Kinetic Inductance Detector with phonon-funneling volumes

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02/07/2025
Ferrara, BULLKID-DM collaboration meeting

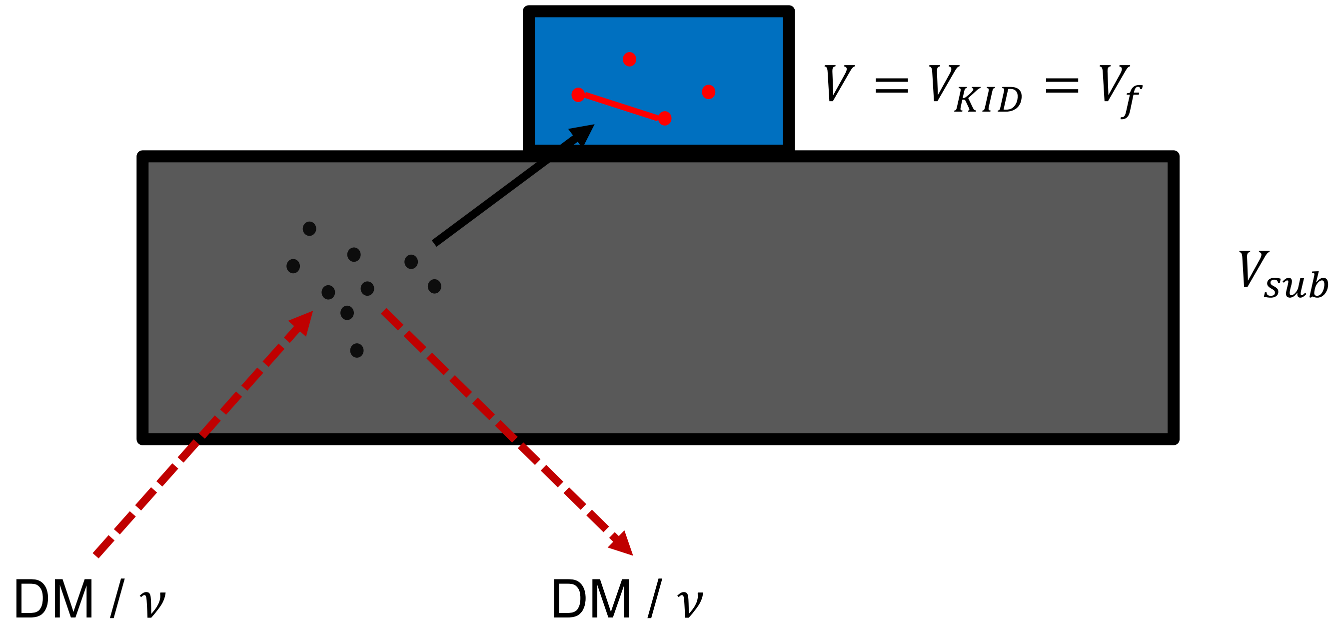
The concept of funneling volume

The concept of funnel

- Active sensor volume coincides $\boldsymbol{V_{KID}}$ coincides with the phonon collection volume $\boldsymbol{V_f}$

- **Maximization** of $\boldsymbol{V}$ needed for energy resolution improvement

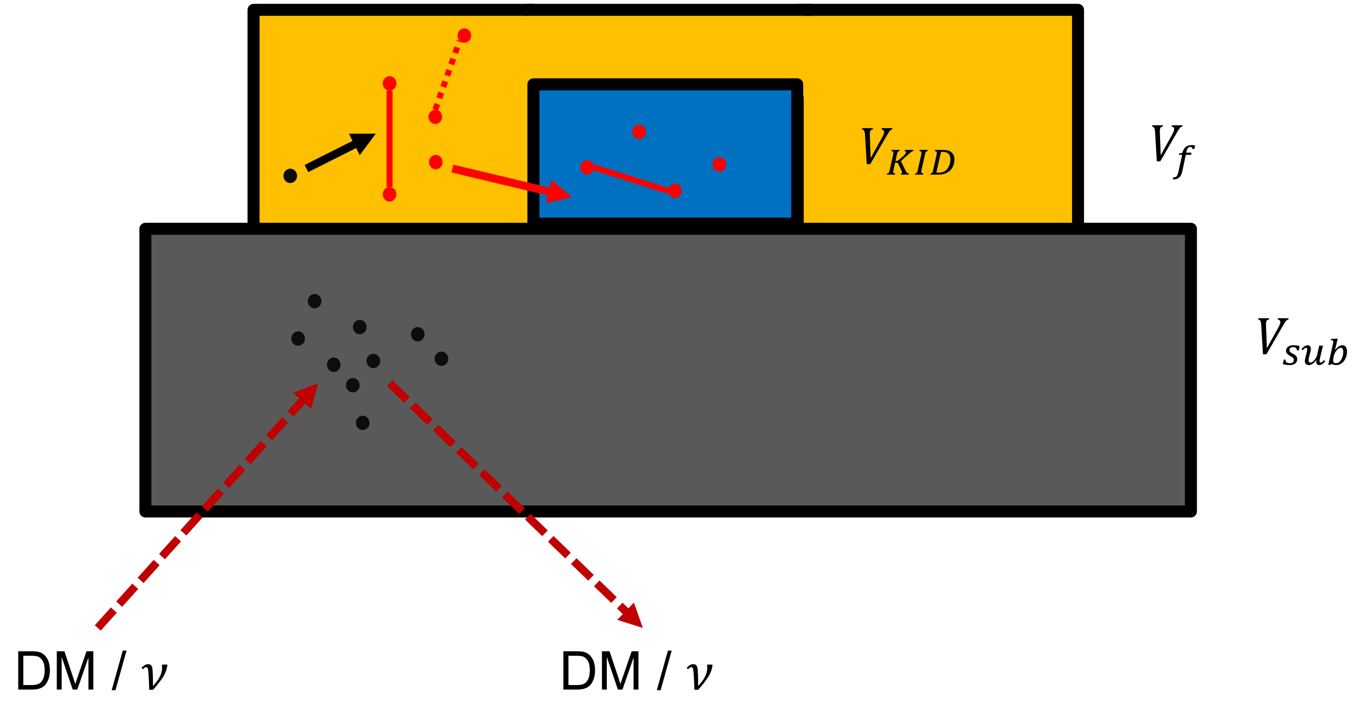
$$\sigma_E \propto 1/\sqrt{\boldsymbol{V}}$$



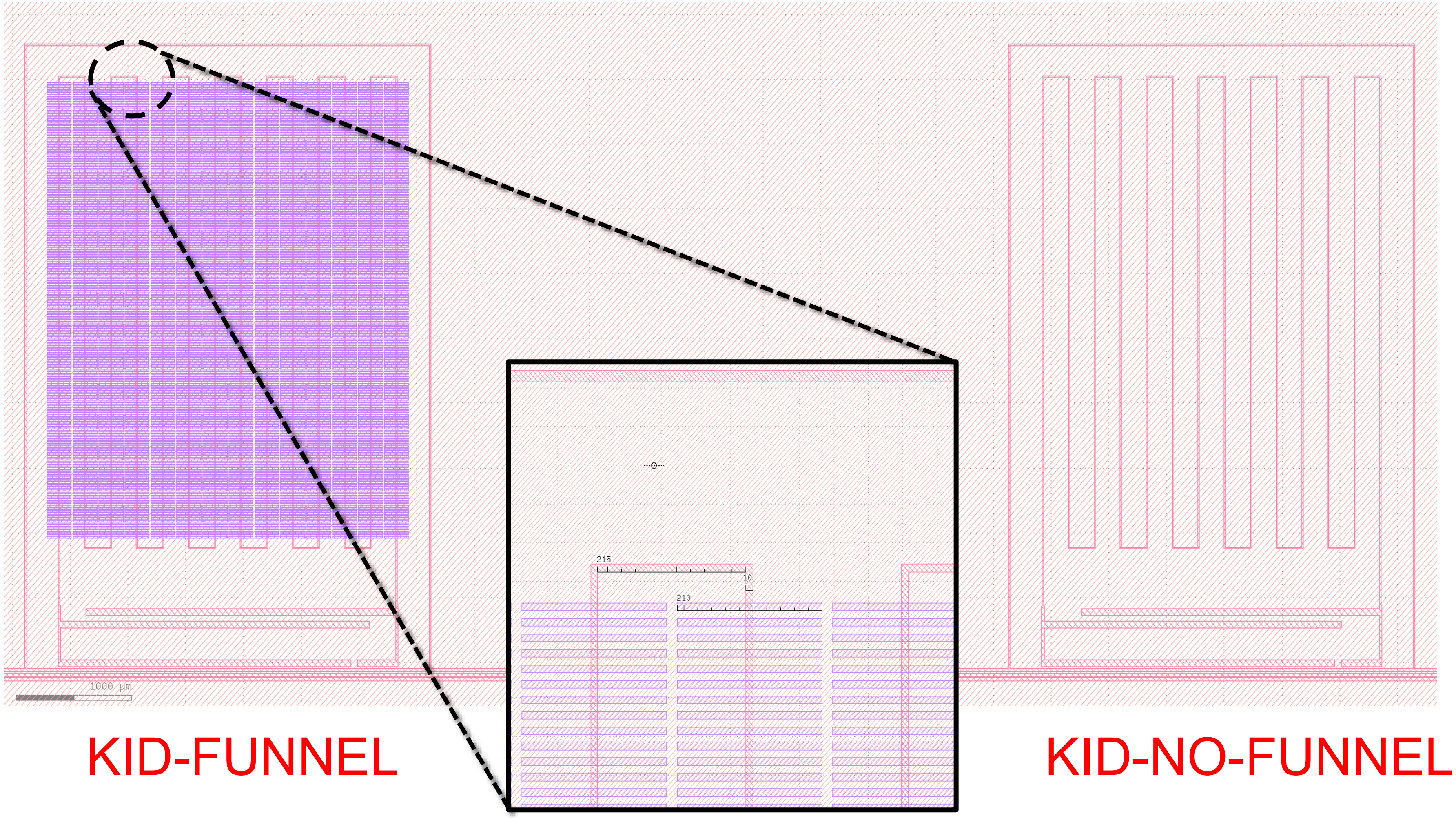
The concept of funnel

- Large collection separate structures surrounding the KID (**Funnels**)
- **Funnels** in **Al** + **KID** in **Al-Ti-Al** (from higher to lower Δ_0 to trap Quasi-Particles)
- Separation of V_f from V_{KID}

$$\sigma_E \propto \sqrt{V_{KID}}/V_f$$



Arrays layout



KID-FUNNEL

KID-NO-FUNNEL

- Two resonators tested
- **Detuning responsivity** and **energy resolution** compared

Arrays layout

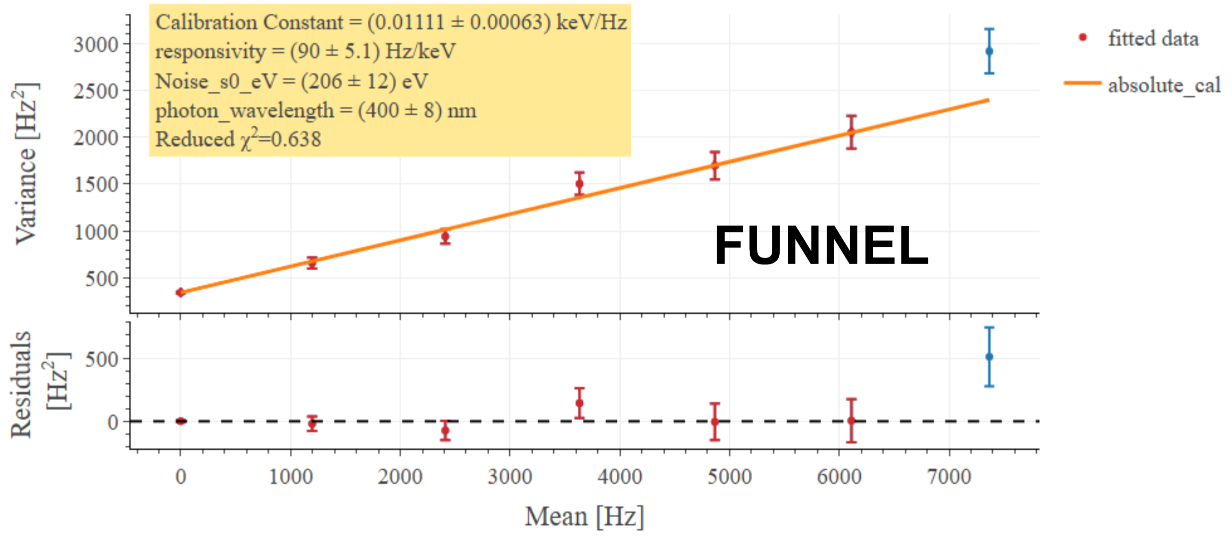
Funnels: Al

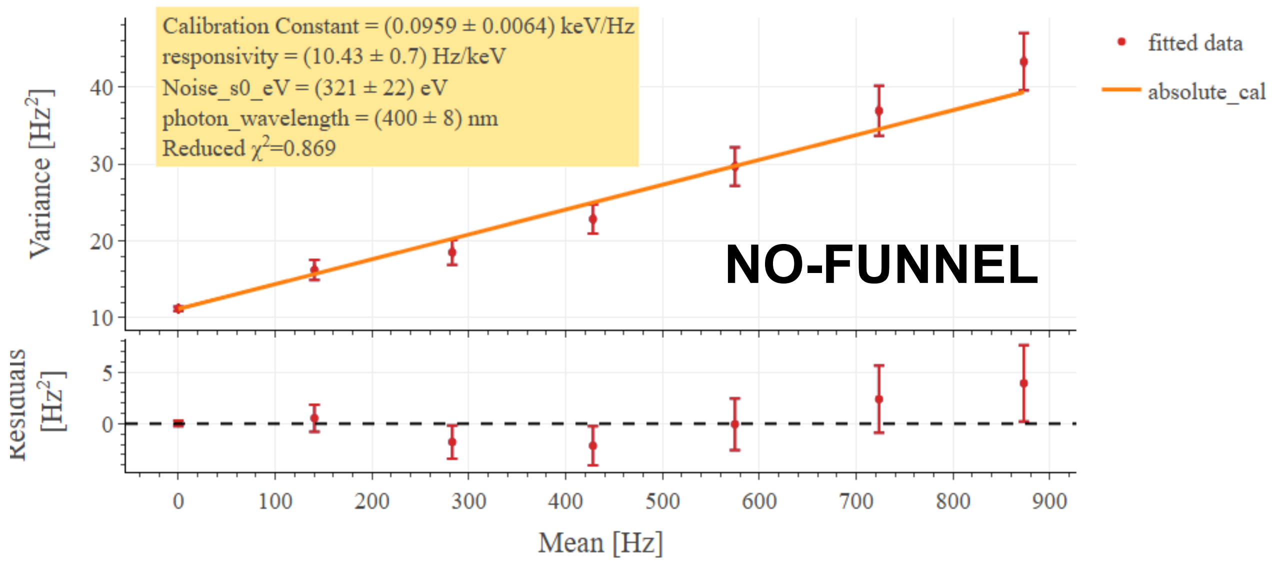
Capacitive coupling

Meander and **feed-line**: **Al-Ti-Al**

Substrate: Si

Last results (Pisa meeting)



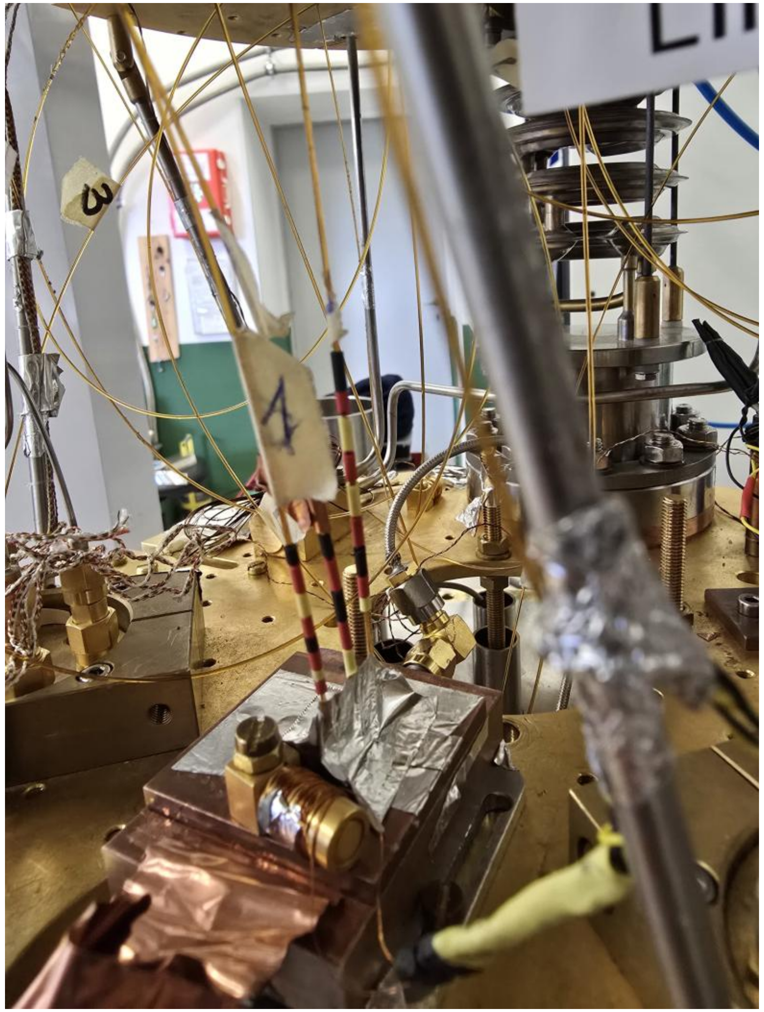


Results of calibration @ **HIGH power ($\boldsymbol{a \sim 0.3}$)**:

FUNNEL	NO-FUNNEL
$\frac{df}{dE} = (90.0 \pm 5.1)\ \mathrm{Hz/keV}$	$\frac{df}{dE} = (10.4 \pm 0.7)\ \mathrm{Hz/keV}$
$\sigma_N = (18.5\ \pm 0.2)\mathrm{Hz}$	$\sigma_N = (3.34\ \pm 0.04)\mathrm{Hz}$
$\sigma_E = (206\ \pm 12)\ \mathrm{eV}$	$\sigma_E = (321\ \pm 22)\ \mathrm{eV}$

