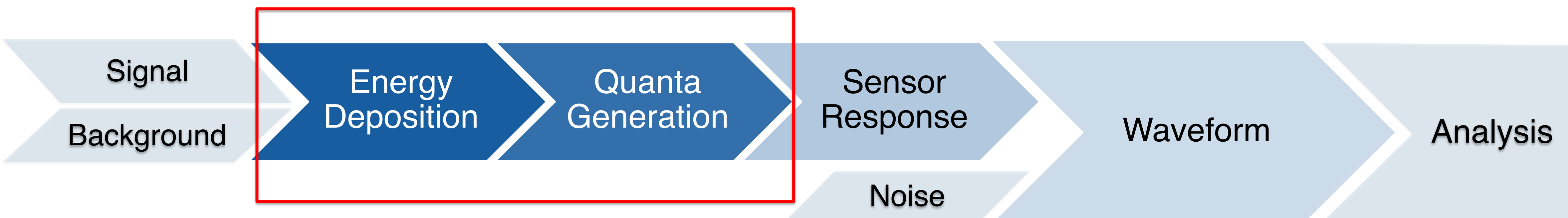
FERMILAB-POSTER-24-0245-STUDENT

Simulating the Phonon Collection Efficiency in KIPMDs

Stella Q. Dang[*†] | Supervisors: Dylan J. Temples[*], Ryan Linehan[*], Daniel Baxter[*‡] | August 7, 2024

[*]Fermi National Accelerator Laboratory, Batavia, IL [†]Cornell University, Ithaca, NY [‡]Northwestern University, Evanston, IL



Introduction to KIPMDs

- Kinetic inductance phonon-mediated detectors (KIPMDs) are superconducting microcalorimeters that use microwave kinetic inductance detectors (MKIDs) to read out phonon signals
- KIPMDs are attractive candidates for light DM searches because of their potential eV-scale sensitivity

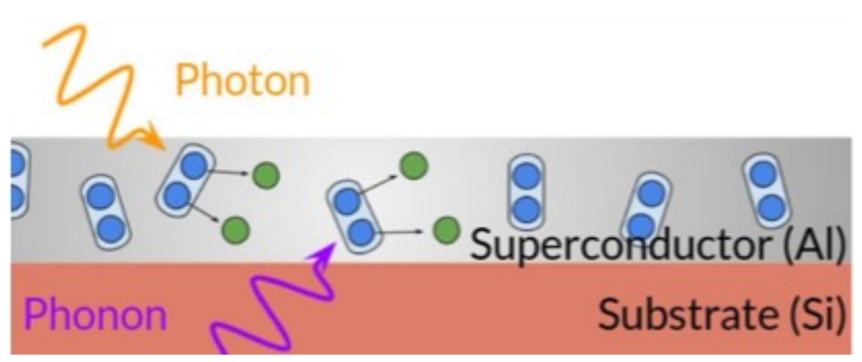


Fig. 1. Energy deposited in the Si detector substrate propagates in the form of phonons, which breaks Cooper pairs in the Al superconductor [2].

Simulation Methods

- G4CMP is used to simulate solid-state processes in Geant4
  - Generate and propagate electron-hole pairs in the Si substrate
  - Produce acoustic phonons and model phonon dynamics
  - Calculate phonon energy depositions in target volumes

Using Geant4/G4CMP simulations, we seek to reconstruct the single-point phonon collection efficiency and study the channels of phonon loss in the KIPMD currently deployed at the NEXUS underground facility.

