Kinetic Inductance Detectors with phonon funneling volume

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The concept of funnel

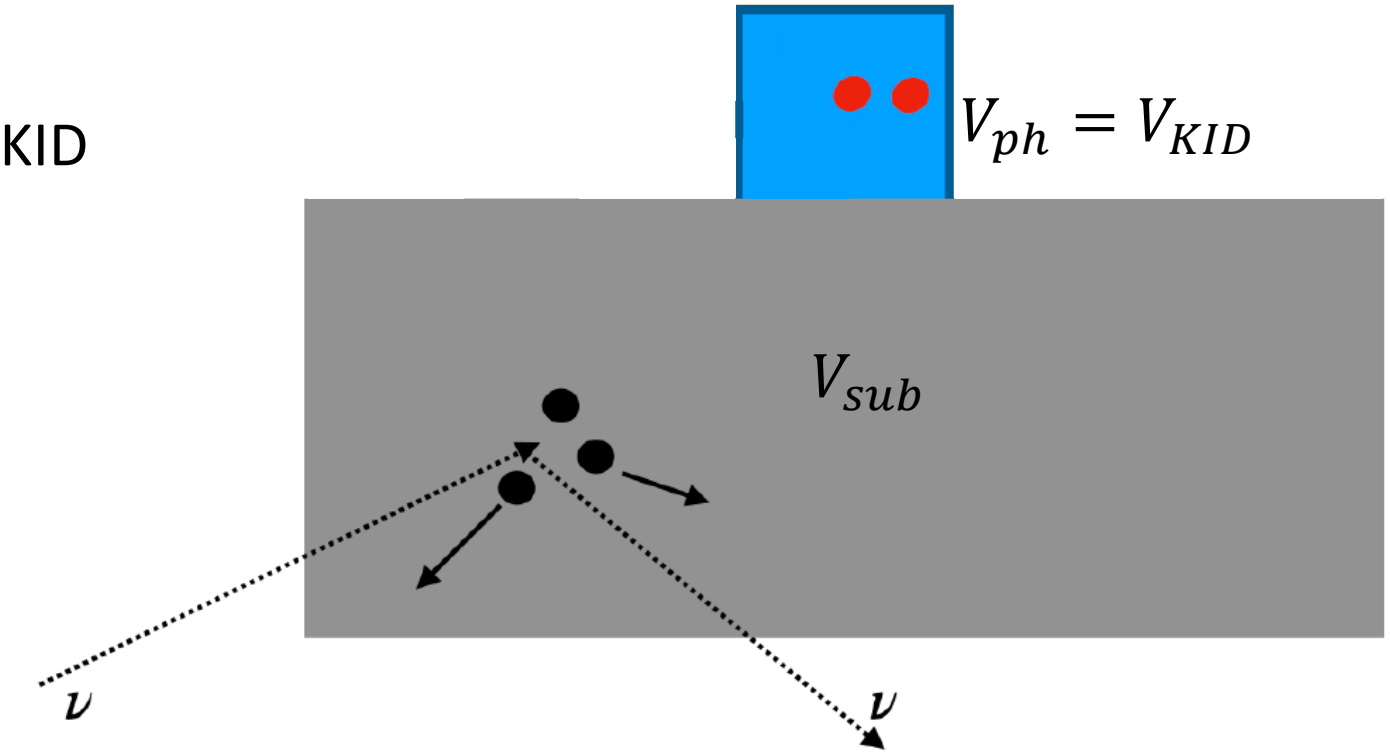
The concept of funnel (Ludovico De Santis's master thesis)

- Energy resolution of a "normal" BULLKID

$$\sigma_E \propto 1/\sqrt{V}$$

- All the volume collects phonons:

$$V \approx V_{ph} = V_{KID}$$



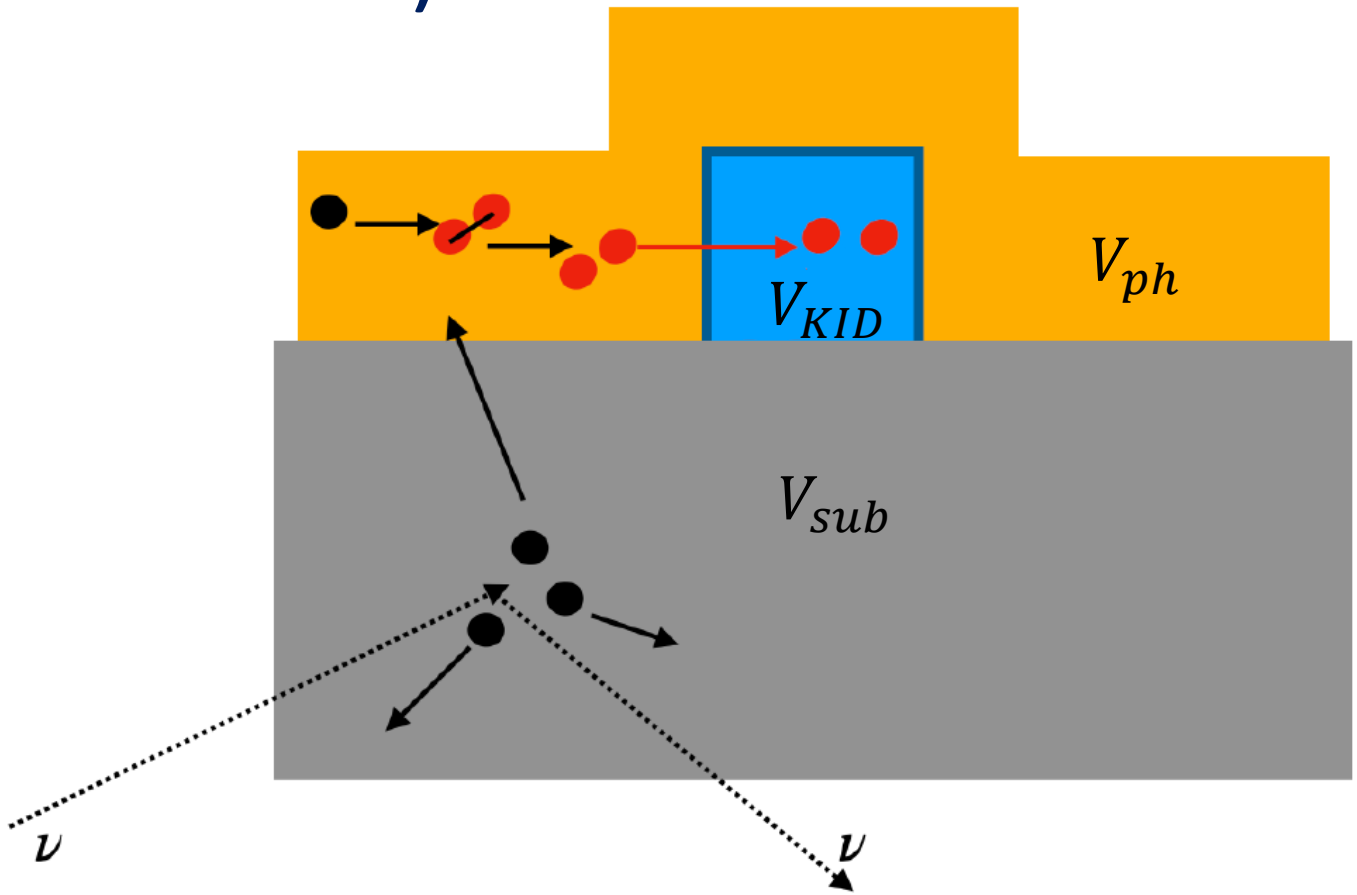
Volume collecting phonons

Volume generating signals

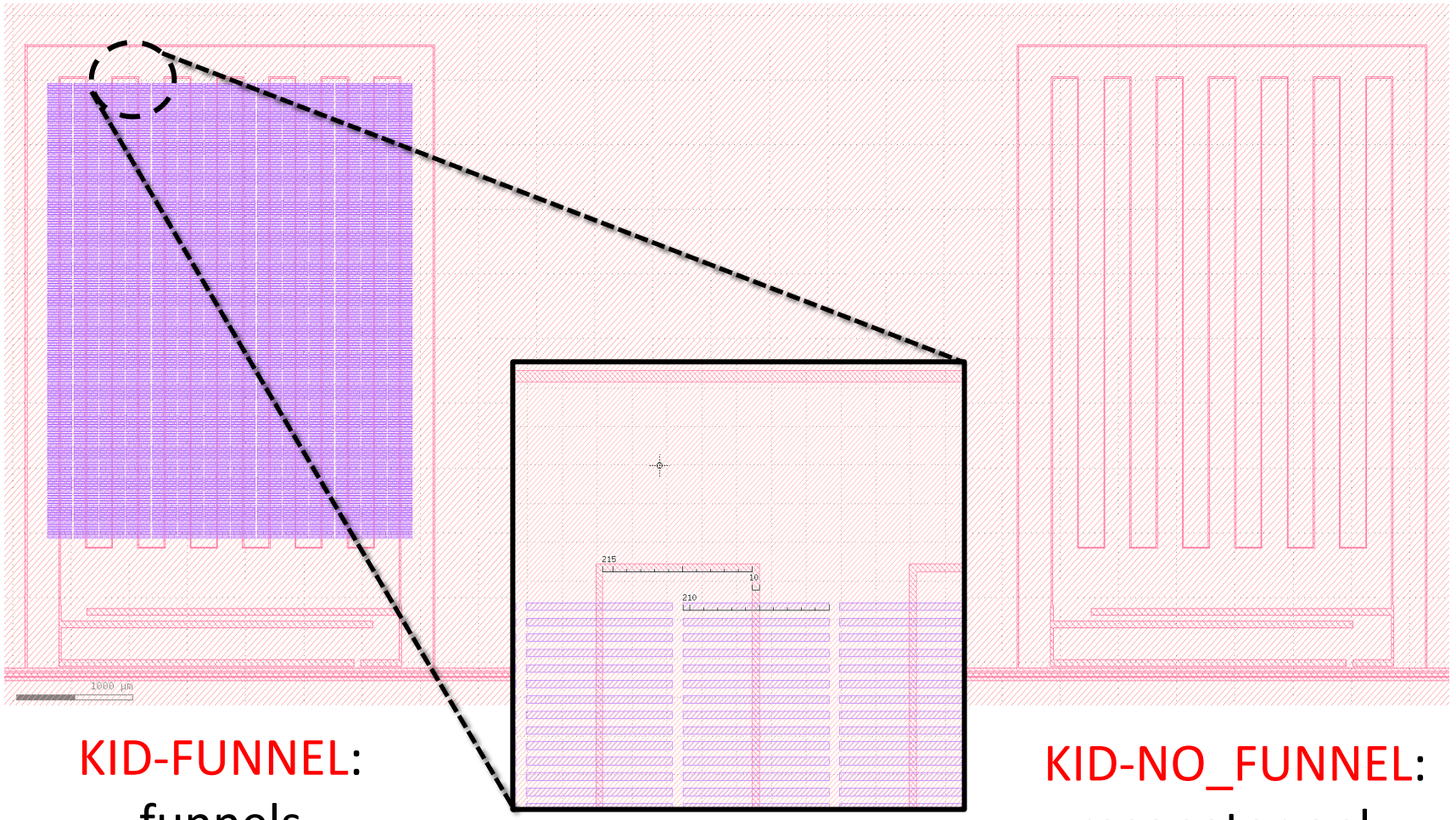
The concept of funnel (Ludovico De Santis's master thesis)

- Goal of funnel: increasing V_{ph} without increasing (excessively) V_{KID}
- How to do that: surrounding KID with "passive" material (no current)
- The result: (Possible) energy resolution improvement

$$\sigma_E \sim \sqrt{V_{KID}}/V_{ph}$$



Arrays layout



KID-FUNNEL:
funnels

KID-NO_FUNNEL:
resonator only

Two KIDs tested

Phase responsivities and resolution compared (at different power)

Arrays layout

Funnels made of Al

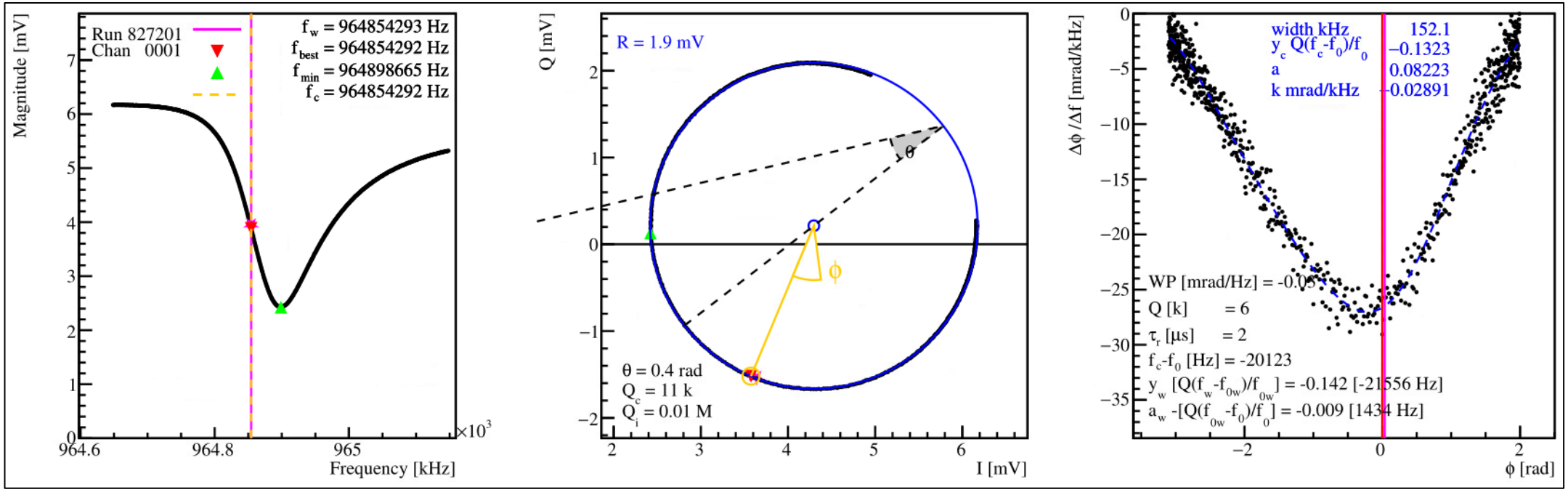
Capacitive coupling

Meander and feed-line made of AlTiAl

Substrate made of Si

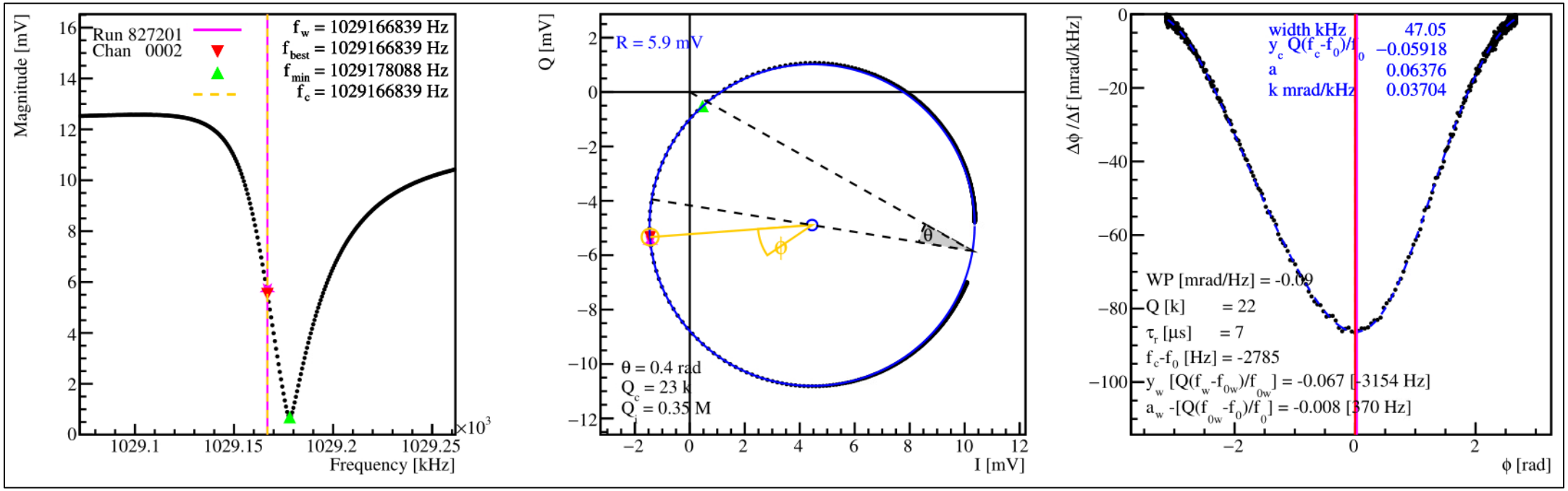
Measures and results

Resonance Circle: KID-FUNNEL



$f_0 \approx 984.97$ MHz $\quad Q_c \approx 11$k $\quad Q \approx 6$k

Resonance Circle: KID-NO_FUNNEL



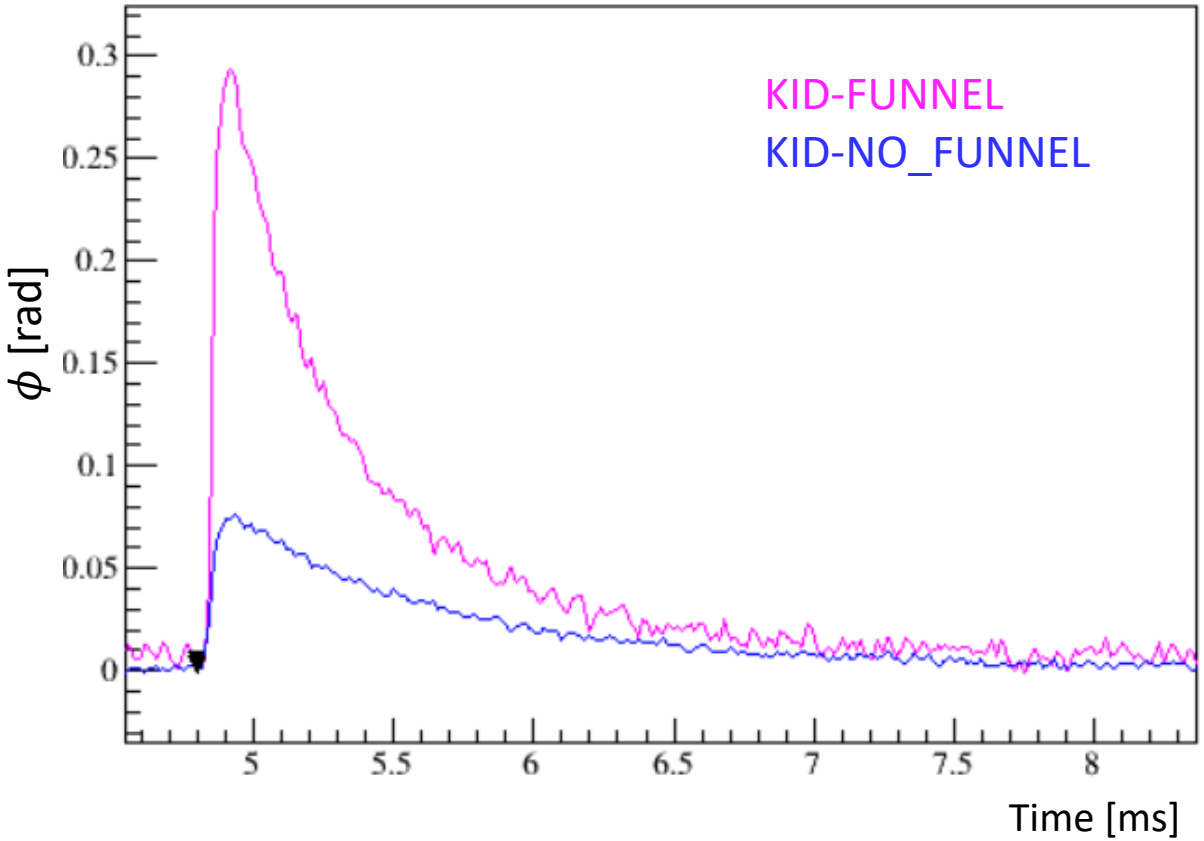
$f_0 \approx 1031.96$ MHz $\quad Q_c \approx 23$k $\quad Q \approx 22$k

Optical Calibration: phase responsivity

- Photons release energy on KIDs
- Phase variation of transfer function → Pulses

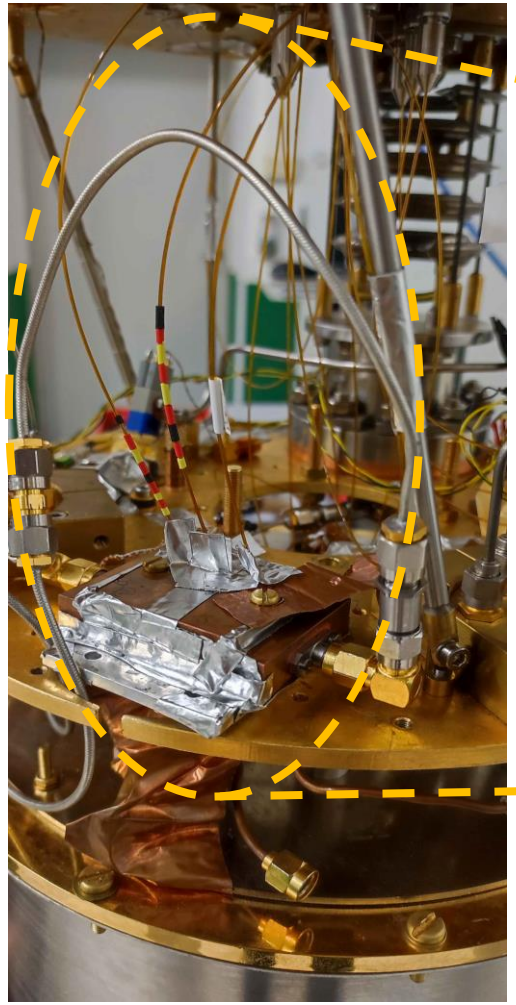
$$\frac{d\phi}{dE} = \eta \frac{\alpha S_\phi(\omega, T) Q}{N_0 V_{KID} \Delta_0^2}$$

$$\eta \propto V_{ph}/V_{sub}$$

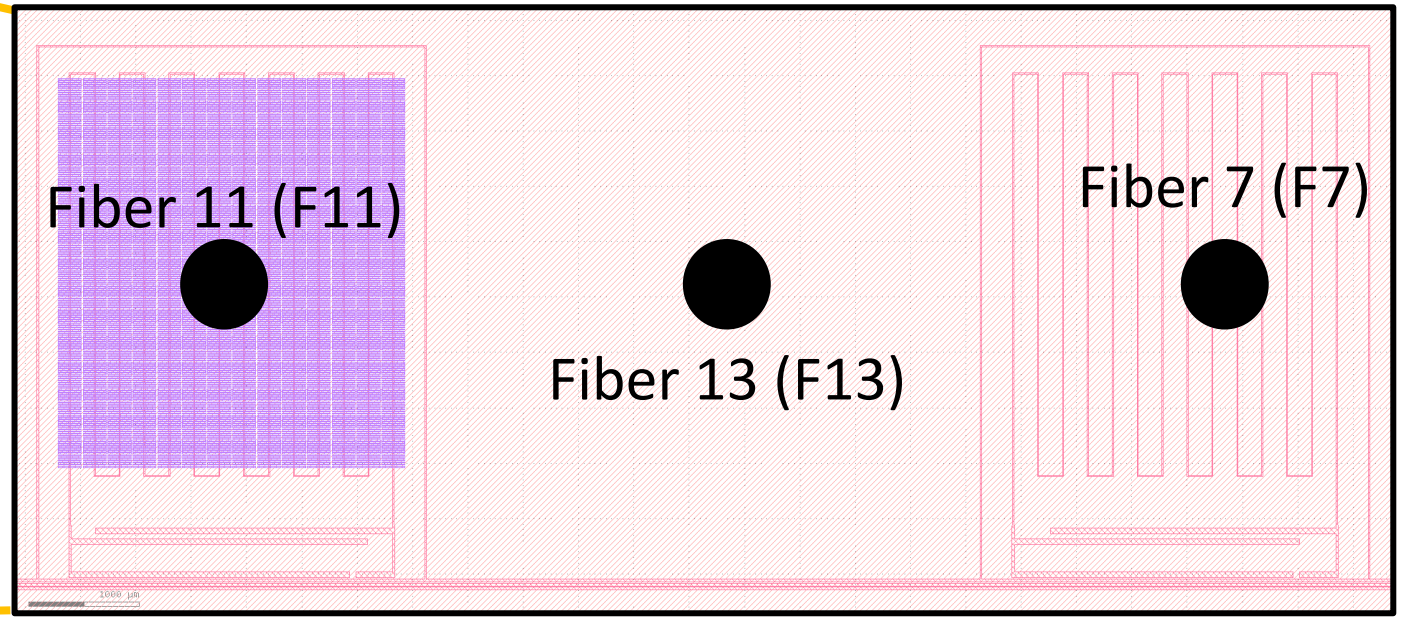


- $\eta =$ Energy to QP conversion efficiency
- $\alpha = \frac{L_k}{L_k + L_g}$ fraction of kinetic inductance
- $\Delta_0 =$ Superconducting gap

