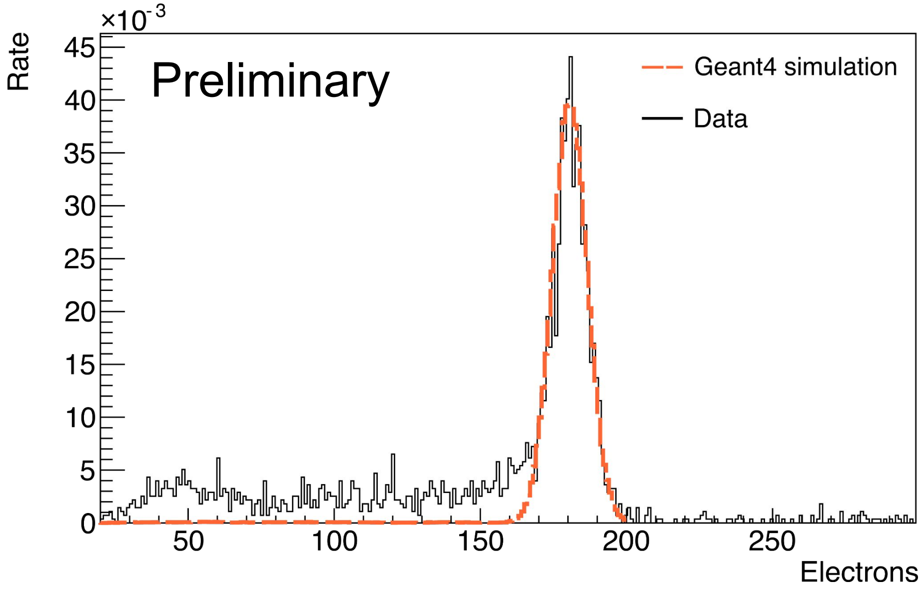


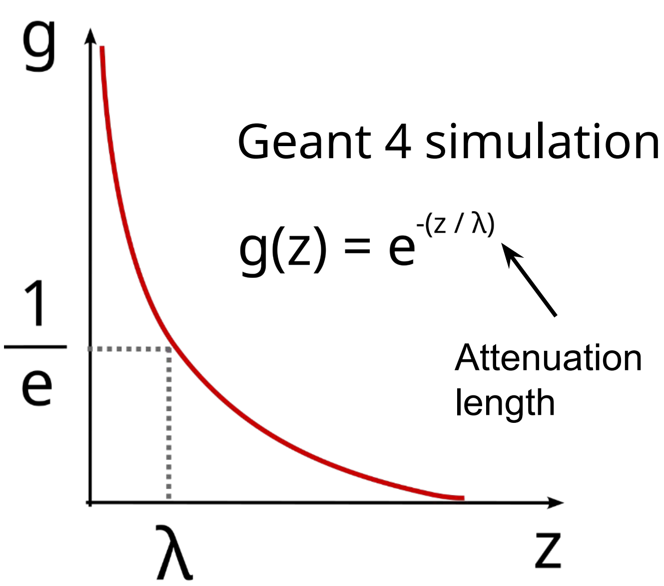


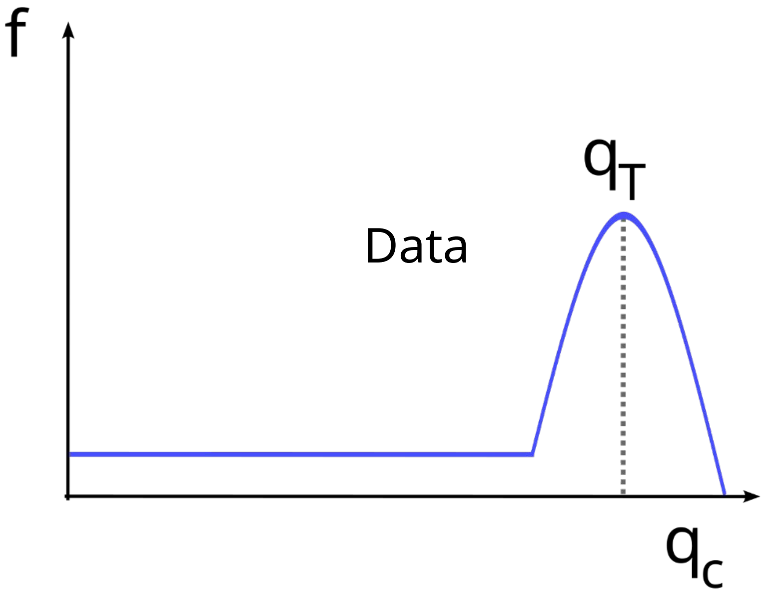
Spectrum reconstruction

- **Minimal cuts**
- Geant4 simulation of death layer and Silicon bulk
- No significant compton scattering
- No significant background from environment
- Excess of events around 50 electrons (probably from pile-up)

