Phonon Collection Modeling in G4CMP with Finite Surface Losses

Toward Direct Absorber Phonon Sensor Design

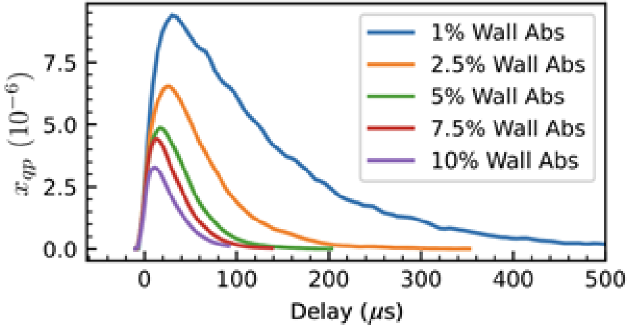
Selby Q Dang / SLAC + Stanford

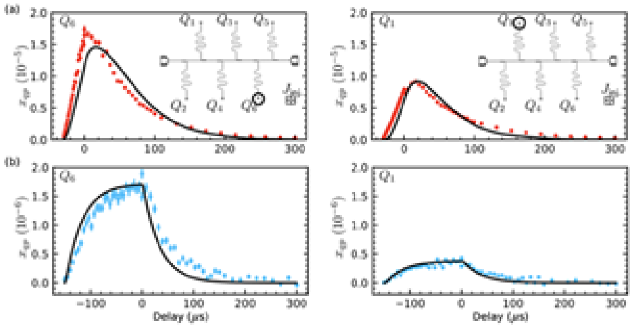
June 15, 2026 | RISQ 2026 G4CMP Workshop

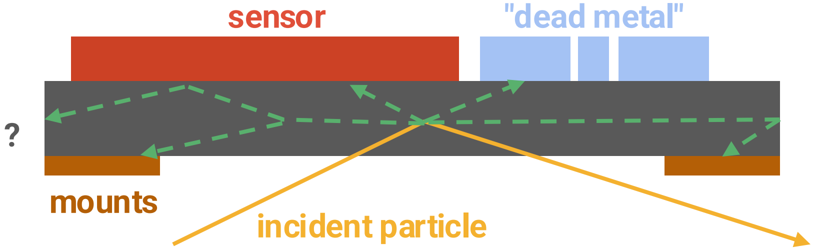
Overview

Benchmarking effects of phonon loss is relevant for modeling diverse phonon sensors in G4CMP.

- Evidence for phonon thermalization in cryogenic crystals is not fully modeled by anharmonic decay or loss to device clamps
- Position-dependent phonon responsivity gives insight into loss mechanisms
- Using one possible loss model, we can optimize sensor layout for efficiency







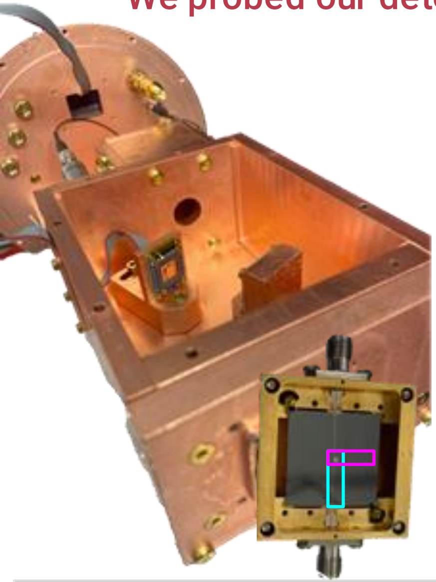
https://journals.aps.org/prb/pdf/10.1103/PhysRevB.110.024519

Part I

Benchmarking Phonon Loss

MEMS Measurement

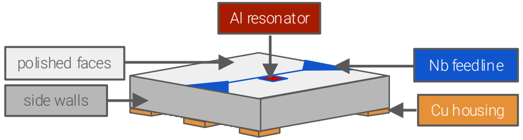
We probed our detector response to LED pulses at different XY positions using the MEMS.



Our KIPM detector:

- MKID as phonon sensor
- Direct absorber: no trapping
- Small sensor (<0.1% coverage on Si substrate)
- Thin film (30 nm Al)
- Single resonator

Image credit: Leonid Sajkov



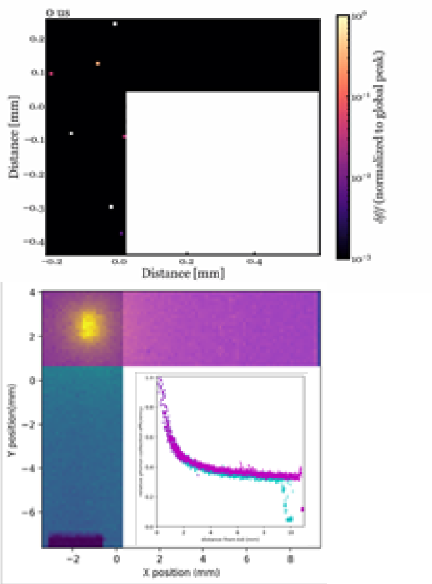


Image credit: Zoë Smith

Journal of Optical Microsystems, Vol. 5, Issue 2, 024503 (June 2025).
https://doi.org/10.1117/1.JOM.5.2.024503
12 June 2025

Cryogenic optical beam steering for superconducting device calibration

Kelly Stifter, Hannah Magoon, Adam J. Anderson, Dylan J. Temples, Noah A. Kurinsky, Chris Stoughton, Israel Hernandez, Anthony Nuñez, Kester Anyang, Ryan Linehan, Matthew R. Young, Peter Barry, Daniel Baxter, Daniel Bowring, Gustavo Cancelo, Aaron Chou, Karla R Dibert, Crectall Figueroa-Feliciano, Lauren Hsu, Rakshya Khatiwada, Simon D. Mork, Leandro Stefanazzi, Noshin Tabassum, Sho Uemura, Betty A. Young

https://custom.cvent.com/B6DBF01384AB4E1CB4B0C6F97B77BDB2/files/event/22930724c2e84b3b93f62c71707461 41/47687c07935646a0acea1924d0112ab4.pdf

Characterizing Position-Dependent Phonon Efficiency in KIPM Detectors Using Cryogenic MEMs Mirrors

Z.J. Smith[*,1,2], Z. Ahmed[2,3], T. Aralis[2,3], S. Golwala[5], S.W. Henderson[2,3], H. Magoon[2,4], A. Nuñez[4], E. Panner[8], G. Peréz[4], B. Sandoval[5], S. Stevens[3], N. Tabassum[2], D. Temples[7], O. Wen[2,3], R. Junwen Xiong[5], B.A. Young[6], and N.A. Kurinsky[*,2,3]

Development Status of the KIPM Detector Consortium

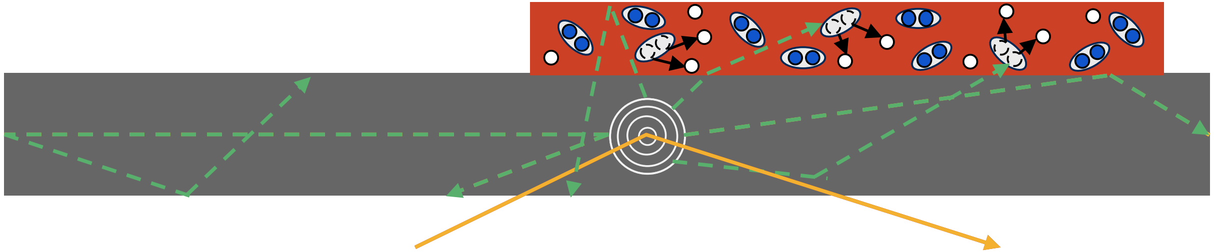
Dylan J Temples, Zoë J. Smith, Selby Q Dang, Taylor Aralis, Chi Cap, Clarence Chang, Yen-Yung Chang, Maurice Garcia-Sciveres, Sunil Golwala, William Ho, Noah Kurinsky, Kungang Li, Xinran Li, Marharyta Lisovenko, Elizabeth Panner, Karthik Ramanathan, Shilin Ray, Brandon Sandoval, Aritoki Suzuki, Gensheng Wang, Osmond Wen, Michael Williams, Junwen Robin Xiong, and Volodymyr Yefremenko

MEMS + KIPM paper in prep!