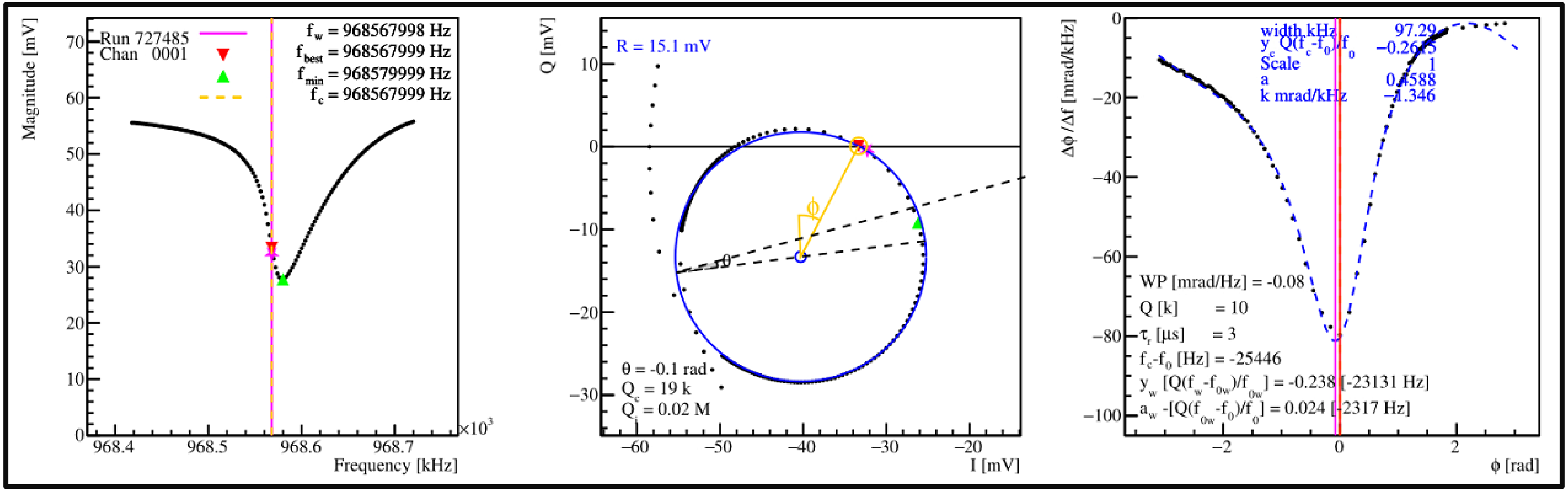
Measurements and results

What we changed from the last test



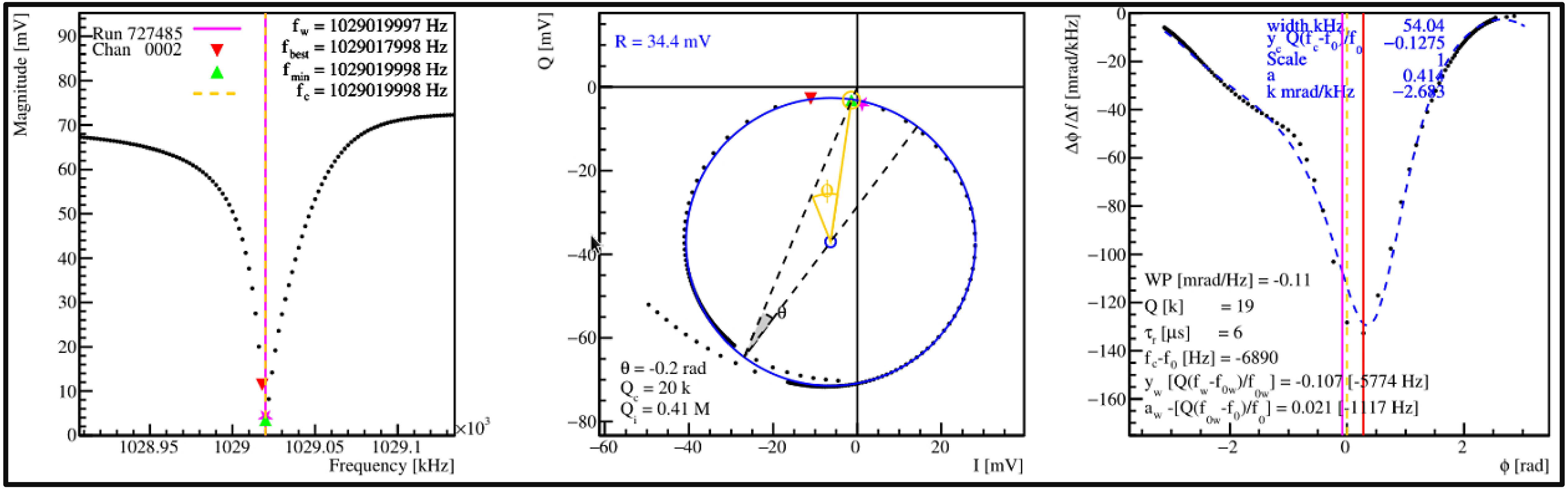
- We increased the funnels' thickness (60 → 100 nm) → **How does the responsivity change** ?
- We passed from USRP to **NIXA** → Smaller noise by the electronic chain
- Lateral fibers connected to **LANTERN**
- Different holder.

Resonance Circle: KID-FUNNEL



$f_0 \approx 968.6$ MHz $\qquad Q_c \approx 19$k $\qquad Q \approx 10$k

Resonance Circle: KID-NO-FUNNEL



$f_0 \approx 1029.0$ MHz

$Q_c \approx 20$k

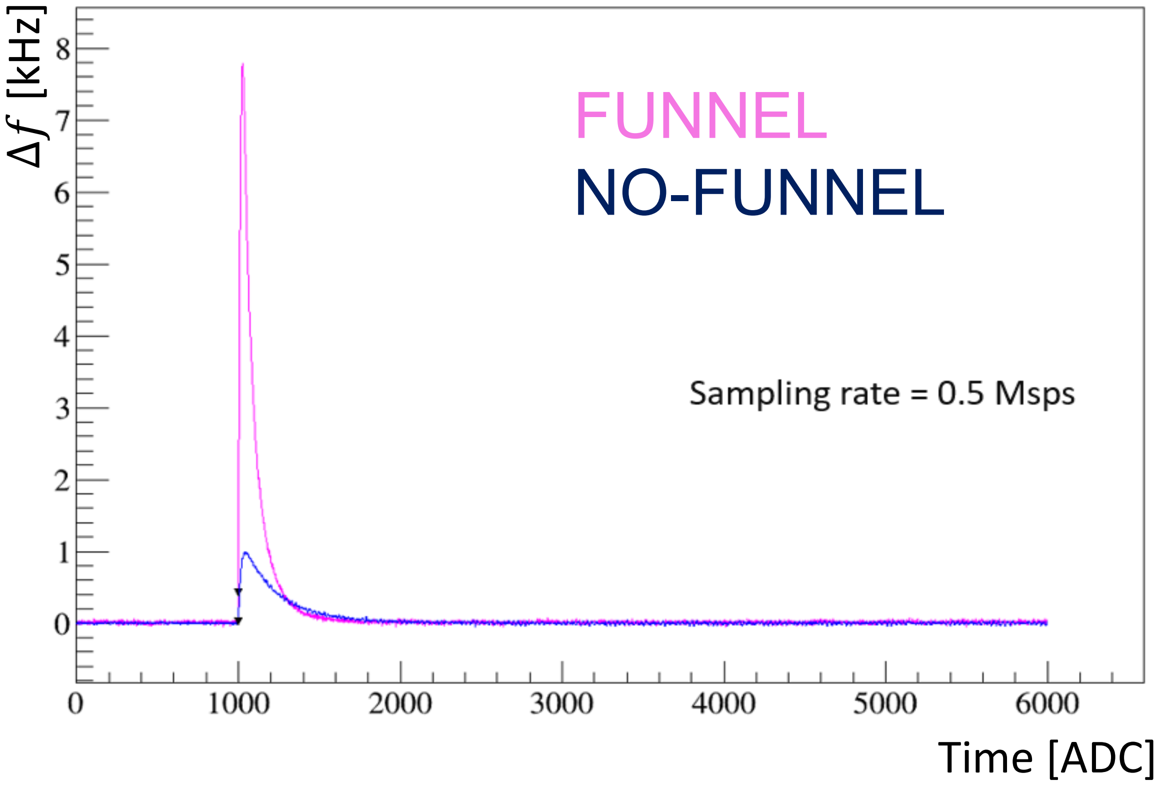
$Q \approx 19$k

Resonance Circle: a comparison

	KID-FUNNEL old	KID-NO-FUNNEL old	KID-FUNNEL new	KID-NO-FUNNEL new
$f_r\,[\mathrm{MHz}]$	964.9	1029.2	968.6	1029.0
$Q_c\,[\mathrm{k}]$	11	23	19	20
$Q_i\,[\mathrm{M}]$	0.01	0.35	0.02	0.41
$Q\,[\mathrm{k}]$	6	22	10	19

- **KID-FUNNEL new** has slightly higher Q_c and similar f_r
- **KID-NO-FUNNEL new** has the same parameters
- Q_i of the resonator still low ($\boldsymbol{Q_i < 0.5\ \mathrm{M}}$)

Optical Calibration: detuning responsivity

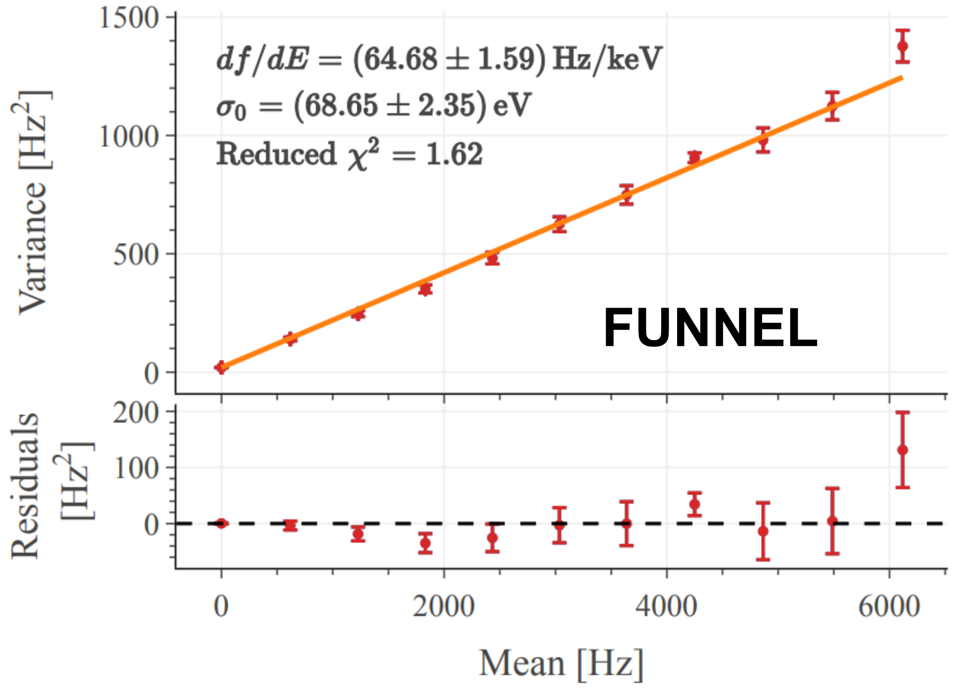


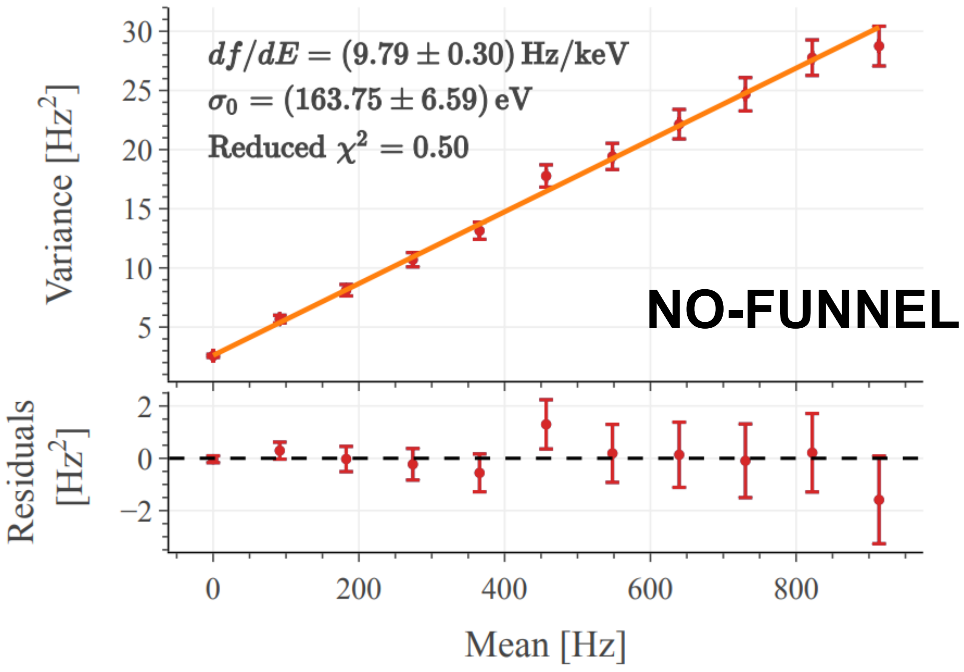
$$\frac{df_r}{dE} = \frac{\eta}{V_{KID}\Delta_0^2}\frac{\alpha S_2(\omega,T)f_r}{4N_0}$$

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

- η = Energy to QP conversion efficiency
- $\alpha = \frac{L_k}{L_g+L_k}$ Fraction of Kinetic Inductance
- Δ_0 = Superconducting gap

Optical Calibration: results ($\alpha \sim 0.4$)





$$\frac{df}{dE} = (64.7 \pm 1.6)\ \mathrm{Hz/keV}$$

$$\sigma_N = (4.44 \pm 0.11)\ \mathrm{Hz}$$

$$\sigma_E = (68.7 \pm 2.4)\ \mathrm{eV}$$

$$\frac{df}{dE} = (9.8 \pm 0.3)\ \mathrm{Hz/keV}$$

$$\sigma_N = (1.60 \pm 0.04)\ \mathrm{Hz}$$

$$\sigma_E = (163.8 \pm 6.6)\ \mathrm{eV}$$

Temperature scan: Mattis-Bardeen theory

- With Mattis-Bardeen theory, $\boldsymbol{\alpha}$ and $\boldsymbol{\Delta_0}$ measured from relative resonance frequency shift in temperature T

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

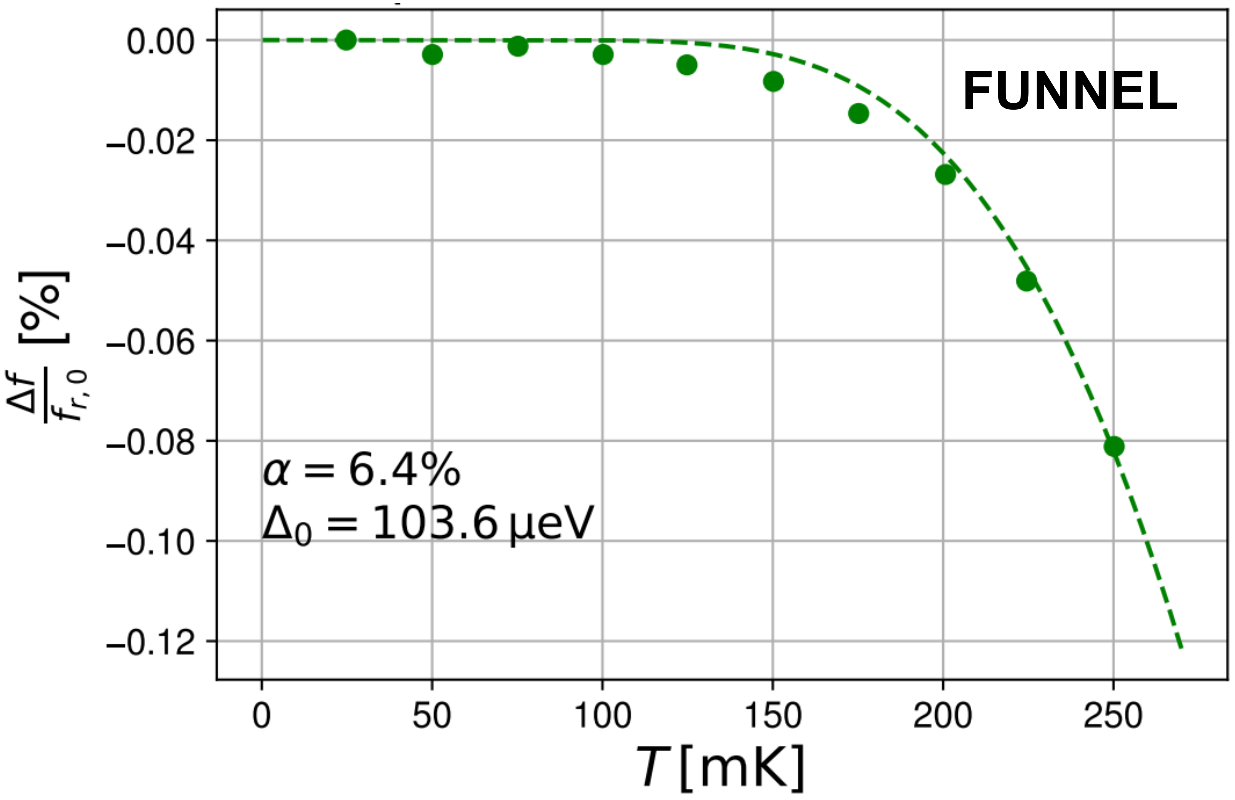
$$\frac{\Delta f\,(T)}{f_0(T)} = -\frac{\alpha}{2}\, S_2(\Delta_0, T)\, \frac{\delta n_{qp}(\Delta_0, T)}{\Delta(\Delta_0, T)}$$

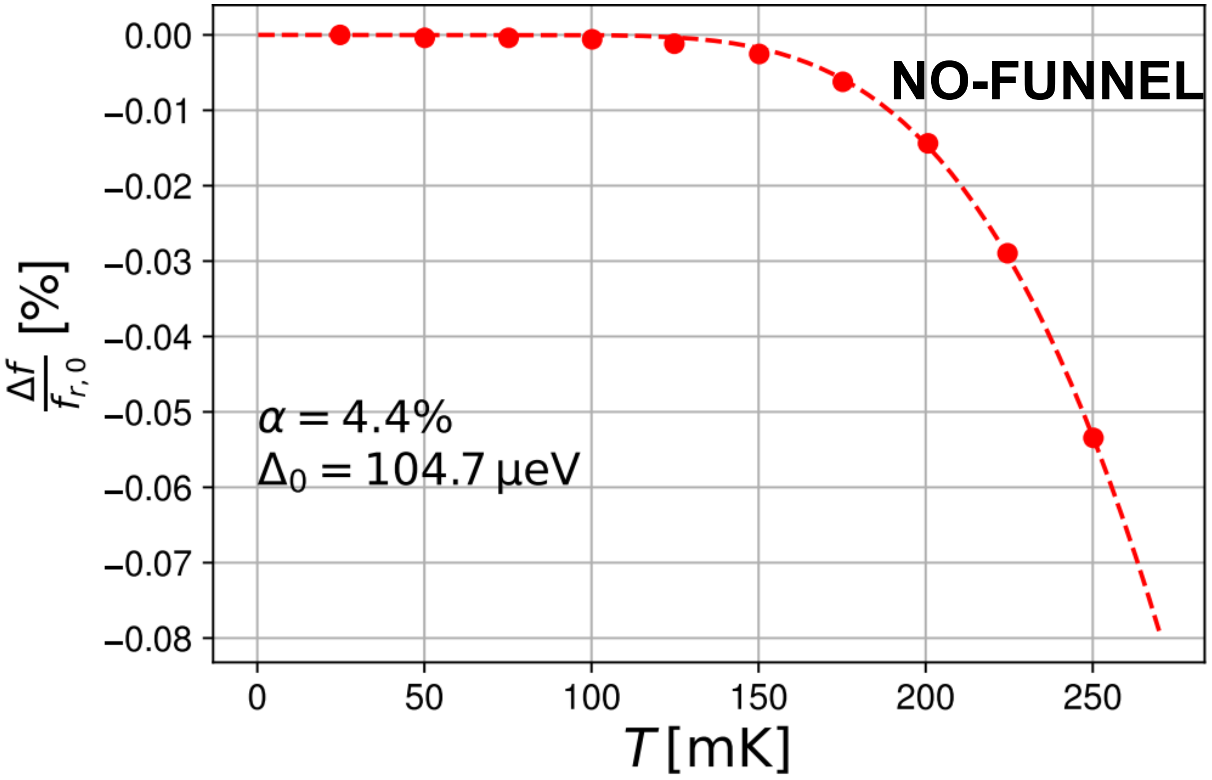
$$S_2 \approx 1 + \left(\sqrt{\frac{2\Delta_0}{\pi k_B T}}\, e^{-\frac{hf_0}{2k_B T}}\right) J_0\left(\frac{hf_0}{2k_B T}\right)$$

