Kinetic Inductance Detectors with phonon funneling volume

15/01/2025

Leonardo Pesce on behalf of BULLKID-DM collaboration

The concept of funnel

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

- Energy resolution of a "normal" BULLKID

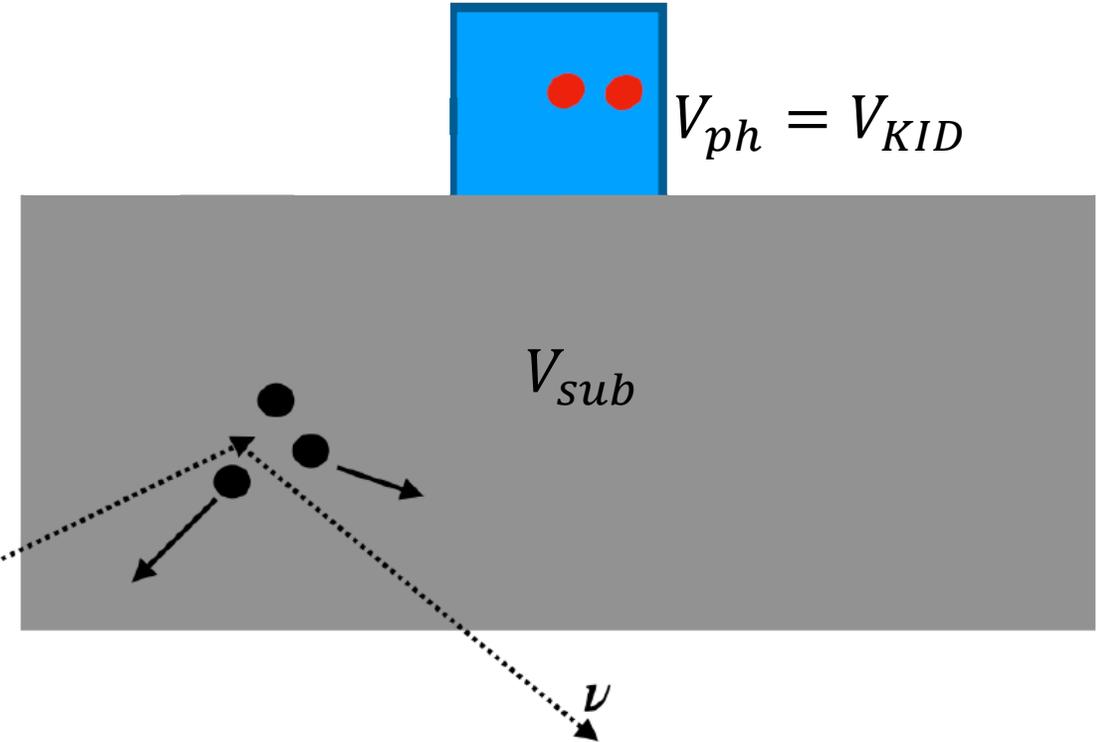$$\sigma_E \propto 1/\sqrt{V}$$

$$V_{ph} = V_{KID}$$

$$V_{sub}$$

- All the volume collects phonons:

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

ν

ν

Volume collecting phonons
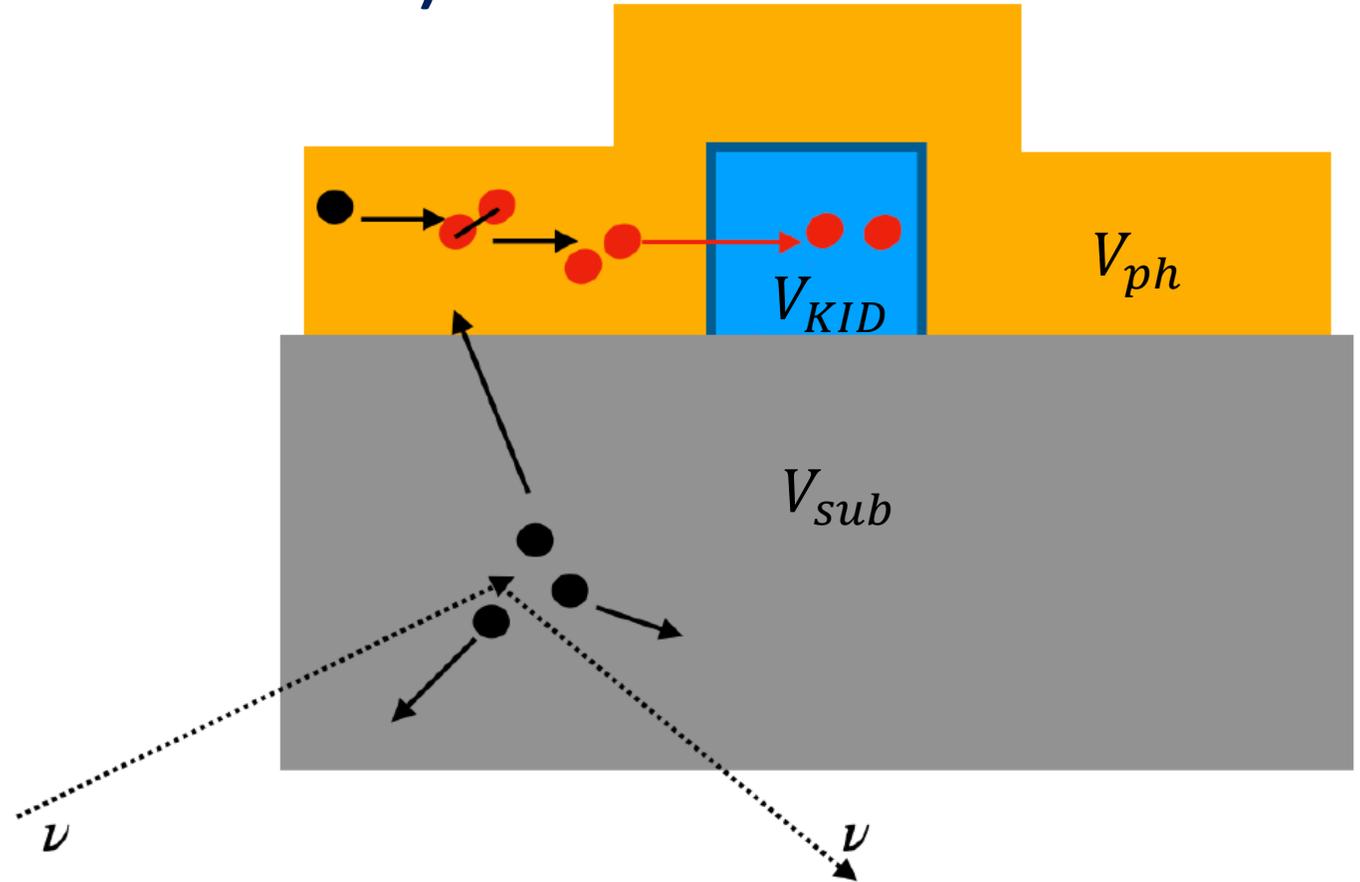
Volume generating signals

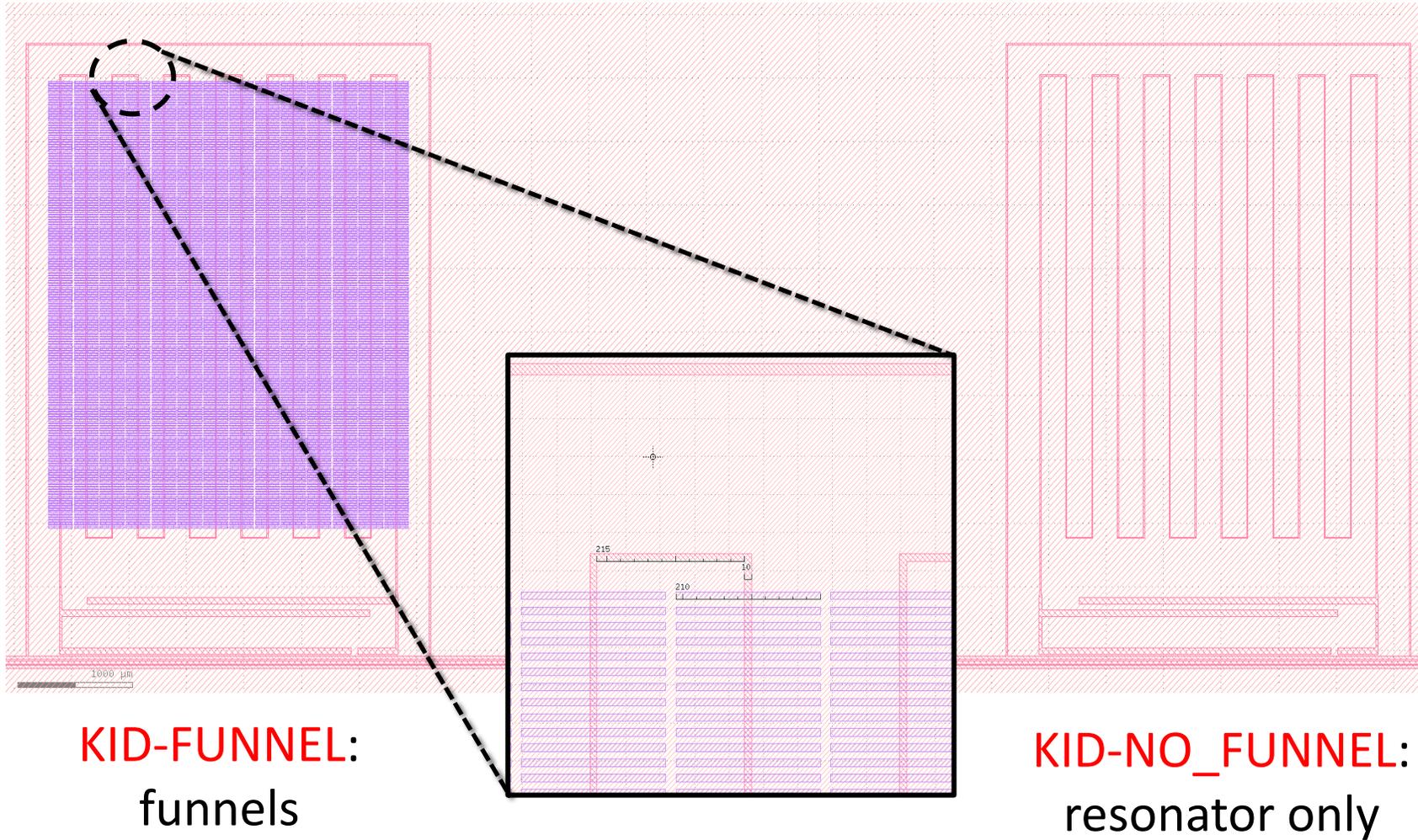# The concept of funnel (Ludovico De Santis's master thesis)

- **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

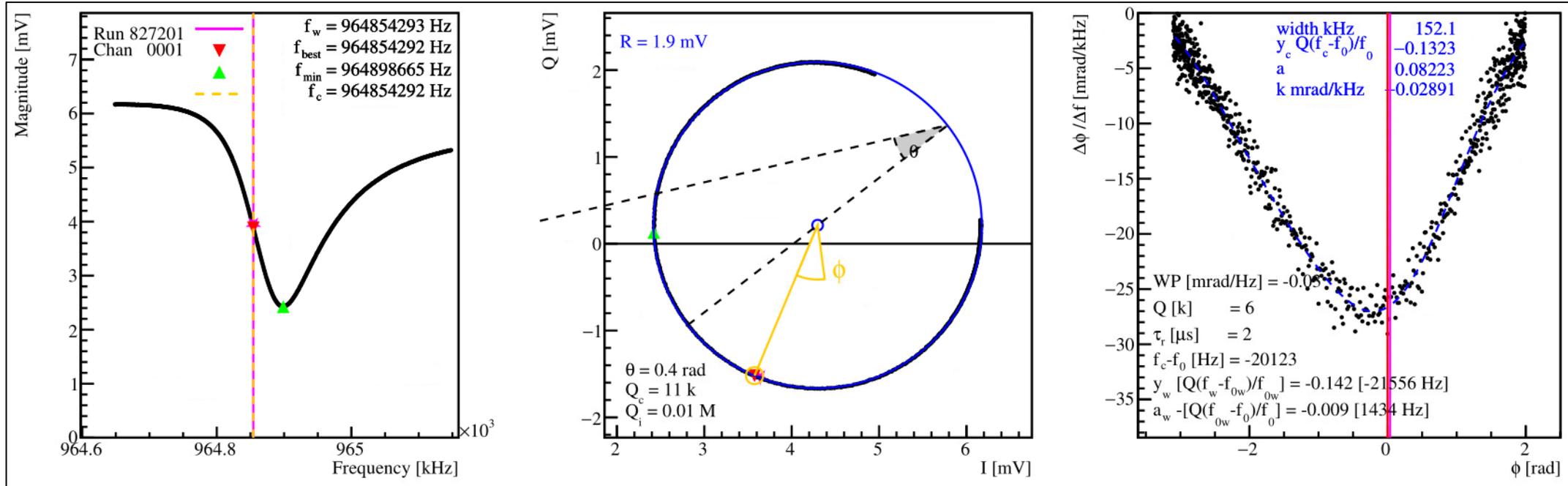Capacitive coupling

Meander and feed-line made of AlTiAl

Substrate made of Si

KID-FUNNEL   KID-NO_FUNNEL

Measures and results

Resonance Circle: KID-FUNNEL

$$f_0 \approx 984.97 \text{ MHz} \qquad Q_c \approx 11\text{k} \qquad Q \approx 6\text{k}$$

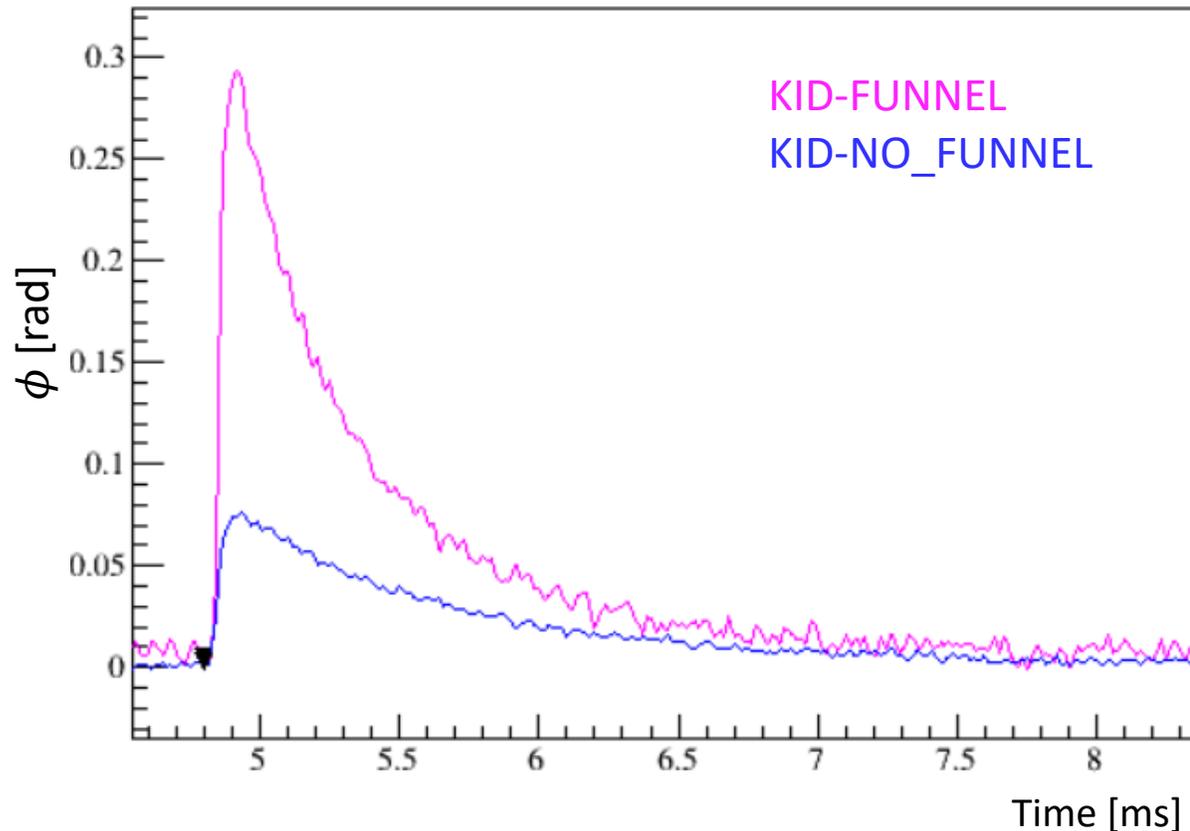$$f_0 \approx 1031.96 \text{ MHz} \qquad Q_c \approx 23\text{k} \qquad Q \approx 22\text{k}$$

Optical Calibration: phase responsivity

- Photons release energy on KIDs

- Phase variation of transfer function → Pulses

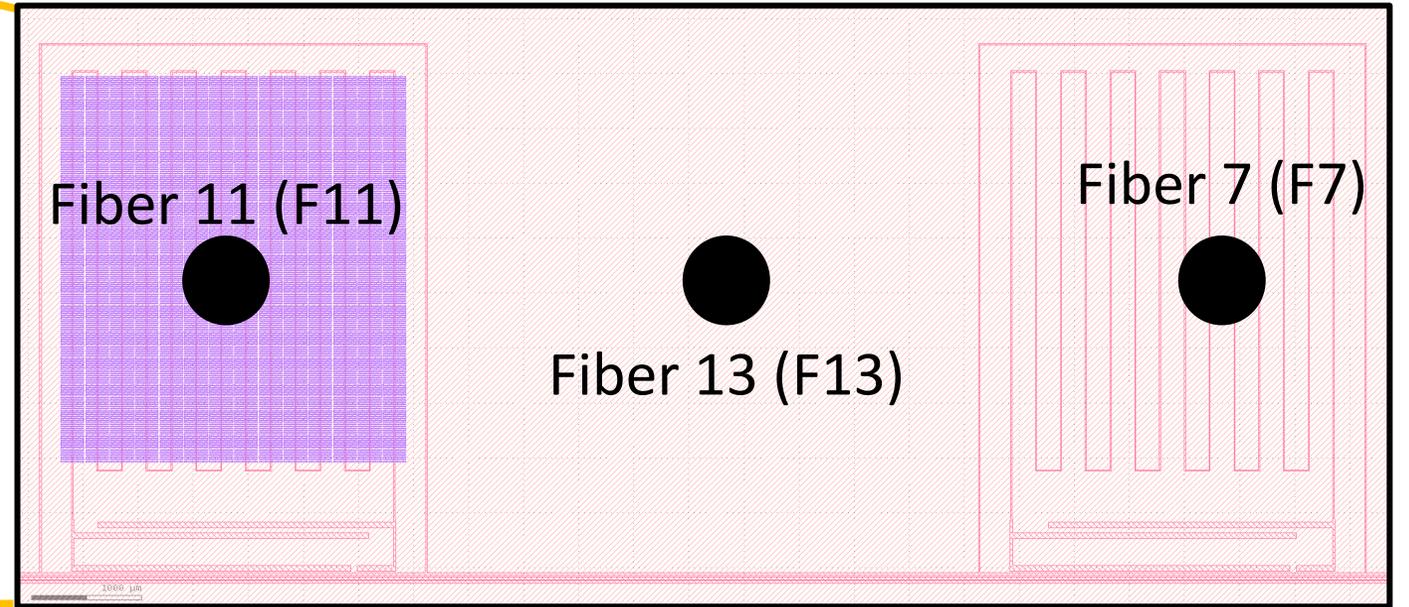$$\frac{d\phi}{dE} = \eta \frac{\alpha S_\phi(\omega, T) Q}{N_0 V_{KID} \Delta_0^2}$$