Direct Absorber Architecture

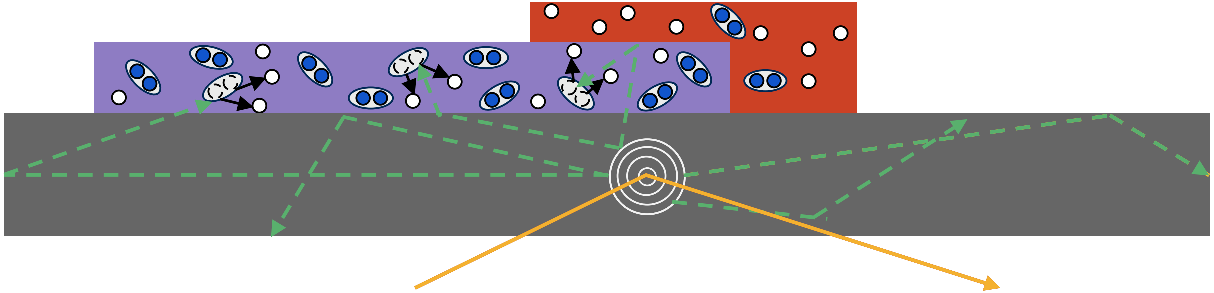
In our detector, phonons are directly absorbed into the MKID inductor, which generates the signal.

Direct absorber (e.g. KIPM):



- Incident Particle
- Cooper Pair
- Quasiparticle
- Athermal Phonon
- Crystalline Substrate
- Sensitive Volume
- Collector Volume

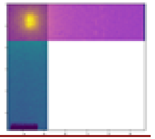
Quasiparticle trapping (e.g. QET, SQUAT):



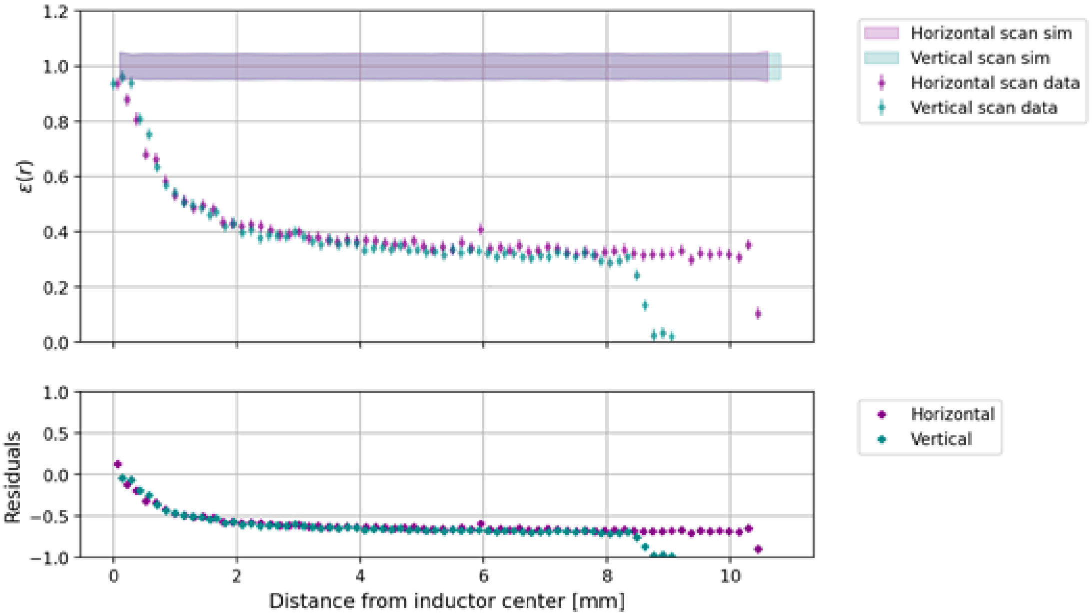
Analysis of Event Position Dependence in HVeV Detectors with G4CMP and MEMS
Caitlyn Stone-Whitehead
6/15, 10:20 am

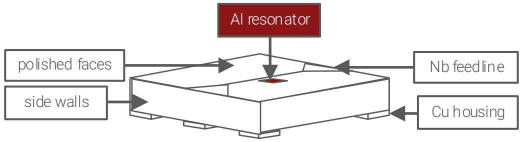
SQUATs: Qubit-Based Sensors for Dark Matter
Hannah Magoon
6/18, 10:00 am

From Phonon Loss to Position Dependence



Loss mechanisms differently affect position dependence in phonon collection efficiency.

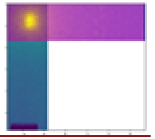




$p_{abs, inductor}$	0.103
$p_{abs, capacitor}$	0
$p_{abs, Nb}$	0
$p_{abs, Cu}$	0
$p_{abs, polished\ surfaces}$	0
$p_{abs, side\ walls}$	0

η: absolute phonon energy collection efficiency
ε: relative phonon energy collection efficiency; **$\varepsilon(x,y) = \eta(x,y) / \eta_{max}$**

From Phonon Loss to Position Dependence



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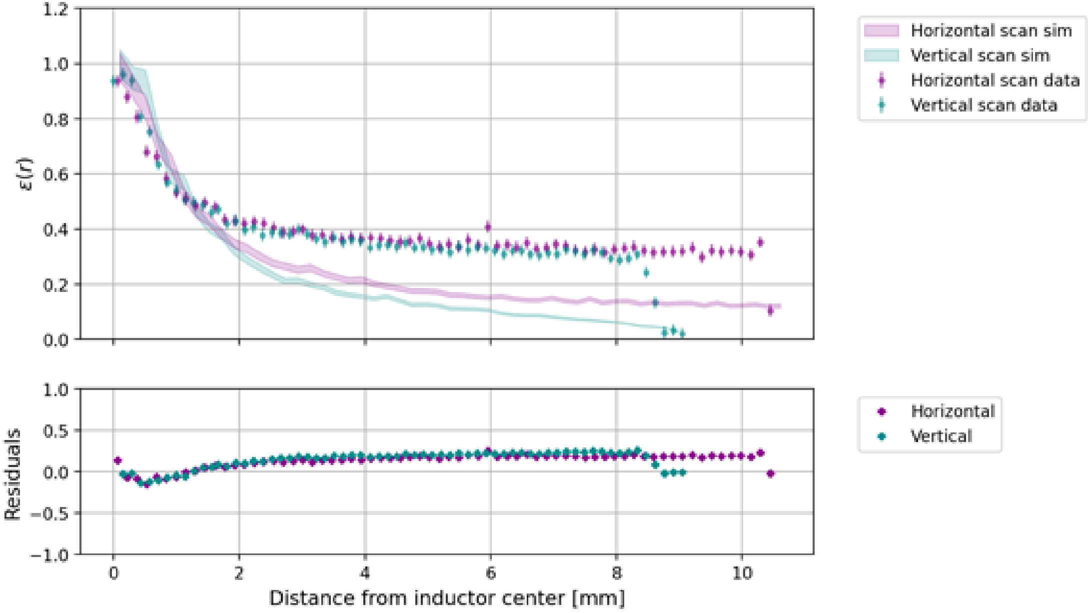

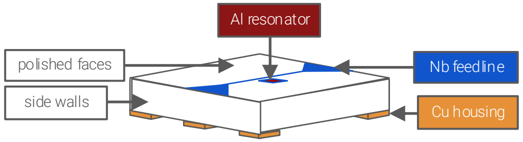

$p_{abs, inductor}$	0.103
$p_{abs, capacitor}$	0
$p_{abs, Nb}$	0.745
$p_{abs, Cu}$	0.736
$p_{abs, polished\ surfaces}$	0
$p_{abs, side\ walls}$	0

η: absolute phonon energy collection efficiency
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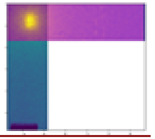
From Phonon Loss to Position Dependence