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

Temperature scan: results

- $\Delta_0 \approx 120\ \mu$eV measured directly for AlTiAl from **transition** of the **feed-line**





KIDs features: a comparison

	KID-FUNNEL old	KID-NO-FUNNEL old	KID-FUNNEL new	KID-NO-FUNNEL new
$\frac{df}{dE}$ [Hz/keV]	90.0	10.4	64.7	9.8
σ_E [eV]	206	321	69	164
σ_N [Hz]	18.54	3.34	4.44	1.60
α [%]	7.9	5.8	6.4	4.4
Δ_0 [μeV]	102.8	103.7	103.6	104.7

For **KID-FUNNEL**:

- The **responsivity decreased** with thicker funnels (but operated at different asymmetry configurations)
- Noise **improved** (different chain) → Not a direct comparision

KIDs features: a comparison

	KID-FUNNEL old	KID-NO-FUNNEL old	KID-FUNNEL new	KID-NO-FUNNEL new
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Δ_0 [μeV]	102.8	103.7	103.6	104.7

For **KID-FUNNEL**:

- **Reduction** of α
- $\boldsymbol{\Delta_0}$ is **similar** → Similar T_c estimated

KIDs features: a comparison

	KID-FUNNEL old	KID-NO-FUNNEL old	KID-FUNNEL new	KID-NO-FUNNEL new
$\frac{df}{dE}$ [Hz/keV]	90.0	10.4	64.7	9.8
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α [%]	7.9	5.8	6.4	4.4
Δ_0 [μeV]	102.8	103.7	103.6	104.7

For **KID-NO-FUNNEL**:

- The **responsivities** are compatible → Same resonator geometry
- Noise **improved** (different chain) → Not a direct comparision

KIDs features: a comparison

	KID-FUNNEL old	KID-NO-FUNNEL old	KID-FUNNEL new	KID-NO-FUNNEL new
$\frac{df}{dE}$ [Hz/keV]	90.0	10.4	64.7	9.8
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For **KID-NO-FUNNEL**:

- **Similar $\boldsymbol{\Delta_0}$** $\rightarrow$ Same T_c
- **Reduction** of α (not expected)

Collection efficiency ratio (an estimate)

- From responsivity ratio we find the **collection efficiency ratio** $\boldsymbol{\frac{\eta_1}{\eta_2}}$ of two KIDs

- **Assumption**: assume S_2 and N_0 **equal** in all the compared KIDs

$$\frac{\eta_1}{\eta_2} \approx \frac{\left(\frac{df}{dE}\right)_1}{\left(\frac{df}{dE}\right)_2} \times \frac{\alpha_2}{\alpha_1} \times \left(\frac{\Delta_{0,1}}{\Delta_{0,2}}\right)^2 \times \frac{f_{r,2}}{f_{r,1}}$$

- The ratio of the two functions $\Delta f_r/f_r$ might also be sensible to the ratio of the two S_2 functions

Collection efficiency ratio: results

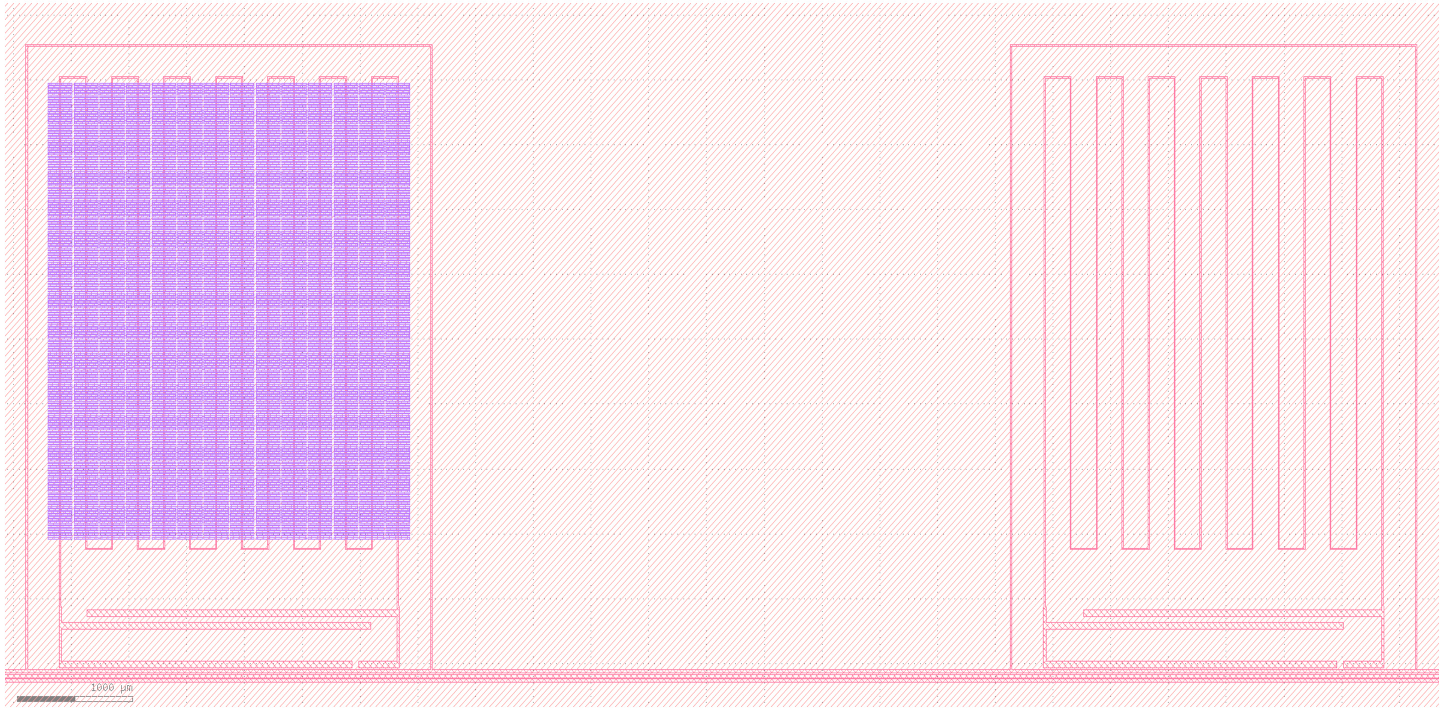
	F/NF old	F/NF new	F old/F new	NF old/NF new
η_1/η_2	6.7	4.7	1.1	0.8

F → FUNNEL
NF → NO-FUNNEL

- **Collection efficiency not significantly changed if we assume no change in S_2** → Reduction of responsivity due to reduction of α
- In all cases, **FUNNEL-KID collects more phonons**
- The collection efficiency became smaller for the new **KID-NO-FUNNEL** → Still reduction of α

Next steps

Funnel and KID with no gap difference



- Same resonator in Al and no gap difference from funnels to meander
- No funneling effect should be seen
- Some problems with these arrays to be studied now

Conclusions and perspectives

- **From these measurement**

1. We observed a change in responsivity → α **changed for both the resonators**

2. FUNNEL-KID has **stable** and **better performances**

- **What's next**

1. Conclusion of analysis with only **Aluminum resonator** → To prove funneling effect

2. Test the old **KID-FUNNEL** resonators with **NIXA at same power of the new resonators** → Same noise from electronic chain

3. Comparision with a **BULLKID** resonator and **higher Q** → Same contact surfaces

Thanks for the attention !

*This work was partially supported through the European Research Council through the Consolidator Grant **DANAE** number 101077663

BACK-UP SLIDES

Energy resolution

Single KID energy resolution

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

Total superconducting (SC) volume

Contact area between resonator and substrate

$$\eta = \eta_{geo}\eta_{ph} \propto \frac{A_{ph}}{A_{sub}}\eta_{ph} \propto \frac{V_{ph}}{V_{sub}}\eta_{ph}$$

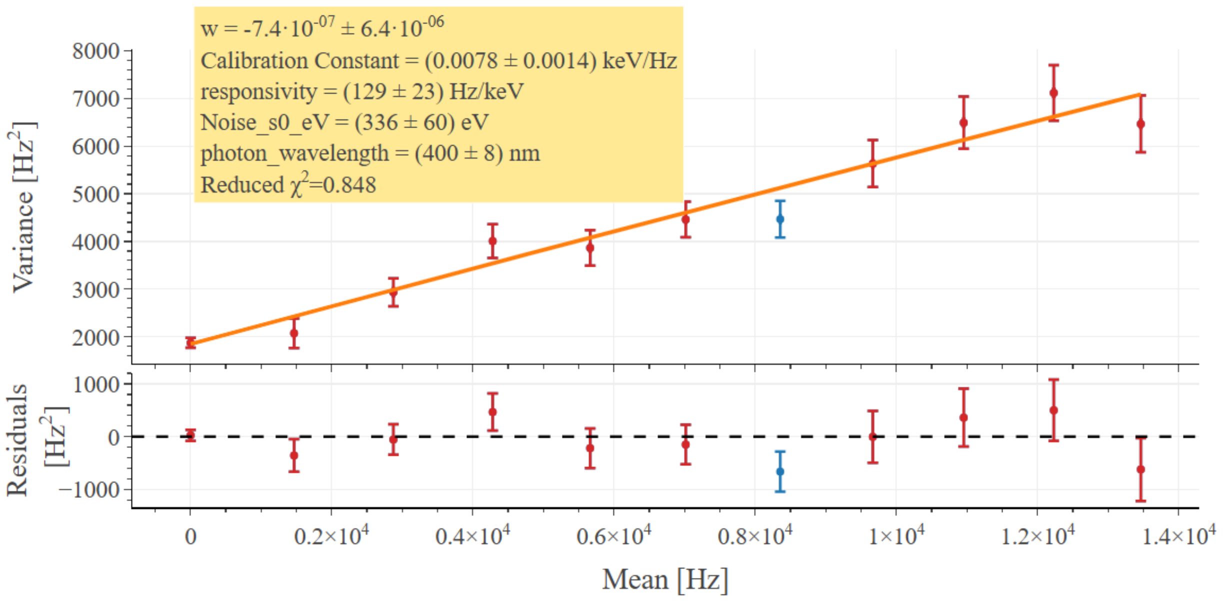
$$\sigma_E \propto \frac{\Delta}{V_{ph}\eta_{ph}}\sqrt{\frac{V}{\alpha}}V_{sub}$$

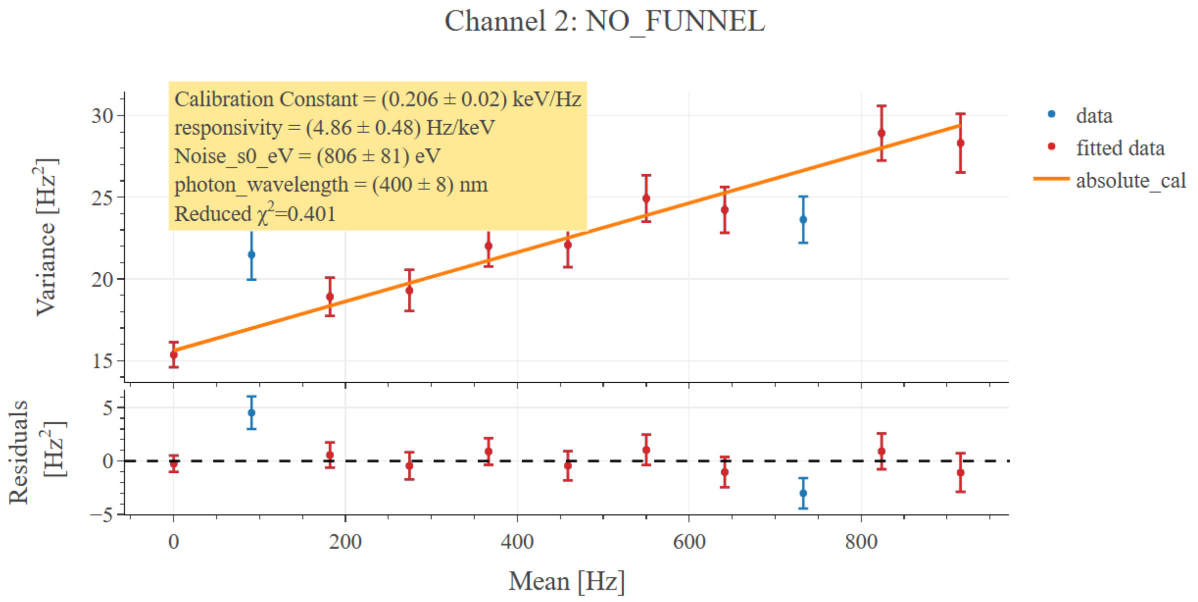
Phonon absorption efficiency

Total substrate area

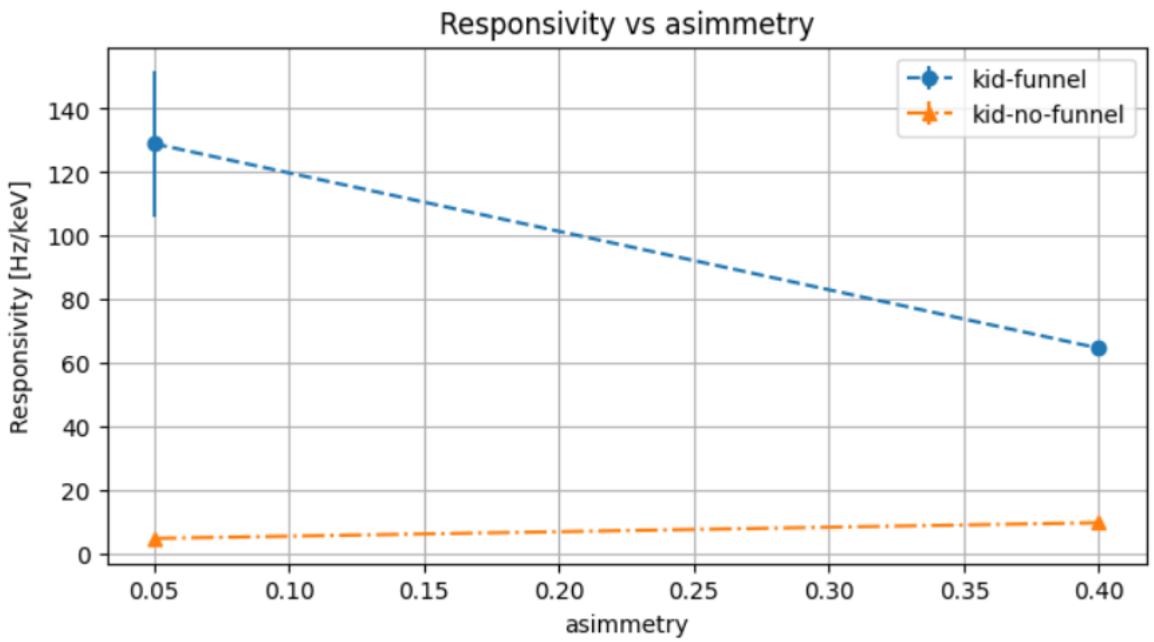
- $V = V_{ph} = V_{sub} \rightarrow \sigma_E \propto 1/\sqrt{V}$ (no funnel)
- $V \neq V_{ph} \rightarrow \sigma_E \propto \sqrt{V_{KID}}/V_{ph}$ (funnel)

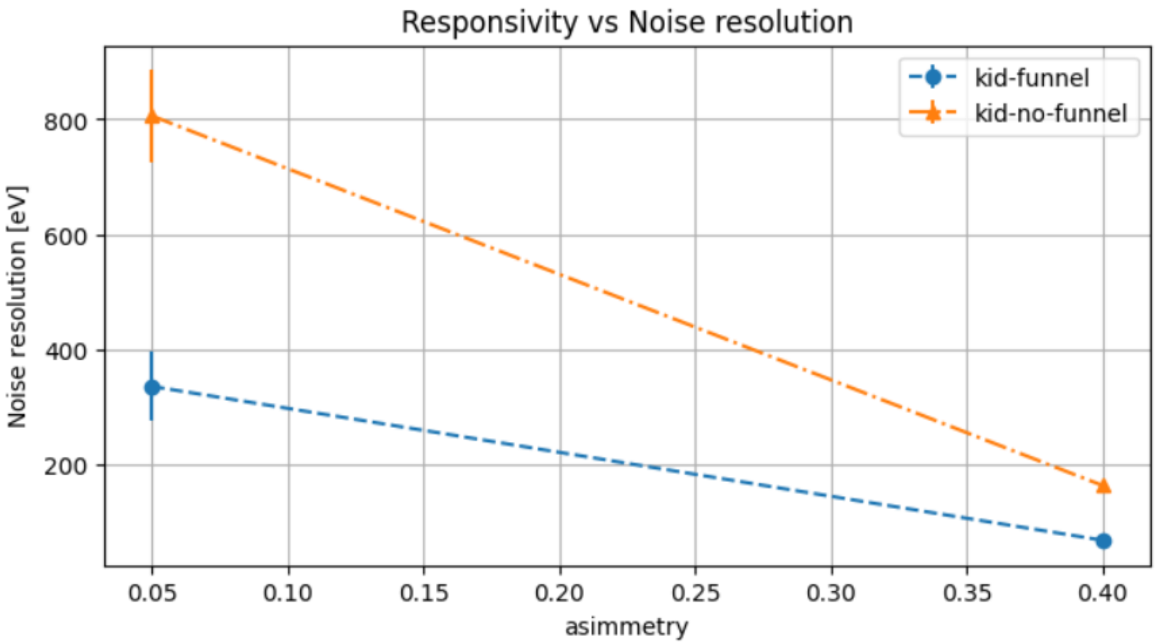
Optical calibration: Low Power (DS7401)