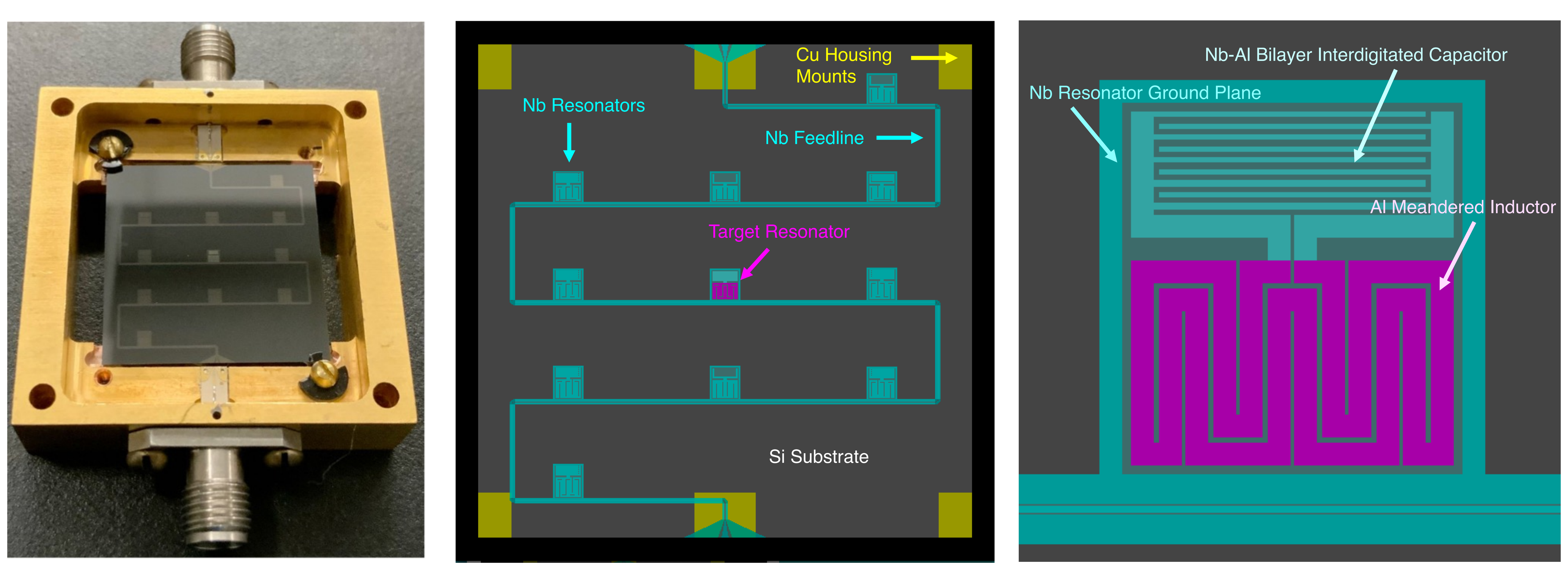


Fig. 2. (Left) The KIPMD at the Northwestern EXperimental Underground Site (NEXUS) [1] in its housing. (Center) Geant4 geometry of the NEXUS KIPMD. (Right) The center resonator of the NEXUS KIPMD, which features an Al meandered inductor (the phonon-absorbing target) and a Nb-Al bilayer interdigitated capacitor.

Single-Point Phonon Collection Efficiency

$p_{a,Al}$	$p_{a,Nb}$	$p_{a,bilayer}$	$p_{a,Cu}$	$\eta_{ph,point}$
0.4878*	**0.745***	**0.7449***	**0.728***	**9.59 %**
0.4878*	1.0	0.7449*	0.728*	9.97%
0.4878*	0.745*	1.0	0.728*	10.0%
0.4878*	0.745*	0.7449*	1.0	10.2%
0.04878	0.745*	0.7449*	0.728*	1.11%

Table 1. *Calculated from equations in [3] by multiplying p_{abs}, the probability of transmission from substrate to metal, and 1-p_{escape}, where p_{escape} is the probability of a phonon with pair-breaking energy entering and escaping the metal film.

Here $p_{a,X}$ denotes phonon absorption probability across the interface between material X and Si, and $\eta_{ph,point}$ denotes the single-point phonon collection efficiency.

- The experimentally determined $\eta_{ph,point}$ for the NEXUS KIPMD is (0.89 ± 0.11) % [1]
- To simulate a pulse of 470 nm optical photons incident on the substrate, we generate 1000 electron-hole pairs each with 2.63 eV total energy (1.46 eV kinetic energy after overcoming the 1.17-eV Si band gap) in a disc with a 100-µm radius and a 100-µm length at the bottom of the substrate
- We observe ~60% uncertainty in $\eta_{ph,point}$ for a 1 mm offset of the source spot
- A factor of ~10 disagreement was observed between the current simulations and the experimentally-measured value. Some potential causes of this, which can be investigated in simulation, are
  - Potential location mismatch between simulated interaction region and photon source in experiment (see previous bullet point);
  - Electron/hole trapping in Si;
  - A higher Cooper pair binding energy for the Al thin film than used in this model

Channels of Phonon Loss

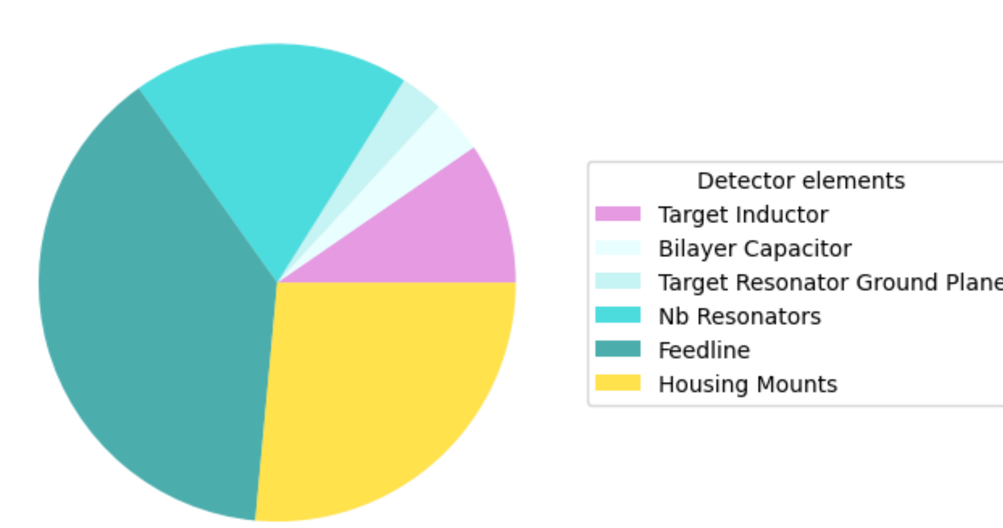


Fig. 3. Portions of total phonon energy collected by various detector elements; colors of the slices correspond to the colors of the annotations in the G4CMP renderings.

Detector Element	$\eta_{ph,point}$
Feedline	38.7%
Housing Mounts	26.4%
Nb Resonators	18.8%
Target Inductor	**9.59%**
Bilayer Capacitor	3.57%
Target Resonator Ground Plane	2.91%

Table 2. $\eta_{ph,point}$ for with different detector elements as targets. Here we use the theoretically-motivated values in bold in the Table 1 or p_a calculated from [3] and generate the distribution of e-h pairs described above.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI).

References:

[1] D. Temples, *et al*, "Performance of a Kinetic Inductance Phonon-Mediated Detector at the NEXUS Cryogenic Facility" (2024). https://doi.org/10.48550/arXiv.2402.04473

[2] D. Temples. "Toward a DM Search with Phonon-Mediated MKID Devices at NEXUS. United States" (2023). doi:10.2172/1974696.

[3] E. Y. et al., "Modeling phonon-mediated quasiparticle poisoning in superconducting qubit arrays" (2024), arXiv:2402.15471 [quant-ph].