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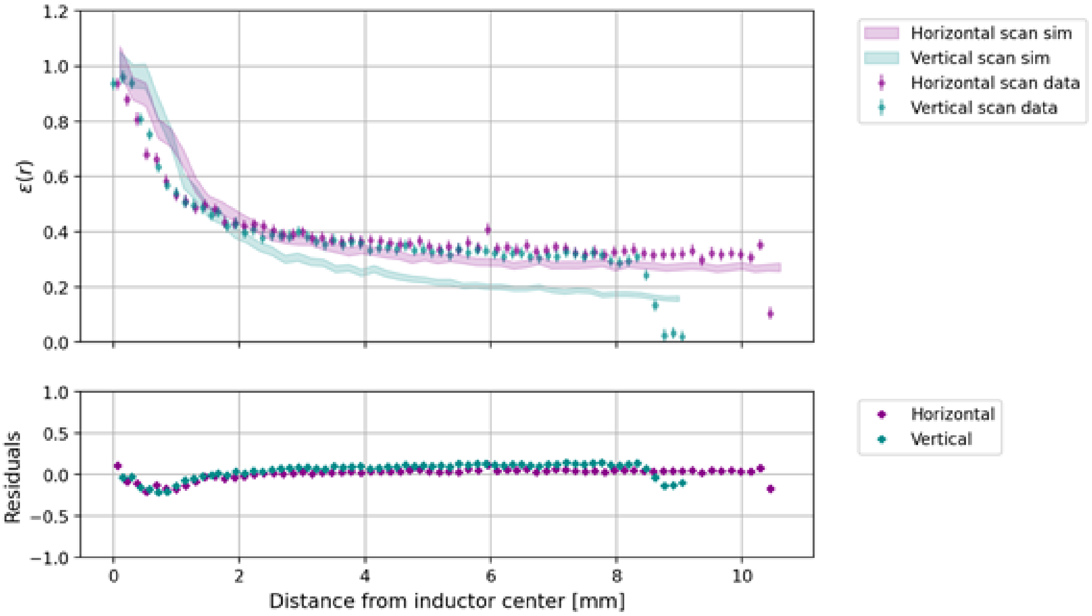

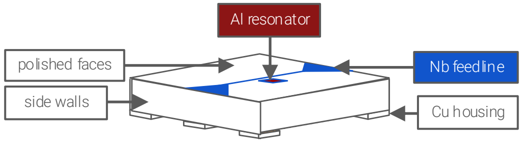

$p_{abs,\ inductor}$	0.103
$p_{abs,\ capacitor}$	0
$p_{abs,\ Nb}$	0.745
$p_{abs,\ Cu}$	0
$p_{abs,\ polished\ surfaces}$	0
$p_{abs,\ side\ walls}$	0

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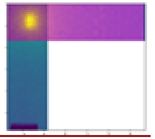

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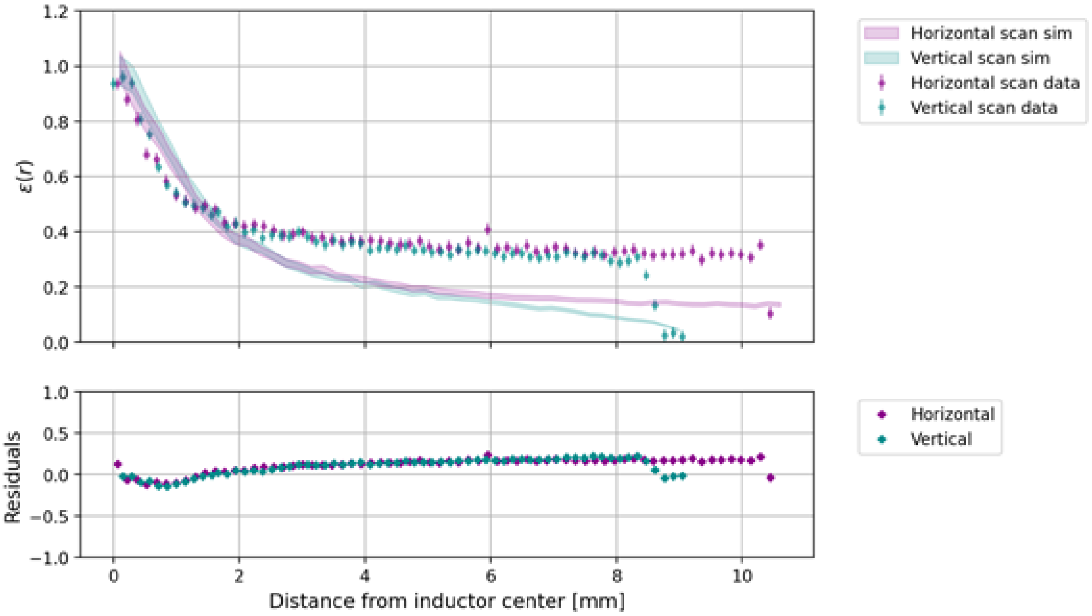
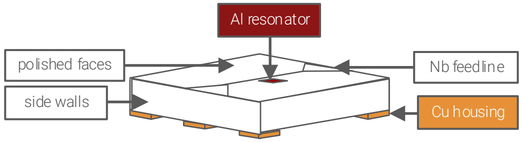
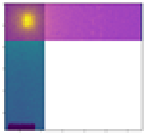




$p_{abs, inductor}$	0.103
$p_{abs, capacitor}$	0
$p_{abs, Nb}$	0
$p_{abs, Cu}$	0.736
$p_{abs, polished\ surfaces}$	0
$p_{abs, side\ walls}$	0

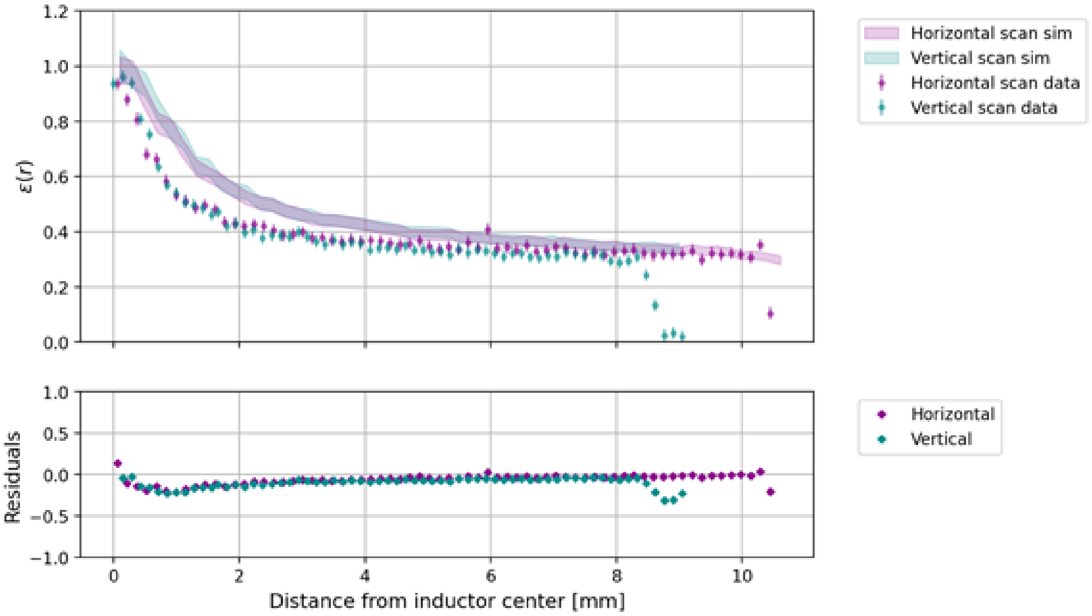
η: absolute phonon energy collection efficiency

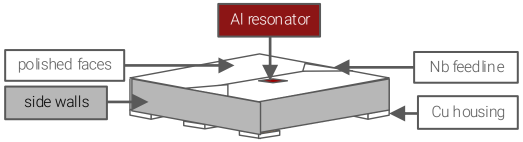
ε: relative phonon energy collection efficiency; $\varepsilon(x,y) = \eta(x,y) / \eta_{max}$



From Phonon Loss to Position Dependence

Loss mechanisms differently affect position dependence in phonon collection efficiency.

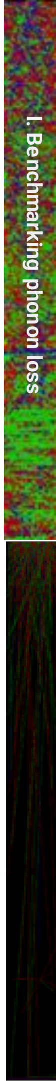




$p_{abs,\ inductor}$	0.103
$p_{abs,\ capacitor}$	0
$p_{abs,\ Nb}$	0
$p_{abs,\ Cu}$	0
$p_{abs,\ polished\ surfaces}$	0
$p_{abs,\ side\ walls}$	0.025

η: absolute phonon energy collection efficiency

ε: relative phonon energy collection efficiency; **$\varepsilon(x,y) = \eta(x,y) / \eta_{max}$**



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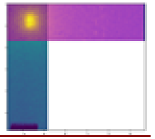