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

KID-FUNNEL
KID-NO_FUNNEL

- η = Energy to QP conversion efficiency

- $\alpha = \frac{L_k}{L_k + L_g}$ fraction of kinetic inductance

- Δ_0 = Superconducting gap

Optical Calibration

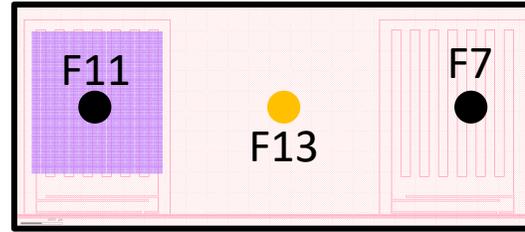- Three optical fibers shoot photons against substrate (opposite side of resonators)

Fiber 11 (F11)

Fiber 13 (F13)

Fiber 7 (F7)

KID-FUNNEL

KID-NO_FUNNEL

Optical Calibration (F13-High power)

KID-FUNNEL

KID-NO_FUNNEL

Channel 1

Channel 2

Calibration Constant = (0.321 ± 0.018) keV/mrad
responsivity = (3.12 ± 0.18) mrad/keV
Noise_s0_eV = (212 ± 12) eV
photon_wavelength = (400 ± 8) nm
Reduced χ^2=0.764

Calibration Constant = (0.974 ± 0.068) keV/mrad
responsivity = (1.027 ± 0.072) mrad/keV
Noise_s0_eV = (339 ± 24) eV
photon_wavelength = (400 ± 8) nm
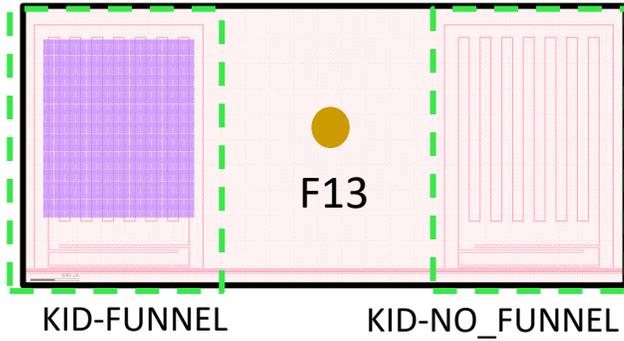Reduced χ^2=1.24

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

$$\left(\frac{d\phi}{dE}\right)_{13}^{NO\_FUNNEL} = (1.07 \pm 0.07) \text{ mrad/keV}$$
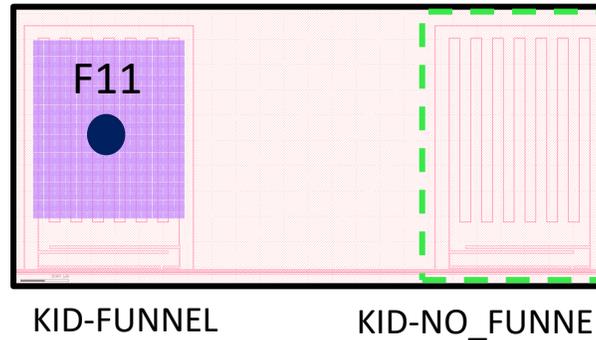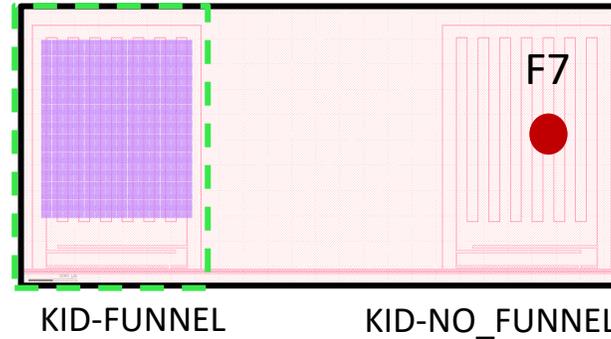
$$\sigma_{0,13}^{FUNNEL} = (212 \pm 12) \text{ eV}$$

$$\sigma_{0,13}^{NO\_FUNNEL} = (339 \pm 24) \text{ eV}$$

Responsivities ratios

Central fiber

KID-FUNNEL   KID-NO_FUNNEL
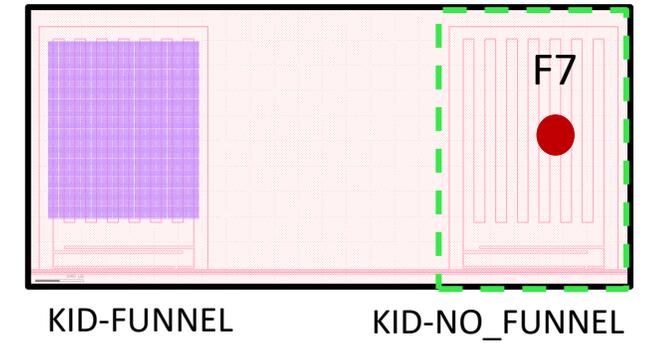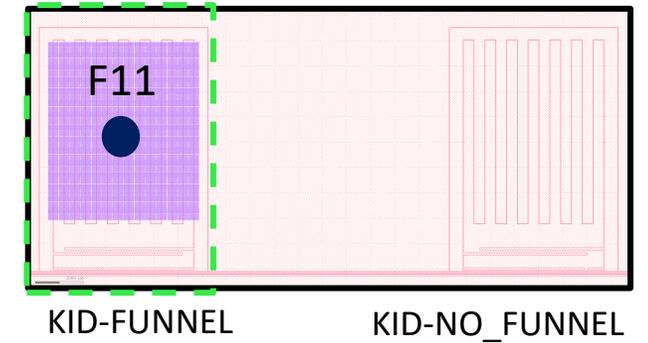
$$\frac{\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{13}^{NO\_FUNNEL}} = 2.92 \pm 0.25$$

Furthest fibers

KID-FUNNEL   KID-NO_FUNNEL

KID-FUNNEL   KID-NO_FUNNEL

$$\frac{\left(\frac{d\phi}{dE}\right)_{7}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{11}^{NO\_FUNNEL}} = 1.35 \pm 0.31$$

Closest fibers

KID-FUNNEL   KID-NO_FUNNEL

KID-FUNNEL   KID-NO_FUNNEL

$$\frac{\left(\frac{d\phi}{dE}\right)_{11}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{7}^{NO\_FUNNEL}} = 1.66 \pm 0.17$$
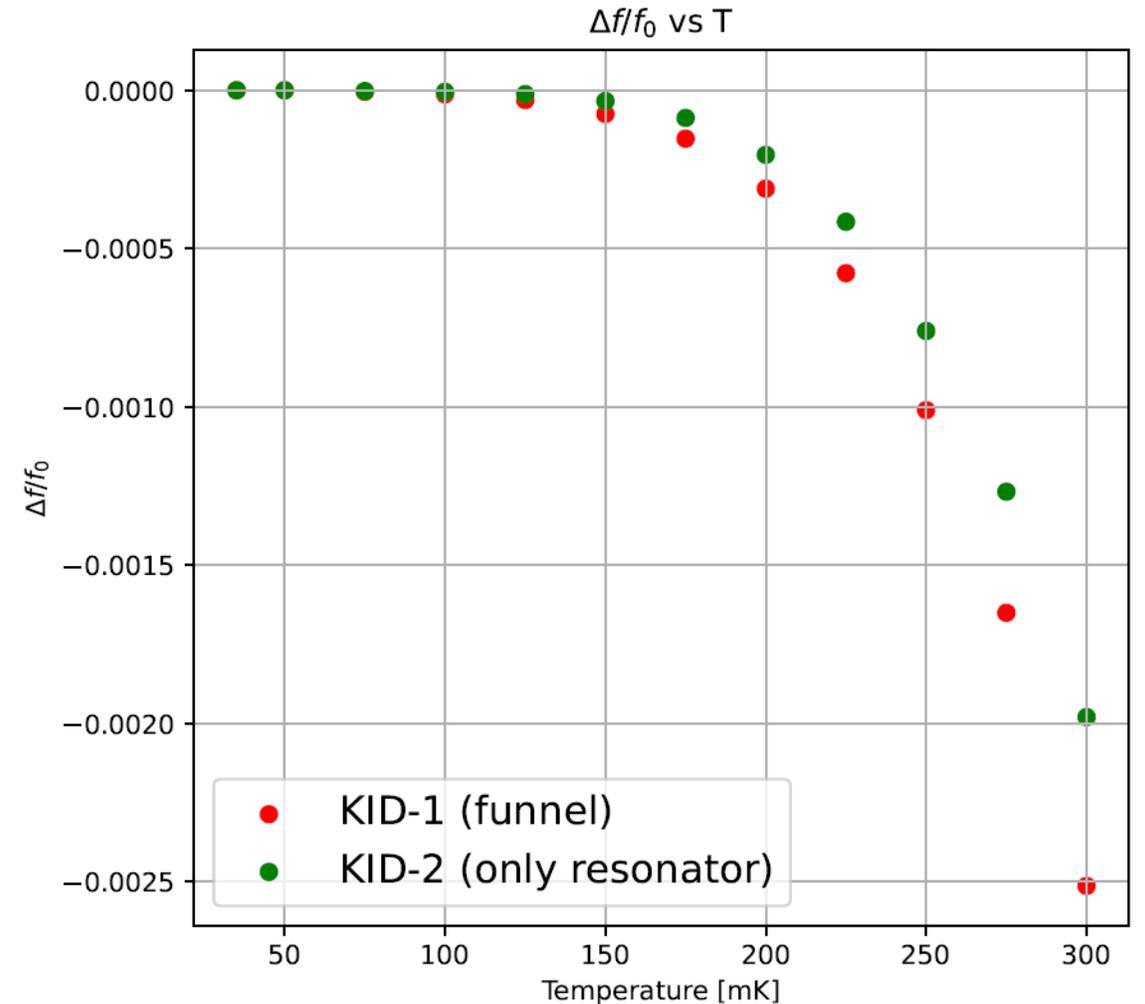
Temperature scan: MB theory

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

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

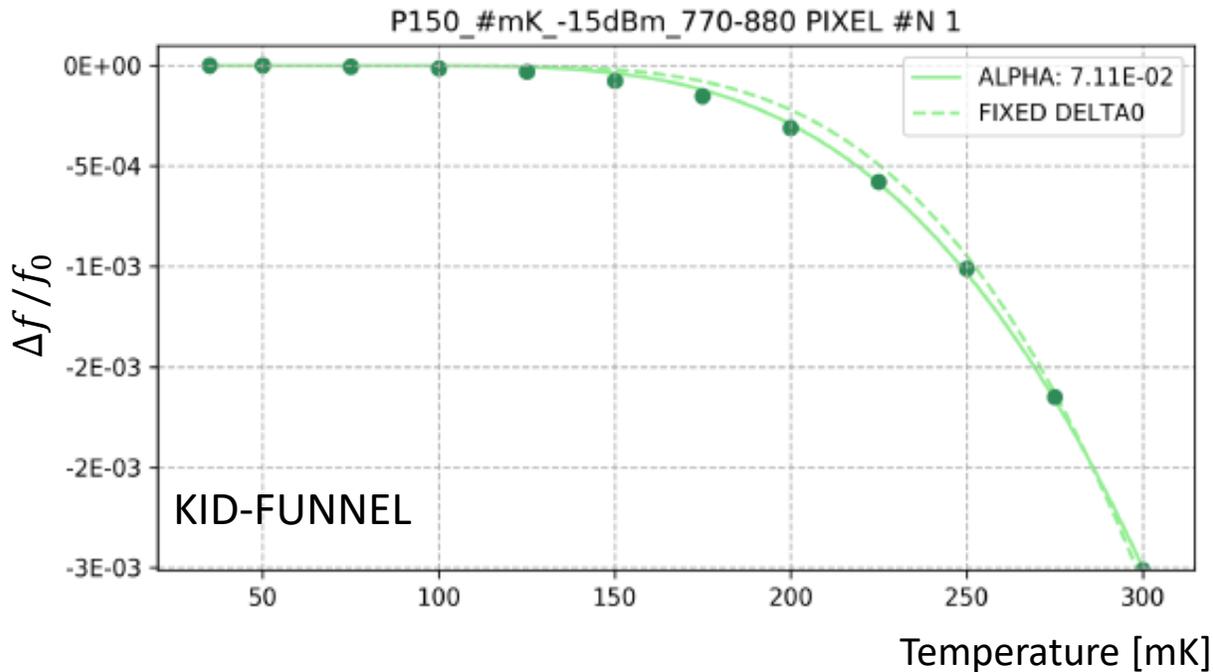- $\Delta = \Delta_0 e^{-\sqrt{\frac{2\pi k_B T}{\Delta_0}}} e^{-\frac{\Delta_0}{k_B T}}$

- $\delta n_{qp} = \sqrt{2\pi k_B T} e^{-\Delta/k_B T}$

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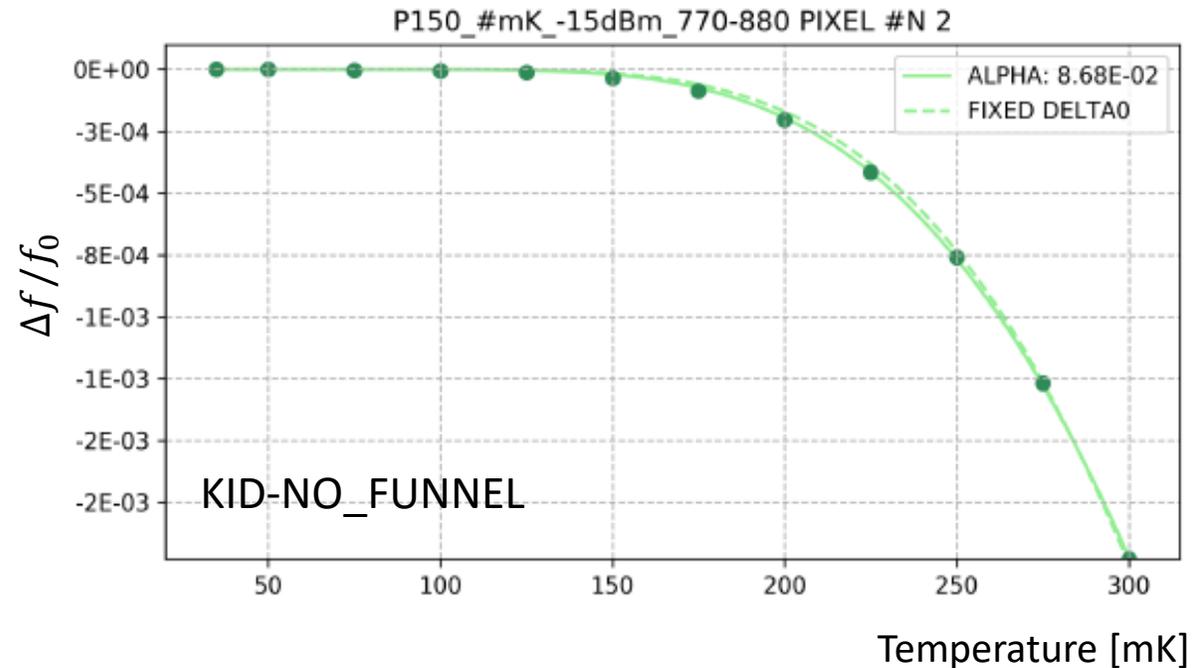

$\Delta f/f_0$ vs T

Temperature scan: MB fit

$$T_c \approx 815 \text{ mK measured} \rightarrow \Delta_0 \approx 1.7 k_B T_c \approx 0.12 \text{ meV}$$

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.
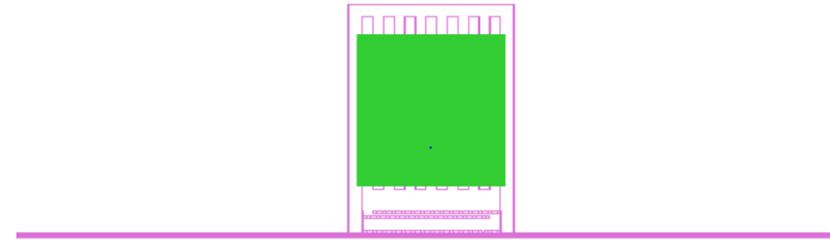
- $L_k = 1.4$ pH/sq

- 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

$Q = 19$ k

f_0 [MHz] = 1033.081

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

$Q = 20$ k

f_0 [MHz] = 1000.548

Next steps

SONNET simulation: Increasing Q_c

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

Q vs central position x (g = 60.0 μm, y = 245.0 μm, d = 17.5 μm)

Legend:
- Best Fit
- Q-factor
- Q = 75 k
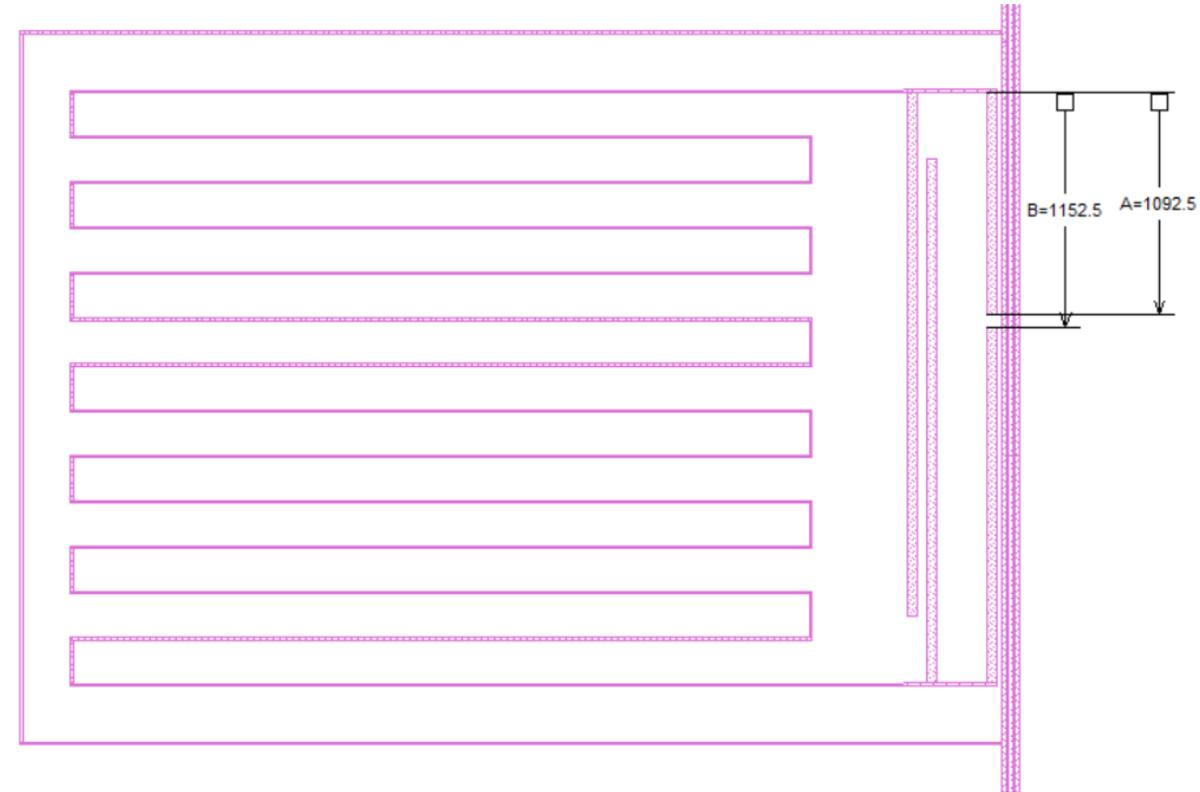- x(Q = 75 k)
- SONNET values $Q_{SONNET} = 74.38$ k