Responsivity & noise AlTiAl: High vs Low

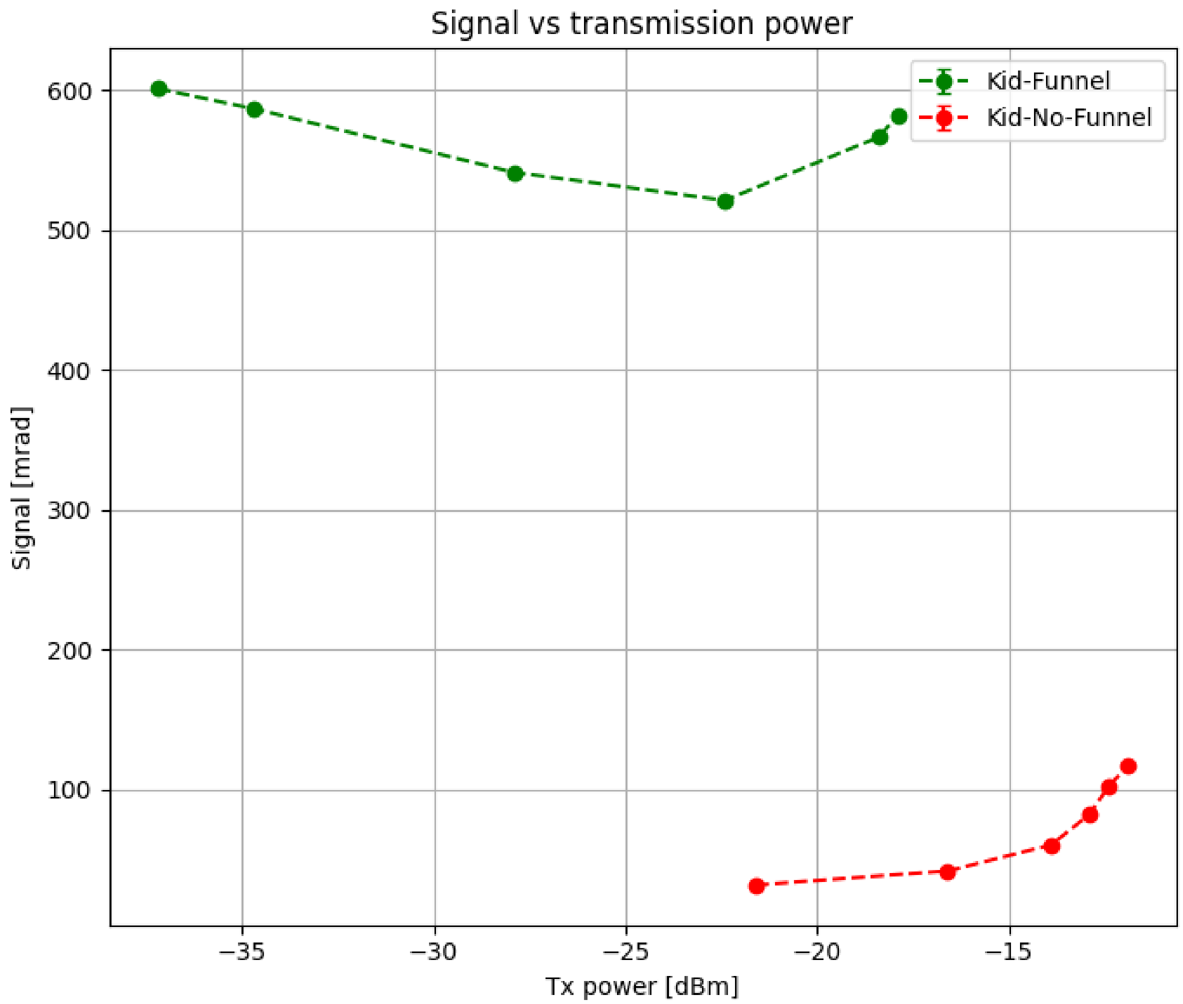


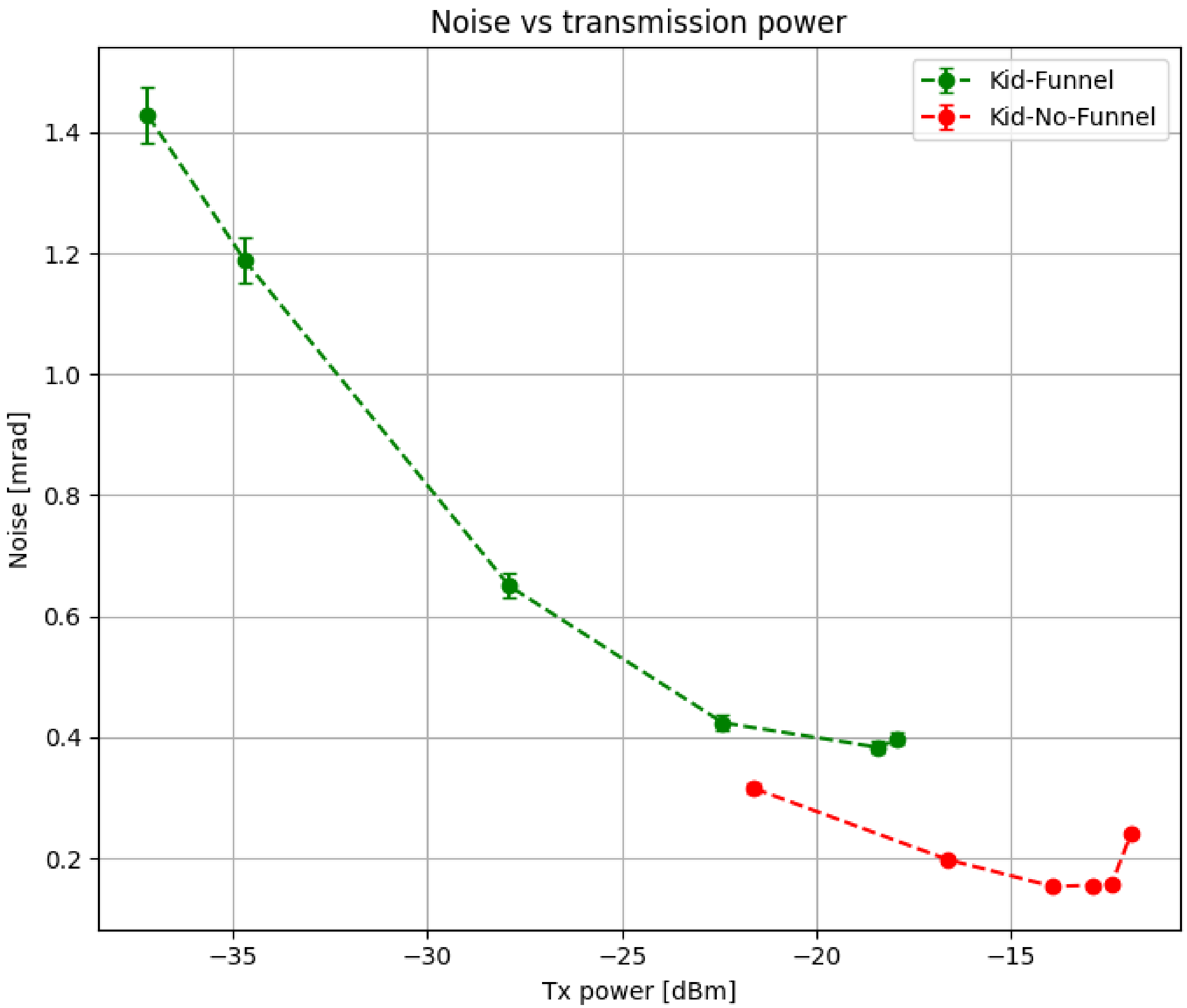


- Responsivity reduces increasing the power for KID-FUNNEL
- Responsivity increases for KID-NO-FUNNEL

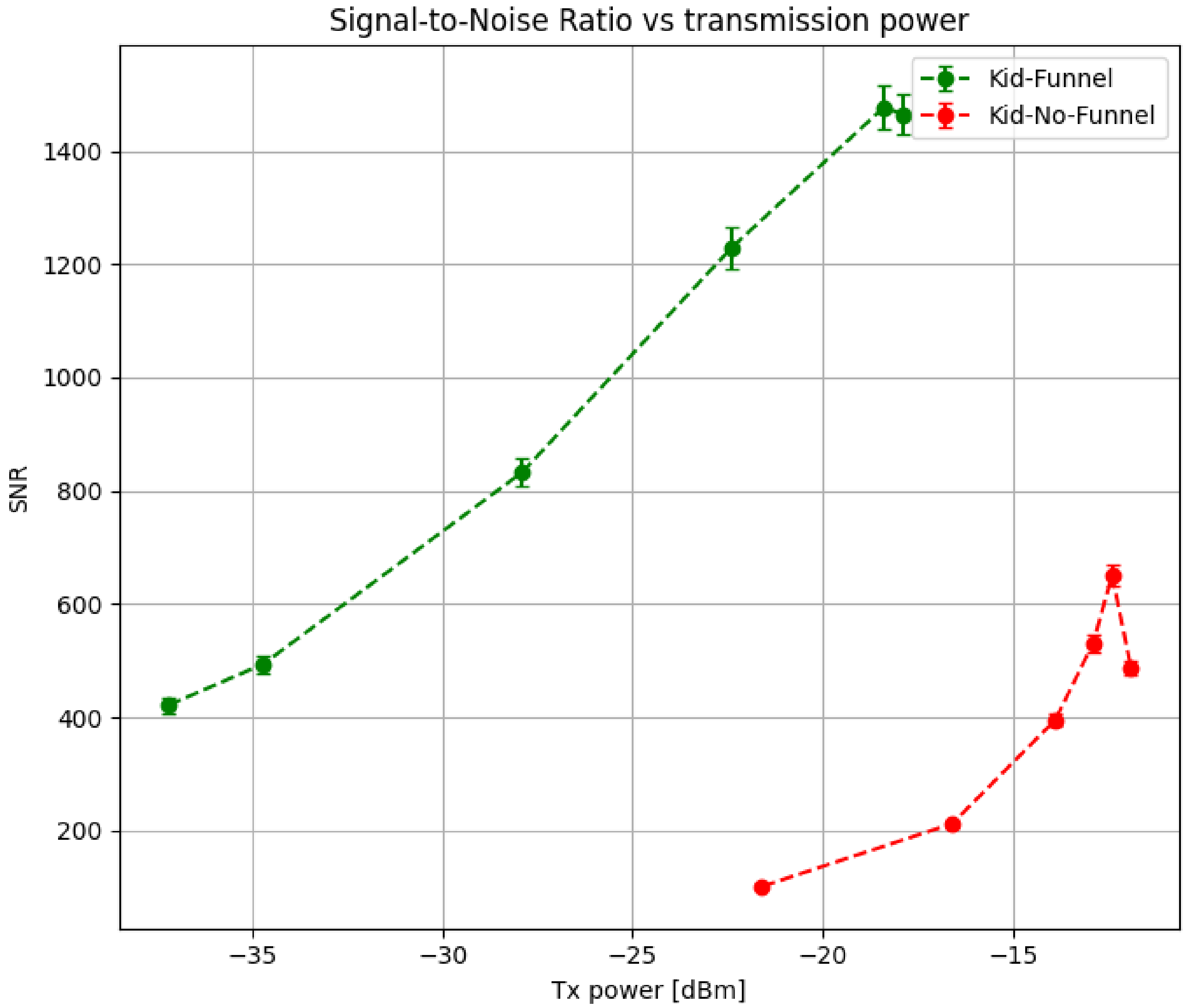
- Noise resolution increases in both cases

New KIDs: power scan (signal and noise)





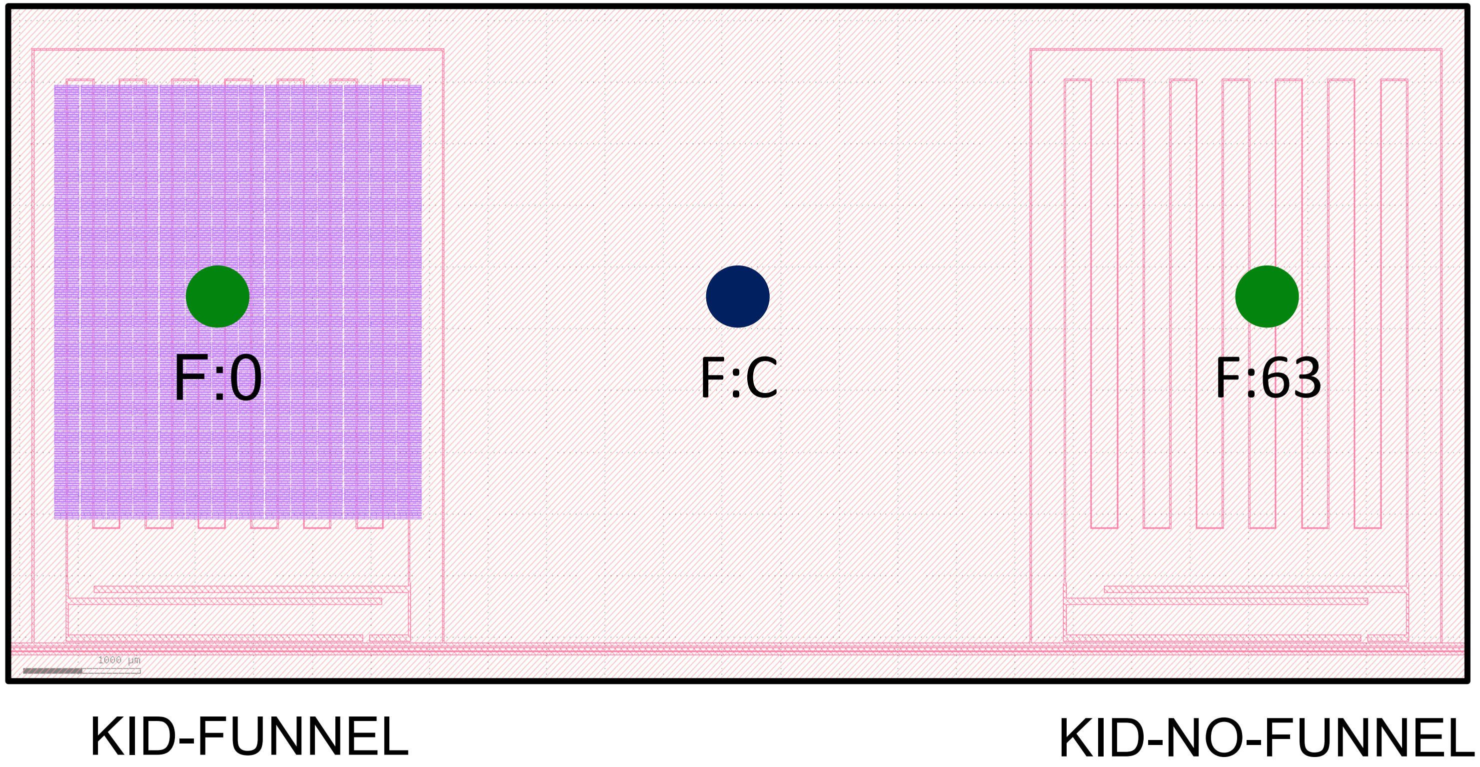
New KIDs: SNR



- Optimal power chosen at $a \sim 0.4$
- Different behavior than Aluminum:

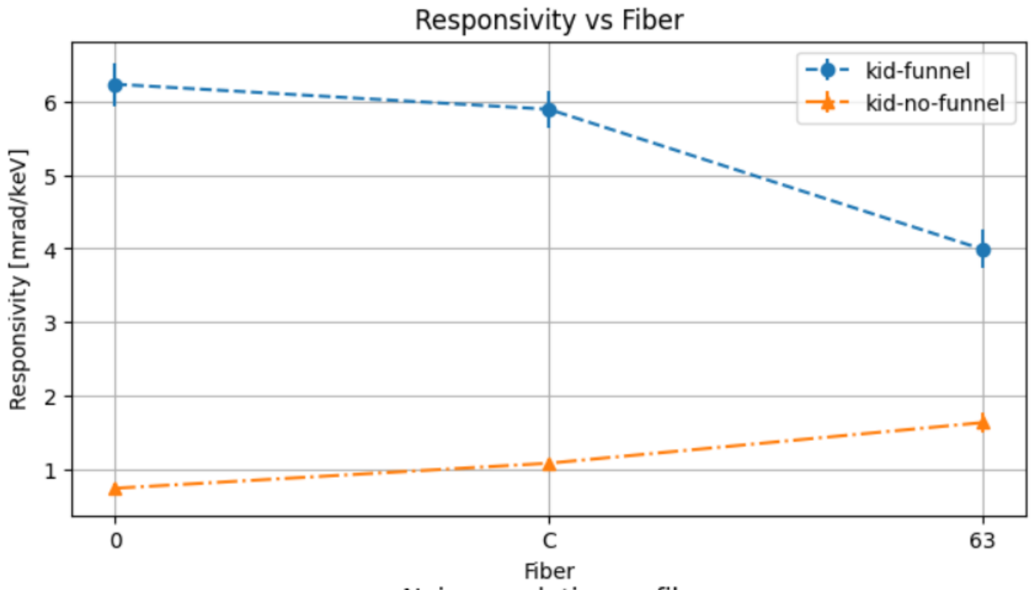
1. The signal for KID-FUNNEL
2. Higher optimal power

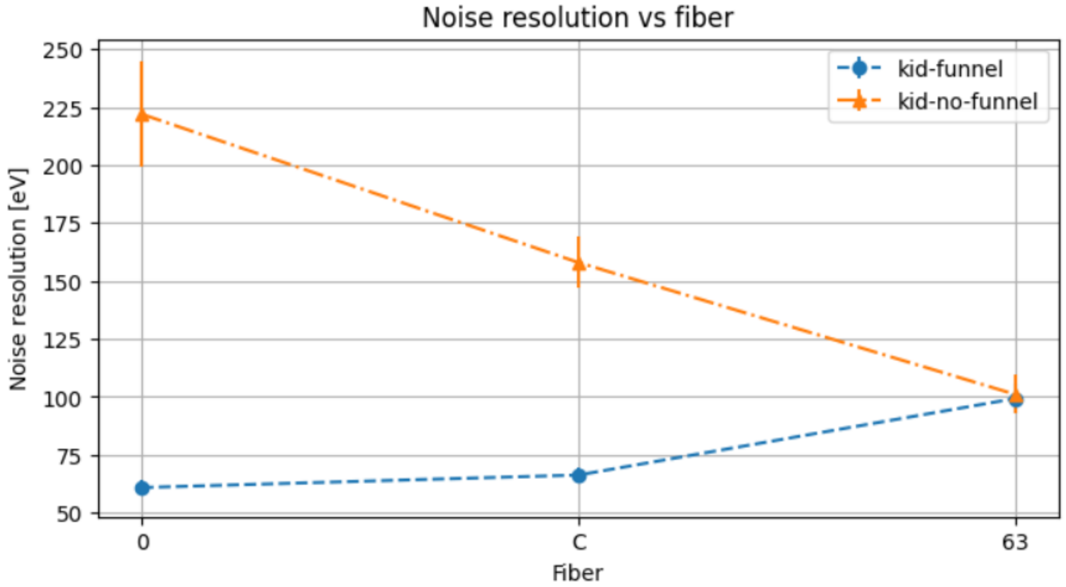
Optical Calibration: three fibers

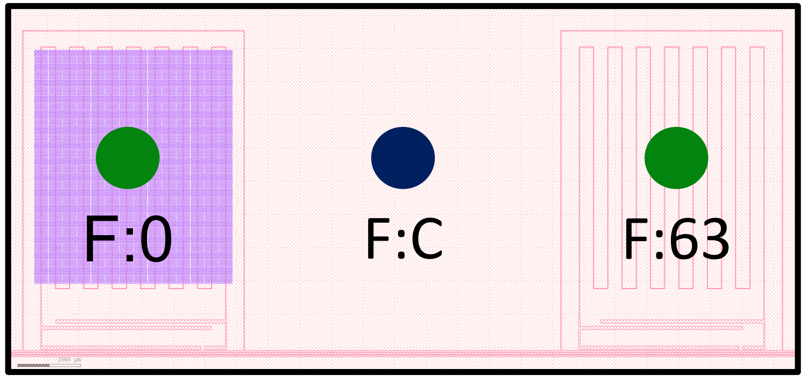


- Three fibers on the **backward of the resonators**
- Sensible to **geometry effects**
- Lateral Fibers: **LANTERN** + Central Fiber: **EXTERNAL LANTERN**