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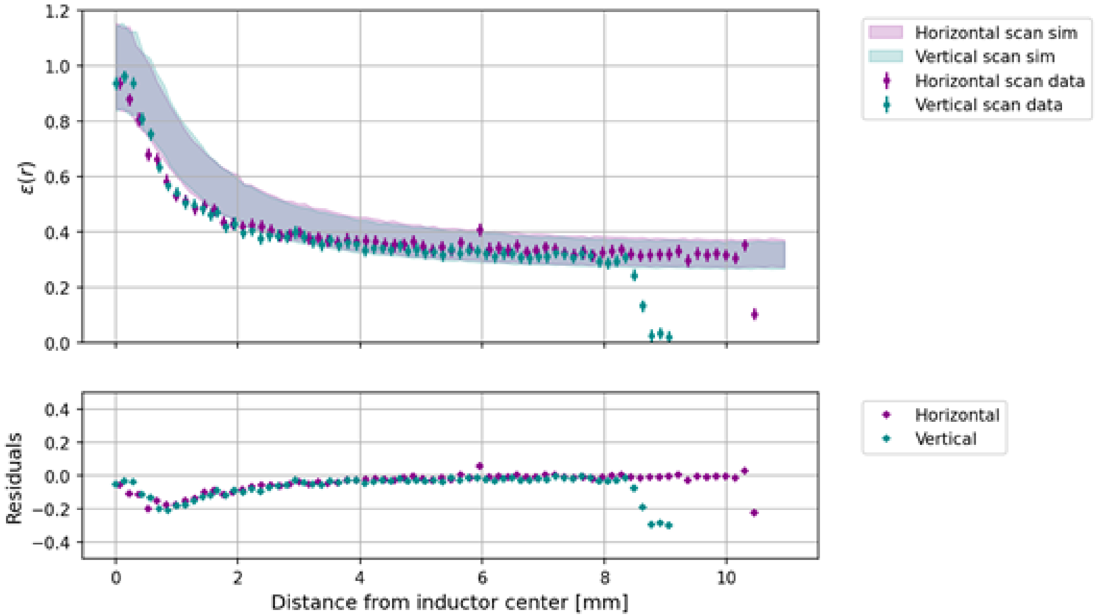
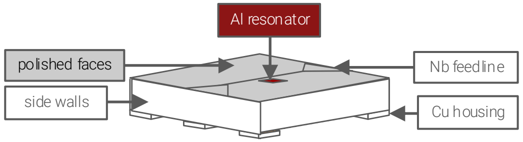


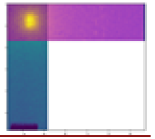


$p_{abs,\ inductor}$	0.103
$p_{abs,\ capacitor}$	0
$p_{abs,\ Nb}$	0
$p_{abs,\ Cu}$	0
$p_{abs,\ polished\ surfaces}$	0.0025
$p_{abs,\ side\ walls}$	0

η: absolute phonon energy collection efficiency

ε: relative phonon energy collection efficiency; $\varepsilon(x,y) = \eta(x,y) / \eta_{max}$

From Phonon Loss to Position Dependence



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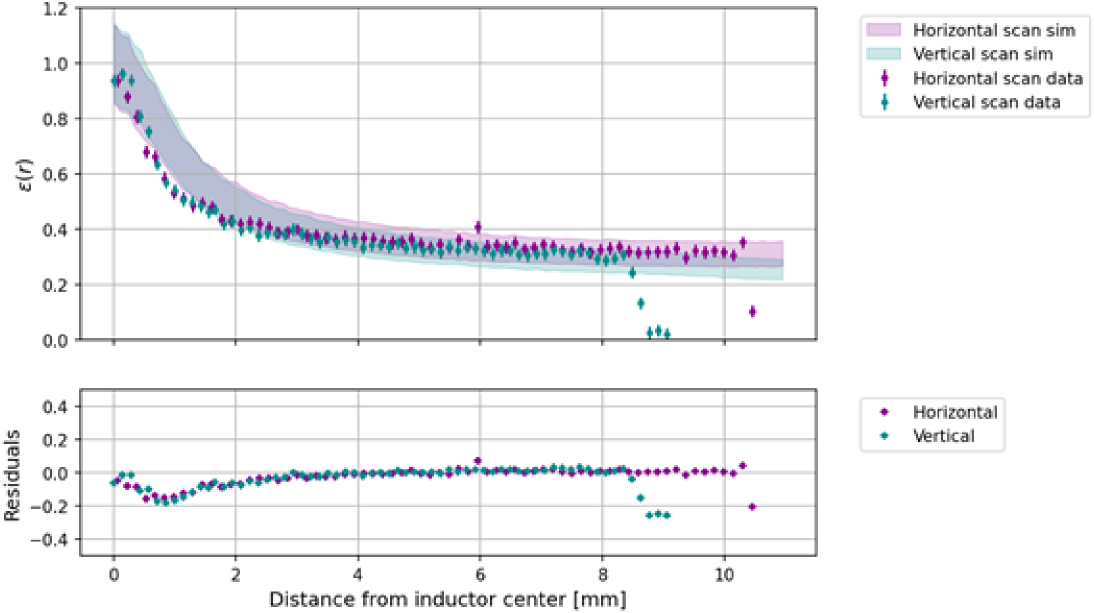
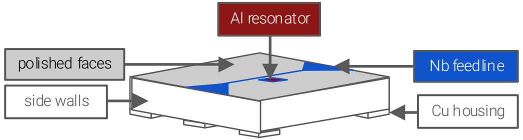




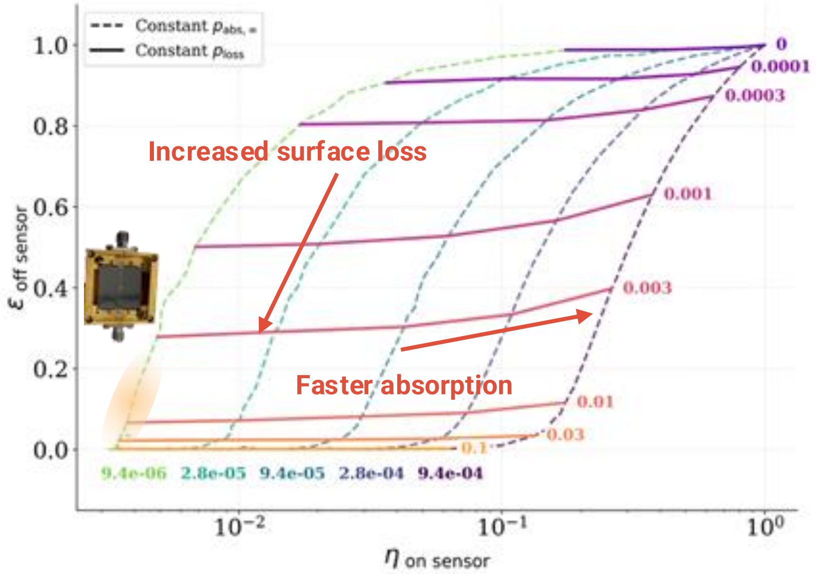
$p_{abs,\ inductor}$	0.103
$p_{abs,\ capacitor}$	0
$p_{abs,\ Nb}$	0.1
$p_{abs,\ Cu}$	0
$p_{abs,\ polished\ surfaces}$	0.002
$p_{abs,\ side\ walls}$	0

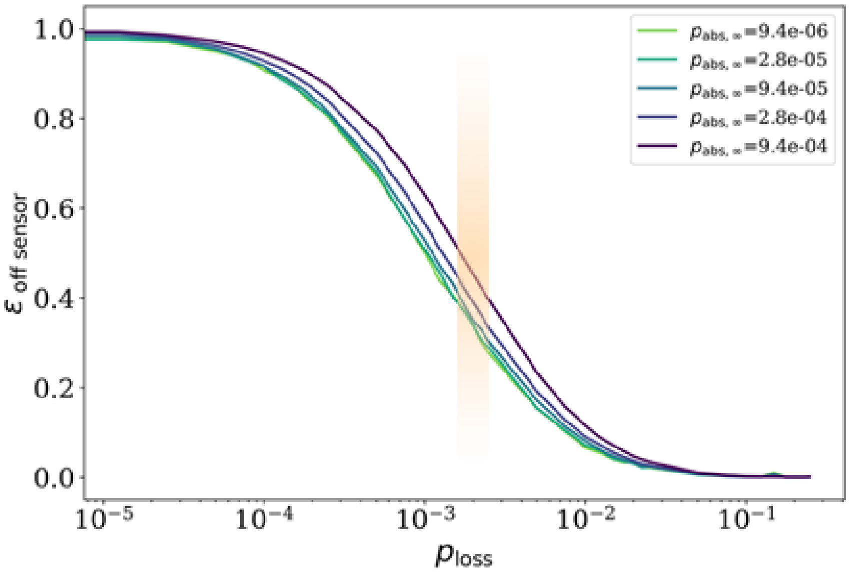
η: absolute phonon energy collection efficiency

ε: relative phonon energy collection efficiency; **$\varepsilon(x,y) = \eta(x,y) / \eta_{max}$**

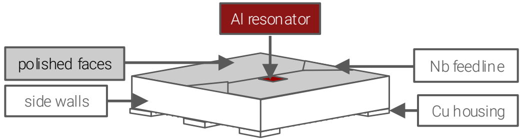
Parameter Space for Low Coverage

Assuming isotropic phonon loss, position dependence is a good indicator for loss probability.