SONNET simulation: 75k Q resonator

- Preliminary results (simulation still running)

KID-FUNNEL

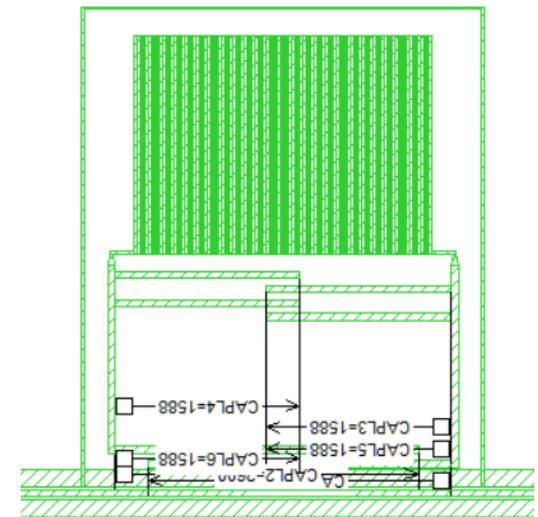KID-NO_FUNNEL
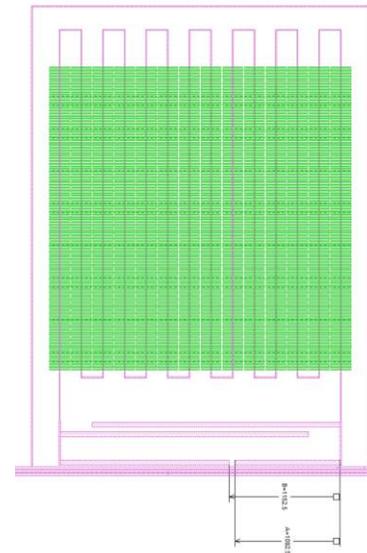
Conclusions and perspectives

o **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

o **What should be next:**

- Increasing Q_c

- Comparison between **funnel-KID** and **BULLKID** resonators
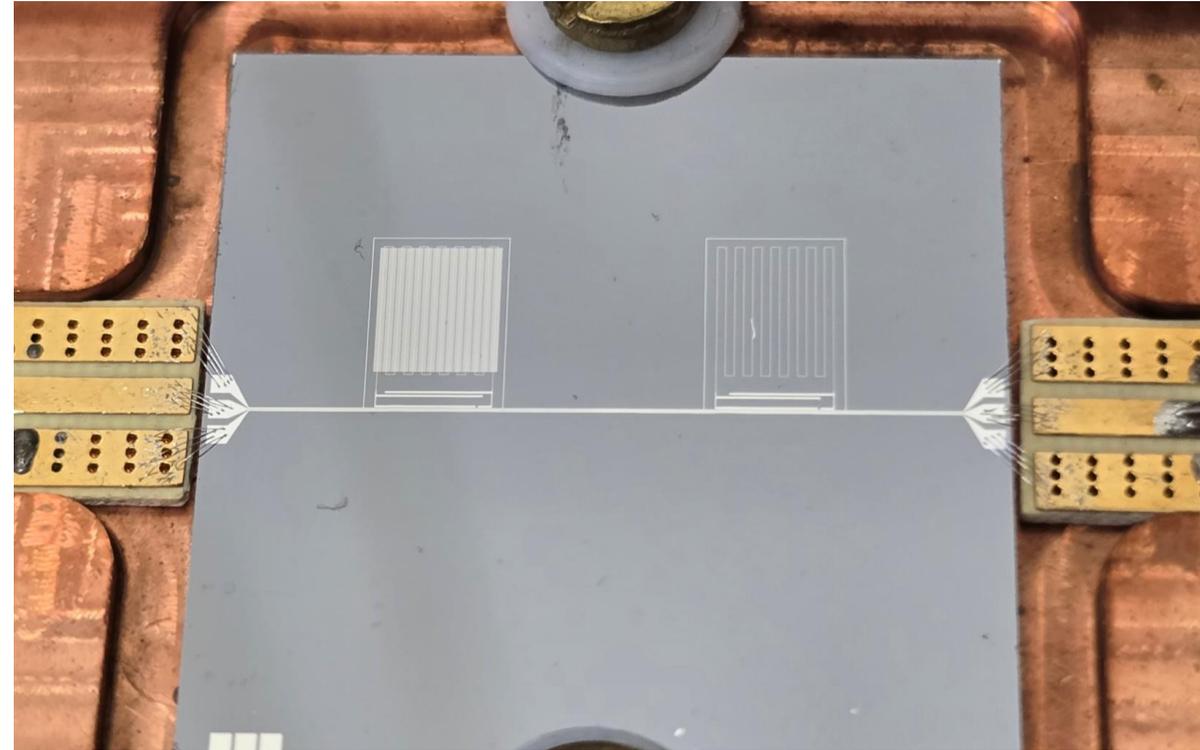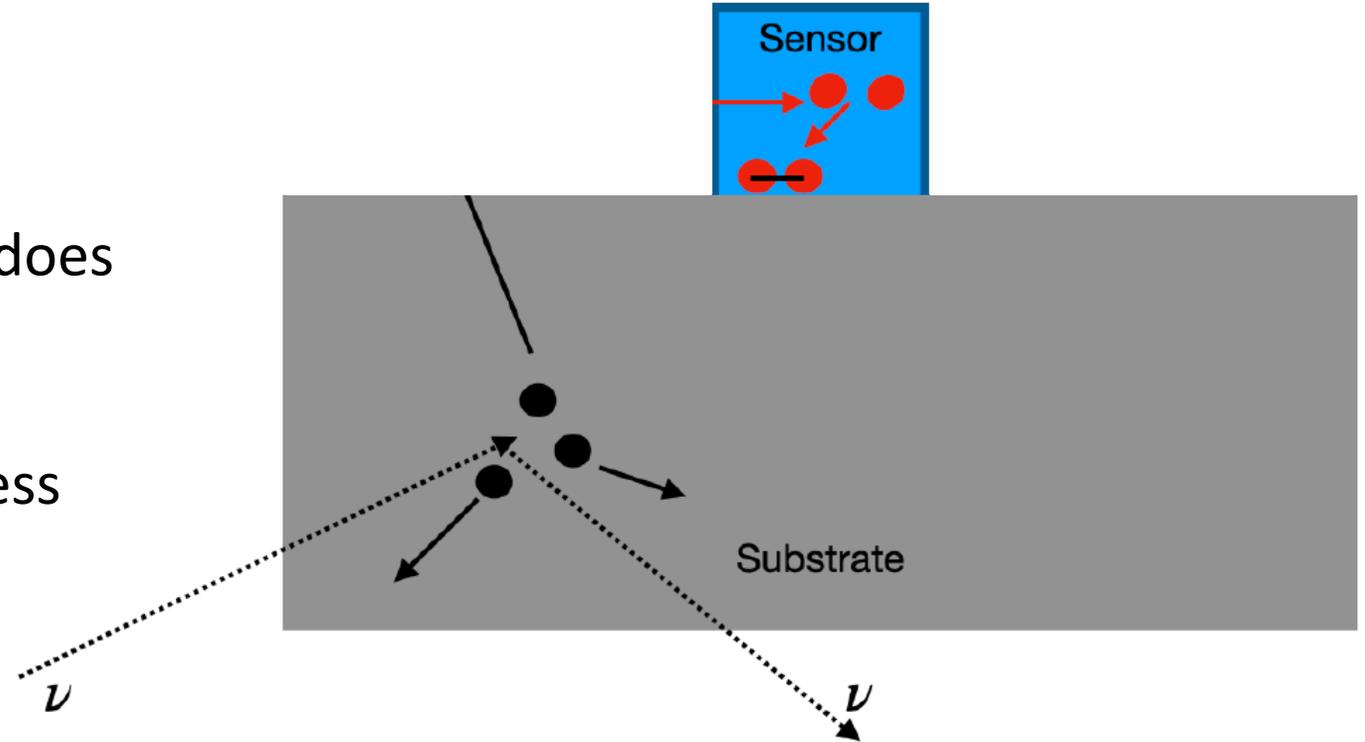
Thanks for the attention
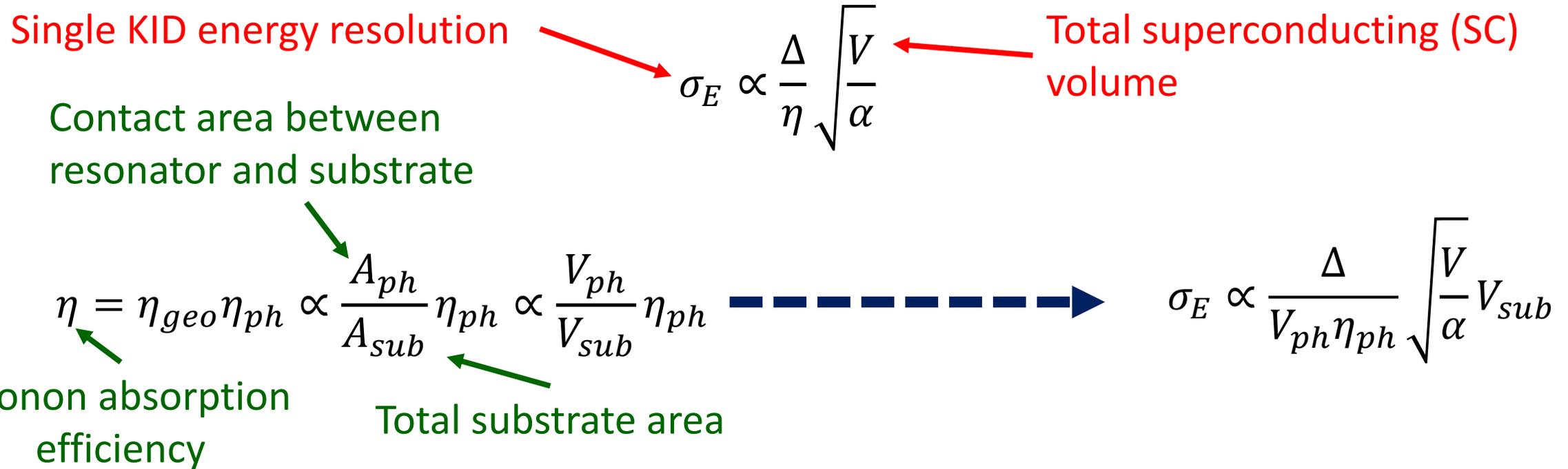
BACK-UP SLIDES

Summary

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

Total superconducting (SC) volume

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

Contact area between resonator and substrate

Phonon absorption efficiency

Total substrate area

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

- $V = V_{ph} = V_{sub} \rightarrow \sigma_E \propto 1/\sqrt{V}$ (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)

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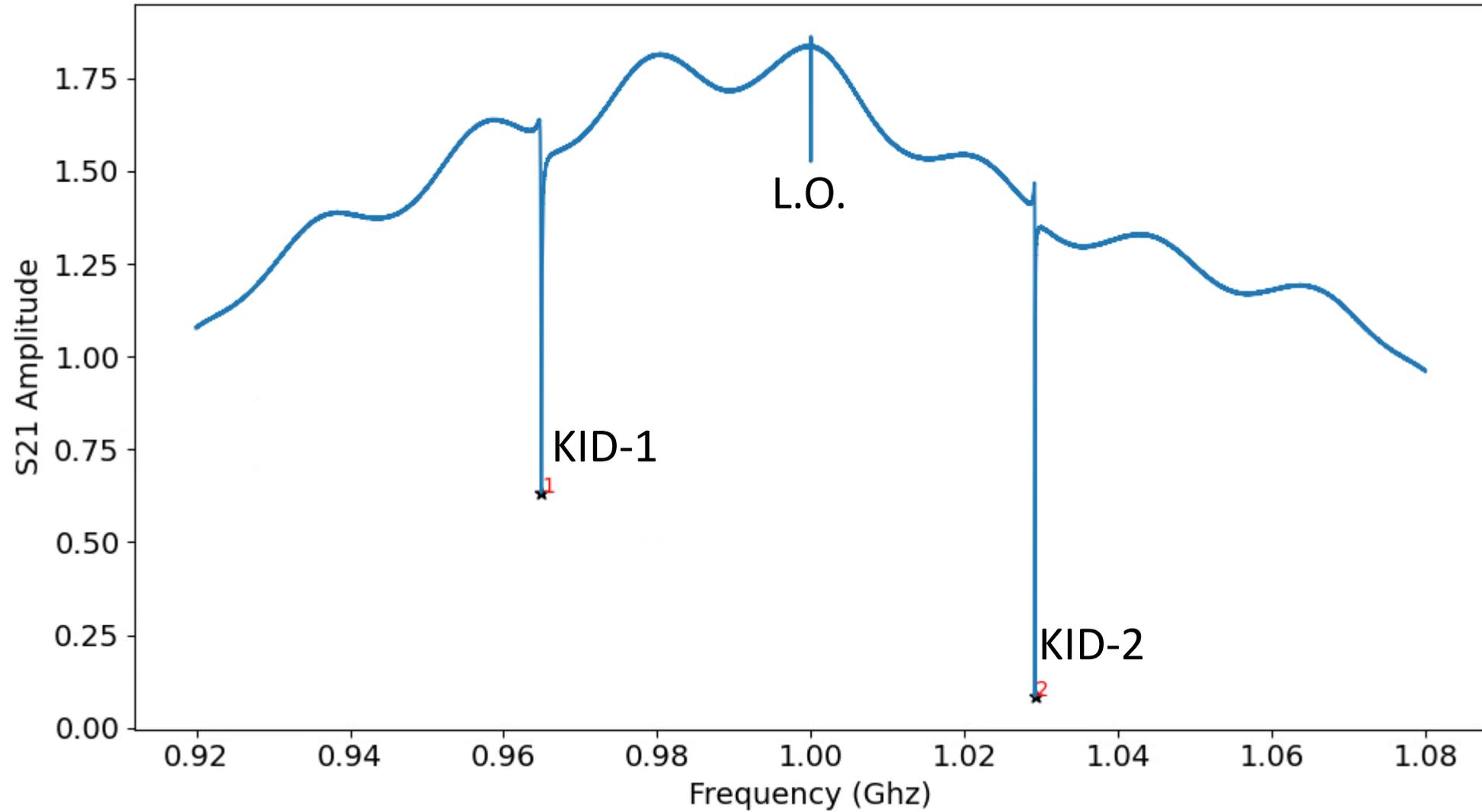
Phonon absorption efficiencies ratio

QP absorption efficiency (≈ 1 without funnels)