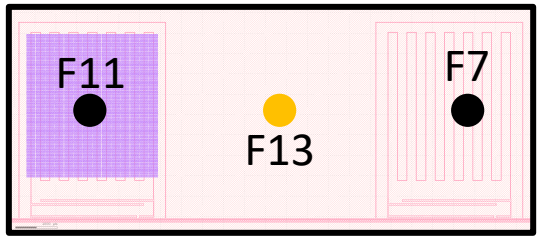
Optical Calibration



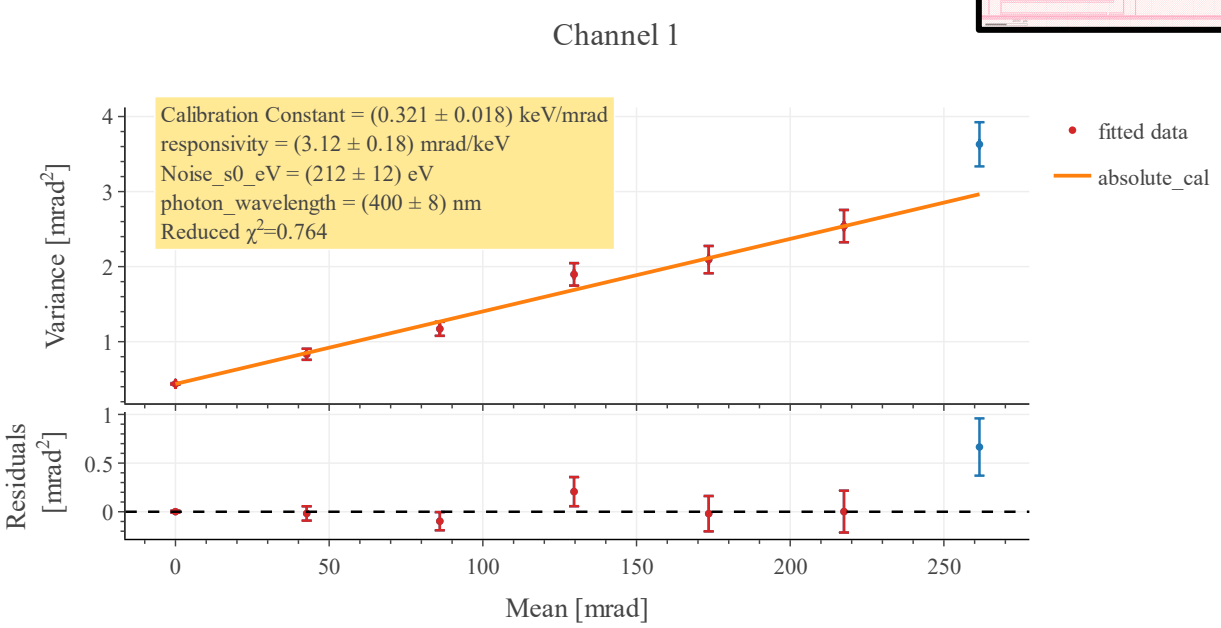
- Three optical fibers shoot photons against substrate (opposite side of resonators)



Optical Calibration (F13-High power)



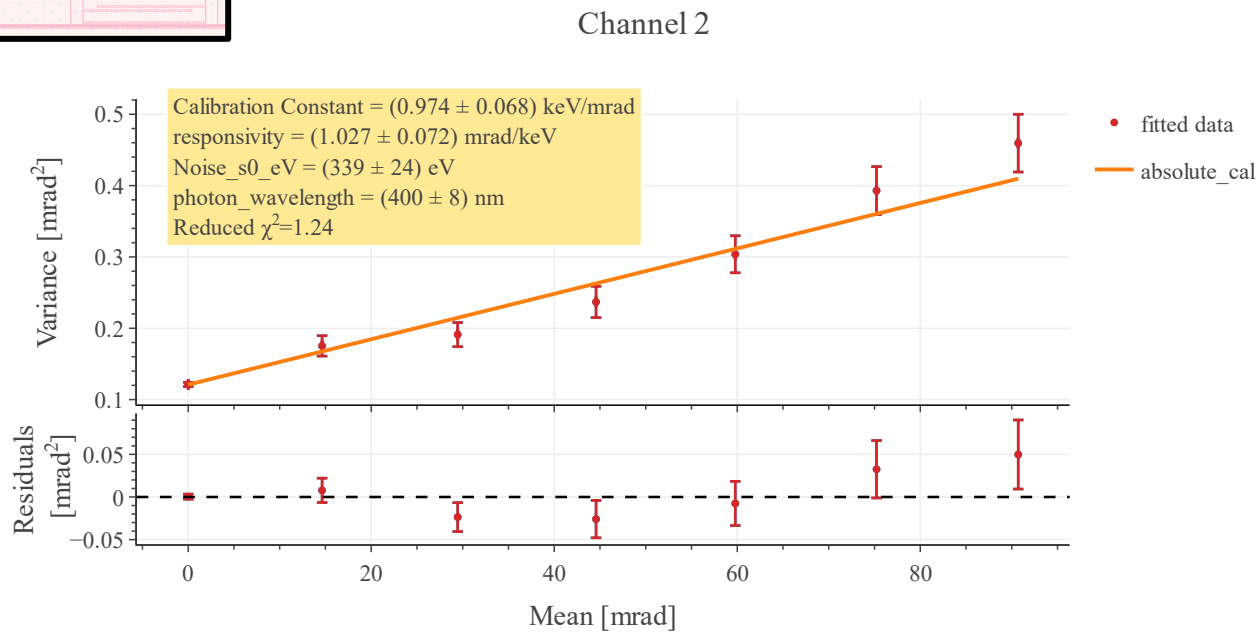
KID-FUNNEL



$$\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL} = (3.12 \pm 0.18)\ \text{mrad/keV}$$

$$\sigma_{0,13}^{FUNNEL} = (212 \pm 12)\ \text{eV}$$

KID-NO_FUNNEL

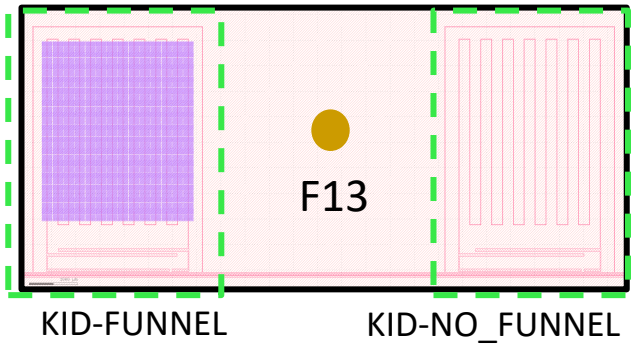


$$\left(\frac{d\phi}{dE}\right)_{13}^{NO_FUNNEL} = (1.07 \pm 0.07)\ \text{mrad/keV}$$

$$\sigma_{0,13}^{NO_FUNNEL} = (339 \pm 24)\ \text{eV}$$

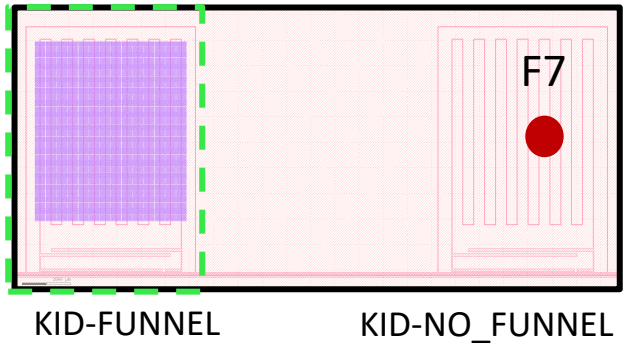
Responsivities ratios

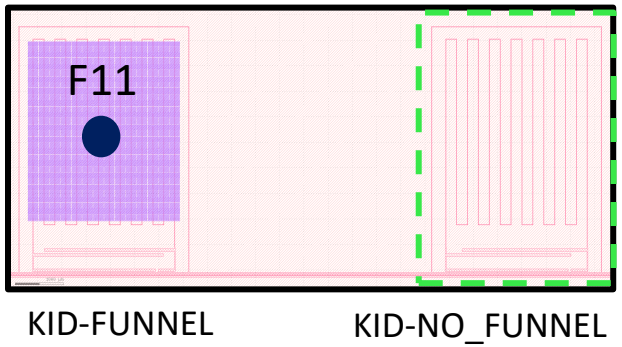
Central fiber



$$\frac{\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{13}^{NO_FUNNEL}} = 2.92 \pm 0.25$$

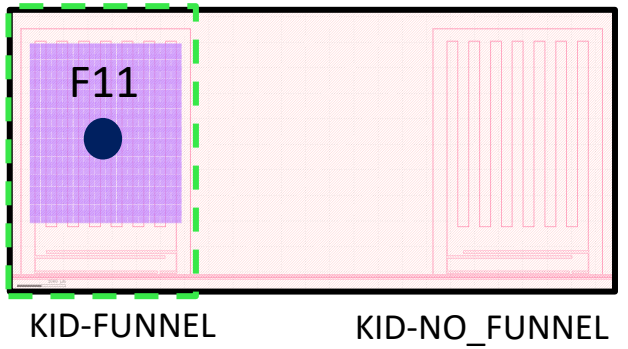
Furthest fibers

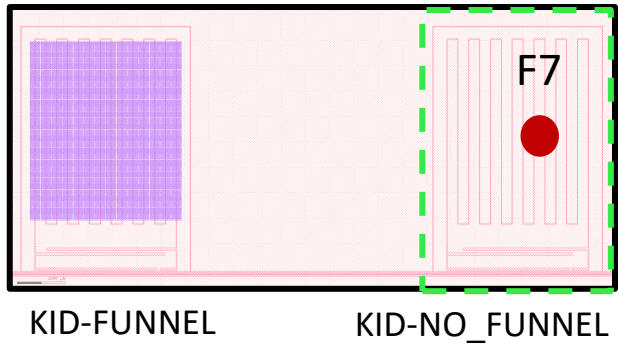




$$\frac{\left(\frac{d\phi}{dE}\right)_{7}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{11}^{NO_FUNNEL}} = 1.35 \pm 0.31$$

Closest fibers





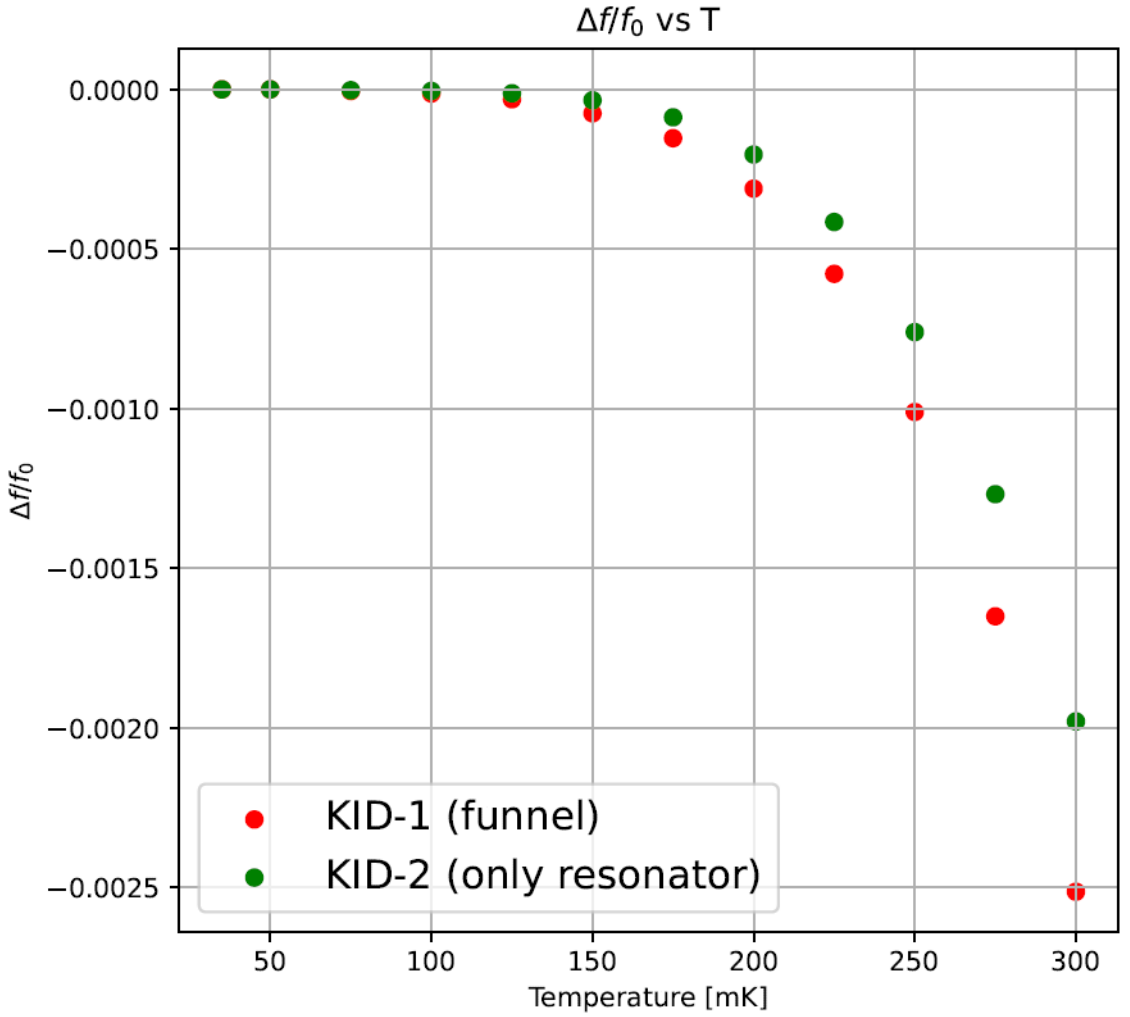
$$\frac{\left(\frac{d\phi}{dE}\right)_{11}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{7}^{NO_FUNNEL}} = 1.66 \pm 0.17$$

Temperature scan: MB theory

- With Mattis-Bardeen theory, α and Δ_0 measured from relative resonance frequency shift in temperature T

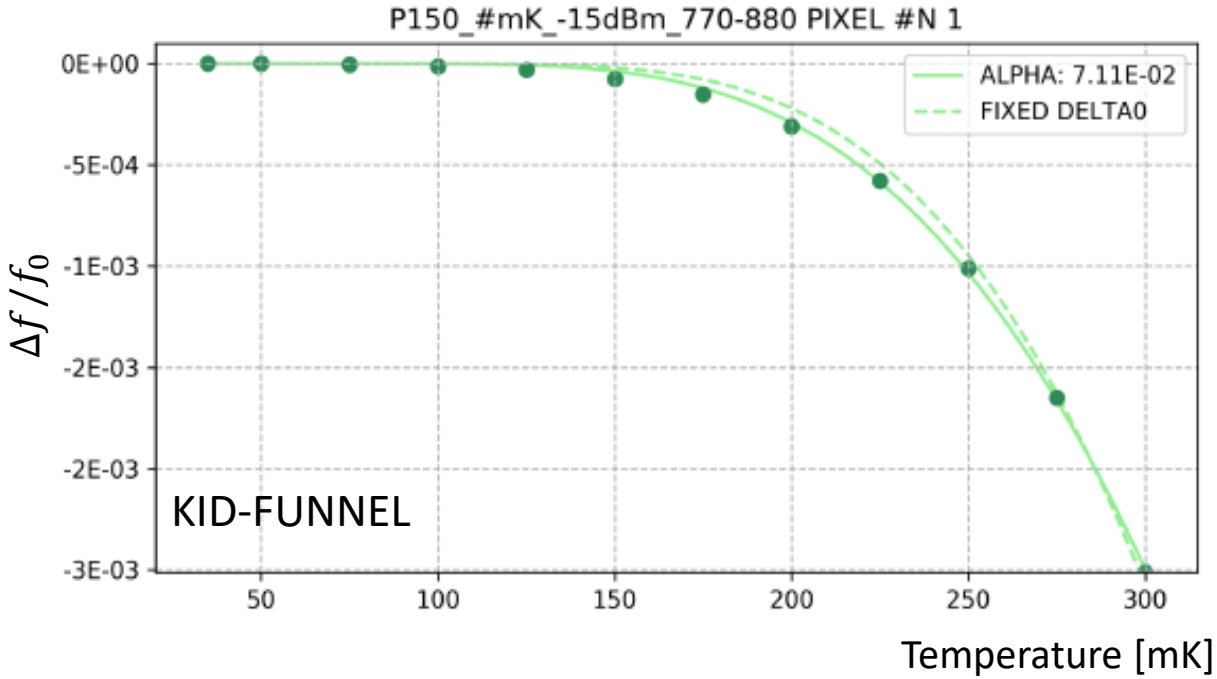
$$\frac{\Delta f\ (T)}{f_0(T)} = -\frac{\alpha}{2}\, S_2(\Delta_0, T)\, \frac{\delta n_{qp}(\Delta_0, T)}{\Delta(\Delta_0, T)}$$

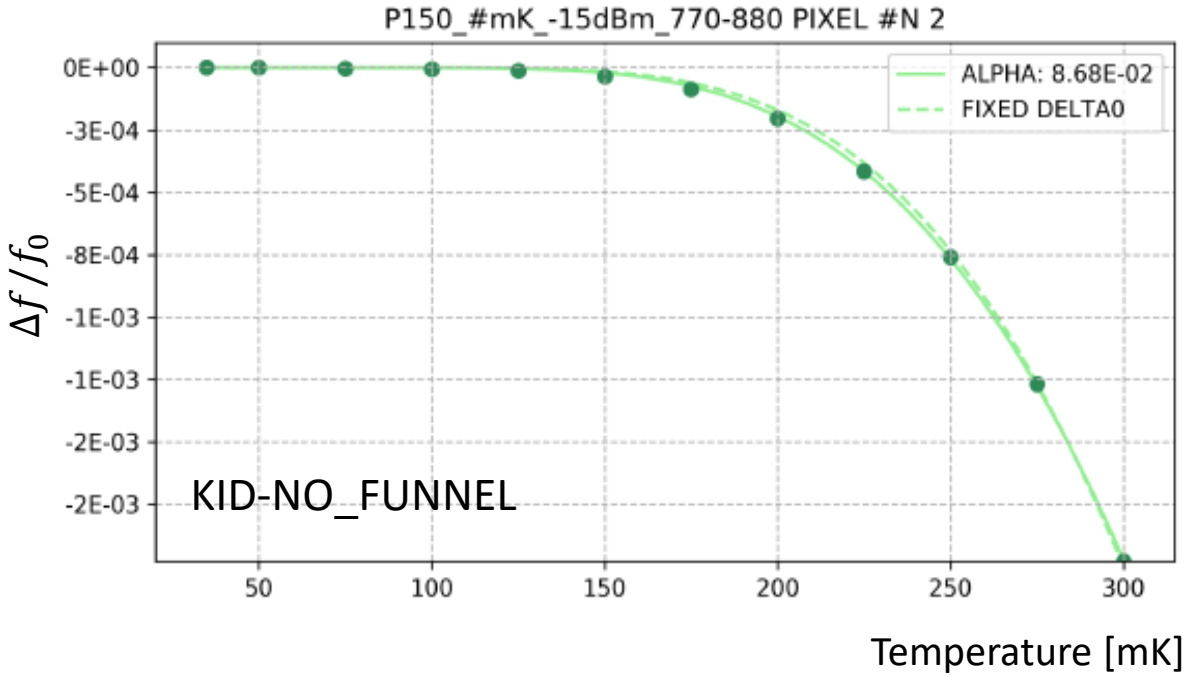
- $\Delta = \Delta_0 e^{-\sqrt{\frac{2\pi k_B T}{\Delta_0}}\, e^{-\frac{\Delta_0}{k_B T}}}$
- $\delta n_{qp} = \sqrt{2\pi k_B T} e^{-\Delta/k_B T}$
- $S_2 = 1 + \left[\sqrt{\frac{2\Delta_0}{\pi k_B T}}\, e^{-\frac{h f_0(T)}{2k_B T}}\right] J_0\left[\frac{h f_0(T)}{2k_B T}\right]$



Temperature scan: MB fit

$T_c \approx$ 815 mK measured → $\Delta_0 \approx 1.7 k_B T_c \approx 0.12$ meV





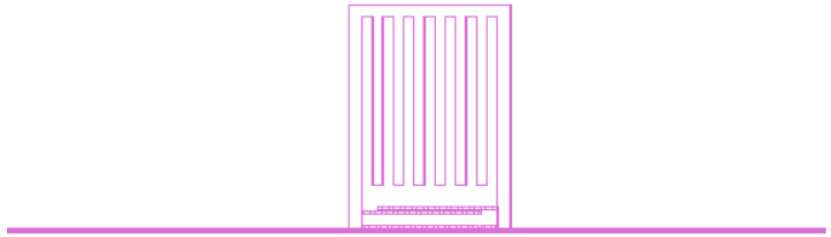
KID-FUNNEL	Δ_0 free	Δ_0 fixed
α [%]	6.28 ± 0.88	16.57 ± 0.33
Δ_0 [meV]	0.100 ± 0.002	≈ 0.12 meV

KID-NO_FUNNEL	Δ_0 free	Δ_0 fixed
α [%]	8.30 ± 0.52	12.99 ± 0.12
Δ_0 [meV]	0.110 ± 0.002	≈ 0.12 meV

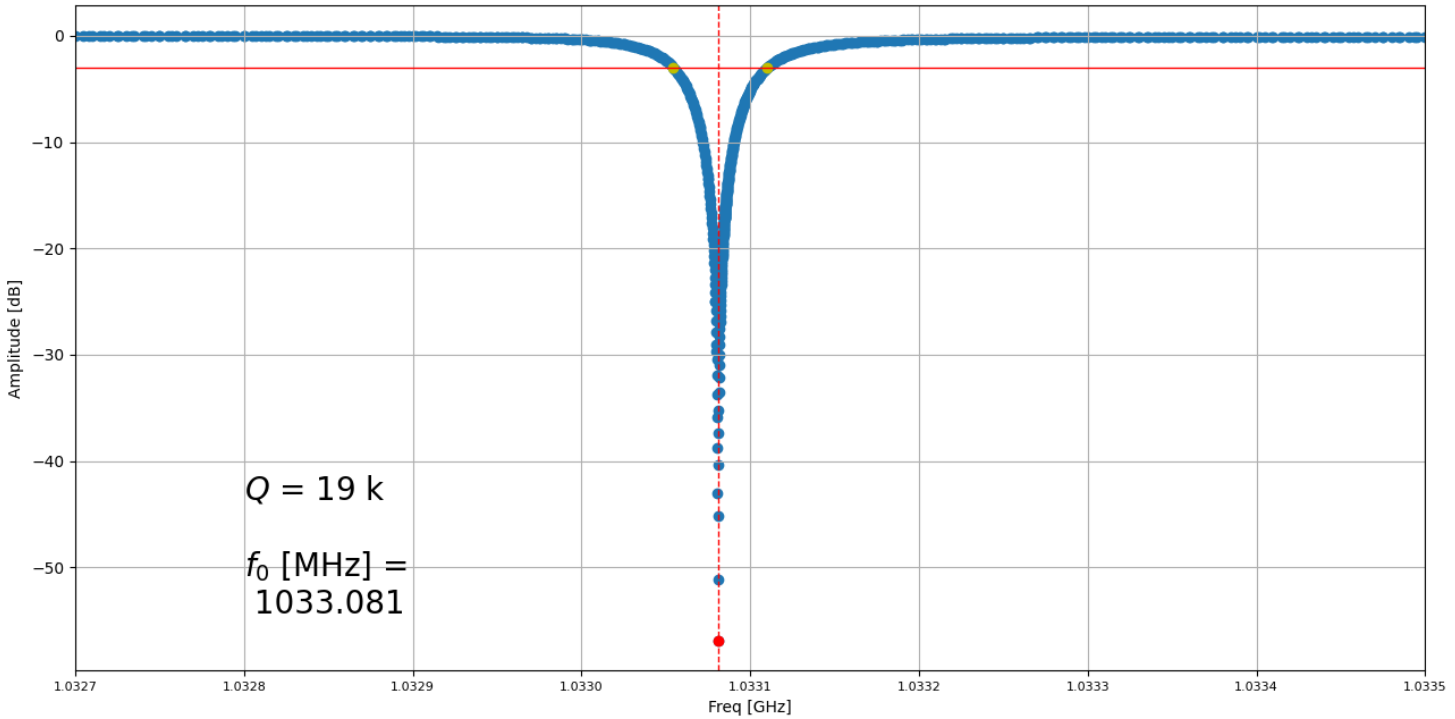
SONNET simulation: KID-NO_FUNNEL

- Experimental Q_c, f_0 and α reproduced.
- $L_k = 1.4$ pH/sq
- Most accurate simulation

$$\alpha = 1 - \left(\frac{f_0|_{L_k \neq 0}}{f_0|_{L_k = 0}}\right)^2$$

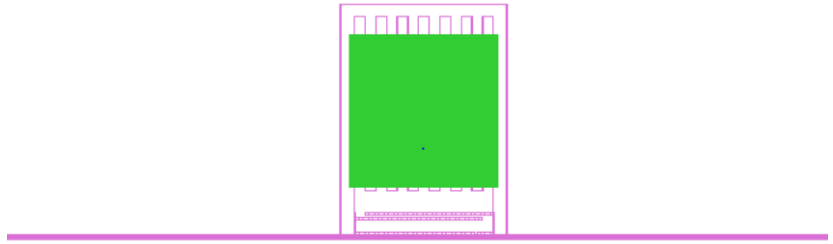


	SONNET	EXPERIMENT
f_0 [MHz]	1033.08	1031.96
Q_c	19k	23k
α [%]	14.53	6.22-16.57



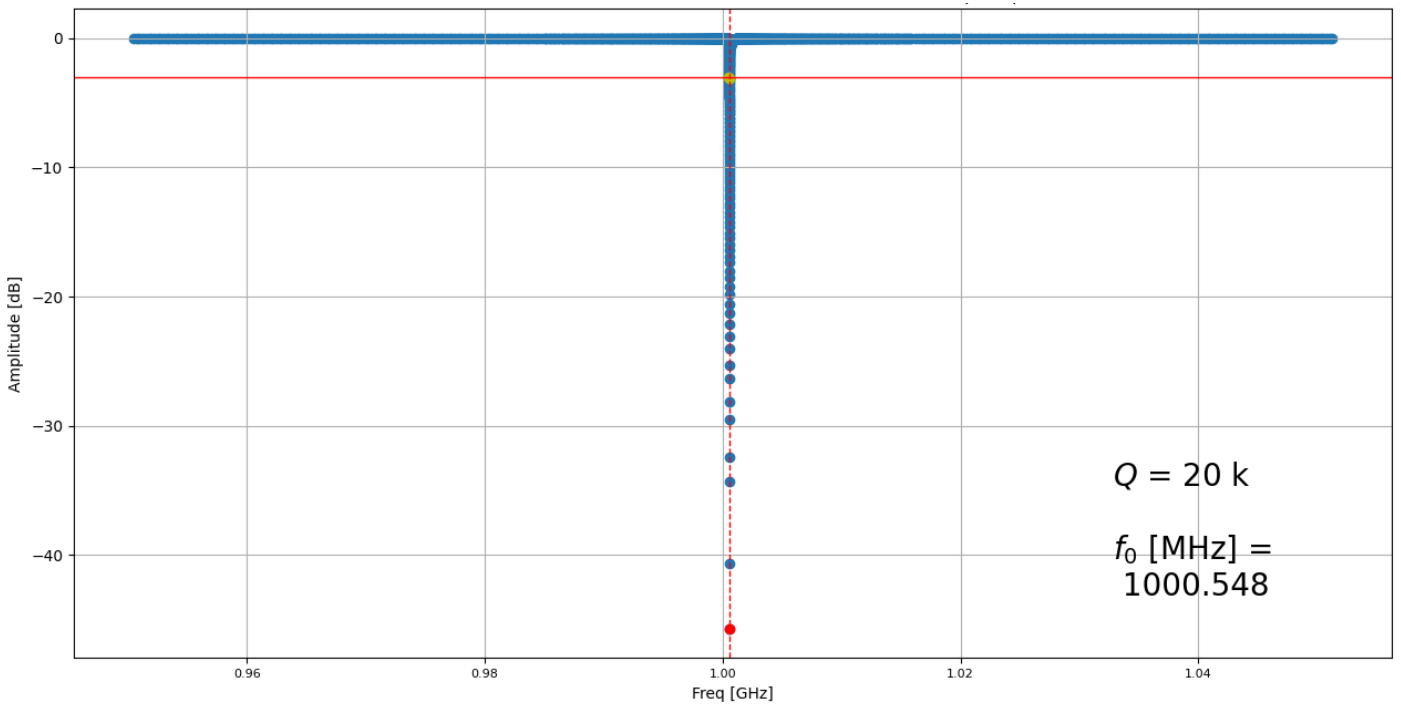
SONNET (preliminary) simulation: KID-FUNNEL

