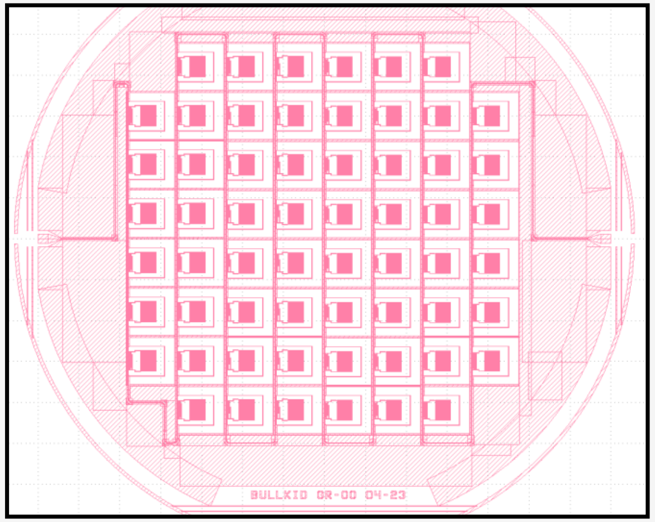
BULLKID: KIDs Research and Developement

20/03/2024 – BULLKID-DM Meeting – LNGS

Daniele Delicato *for the BULLKID collaboration*

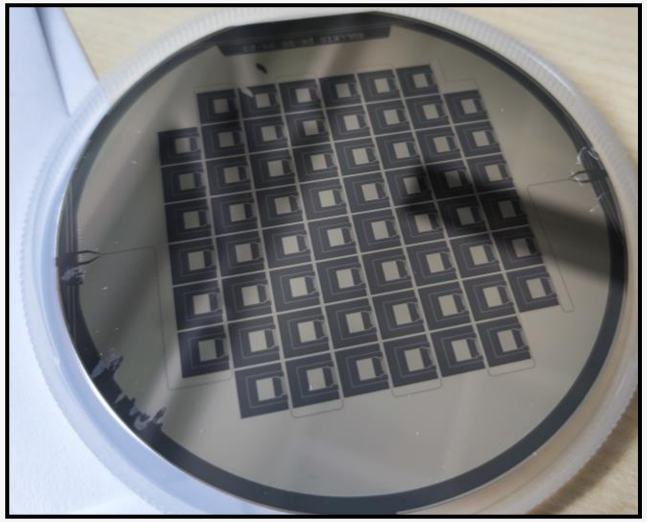
Device fabrication in Grenoble (PTA Cleanroom)



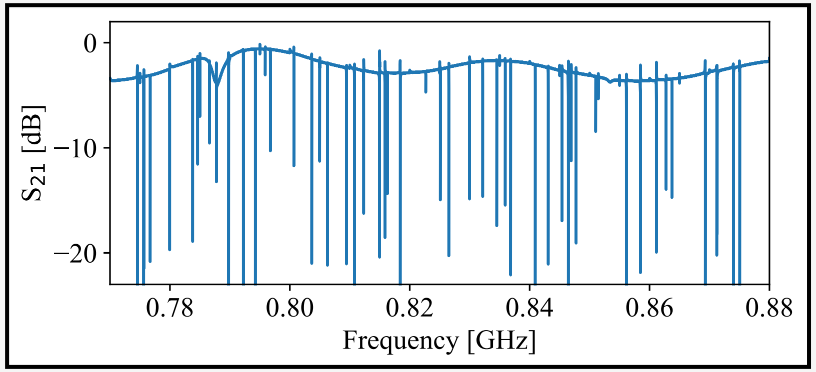
Design

Goals of the KID R&D:

- **Increase device robustness**
- **Increase responsivity** to phonon signals
- **Scale to 100mm array**
- Test KIDs on **Germanium**



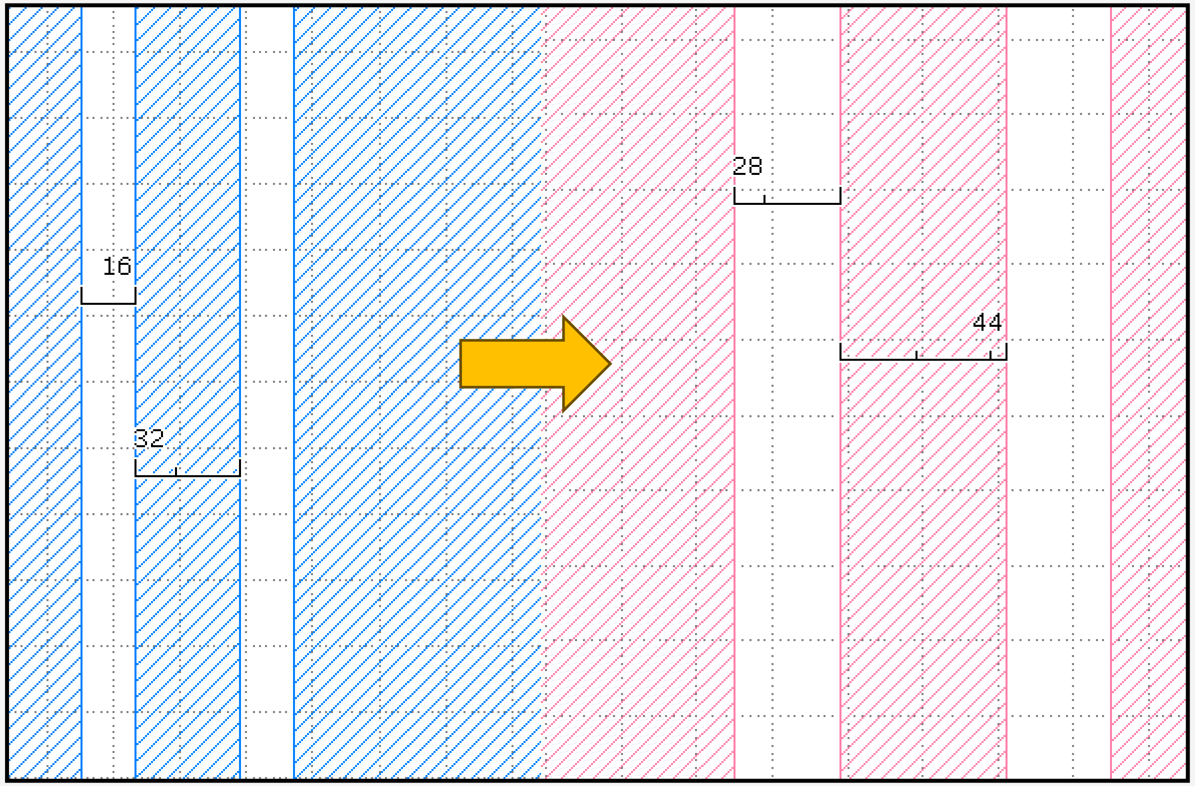
Fabrication

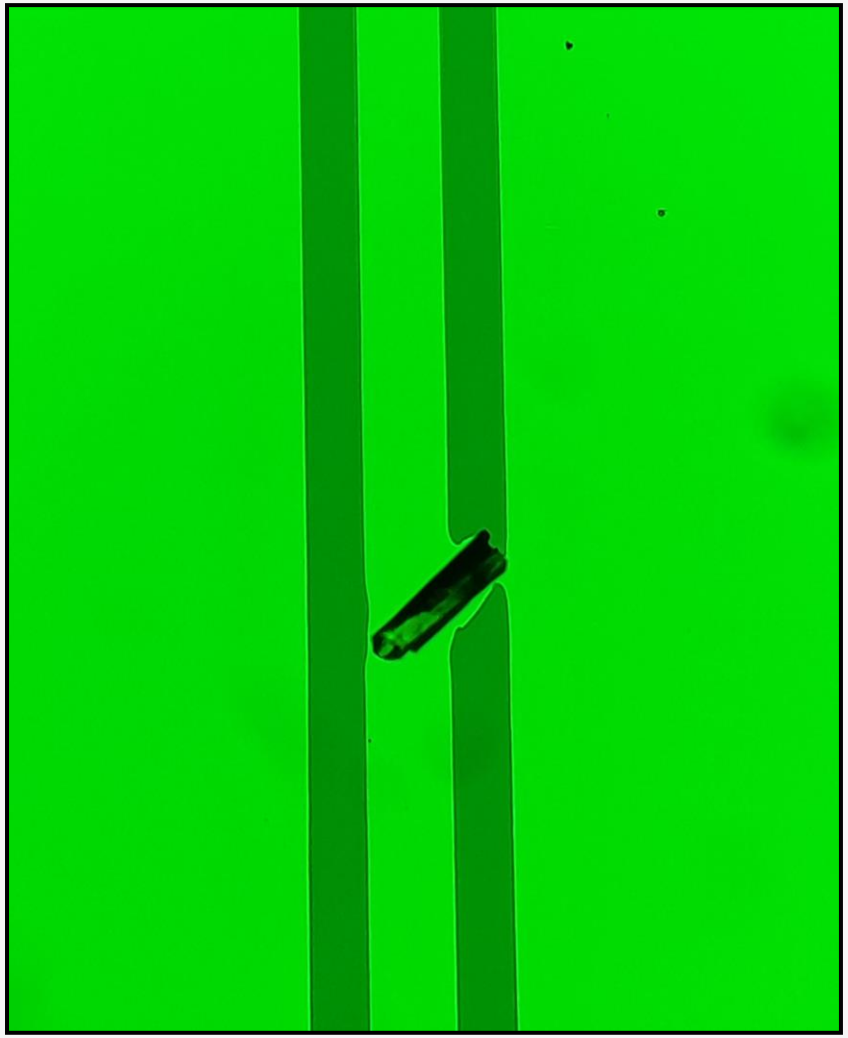


Testing

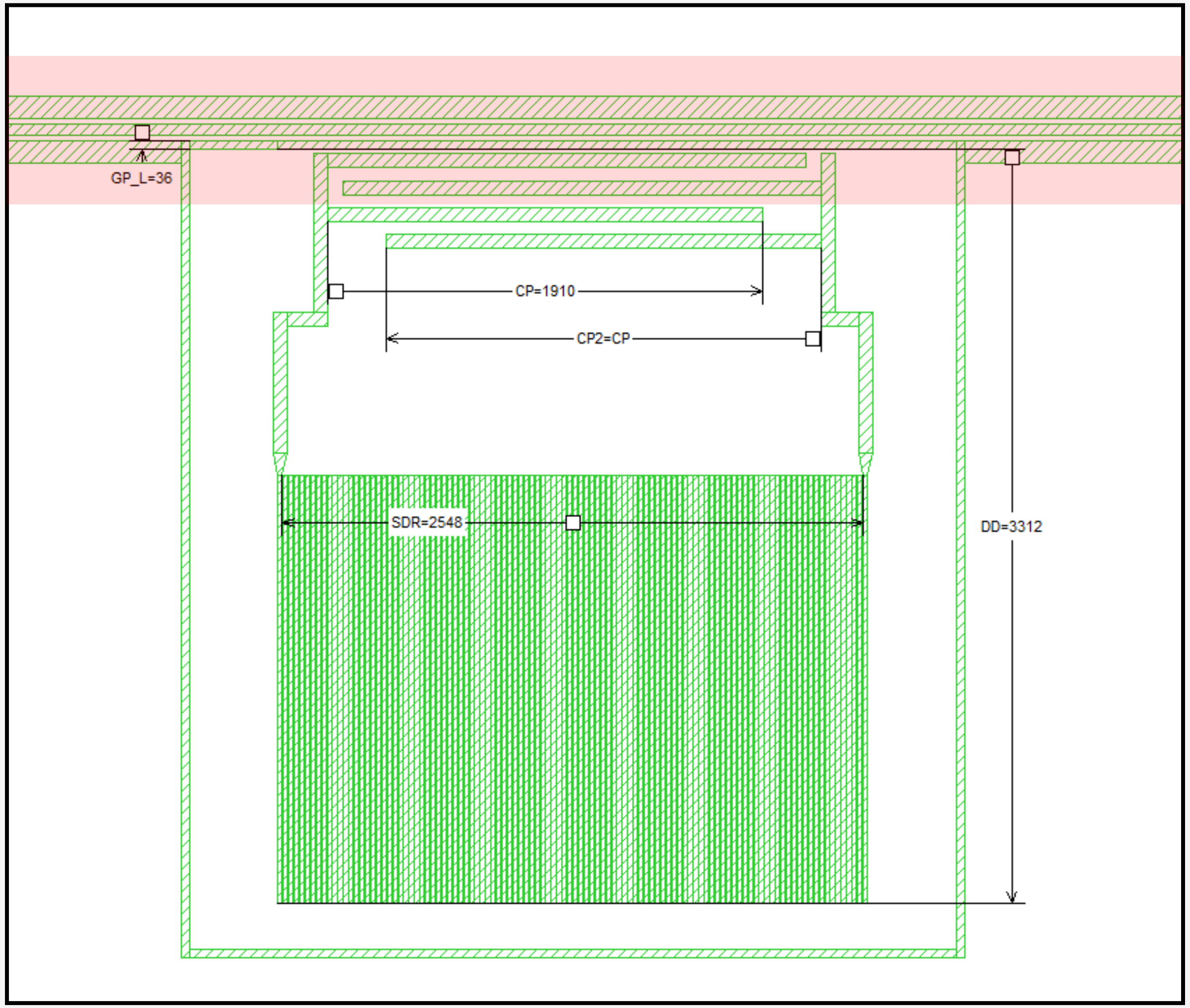
Robustness: feedline improvements

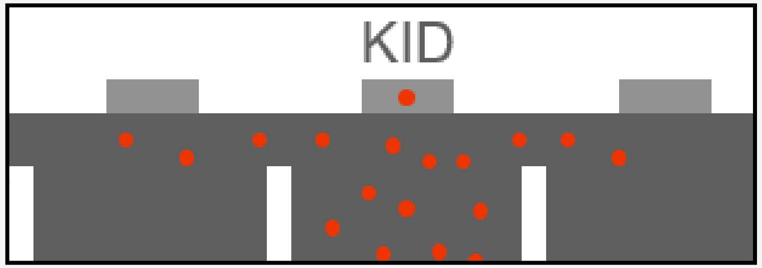
A wider coplanar waveguide is more resistant to defects -> **higher yield**