η: absolute phonon energy collection efficiency
ε: relative phonon energy collection efficiency; **$\varepsilon(x,y) = \eta(x,y) / \eta_{max}$**
$p_{abs,\infty}$: absorption probability at interface × area coverage fraction



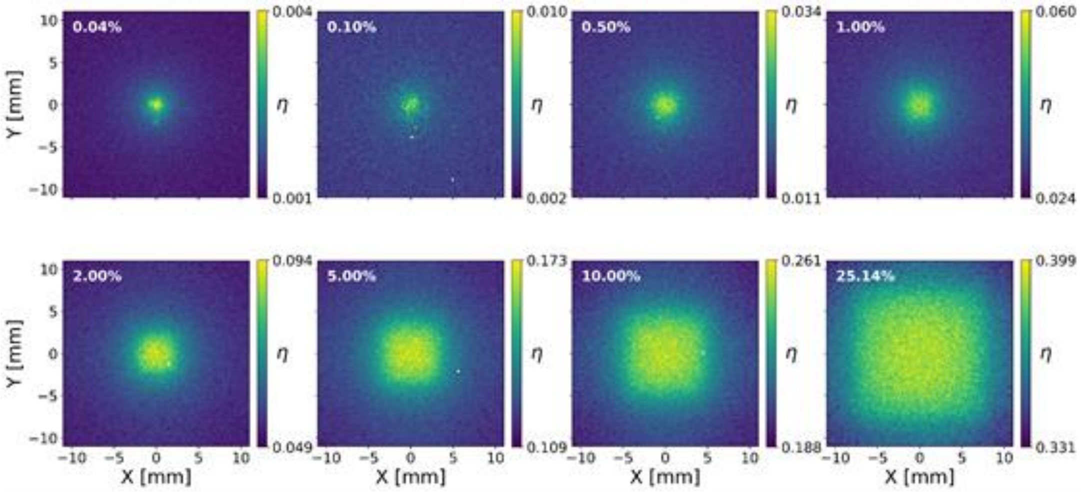
Part II

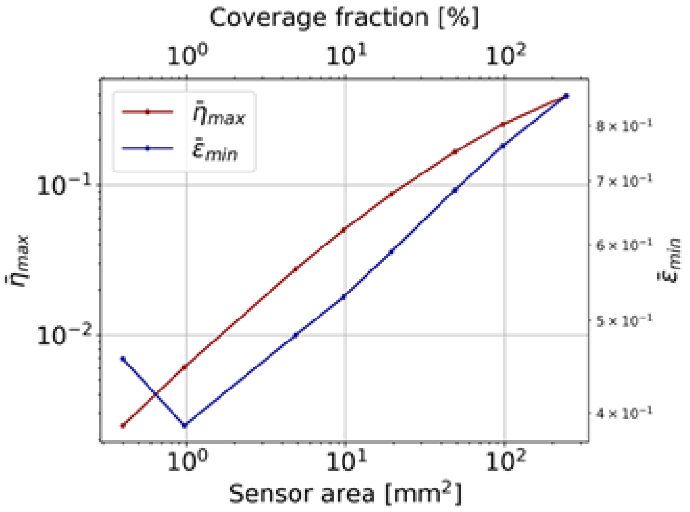
Impact of Phonon Loss on Forward Modeling

SLAC DMQiS G4 CMP

Varying Sensor Area

Assuming isotropic phonon loss, we can map out how different phonon sensor layouts perform.



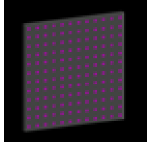


η: absolute phonon energy collection efficiency
ε: relative phonon energy collection efficiency; **ε(x,y) = η(x,y) / η_{max}**

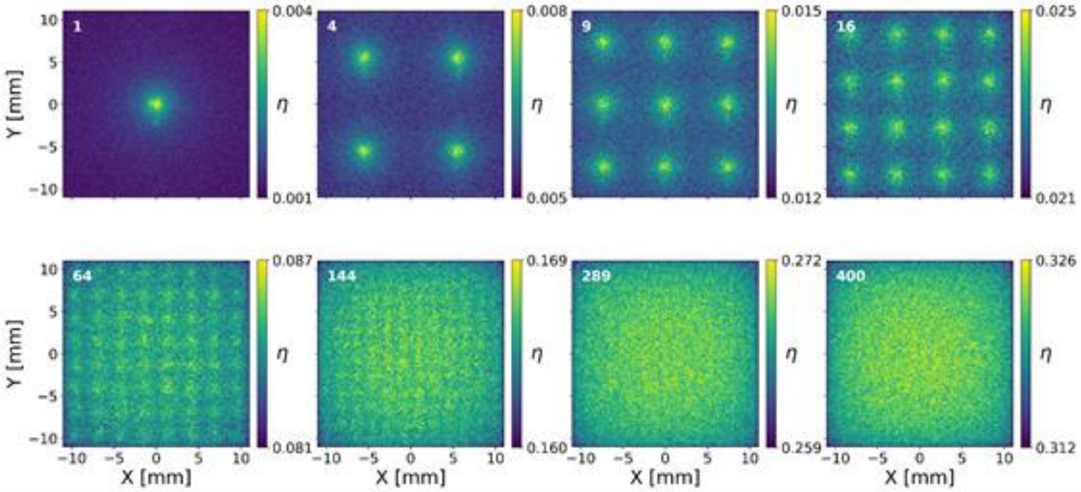
$\bar{\eta}$: average η(x,y) above 2σ

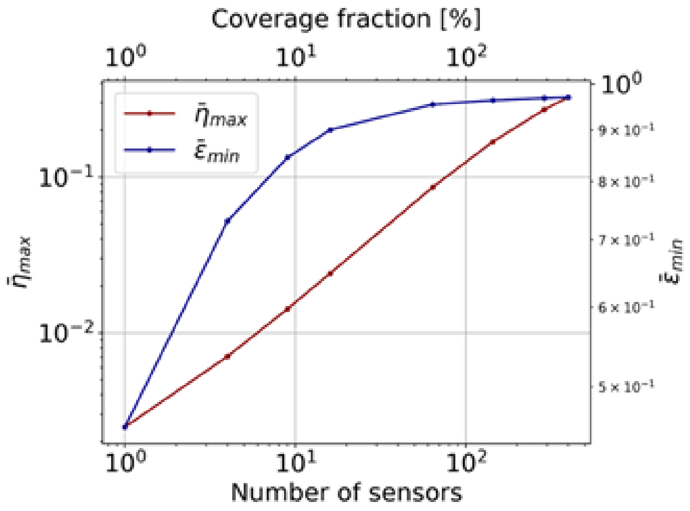
$\bar{\varepsilon}$: $\dfrac{\text{average } \eta(x,y) \text{ below } 2\sigma}{\text{average } \eta(x,y) \text{ above } 2\sigma}$

Varying Number of Sensors



Assuming isotropic phonon loss, we can map out how different phonon sensor layouts perform.





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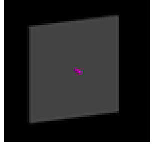
ε: relative phonon energy collection efficiency; $\boldsymbol{\varepsilon(x,y) = \eta(x,y) / \eta_{max}}$

$\bar{\eta}$: average η(x,y) above 2σ

$$\bar{\varepsilon} = \frac{\text{average } \eta(x,y) \text{ below } 2\sigma}{\text{average } \eta(x,y) \text{ above } 2\sigma}$$