- $L_k = 1.4$ pH/sq (AlTiAl)
- $L_k = 0.33$ pH/sq (Al)
- Medium-fast simulation



$$\alpha = 1 - \left(\frac{f_0|_{L_k \neq 0}}{f_0|_{L_k = 0}}\right)^2$$

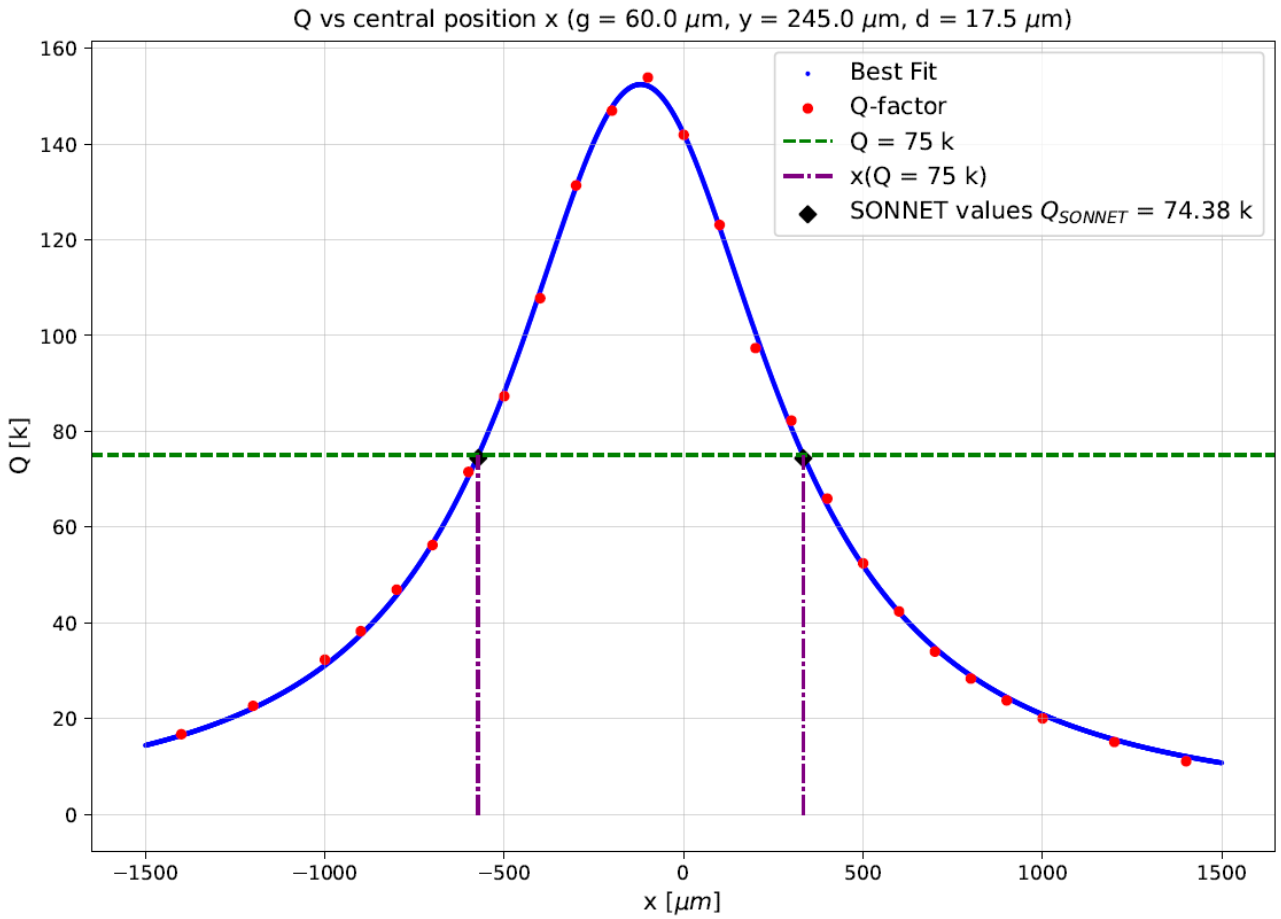
	SONNET	EXPERIMENT
f_0 [MHz]	1000.55	984.97
Q_c	20k	11k
α [%]	11.87	8.30-12.99

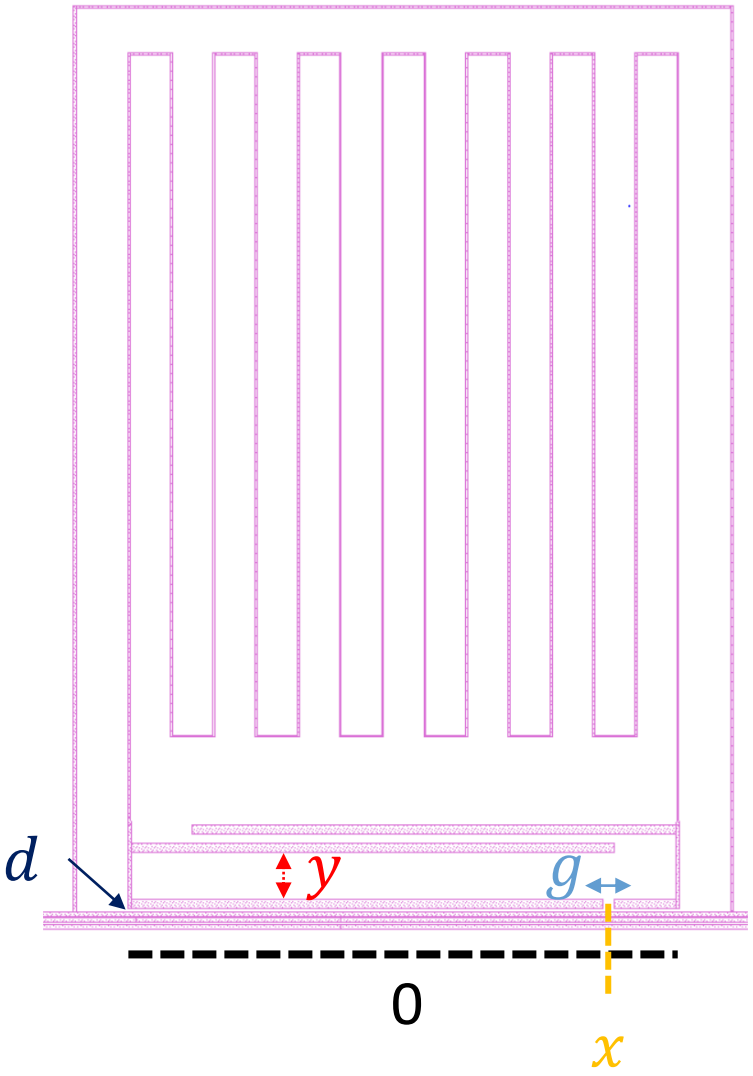


Next steps

SONNET simulation: Increasing Q_c

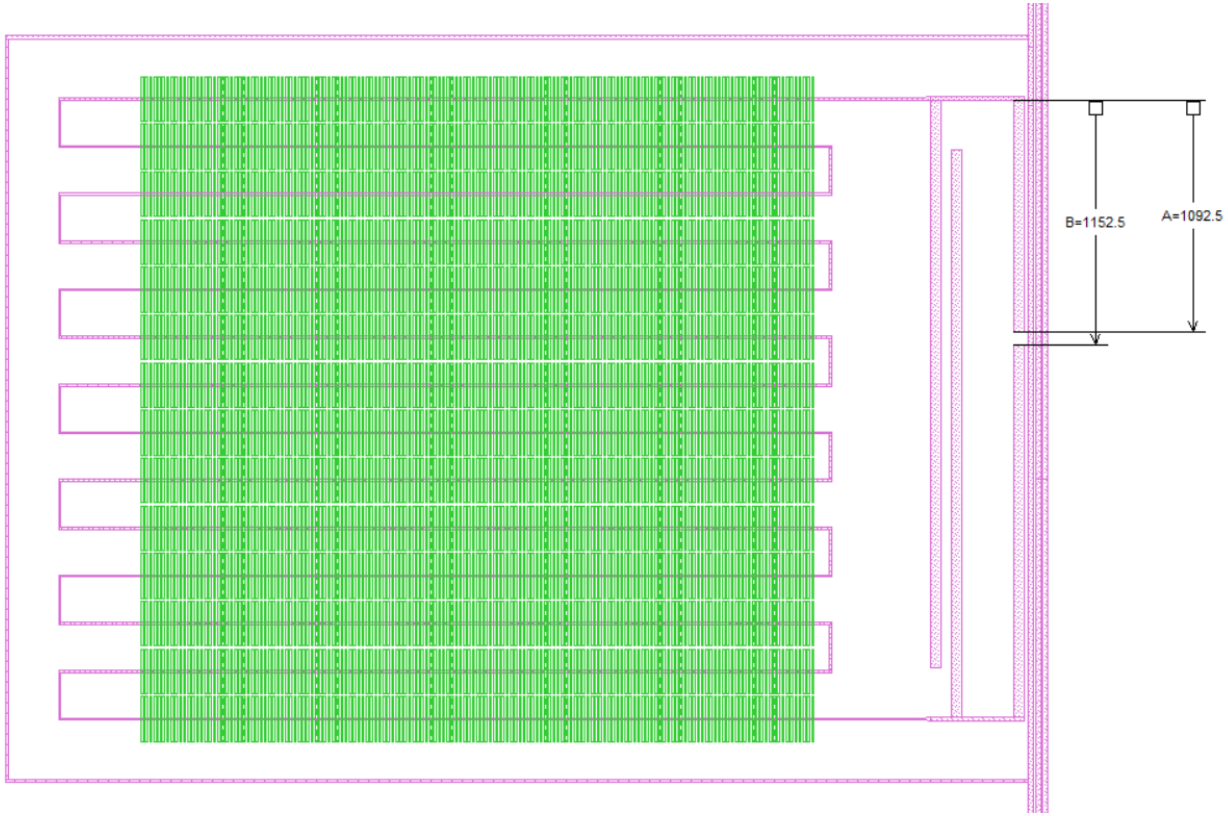
- Increasing $Q_c \sim 50 - 75\text{k}$ (more narrow resonances)



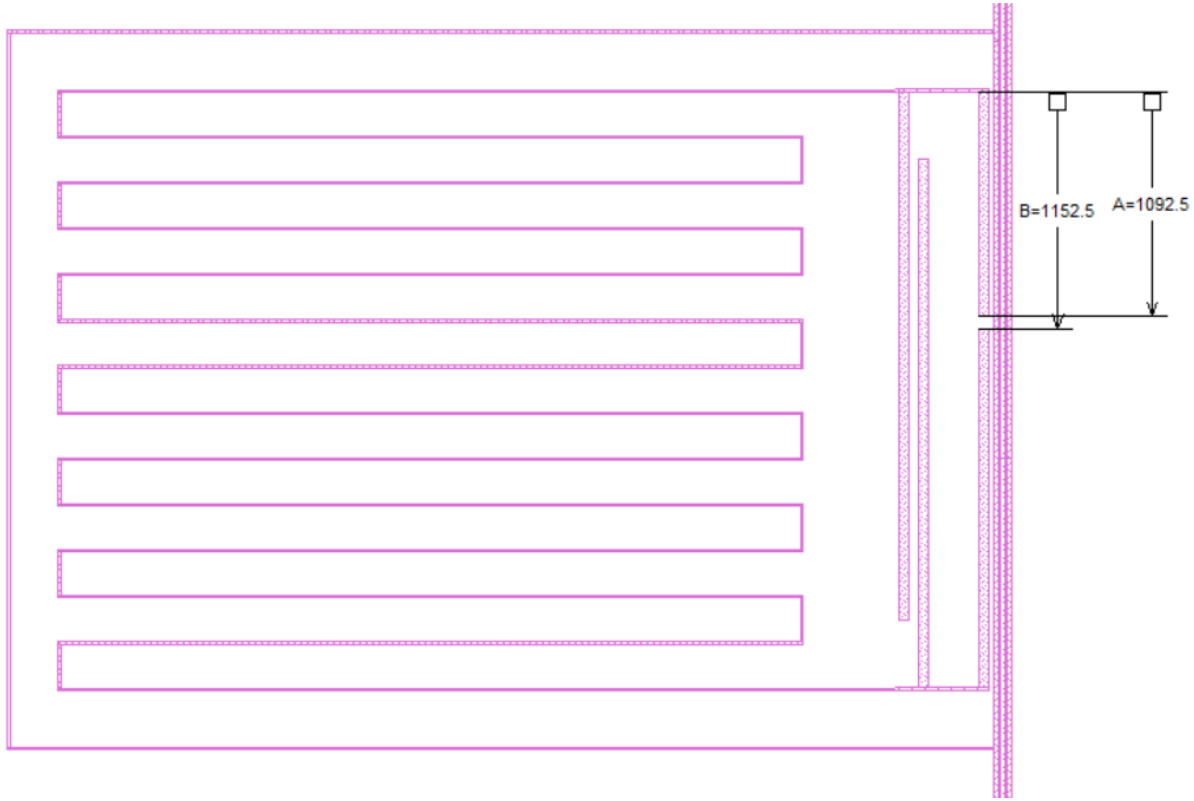


SONNET simulation: 75k Q resonator

- Preliminary results (simulation still running)



KID-FUNNEL



KID-NO_FUNNEL

Conclusions and perspectives

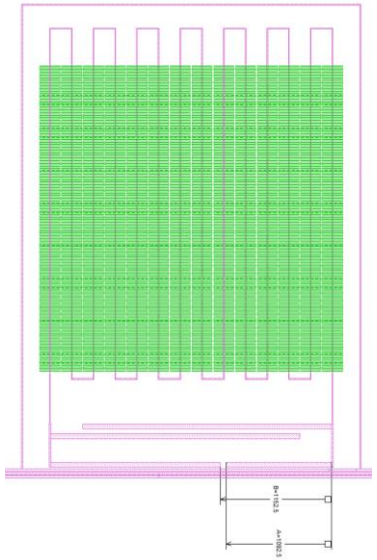
- What we saw:

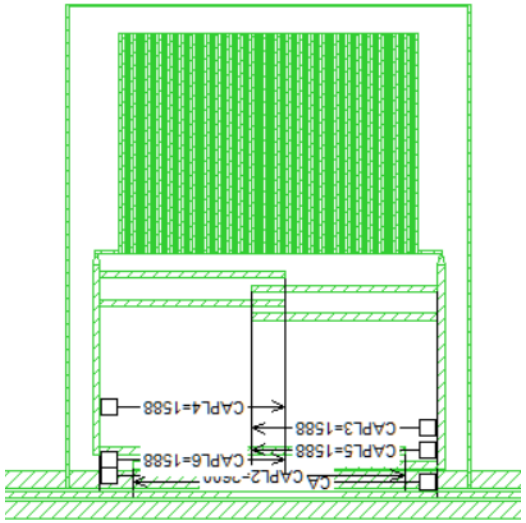
- KID-FUNNEL observed to have larger responsivity than KID-NO_FUNNEL
- Funnel resonator has better resolution at high power

→ Measurable and promising effects of funnels

- What should be next:

- Increasing Q_c
- Comparison between funnel-KID and BULLKID resonators



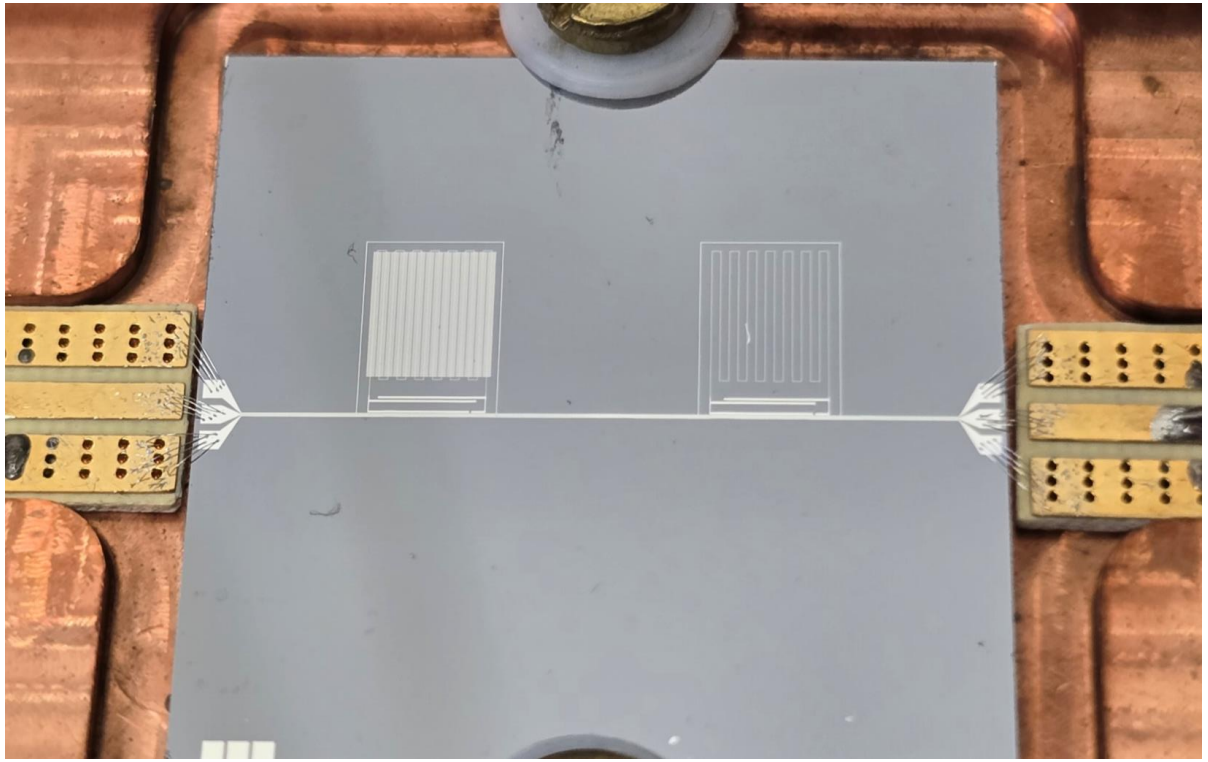


Thanks for the attention

BACK-UP SLIDES

Summary

1. Brief introduction to the concept of funnel and description of tested KIDs
2. KIDs characterization and analysis
3. (Preliminary) further simulation studies
4. Conclusions



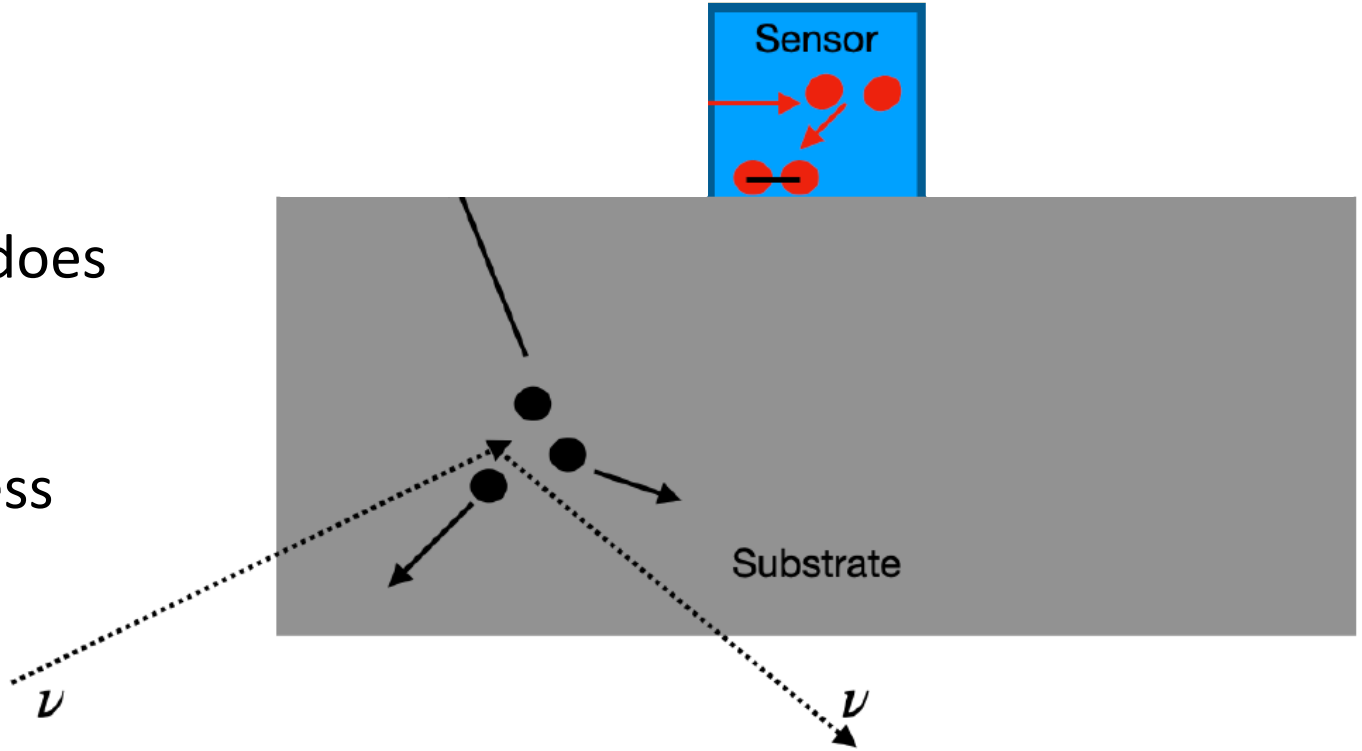
The concept of funnel (Ludovico De Santis's master thesis)

- Many outcomes arise if increasing arbitrarily V_{ph}:

1. Meisner effect: the sensitive volume does not increase with the thickness

2. Power output: larger power implies less KIDs on feed-line

3. Geometric inductance ($L_g \propto V$): multiplexing is limited



Energy resolution with funnels (Ludovico De Santis's master thesis)

Single KID energy resolution

$$\sigma_E \propto \frac{\Delta}{\eta}\sqrt{\frac{V}{\alpha}}$$

Total superconducting (SC) volume

Contact area between resonator and substrate

$$\eta = \eta_{geo}\eta_{ph} \propto \frac{A_{ph}}{A_{sub}}\eta_{ph} \propto \frac{V_{ph}}{V_{sub}}\eta_{ph} \dashrightarrow \sigma_E \propto \frac{\Delta}{V_{ph}\eta_{ph}}\sqrt{\frac{V}{\alpha}}V_{sub}$$

Phonon absorption efficiency

Total substrate area

- $V = V_{ph} = V_{sub} \rightarrow \sigma_E \propto 1/\sqrt{V}$ (no funnel)
- $V \neq V_{ph} \rightarrow \sigma_E \propto \sqrt{V_{KID}}/V_{ph}$ (funnel)

Figure Of Merit FOM (Ludovico De Santis's master thesis)

- Ratio between the energy resolution of KIDs with and without funnels

"Usual" phonon to QP conversion efficiencies ratio

Geometric contribution (contact area with funnels over total area)

$$FOM = \frac{\eta^{abs,f}}{\eta^{abs,s}} \eta_{abs} \frac{\eta_{ph}^{c}}{\eta_{ph}} \frac{\Delta}{\Delta_c} \frac{A_c^f}{A} \sqrt{\frac{\alpha_c}{\alpha} \frac{V}{V_c^s} \frac{\chi_{BW}^{funnel}}{\chi_{BW}}}$$

