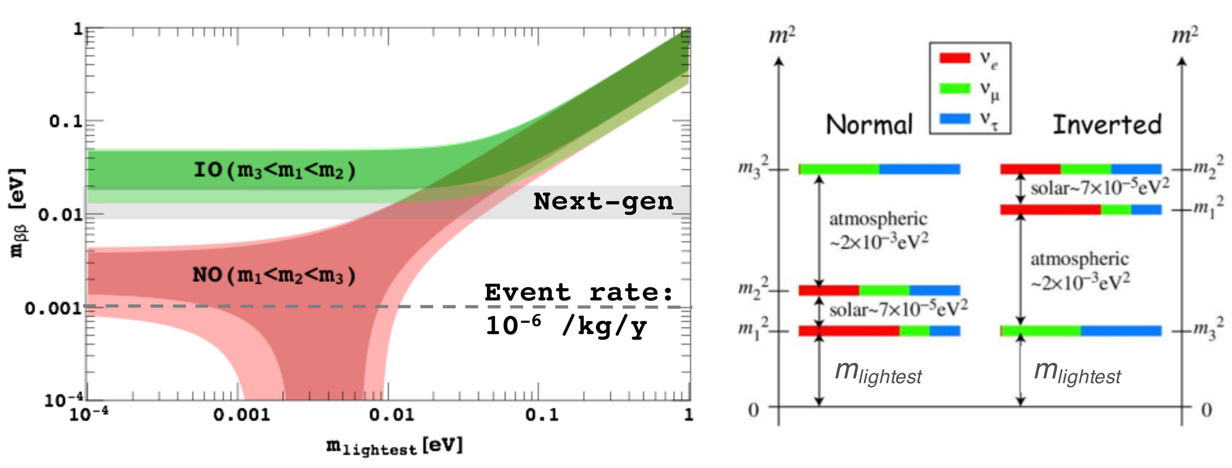
^{82}Se imaging detectors for a definitive search for neutrinoless ββ decay

A.E. Chavarria[1], C. Galbiati[2], X. Li[2], A. Piers[1], A. Razeto[3]

[1]University of Washington, [2]Princeton University, [3]Laboratori Nazionali del Gran Sasso

Motivation

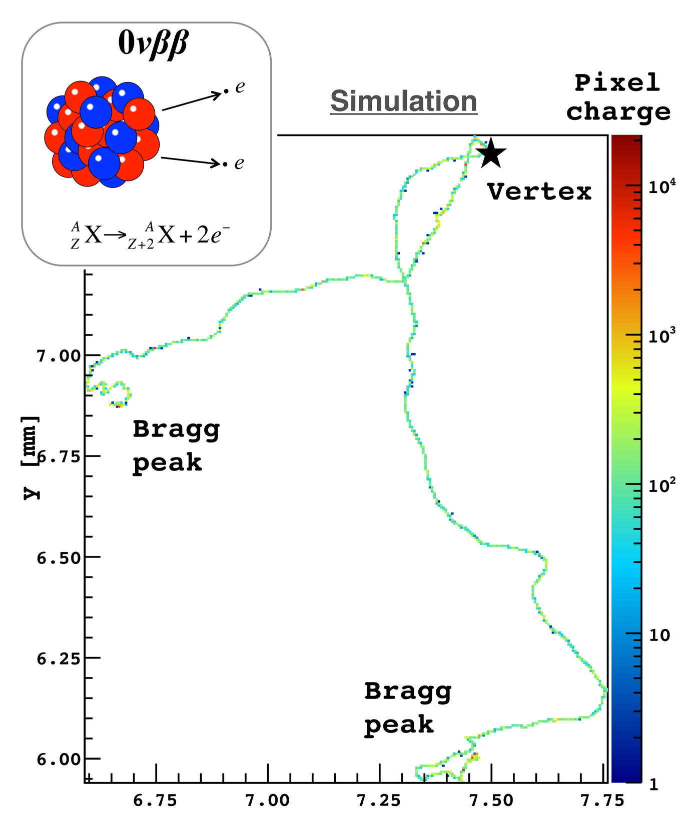
The study of ββ decay is a powerful method of inquiry into the nature of neutrinos: the observation of a neutrinoless branching ratio would indeed prove that neutrinos are Majorana fermions. Neutrinoless ββ decay is also a lepton number-violating process, creating a pair of electrons without the corresponding antineutrinos: its discovery would demonstrate at once that lepton number conservation is not a fundamental law of nature. Breaking this symmetry in the early universe is necessary for leptogenesis, a hypothesized mechanism to explain one of the greatest puzzles in all of science: how did matter become dominant over antimatter after the Big Bang, i.e., why are we here?



