Development of a Massive, Highly Multiplexible, Phonon-Mediated Particle Detector using Kinetic Inductance Detectors

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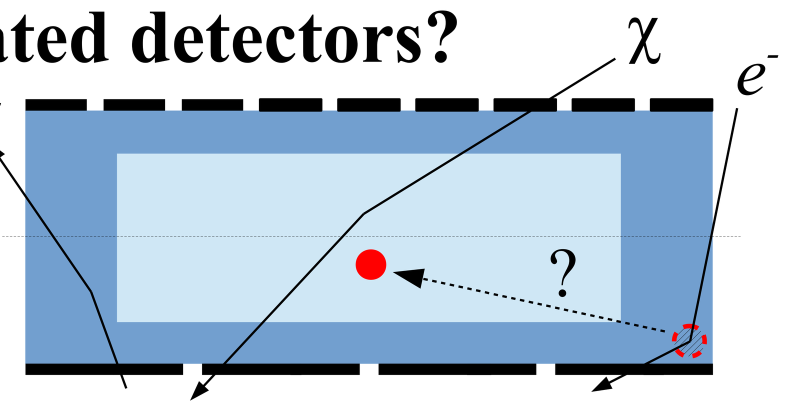
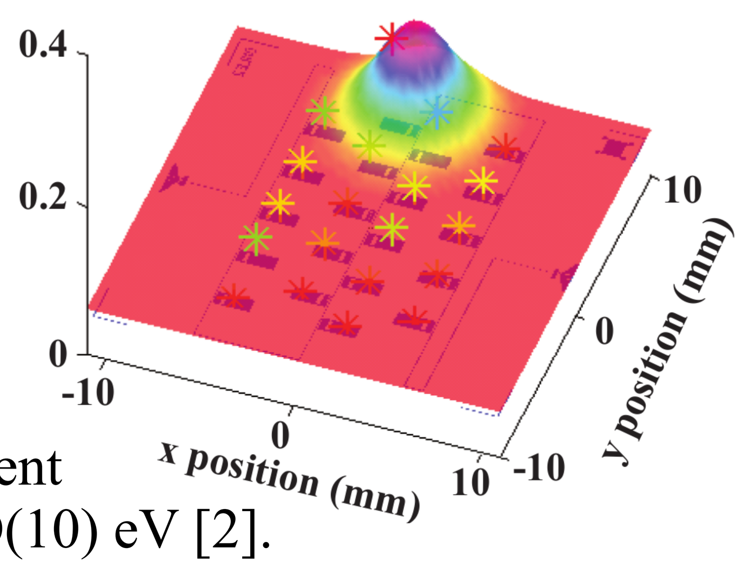
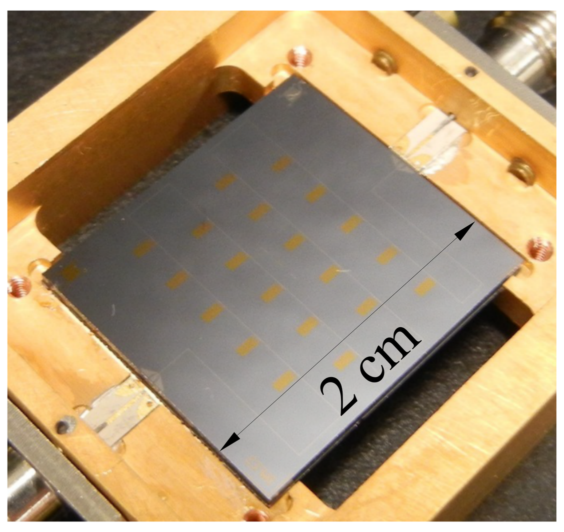
- **Scientific motivation**: Improve position reconstruction fidelity and energy resolution for rare-event experiments, such as low-threshold dark matter search, coherent neutrino scattering, and neutrino-less double beta decay (0νββ).
- **Technical requirement**: O(10) eV energy resolution, robust position reconstruction with 1 mm resolution.
- **Technological approach**: Phonon-mediated detector using O(10^2) KIDs on O(1) kg Si or Ge substrate.
- **Result**: We have validated the RF design of an 80-KID prototype on a 1 mm × ⌀76 mm wafer.
- **Future work**: Increase to 180 KIDs, calibrate with X-rays, scale up to O(2.5) cm thick substrates.