Optical Calibration: geometry effects

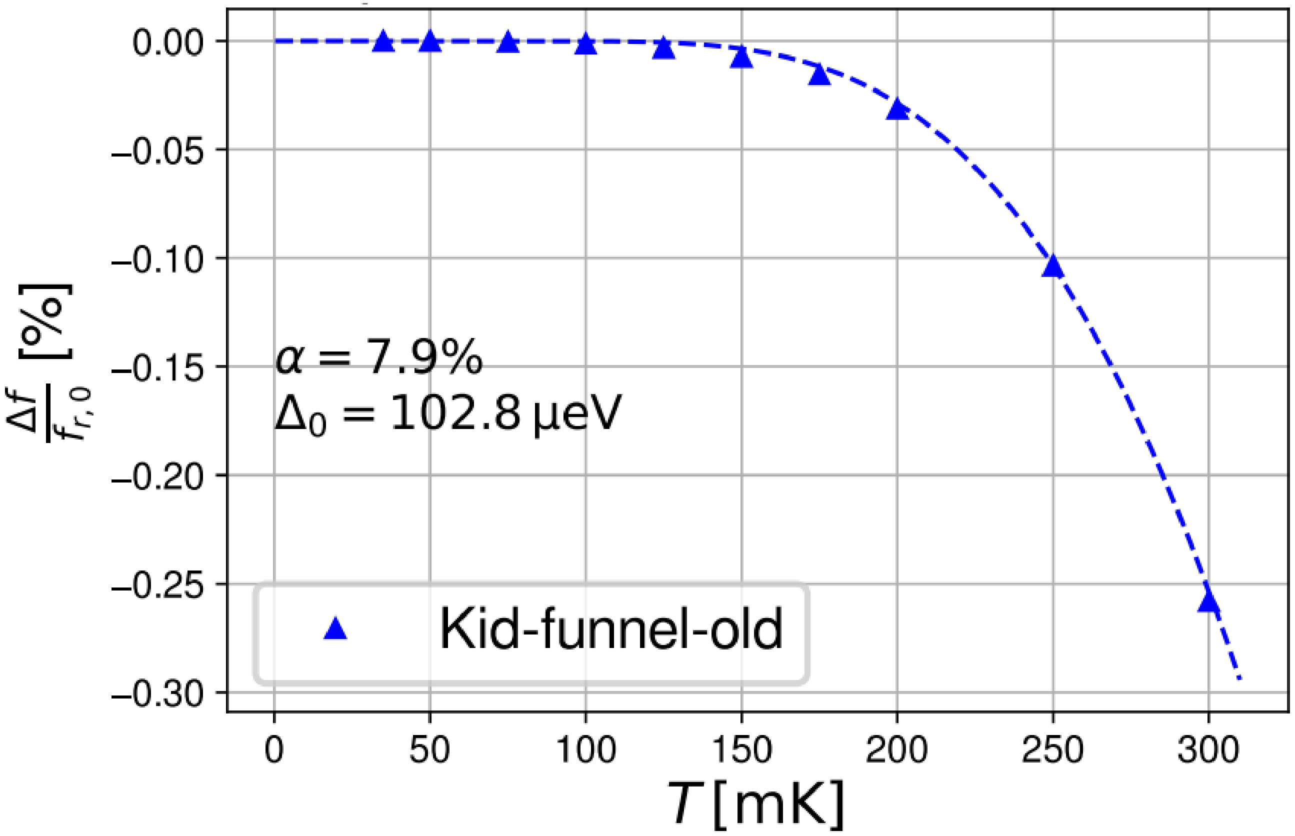


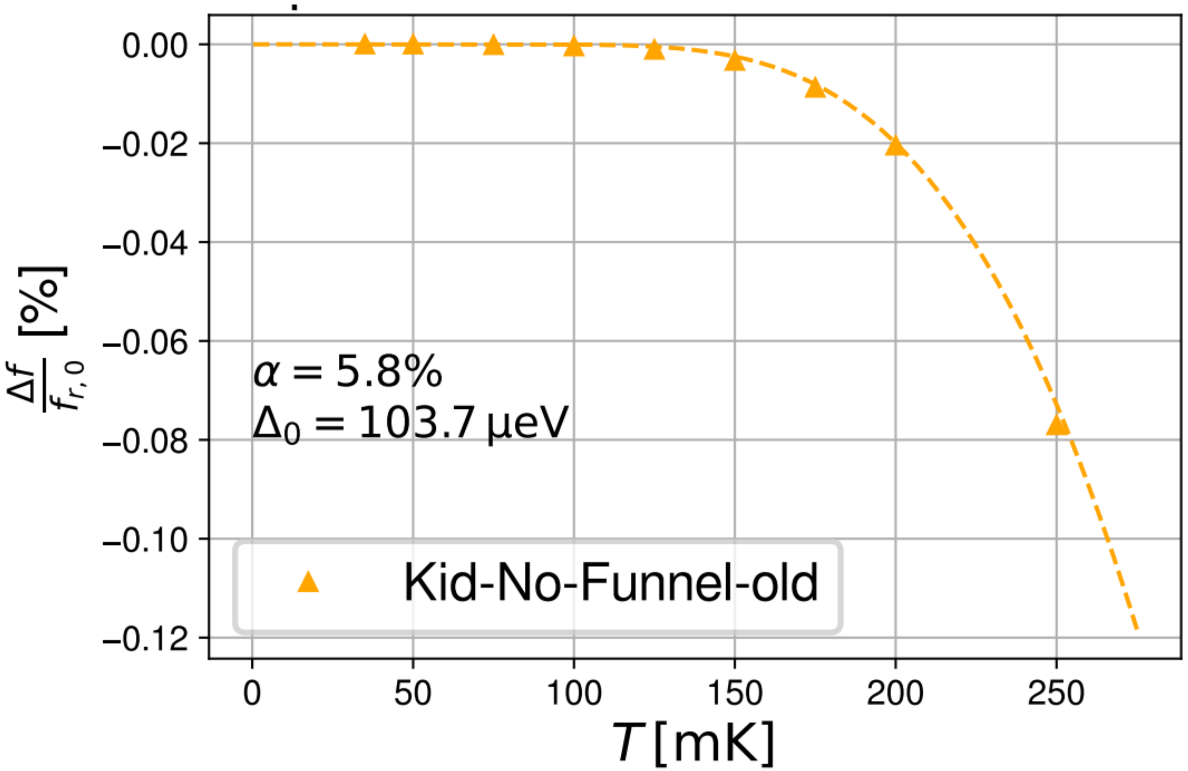




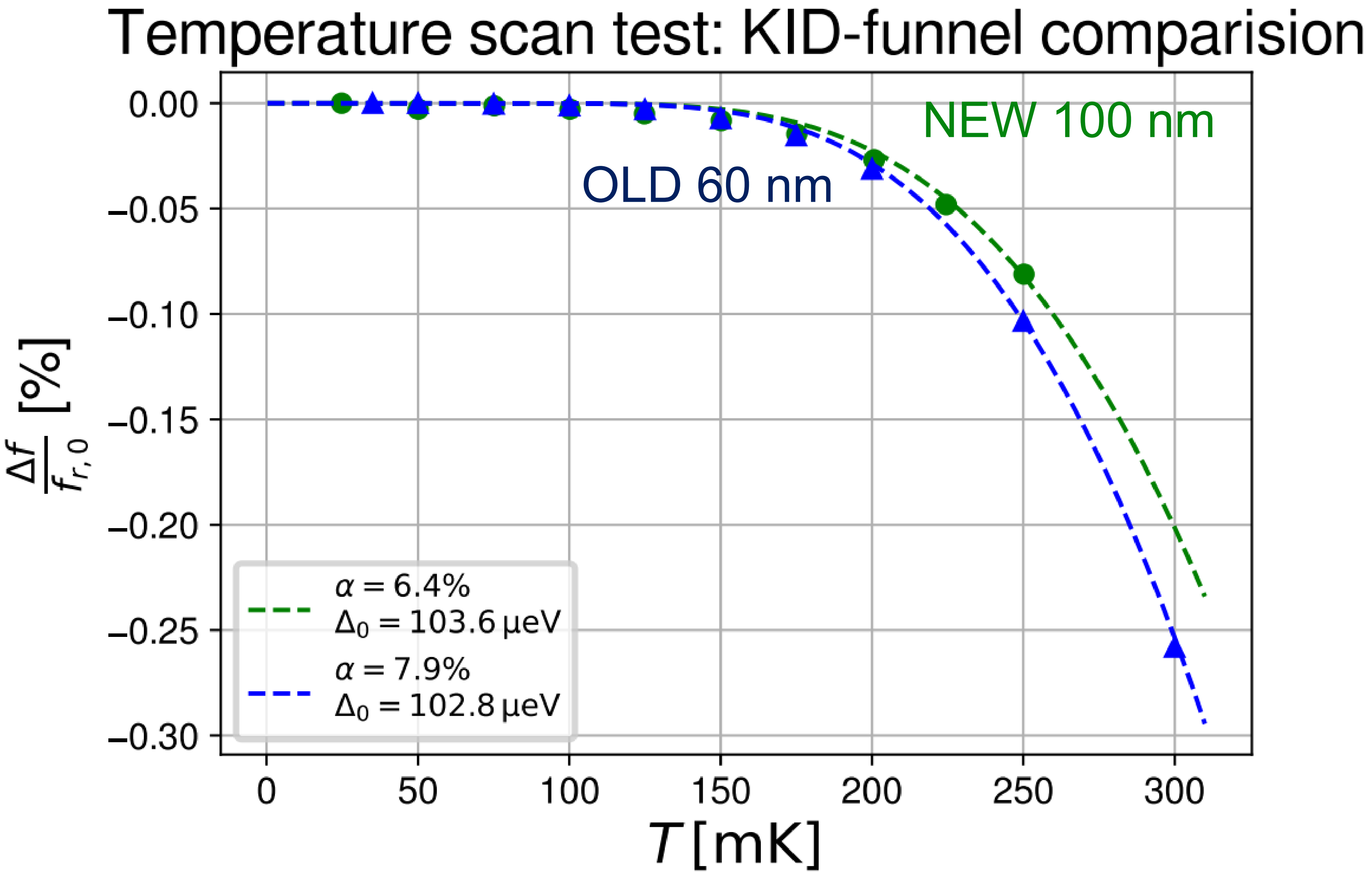
- Responsivity and noise depends on the fiber → **KIDs identification**
- Better performances for **KID-FUNNEL** in (almost) all the tile

Temperature scan old: results

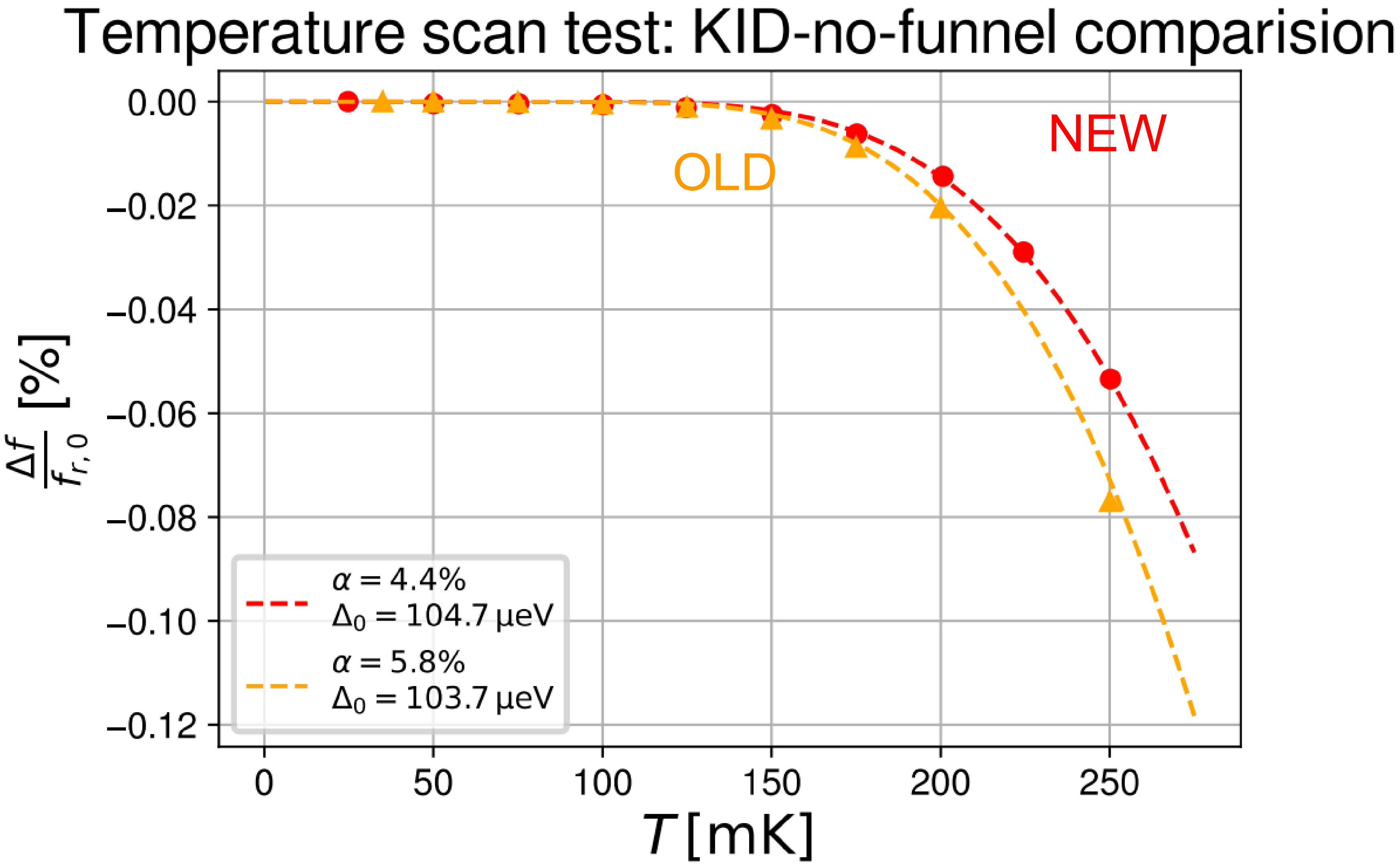




Temperature scan: new vs old (FUNNEL)



Temperature scan: new vs old (NO-FUNNEL)



Temperature scan ratio

- From the responsivity ratio:

$$r_f = \frac{\left(\frac{df}{dE}\right)_F}{\left(\frac{df}{dE}\right)_{NF}} = \frac{\eta_F}{\eta_{NF}} \frac{f_F}{f_{NF}} \boldsymbol{\frac{\alpha_F}{\alpha_{NF}} \left(\frac{\Delta_{0,NF}}{\Delta_{0,F}}\right)^2 \frac{N_{0,NF}}{N_{0,F}} \frac{S_{2,F}}{S_{2,NF}}} = \frac{\eta_F}{\eta_{NF}} \frac{f_{NF}}{f_F} \boldsymbol{A}$$

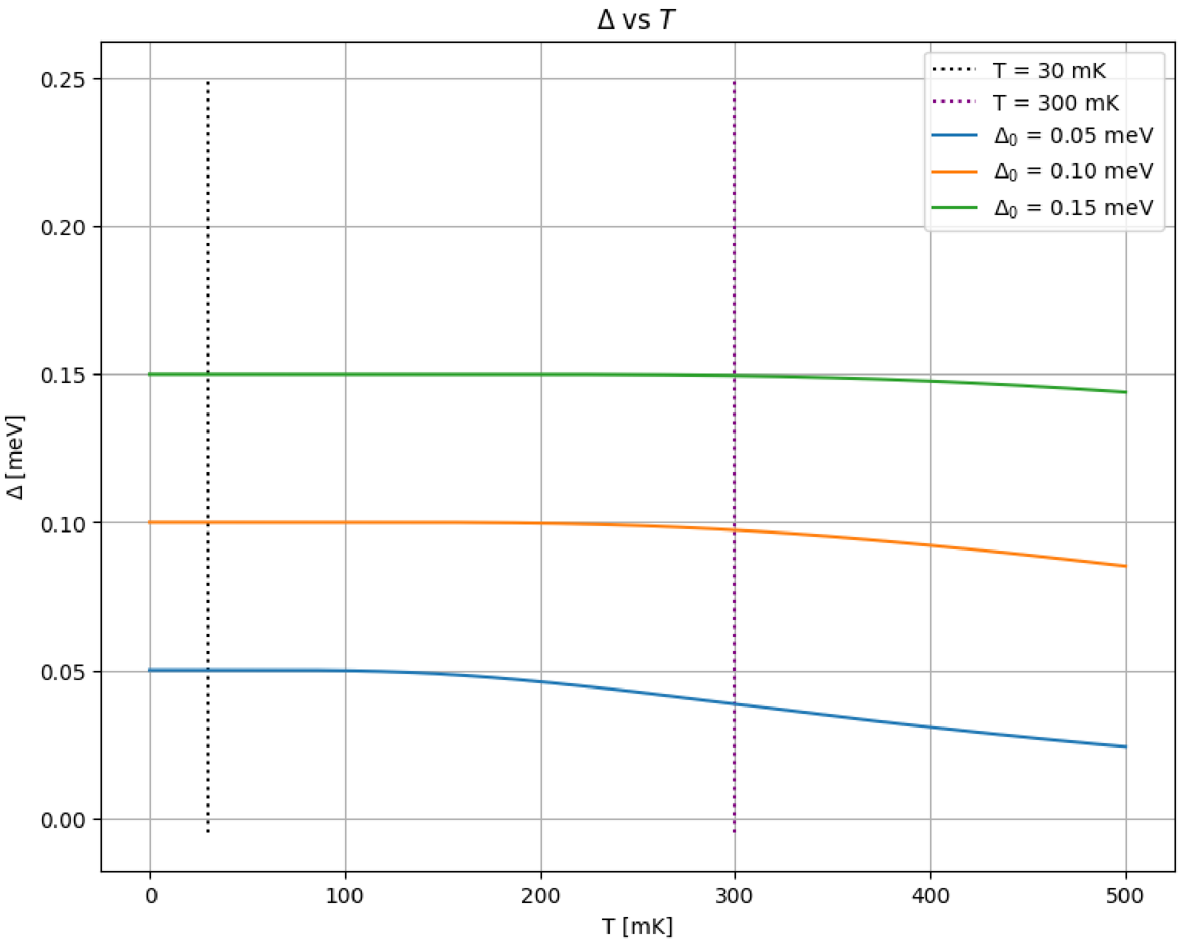
- Frome the T-scan ratio we get:

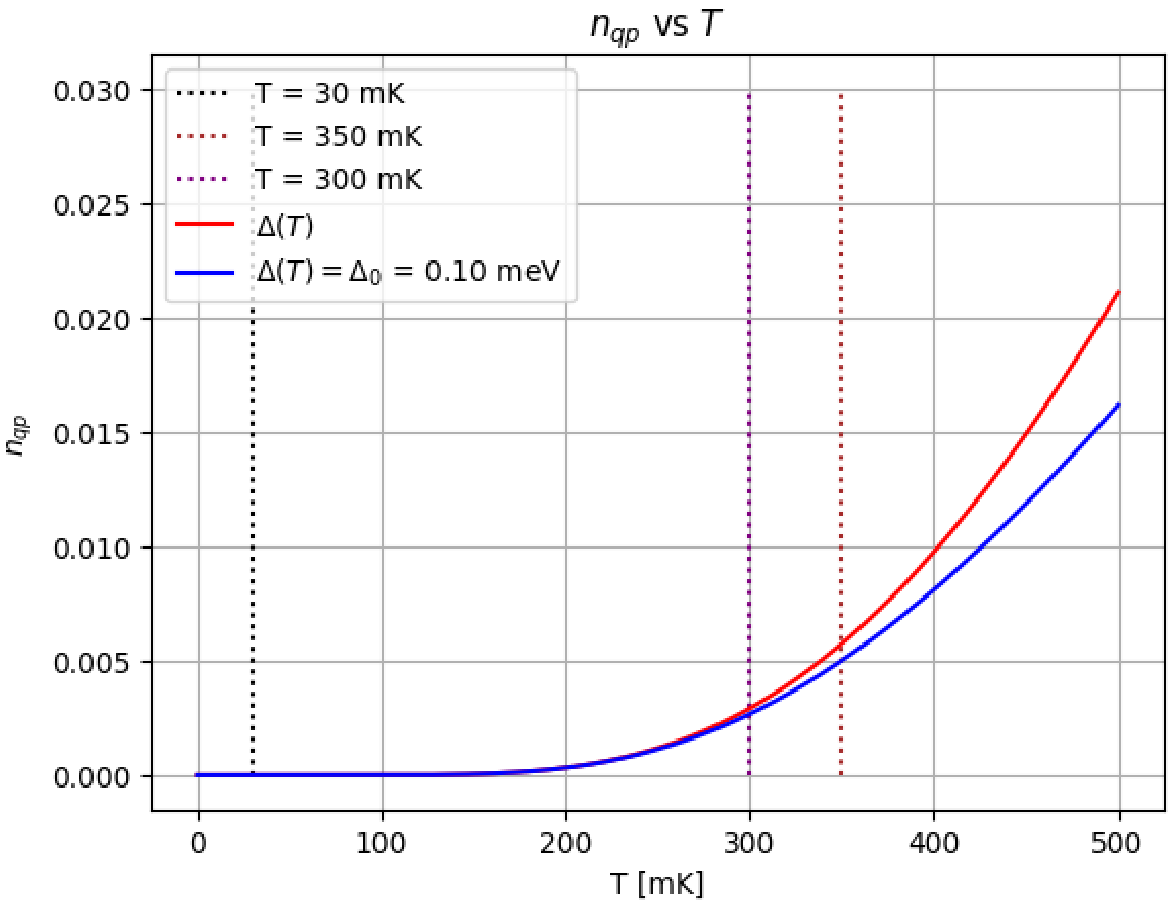
$$R_T = \frac{\left(\frac{\Delta f}{f}\right)_F}{\left(\frac{\Delta f}{f}\right)_{NF}} \approx \boldsymbol{A} \boldsymbol{\frac{N_{0,F}}{N_{0,NF}}} \left(\boldsymbol{\frac{\Delta_{0,F}}{\Delta_{0,NF}}}\right)^{\boldsymbol{\frac{3}{2}}} e^{\boldsymbol{\Delta_{0,NF}-\Delta_{0,F}}/k_B T} = \boldsymbol{C}\, e^{\boldsymbol{\delta\Delta}/k_B T}$$