Varying Sensor Film Thickness



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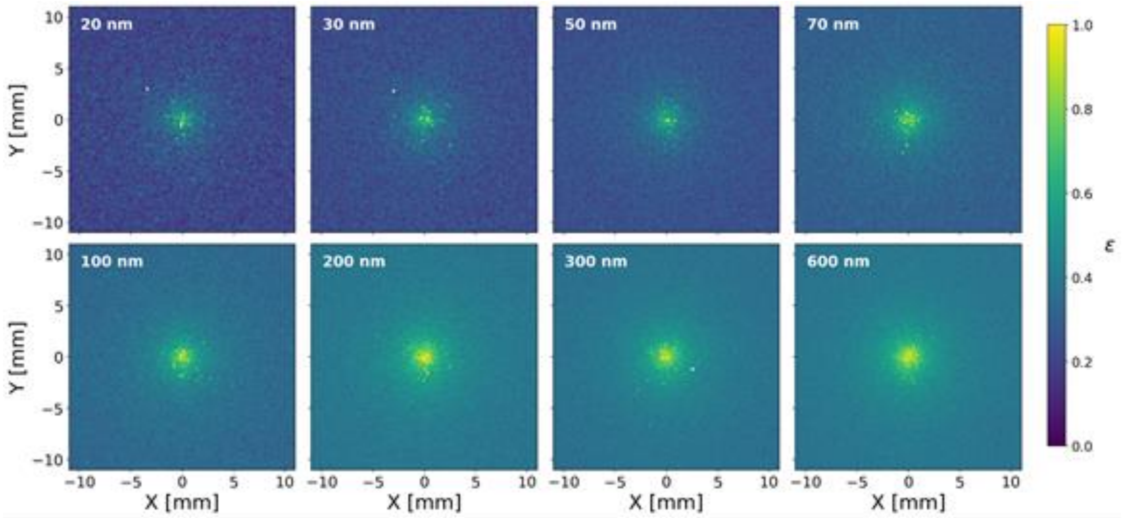

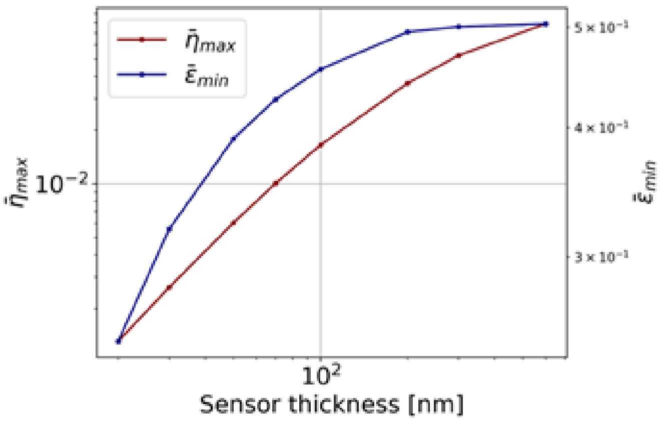

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$\bar{\eta}$: average η(x,y) above 2σ

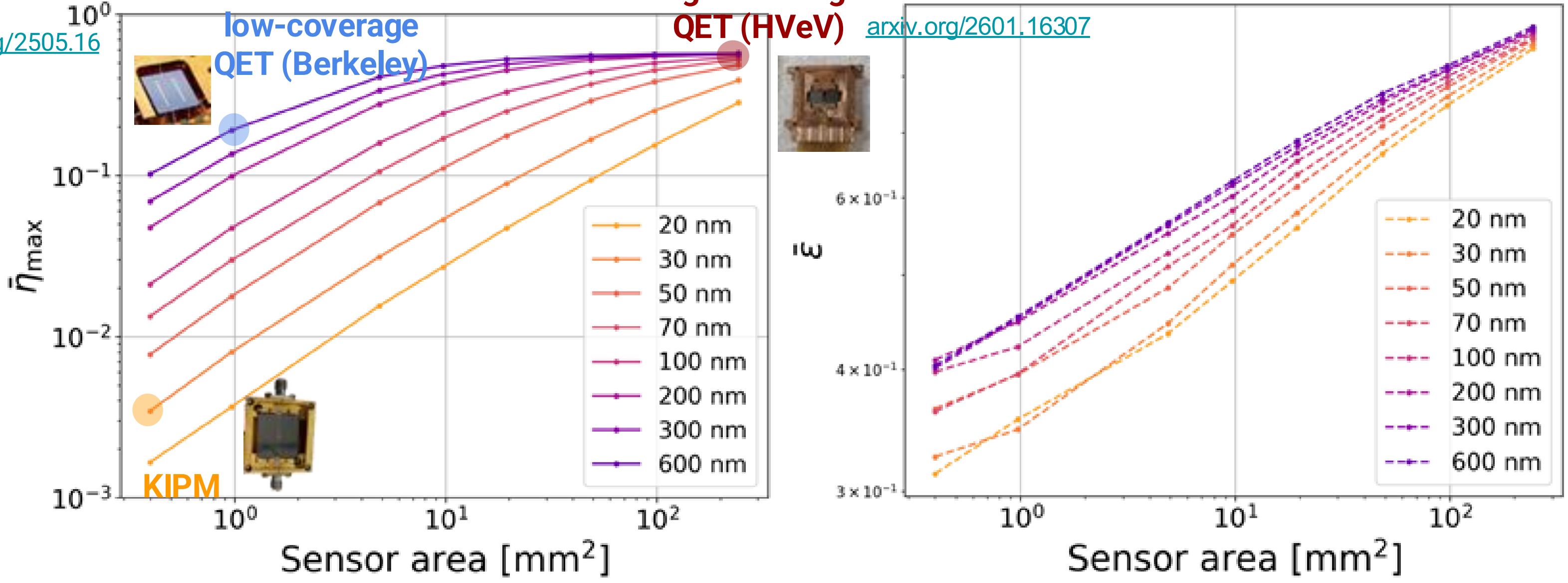
$$\bar{\varepsilon} = \frac{\text{average } \eta(x,y) \text{ below } 2\sigma}{\text{average } \eta(x,y) \text{ above } 2\sigma}$$

Parameter Space Beyond Low Coverage

From our assumptions of phonon loss, we can create a "lookup table" for the optimization space relevant to different sensor layouts.

arxiv.org/2505.16092v1

arxiv.org/2601.16307



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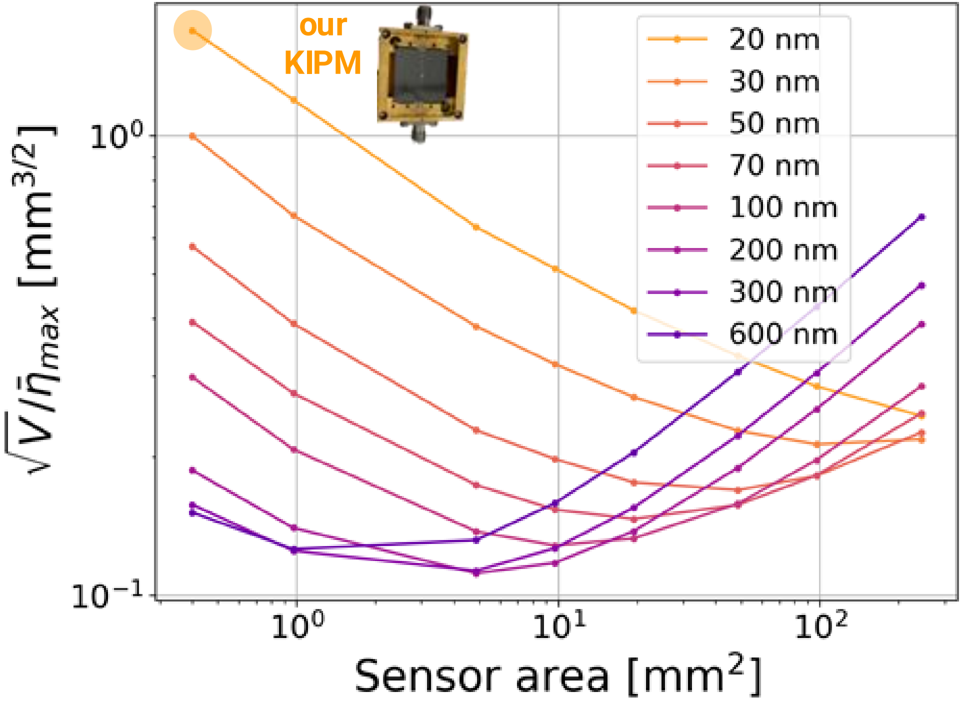
$$\bar{\varepsilon}: \frac{\text{average } \eta(x,y) \text{ below } 2\sigma}{\text{average } \eta(x,y) \text{ above } 2\sigma}$$

Direct Absorber Volume Optimization

We explore the volume optimization for direct absorber phonon sensors as a trade off between collection efficiency and sensor resolution.



The ideal calorimeter, without any trapping enhancement, will have resolution scale as the square root of absorber volume.

$$\sigma_E^{\text{abs}} \propto \sqrt{V_{\text{ind}}}$$

$$\sigma_E \propto \frac{\sigma_E^{\text{abs}}}{\eta_{\text{ph}}}$$

η: absolute phonon energy collection efficiency
$\bar{\eta}$: average η(x,y) above 2σ

Conclusion

Benchmarking effects of phonon loss is relevant for modeling diverse phonon sensors in G4CMP.