Capacitive coupling: meander no longer overlaps grooves





Phonons are less likely to be in the grooved region connecting the dice

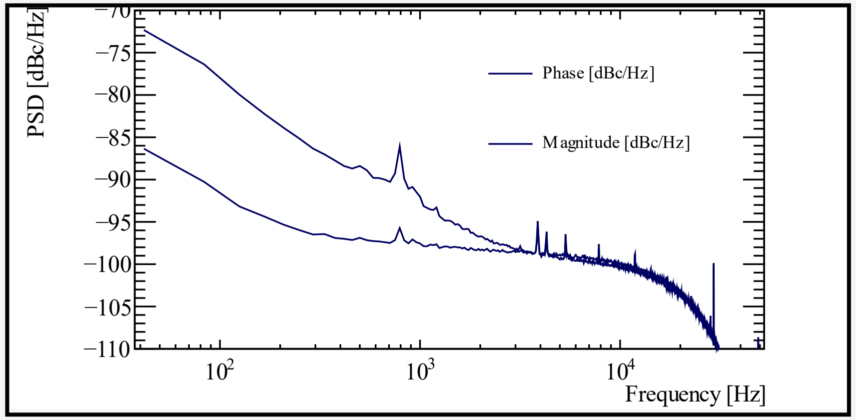
Move inert capacitive fingers over the groove increases phonon collection

Optimization of the KID responsivity

Goal: maximize SNR

$$\frac{\boldsymbol{Signal}}{\boldsymbol{Noise}}$$

Difficult to reduce



Noise not fully understood

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

$\frac{L_k}{L_{tot}}$ depends on pixel geometry and material

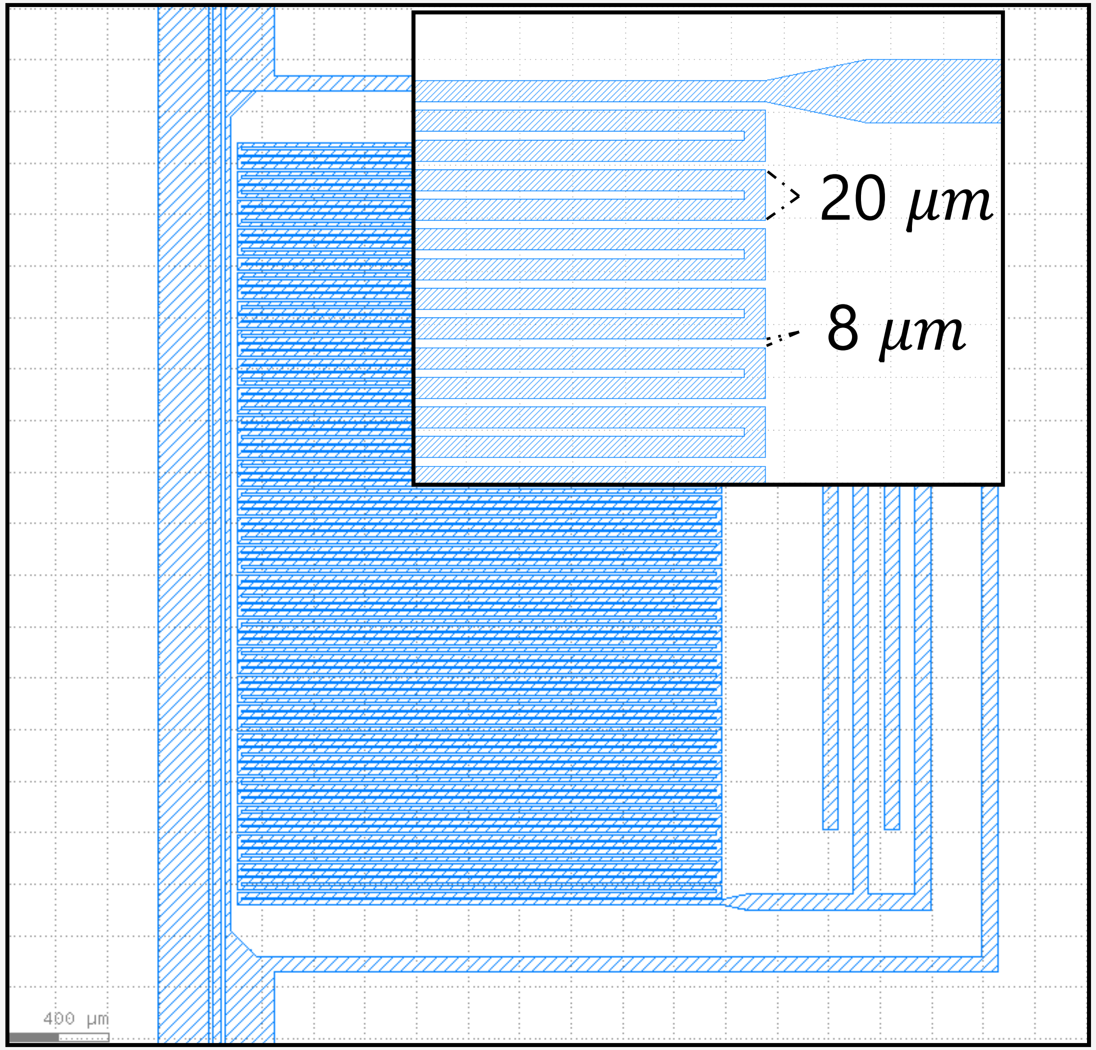
Quality factor of the resonator

Energy to quasi-particles efficiency

Volume of the KID

Gap of the superconductor metal

Optimization of the KID responsivity: α



Base design: 60nm Al

α = 5%

Q around 100k

$\Delta_0 = 1.880 \cdot 10^{-4} eV$

KID Volume: $4mm^2 \times 60nm = 2.4 \cdot 10^5 \mu m^3$

To increase $\frac{L_k}{L_k + L_{MAG}}$ we can

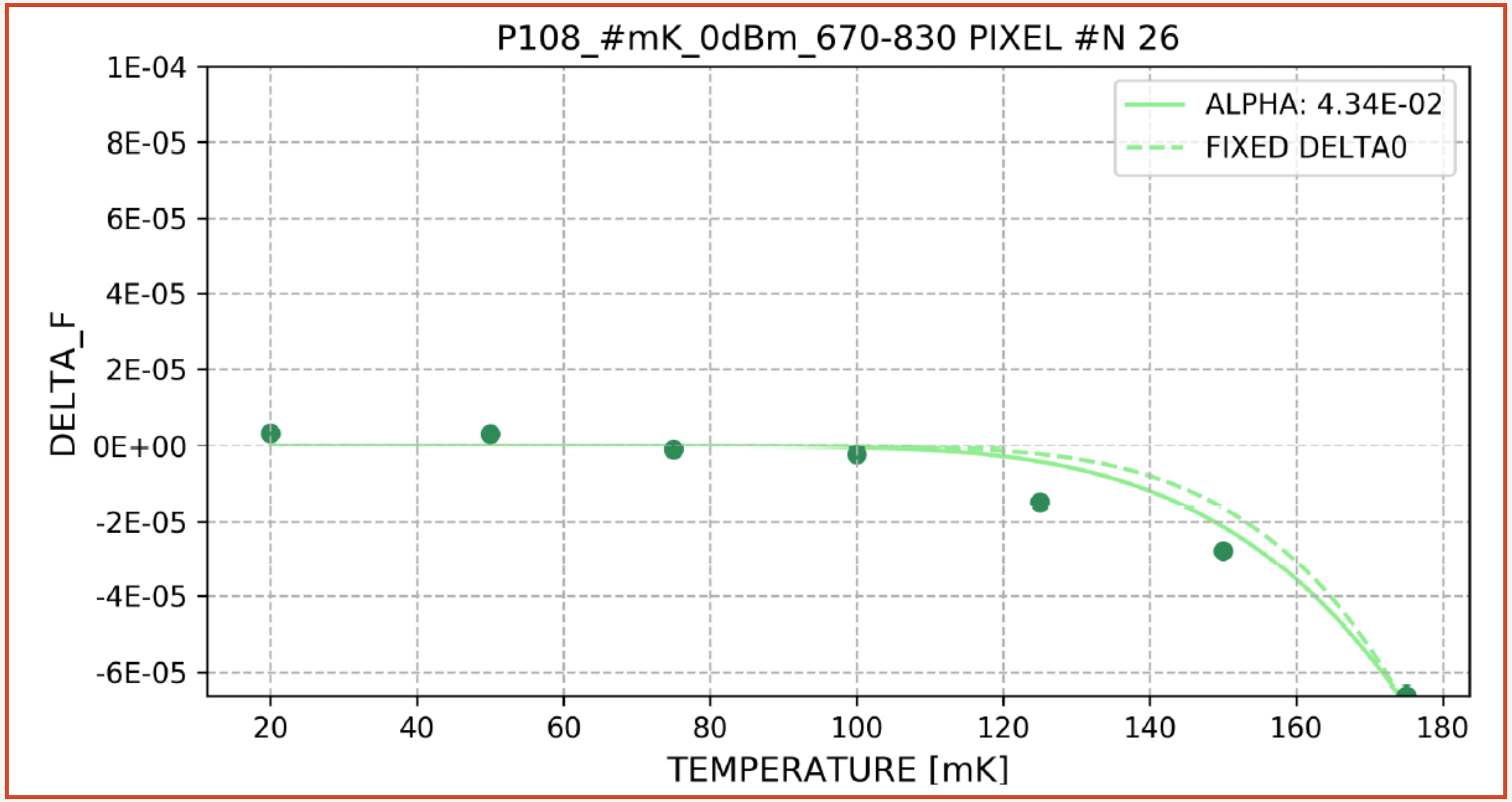
Tune the geometry to reduce L_{MAG}

Tune the metallic layer to increase L_k

Optimization of the KID responsivity: α – AlTiAl trilayer

Al 14 nm / Ti 33 nm / Al 30 nm
$T_c = (835 \pm 5)$ mK; $\Delta_0 = 1.266 \cdot 10^{-4} eV$

$$\Delta(T_{\mathrm{low}}) \approx \Delta_0 \cdot e^{-\sqrt{2\pi k_B T/\Delta_0} \cdot e^{-\Delta_0/k_B T}}$$



$$\frac{\delta f}{f_0} = -\frac{\alpha}{2} S_2(\omega, T) \frac{\delta n_{qp}}{2N_0\Delta}$$

Fit for α with Δ_0 fixed:

- **$\alpha = 24\%$**

(Cardani2018 reports $\alpha = 17\%$ and $T_c = 805$ mK)

Optimization of the KID responsivity: α – AlTiAl trilayer

Al 14 nm

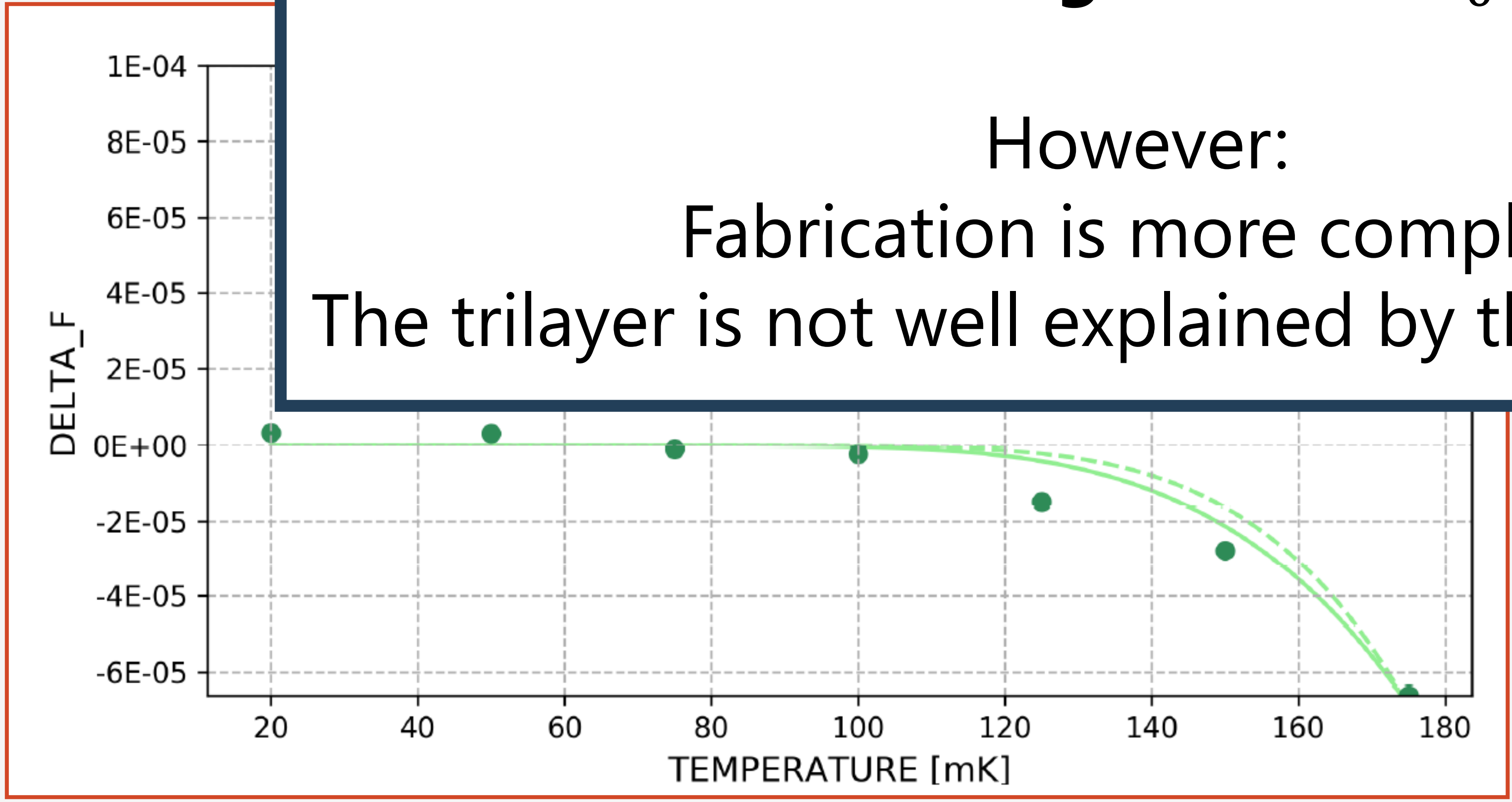
$T_c = (83$

Huge increase in α (x4!)
Smaller gain from Δ_0

However:
Fabrication is more complex
The trilayer is not well explained by the BCS theory