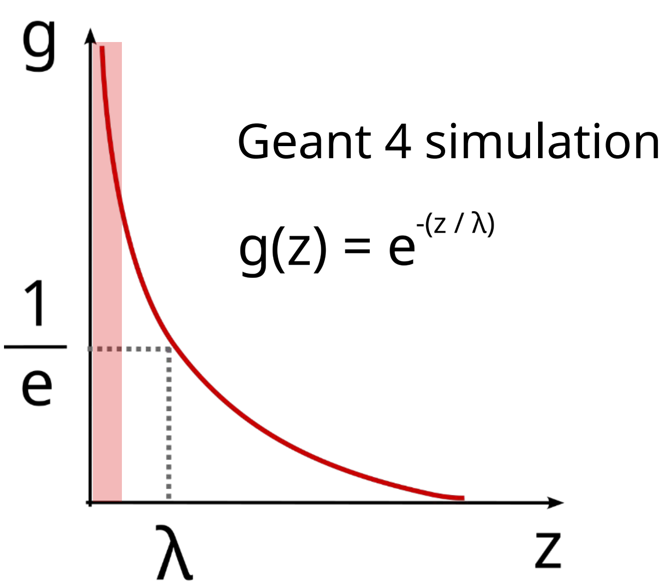


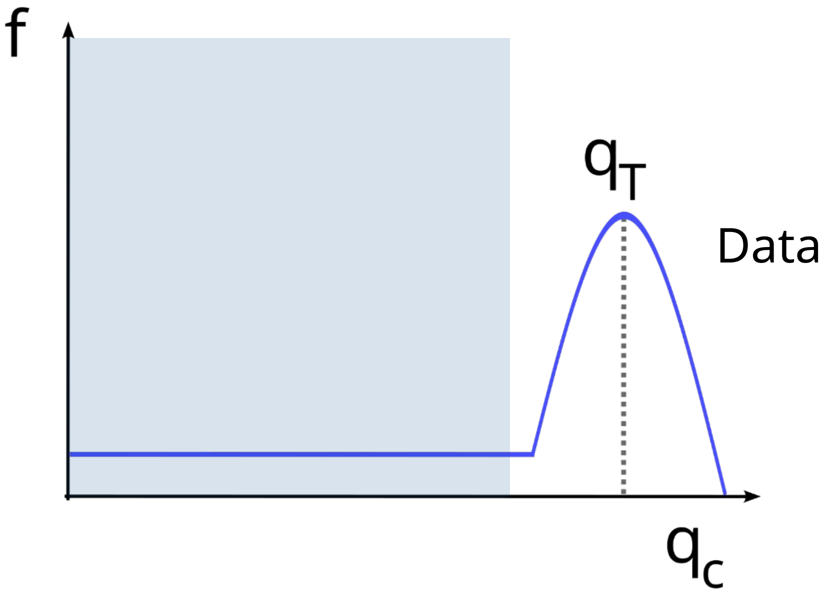
Method


g
Geant 4 simulation
g(z) = e^-(z / λ)
1
e
Attenuation
length
λ
z


f
Data
qT
qc

Method

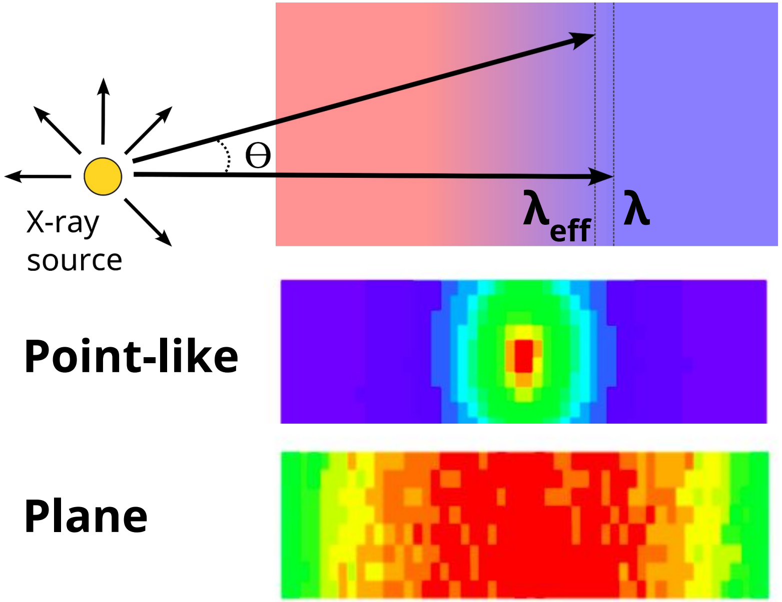




$$\mathbf{G(z)} = \int_0^z g(x)\,dx = \int_0^{q_c} f(x)\,dx = \mathbf{F(q_c)} \Rightarrow \mathcal{E}\mathbf{(z)} = \mathbf{q_c(z)} / \mathbf{q_T}$$

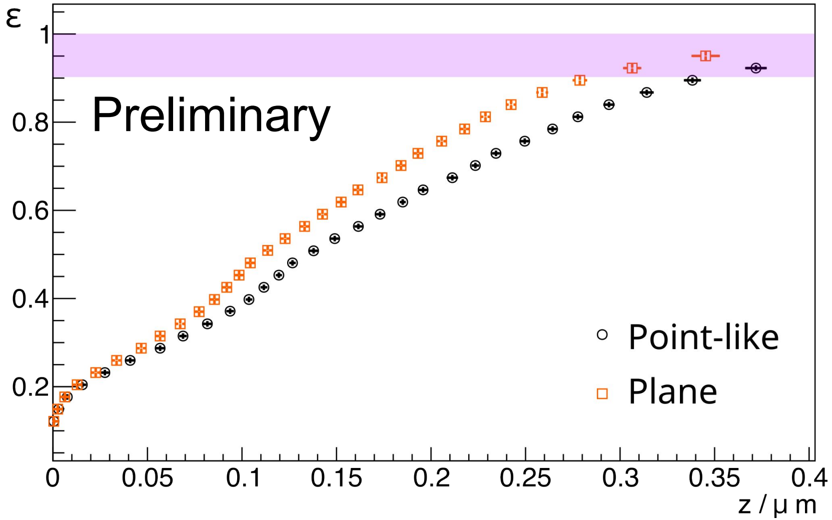
Attenuation length

- 676 eV X-ray in Silicon + dead layer: λ = 0.74 μm
- Real source geometry unknown
- Toy monte-carlo simulation to determine effective λ (λ_{eff})