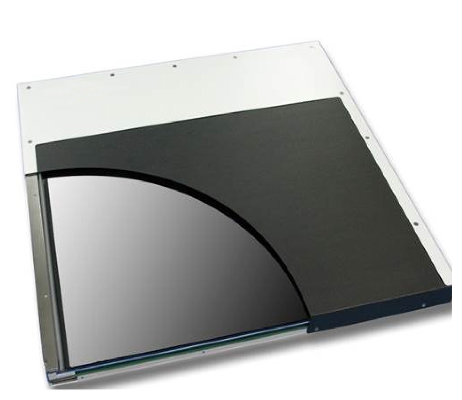
We propose a new technology of detectors for the search of the neutrinoless ββ decay of ^{82}Se: devices made from an active layer of amorphous Se (aSe) coupled to a complementary metal-oxide-semiconductor (CMOS) active pixel array (APS) to image, with high spatial and energy resolution, the two electrons with energy $Q_{\beta\beta}$ emitted by 0νββ decay.

Main features

- ^{82}Se has a 3 MeV Q-value, significantly above U+Th backgrounds.
- Background suppression from the event localization + topology, not fiducialization, i.e., most of the isotopically-enriched detector volume is fully sensitive to the signal.
- Good energy resolution: 24 keV FWHM at $Q_{\beta\beta}$.
- Good sensitivity to $m_{\beta\beta}$ per target mass (e.g. ~2.5x better than ^{136}Xe).



Amorphous selenium (aSe) detectors



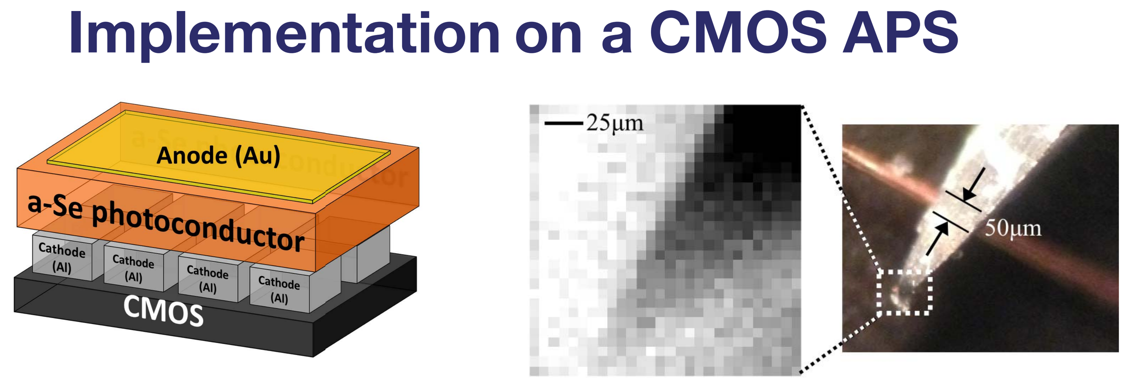
Commercial aSe imager

Breast

Hand

- Amorphous selenium (aSe) flat panel detectors are used in medical imaging: 750 cm², 1 mm-thick, 85x85 μm² pixel size.
- Operated at high electric fields (~10s V/μm) and ~50 e-h pair per keV for 140 keV X-rays.
- Large band gap: negligible dark current at **room temperature**.
- Current implementation on TFT pixel array on glass substrate: 1000 e^- RMS noise per pixel.