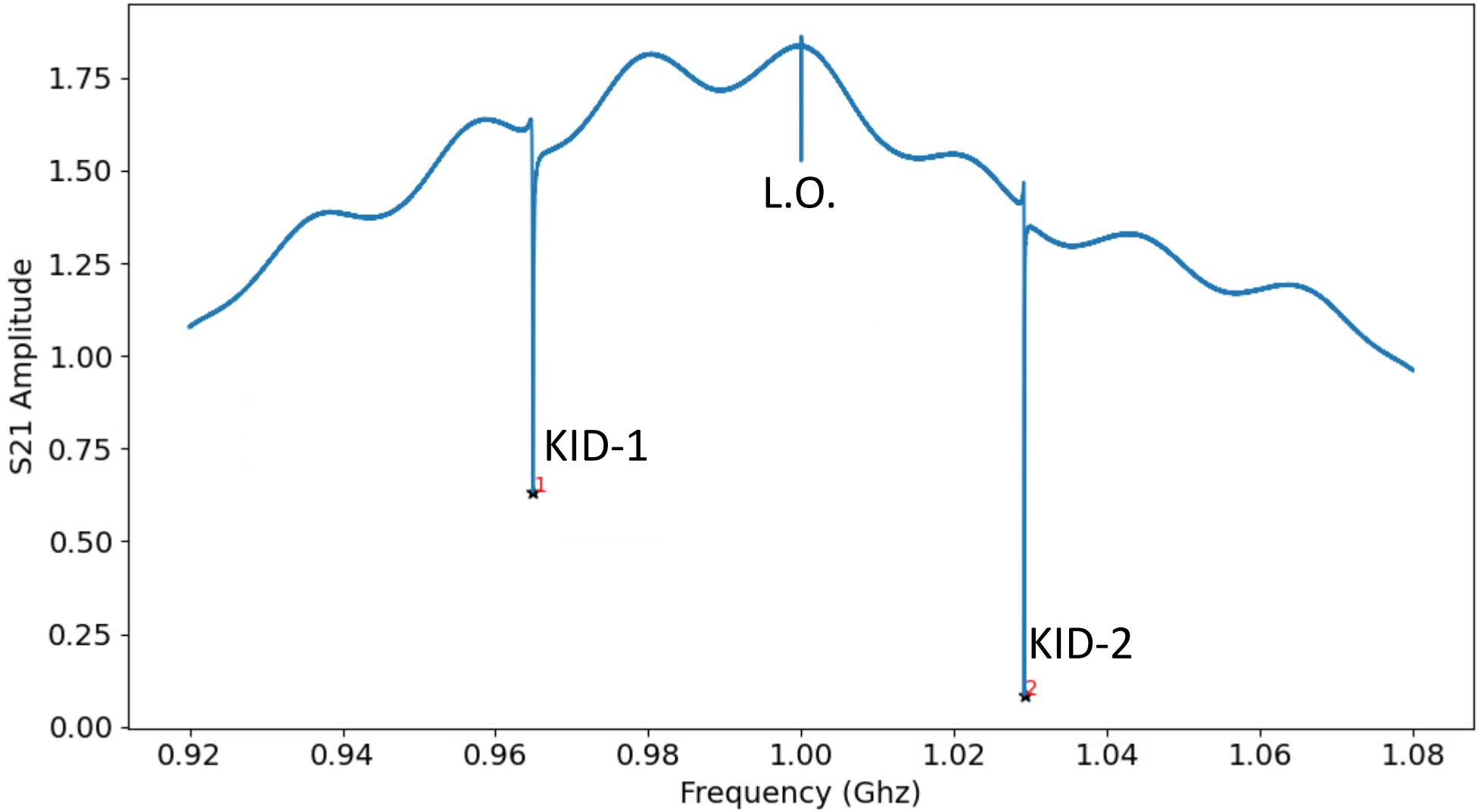
Phonon absorption efficiencies ratio

QP absorption efficiency (≈ 1 without funnels)

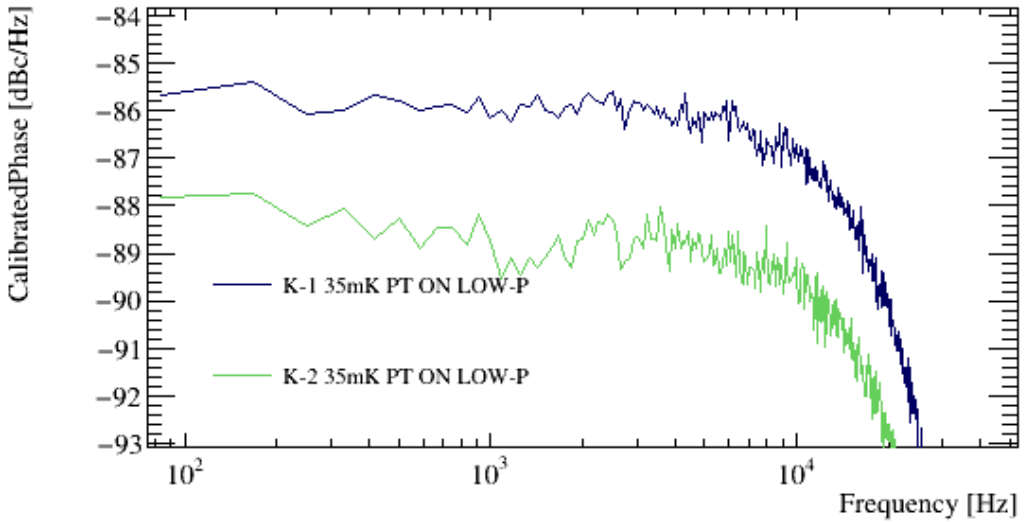
Sensor volume

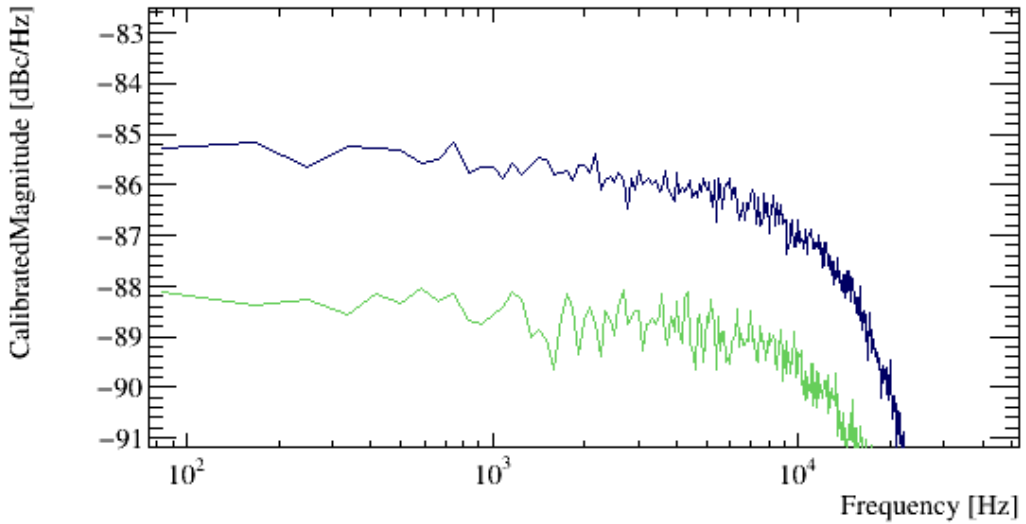
- Deeper studies for AlTiAl feed-line and Al funnels parameters currently carried out

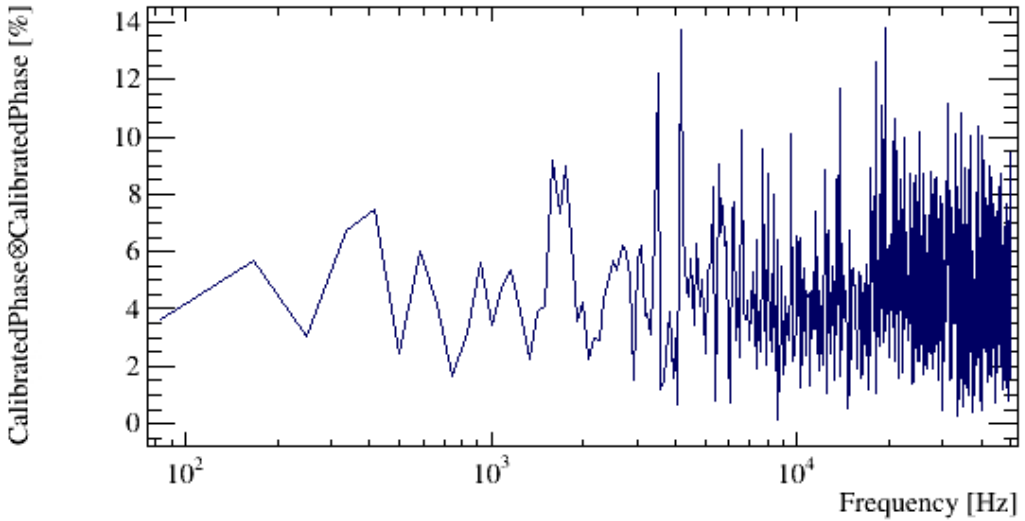
P150: VNA scan

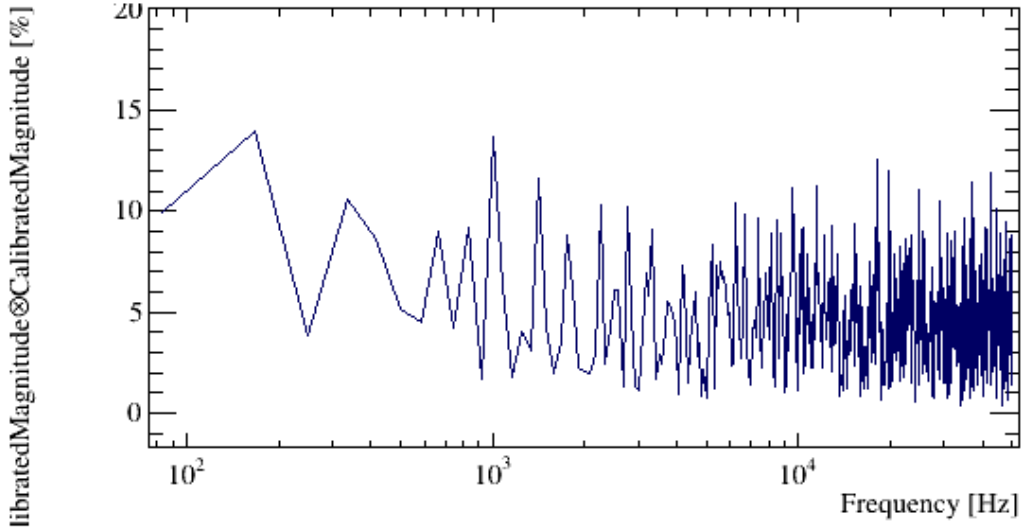


Noise power spectrum - Low power (-21 dBm)

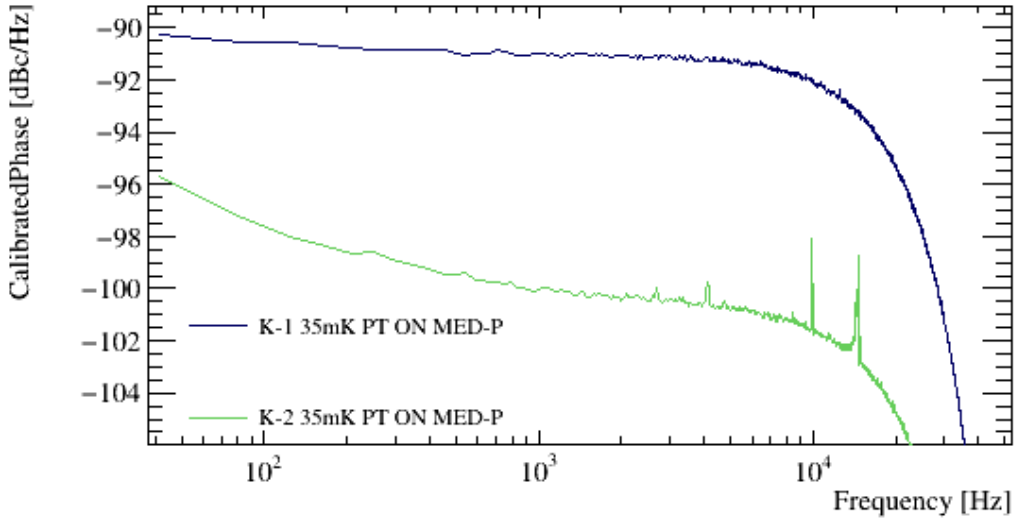


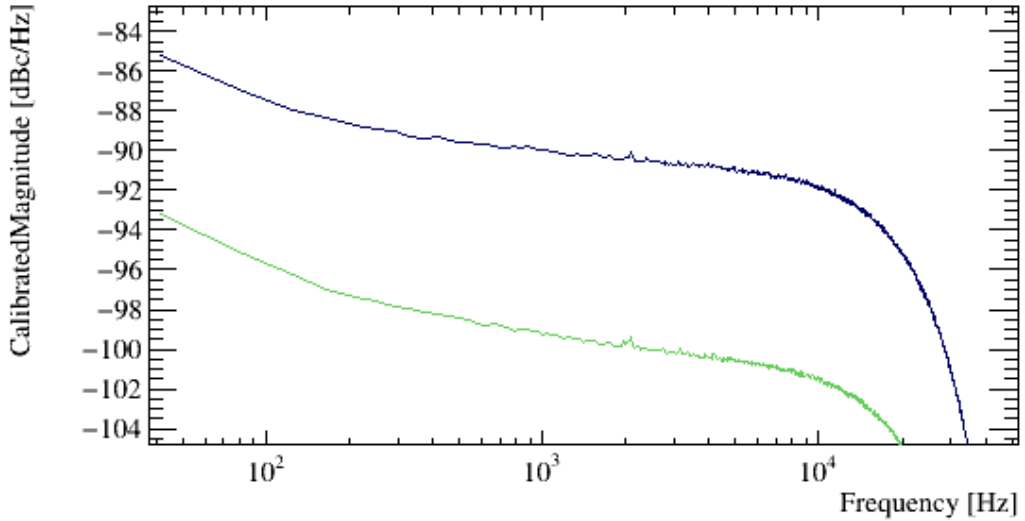


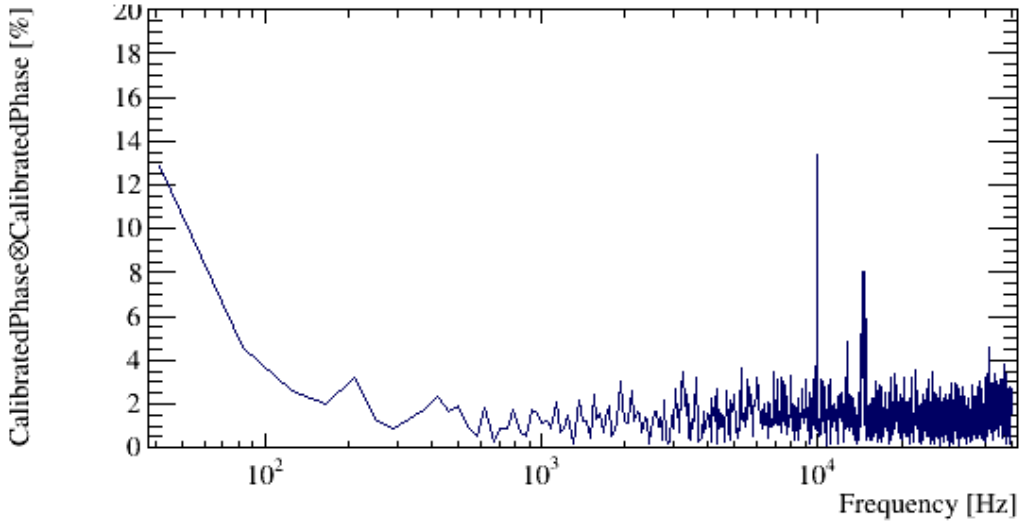


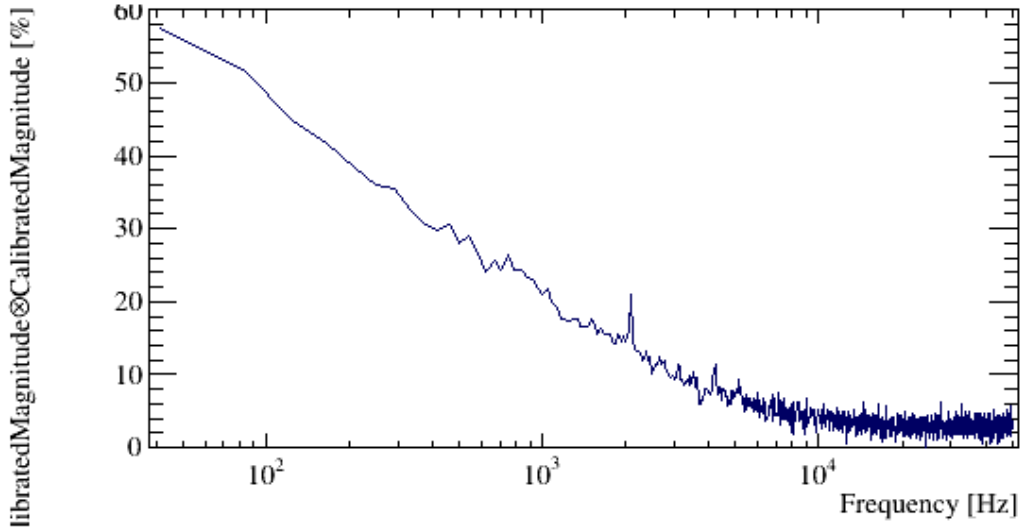


Noise power spectrum - Medium power (-16,-9 dBm)

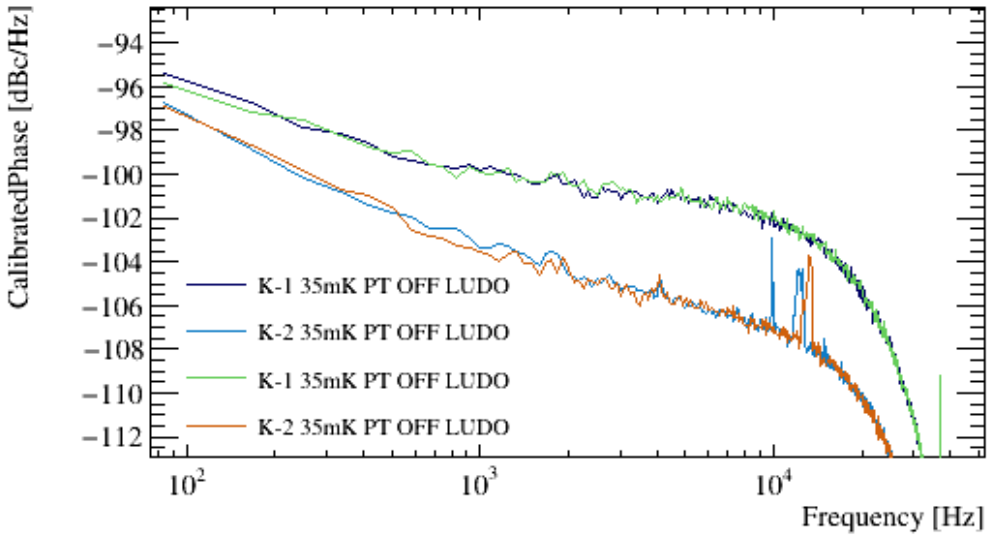


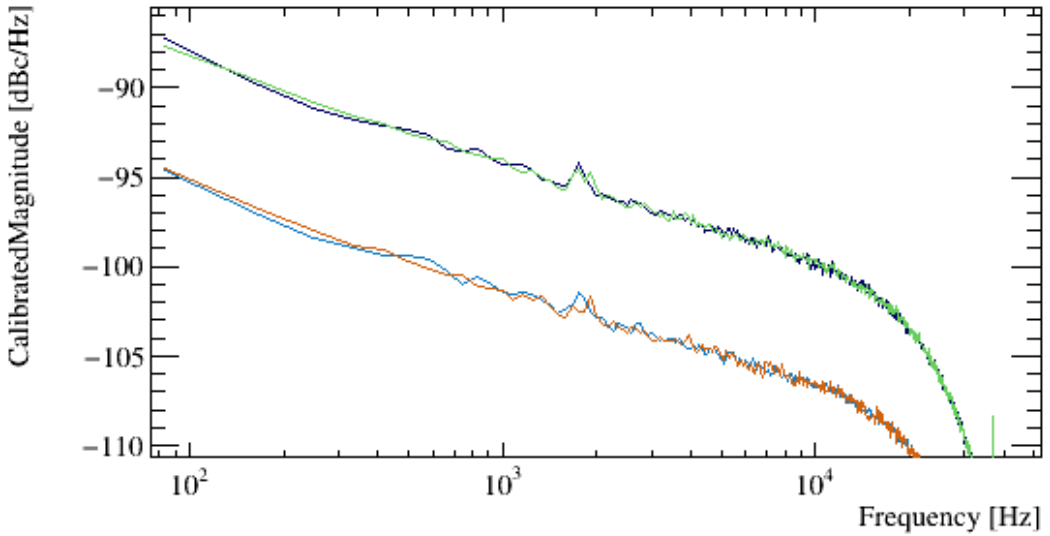


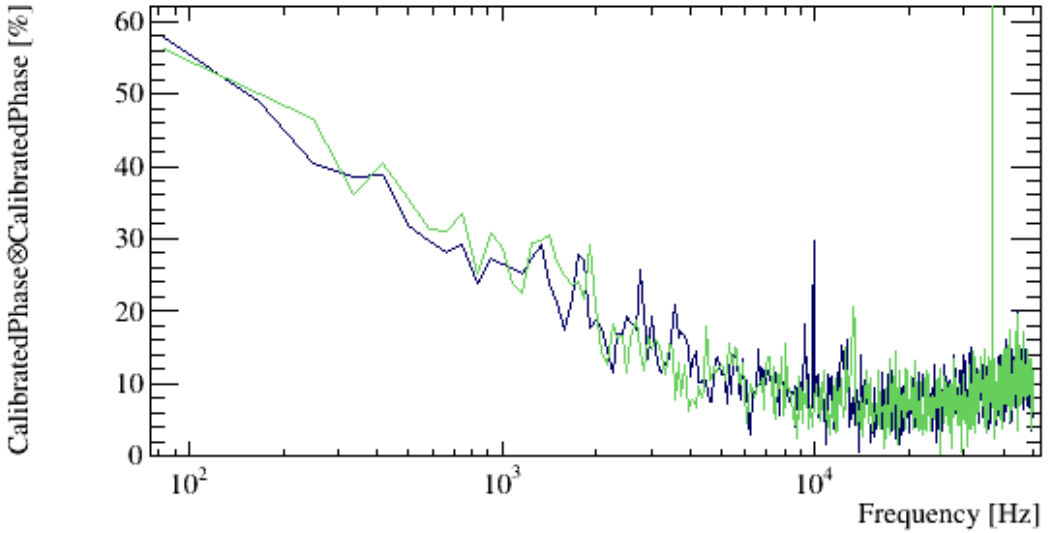


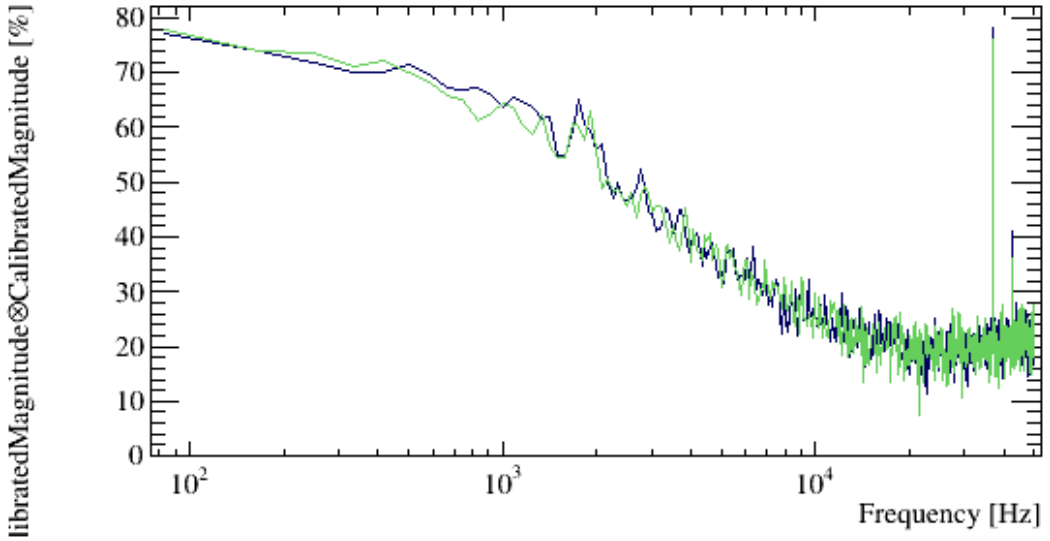


Noise power spectrum - High power (-6,-3 dBm)