Why KID-based phonon-mediated detectors?

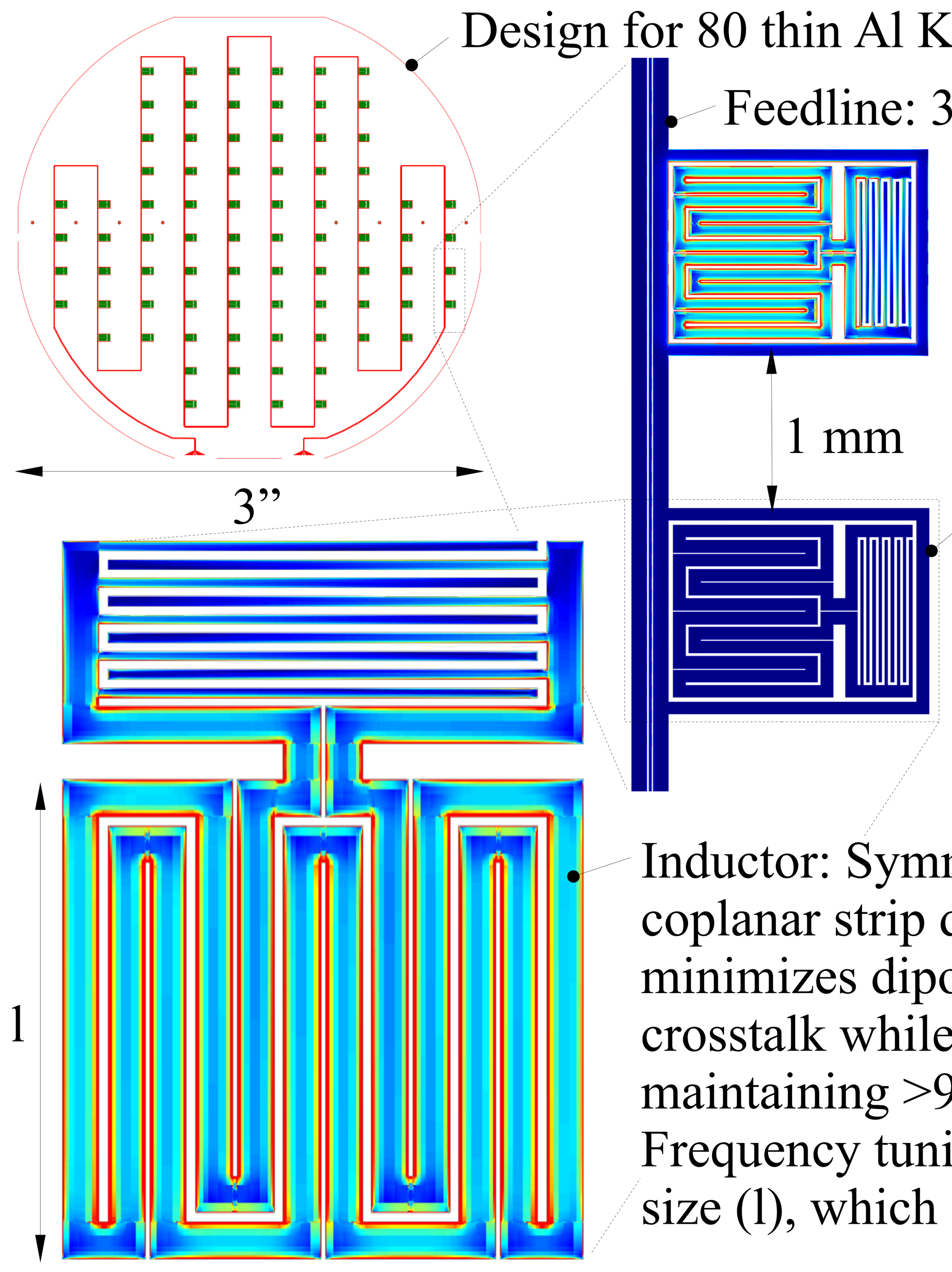


- Surface and/or incomplete ionization collection events may limit the sensitivity of experiments using phonon-mediated detectors [1].
- Rejection of such events improves with position reconstruction fidelity and energy resolution.
- This fidelity can be improved by high phonon sensor density, for which KIDs are a natural approach. KIDs also promise excellent energy resolution O(10) eV [2].