$\Delta_0 \cdot e^{-\Delta_0/k_B T}$

$\omega, T)\frac{\delta n_{qp}}{2N_0\Delta}$



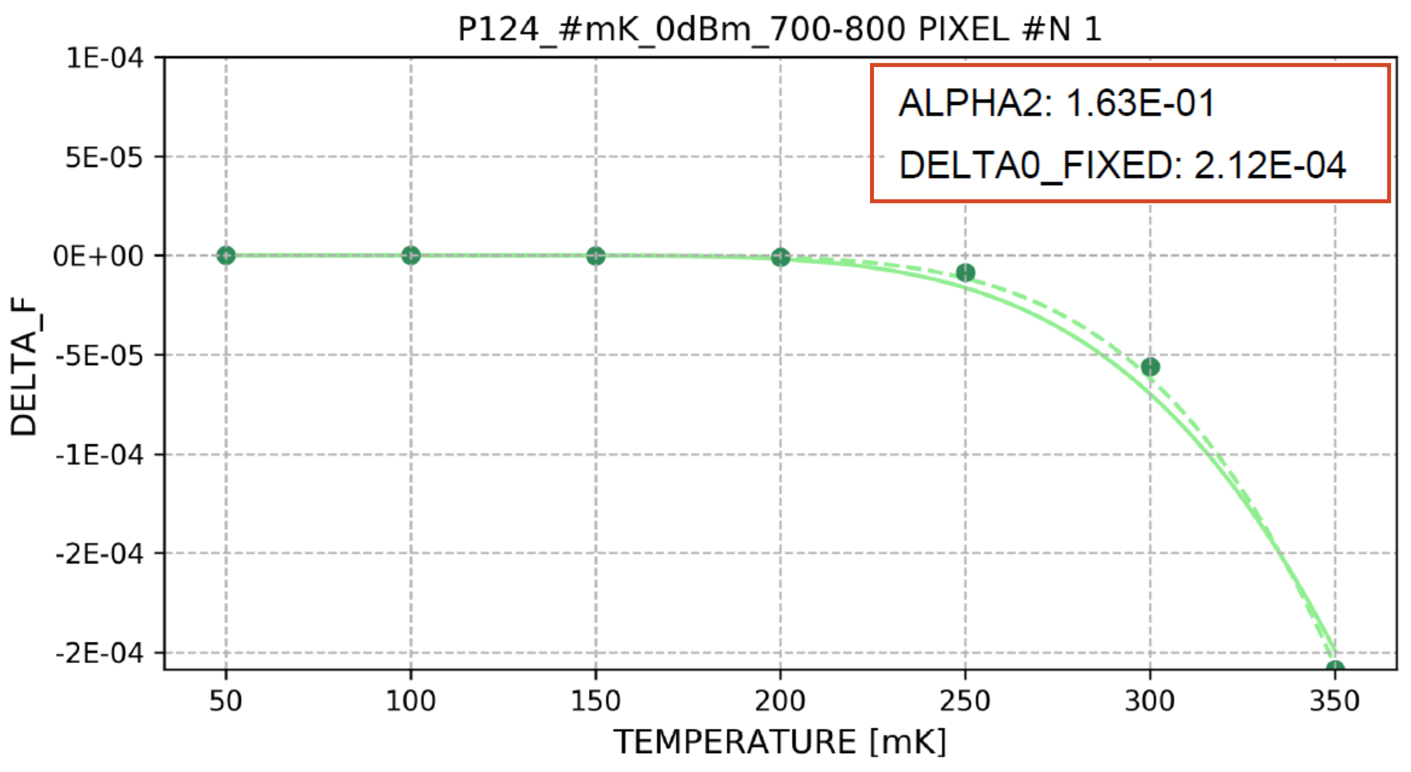
$_0$ fixed:

- **$\alpha = 24\%$**

(Cardani2018 reports $\alpha = 17\%$ and $T_c = 805$ mK)

Optimization of the KID responsivity: α – 30nm Al (Thin wafer)

$T_c = 1.4$ K –> $\Delta_0 = 2.12 \cdot 10^{-4} eV$



Fit for α with Δ_0 fixed:

- $\alpha \approx 16\%$

$\boldsymbol{\alpha_{30nm} \approx 3 \cdot \alpha_{60nm}}$

$\boldsymbol{V_{30nm} = 0.5 \cdot V_{60nm}}$

However we expect

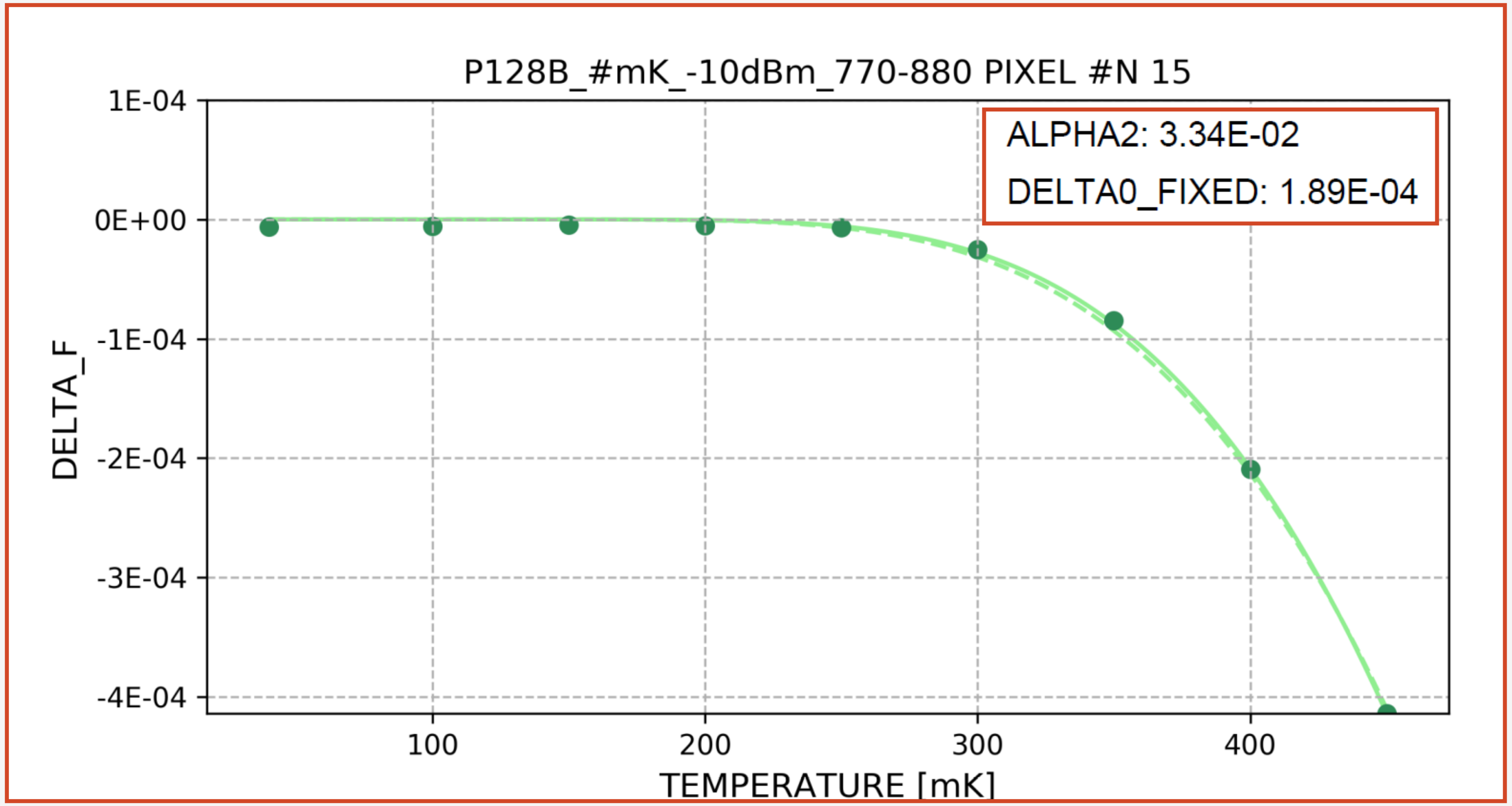
$\boldsymbol{\eta_{30nm} < \eta_{60nm}}$

- BCS Compatible
- Overall gain in $\frac{d\phi}{dE}$
- Standard fabrication process

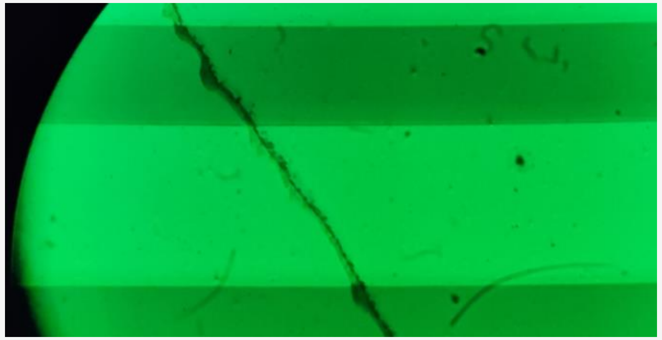
Optimization of the KID responsivity: α – 90nm Al (STACK-02)

$T_c = 1.2$ K

$\Delta_0(T_c) = 1.76 \cdot k_B \cdot T_c = 1.880 \cdot 10^{-4} eV$



More resilient to defects

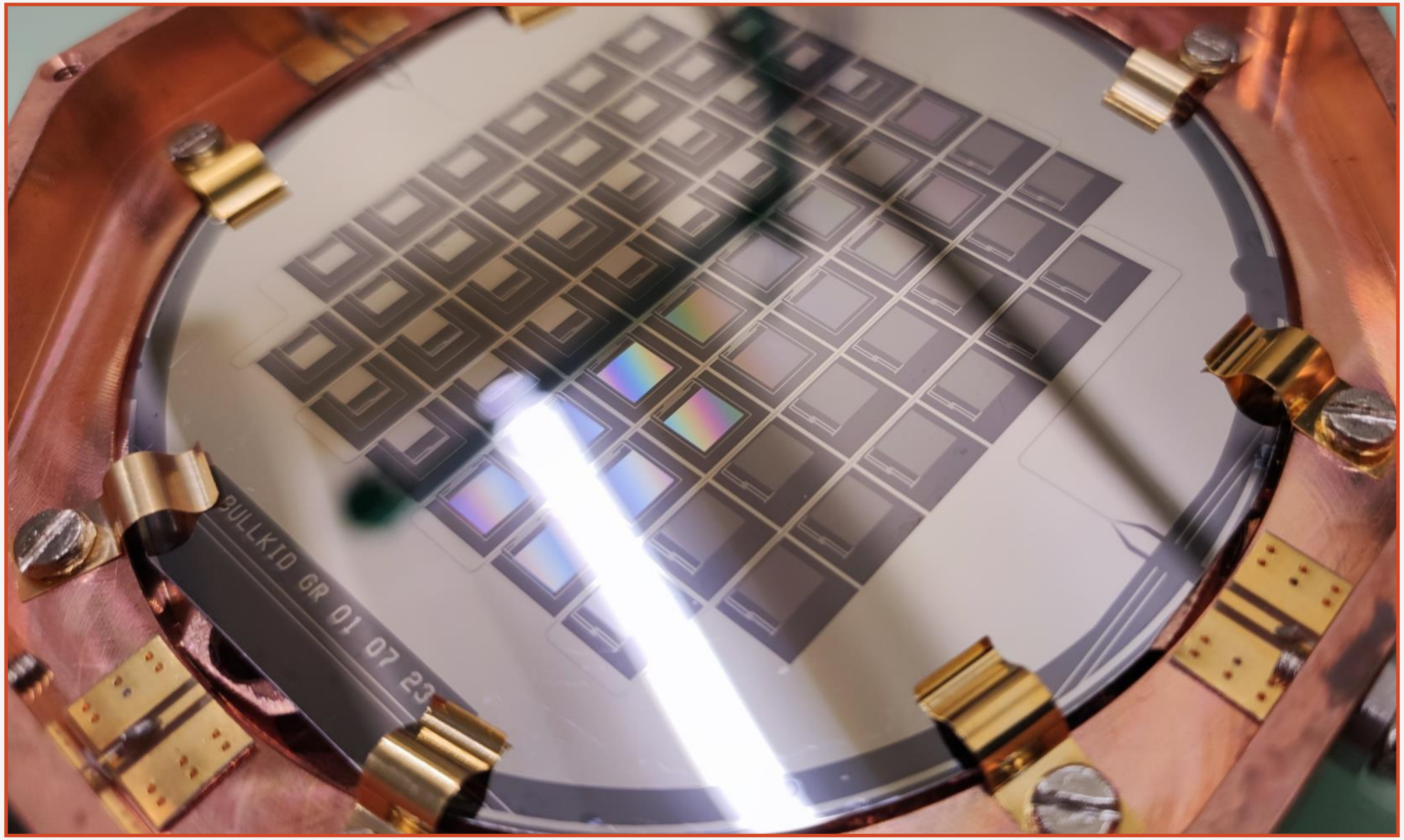


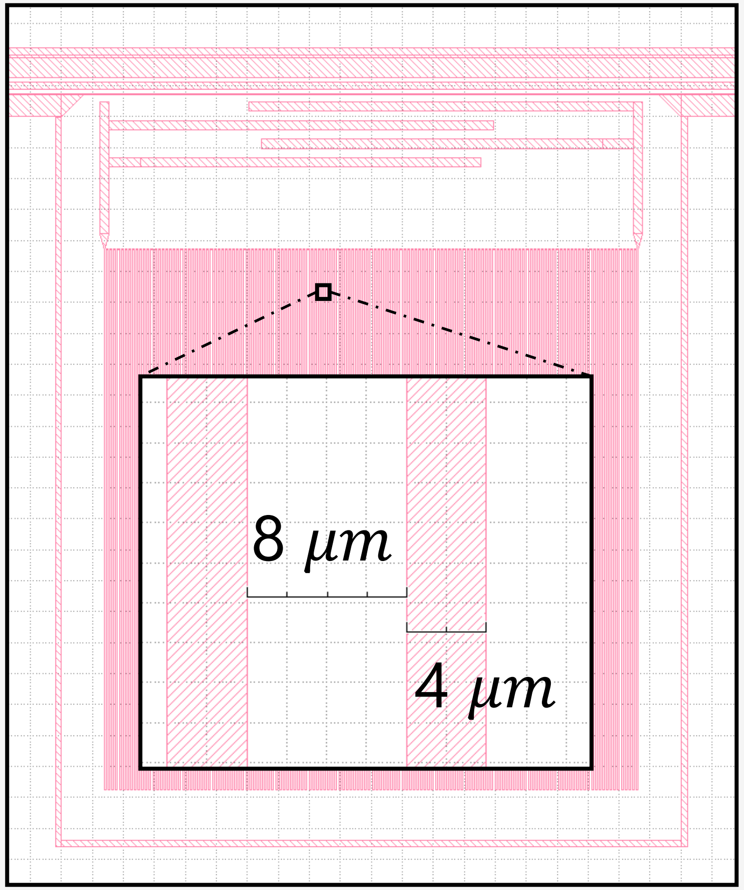
Fit for α with Δ_0 fixed:

- $\boldsymbol{\alpha \approx 3.3\%}$

$\alpha_{90nm} \approx \frac{2}{3} \cdot \alpha_{60nm}$ that compensates $\eta_{90nm} > \eta_{60nm}$

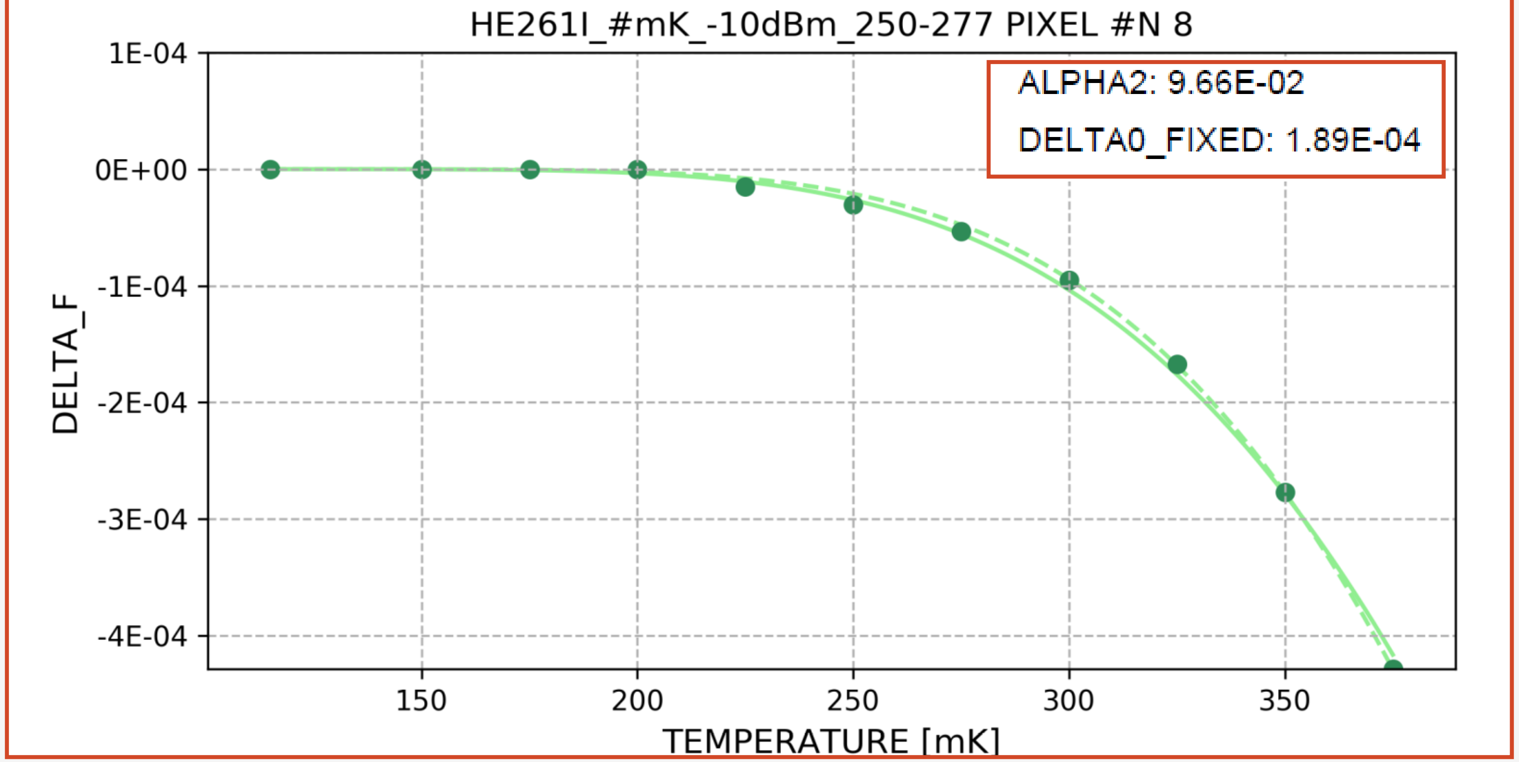
Optimization of the KID responsivity: α – Alternate geometries





Optimization of the KID responsivity: $\boldsymbol{\alpha}$ – Alternate geometries

$T_c = 1.2\ \mathrm{K}$
$\Delta_0(T_c) = 1.76 \cdot k_B \cdot T_c = 1.880 \cdot 10^{-4} eV$



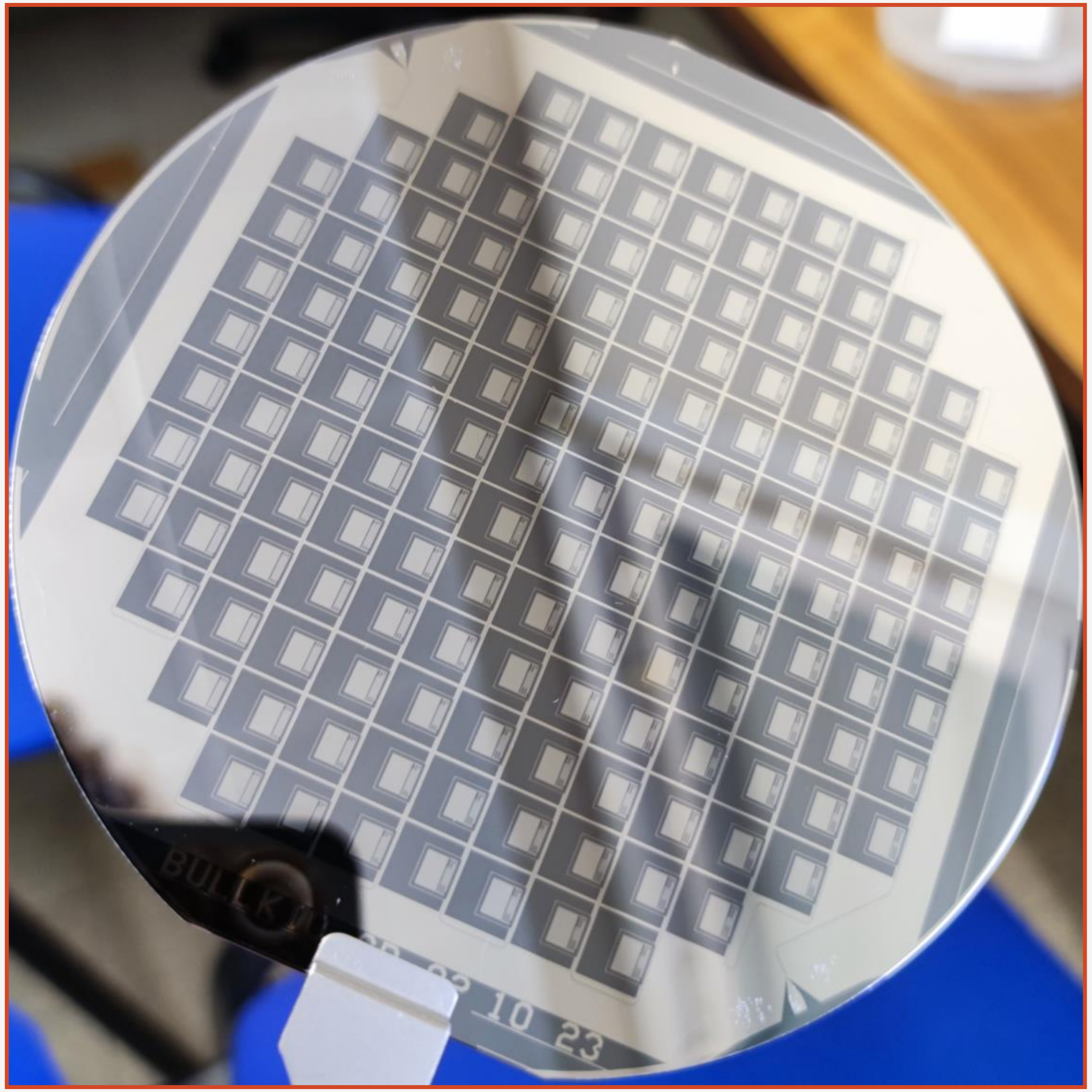
Fit for α with Δ_0 fixed:

- $\boldsymbol{\alpha \approx 10\%}$

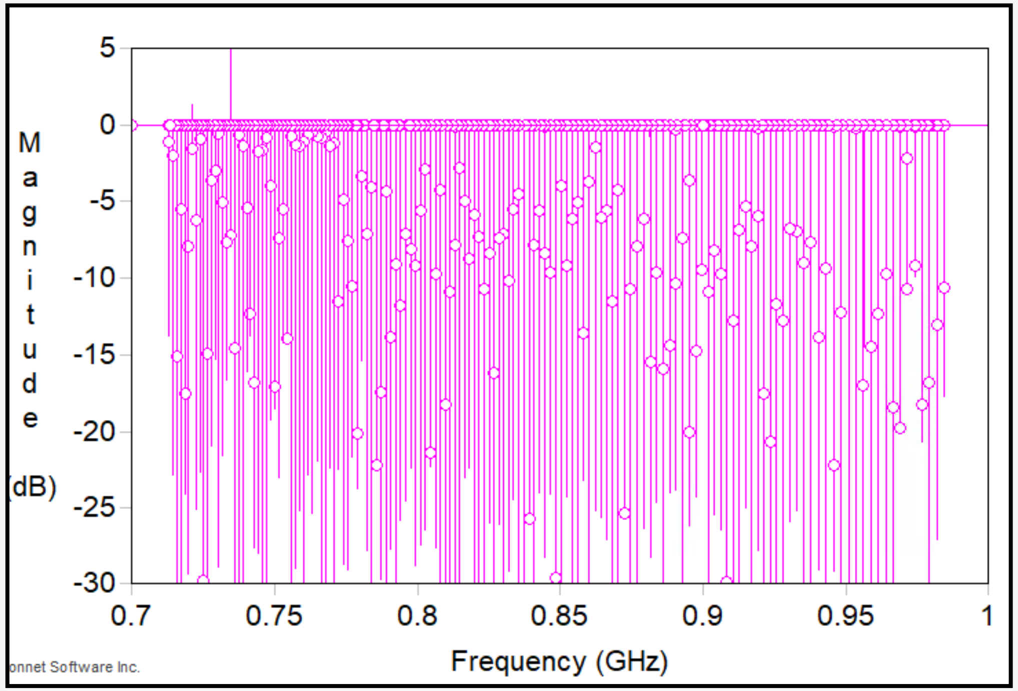
Increase in $\boldsymbol{\alpha}$ without reducing $\boldsymbol{\eta}$

Compromise on a low f_0 and reduced yield

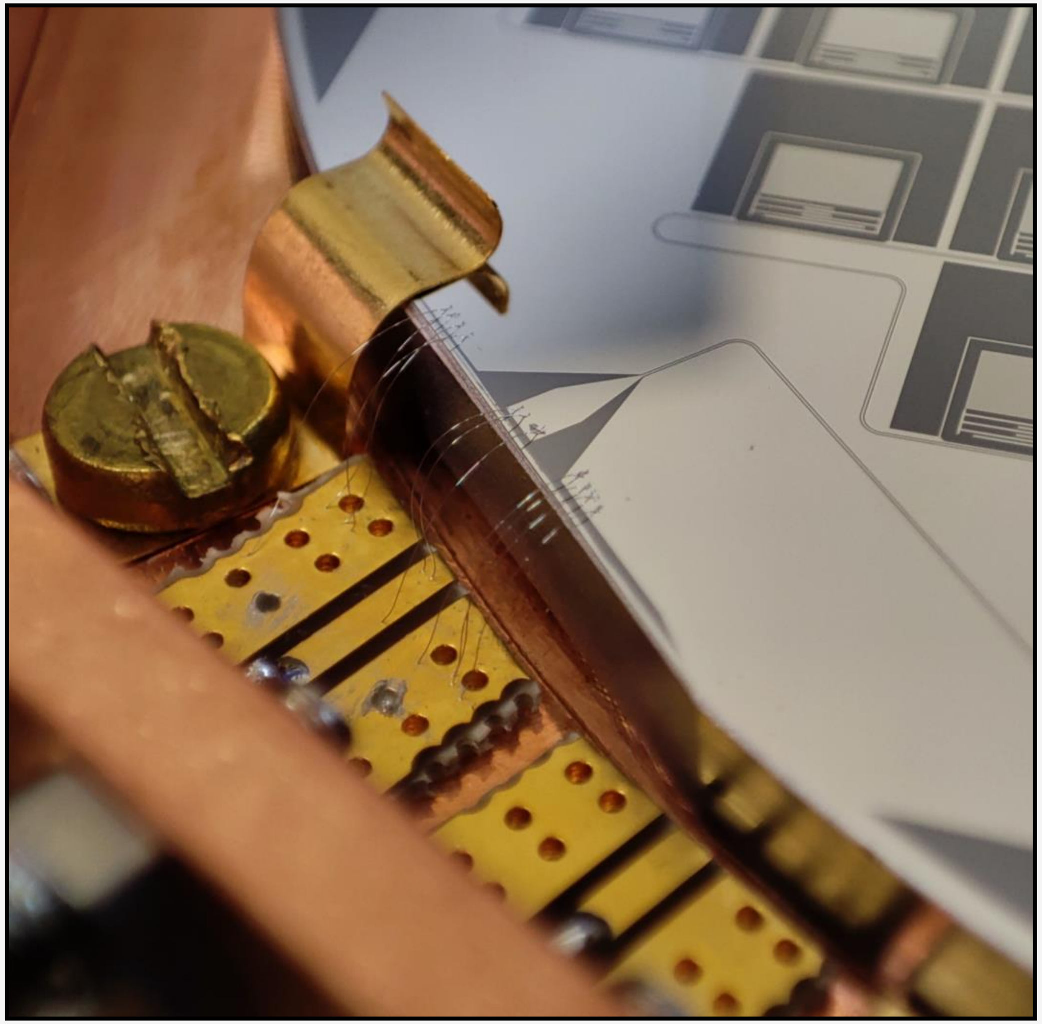
Scalability for the 100mm mask: simulations and thin wafer test