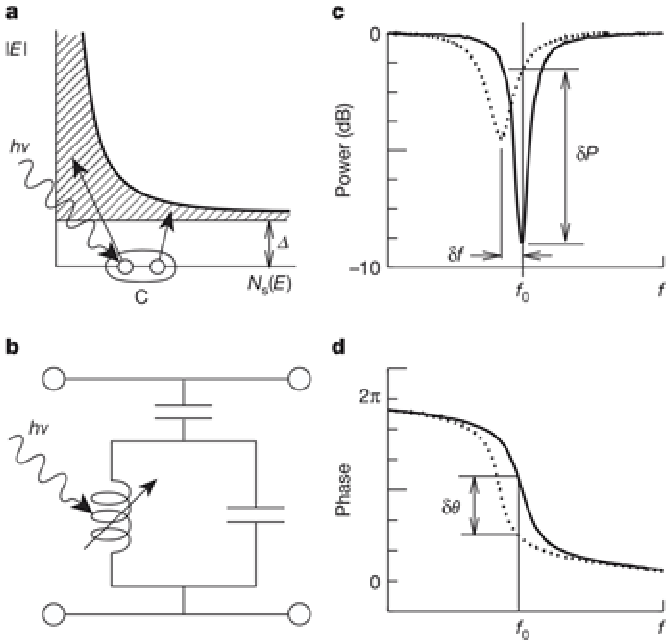
- Our MEMS measurement of position-dependent phonon responsivity provides a benchmark for phonon loss, which we think is isotropic & potentially at crystal surfaces
- Assuming this isotropic loss, we can project efficiency for different sensor layouts
- Next steps: given models of sensor resolution, we can make sensitivity projections for different sensor layouts and architectures

Thank you!

Backup

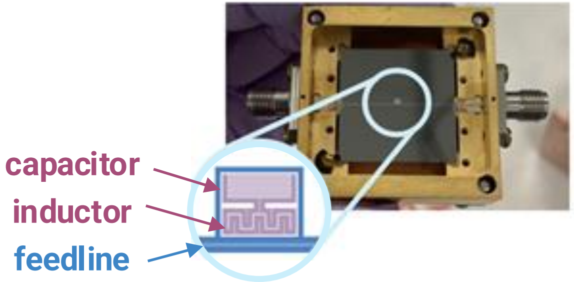
Microwave Kinetic Inductance Detectors

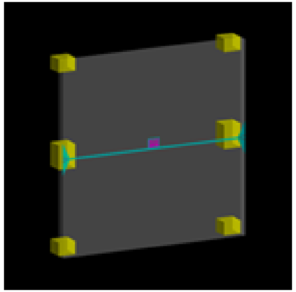
Quasiparticles from broken Cooper pairs shift kinetic inductance in a superconducting resonator.



https://doi.org/10.7907/GZ72-V784

Kinetic Inductance Phonon-Mediated Detectors



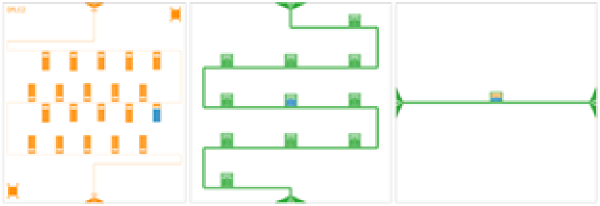


Our KIPM (OW230427)
1mm x 2cm x 2cm Si chip
30 nm Al resonator, 70 nm Nb feedline
0.09% sensor surface area coverage
<13,695.6 μm^3 active inductor volume
Fabricated at JPL by Osmond Wen and Bruce Bumble

- Use cases: low-threshold rare event searches, co-sensors for qubits
- Overall detector resolution is limited by low phonon collection efficiency

$$\sigma_E = \frac{\sqrt{N_r}}{\eta_{ph}} \sigma_E^{abs}$$

- number of resonators → $\sqrt{N_r}$
- resolution on energy deposited in the substrate **(hundreds of eV)** → σ_E
- resolution on energy absorbed by the sensor **(few eV)** → σ_E^{abs}
- phonon collection efficiency **(<1%)** → η_{ph}

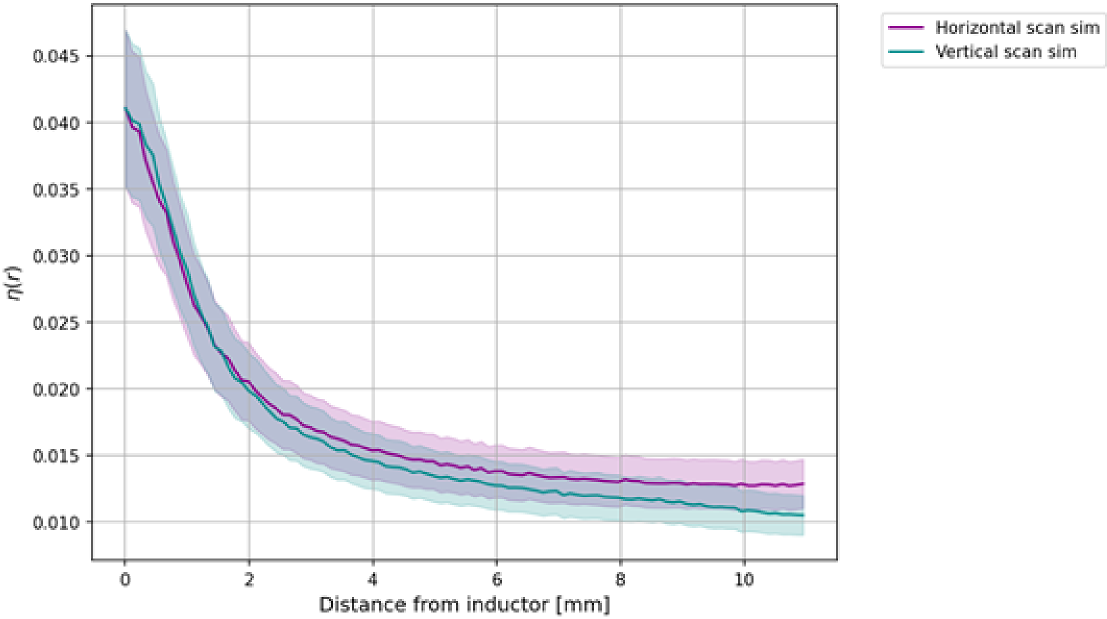


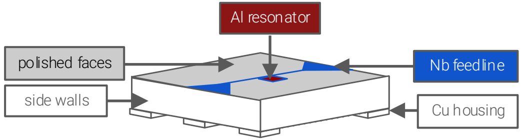
σ_{Edep} [eV]	380	320	850
σ_{Eabs} [eV]	5.9 ± 0.9	2.1 ± 0.1	23
η [%]	7.0 ± 1.1	0.78 ± 0.07	1.1 ± 0.2

Note on Parameters for Part I

- Studies in Part I do not model quasiparticles using either KaplanQP or TrackedFilmResponse
  - Any above-gap phonons that are absorbed according to the phonon absorption probability are counted toward energy depositions
- Other relevant parameters:
  - For slides 6-12, electron-hole pairs are generated in a uniform (x,y) distribution across the L-scan region & an exponential z distribution consistent with the attenuation of a 625-nm optical photon in Si
  - For slide 13, electron-hole pairs are generated at the center of the inductor for the "on-sensor" (x,y) position and (-9.3 mm, 8.52 mm) for the "off-sensor" (x,y) position; the z position is still sampled from the exponential distribution
  - Electron-hole pairs each have a 0.814-eV kinetic energy partitioned in an "all-to-one" scheme to electron or hole
  - Charge trapping is off
  - Maximum phonon bounces = 100000

η(r) in Part I





$p_{abs,\ inductor}$	0.103
$p_{abs,\ capacitor}$	0
$p_{abs,\ Nb}$	0.1
$p_{abs,\ Cu}$	0
$p_{abs,\ polished\ surfaces}$	0.002
$p_{abs,\ side\ walls}$	0