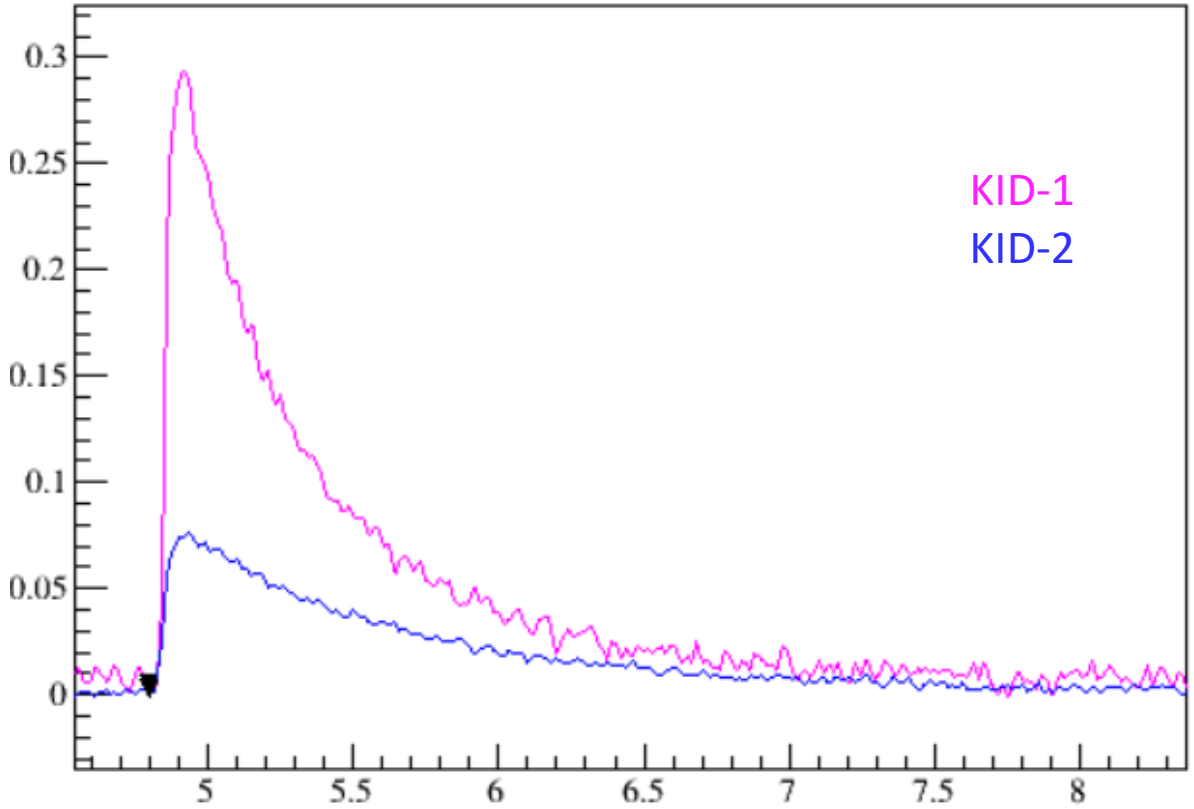


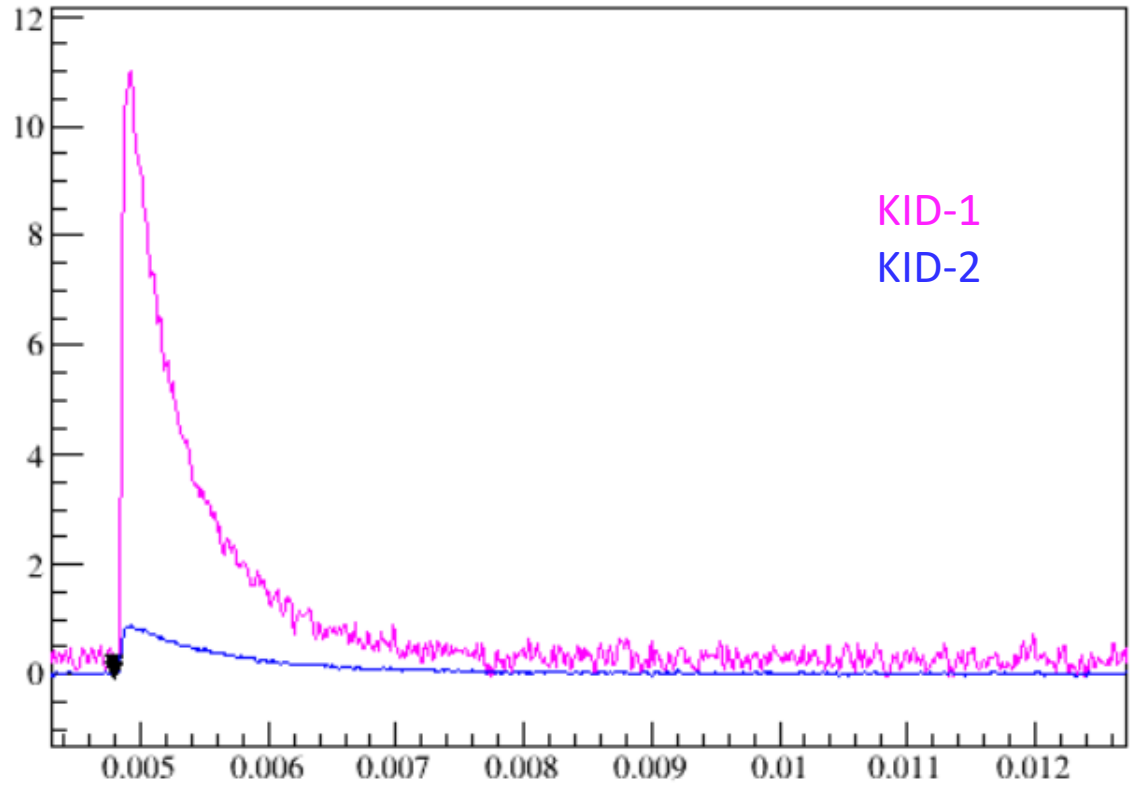






F13 Calibration: Medium power





$(\Delta\phi)_1 / (\Delta\phi)_2 \approx 3.75$ → $(\Delta f)_1 / (\Delta f)_2 \approx 13.75$

$\frac{Q_1}{Q_2} \approx 3.67$

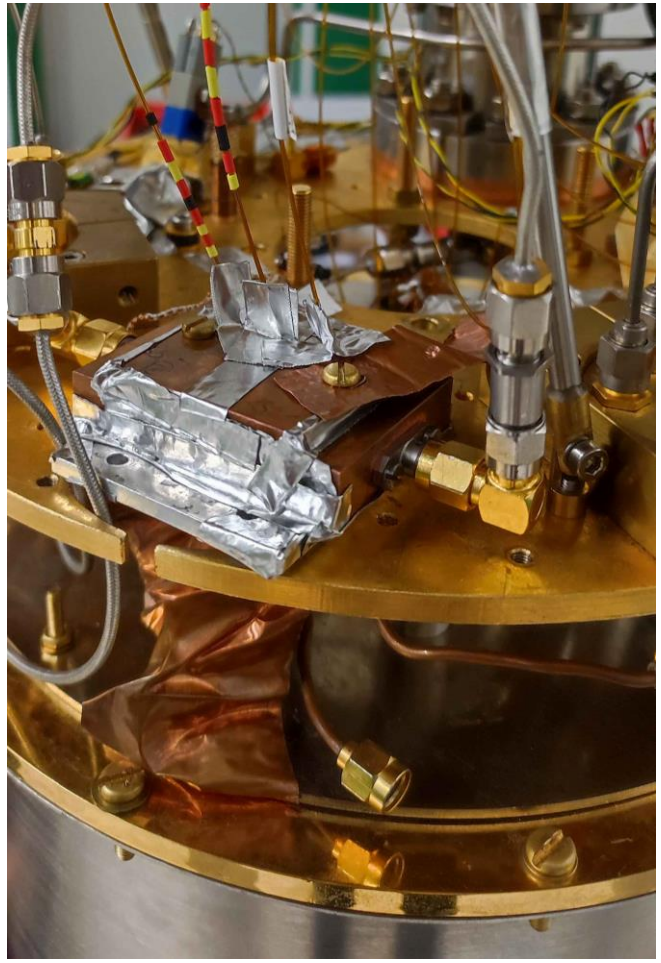
Optical Calibration

- Calibration based on Poisson statistics.
- Photons shotted against KIDs with different energies
- For each energy, pulses distribution described by Gaussian m and σ .

$$\sigma = \sqrt{m \times r + \sigma_0^2}$$

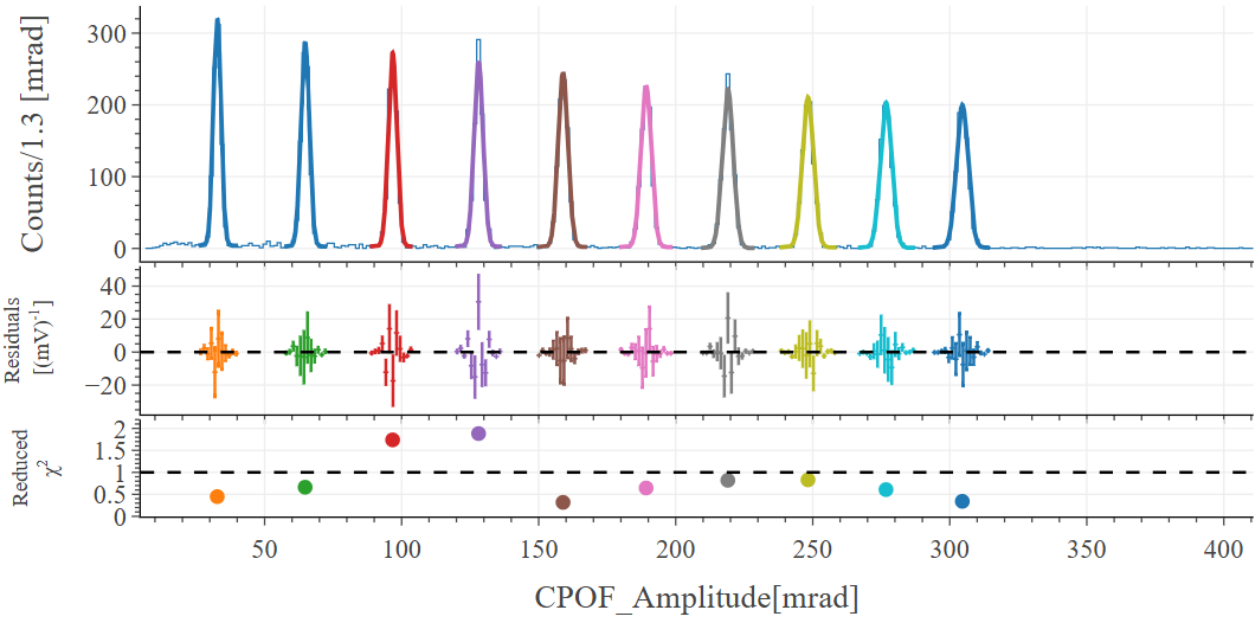
$$N_{ph} = \frac{m}{r} \rightarrow \sigma_{ph} = \sqrt{N_{ph}} \times r$$

Baseline resolution

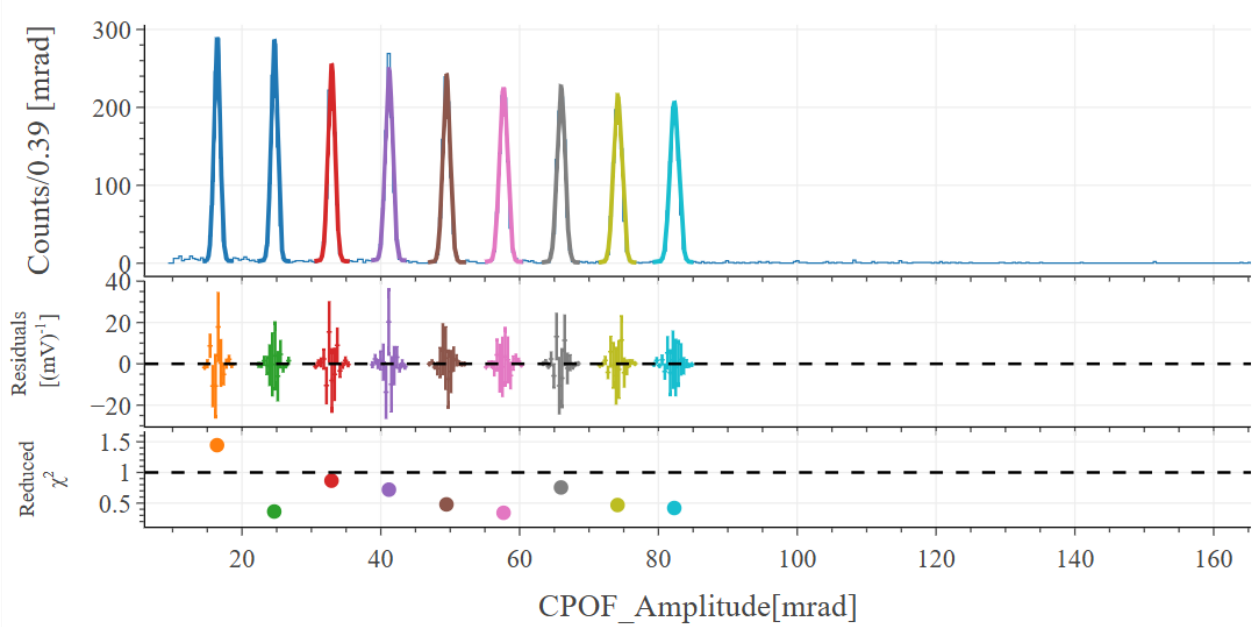


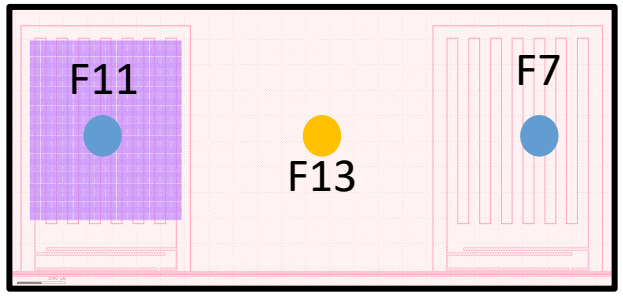
Optical Calibration (F13-Medium power)

KID-1



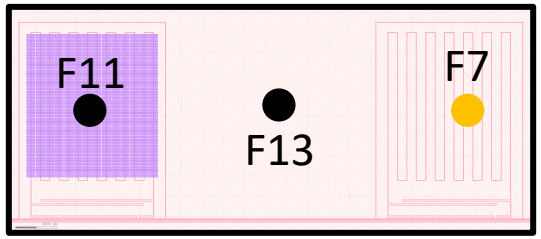
KID-2





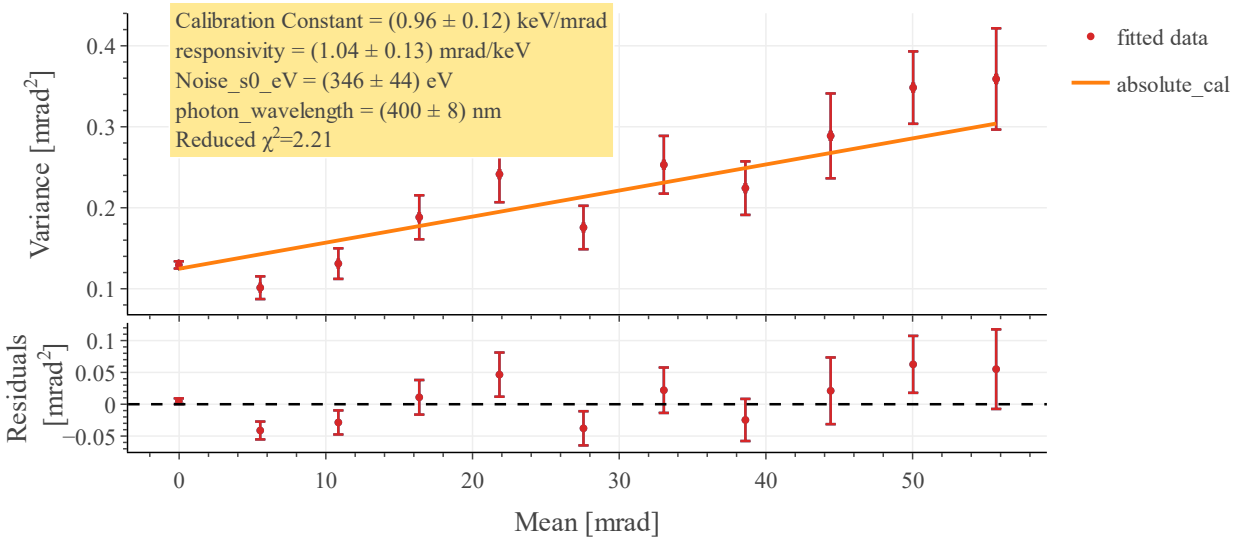
Optical Calibration (F7-High power)

KID-FUNNEL

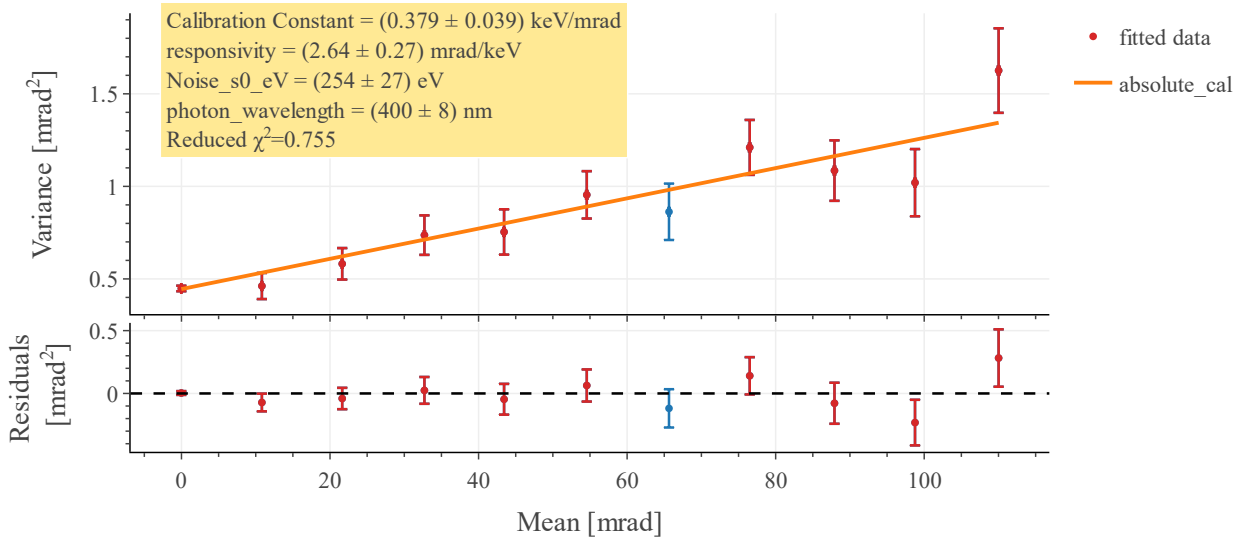


KID-NO_FUNNEL

Channel 2



Channel 1



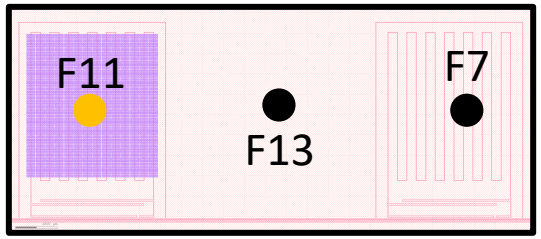
$$\left(\frac{d\phi}{dE}\right)_7^{FUNNEL} = (1.04 \pm 0.13)\ \text{mrad/keV}$$

$$\left(\frac{d\phi}{dE}\right)_7^{NO_FUNNEL} = (2.64 \pm 0.27)\ \text{mrad/keV}$$

$$\sigma_{0,7}^{FUNNEL} = (346 \pm 44)\ \text{eV}$$

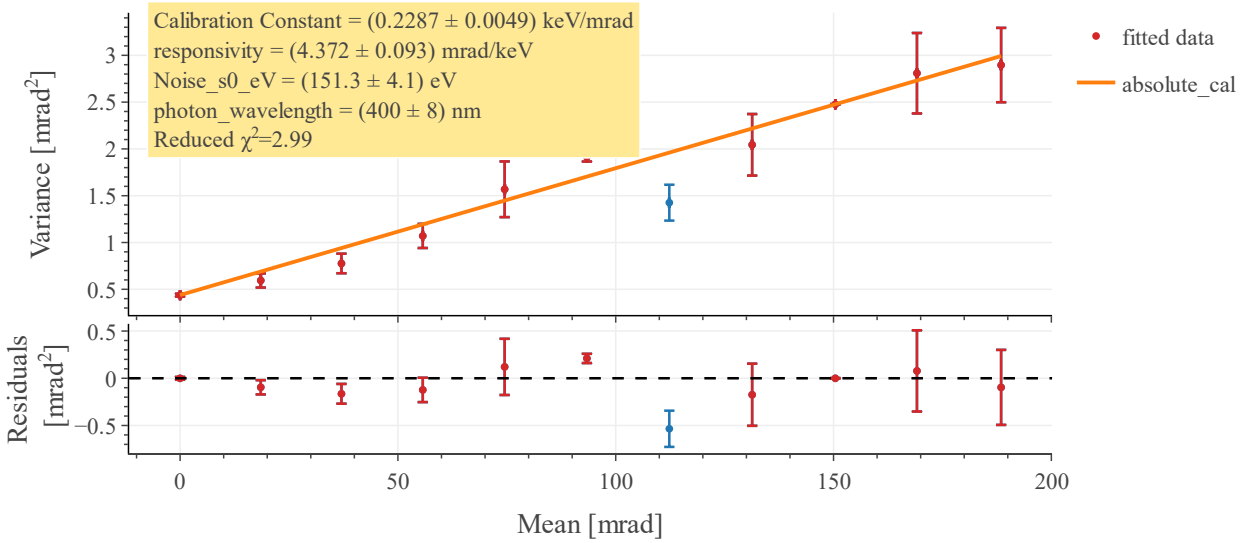
$$\sigma_{0,7}^{FUNNEL} = (254 \pm 27)\ \text{eV}$$

Optical Calibration (F11-High power)



KID-FUNNEL

Channel 1

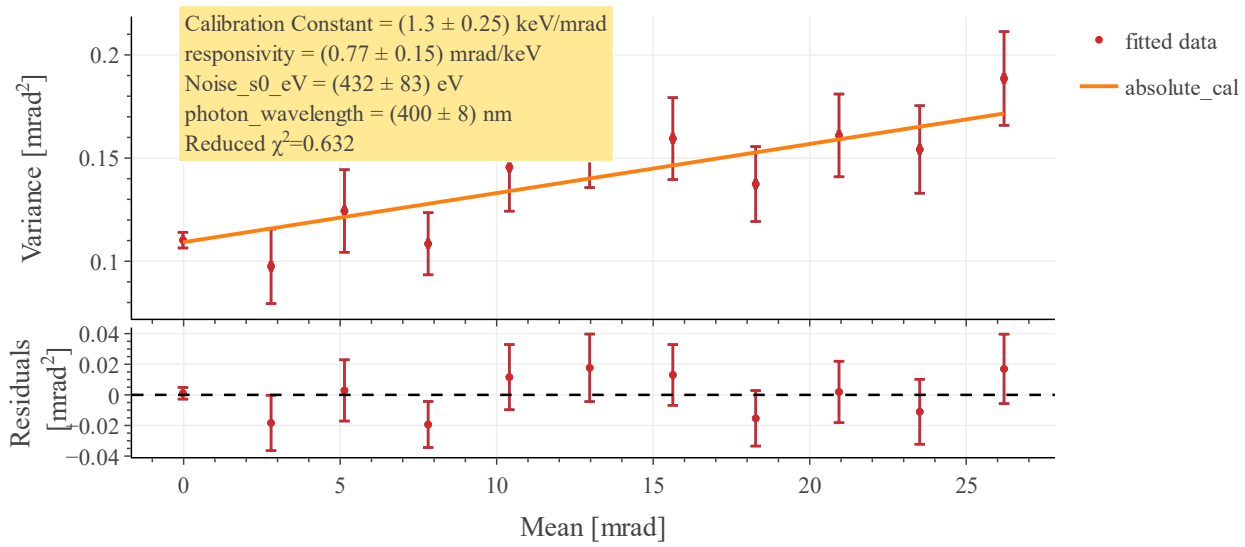


$$\left(\frac{d\phi}{dE}\right)_{11}^{FUNNEL} = (4.37 \pm 0.09)\ \text{mrad/keV}$$

$$\sigma_{0,11}^{FUNNEL} = (151.3 \pm 4.1)\ \text{eV}$$

KID-NO_FUNNEL

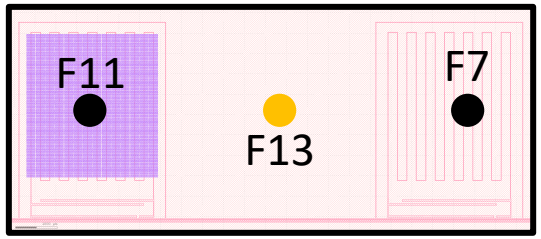
Channel 2



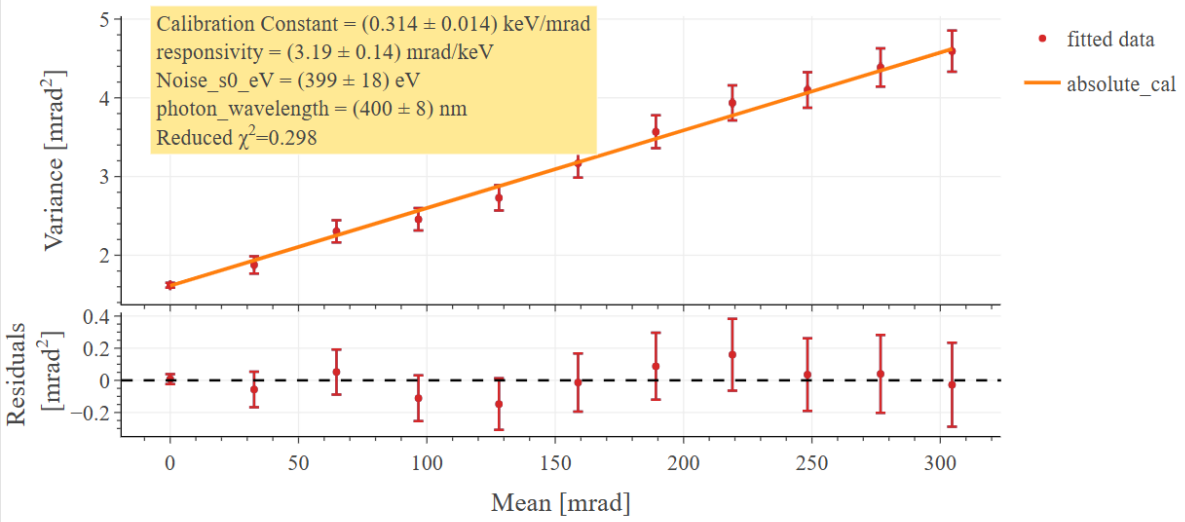
$$\left(\frac{d\phi}{dE}\right)_{11}^{NO_FUNNEL} = (0.77 \pm 0.15)\ \text{mrad/keV}$$

$$\sigma_{0,11}^{FUNNEL} = (432 \pm 83)\ \text{eV}$$

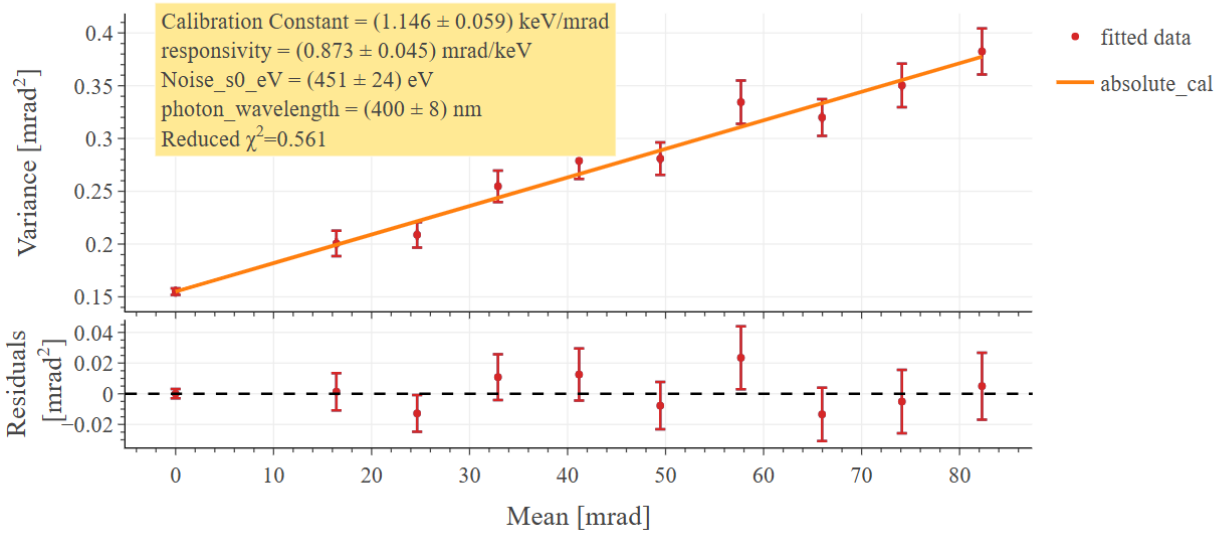
Optical Calibration (F13-Medium power)



