Quantum sensor for detection of dark matter

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Abstract

Dark matter remains one of the central question in field of cosmology and high energy physics. Fermilab aims to expand the section of mass range for dark matter search. A novel approach involving MKID is used to detect direct deposition of energy from light dark matter. Simulation of the detector technology helps in understanding the signal from the detector and to calibrate it. This internship project involves involves simulating simplified model of the detector. Simulation was set up in Geant4/G4CMP. Python was used to create script for batch simulation and data analysis.

1 Background

1.1 Dark matter

Dark matter is defined as the component of the universe that is discerned by its gravitational attraction rather than it's luminosity. The evidence for the existence of dark matter has been known from astronomical observations for over eighty years.[1] In 1933, Fritz Zwick showed that the velocities of galaxies in the Coma cluster greatly exceeded the expectations based solely on the sum of the individual galaxy masses, thus requiring significant additional "dark matter" [2]. Since then, it has been tested and reinforced by a broad range of astronomical data. Observations in the 1970s of the motion of gas and stars in the outskirts of galaxies established the early recognition of the existence of dark matter[3]. More detailed observations of clusters of galaxies and large-scale structure further revealed the amount and distribution of the dark matter on large scales, showing that the total mass density of the universe is ~25% of the critical density [4]. Gravitational lensing observations by galaxies, clusters of galaxies, and large-scale structure provided important results that directly confirmed the existence of dark matter and measured its distribution on both small and large scales [5]. The accumulated data showed that the total amount of matter in the universe is approximately five times greater than the amount of baryonic matter [6]. Figure 1 show cases the distribution of energy density of the Universe. It is very important to understand the nature of dark matter in order to get comprehensive description of the Universe.

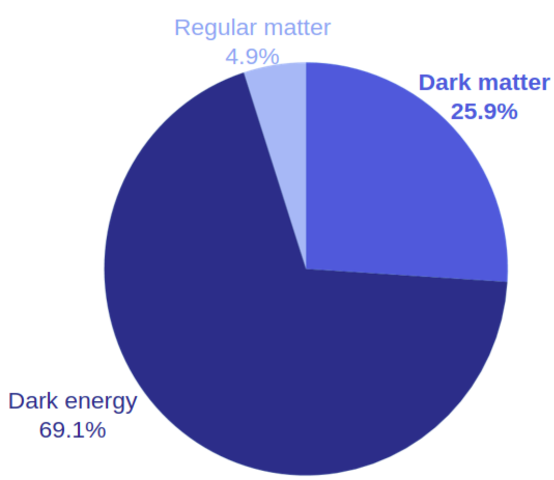


Fig. 1: Distribution of energy density of the Universe

2 Motivation

For the most part of history of dark matter search, WIMP have been the most favored kind. WIMPs are expected to have mass at the electroweak scale. So, the experiment searching for WIMPs are optimized to detect energy deposit in order of keV. However, there hasn't been definite evidence for WIMPs to date. This pushes the researchers to look towards the unexplored regime which requires probing into Light Dark Matter (LDM) parameter space. Figure 2 shows the reach of the currently funded DOE dark matter experiments. [7]

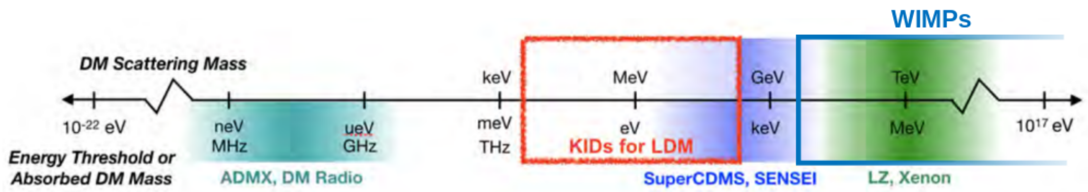


Fig. 2: Current and Future Coverage of LDM Parameter Space
Image Credit: Noah Kurinsky

3 Objective

3.1 Direct detection of dark matter

Many of the new ideas for dark matter involve a Hidden Sector; i.e., dark matter interacts with itself and the Standard Model via a new and unobserved ("hidden") force, with the DM-SM coupling weak enough to have previously escaped detection. This force is often mediated by a "dark photon," the gauge boson of a new U (1) symmetry[7]. Regardless of the interaction, the objective of designed detector is to detect energy deposition in said range. The proposed detector will be the first step in a longer-term program to achieve sub-meV resolution.