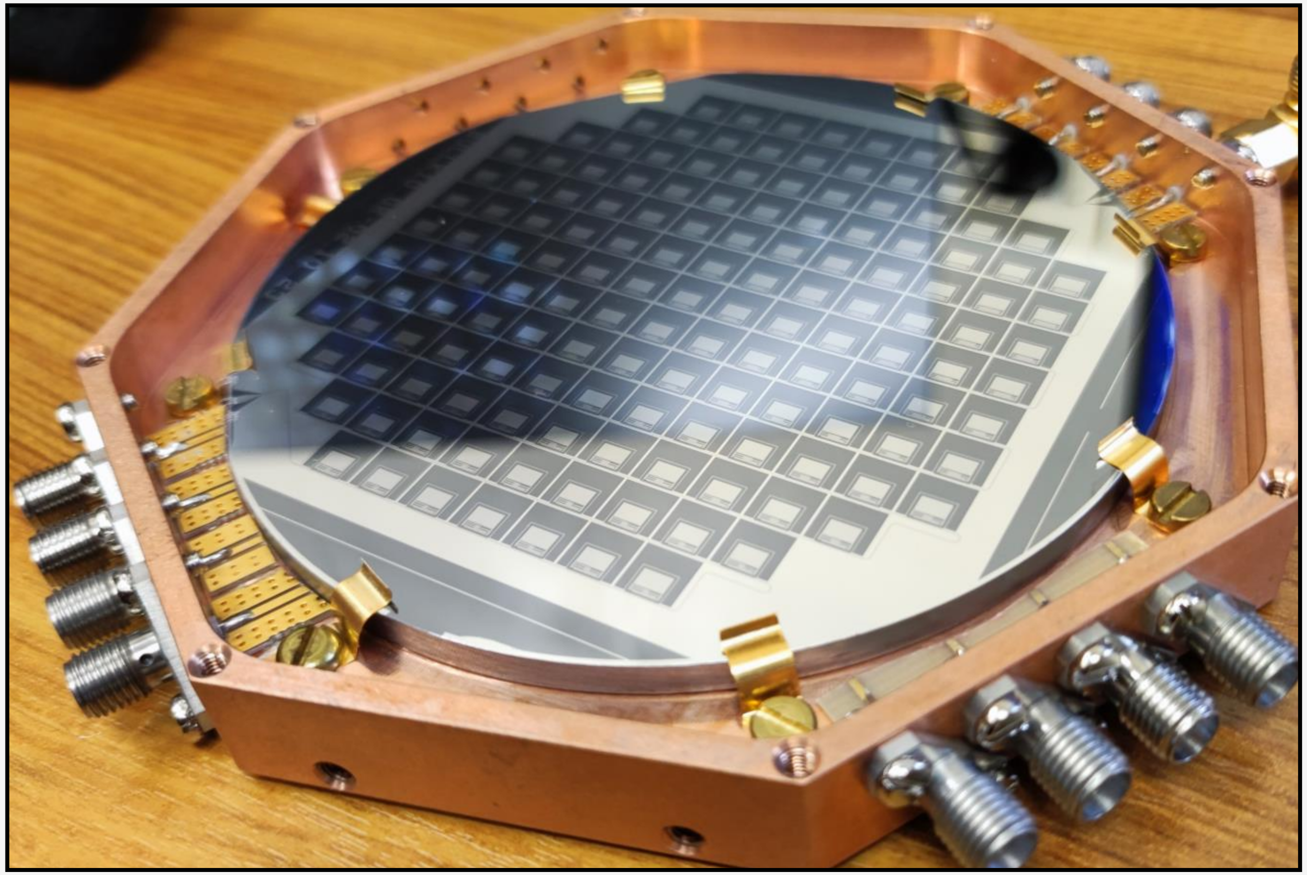


- 145 pixels
- 49.3g of active silicon per wafer
- Constant cap trimming: 8um per step
- F∈ 720 ÷ 970 MHz
- dF ∈ 0.7 ÷ 3 MHz



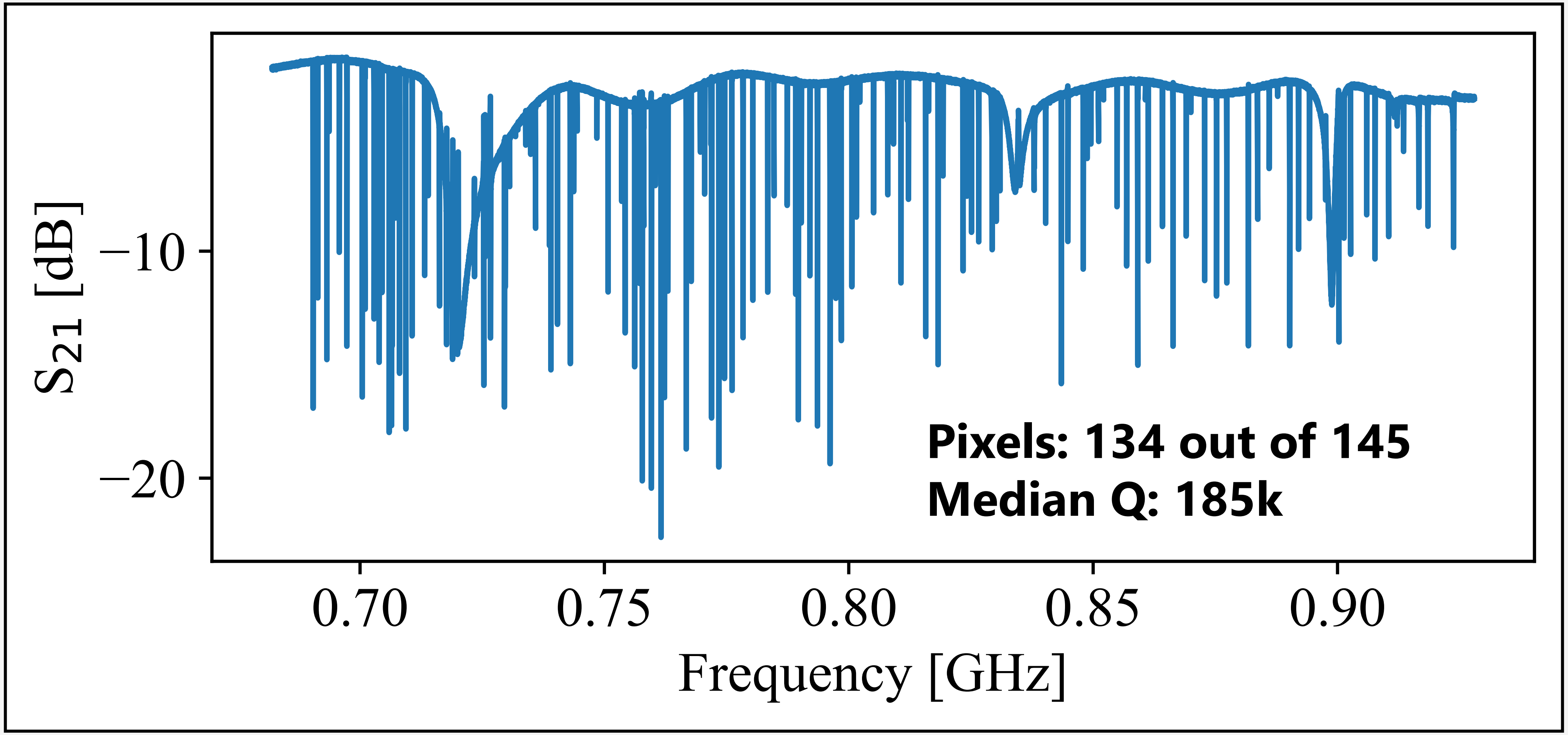
Scalability for the 100mm mask: thick wafer



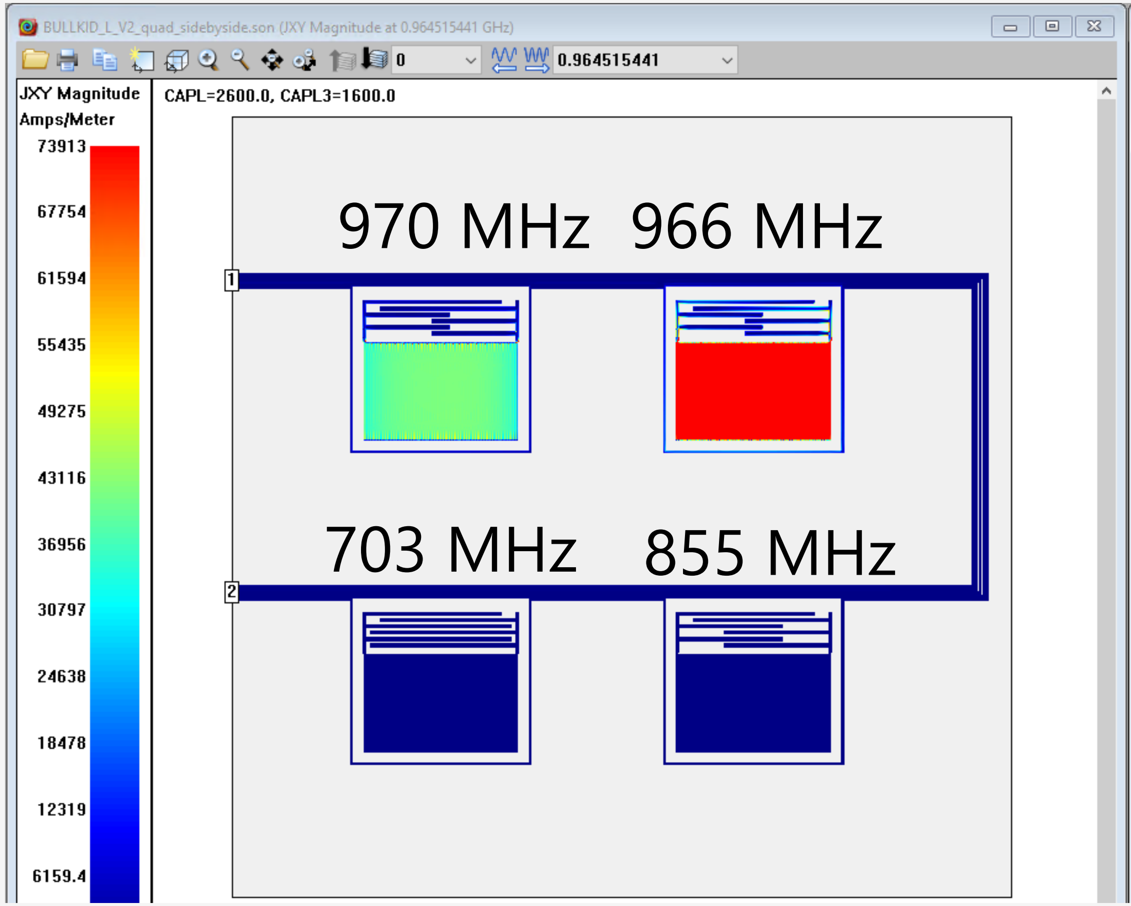


Temporary holder, still a work in progress, dicing will be tested soon

Scalability for the 100mm mask: thick wafer



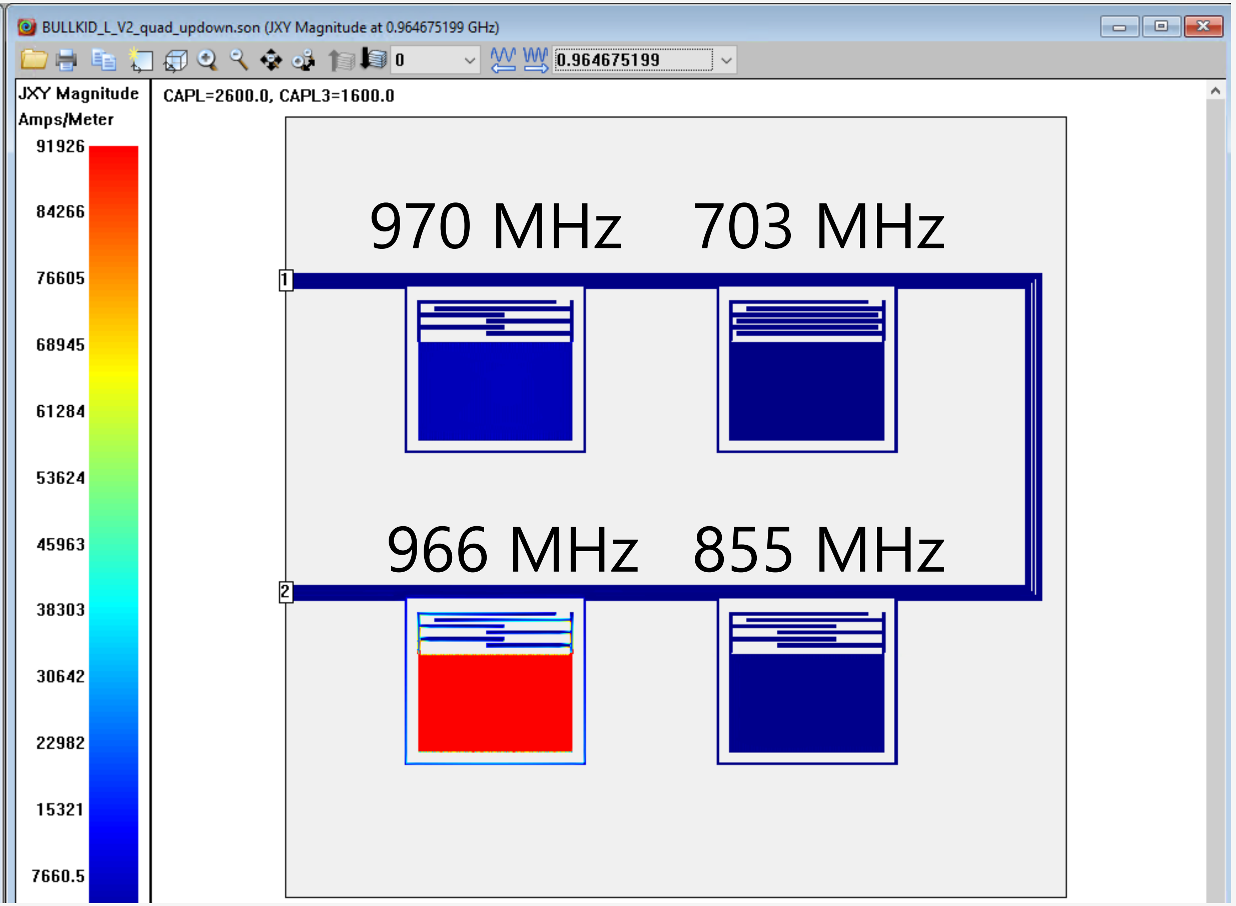
Simulations of x-talk induced by proximity



BULLKID_L_V2_quad_sidebyside.son (JXY Magnitude at 0.964515441 GHz)