Channel 1



Channel 2



$$\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL} = (3.19 \pm 0.14)\ \text{mrad/keV}$$

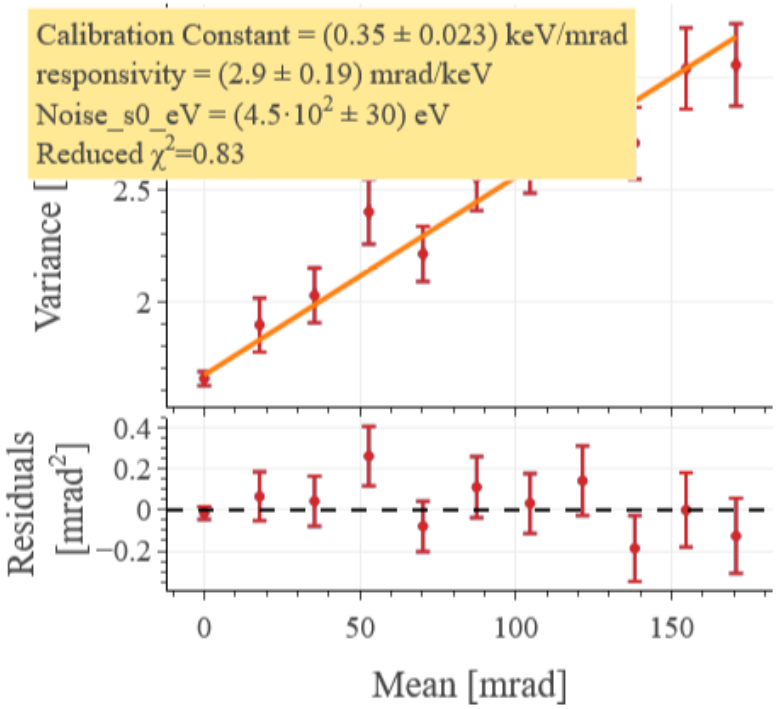
$$\sigma_{0,13}^{FUNNEL} = (399 \pm 18)\ \text{eV}$$

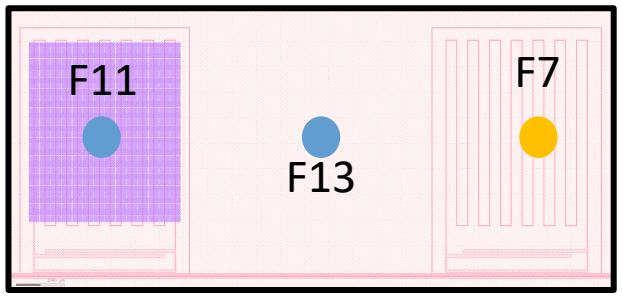
$$\left(\frac{d\phi}{dE}\right)_{13}^{NO_FUNNEL} = (0.87 \pm 0.04)\ \text{mrad/keV}$$

$$\sigma_{0,13}^{NO_FUNNEL} = (451 \pm 24)\ \text{eV}$$

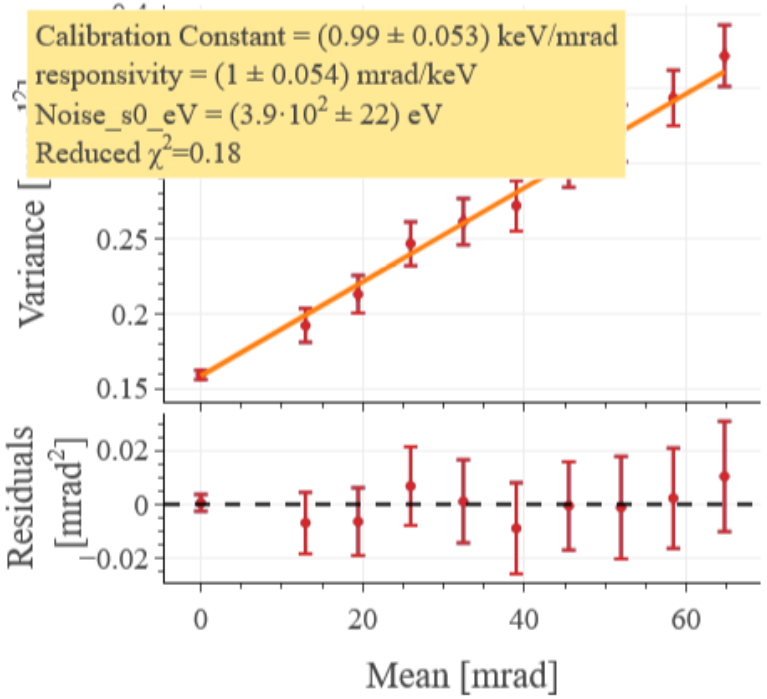
Optical Calibration (F7-Medium power)

KID-FUNN





KID-NO_F



$$\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL} = (2.90 \pm 0.19)\ \text{mrad/keV}$$

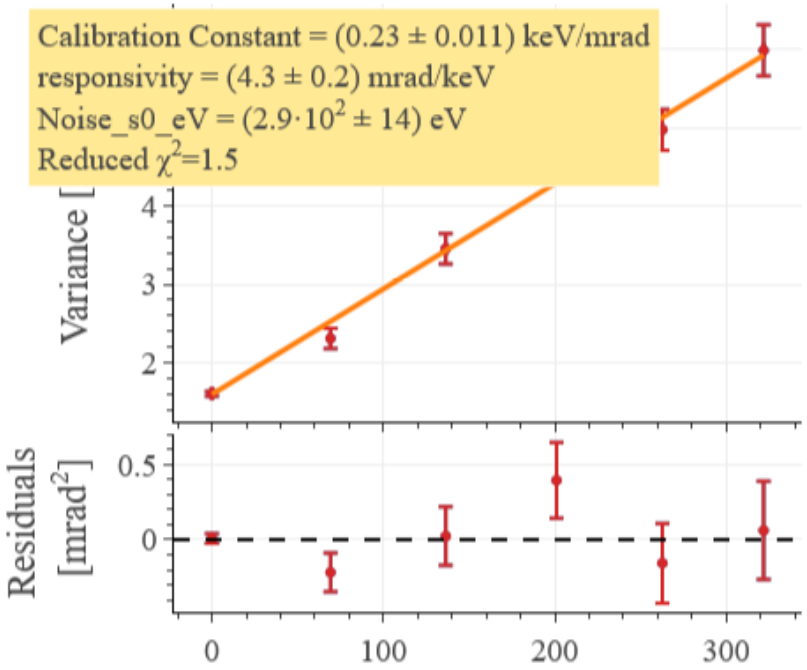
$$\left(\frac{d\phi}{dE}\right)_{13}^{NO_FUNNEL} = (1.00 \pm 0.05)\ \text{mrad/keV}$$

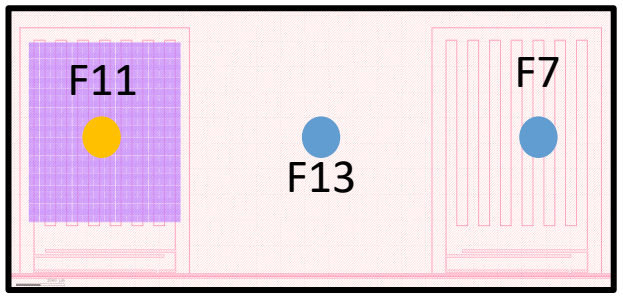
$$\sigma_{0,13}^{FUNNEL} = (450 \pm 30)\ \text{eV}$$

$$\sigma_{0,13}^{NO_FUNNEL} = (390 \pm 22)\ \text{eV}$$

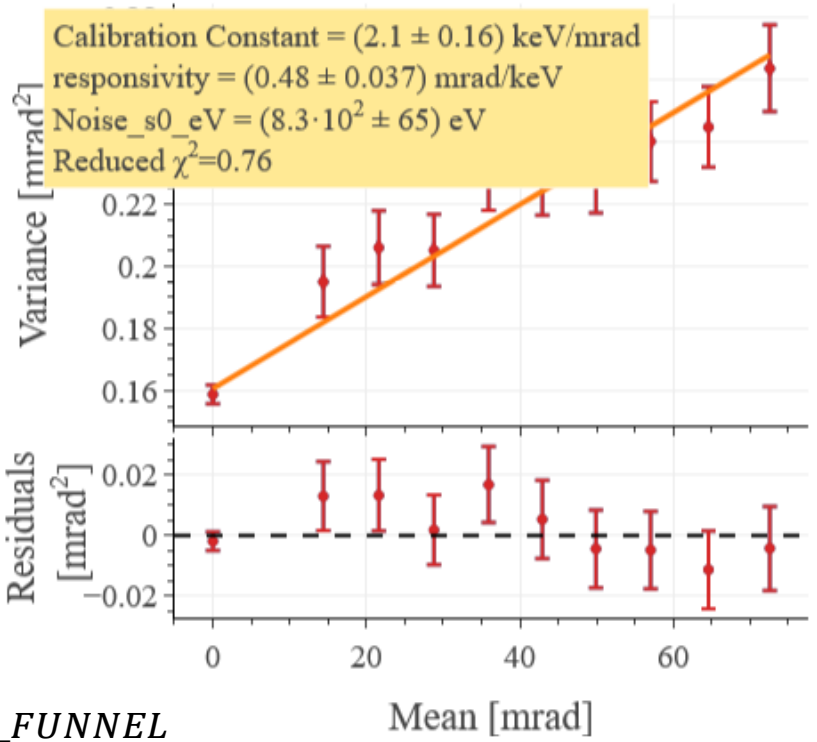
Optical Calibration (F11-Medium power)

KID-1





KID-2



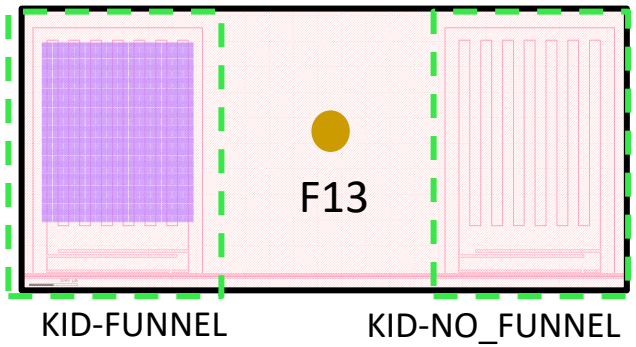
$$\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL} = (4.30 \pm 0.20)\ \text{mrad/keV}$$

$$\left(\frac{d\phi}{dE}\right)_{13}^{NO_FUNNEL} = (0.48 \pm 0.04)\ \text{mrad/keV}$$

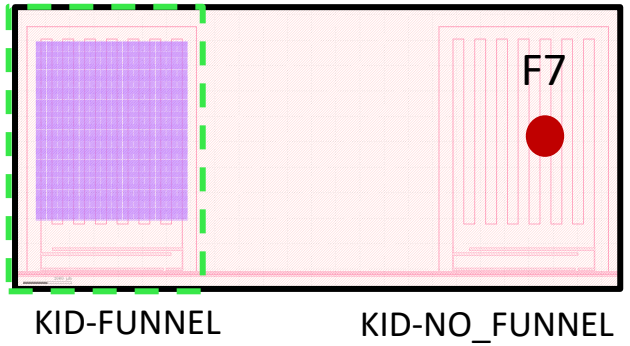
$$\sigma_{0,13}^{FUNNEL} = (290 \pm 14)\ \text{eV}$$

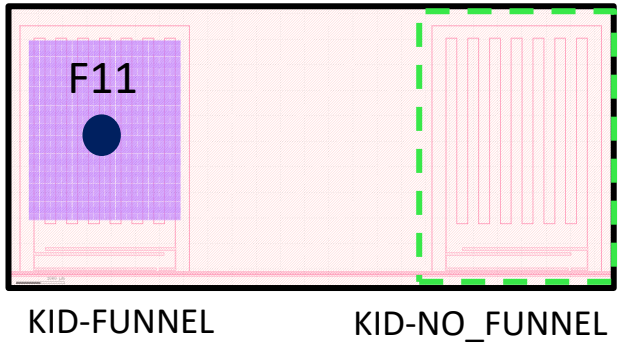
$$\sigma_{0,13}^{NO_FUNNEL} = (830 \pm 65)\ \text{eV}$$

Optical Calibration: medium power responsivities

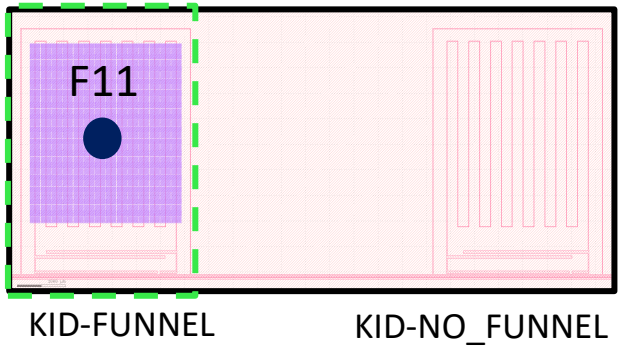


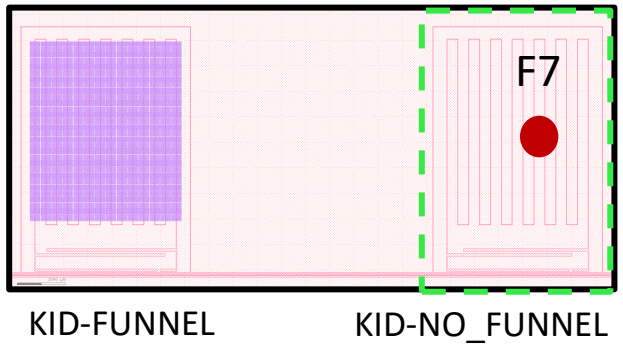
$$\frac{\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{13}^{NO_FUNNEL}} = 3.67 \pm 0.23$$





$$\frac{\left(\frac{d\phi}{dE}\right)_{7}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{11}^{NO_FUNNEL}} = 6.04 \pm 0.61$$

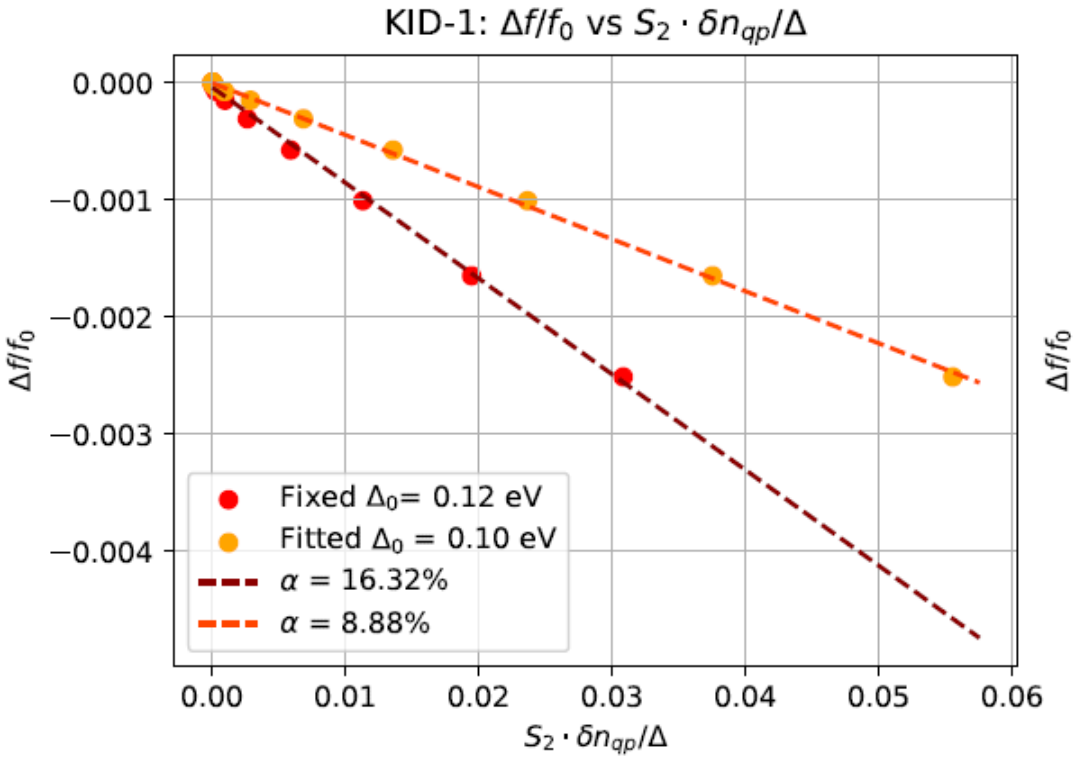


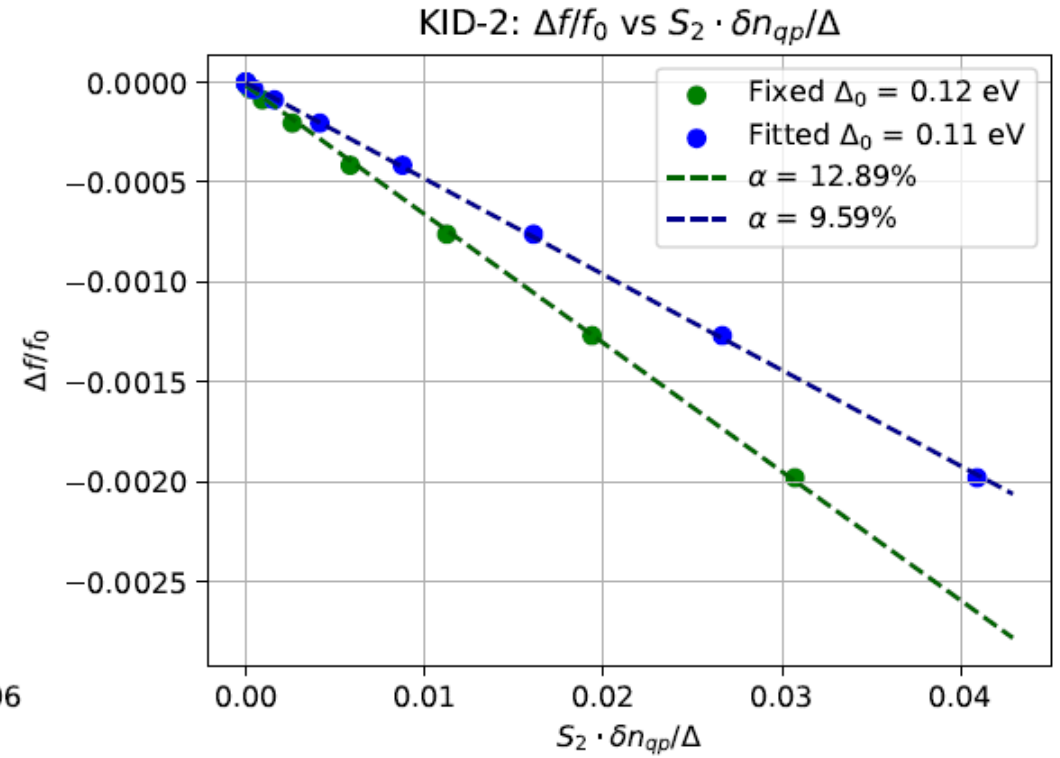


$$\frac{\left(\frac{d\phi}{dE}\right)_{11}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{7}^{NO_FUNNEL}} = 4.30 \pm 0.31$$

Temperature scan: $\Delta f / f_0$ vs n_{qp}

Linear trend observed

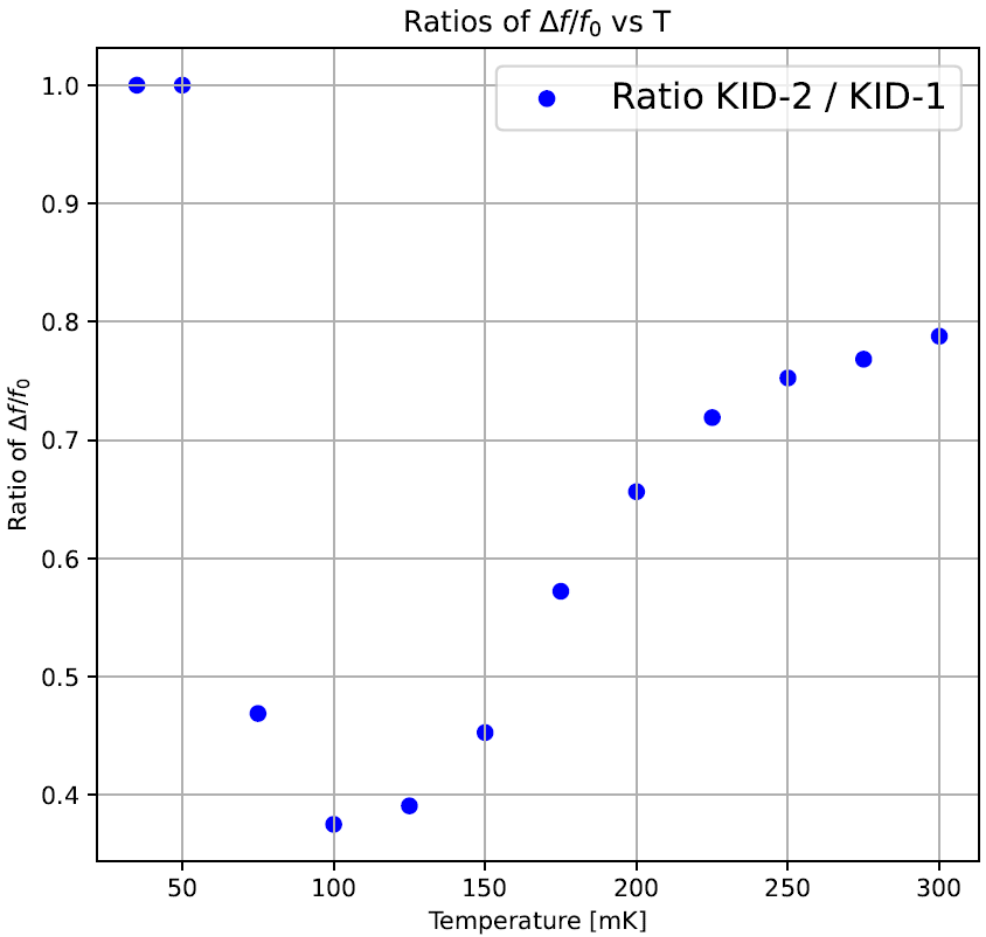


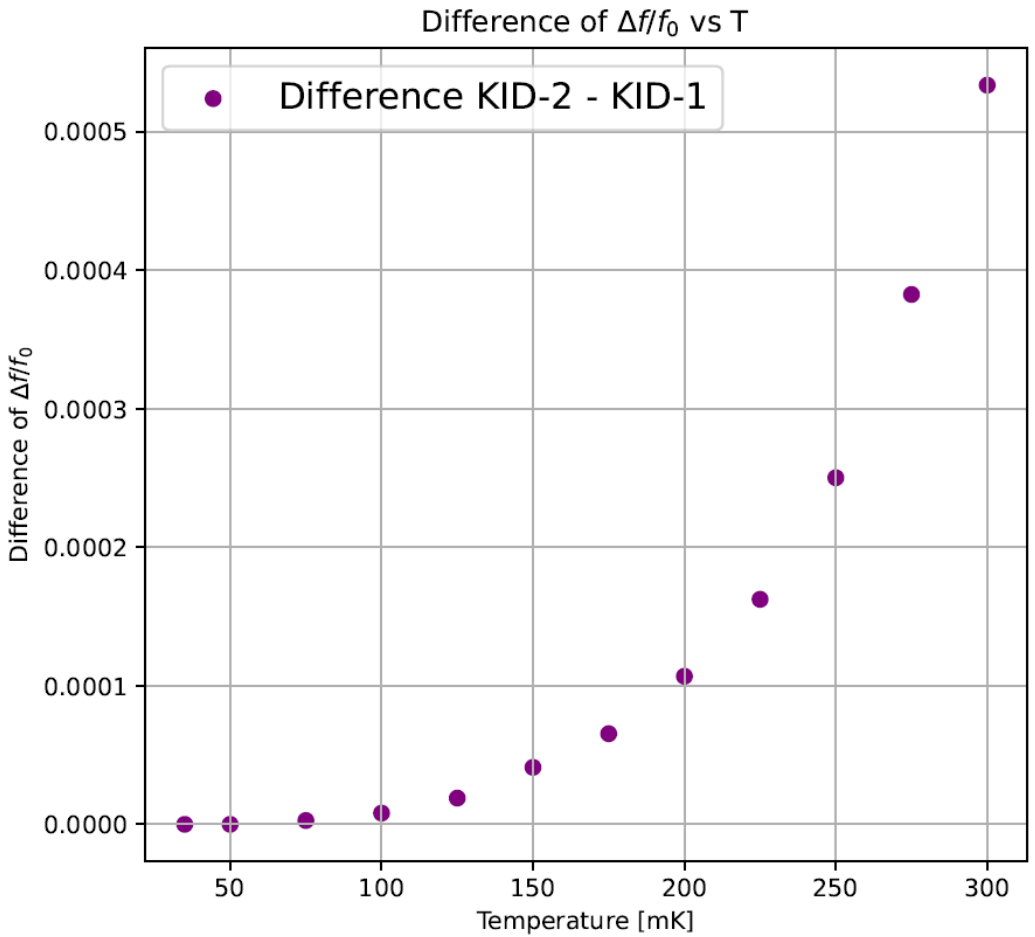


- $\alpha^{\Delta,free} \approx (8.88 \pm 0.01)$ %
- $\alpha^{\Delta,fitted} \approx (16.32 \pm 0.01)$%