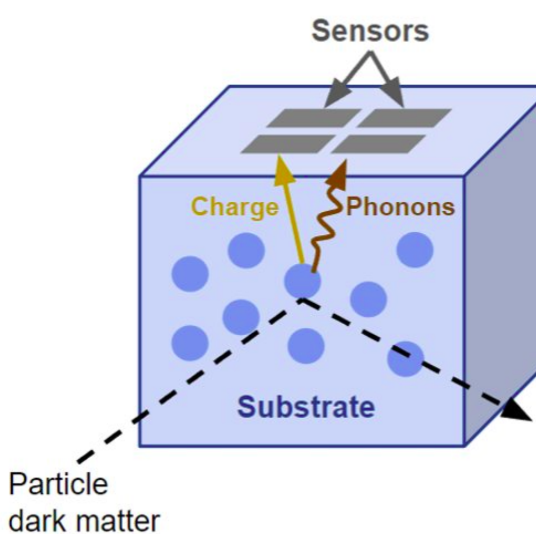


Fig. 3: Particle matter interacting with substrate to produce charge-hole pair
Image Credit: Kelly Stifter

4 Design

4.1 Microwave Kinetic Inductance Detectors

Microwave kinetic inductance detectors (MKIDs) deploy superconductors to detect particles with ~1000 times less energy than that of band gap energy of semiconductors. MKID relies on the fact that absorption of energetic particles in superconductor breaks the Cooper pairs, which results in the generation of numerous quasiparticles. This leads to a change in the inductance of the superconductor. When MKID is used in a resonator circuit, the change in inductance can be measured as a change in resonance frequency and Q-factor. Figure 5 shows the frequency response of a KID for different temperatures. An increase in temperature is associated with an increase in quasiparticle density. It can be observed that an increase in density of quasiparticles is associated with diminishing Q-factor and lowering of the resonance frequency.

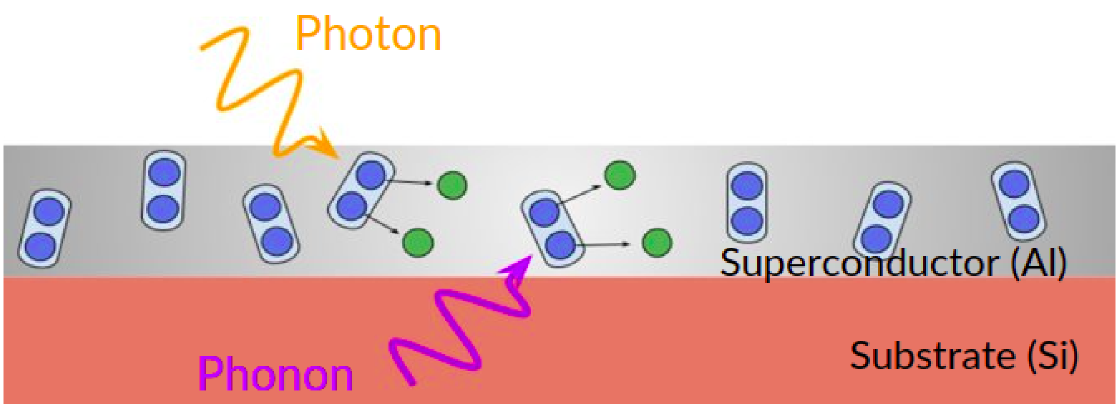


Fig. 4: Simplistic model of Microwave kinetic inductance detector. The image depicts breaking of Cooper pair and generation of quasiparticles due to absorption of energetic particles

Image Credit: Gabriel Spahn

4.2 Detector design

The detector design consists of a high-purity silicon substrate with a single KID with aluminum inductor (superconducting transition temperature $T_c \approx 1.2K$, Cooper-pair binding energy $2\Delta \approx 350\mu eV$) and niobium capacitor as well as a niobium feedline ($T_c \approx 9.3K, 2\Delta \approx 3meV$) as shown in see Figure 6. Niobium is used everywhere except for the KID inductor because its Cooper pair binding energy exceeds the typical athermal phonon energy $(0.5\check{}1meV)$, thus preventing it from degrading phonon collection. [7]