Sensor volume

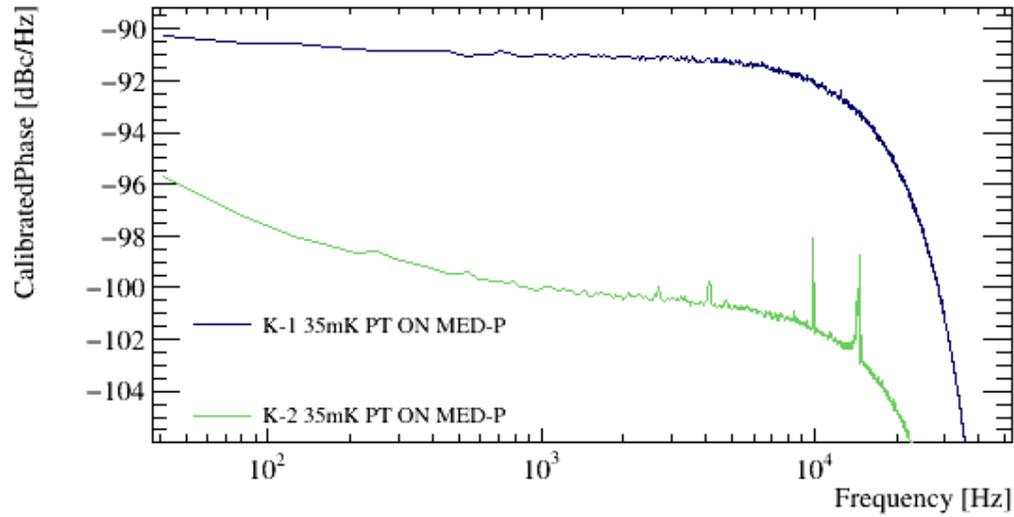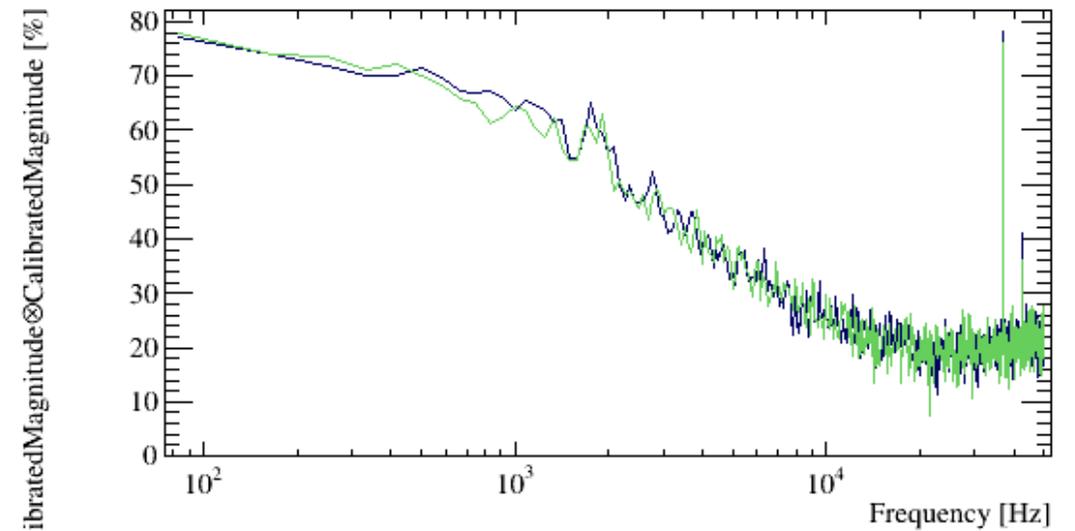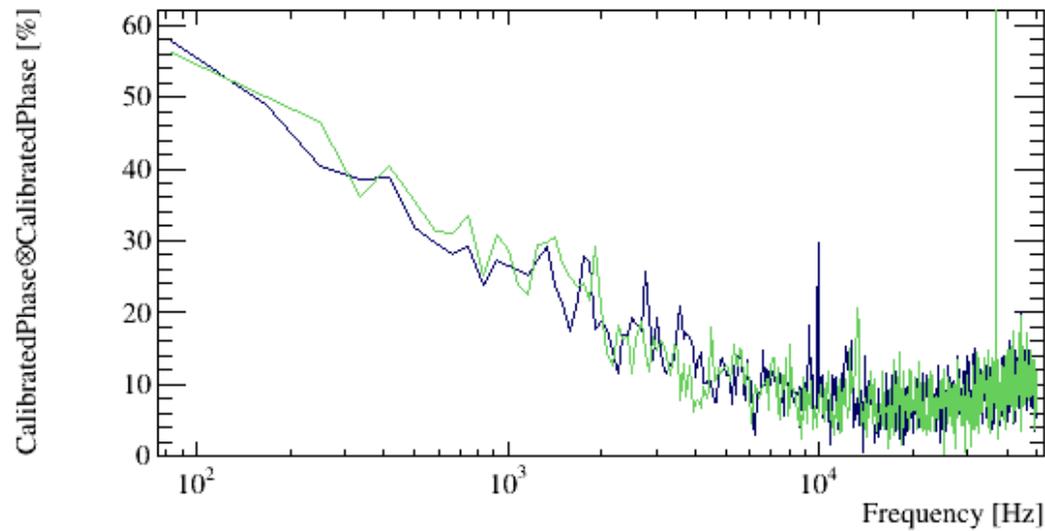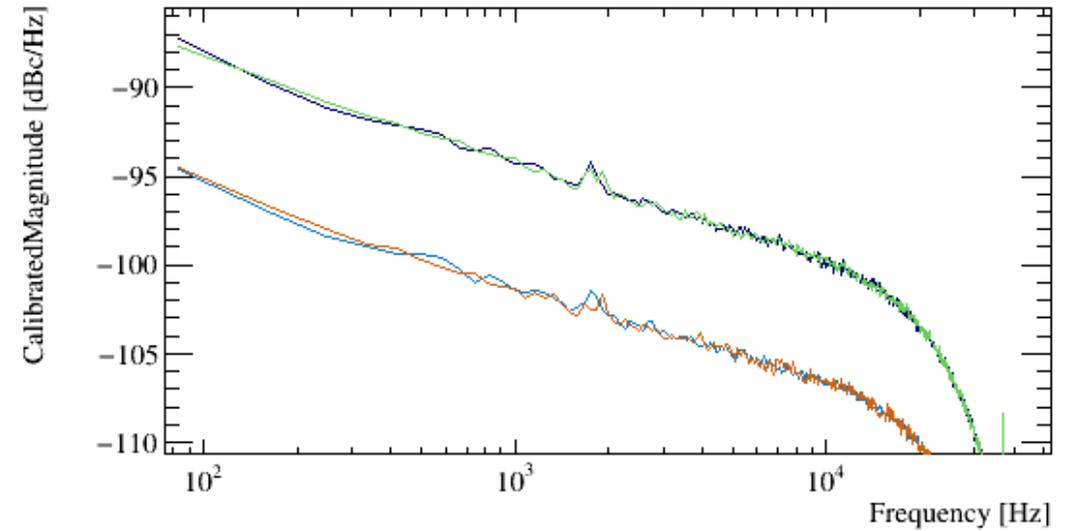- Deeper studies for AlTiAl feed-line and Al funnels parameters currently carried out
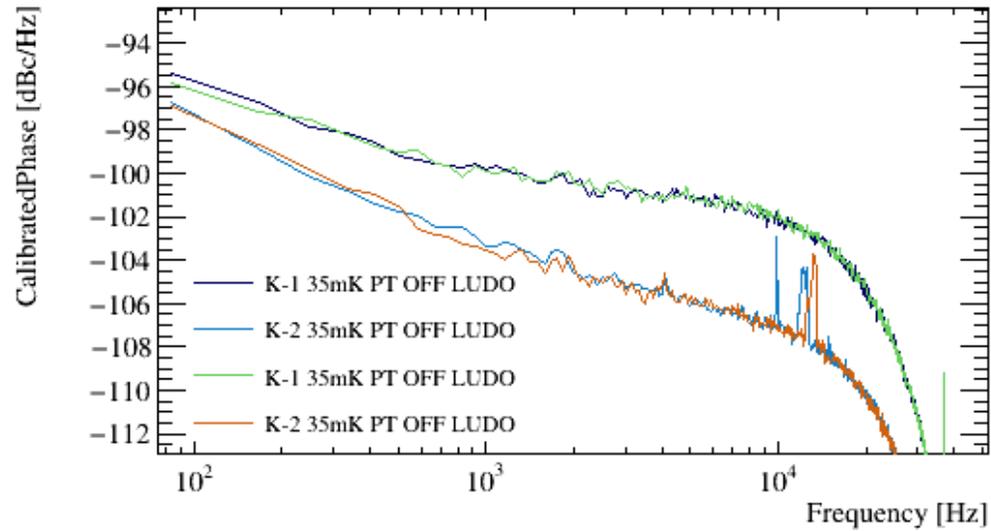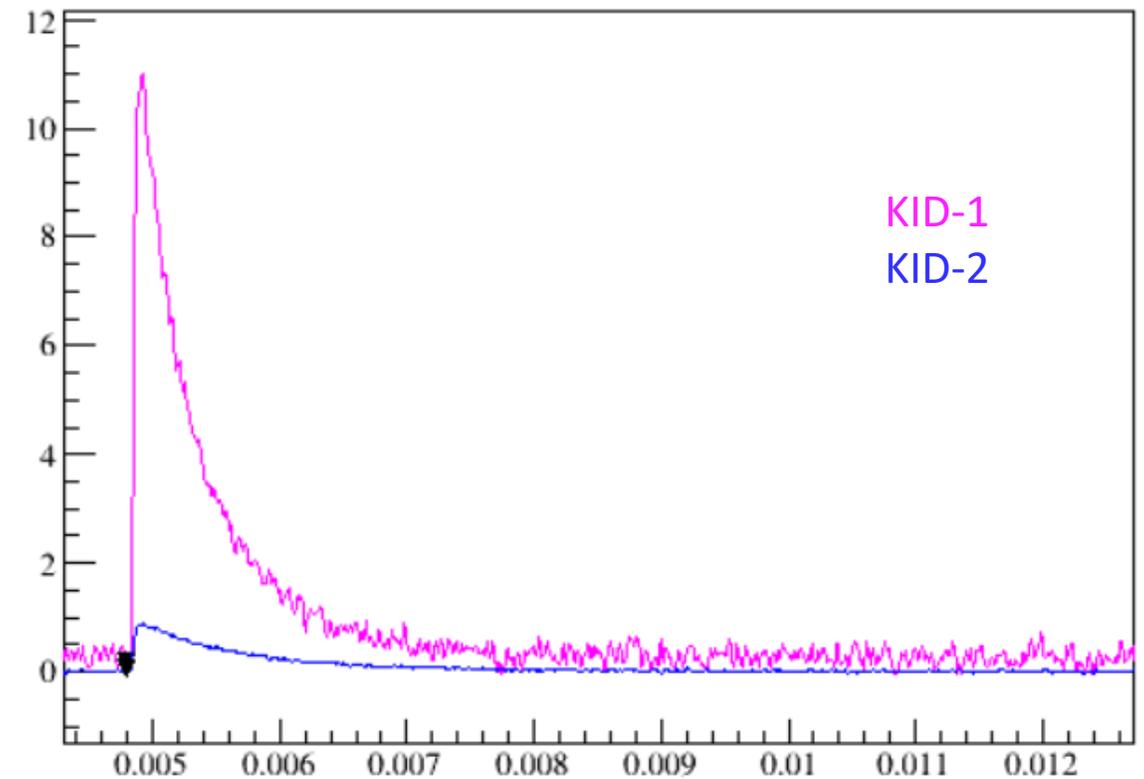
P150: VNA scan

Noise power spectrum - Low power (-21 dBm)
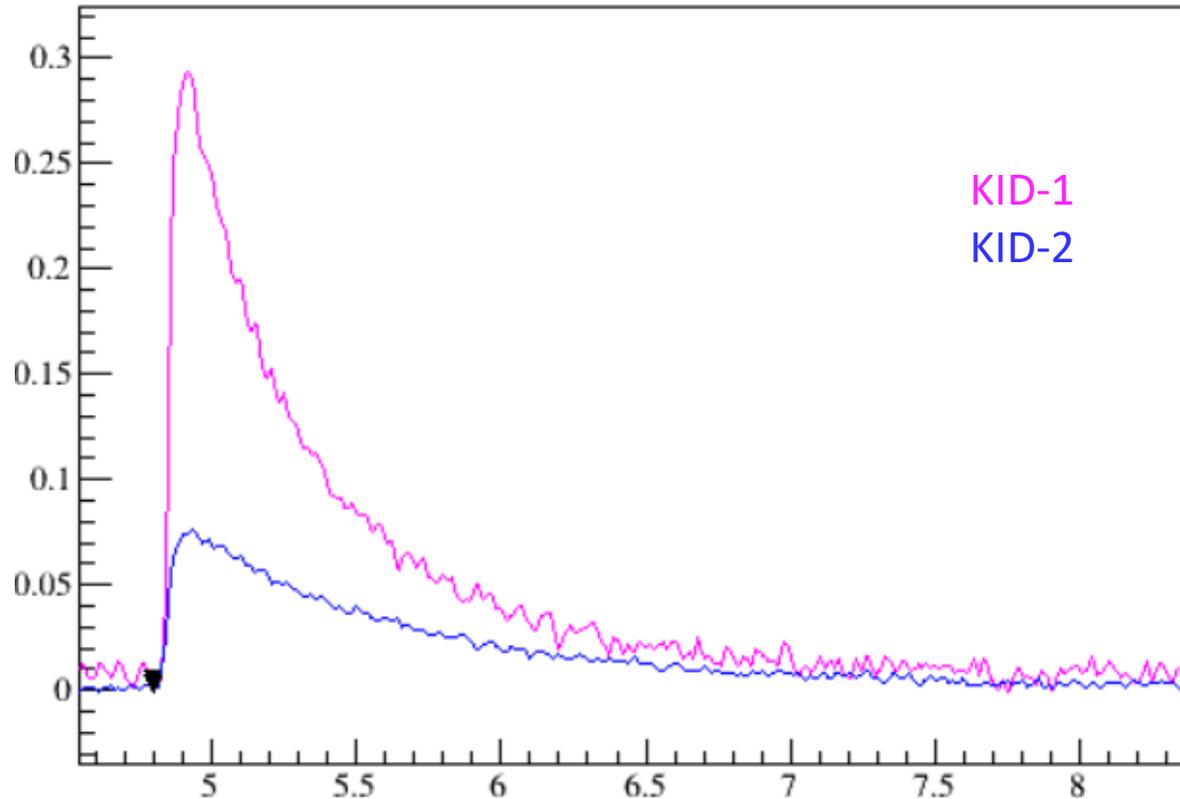
Noise power spectrum - Medium power (-16,-9 dBm)

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

$$(\Delta\phi)_1 / (\Delta\phi)_2 \approx 3.75 \longrightarrow (\Delta f)_1 / (\Delta f)_2 \approx 13.75$$
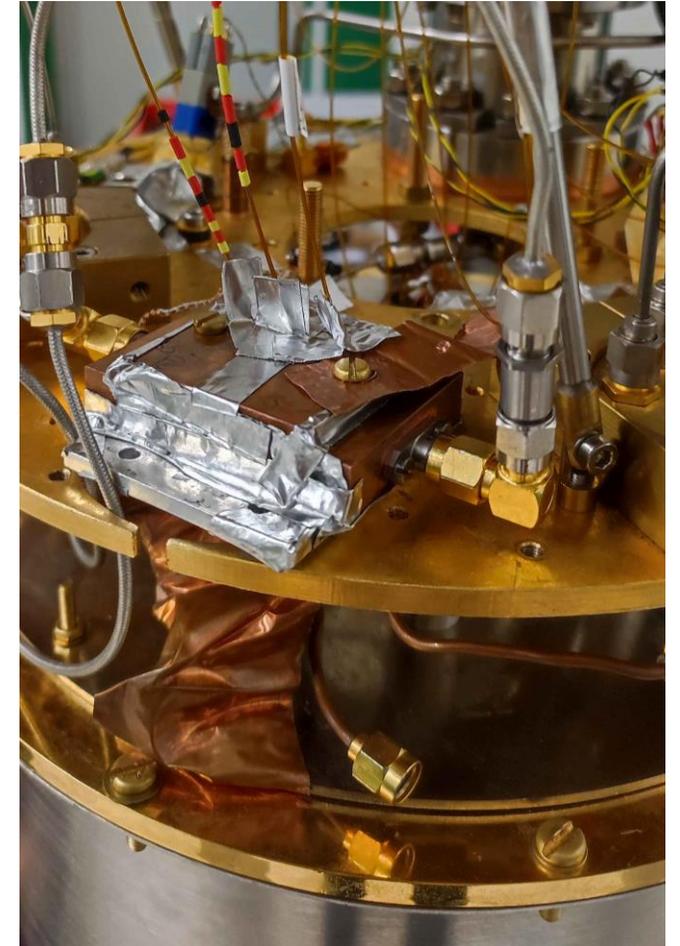
$$\frac{Q_1}{Q_2} \approx 3.67$$

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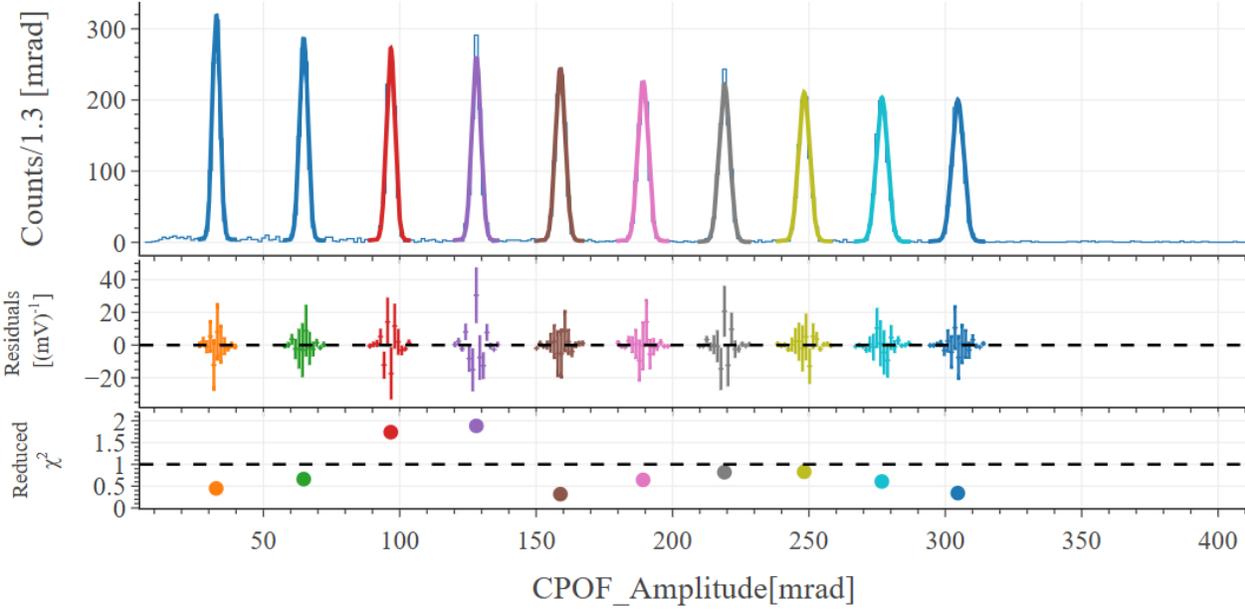
$$\sigma = \sqrt{m \times r + \sigma_0^2}$$

$$N_{ph} = \frac{m}{r} \rightarrow \sigma_{ph} = \sqrt{N_{ph} \times r}$$
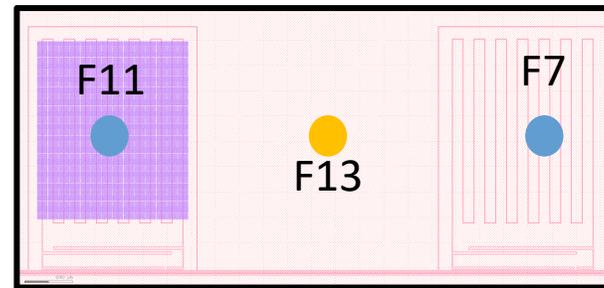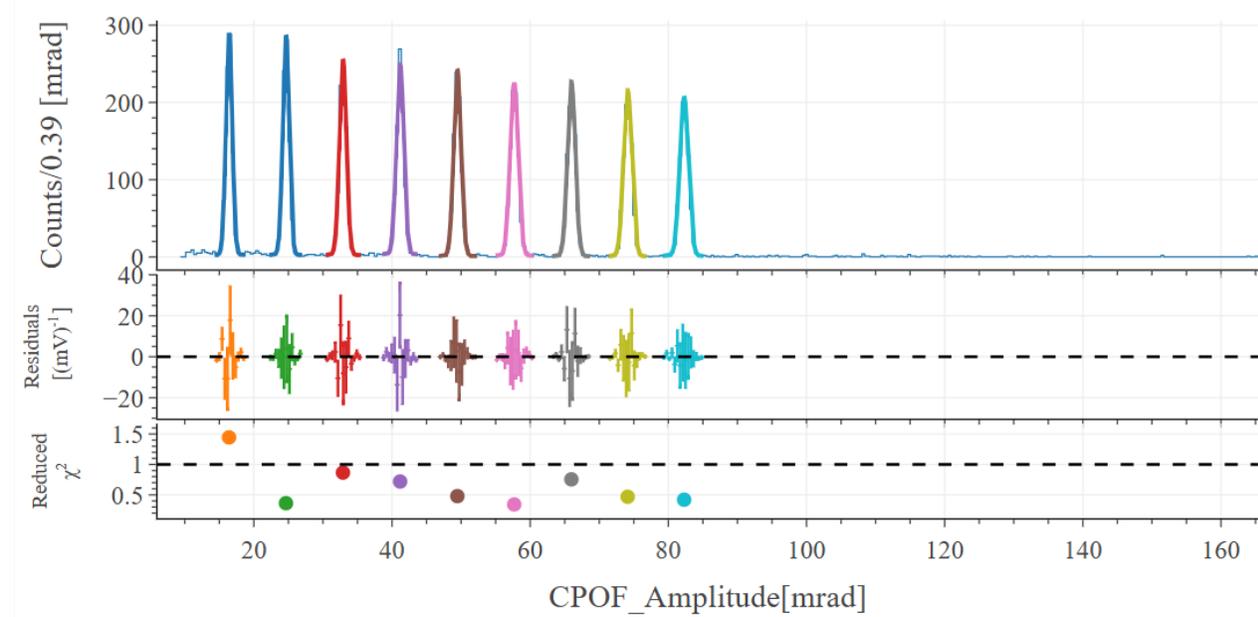
Baseline resolution
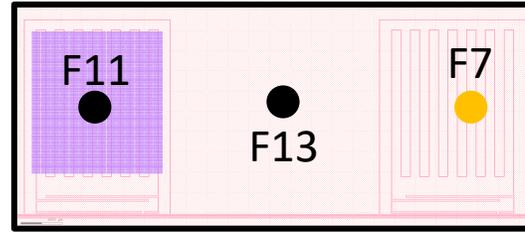
Optical Calibration (F13-Medium power)

KID-1

KID-2

KID-1

KID-2

Optical Calibration (F7-High power)

KID-FUNNEL

KID-NO_FUNNEL

Channel 2

Channel 1

Calibration Constant = (0.96 ± 0.12) keV/mrad
responsivity = (1.04 ± 0.13) mrad/keV
Noise_s0_eV = (346 ± 44) eV
photon_wavelength = (400 ± 8) nm
Reduced χ^2=2.21