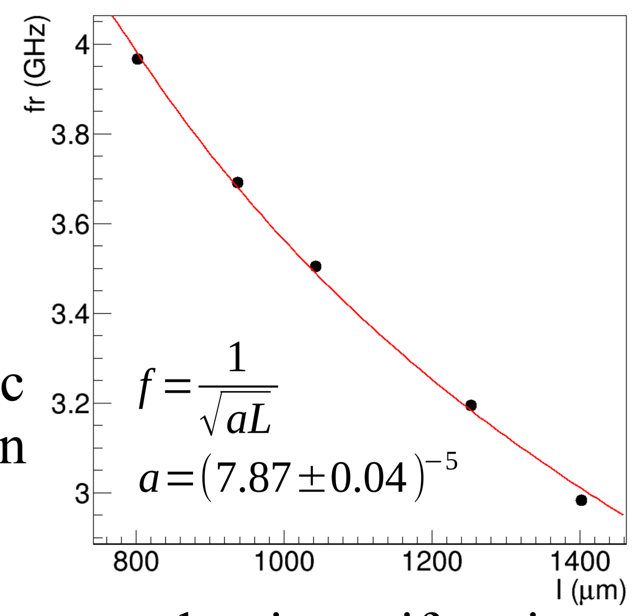




Design and simulation



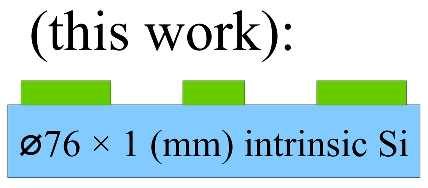
Crosstalk: Using the specialized inductor design with ground shield [3, 4], the simulation shows negligible crosstalk between KIDs.

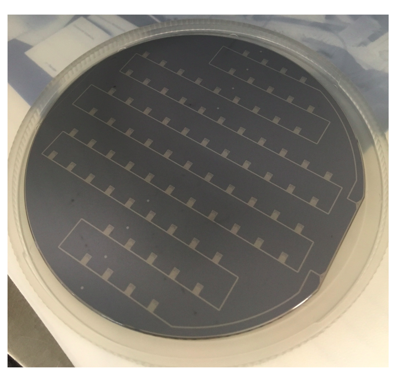


Inductor: Symmetric coplanar strip design minimizes dipole crosstalk while maintaining >95% current density uniformity. Frequency tuning is done by adjusting inductor size (l), which is found to follow $f \propto 1/\sqrt{l}$.

Fabrication

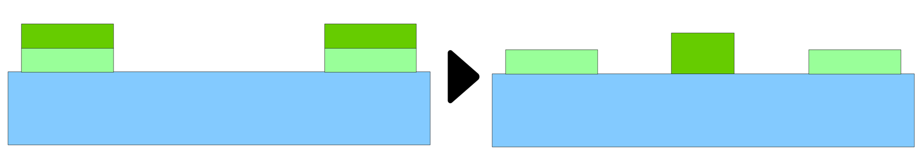
- Nb prototype for RF validation (this work):