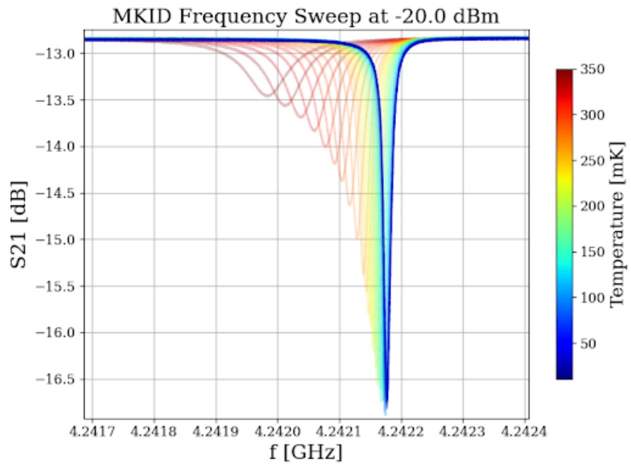


Fig. 5: Frequency sweep of Aluminum resonator in different temperature

5 Internship Project Specification

To understand the signals from the device, it is important to see the response for simplistic controlled input such as excitation of electron out of bound state in semiconductor lattice using a laser. The objective of this internship project was to simulate such a case. To get a broad scope of the signal, the following parameters of the simulation were to be varied.

- Energy deposited
- Position of interaction
- Initial momentum gained by electron and hole

Additional objectives included packaging the batch simulation with a simple UI that allows users to input different combinations of parameters.

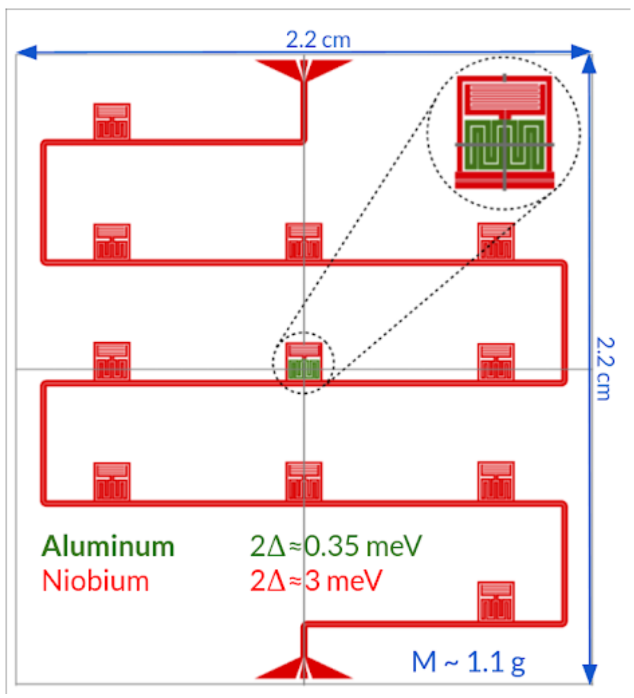


Fig. 6: LDM detector design. Green indicates Al, Red indicates Nb. The inset shows a close-up of the individual KID design.

6 Development

Geant4 is a sophisticated C++-based Monte Carlo simulation toolkit maintained by an international collaboration and freely available under an open source license. The toolkit was originally developed in support of High Energy Physics (HEP) experiments and provides a framework for simulating the passage of particles through complex geometries and materials. In its current incarnation, the Geant4 toolkit is entirely focused on free particles and does not take into account crystal physics or conduction/valence band interactions of the low-energy charge carriers and phonons relevant to condensed matter physics. Thus G4CMP, an add-on library to Geant4 that specializes in the transport of phonons through the crystal is deployed. The original purpose of G4CMP was to accurately reproduce data from the Cryogenic DarkMatter Search (CDMS). Geant4 along with G4CMP is used to simulate a given scenario. Python is used to create macro files to iterate through different combinations of varying energy, the position of interaction, and initial momentum. Python is also used for data analysis. Figure 7 shows the I/O model. A simplistic UI is created in python to take energy, position, and momentum as input to create the macro for batch simulations. The simulation is run on the SLAC cluster which creates the hit file or the output which was analysed using Python.