Calibration Constant = (0.379 ± 0.039) keV/mrad
responsivity = (2.64 ± 0.27) mrad/keV
Noise_s0_eV = (254 ± 27) eV
photon_wavelength = (400 ± 8) nm
Reduced χ^2=0.755

$$\left(\frac{d\phi}{dE}\right)_7^{FUNNEL} = (1.04 \pm 0.13) \text{ mrad/keV}$$
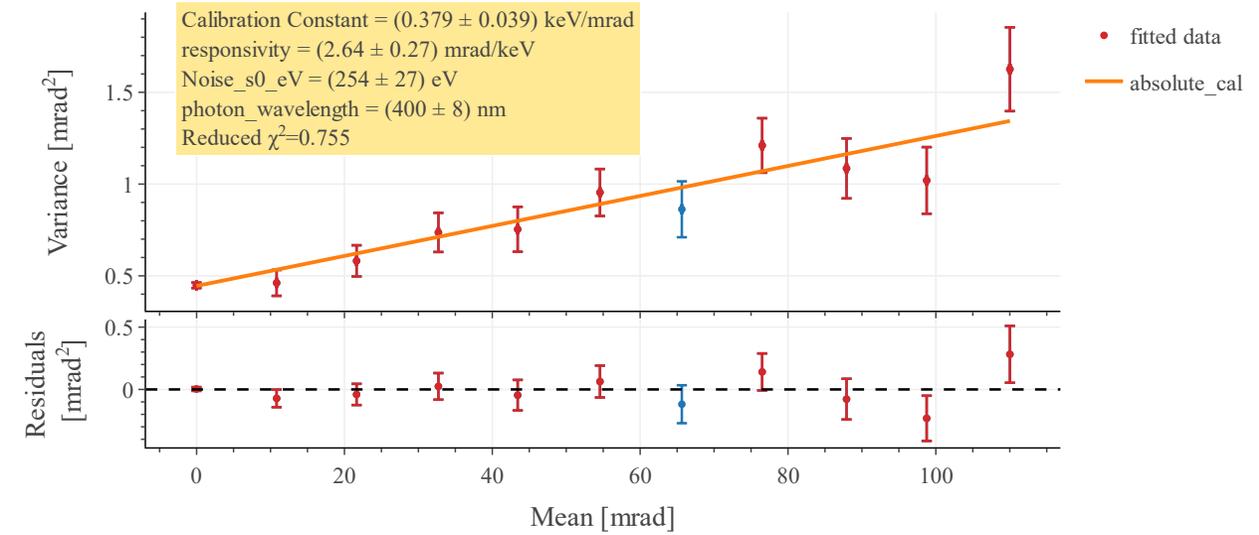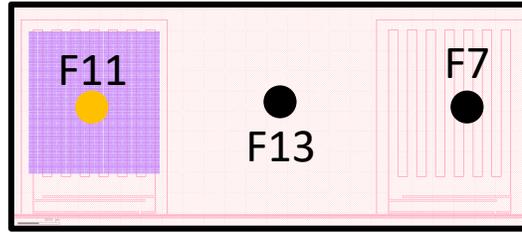
$$\left(\frac{d\phi}{dE}\right)_7^{NO\_FUNNEL} = (2.64 \pm 0.27) \text{ mrad/keV}$$

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

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

Optical Calibration (F11-High power)

KID-FUNNEL
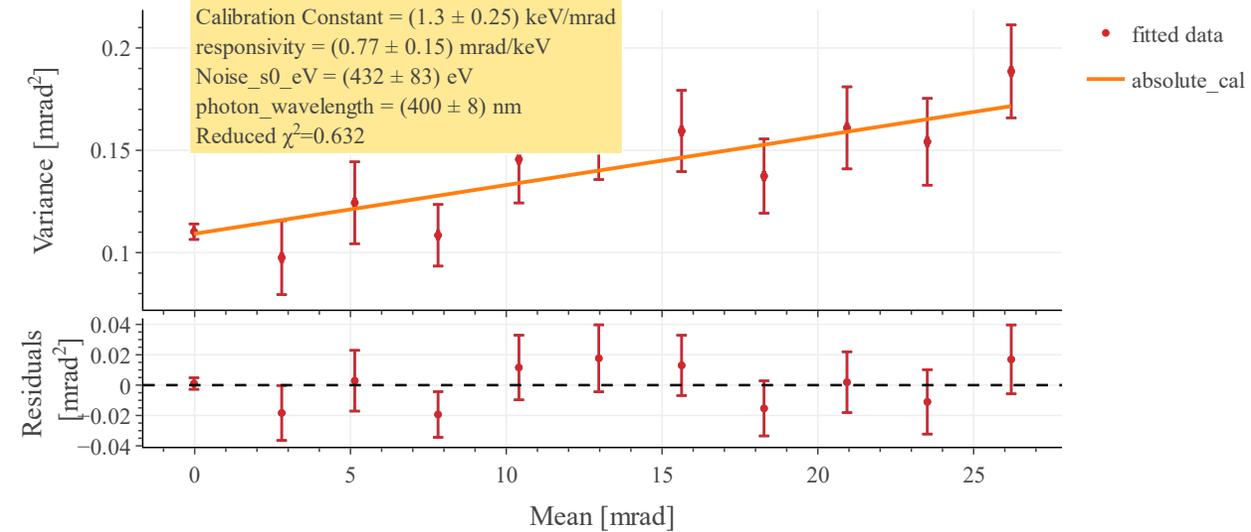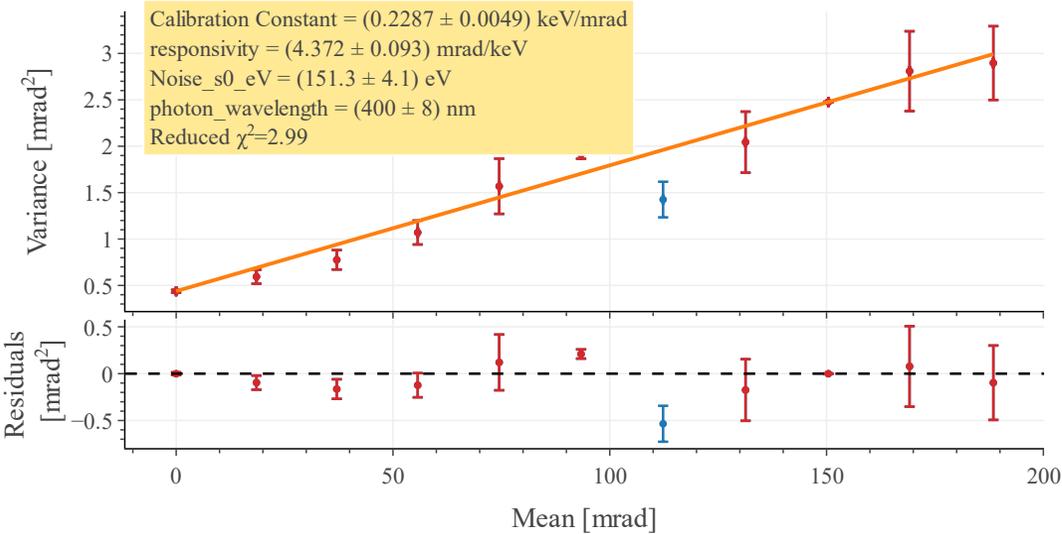### Channel 1

Calibration Constant = (0.2287 ± 0.0049) keV/mrad
responsivity = (4.372 ± 0.093) mrad/keV
Noise_s0_eV = (151.3 ± 4.1) eV
photon_wavelength = (400 ± 8) nm
Reduced χ^2=2.99

KID-NO_FUNNEL
Channel 2

Calibration Constant = (1.3 ± 0.25) keV/mrad
responsivity = (0.77 ± 0.15) mrad/keV
Noise_s0_eV = (432 ± 83) eV
photon_wavelength = (400 ± 8) nm
Reduced χ^2=0.632

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

$$\left(\frac{d\phi}{dE}\right)^{NO\_FUNNEL}_{11} = (0.77 \pm 0.15) \text{ mrad/keV}$$

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

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

Optical Calibration (F13-Medium power)

$$\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL} = (3.19 \pm 0.14) \text{ mrad/keV}$$
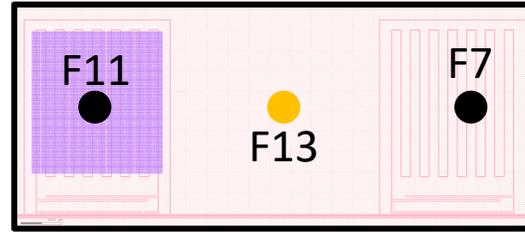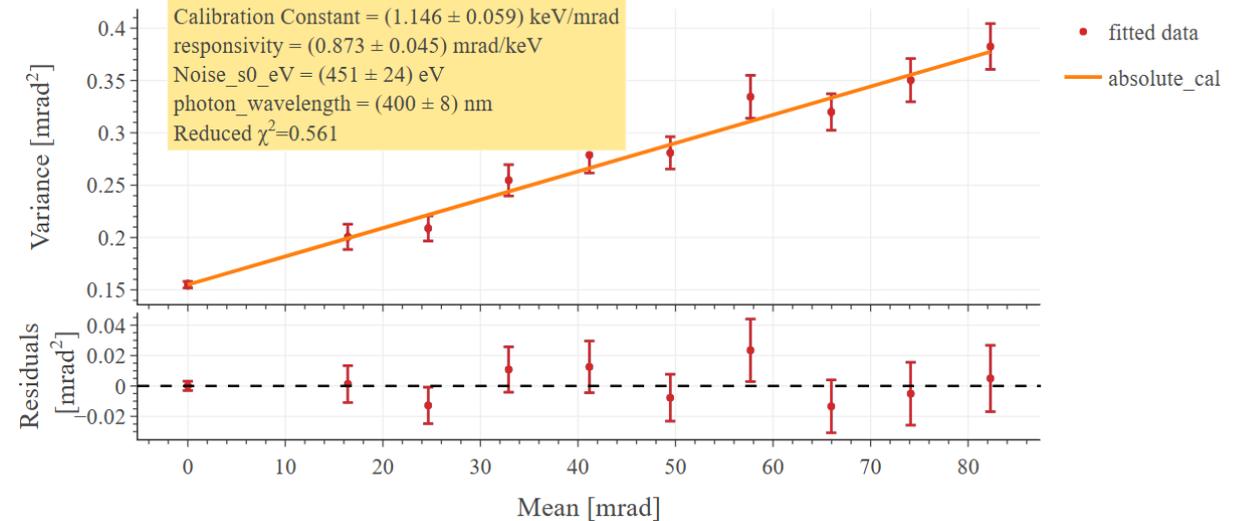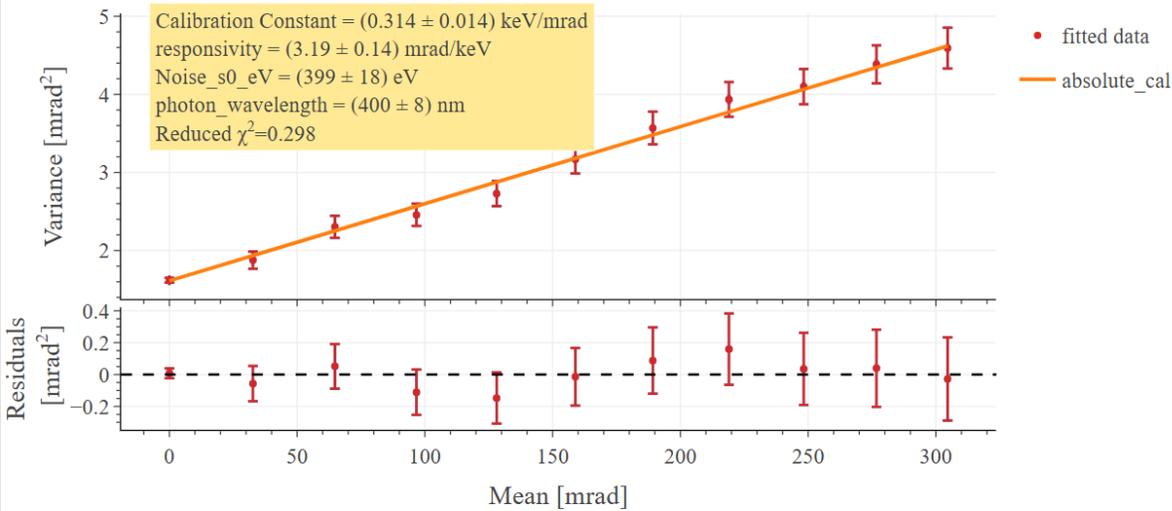
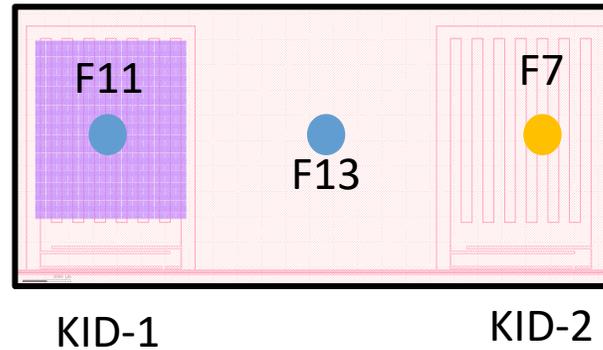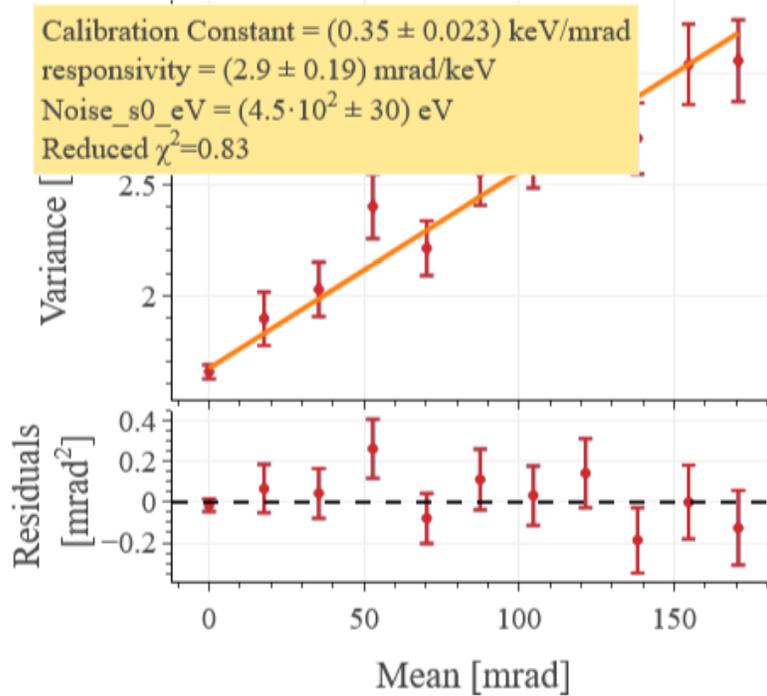$$\left(\frac{d\phi}{dE}\right)_{13}^{NO\_FUNNEL} = (0.87 \pm 0.04) \text{ mrad/keV}$$
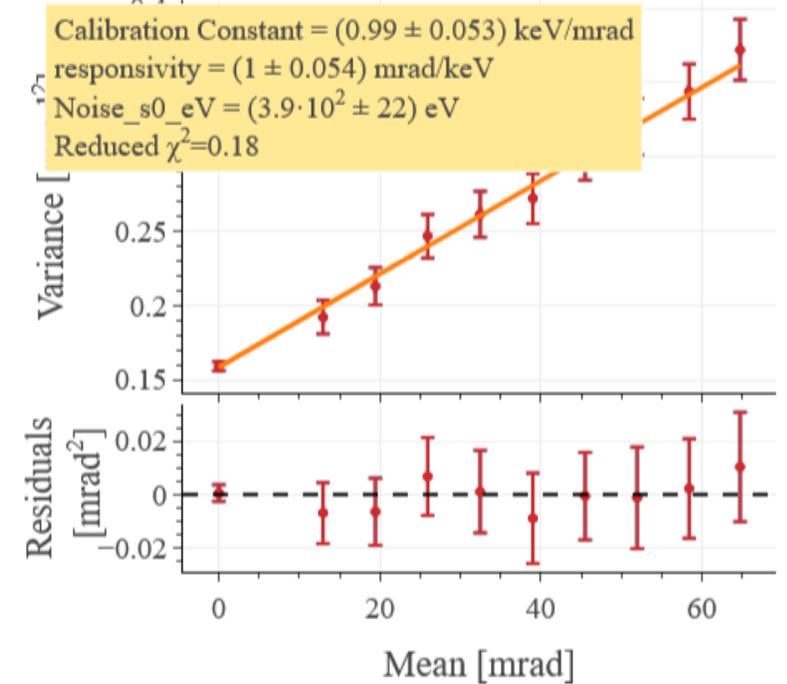
$$\sigma_{0,13}^{FUNNEL} = (399 \pm 18) \text{ eV}$$

$$\sigma_{0,13}^{NO\_FUNNEL} = (451 \pm 24) \text{ eV}$$

Optical Calibration (F7-Medium power)

KID-FUNN

KID-NO_F

Calibration Constant = (0.35 ± 0.023) keV/mrad
responsivity = (2.9 ± 0.19) mrad/keV
Noise_s0_eV = $(4.5 \cdot 10^2 \pm 30)$ eV
Reduced χ^2=0.83

Calibration Constant = (0.99 ± 0.053) keV/mrad
responsivity = (1 ± 0.054) mrad/keV
Noise_s0_eV = $(3.9 \cdot 10^2 \pm 22)$ eV
Reduced χ^2=0.18

F11

F13

F7

KID-1

KID-2

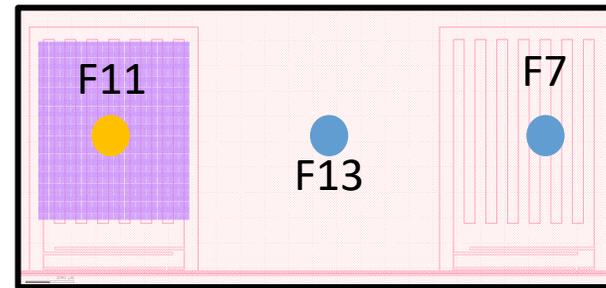$$\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL} = (2.90 \pm 0.19) \text{ mrad/keV}$$

$$\left(\frac{d\phi}{dE}\right)_{13}^{NO\_FUNNEL} = (1.00 \pm 0.05) \text{ mrad/keV}$$

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

$$\sigma_{0,13}^{NO\_FUNNEL} = (390 \pm 22) \text{ eV}$$

Optical Calibration (F11-Medium power)

KID-1

KID-2

Calibration Constant = (0.23 ± 0.011) keV/mrad
responsivity = (4.3 ± 0.2) mrad/keV
Noise_s0_eV = $(2.9 \cdot 10^2 \pm 14)$ eV
Reduced $\chi^2 = 1.5$

Calibration Constant = (2.1 ± 0.16) keV/mrad
responsivity = (0.48 ± 0.037) mrad/keV
Noise_s0_eV = $(8.3 \cdot 10^2 \pm 65)$ eV
Reduced $\chi^2 = 0.76$