- From $R_T \rightarrow C$ and $\delta\Delta \rightarrow \Delta_{0,F} \rightarrow A \rightarrow \eta_F/\eta_{NF}$ (assuming $N_{0,NF} \approx N_{0,F}$)

Temperature scan ratio: the study

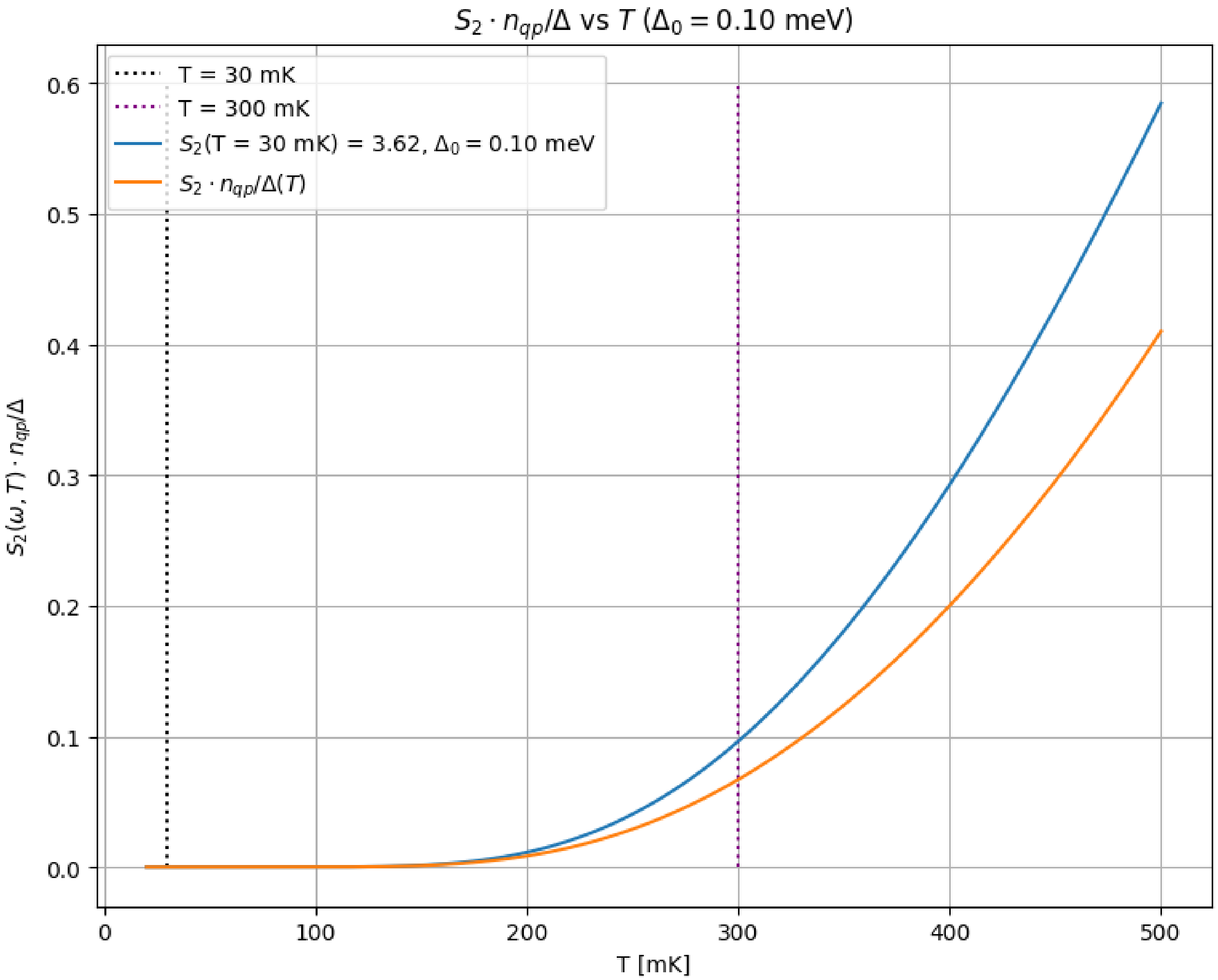
- ASSUMPTIONS (I): Δ_0 assumed constant (small variations) → $n_{qp} \sim \sqrt{T} e^{-\Delta_0/k_B T}$



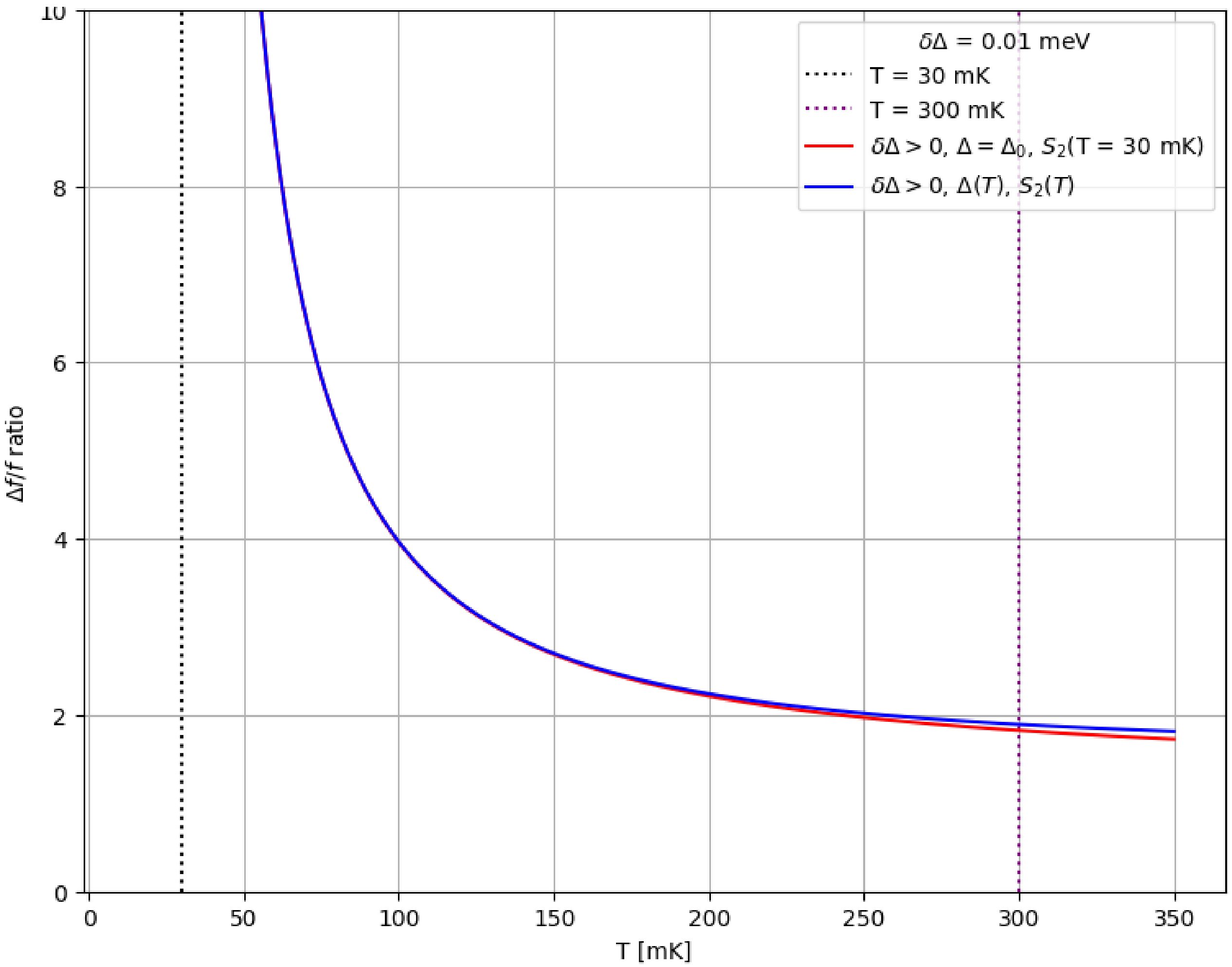


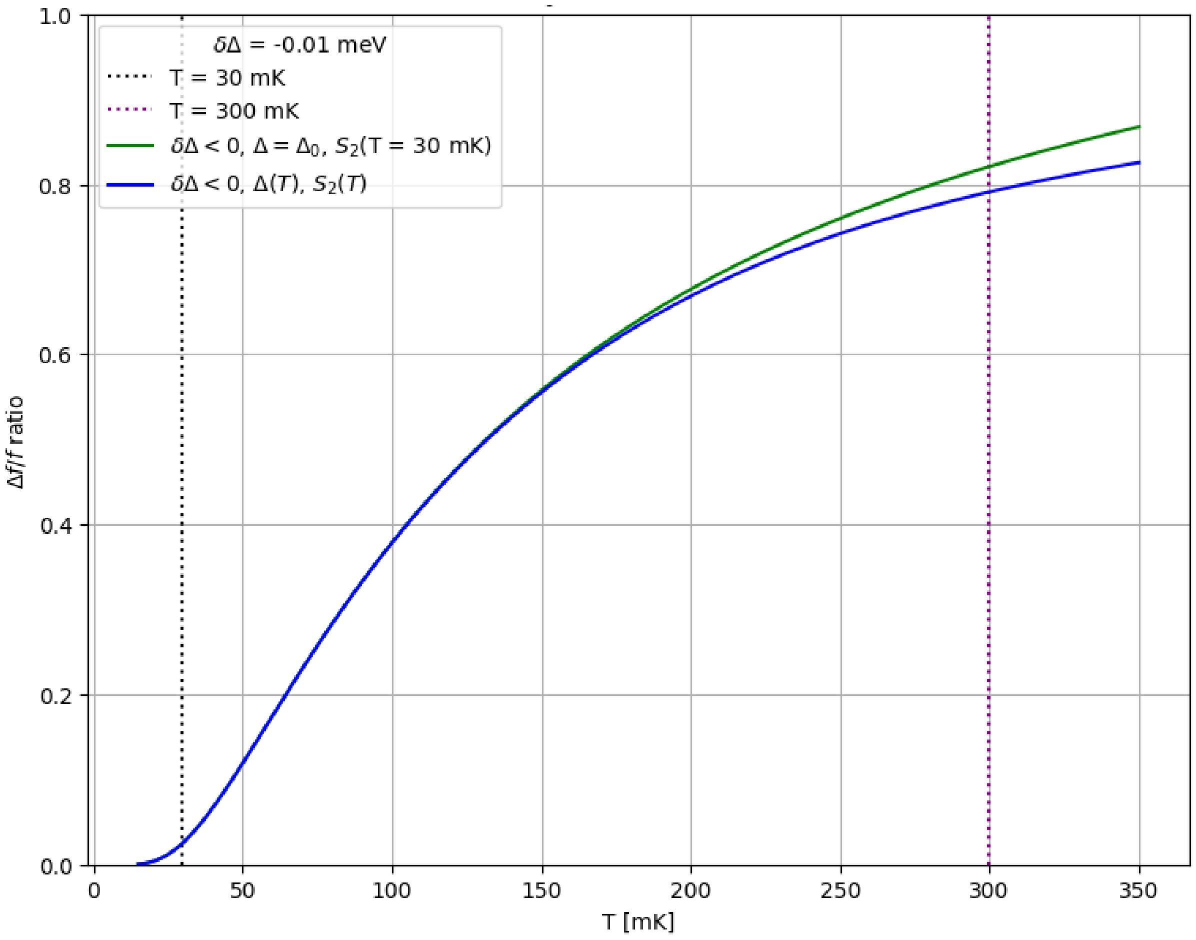
Temperature scan ratio: the study

- ASSUMPTIONS (II): S_2 taken constant at low temperature ($T = 30$ mK)



Temperature scan ratio: expectations

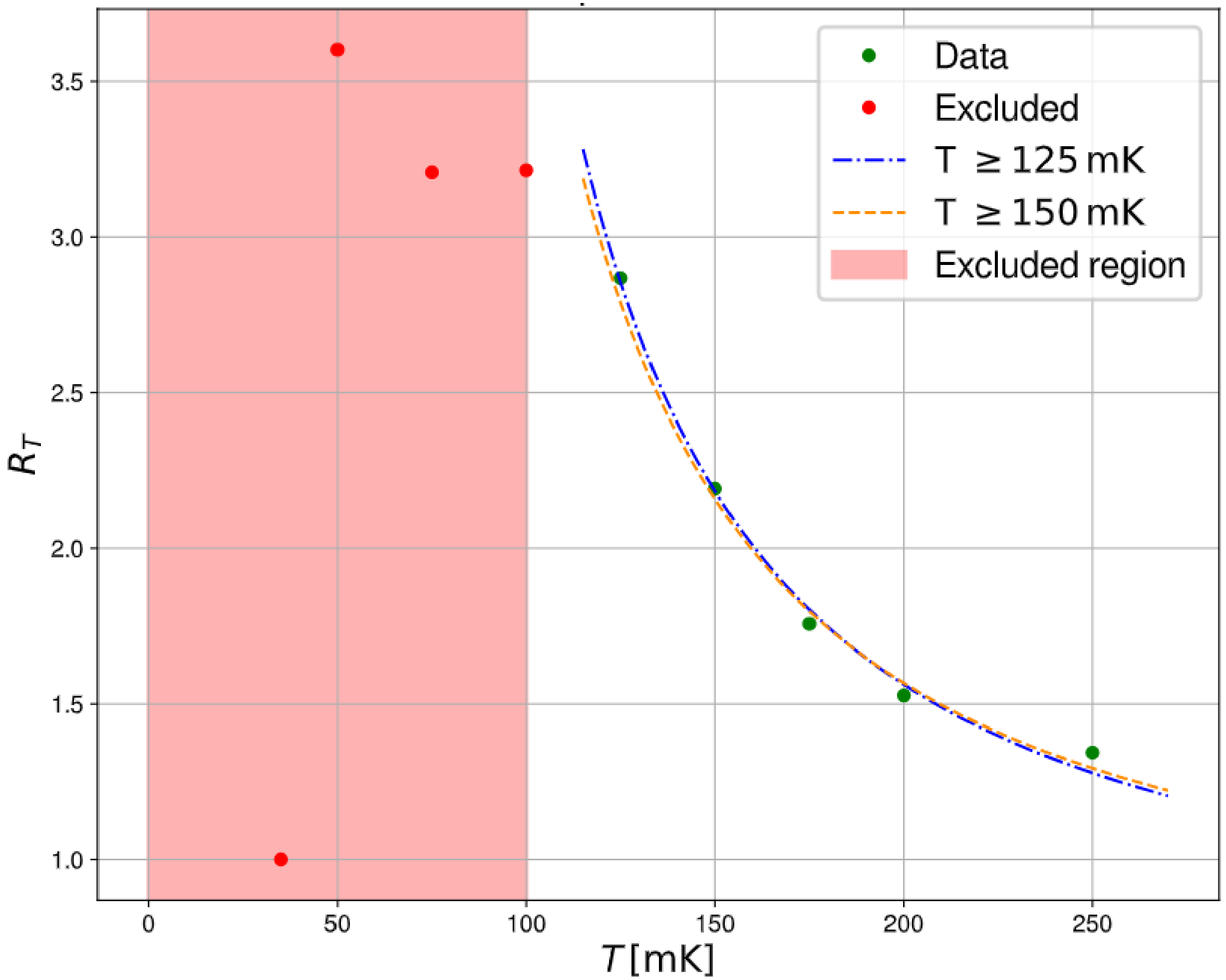




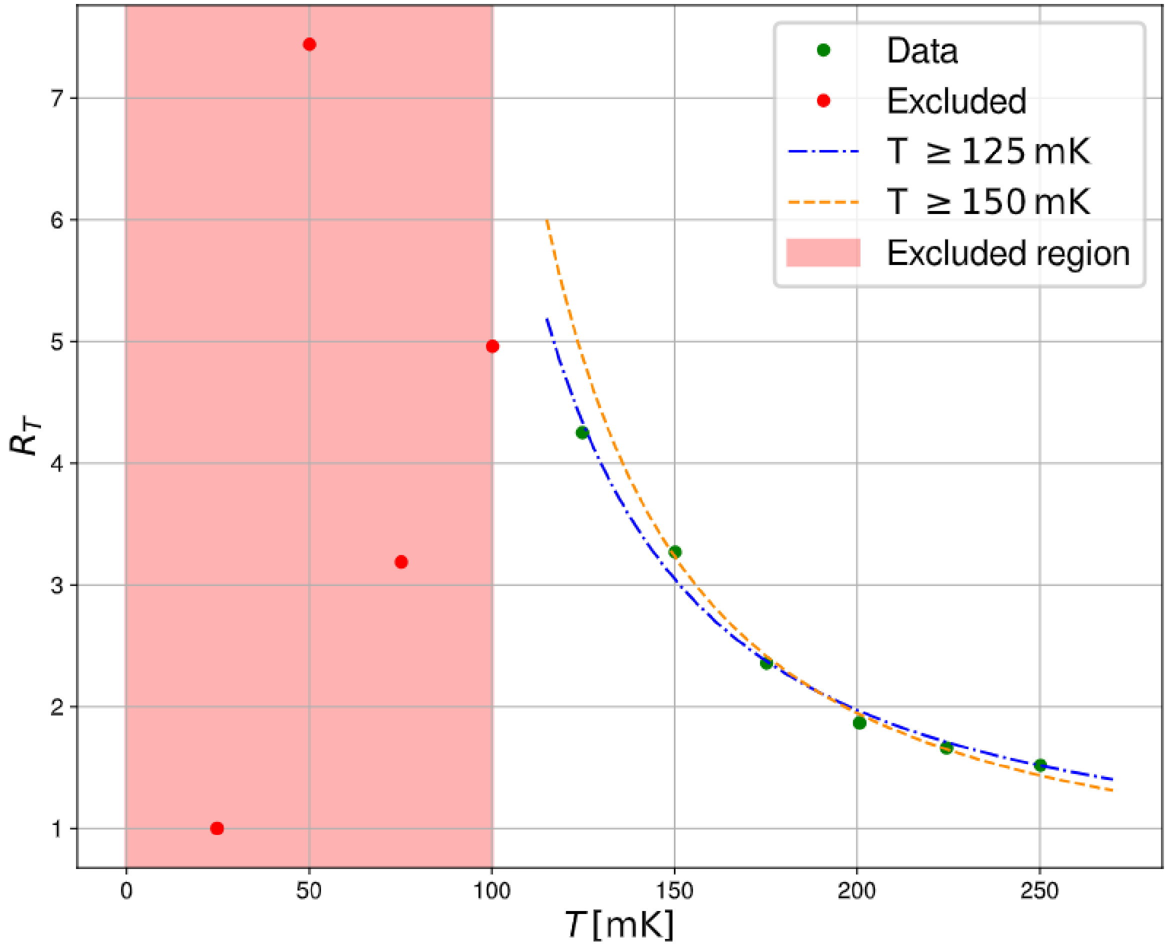
$\delta\Delta > 0$ $\delta\Delta < 0$

Temperature scan ratio: preliminary results

OLD RESONATORS



NEW RESONATORS



Temperature scan ratio: preliminary results

	C	$\delta\Delta$ [μeV]	A	η_F/η_{NF}	η_F/η_{NF} with S_2 equal
NEW	0.46	24.22	0.83	8.39	4.7
OLD	0.58	17.17	0.94	9.85	6.7
NEW	0.46	24.22	0.65	10.81	//
OLD	0.58	17.17	0.72	12.75	//

- **$\Delta_{0,NF}$ inferred from the T- scan fit**
- **$\Delta_{0,NF}$ measured from the feed-line transition**

- In both cases, a correction of a factor 1.7-1.5 is seen → **Can this be the correction of the S_2 ratio** ?