- $\alpha^{\Delta,free} \approx (9.59 \pm 0.01)$ %
- $\alpha^{\Delta,fitted} \approx (12.89 \pm 0.01)$ %

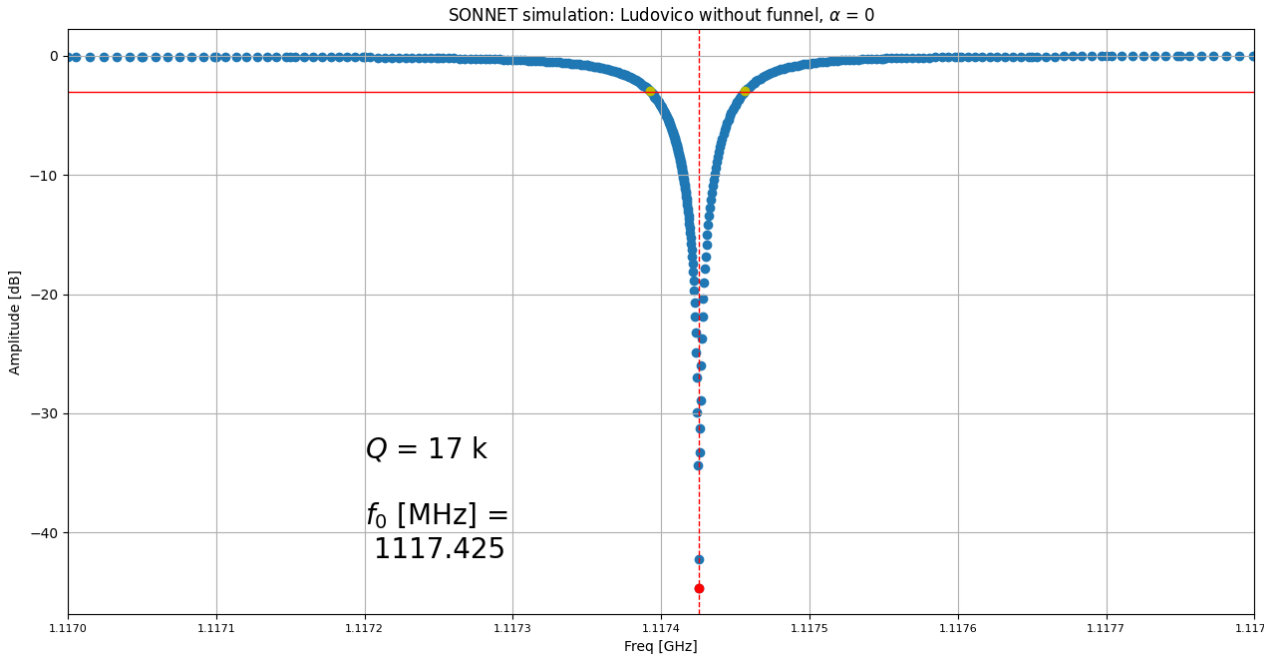
Temperature scan: KIDs comparison

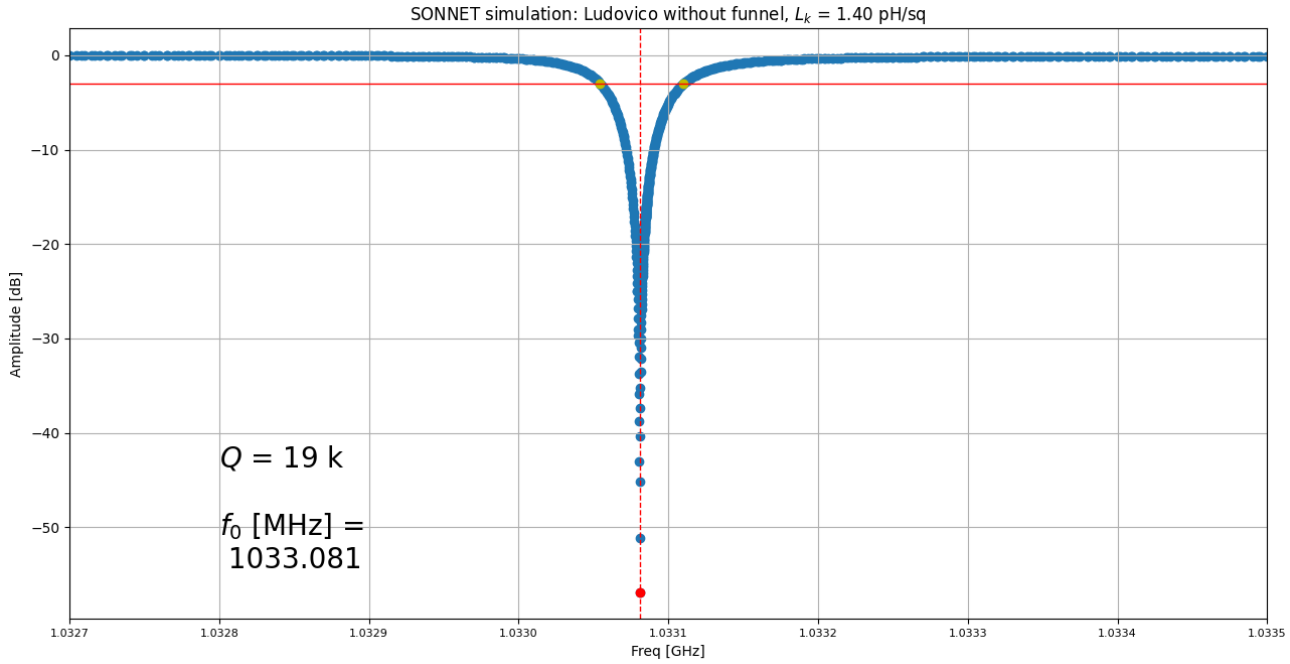




- KID-2 has lower responsivity at every temperature (power fixed)

SONNET simulation: results KID-2





$L_k = 0$ (lossless)

$Q_c \approx 17$k

$f_0 = 1117.425$ MHz

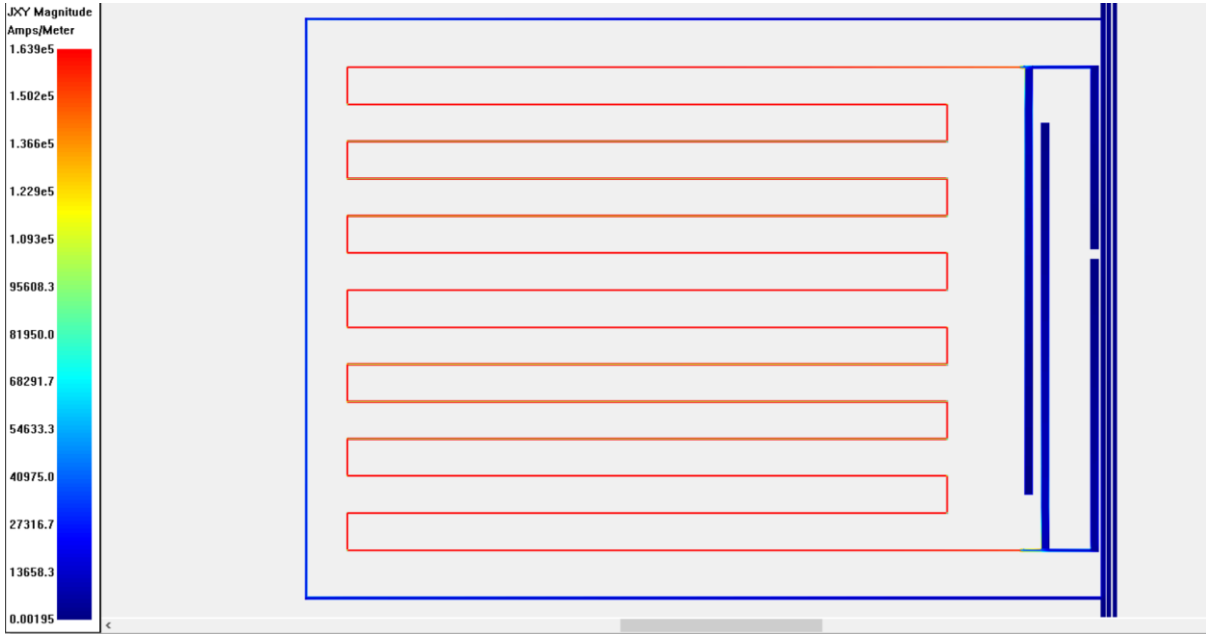
$L_k = 1.4$ pH/sq

$Q_c \approx 19$k

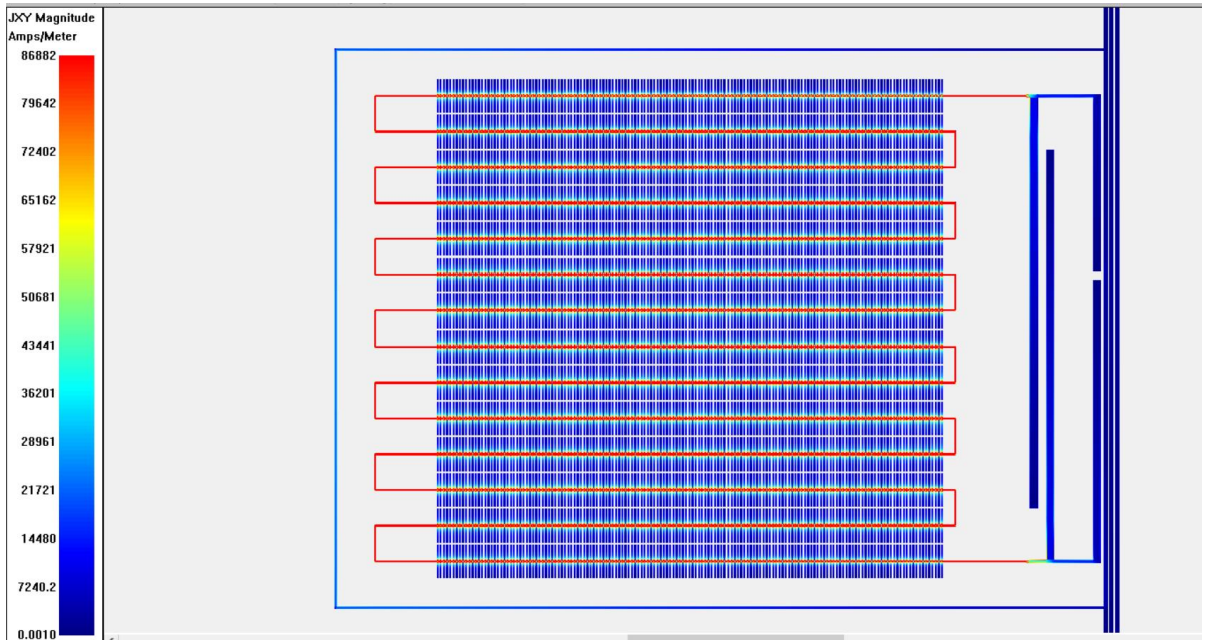
$f_0 \approx 1033.081$MHz

SONNET simulation: resonances

KID-1

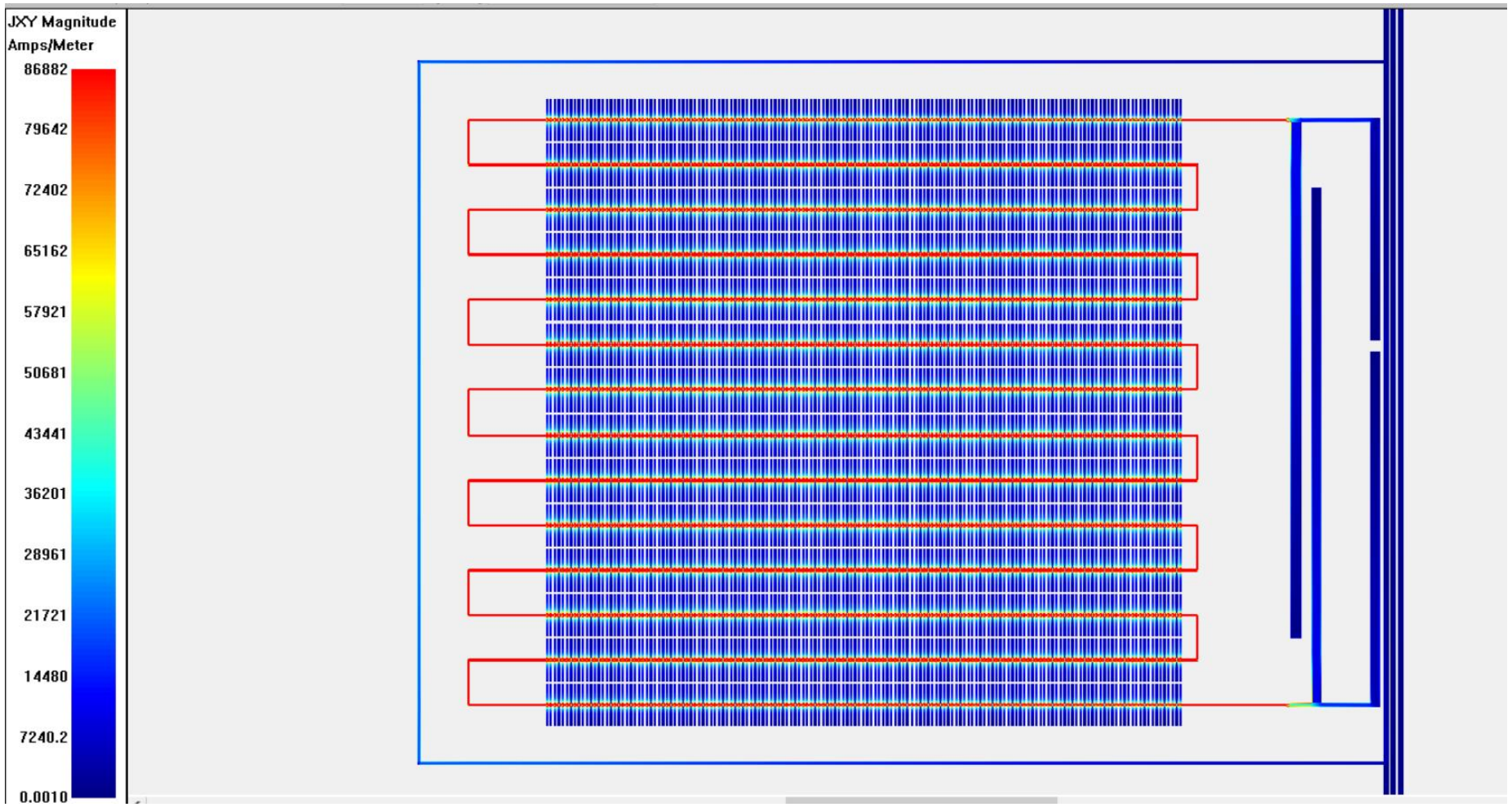


KID-2



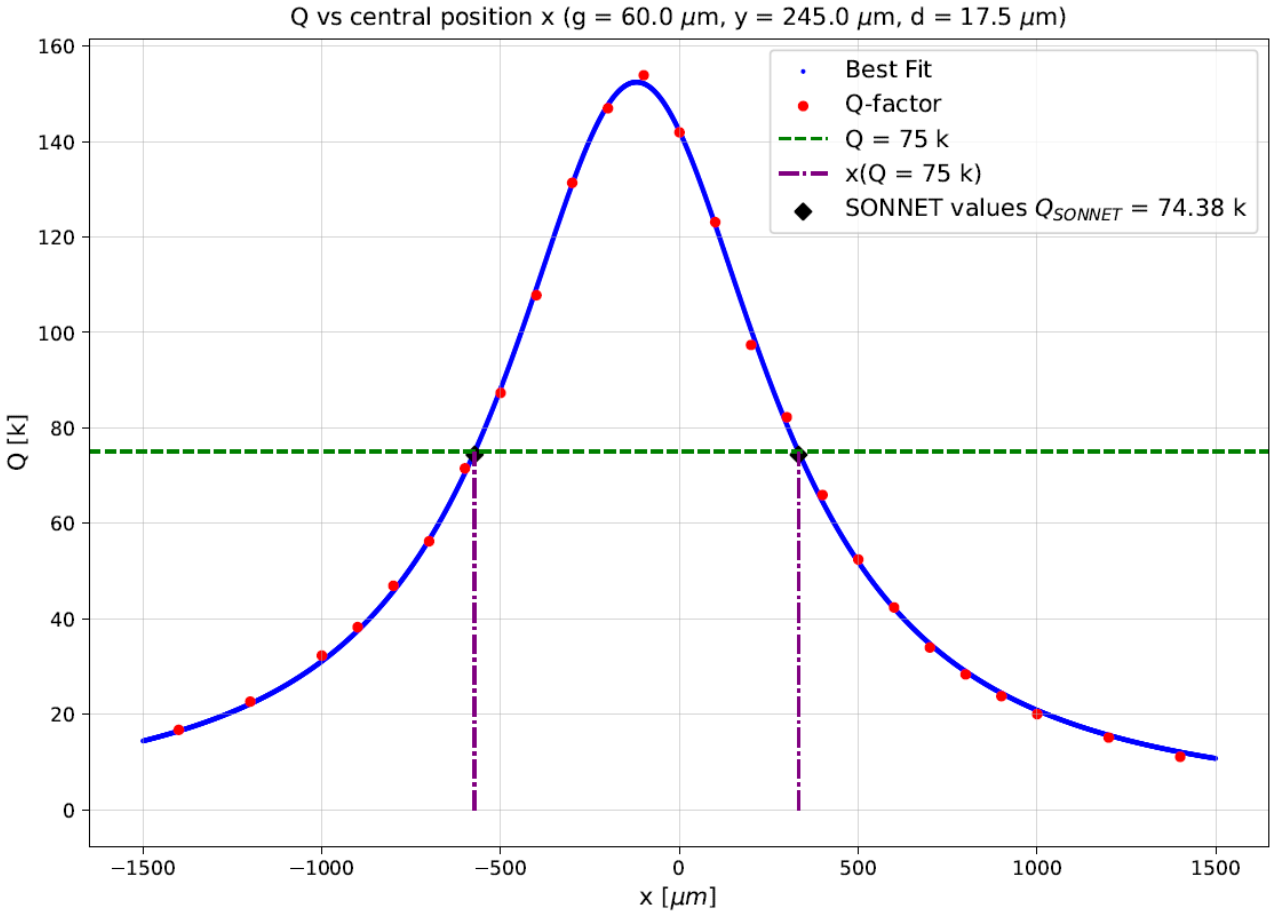
- Currents at resonances
- No current in funnels (“passive” material)

SONNET simulation: current in funnels



No current in funnels → Passive material (only collecting phonons)

SONNET simulation: Q vs x



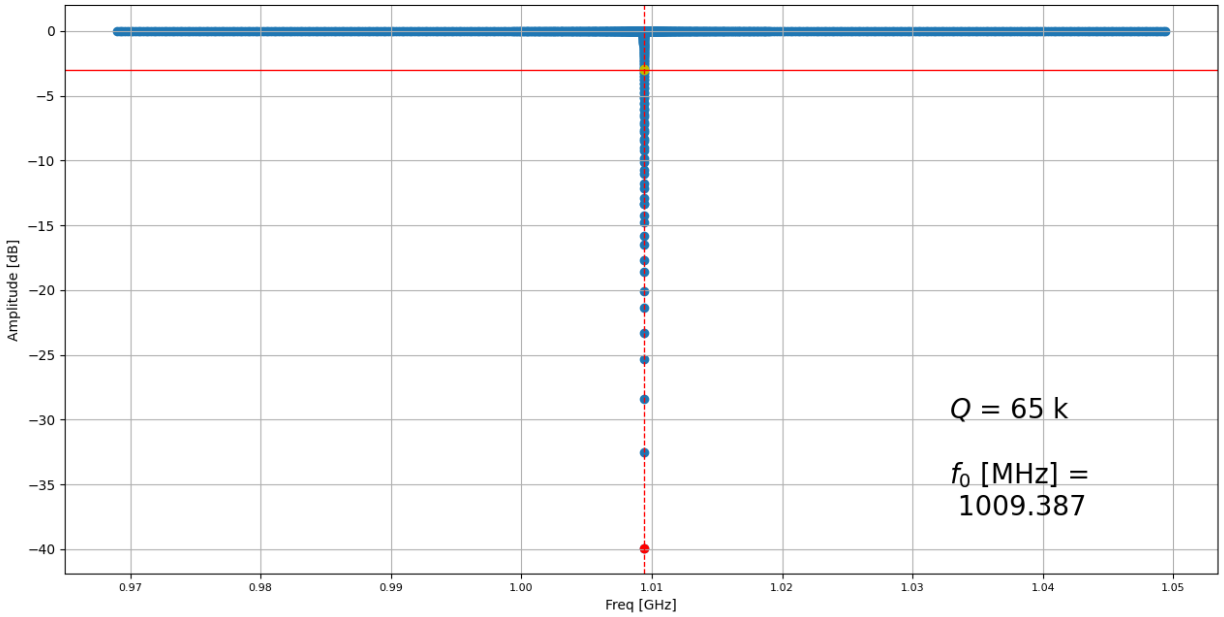
- Lorentzian dependence simulated

$$Q(Q_{max}, \bar{x}, \sigma_x; x) = \frac{Q_{max}}{\pi} \frac{\sigma_x}{[\sigma_x^2 + (x - \bar{x})^2]}$$

- Best fit parameters:
  - $Q_c = (213.37 \pm 0.94)$k
  - $\bar{x} = (-119.97 \pm 1.83)\mu$m
  - $\sigma_x = (445.44 \pm 2.79)\mu$m

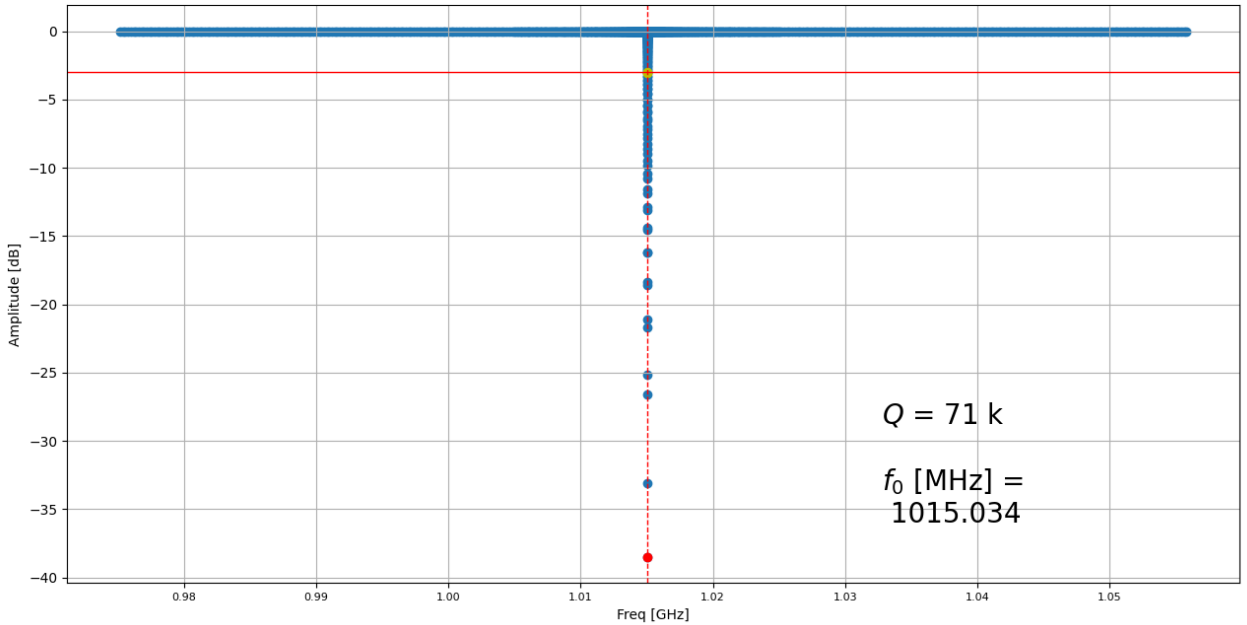
SONNET simulation: preliminary results

KID-FUNNEL



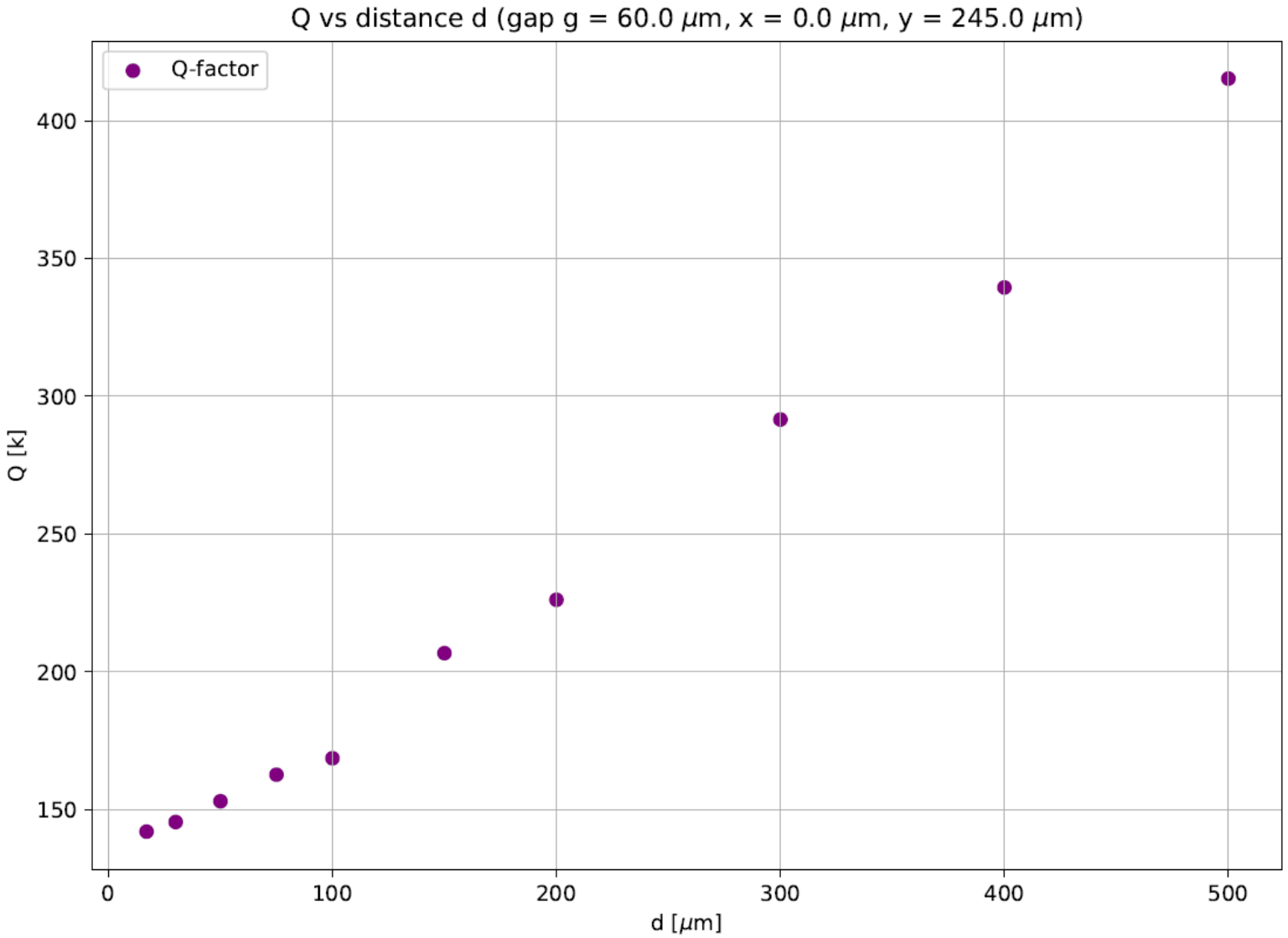
- $f_0 = 1009.39$ MHz
- $Q_c = 65\text{k}$
- $\alpha = ??$ (in progress)