- Far point-like source: mostly normal incidence (λ = 0.74 μm)
- Inclined plane similar to teflon in setup (λ = 0.60 μm)



Charge collection efficiency (Ɛ)

- Calculation for two ("opposite") source geometries
- Analysis limited to 0.1 ~ 0.9 range due to SR background at low energy
- Different source geometries result in a 10% efficiency difference

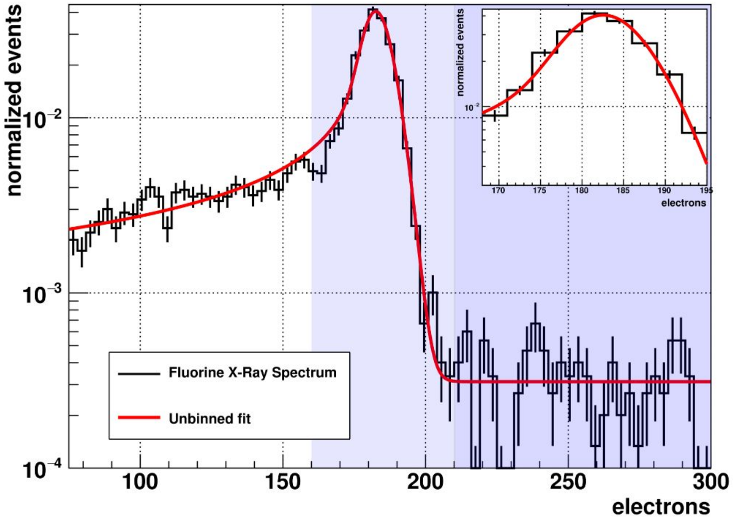


Comparison with model dependant method

- Method developed for absolute measurement of fano factor and ionization energy
- Assuming ε(z) shape:

$$\varepsilon(z) = 1 - (1 - \varepsilon_0)\exp\left(-\frac{z}{\tau_{CEE}}\right)$$