Temperature scan ratio: preliminary results

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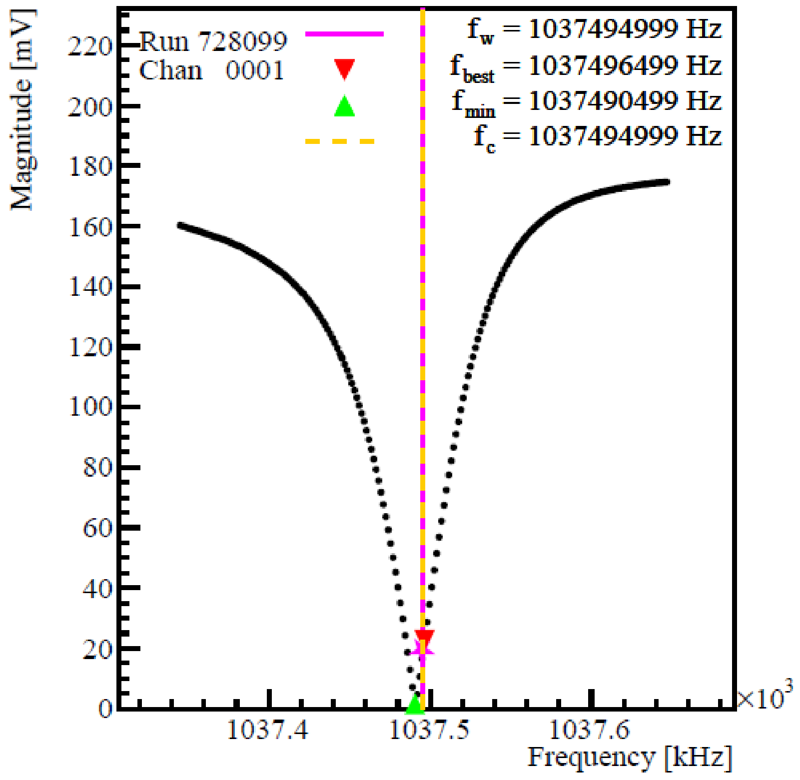
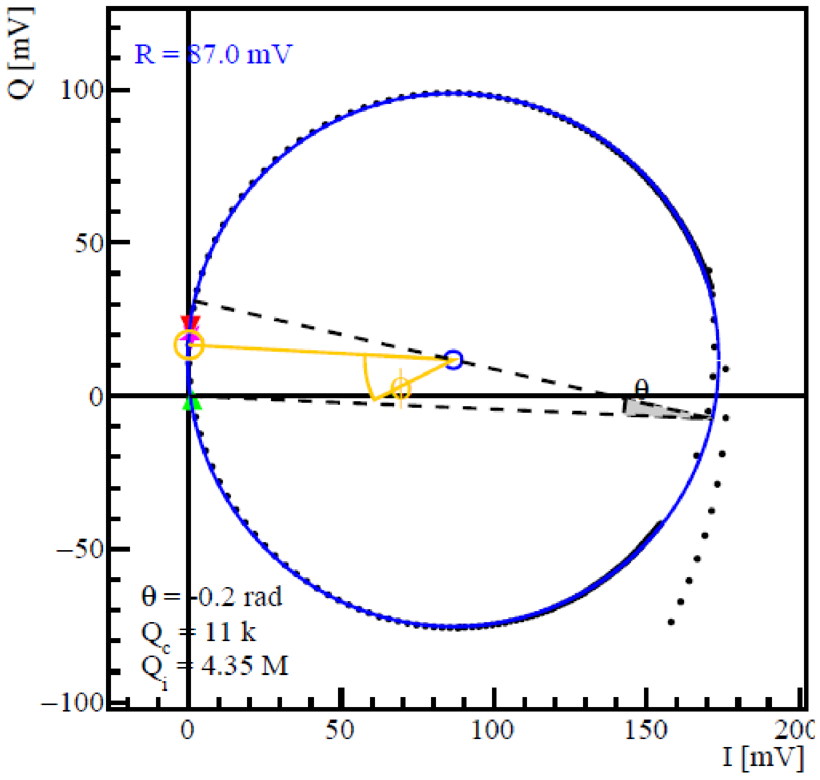
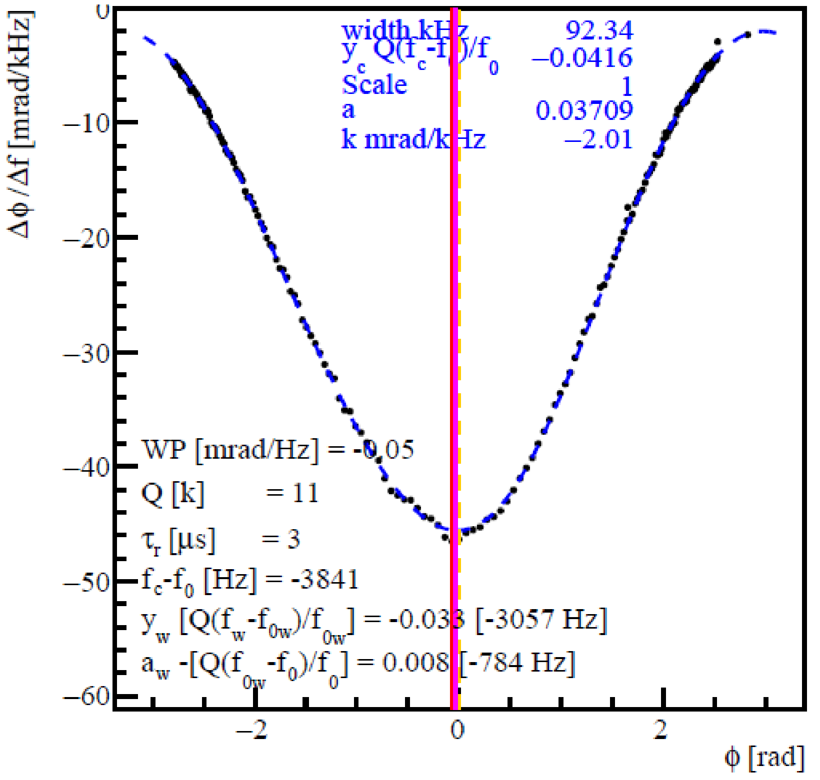
NEW	0.46	24.22	0.65	10.81	//
OLD	0.58	17.17	0.72	12.75	//

- The method seems consistent despite systematic effects to be evaluated
- To do for **OLD** vs **NEW KID-FUNNEL** to better understand the change of responsivity → **Not only reduction of α but of S_2, too** ?

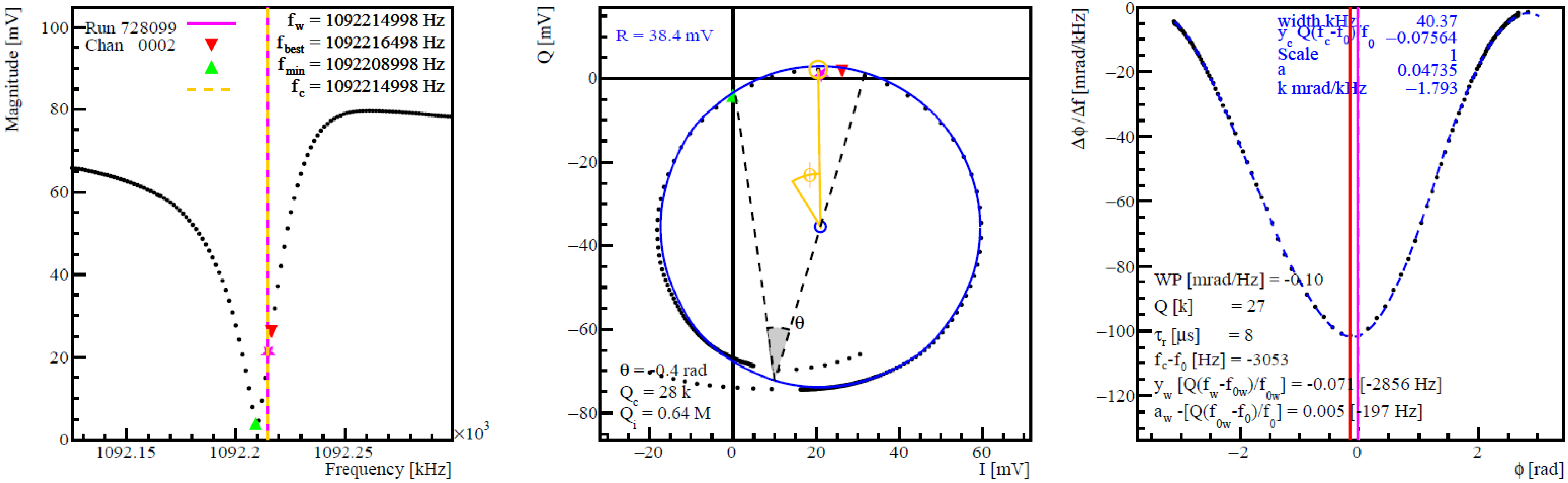
Resonance Circles: KID-FUNNEL Al (low power)







Resonance Circles: KID-NO-FUNNEL Al (low power)

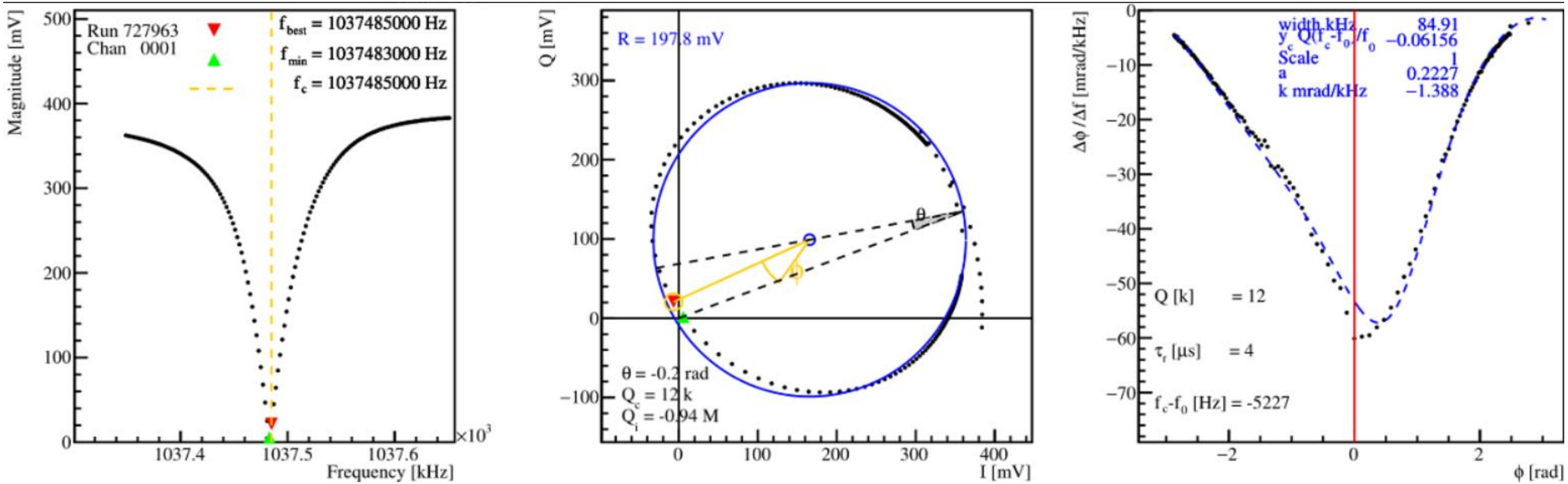


Resonance Circles: comparision

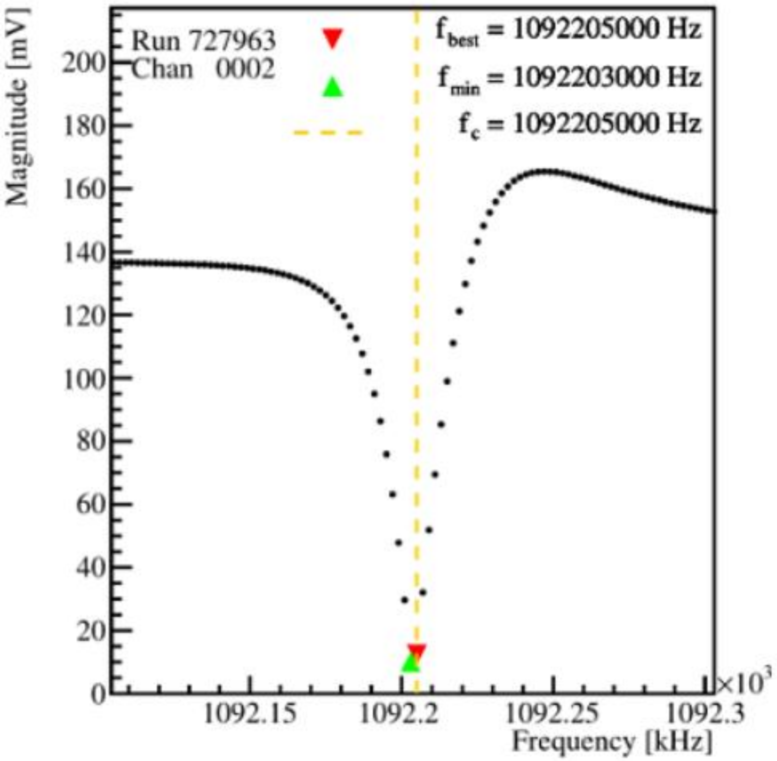
	KID-FUNNEL Al	KID-NO-FUNNEL Al	KID-FUNNEL new	KID-NO-FUNNEL new
$f_r\,[\mathrm{MHz}]$	**1037.4**	**1029.2**	**968.6**	**1029.0**
$Q_c\,[\mathrm{k}]$	**11**	**28**	**19**	**20**
$Q_i\,[\mathrm{M}]$	**4.35**	**0.64**	**0.02**	**0.41**
$Q\,[\mathrm{k}]$	**11**	**27**	**10**	**19**

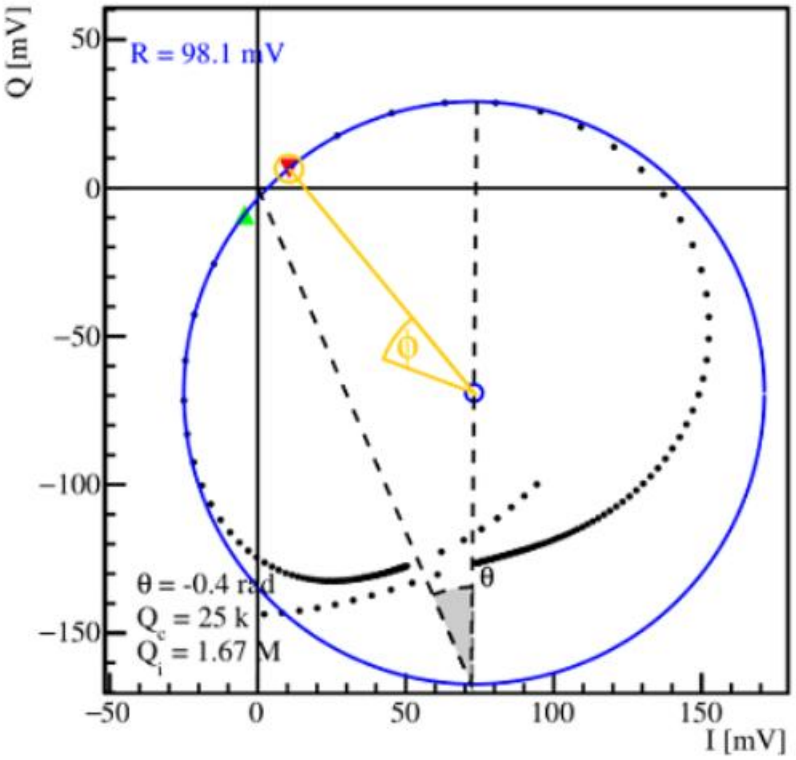
- f_r for **KID-NO-FUNNEL Al** matches **SONNET simulation**
- Q_c patterns are **consistent** (smaller for KID-FUNNEL Al)
- Why $\boldsymbol{Q_i}$ **is higher** for **KID-FUNNEL** in this case ?