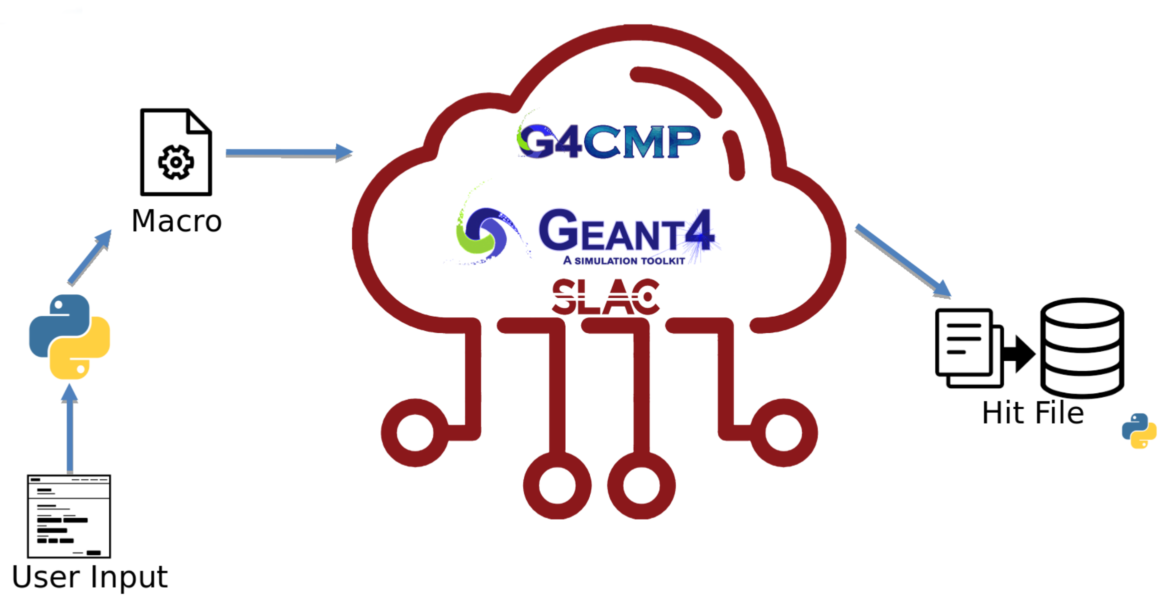


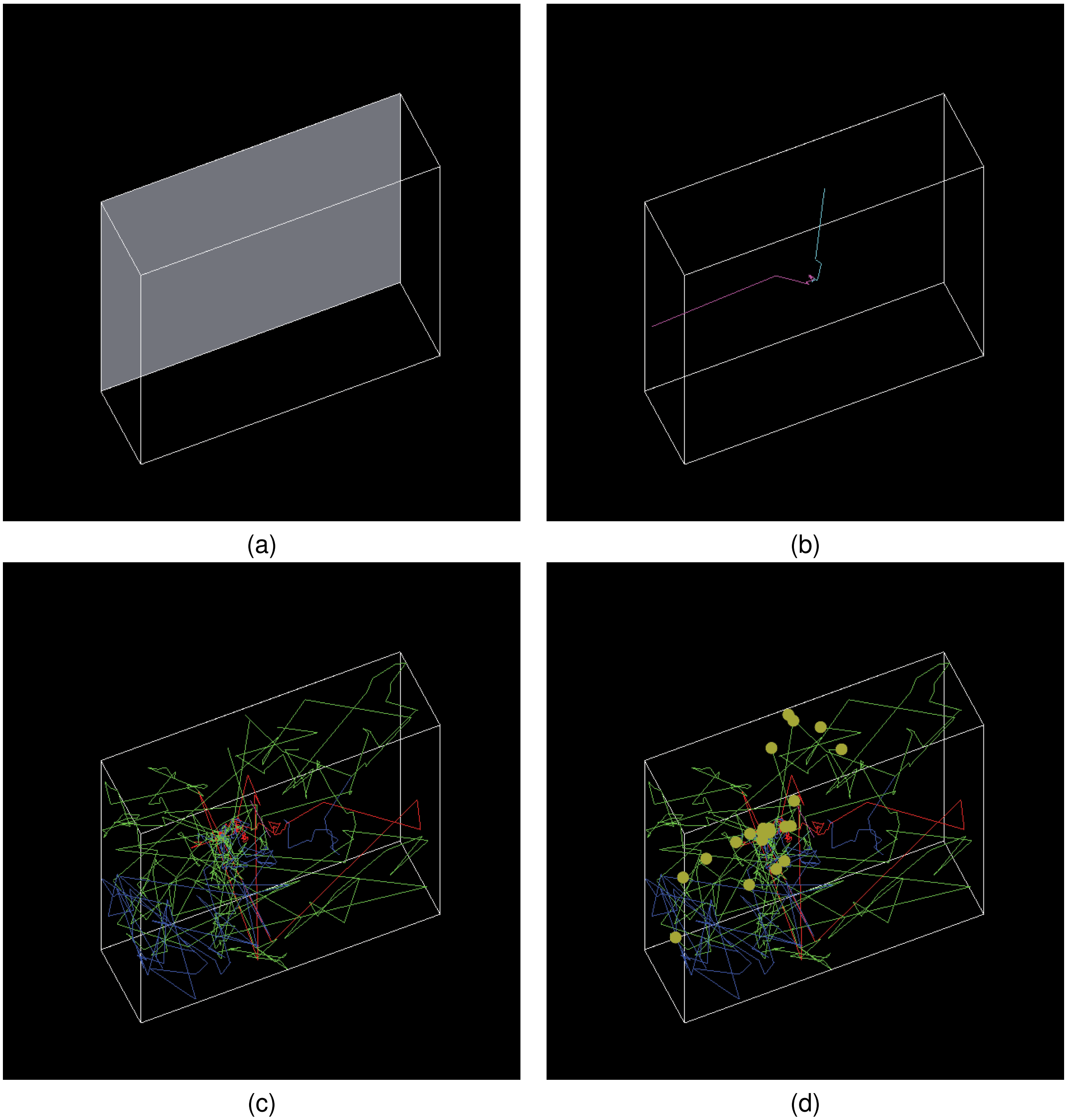
Fig. 7: Dataflow for simulation

6.1 Simulation setup

For a preliminary simulation, a 2 mm x 2mm x 600 nm silicon substrate with a 100 nm layer of superconducting aluminum electrode is set up. The energy given to the electron is 1.95 eV (in order to emulate the 695-nm laser). The position and initial momentum can be varied. An iteration of such simulation is visualized in figure 8.

7 Results and analysis

7.1 Simulation visualization



(a) (b) (c) (d)

Fig. 8: Simulation Visualization. (a) Geometry of the simulation. Alumunium electrode is shaded. (b) Production electron-hole pair (c) Generation of phonon (d) Phonons collected at electrode and registered as 'hit'