KID-1

KID-2

$$\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL} = (4.30 \pm 0.20) \text{ mrad/keV}$$
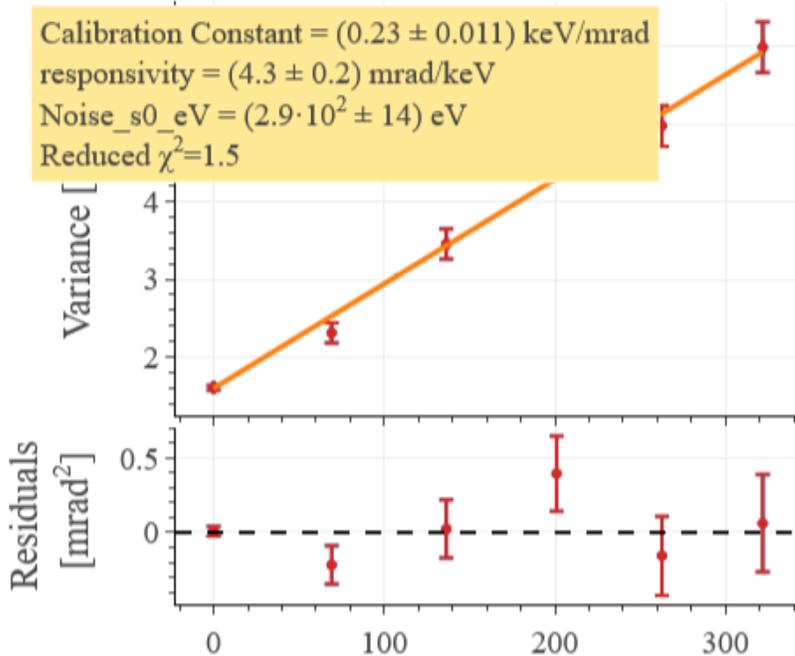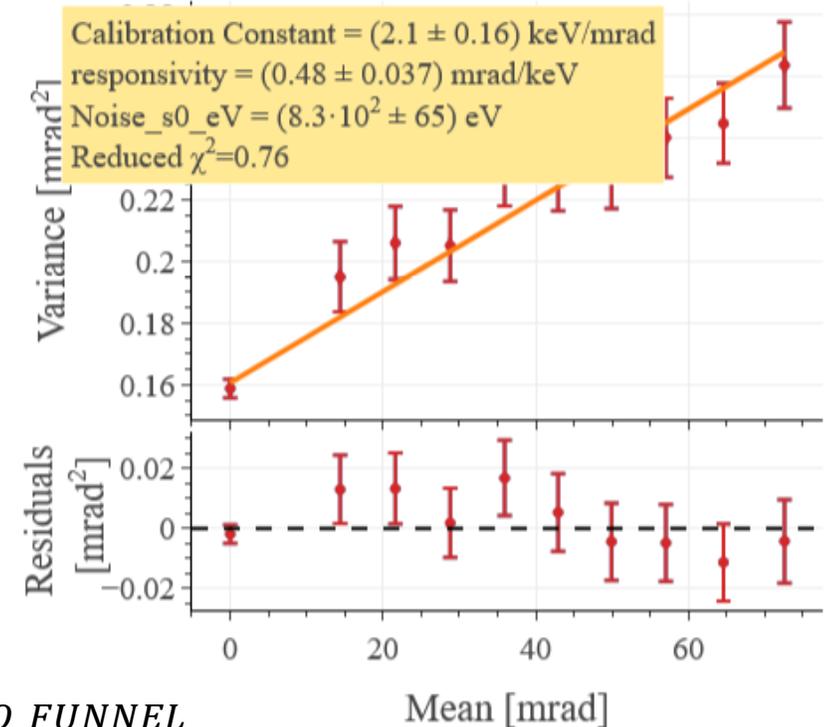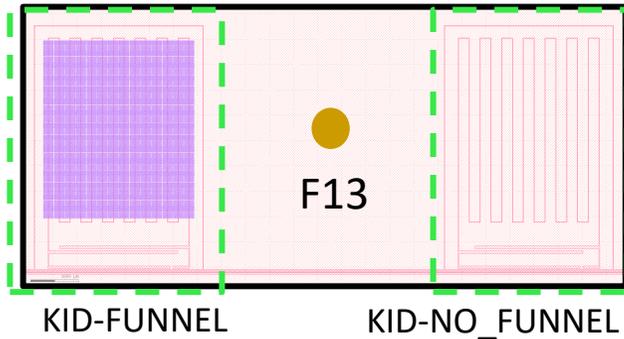
$$\left(\frac{d\phi}{dE}\right)_{13}^{NO\_FUNNEL} = (0.48 \pm 0.04) \text{ mrad/keV}$$
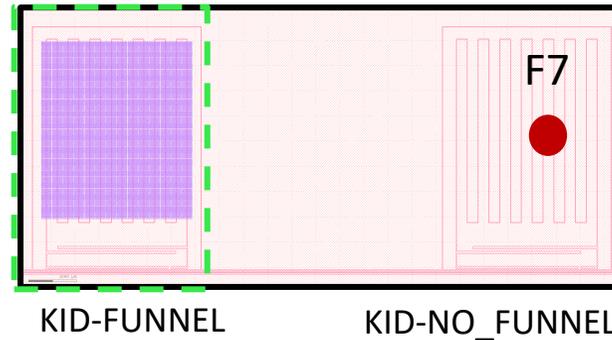
$$\sigma_{0,13}^{FUNNEL} = (290 \pm 14) \text{ eV}$$

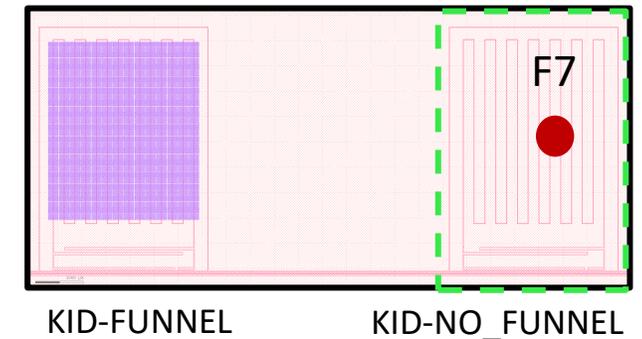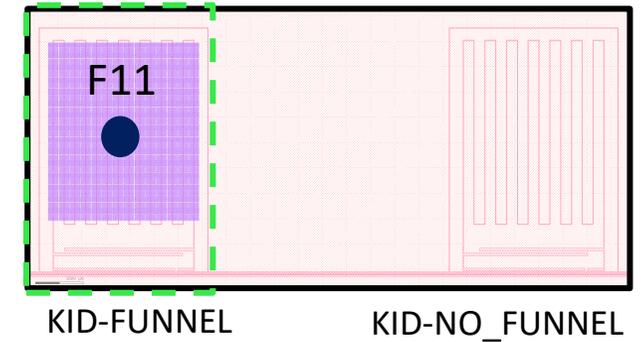$$\sigma_{0,13}^{NO\_FUNNEL} = (830 \pm 65) \text{ eV}$$

Optical Calibration: medium power responsivities

KID-FUNNEL   KID-NO_FUNNEL

F13

$$\frac{\left(\frac{d\phi}{dE}\right)_{13}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{13}^{NO\_FUNNEL}} = 3.67 \pm 0.23$$

F7

KID-FUNNEL   KID-NO_FUNNEL

F11

KID-FUNNEL   KID-NO_FUNNEL

$$\frac{\left(\frac{d\phi}{dE}\right)_{7}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{11}^{NO\_FUNNEL}} = 6.04 \pm 0.61$$

F11

KID-FUNNEL   KID-NO_FUNNEL

F7

KID-FUNNEL   KID-NO_FUNNEL

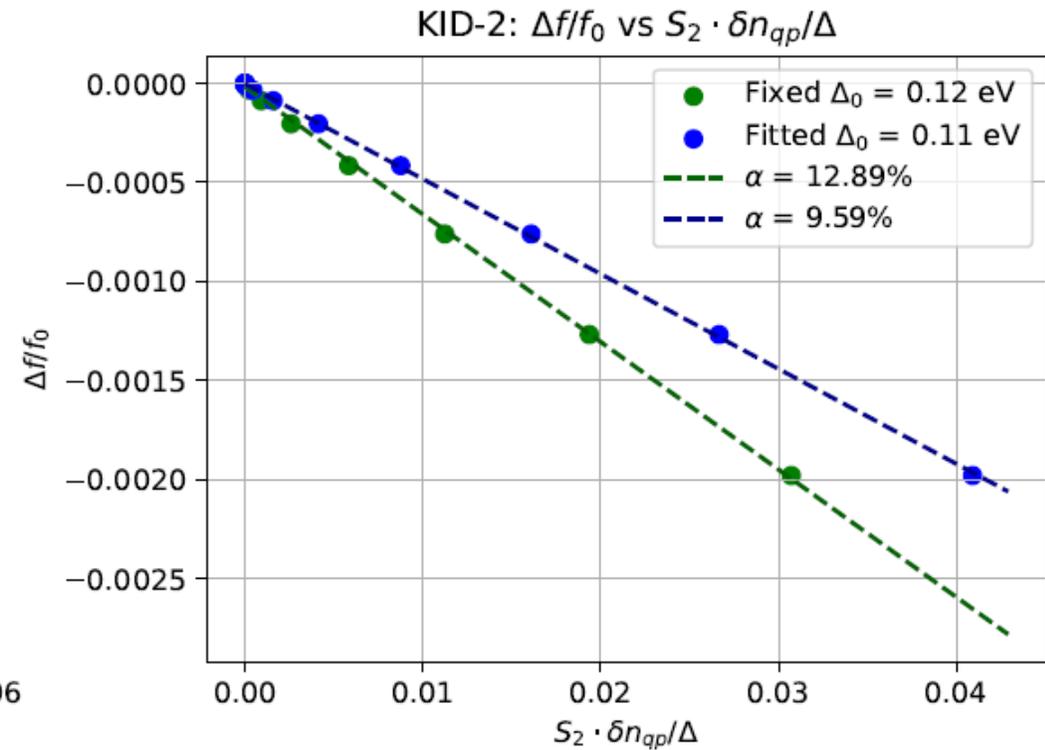$$\frac{\left(\frac{d\phi}{dE}\right)_{11}^{FUNNEL}}{\left(\frac{d\phi}{dE}\right)_{7}^{NO\_FUNNEL}} = 4.30 \pm 0.31$$

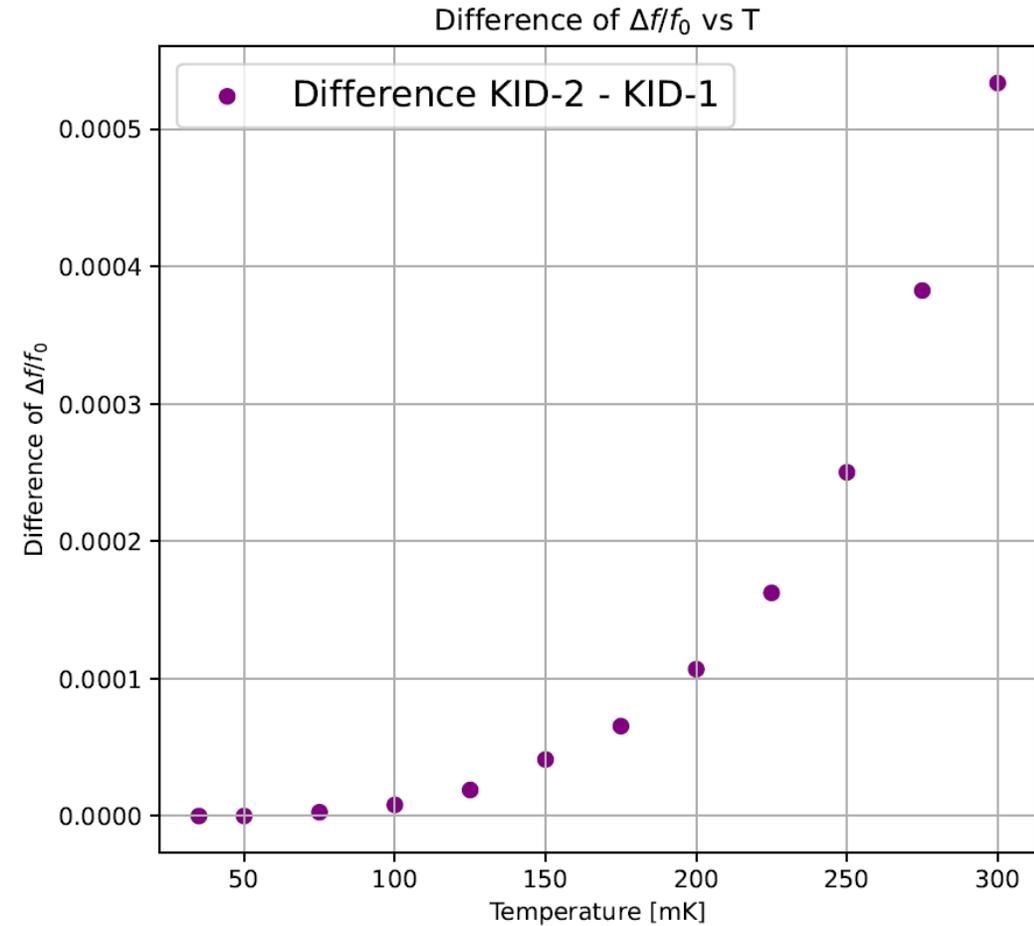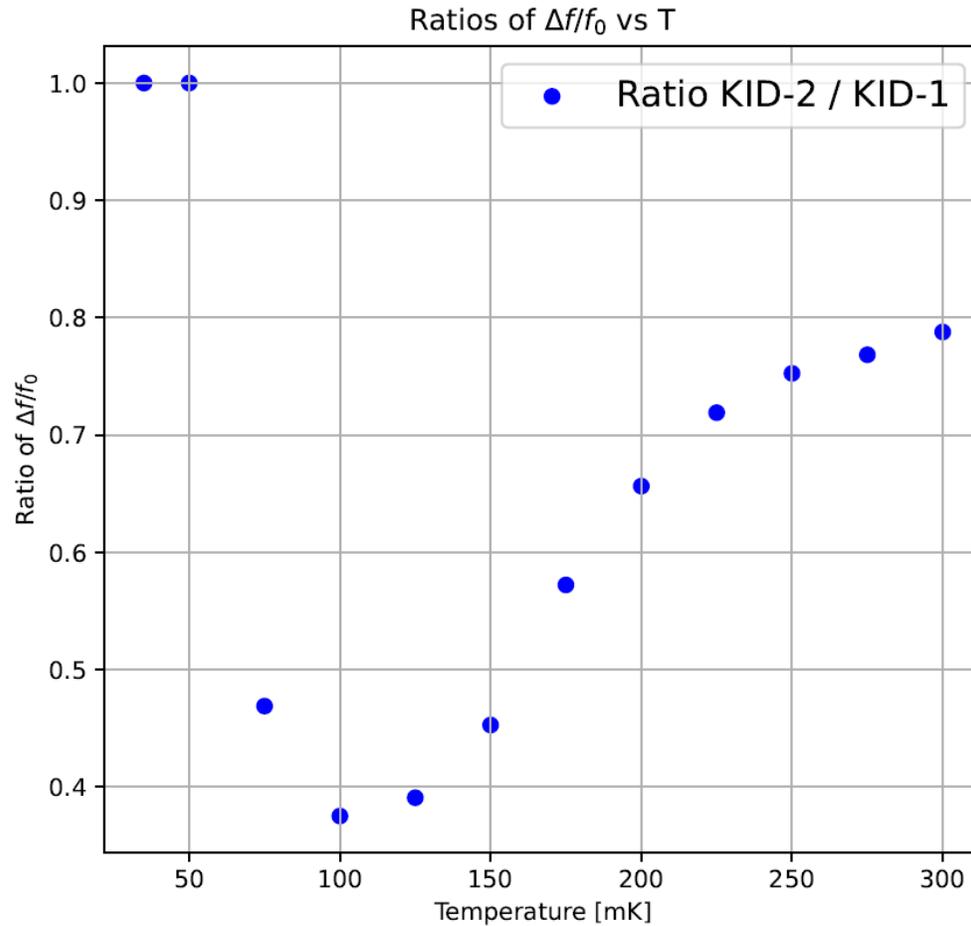# Temperature scan: $\Delta f / f_0$ vs n_{qp}

Linear trend observed

KID-1: $\Delta f/f_0$ vs $S_2 \cdot \delta n_{qp}/\Delta$

- Fixed $\Delta_0 = 0.12$ eV
- Fitted $\Delta_0 = 0.10$ eV
- $\alpha = 16.32\%$
- $\alpha = 8.88\%$

KID-2: $\Delta f/f_0$ vs $S_2 \cdot \delta n_{qp}/\Delta$

- Fixed $\Delta_0 = 0.12$ eV
- Fitted $\Delta_0 = 0.11$ eV
- $\alpha = 12.89\%$
- $\alpha = 9.59\%$

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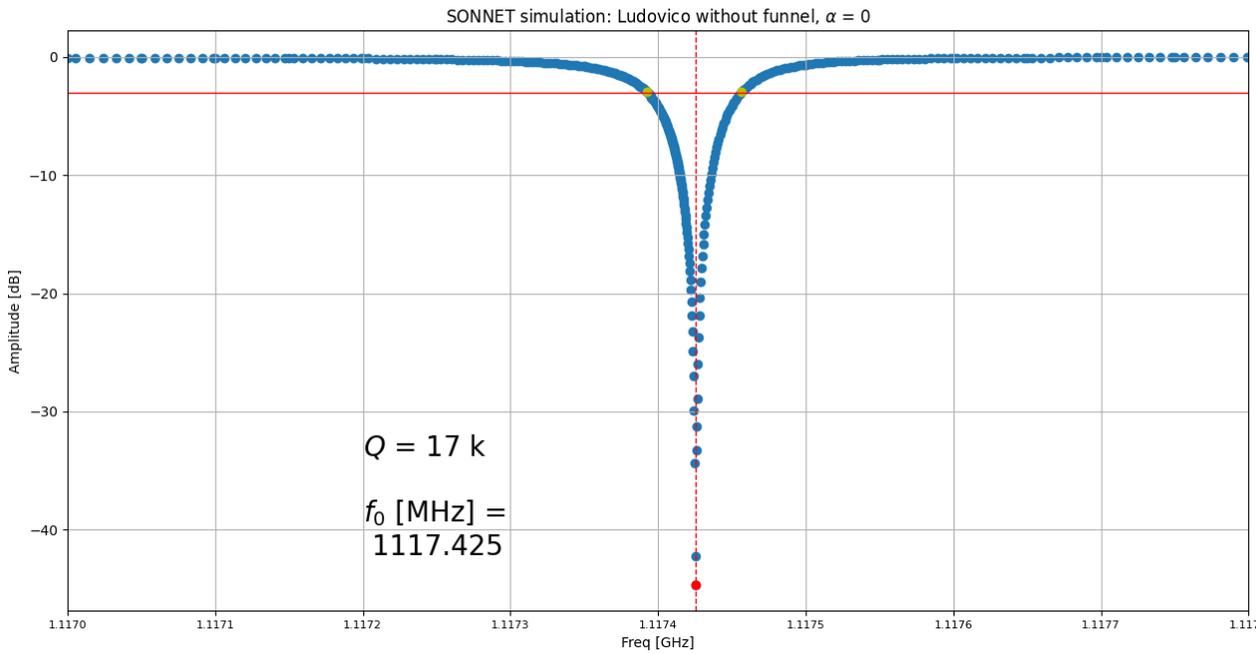
- $\alpha^{\Delta,fitted} \approx (16.32 \pm 0.01)\%$