CAPL=2600.0, CAPL3=1600.0

Induced current density: 30%

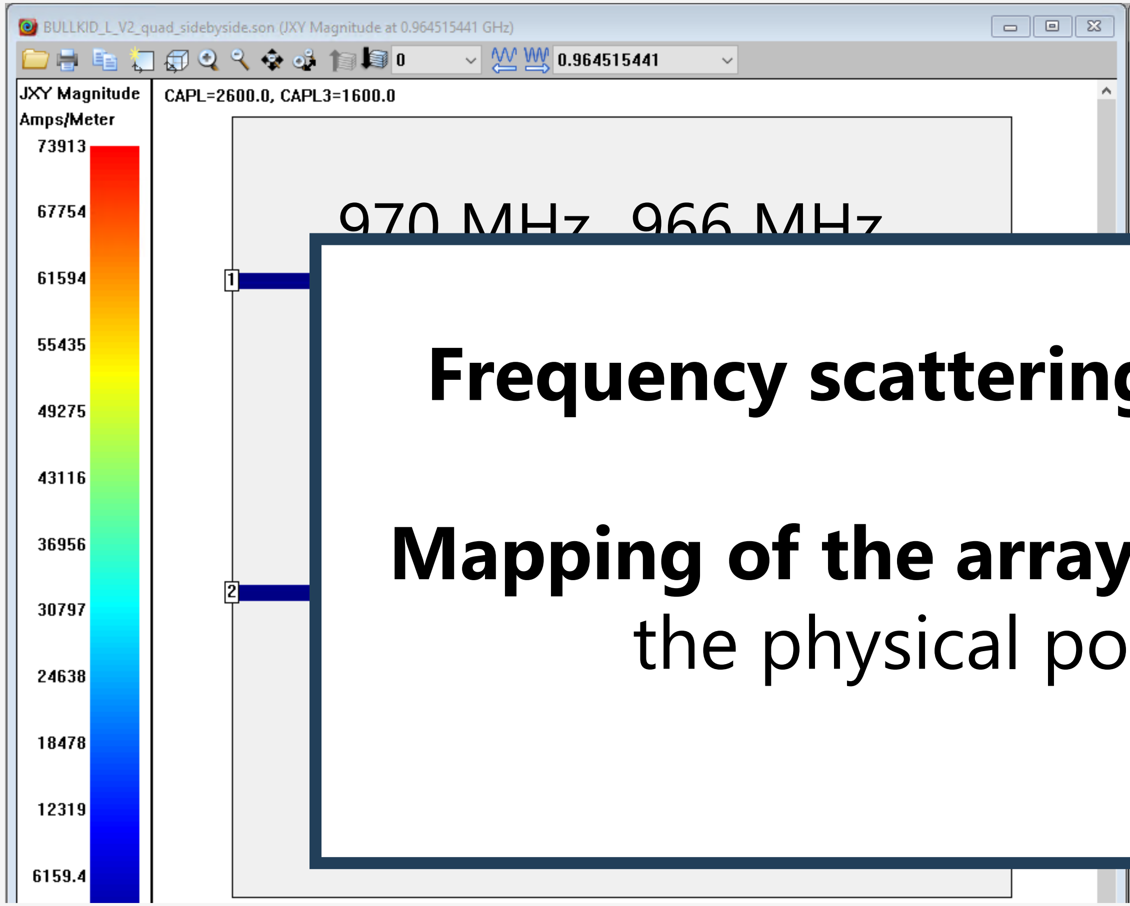


BULLKID_L_V2_quad_updown.son (JXY Magnitude at 0.964675199 GHz)

CAPL=2600.0, CAPL3=1600.0

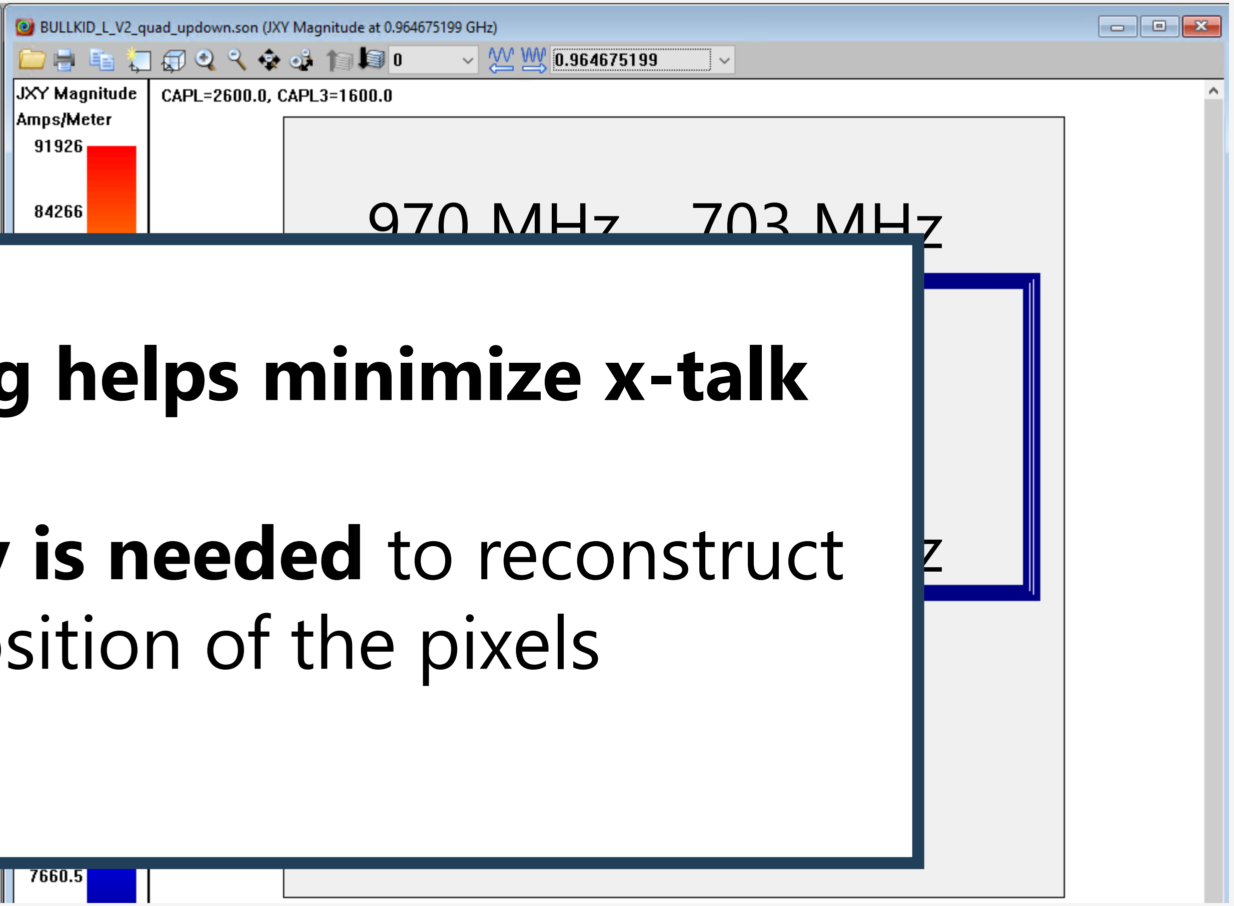
Induced current density: 3%

Simulations of x-talk induced by proximity



CAPL=2600.0, CAPL3=1600.0

Induced current density: 30%



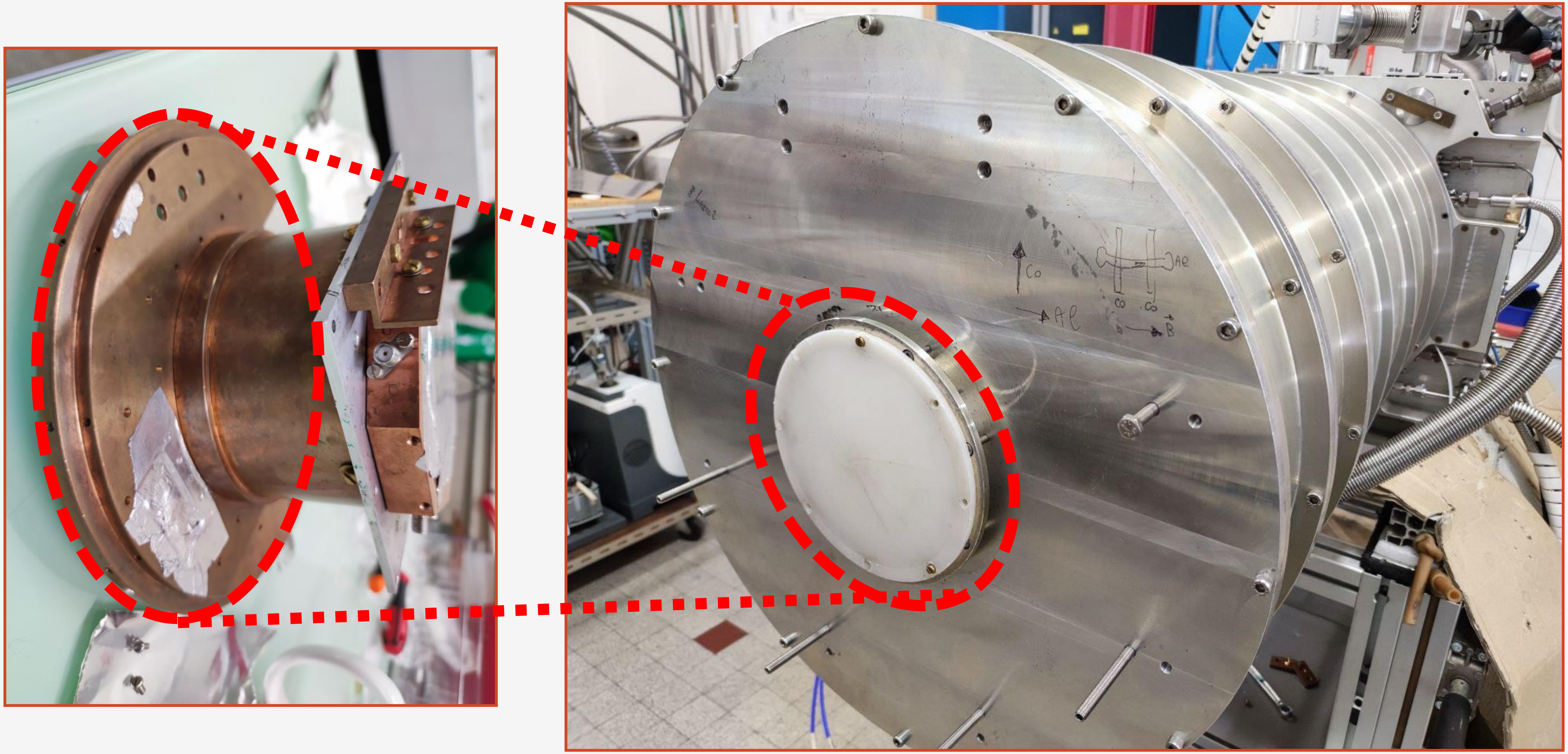
CAPL=2600.0, CAPL3=1600.0

Induced current density: 3%

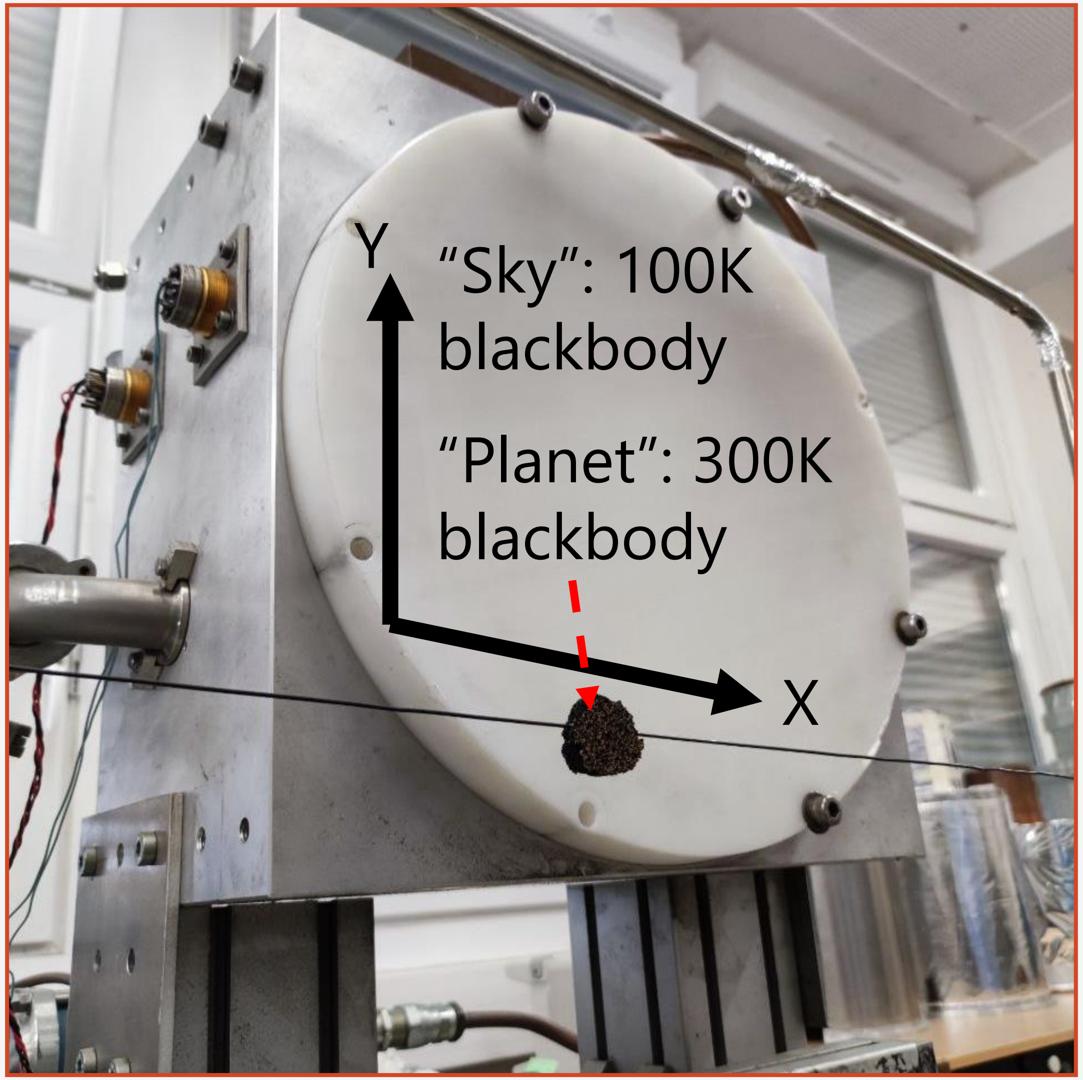
Frequency scattering helps minimize x-talk