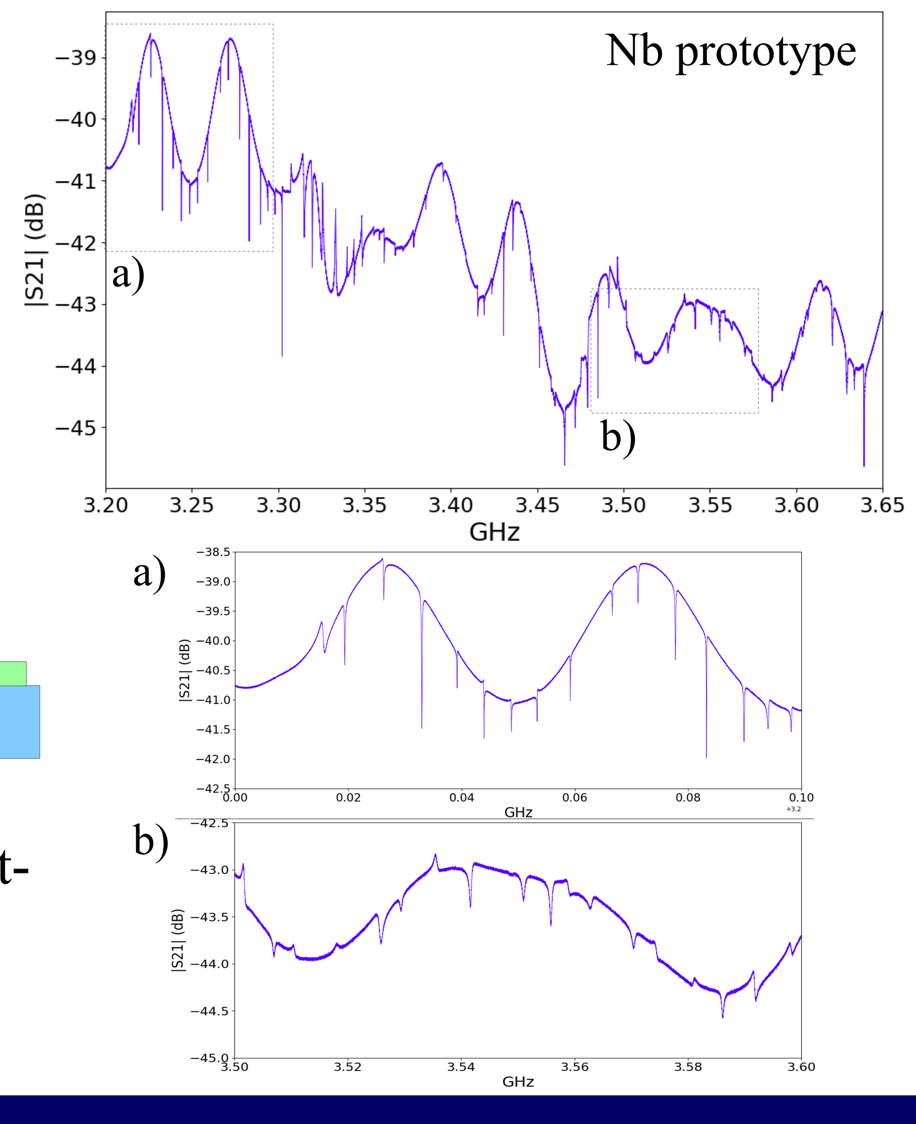
1) 300 nm Nb, single deposition
2) Fluorine Reactive Ion Etching (RIE) to produce KIDs and CPW

- Al-KIDs phonon detector (ongoing):