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

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

Temperature scan: KIDs comparison

Ratios of $\Delta f/f_0$ vs T

Difference of $\Delta f/f_0$ vs T

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

SONNET simulation: results KID-2

SONNET simulation: Ludovico without funnel, $\alpha = 0$

$Q = 17$ k

f_0 [MHz] = 1117.425

SONNET simulation: Ludovico without funnel, $L_k = 1.40$ pH/sq

$Q = 19$ k

f_0 [MHz] = 1033.081

$L_k = 0$ (lossless)

$Q_c \approx 17k$

$f_0 = 1117.425$ MHz

$L_k = 1.4$ pH/sq
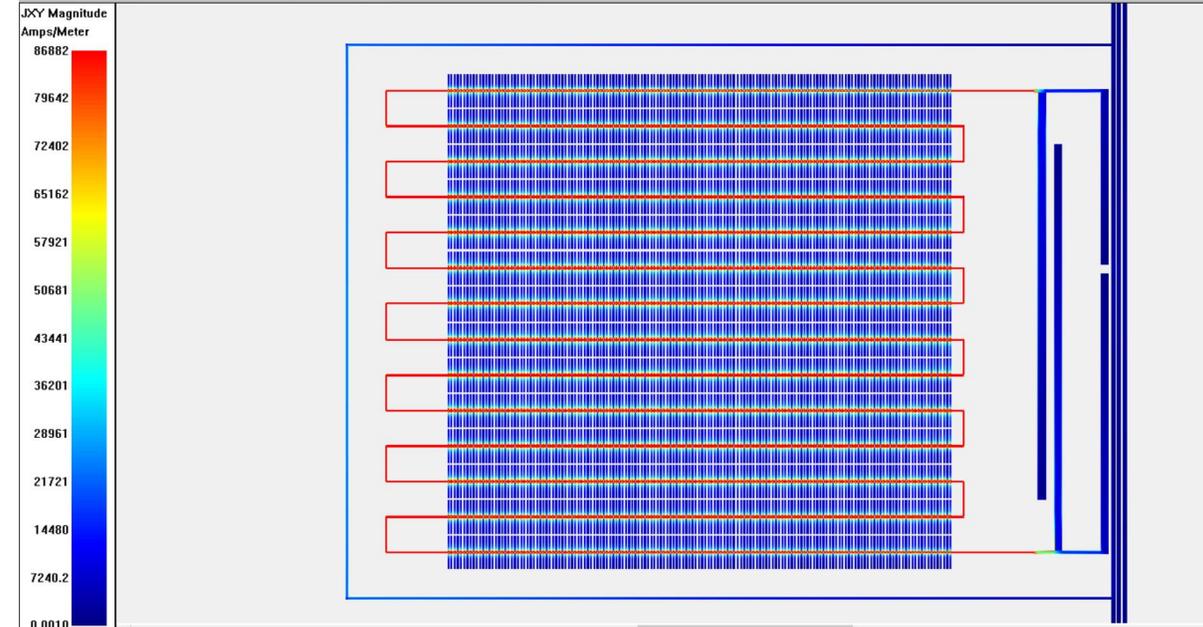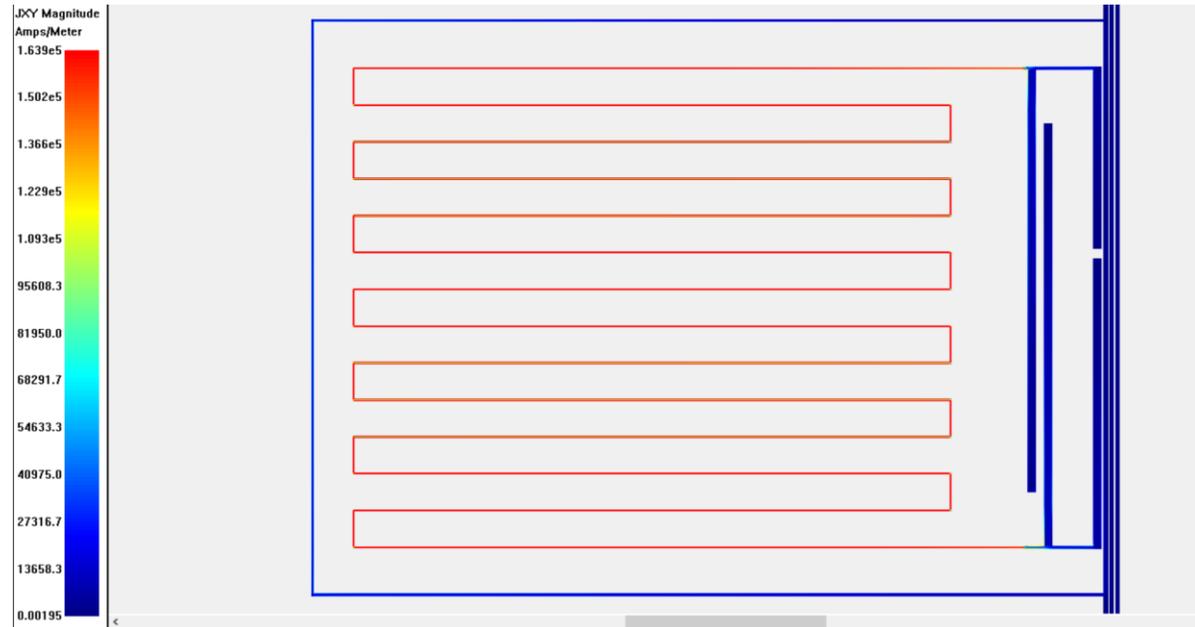
$Q_c \approx 19k$

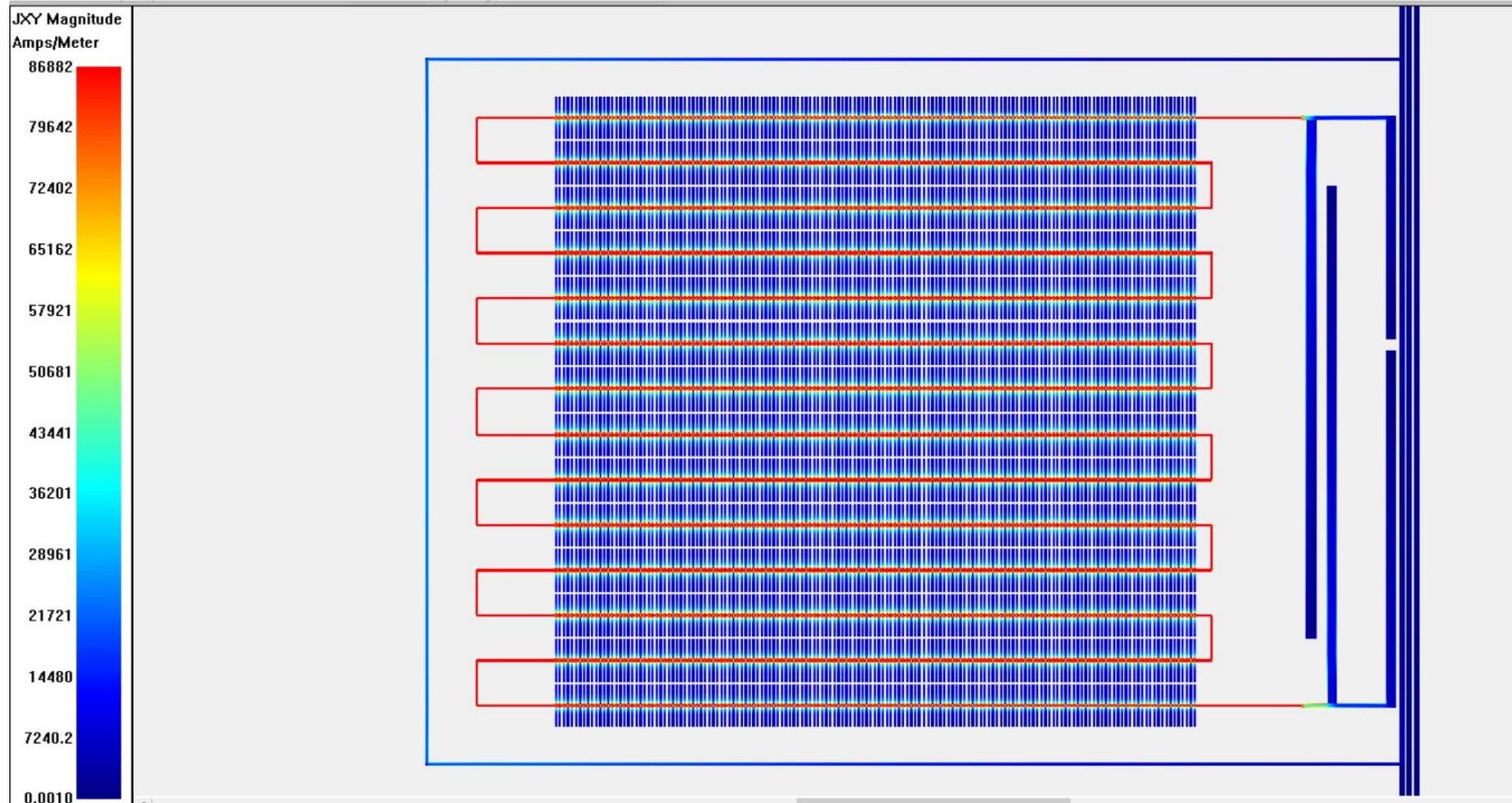$f_0 \approx 1033.081 MHz$

SONNET simulation: resonances

KID-1

KID-2
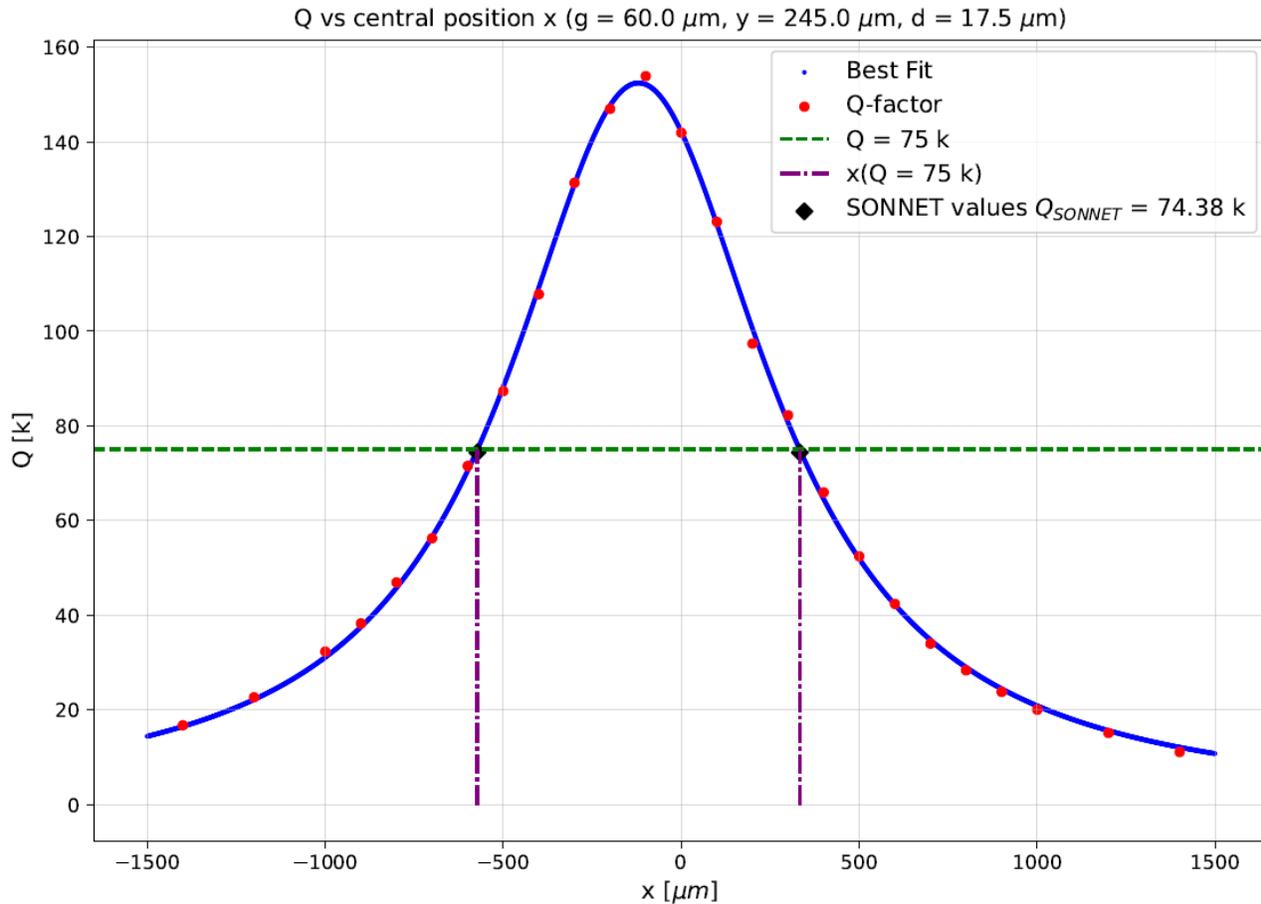

- Currents at resonances

- 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

Q vs central position x (g = 60.0 μm, y = 245.0 μm, d = 17.5 μm)

Legend:
- Best Fit
- Q-factor
- Q = 75 k
- x(Q = 75 k)
- SONNET values Q_{SONNET} = 74.38 k
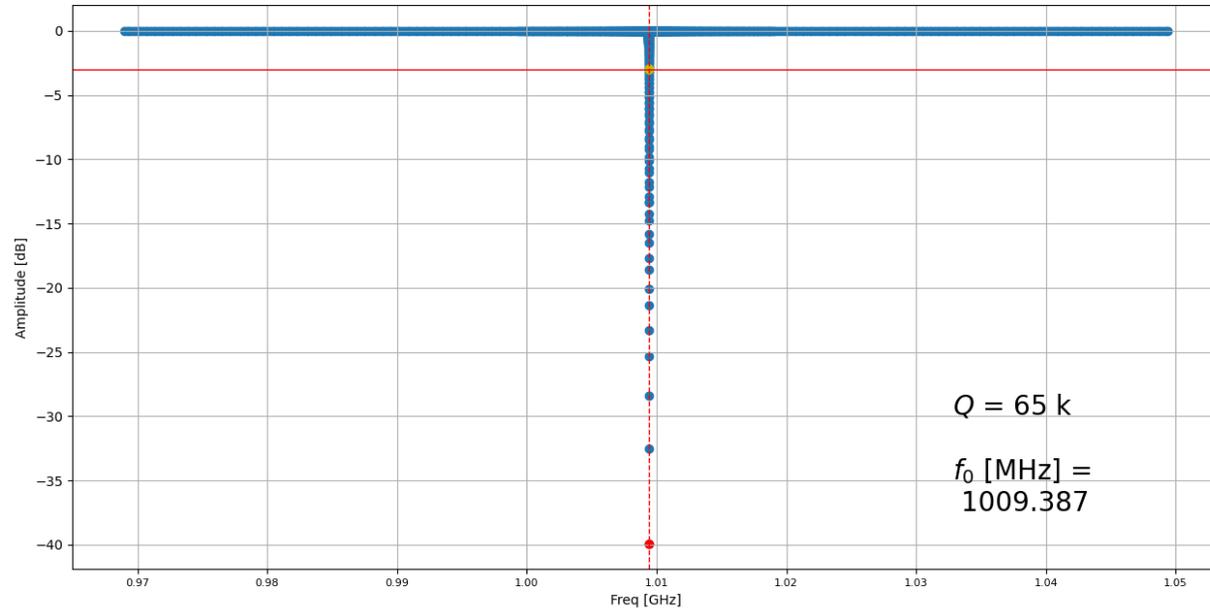
- **Lorentzian dependence simulated**

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

- **Best fit parameters:**

  - $Q_c = (213.37 \pm 0.94)$k

  - $\bar{x} = (-119.97 \pm 1.83)\mu m$
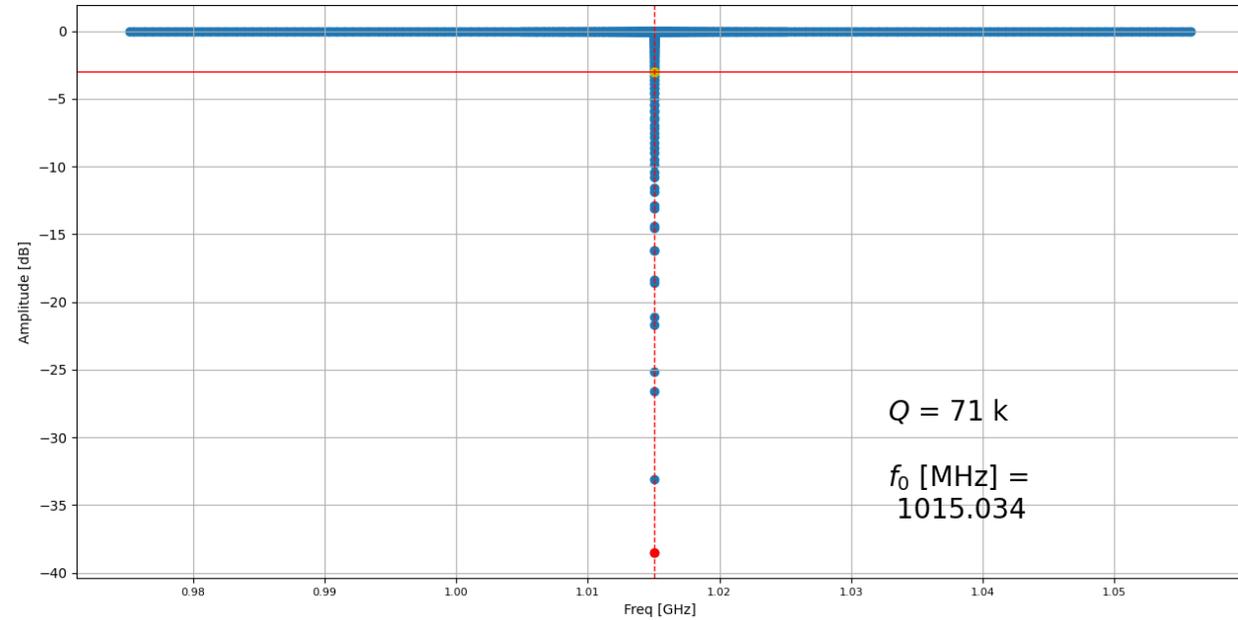
  - $\sigma_x = (445.44 \pm 2.79)\mu m$