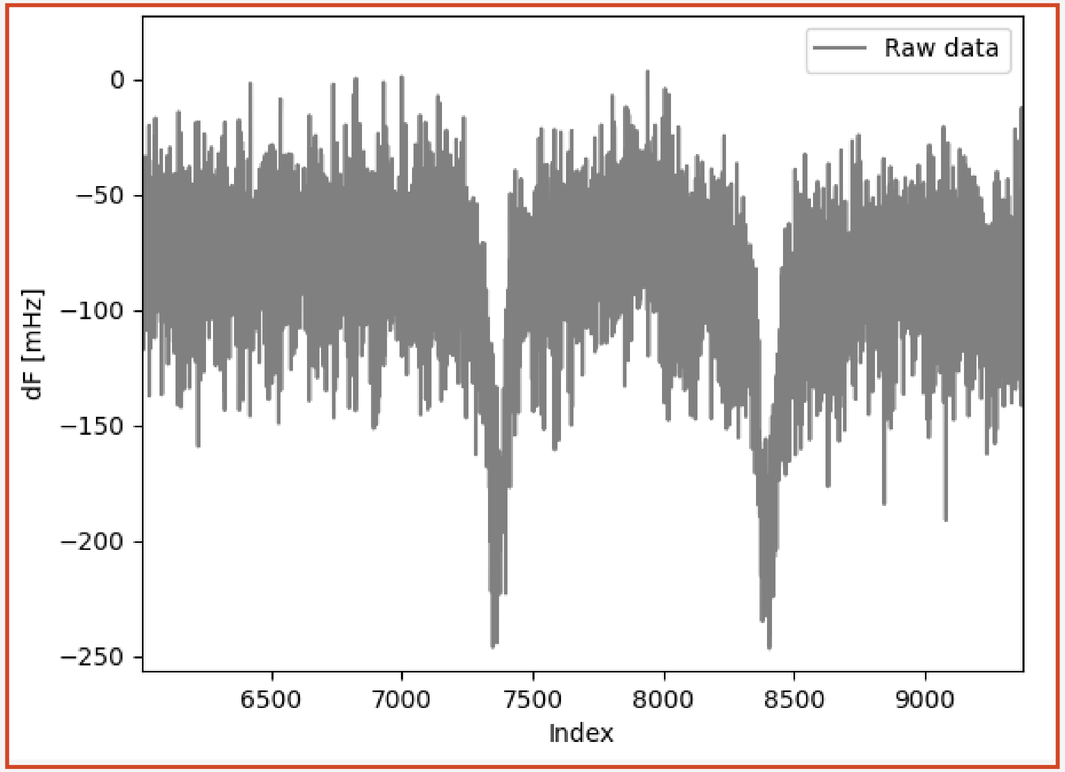
Mapping of the array is needed to reconstruct the physical position of the pixels

BULLKID v7 – Al90nm cryostat with optical window



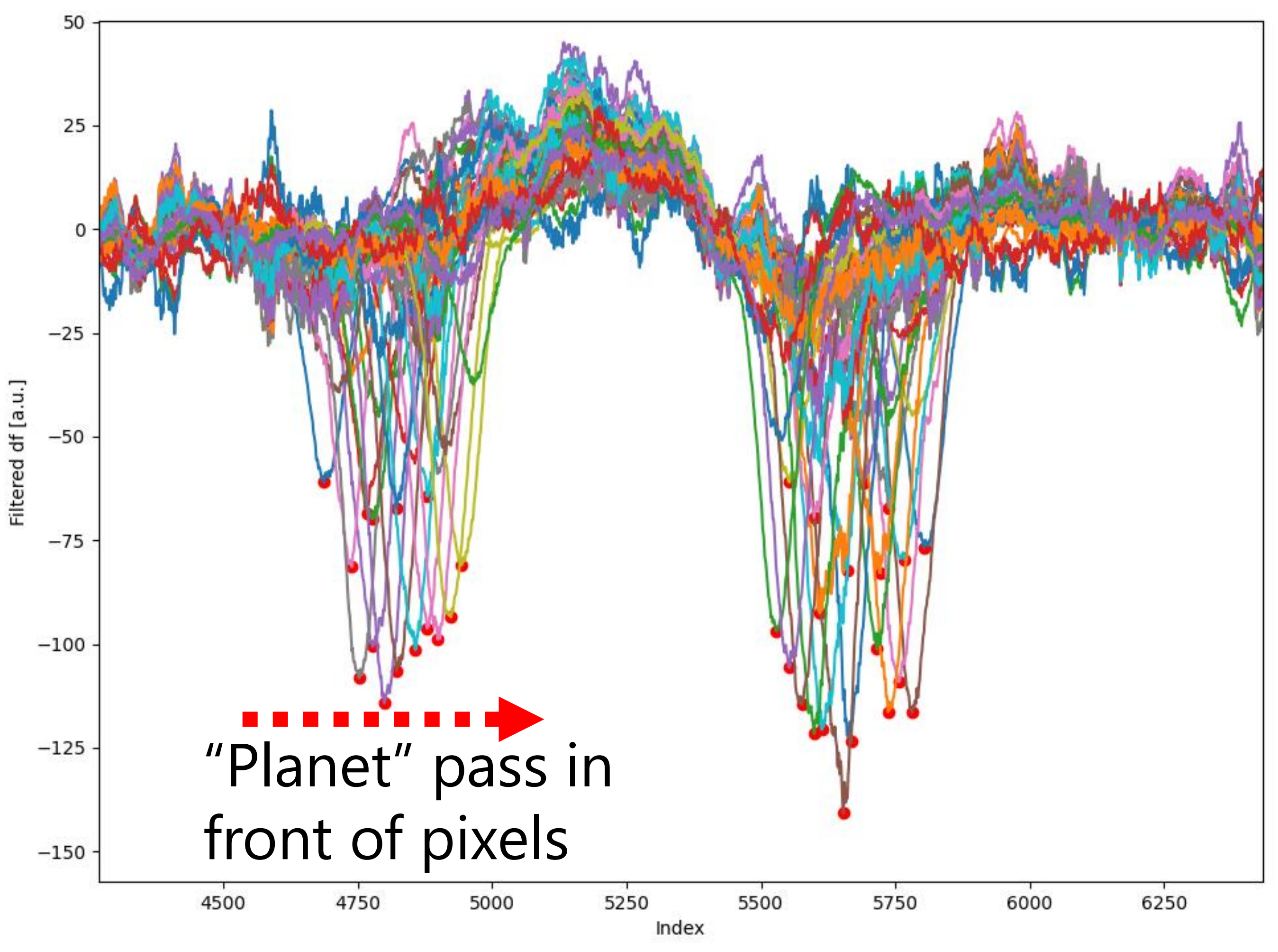
BULLKID v7 – Sky simulator



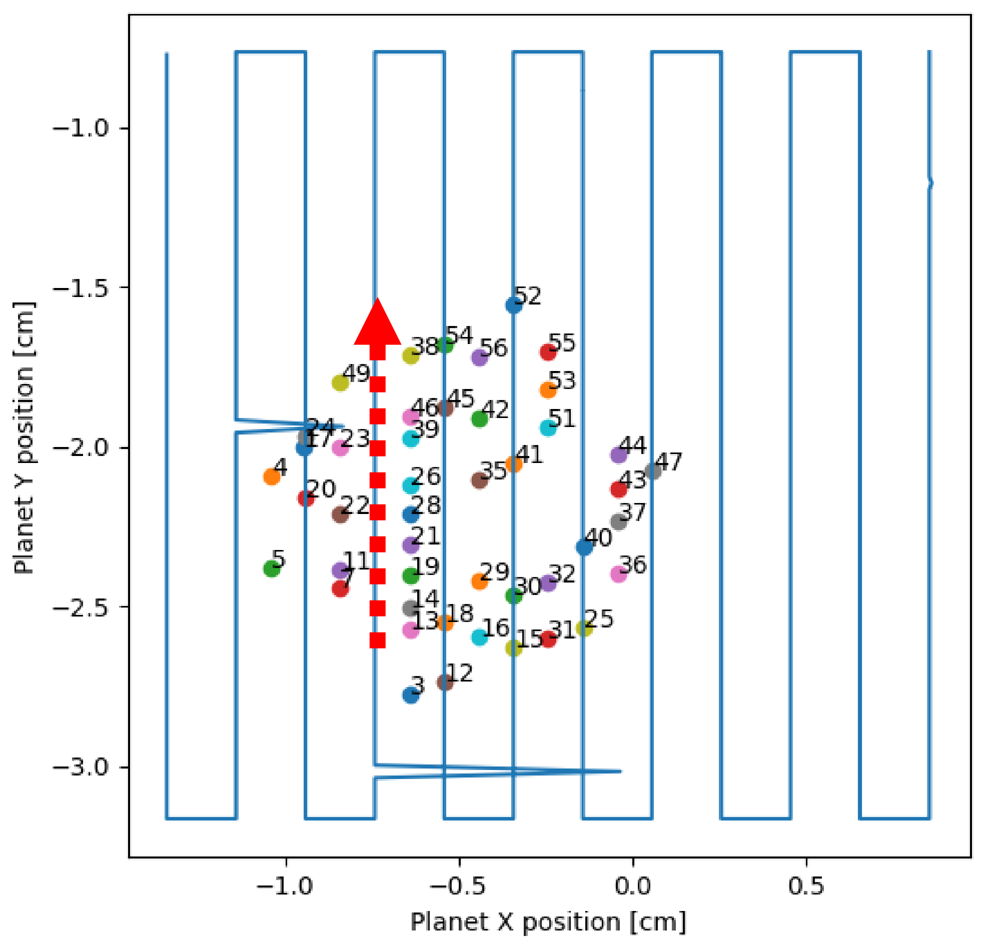


Frequency shift observed when the planet passes in front of a pixel

BULLKID v7 – Sky simulator mapping proof of concept



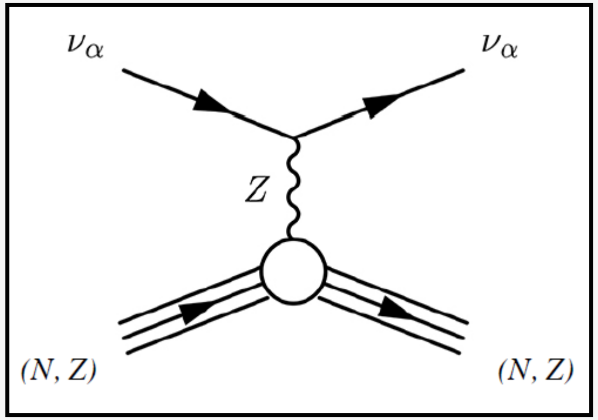
“Planet” pass in front of pixels



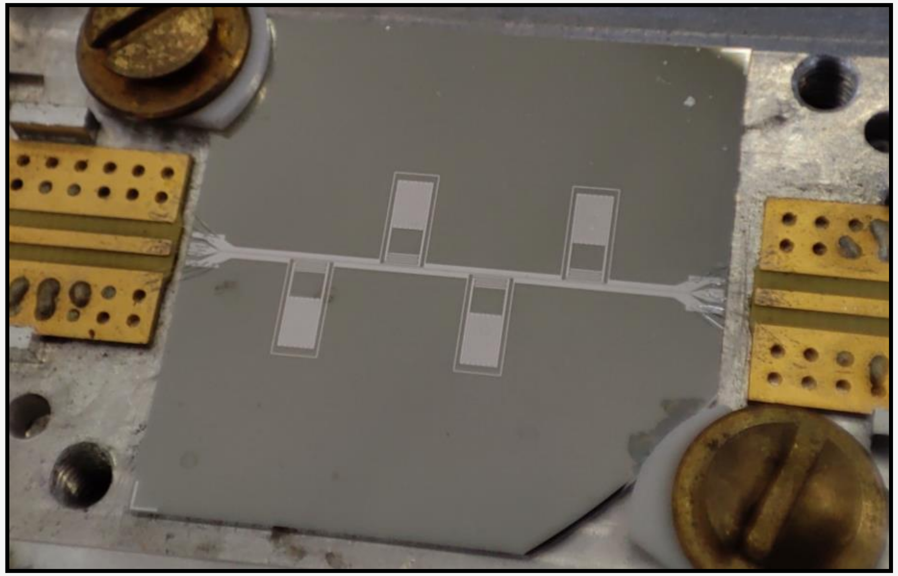
KIDs on Germanium for (CEνNS and DM)

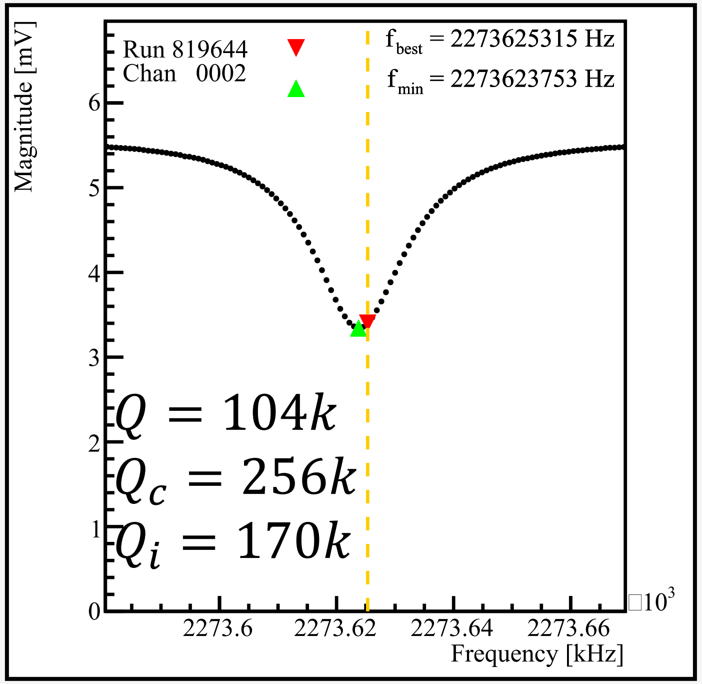
Observed in 2017 by COHERENT

Same detection principle as WIMPs!



$$\sigma_{CE\nu NS} \approx \frac{G_F^2}{4\pi} E_\nu^2 N^2$$





- Precision **tests of the standard model** (es $\sin^2\theta_W$)
- **Nuclear waste monitoring**