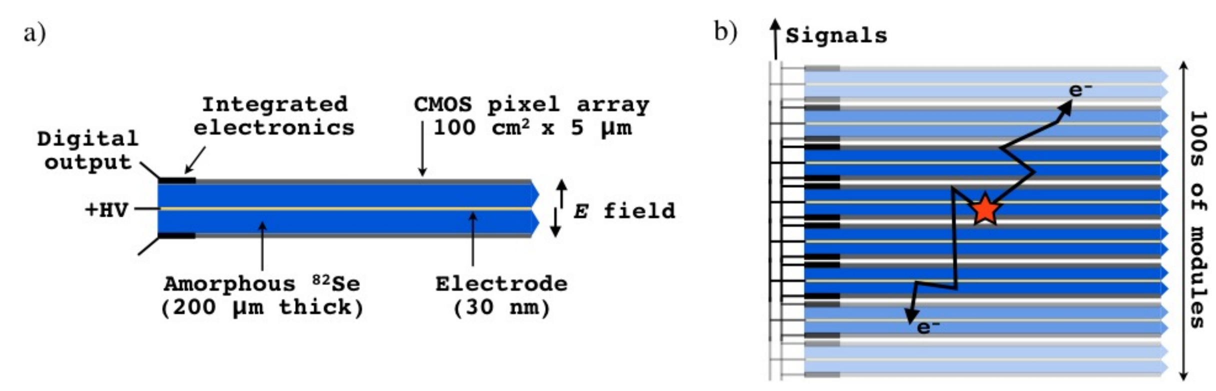
Implementation on a CMOS APS



Implementation sketch + high-resolution X-ray images
DOI:10.1109/IEDM.2015.7409803, DOI:10.1109/LED.2015.2410304

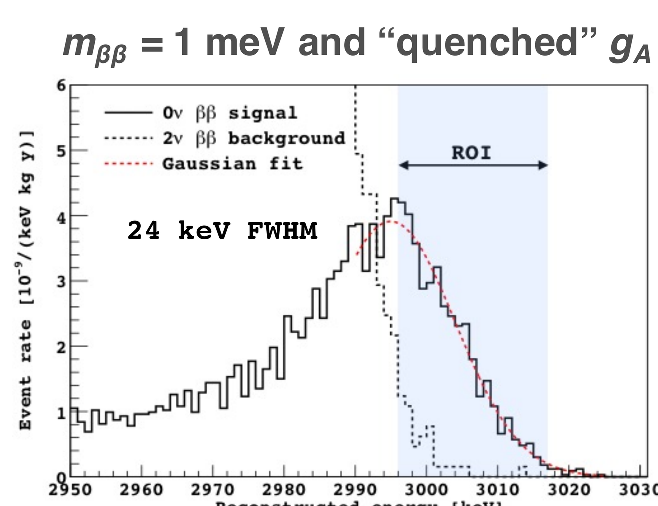
- Standard foundry process on 20-cm silicon wafers: low cost and scalable technology.
- Tested for 1 Mpixel arrays with 100 μm-thick aSe.
- Pixel sizes as small as 6x6 μm².
- 4-transistor active pixel design improves noise to **~100 e^-** RMS.
- Possible functionality: A/D conversion and zero suppression on board.

Detector concept



a) Module of two back-to-back imagers. b) Detector tower.

- Full simulation of particle tracks in tower of rectangular pixel arrays.
- E.g., for a 160 kg target (10 meV $m_{\beta\beta}$ sensitivity): few thousand modules and ~100 m² imaging area.
- CMOS APS: 10 e^- noise, 15x15 μm² pixels, 5 μm-thick dead layer.



- Best available knowledge of aSe ionization response at E = 30 V/μm (15 eV per e-h pair and Fano = 0.6).
- Developed clustering and energy reconstruction algorithms.
- **2νββ decay background in ROI:** 5 x 10^{-9} /kg/y (*at most* 10% of signal).