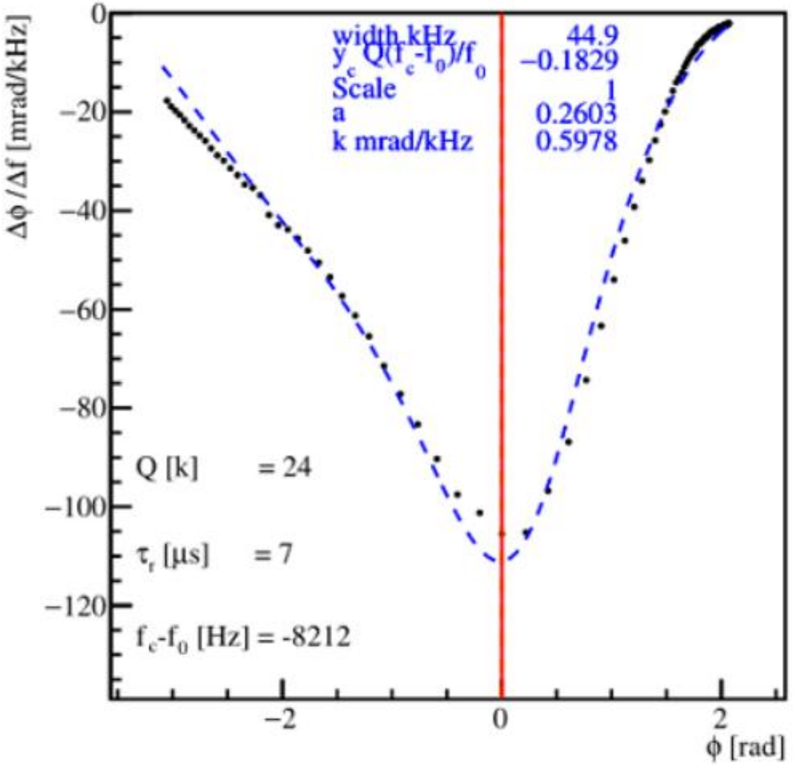
Resonance Circles: KID-FUNNEL Al (High power)



Resonance Circles: KID-NO-FUNNEL Al (High power)

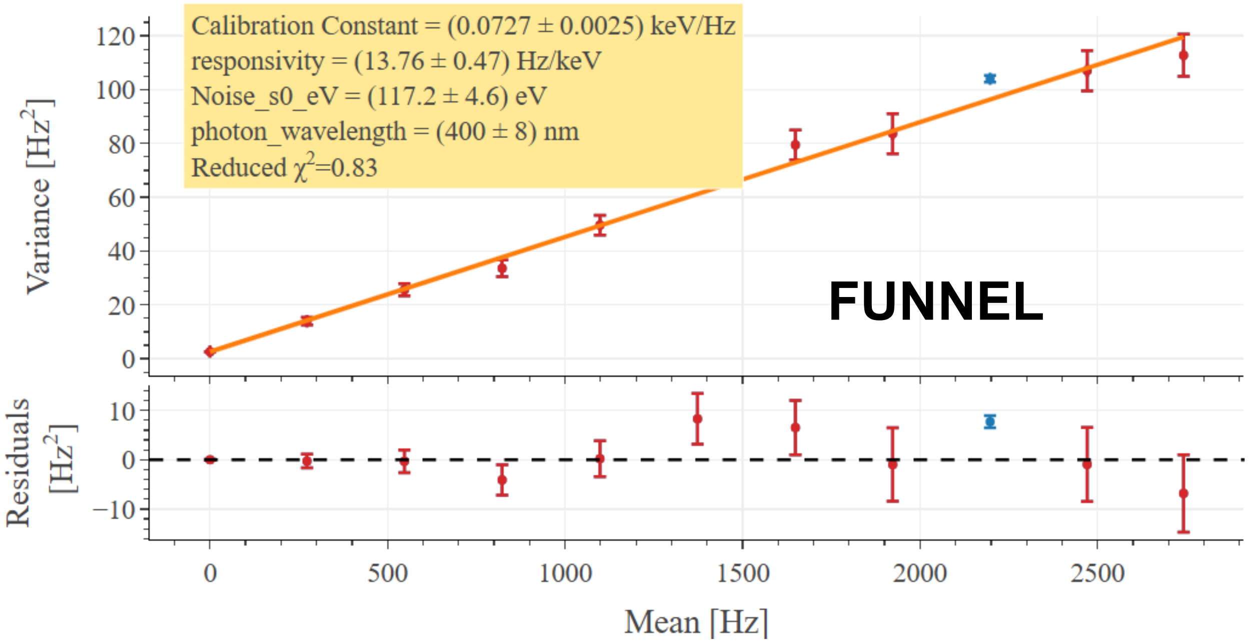


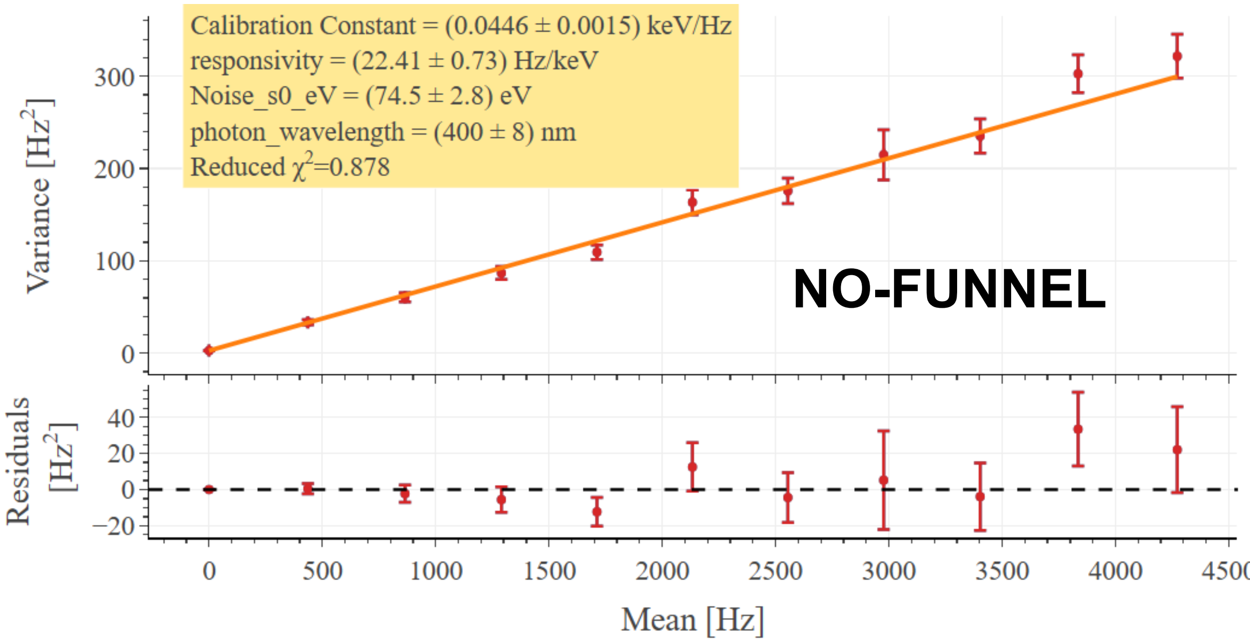




- Distortion of the resonance circles at optimal power

Al Funnel KID: preliminary results



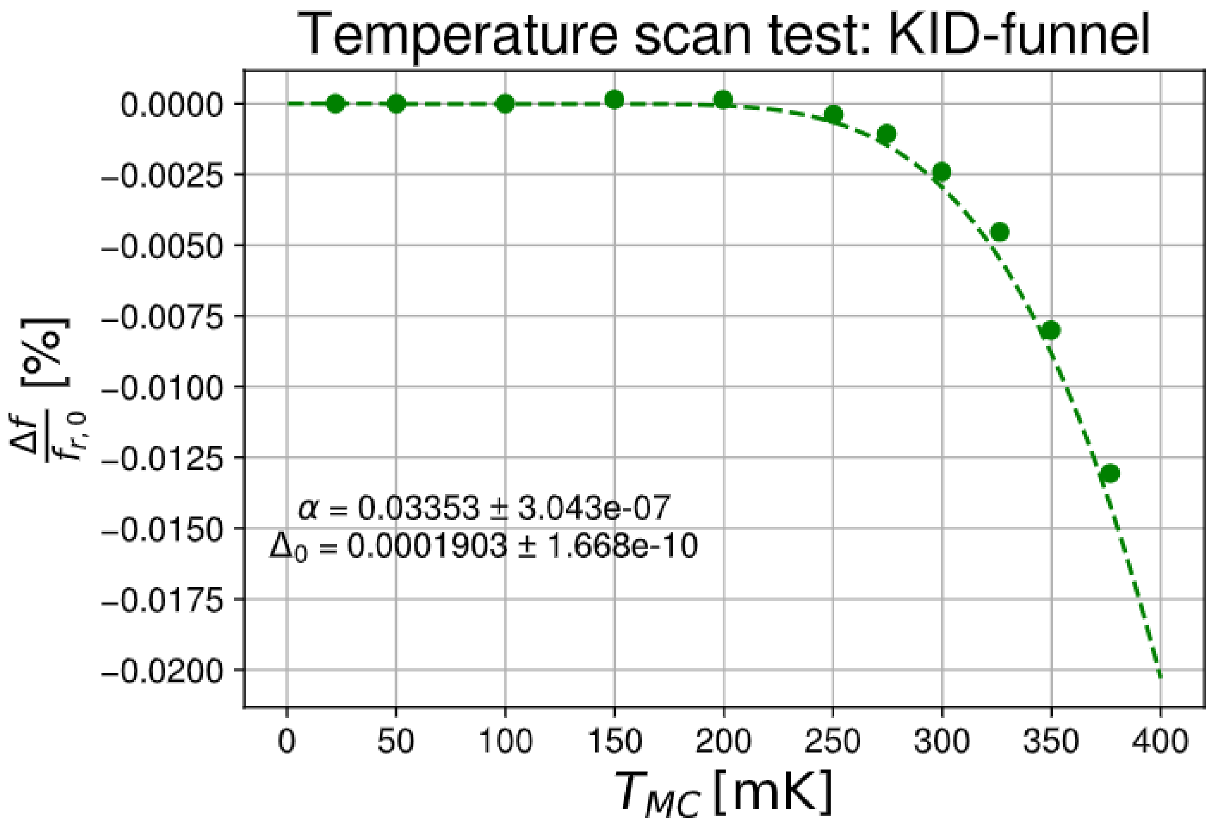


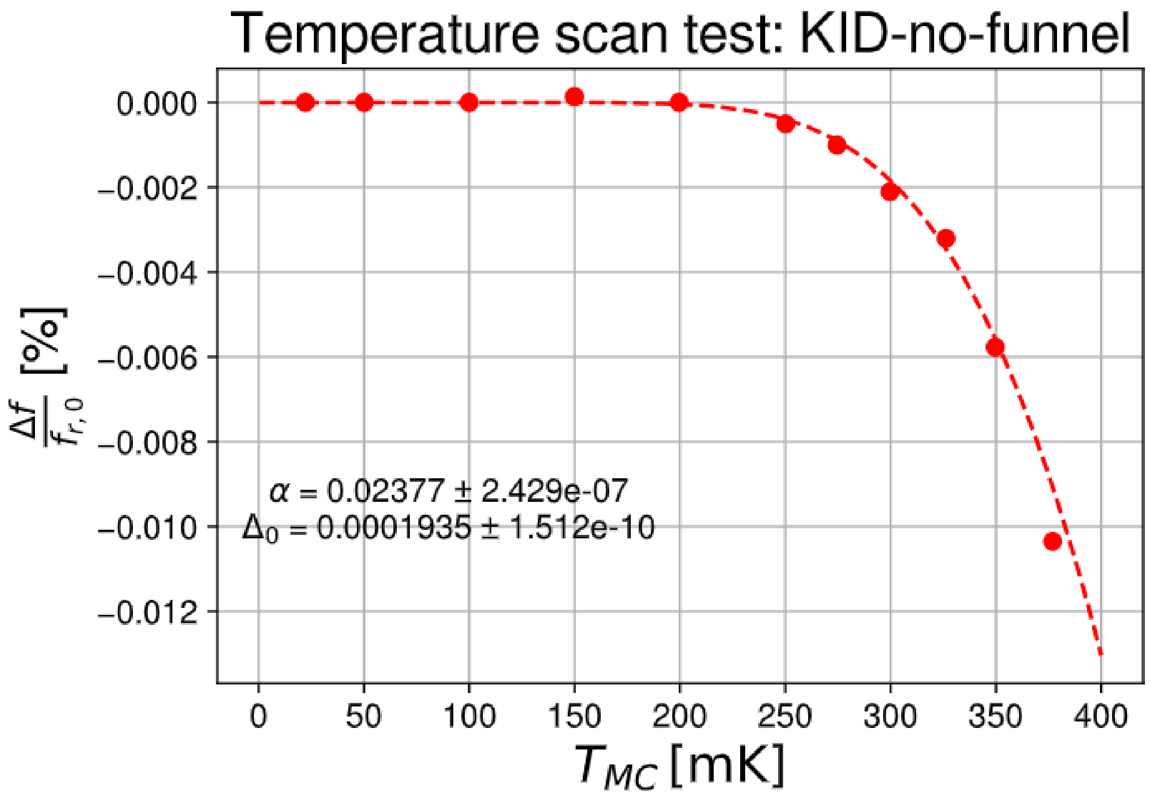
- Preliminary calibration at **LOW power** seem to confirm the absence of funneling effect

- **Some problems** with these arrays to be studied now (**unstable behavior at HIGH power**, **hard identification of the resonators**)

Al KIDs: temperature scan

- $\Delta_0 \approx 186\ \mu$eV measured directly for Al from **transition** of the **feed-line**



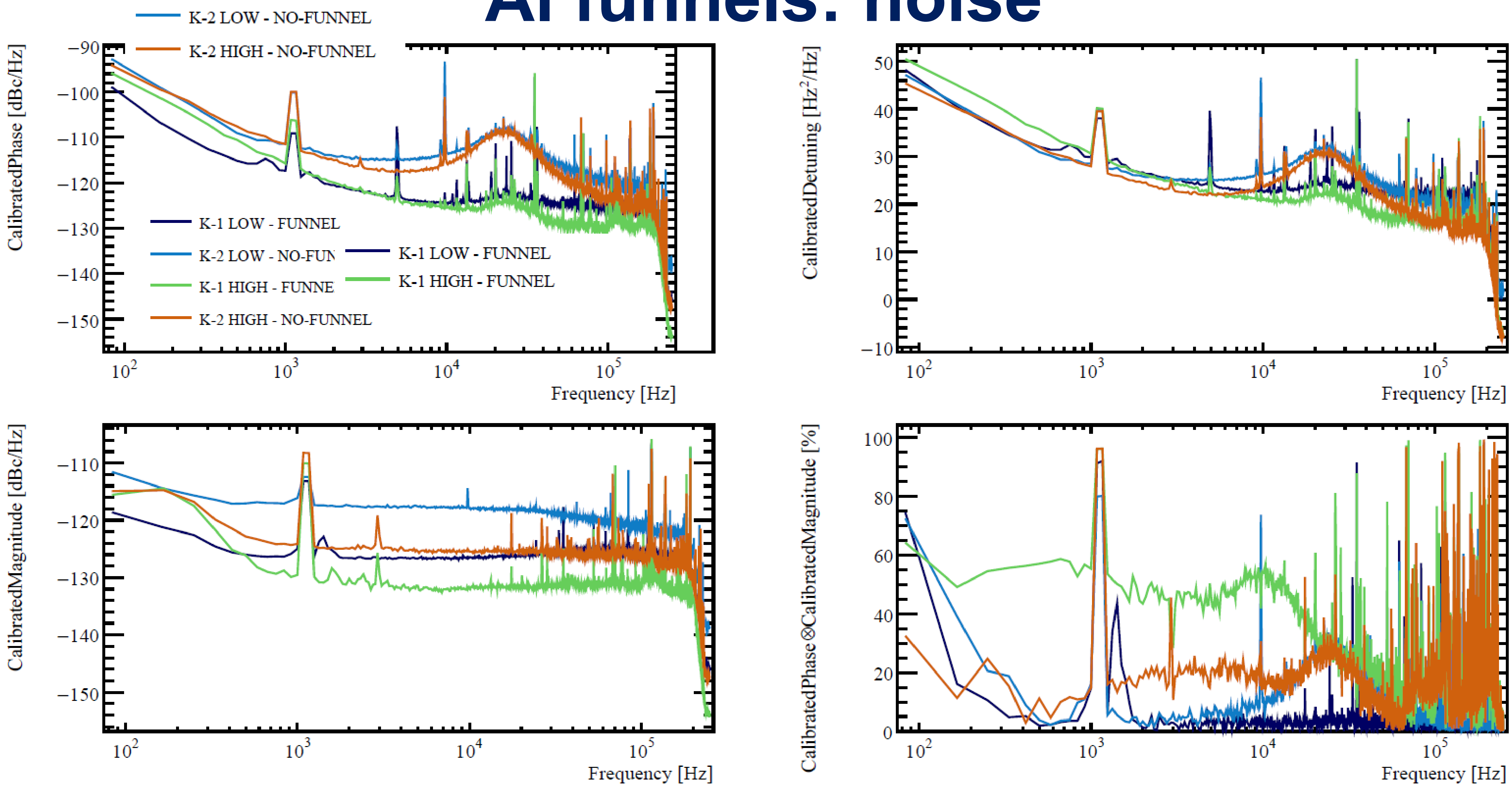


Al vs AlTlAl comparision @ Low power: preliminary

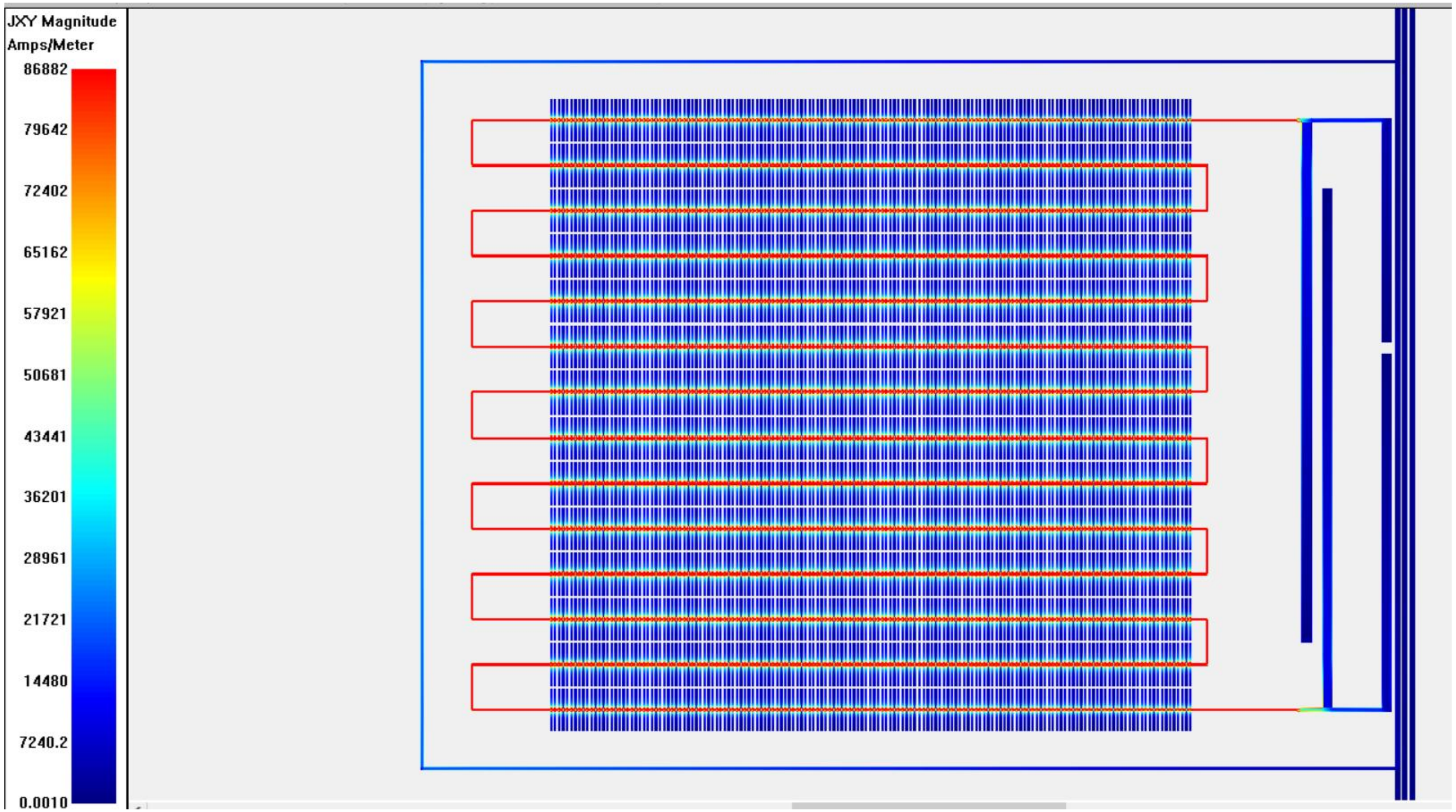
	AlTiAl KID-FUNNEL new	AlTiAl KID-NO-FUNNEL new	Al KID-FUNNEL	Al KID-NO-FUNNEL
$\frac{df}{dE}$ [Hz/keV]	129	4.86	13.8	22.4
σ_E [eV]	336	806	117.2	74.5
σ_N [Hz]	43.4	3.9	1.6	1.7
α [%]	6.4	4.4	3.4	2.37
Δ_0 [μeV]	103.6	104.7	190.3	193.5

- To check

Al funnels: noise



SONNET simulation: currents



No current flowing into the funnels at resonance