7.2 Phonon Hit Profiles

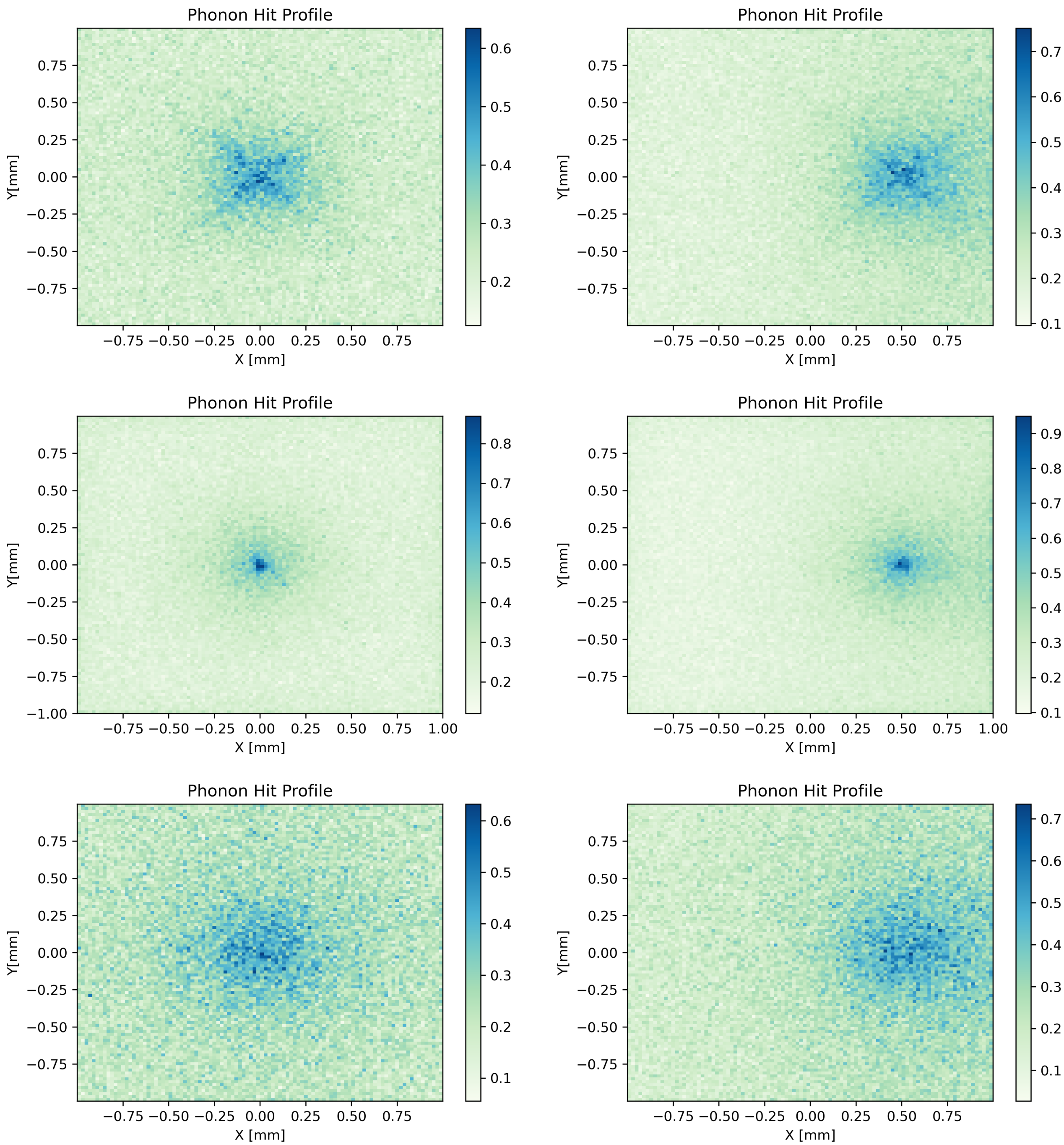


Fig. 9: End position of phonons. (Top) Transverse Fast phonon, (Middle) Transverse Slow phonon, (Bottom) Longitudinal phonon. Left pane shows the collection of phonon when the charge-hole pair is generated at centre of the substrate while right pane has the point of generation shifted by 0.5mm toward +X axis