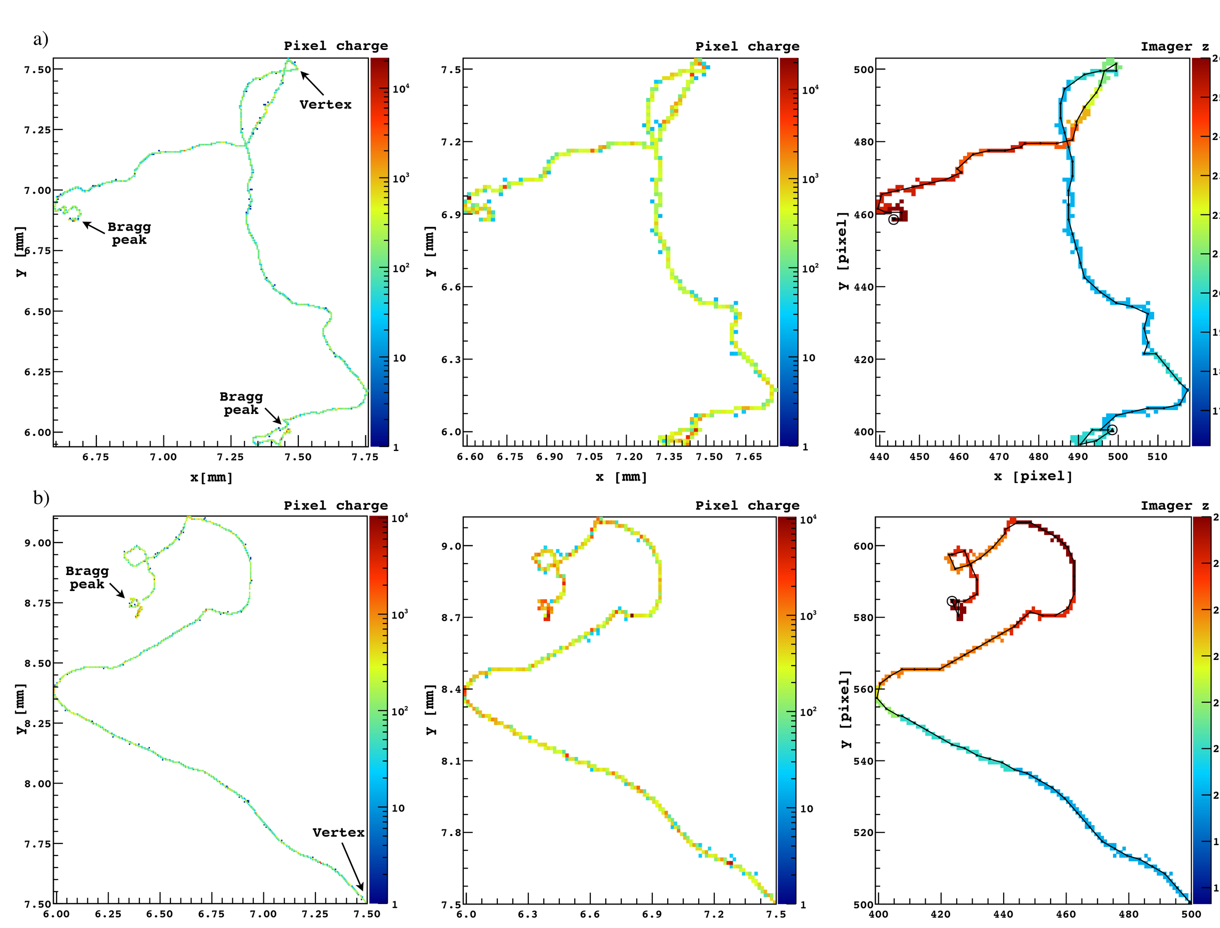
Radioactive background suppression

Experimentally demonstrated by DAMIC **JINST 10 P08014 (2015)**

- The high spatial resolution of imaging devices allows for particle identification (α, β) based on the topology of the ionization track.
- Precise determination of a radioactive decay site (+ solid-state device) allows for superb efficiency in the identification of radioactive decay sequences. E.g., ^{220}Rn–^{208}Pb and ^{222}Rn–^{210}Pb.

Monte Carlo study **JINST 12 P03022 (2017)**

- By identification of the Bragg peak(s) can achieve 10^{-3} suppression of single-electron background with 50% signal acceptance.



Simulated tracks: a) two-electron signal, b) single-electron background.