SONNET simulation: preliminary results

KID-FUNNEL

$Q = 65$ k

f_0 [MHz] = 1009.387

KID-NO_FUNNEL

$Q = 71$ k

f_0 [MHz] = 1015.034

- $f_0 = 1009.39$ MHz

- $Q_c = 65$k

- $\alpha = ??$ (in progress)
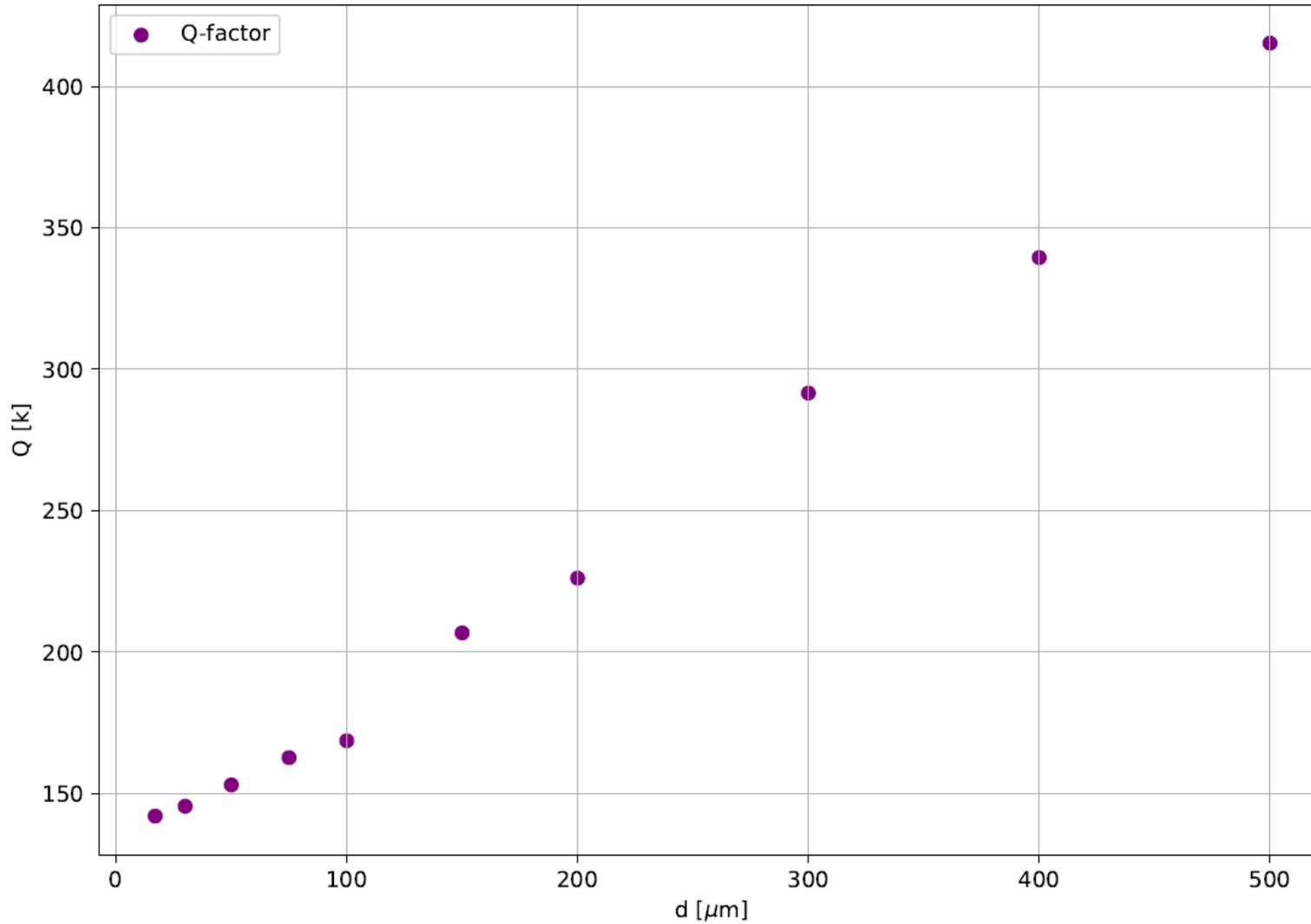
- $f_0 = 1015.03$ MHz

- $Q_c = 71$k

- $\alpha = ??$ (in progress)
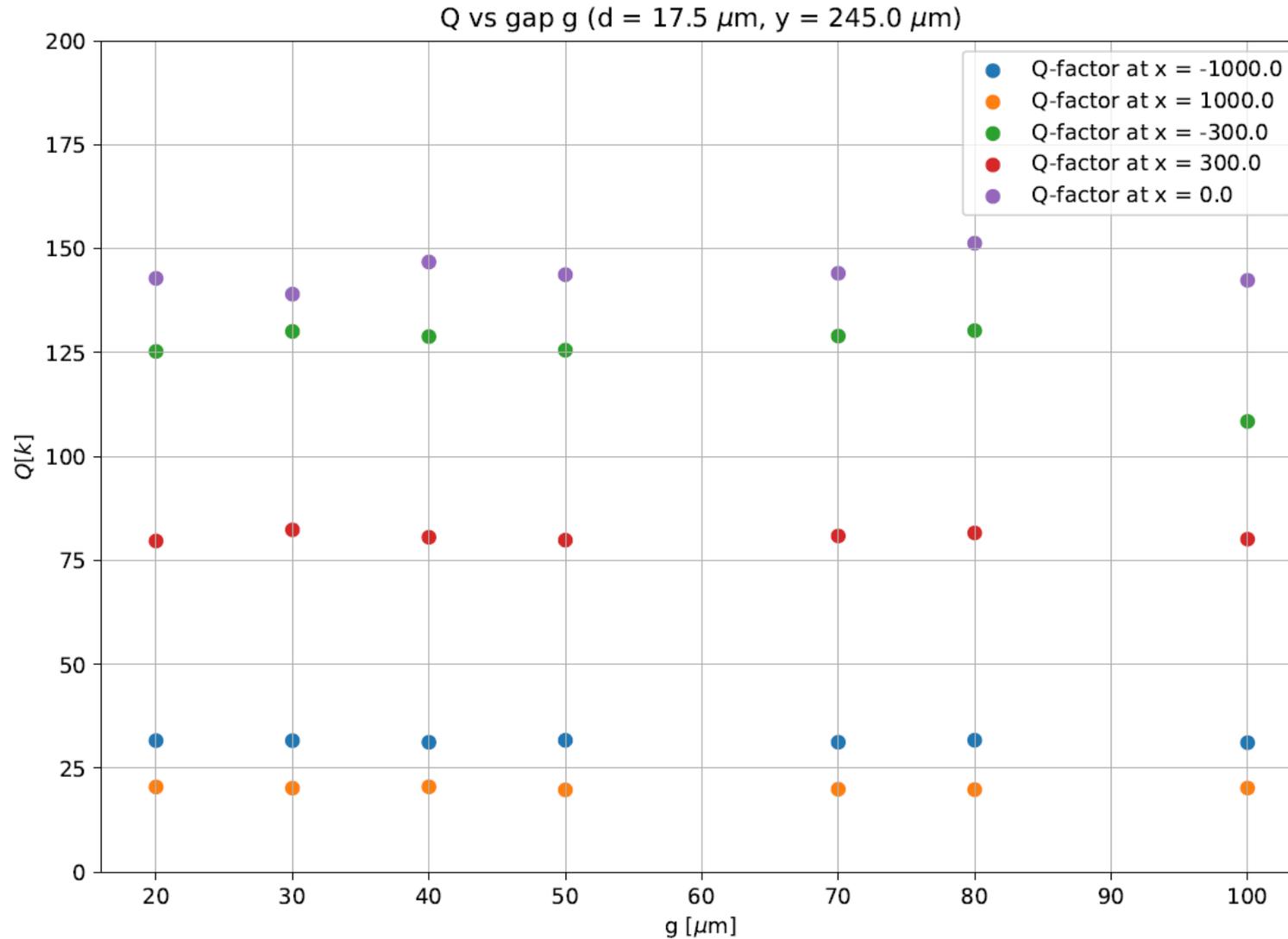
SONNET simulation: Q vs d

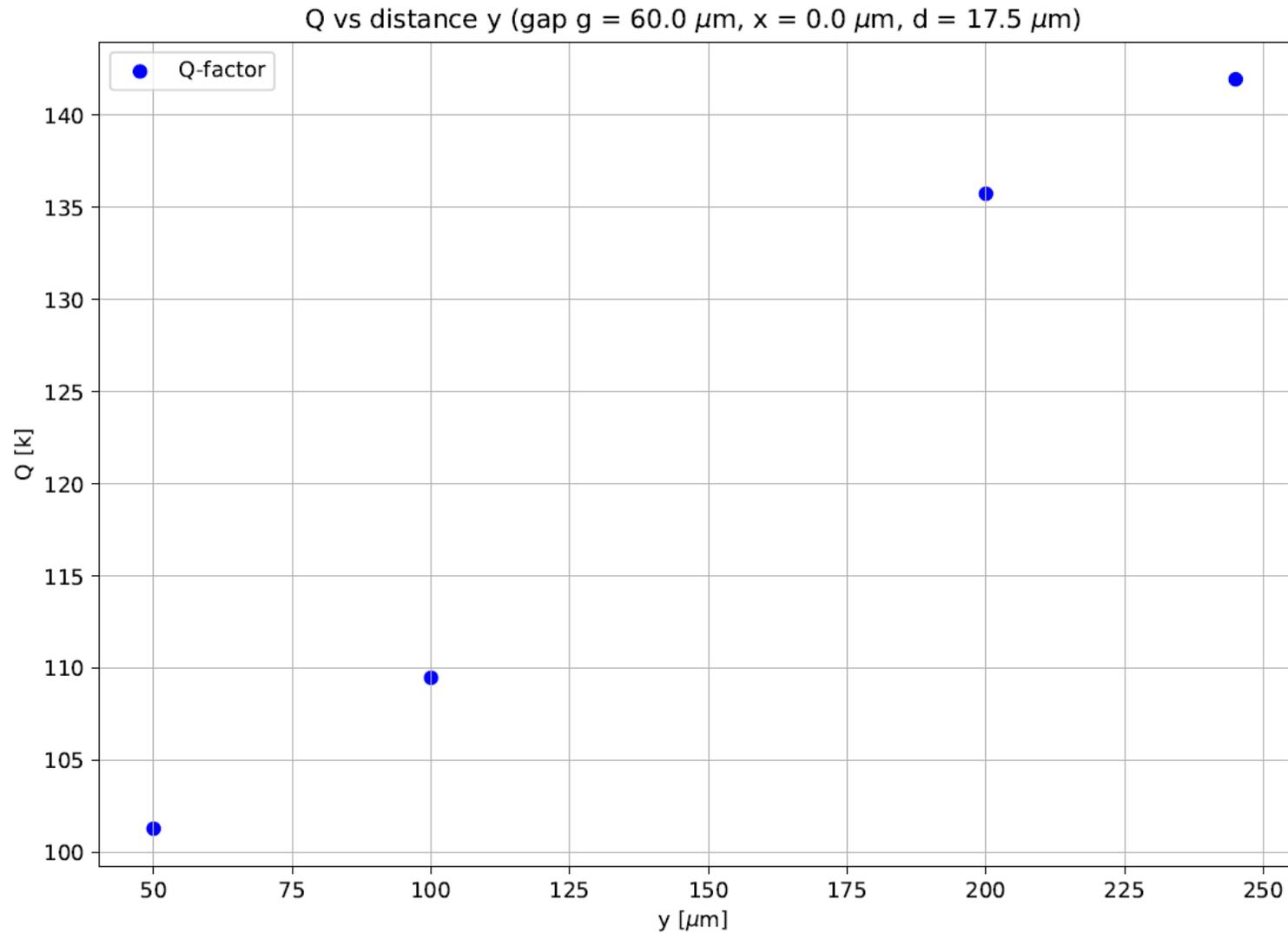Q vs distance d (gap g = 60.0 μm, x = 0.0 μm, y = 245.0 μm)

- Q increases with distance d from simulation.

SONNET simulation:Q vs g
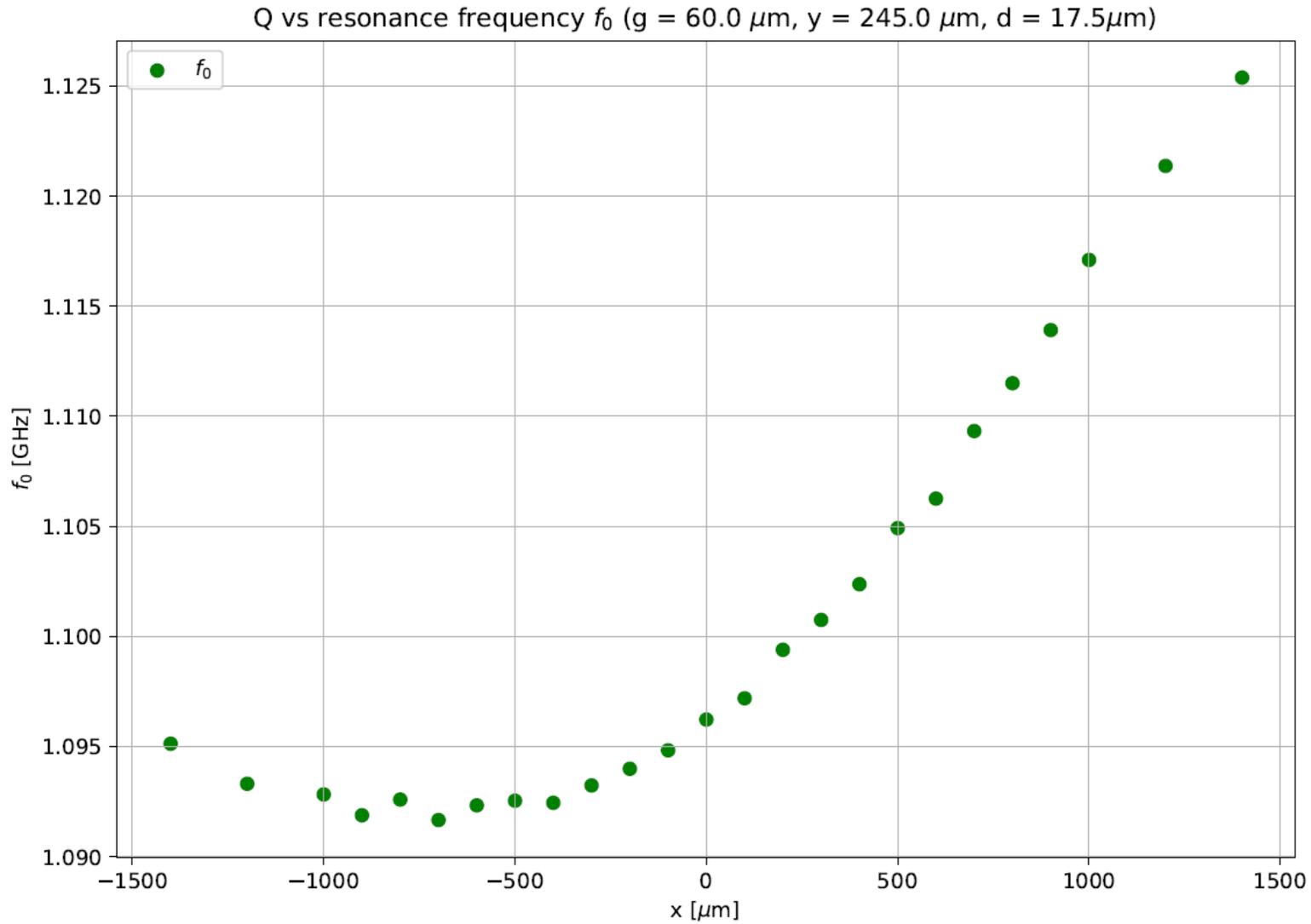

Q vs gap g (d = 17.5 μm, y = 245.0 μm)

- Q is Independent on g.

- Such effect independent on x

SONNET simulation: Q vs y

- Q increases with distance y from simulation.
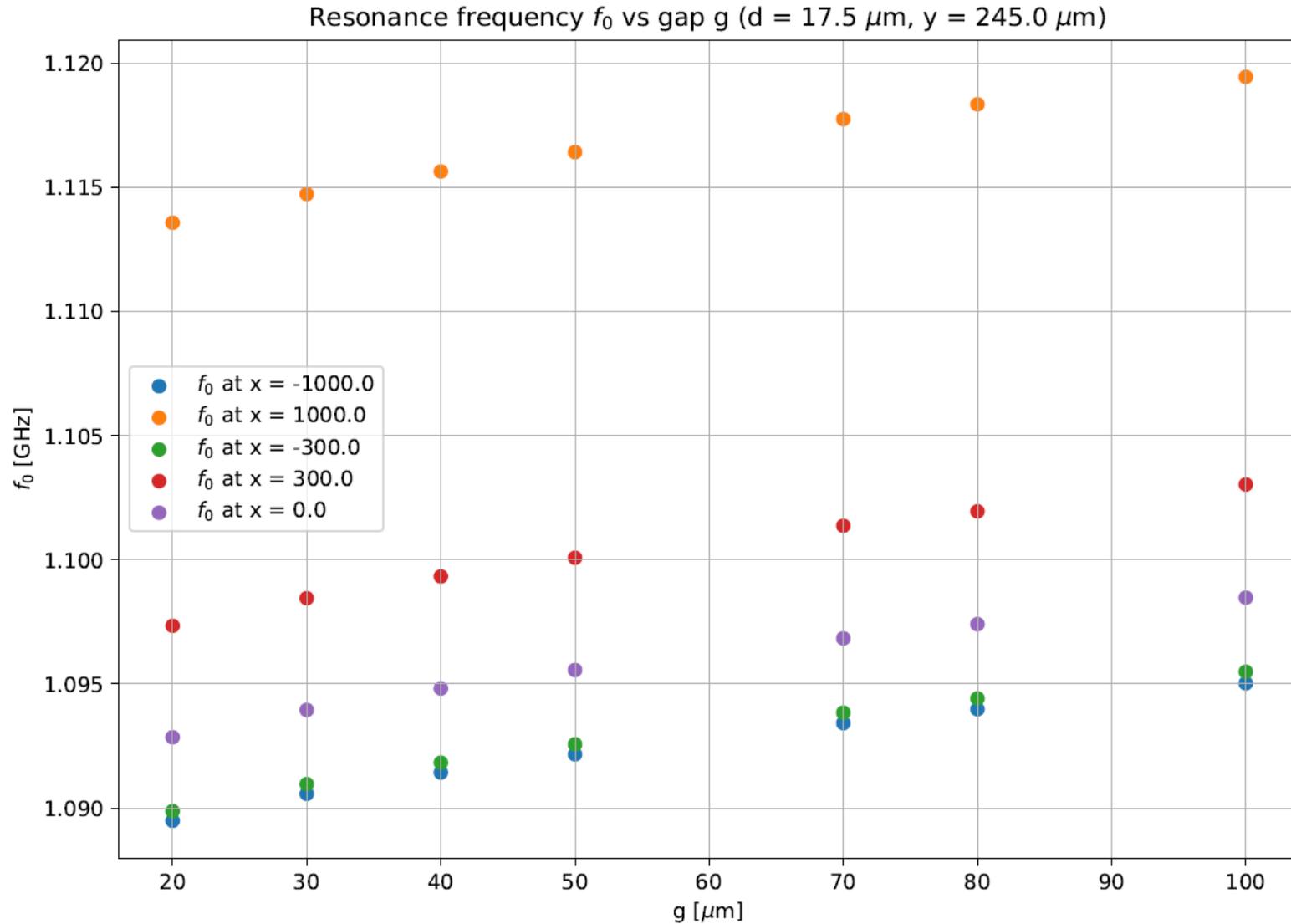
SONNET simulation: f_0 vs x

Q vs resonance frequency f_0 (g = 60.0 μm, y = 245.0 μm, d = 17.5μm)

- f_0 (slightly) depends on x from simulation.

SONNET simulation: f_0 vs d

Q vs distance d (gap g = 60.0 μm, x = 0.0 μm, y = 245.0 μm)

- f_0 (slightly) increases with d from simulation.

SONNET simulation: f_0 vs g

Resonance frequency f_0 vs gap g (d = 17.5 μm, y = 245.0 μm)

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

SONNET simulation:f_0 vs y

- f_0 (slightly) increases with y from simulation.