KID-NO_FUNNEL



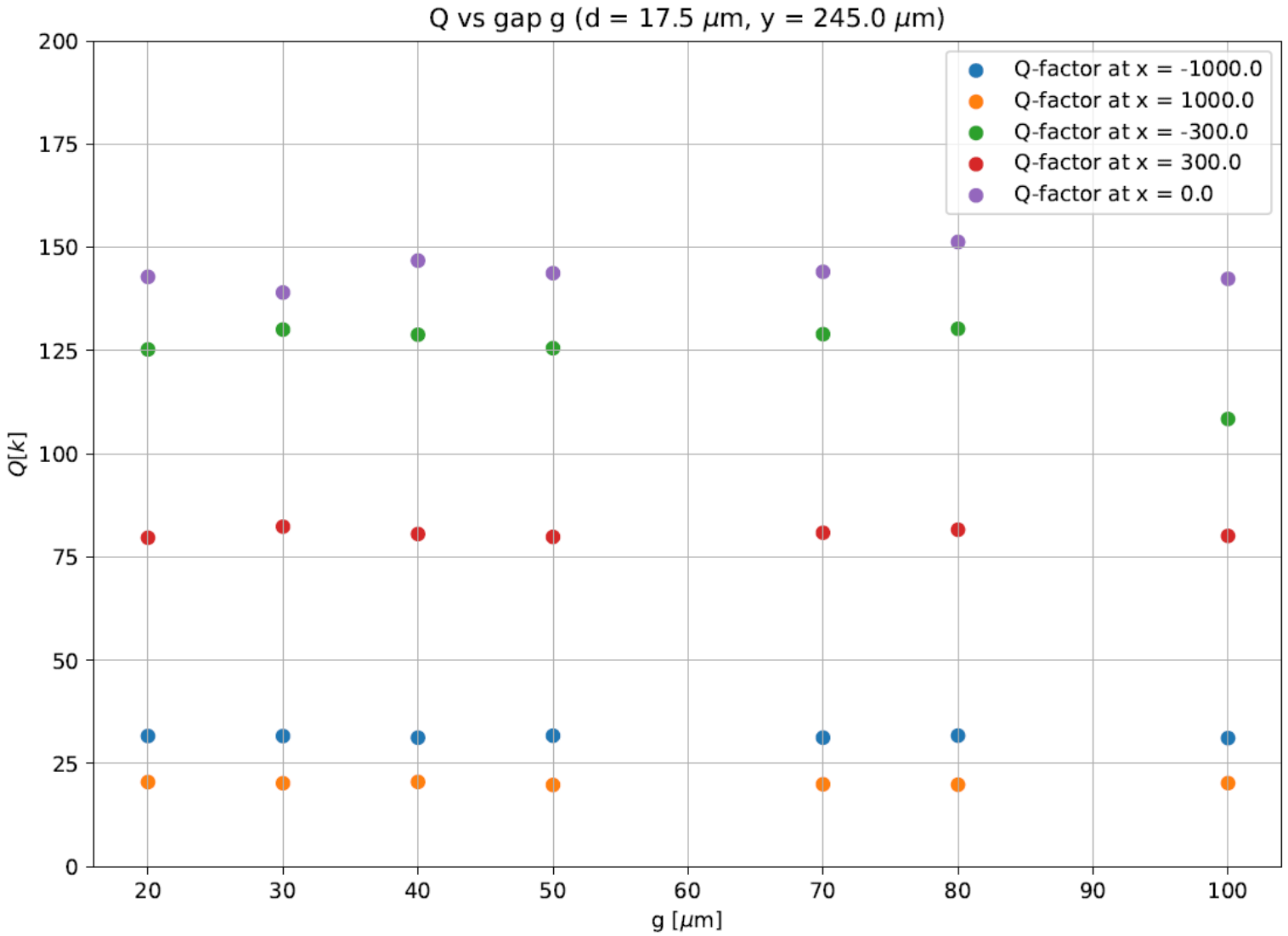
- $f_0 = 1015.03$ MHz
- $Q_c = 71\text{k}$
- $\alpha = ??$ (in progress)

SONNET simulation: Q vs d



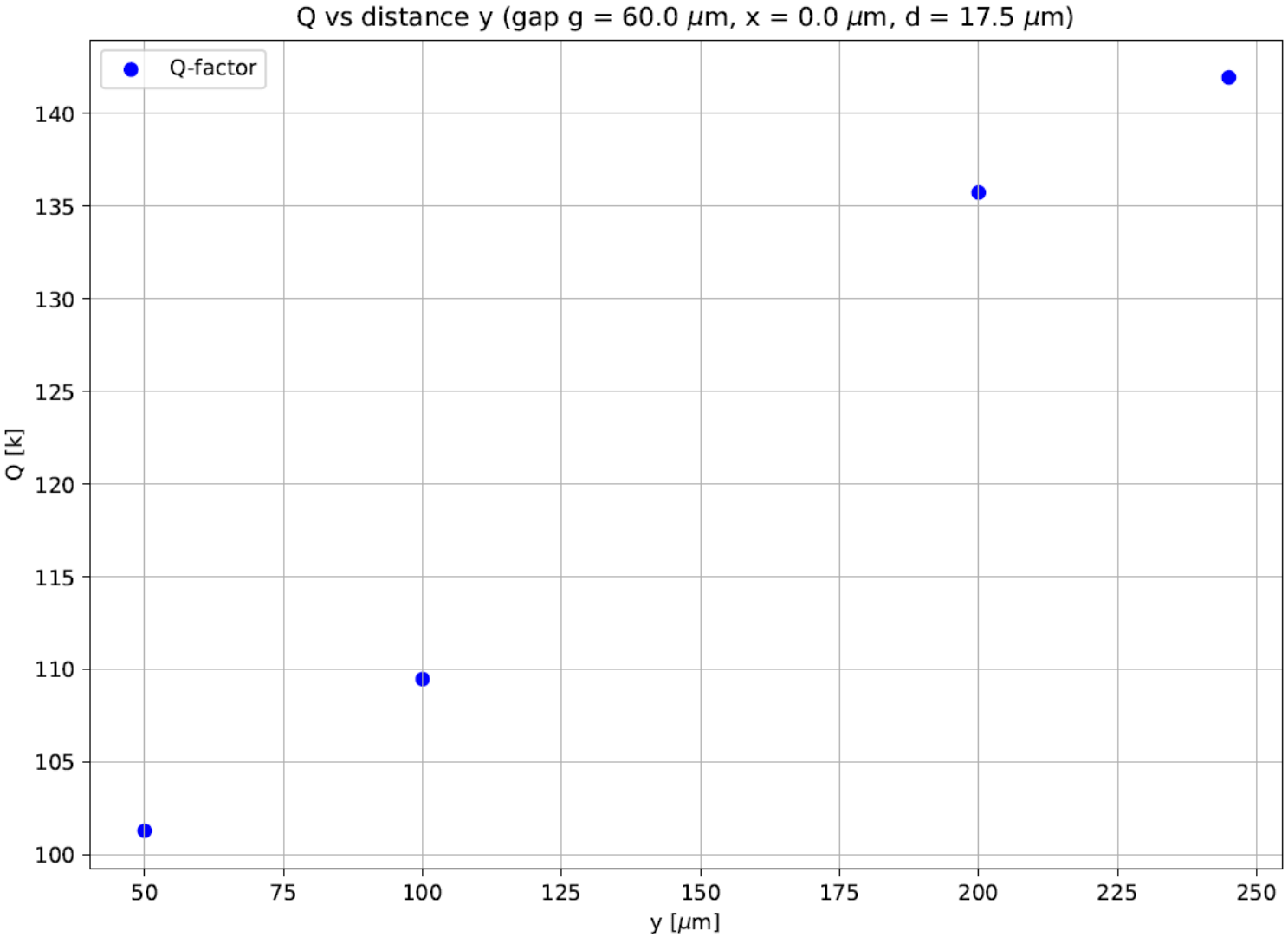
- Q increases with distance d from simulation.

SONNET simulation: Q vs g



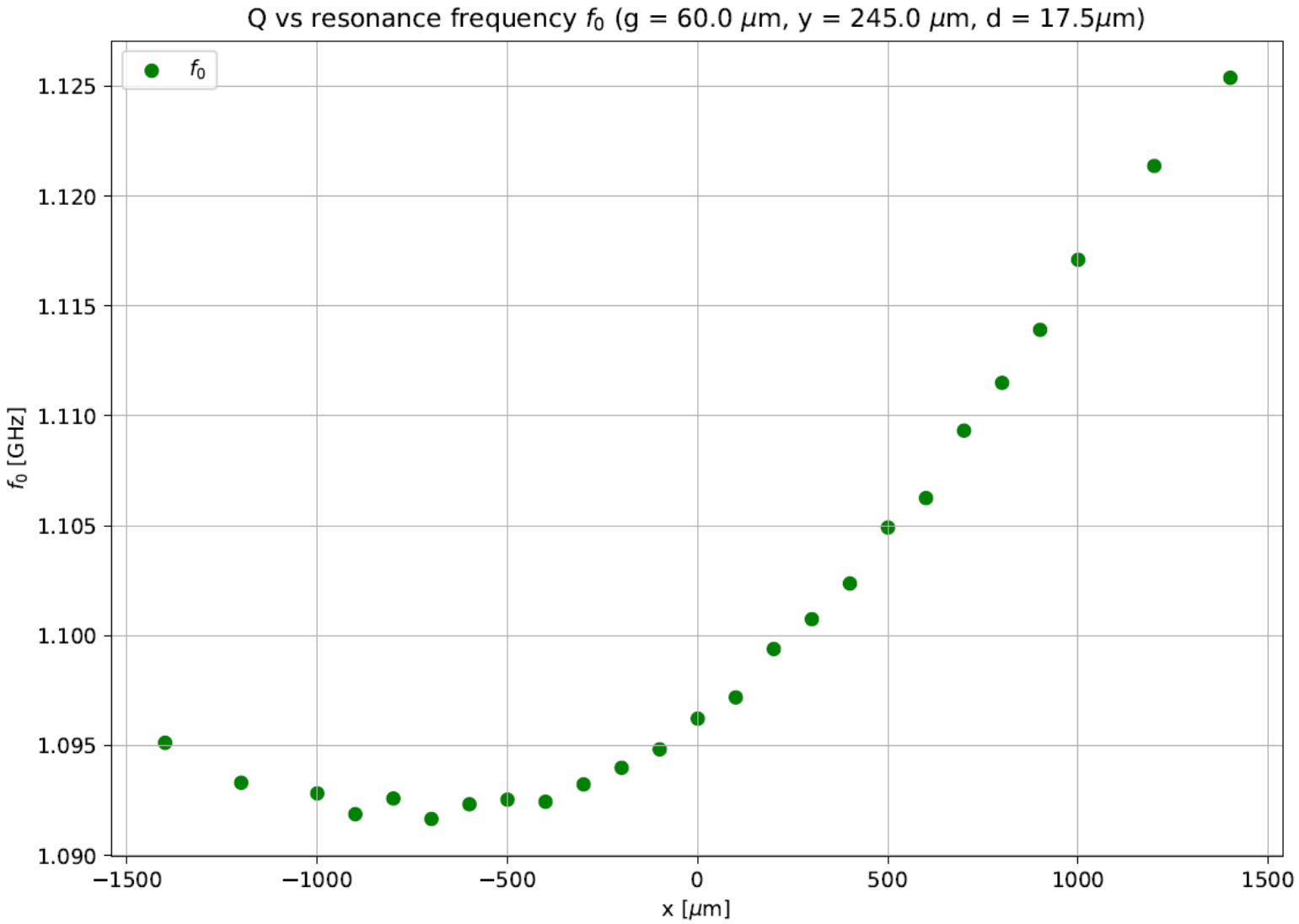
- Q is Independent on g.
- Such effect independent on x

SONNET simulation: Q vs y



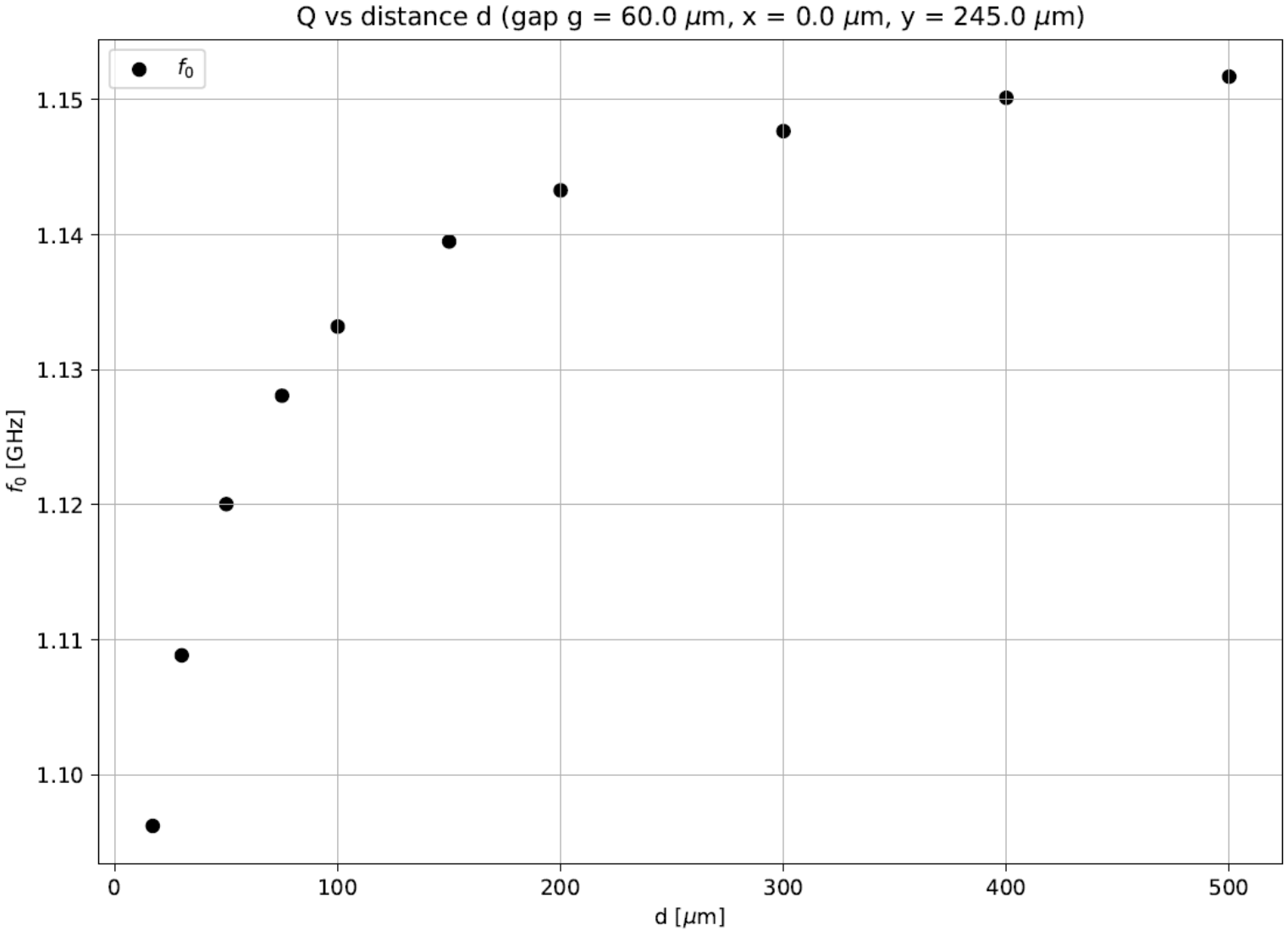
- Q increases with distance y from simulation.

SONNET simulation: f_0 vs x



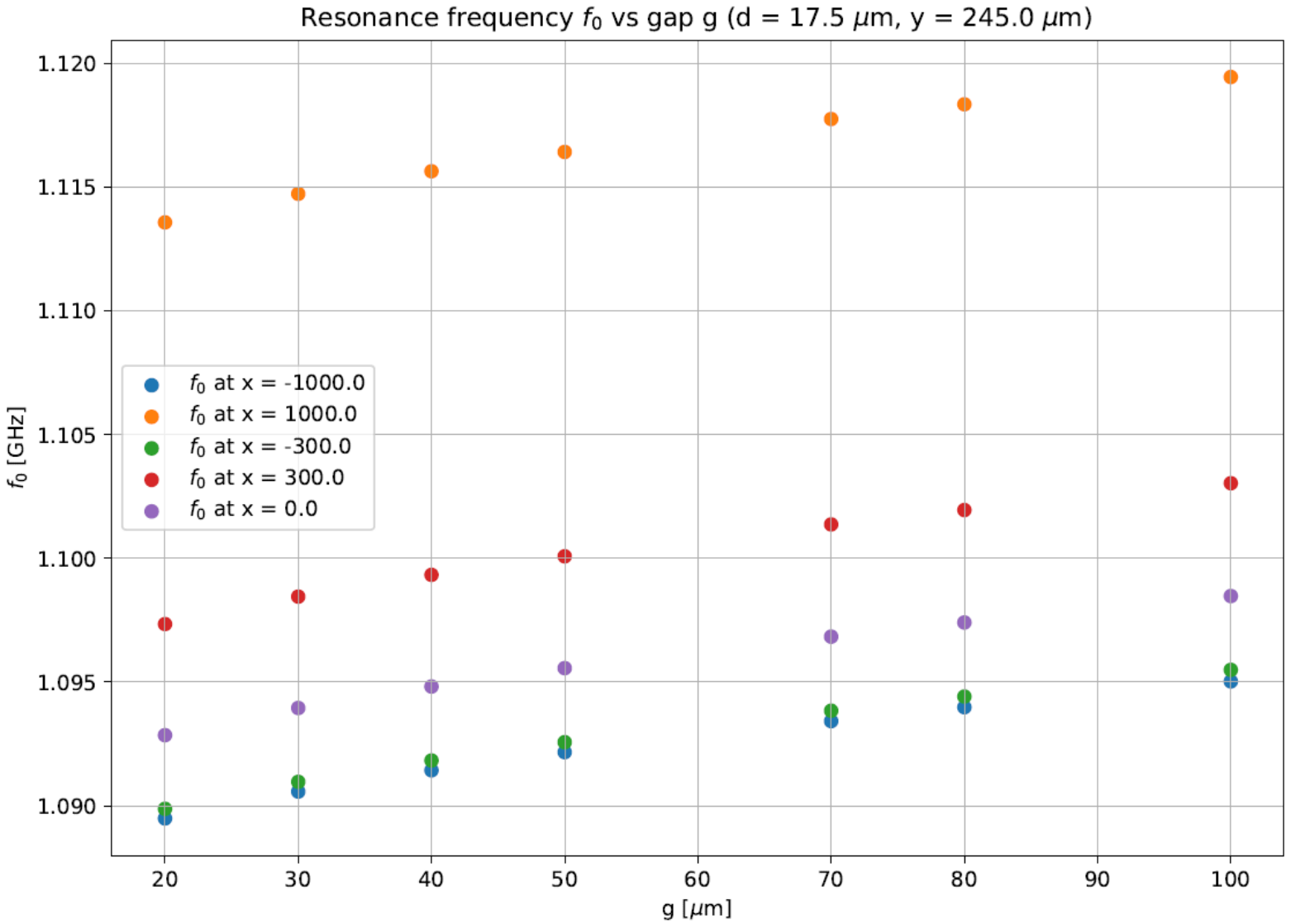
- f_0 (slightly) depends on x from simulation.

SONNET simulation: f_0 vs d



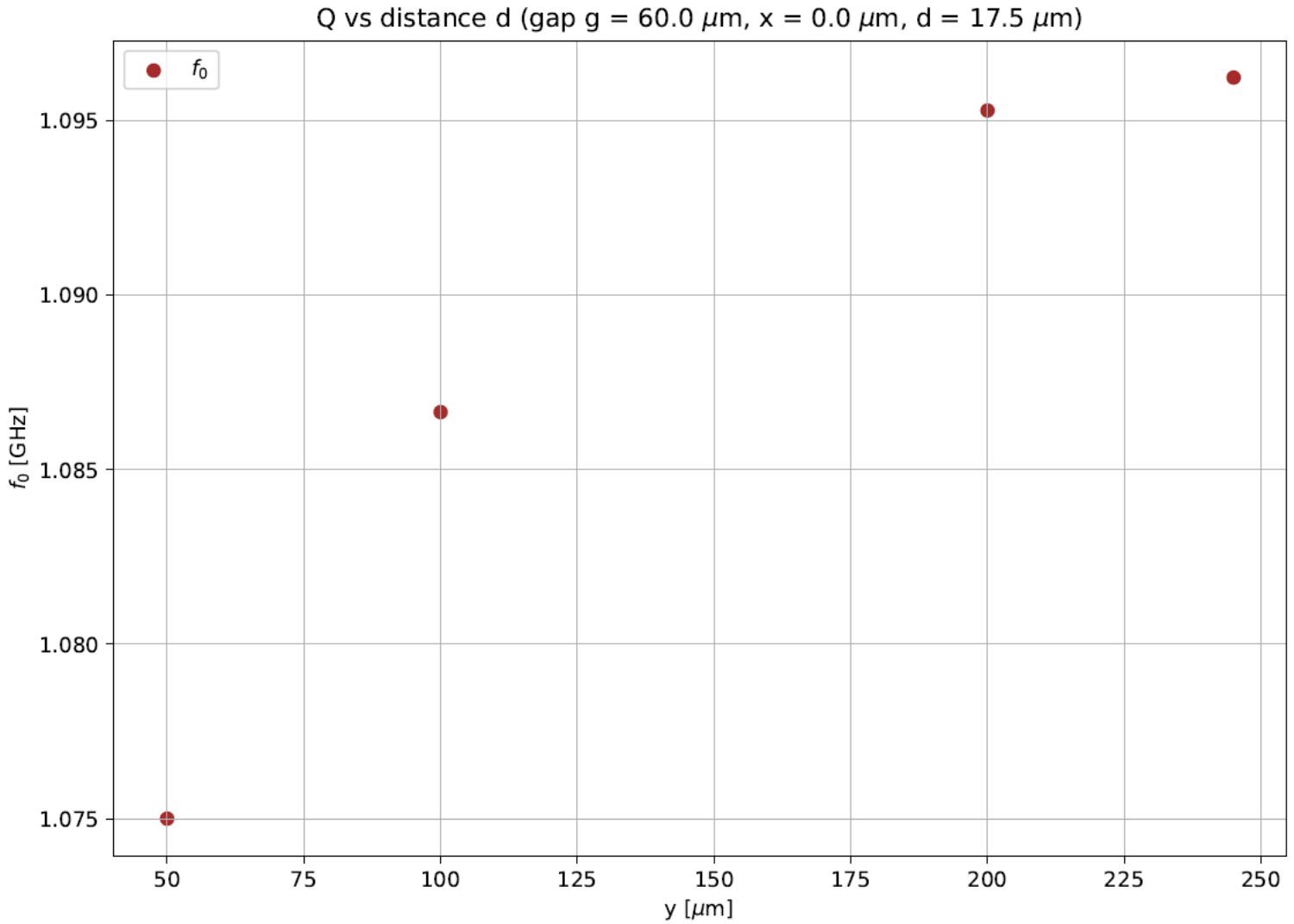
- f_0 (slightly) increases with d from simulation.

SONNET simulation: f_0 vs g



- f_0 (almost) Independent on g (for small variations)

SONNET simulation: f_0 vs y



- f_0 (slightly) increases with y from simulation.