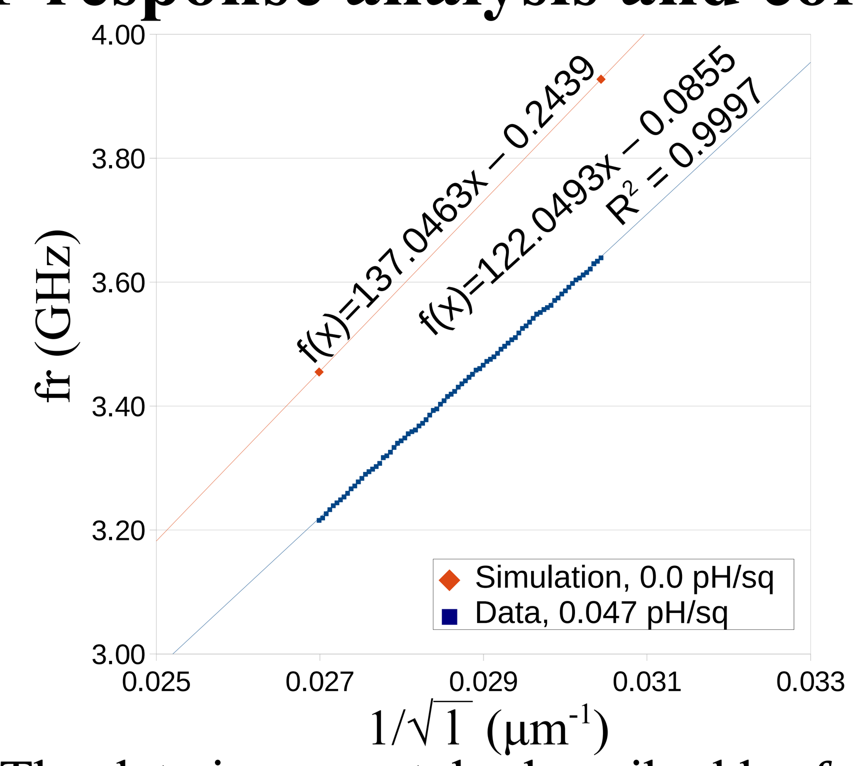


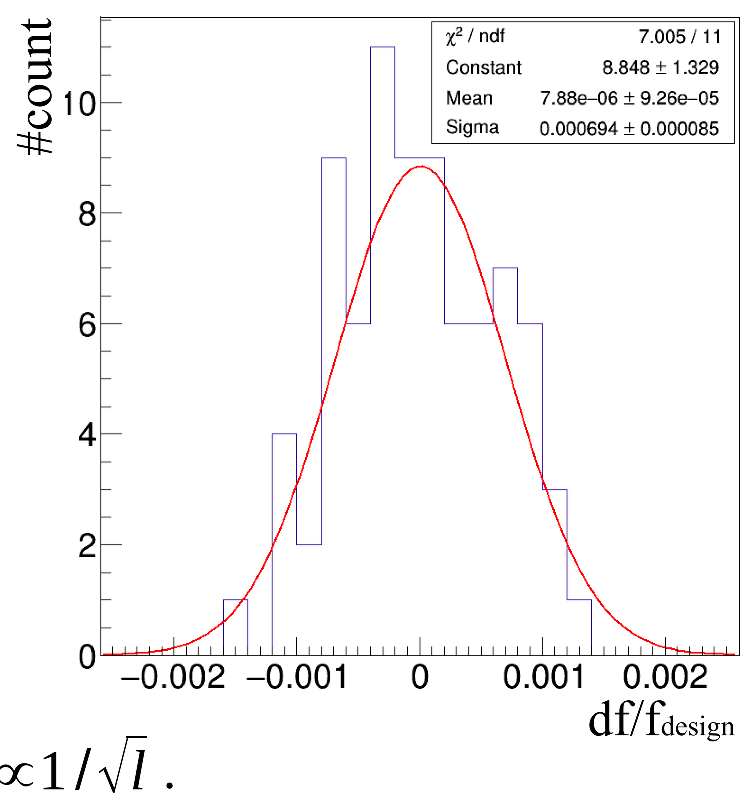
1) Chlorine RIE to produce KIDs
2) 50 nm Nb over 30 nm Al as protection layer, deposited in succession
3) 300 nm Nb, 2nd deposition
4) Fluorine RIE to produce CPW