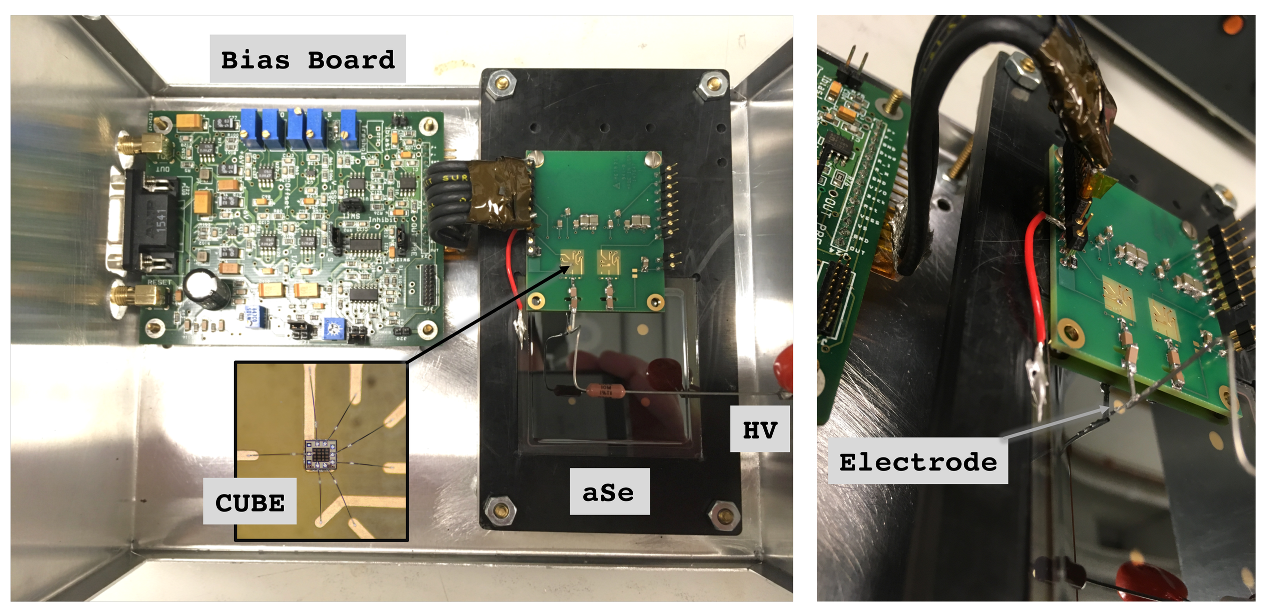
Final background tally in ROI

Source	Raw background rate / kg^{-1} y^{-1}	After discrimination / kg^{-1} y^{-1}
β-decay (bulk)	< 3.3 x 10^{-1}	< 3.7 x 10^{-9}
β-decay (surface)	< 4.1 x 10^{-1}	< 1.2 x 10^{-8}
β-decay (cosmogenic)	< 9.9 x 10^{-5}	< 1.5 x 10^{-7}
γ-ray (photoelectric)	< 7.2 x 10^{-4}	< 7.2 x 10^{-7}
γ-ray (Compton)	< 1.6 x 10^{-3}	< 4.1 x 10^{-7}
γ-ray (pair-production)	< 1.9 x 10^{-6}	< 1.9 x 10^{-7}
Total	**< 7.4 x 10^{-1}**	**< 1.5 x 10^{-6}**

- Starting from measured radioactive contaminations of enriched ^{82}Se and silicon pixel arrays. Characteristic values for construction materials.
- Cosmogenic activation estimated at LNGS overburden.
- Bulk backgrounds strongly suppressed by particle ID and spatial coincidences.
- For suppression of γ-ray backgrounds, assumed single/double electron discrimination and multiple scattering cut (~10^{-1} suppression).
- Require tracks to be fully contained, no fiducialization otherwise.

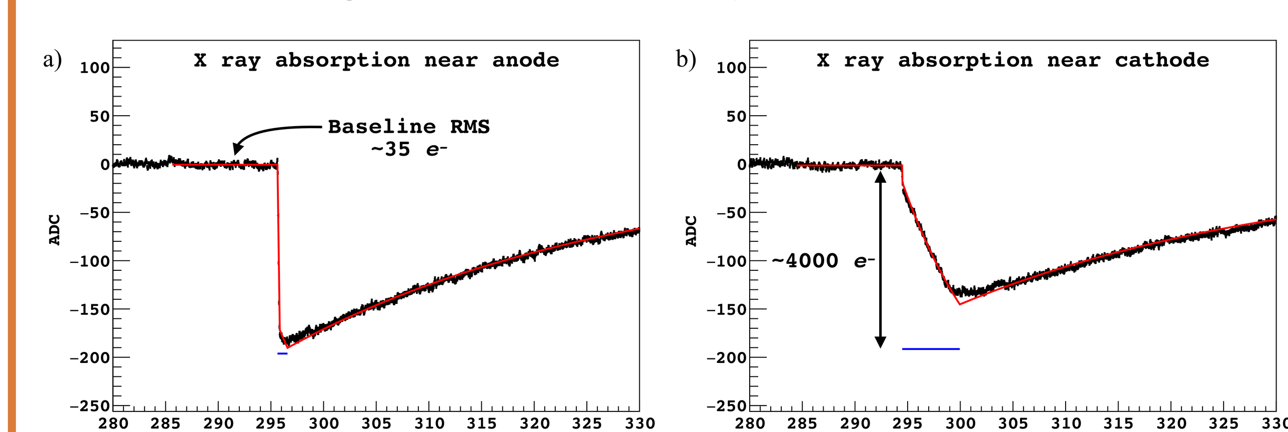
Single-pixel prototype

- Single-pixel detector to confirm the energy resolution of aSe to minimum-ionizing βs.
- Started with simple "planar" design: 75μm-thick aSe target layer sandwiched in between two electrodes, with a strong electric field (10–20V/μm) applied across the aSe.
- Connected a novel low-capacitance (50 pF) CMOS front end, the CUBE preamplifier, directly to the cathode (ground).
- The setup already demonstrates a significant improvement in performance over previous aSe devices, with a baseline noise of the output signal of 35 e^- RMS, relative to the ~1000 e^- expected from the absorption of 50 keV X rays.