- Both methods reconstruct a 80% collection efficiency at ~ z = 230 nm



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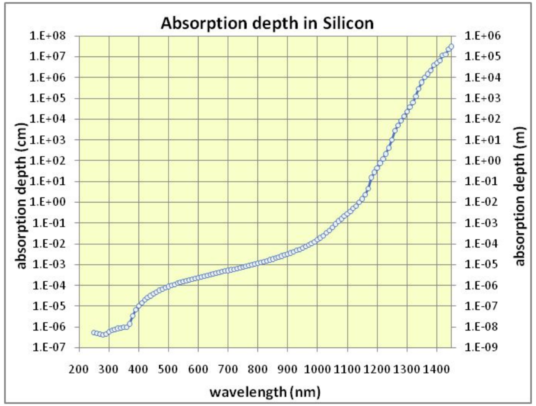
Quantum efficiency calculation (QE) for visible wavelengths

- Quantum efficiency (QE) at z = ε(z)
- Total QE convolution between ε(z) and probability of interaction at z
- Numerical calculation using measured ε(z) and tabulated attenuation

$$\mathbf{QE}(\lambda) = \int_0^{200} \frac{1}{\lambda} e^{\frac{-z}{\lambda}} \epsilon(z)\, dz$$

Measured charge collection efficiency

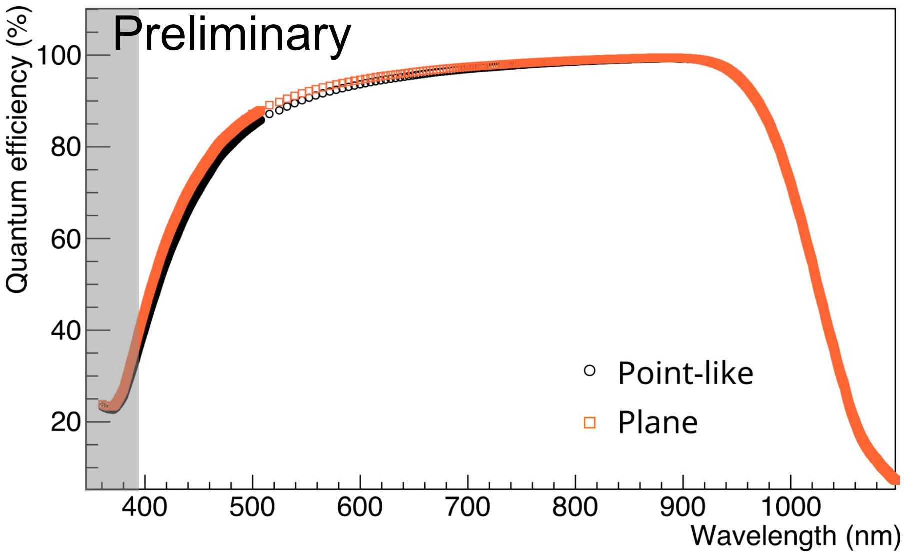
Photon attenuation length



M. A. Green, "Self-consistent optical parameters of intrinsic silicon at 300 K including temperature coefficients", Solar Energy Materials and Solar Cells, vol. 92, pp. 1305–1310, 2008.

Quantum efficiency

- Overestimation of PCC layer size will produce a lower QE in the blue
- No significant difference in source geometry (could be quantified as a systematic uncertainty)
- Reducing backgrounds at low energy (serial register hit) can improve resolution below 400 nm



Summary and outlook

- First **model independent measurement** of partial charge collection layer using **676 eV X-rays**
- Simulation and analysis tools acknowledge for **geometry effects** of the X-rays source
- Discussion on method to obtain **quantum efficiency** for visible wavelengths without a calibrated photo-detector or source

- **Improve data quality** by shielding the serial register and reducing occupancy
- **Improve efficiency estimation** with new analysis method
- Implement effects of **optical coating**
- **Compare** method with **absolute calibration** of quantum efficiency.

SPIE 6068, temp: 101–111 (2006) (Electronic Imaging 2006) 19 Jan 2006 LBNL-59227

Quantum efficiency characterization of LBNL CCD's Part 1: the Quantum Efficiency Machine

Donald E. Groom, Christopher J. Bebek, Maximilian Fabricius, Armin Karcher, William F. Kolbe, Natalie A. Roe, and Jens Steckert