7.3 Collection Time

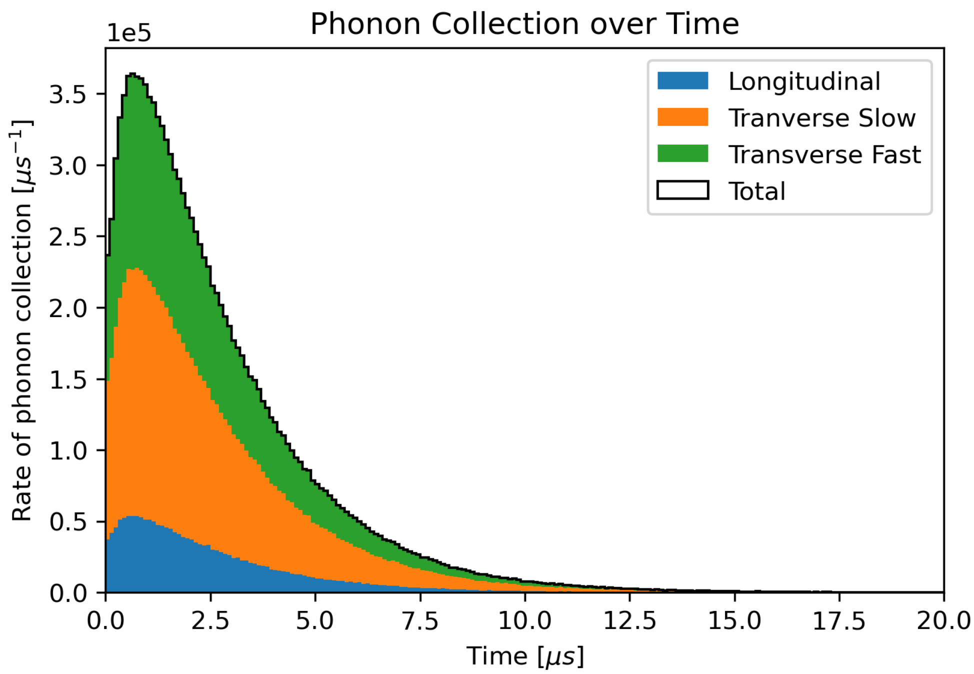


Fig. 10: Collection time of the phonon for energy deposition of 1.95 eV at centre of substrate

7.4 Final energy of phonons

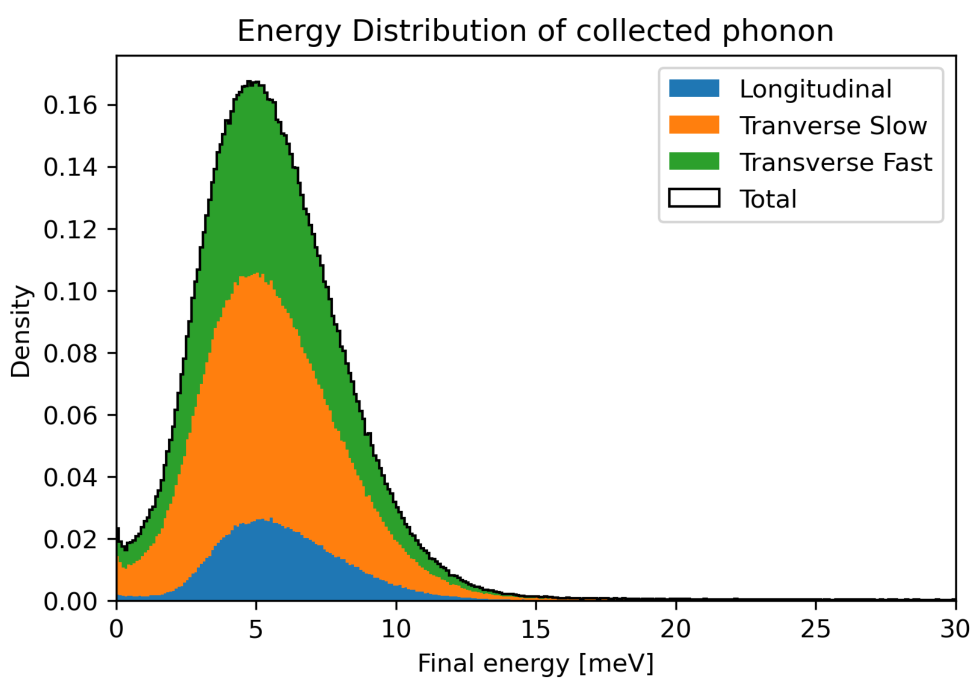


Fig. 11: Energy of phonons when collected at superconducting electrode for energy deposition of 1.95eV at centre of substrate

8 Future works

8.1 G4CMP library

G4CMP library is still in its development phase. Additional work is needed to be done to fully integrate Geant4 with G4CMP. For example: currently, the simulation uses `G4ParticleGun` to individually generate an electron and a hole. So simulating deposition of 1.95 eV required manual correction for the band gap energy of silicon (1.17 eV) and assign 0.78 eV to the electron-hole pair. Ideally, we would want to provide the energy to an electron in the semiconductor lattice, which would get excited out of its bound state to create charge-hole pair.

8.1.1 Known issue

Energy Assignment Problem: When a certain amount of energy is assigned to the charge-hole pair, instead of distributing the energy between electron and hole, the hole gets entirely of assigned energy while the electron get either 28% or 135% of the assigment energy.

8.2 Simulation refinement

This simulation project makes a lot of approximation on geometry of detector, boundary properties. Further iteration of the simulation can be more realistic by implementing geometry closer to the real detector.

9 Acknowledgment

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