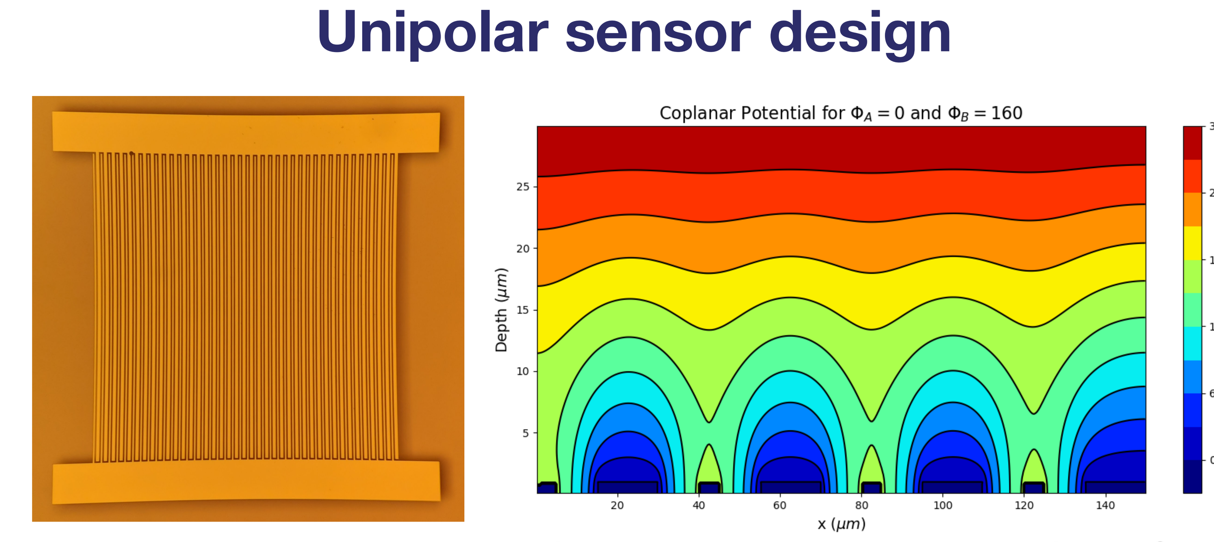
aSe planar detector and front-end electronics.

- Exposed the aSe target to various X-ray radioactive sources and digitized the output waveforms.
- Noticed strong dependence of the shape of the output pulses on the depth of the interaction in the aSe layer.
- This is because the device is "bipolar", i.e., the output signal is sensitive to both the holes and the electrons as they drift in the aSe. Holes are 30 times more mobile than electrons in aSe.
- Currently analyzing the time profiles of the pulses to understand the charge generation and transport properties of aSe and correct for these effects.
- Energy reconstruction will be ultimately limited because the energy deposited by a single X ray has a spatial distribution that extends throughout the active aSe layer.



Digitized 122 keV X-ray pulses from ^{57}Co. The rise time depends on the depth of the interaction, while the decay time is set by the output band-pass noise filter. The horizontal blue line shows the corrected signal amplitude by a preliminary algorithm.

Unipolar sensor design



Interlaced electrode structure fabricated on a glass slide before aSe deposition, and electrostatic potential simulation with COMSOL.

- The negative effects in the energy response of aSe due to the slow mobility of the electrons can be strongly mitigated in unipolar charge sensors
- E.g., replace the cathode plane with two interlaced electrodes held at slightly different potentials. All the charge will be collected by one of the electrodes.
- Each electrode will be connected to an independent CUBE preamplifier circuit and the time profiles of the signal pulses will be digitized.
- The difference in the induced current between the two electrodes is only sensitive to the holes as they drift in the vicinity of the cathode, effectively sensing only the hole signal.
- A unipolar device with a thicker 1 mm aSe layer will allow us to reliably calibrate the response to MeV-scale minimum-ionizing βs, as those emitted in 0νββ.