η: absolute phonon energy collection efficiency

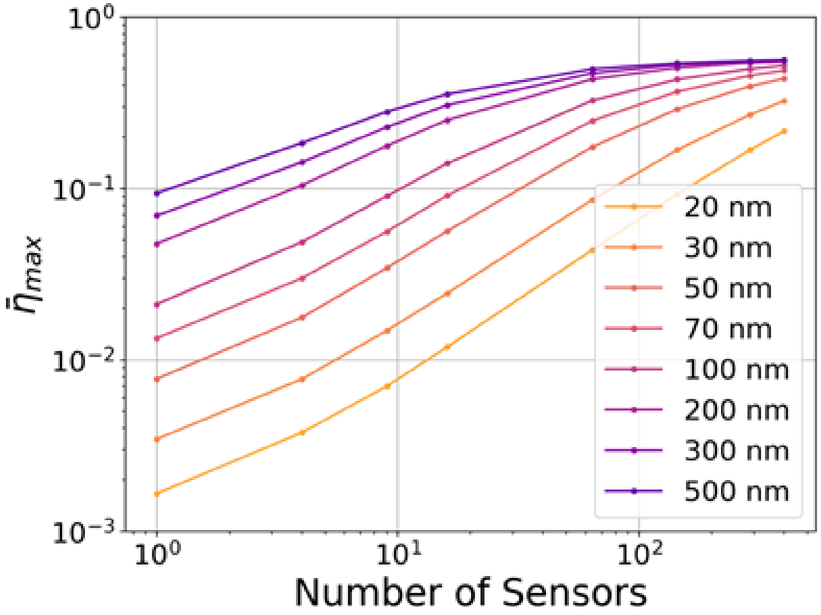
ε: relative phonon energy collection efficiency; **$\varepsilon(x,y) = \eta(x,y) / \eta_{max}$**

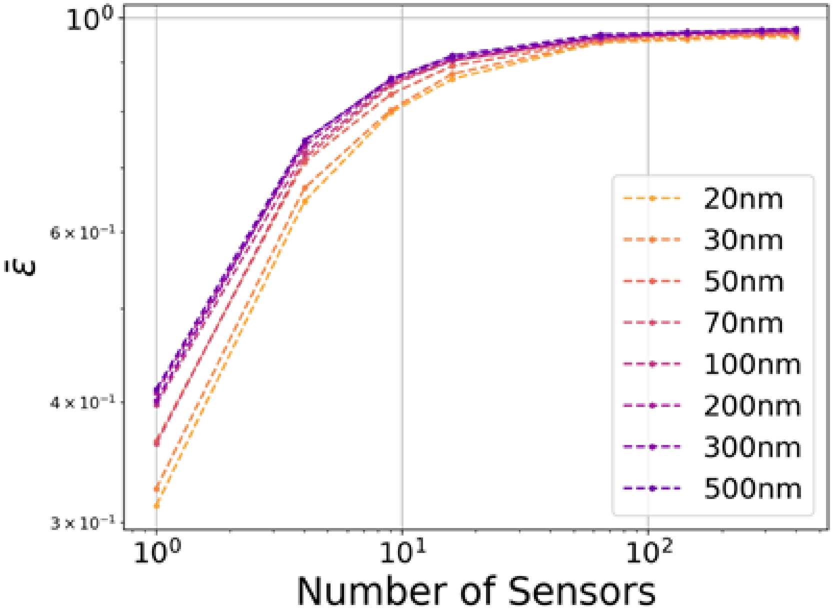
Note on Parameters for Part II

- Studies in Part II model quasiparticles in 0D using KaplanQP
  - Phonon transmission probability: $p_{trans,\, Si \rightarrow Al} = 0.795$*
  - Pairbreaking probability: $p_{break} = 1 - \exp(-4d/\lambda_{pb})$
    - d = sensor film thickness, λ_{pb}= pairbreaking length ≈ 866 nm*
  - `filmAbsorption`: $p_{abs} = p_{trans} \times p_{break}$
- Other relevant parameters:
  - For slides 15-17, electron-hole pairs are generated in a uniform (x,y) distribution and an exponential z distribution consistent with the attenuation of a 625-nm optical photon in Si
  - For slides 18-19, electron-hole pairs are generated in a diagonal (x,y) distribution from (0 mm, 0 mm) to (11 mm, 11 mm) and an exponential z distribution
  - Electron-hole pairs each have a 0.814-eV kinetic energy partitioned in an "all-to-one" scheme to electron or hole
  - Charge trapping is off
  - Maximum phonon bounces = 100000

*https://journals.aps.org/prb/pdf/10.1103/PhysRevB.110.024519

More Sensor Layout Studies



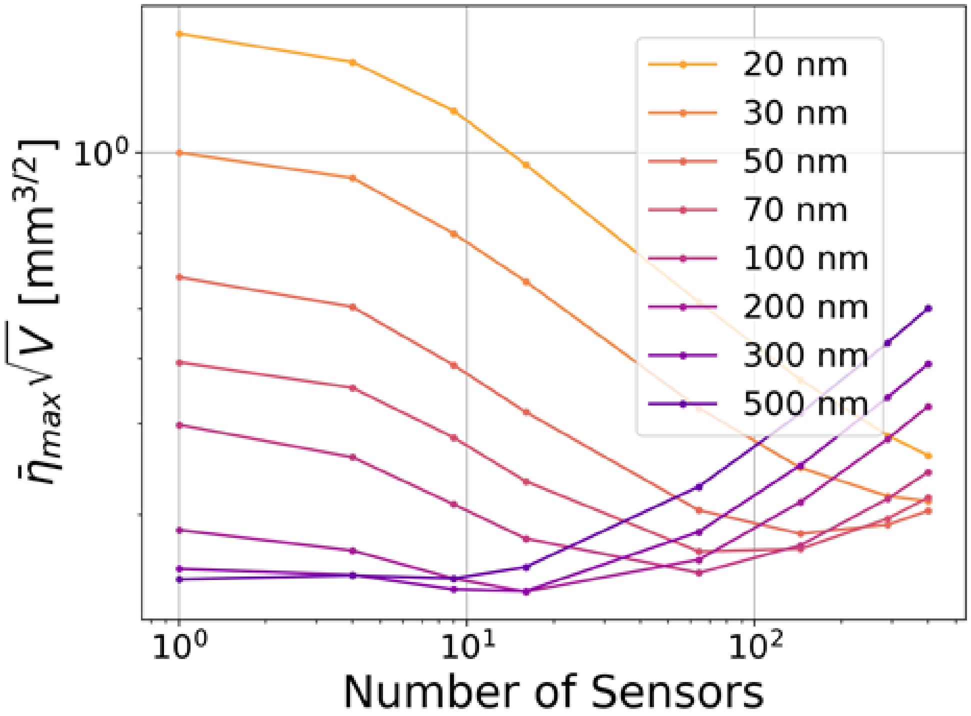


η: absolute phonon energy collection efficiency
ε: relative phonon energy collection efficiency; **ε(x,y) = η(x,y) / η_{max}**

$\bar{\eta}$: average η(x,y) above 2σ

$\bar{\varepsilon}$: $\dfrac{\text{average } \eta(x,y) \text{ below } 2\sigma}{\text{average } \eta(x,y) \text{ above } 2\sigma}$

More Sensor Layout Studies



η: absolute phonon energy collection efficiency
$\bar{\eta}$: average η(x,y) above 2σ

Volume Scaling of an Ideal Calorimeter

Temperature evolution, in the limit of mapping sensor response to equilibrium temperature state:

$$C(T)\frac{dT}{dt} = -K\left[T_{film}^5 - T_{bath}^5\right]$$

Linearize first term & assume film thermalizes in steady state, we get $\frac{\Delta T}{dt} = -\frac{G(T)}{C(T)}\Delta T = -\frac{\Delta T}{\tau(T)}$

Solution with initial ΔT=E/C: $\Delta T = \frac{E}{C(T)}\exp(-t/\tau(T))\Theta(t)$ → pulse amplitude ∝ energy deposited

Power signal from fluctuation-dissipation theorem: $P_{sig} = G(T)\Delta T(t) = \frac{\eta E}{\tau}\exp\left(-t/\tau(T)\right)\Theta(t) = ES(t)$

Noise in Fourier space: $P_N^2(f) = 4k_bT^2Gf_{link}$

Energy resolution:

$$\sigma_E^2 = \left[4\int_0^\infty \frac{s(f)^2}{P_N^2(f)}df\right]^{-1}$$
$$= k_bT^2Gf_{link}\left[\int_0^\infty s(f)^2 df\right]^{-1}$$
$$\geq \frac{4k_bT^2Cf_{link}}{\eta^2}$$

In the limit that $C = c_{VT}VT$, where C_{VT} is the volumetric specific heat:

$$\sigma_E^2 \geq \frac{2k_bT^3Vc_{VT}}{\eta^2} \rightarrow \sigma_E \geq \frac{\sqrt{2k_bV}T^{3/2}}{\eta}$$

I. Benchmarking phonon loss

II. Impact of phonon loss on forward modeling