- Transmission at 270 mK

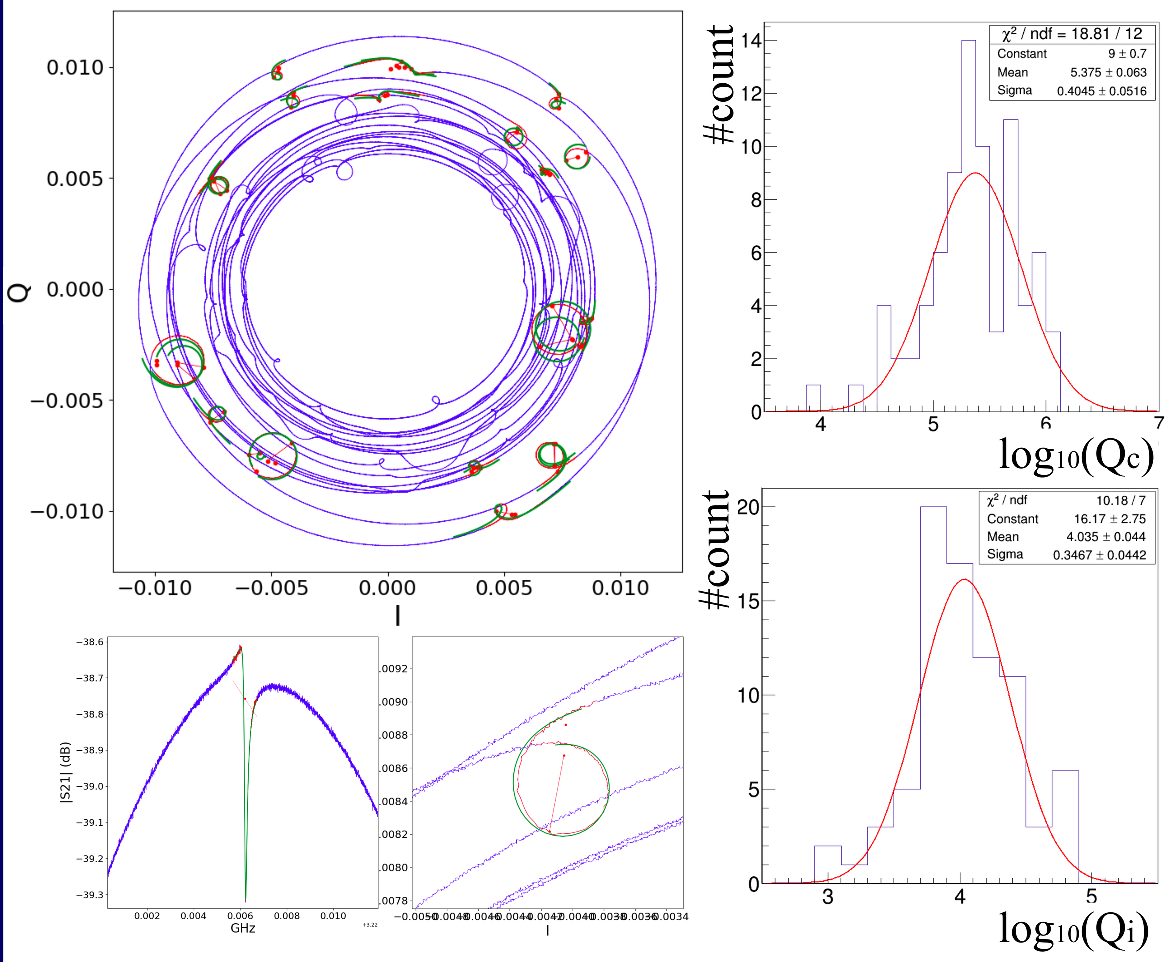


RF response analysis and correction

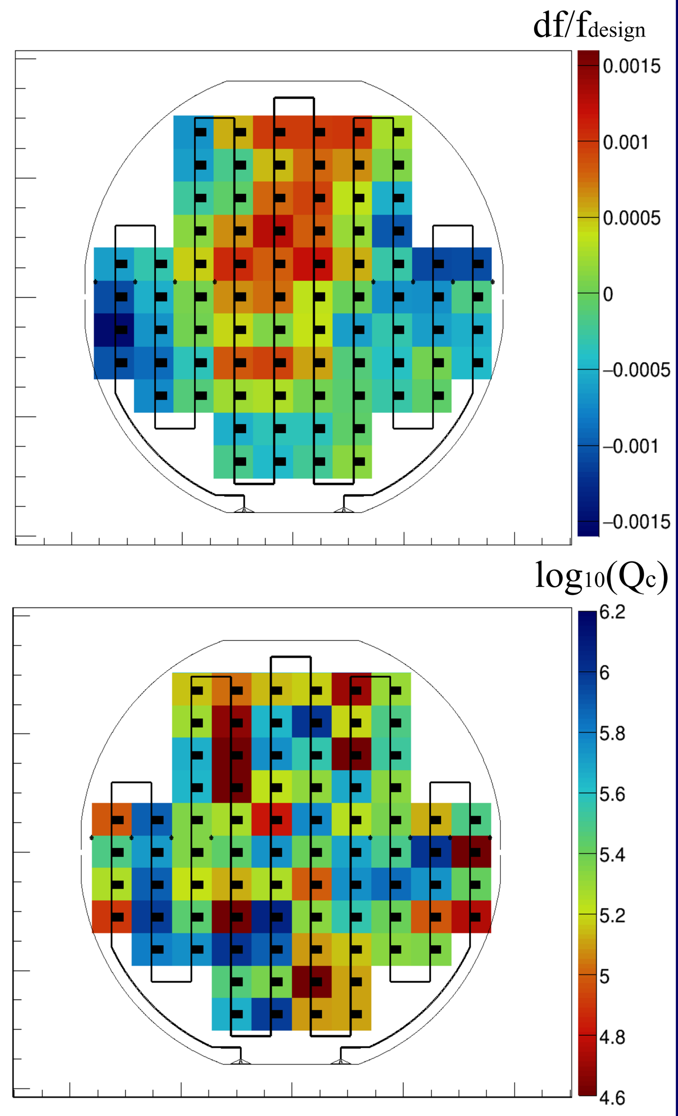




- The data is accurately described by $f \propto 1/\sqrt{l}$.
- Kinetic inductance fraction (α): Inferred from 0.0 pH/sq simulation, we have $\alpha_{data} \sim 0.076$
- $\sigma_{df/f_{design}} \sim 0.07\,\%$: Expect future devices with 180 resonances in 3.05~3.45 GHz to have 10% probability of one out-of-sequence KID.



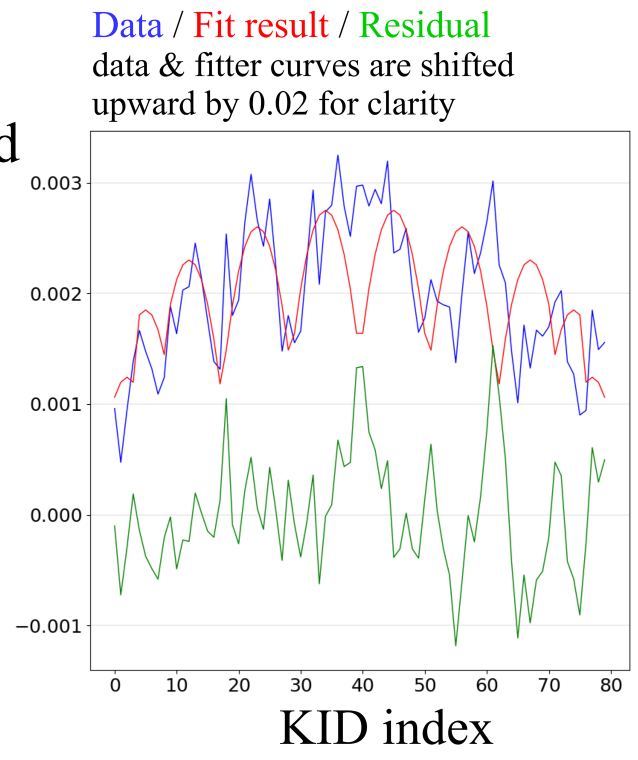
- The average coupling quality factor $Q_c \sim 2\times10^5$ is 3 times lower than design.
- The internal quality factor of thick Nb film, $Q_i \sim 10^4$, dominates the total resonant quality factor and produces shallow resonances.



- Inspired by the correlation between Qc, KID locations, and df/f, we model df/f by empirical KID-CPW coupling strength

$$\int_{CPW} |\vec{r}_{KID} - \vec{r}_x|^{-0.1}\, dx$$

- Suggest a systematic component to $\sigma_{df/f}$ that can be reduced in the future



Future work

- Increase the number of KIDs by 2~3 times
- Fabricate with Al KIDs and measure resolution with X-rays. Expected energy resolution: [2]

$$\sigma_E = \frac{\Delta_{Al}}{\eta_{ph}\beta(f_0,T)}\sqrt{\frac{\eta_{read}}{\alpha\, p_t}\frac{A_{sub}k_b T_N}{2\pi f_0}\frac{N_0\lambda_{pb}}{\tau_{qp}S_1(f_0,T)}} \sim 10-20 \text{ eV}$$

- Scale up to O(2.5) cm-thick substrates

[1] R. Agnese, et. al. (SuperCDMS Collaboration), Phys. Rev. D 95, 082002 (2017)
[2] D. C. Moore, et. al., Appl. Phys. Lett. 100, 232601 (2012)
[3] O. Noroozian, et. al., IEEE TMTT 60, 5, 1235 (2102)
[4] E. S. Battistelli, et. al., Eurp. Phys. J. C75, 8, 353 (2105)

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