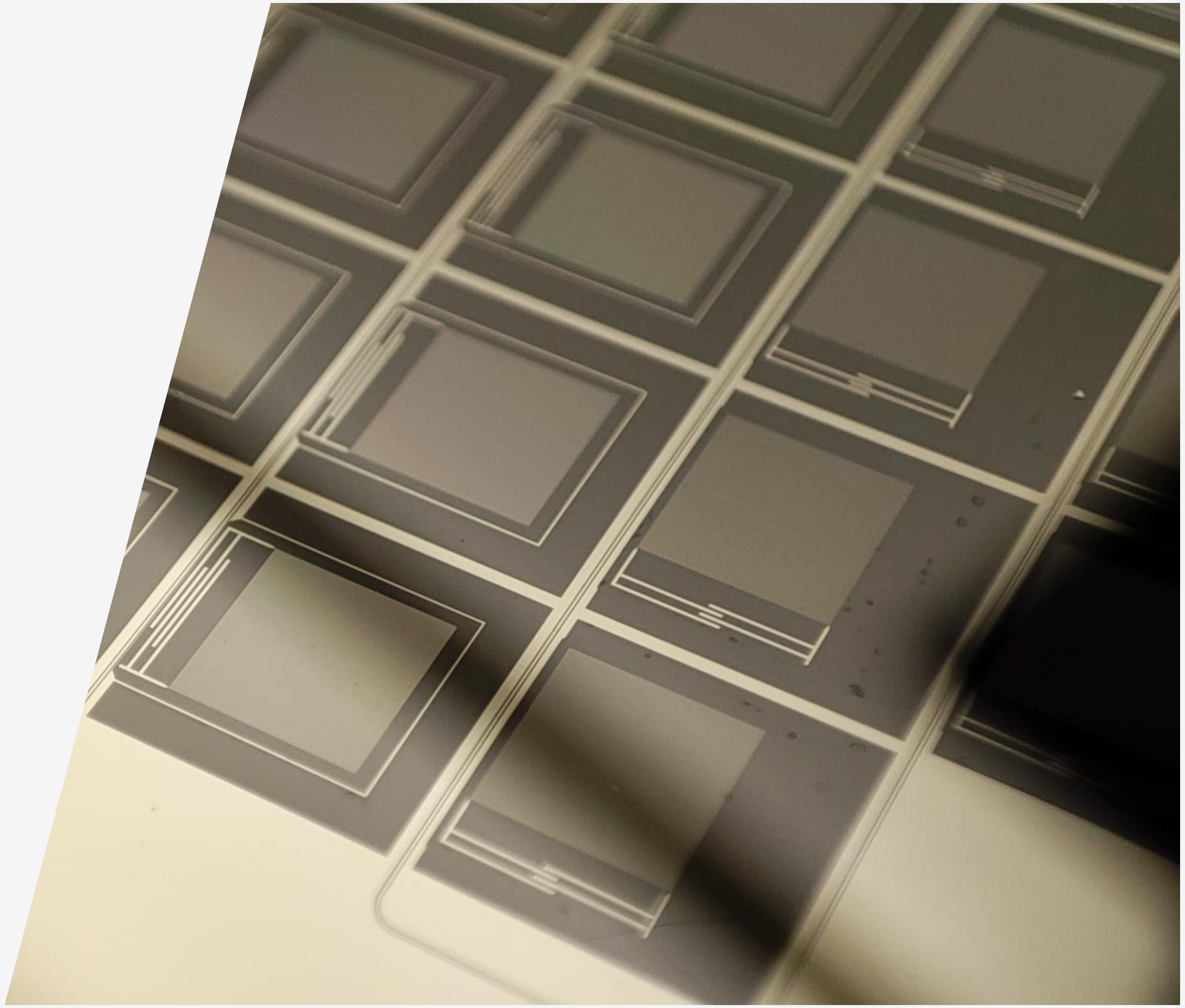
$\boldsymbol{\sigma_{Ge} \approx 10 \cdot \sigma_{Si}}$

However **Ge oxide is not inert**!

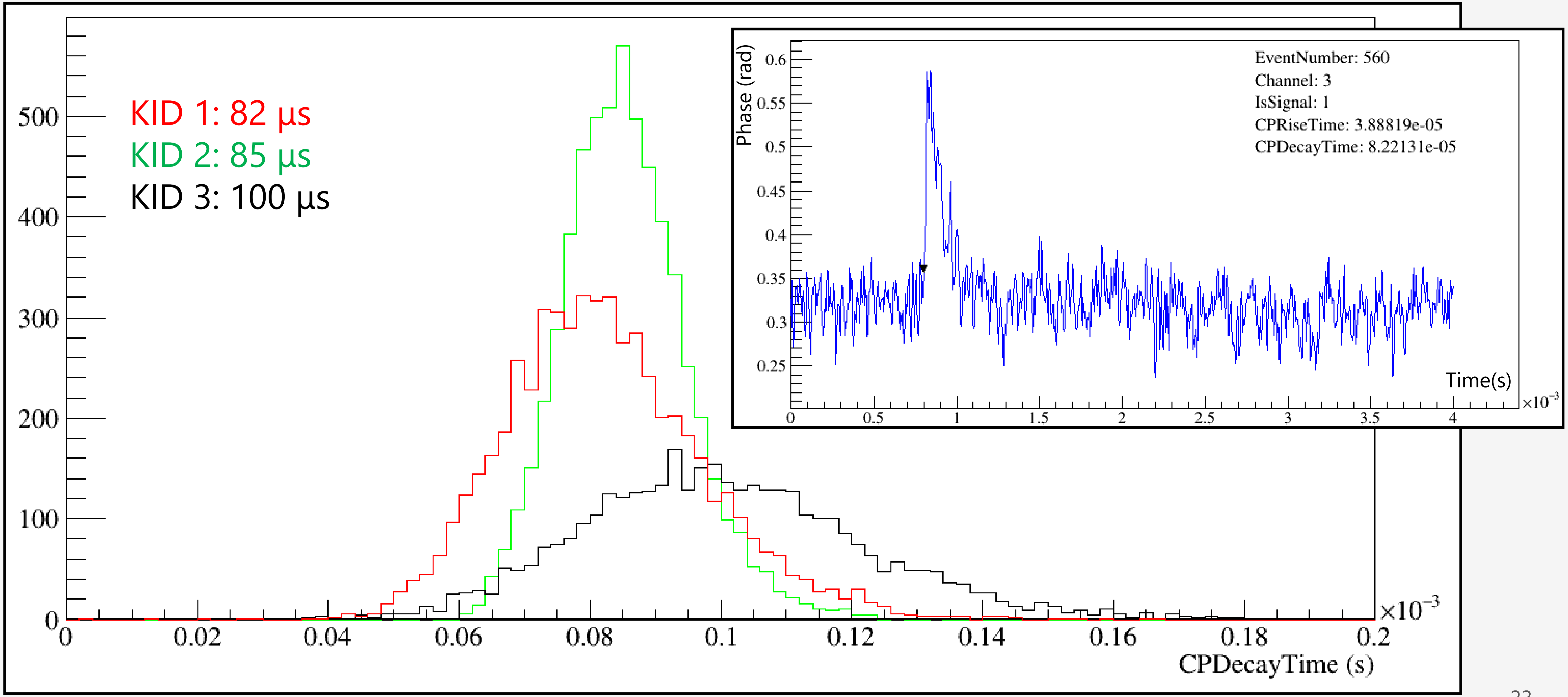
Qi seems promising, energy calibration is the next step

Conclusion: next work

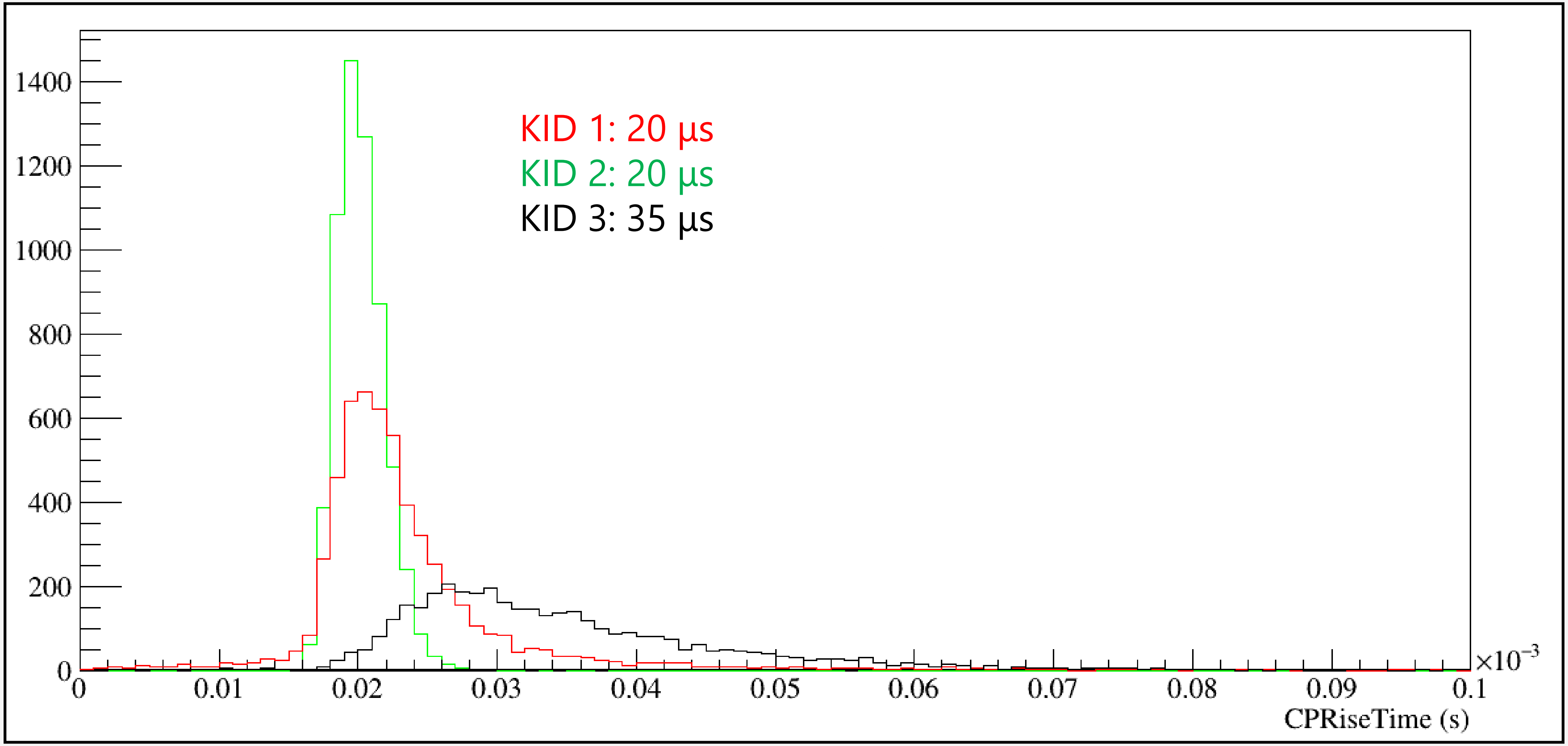
- Finalizing the **4 inch mask**
- Settle for an optimized pixel to achieve **lower threshold**
- Energy resolution + **improved process** for a **germanium** 4-pixel sample



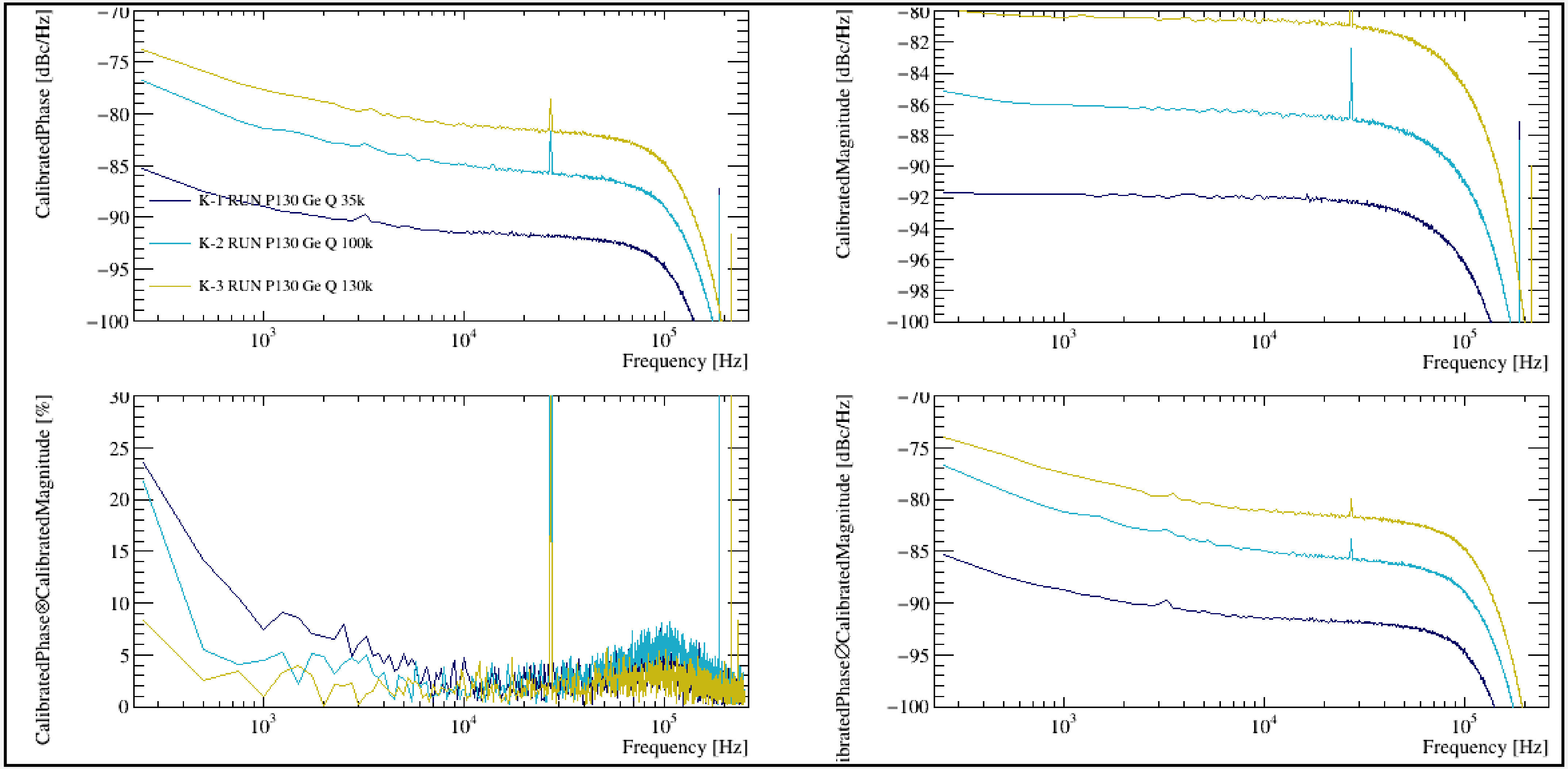
(Extra) Calder-GE Pulse Decay Time



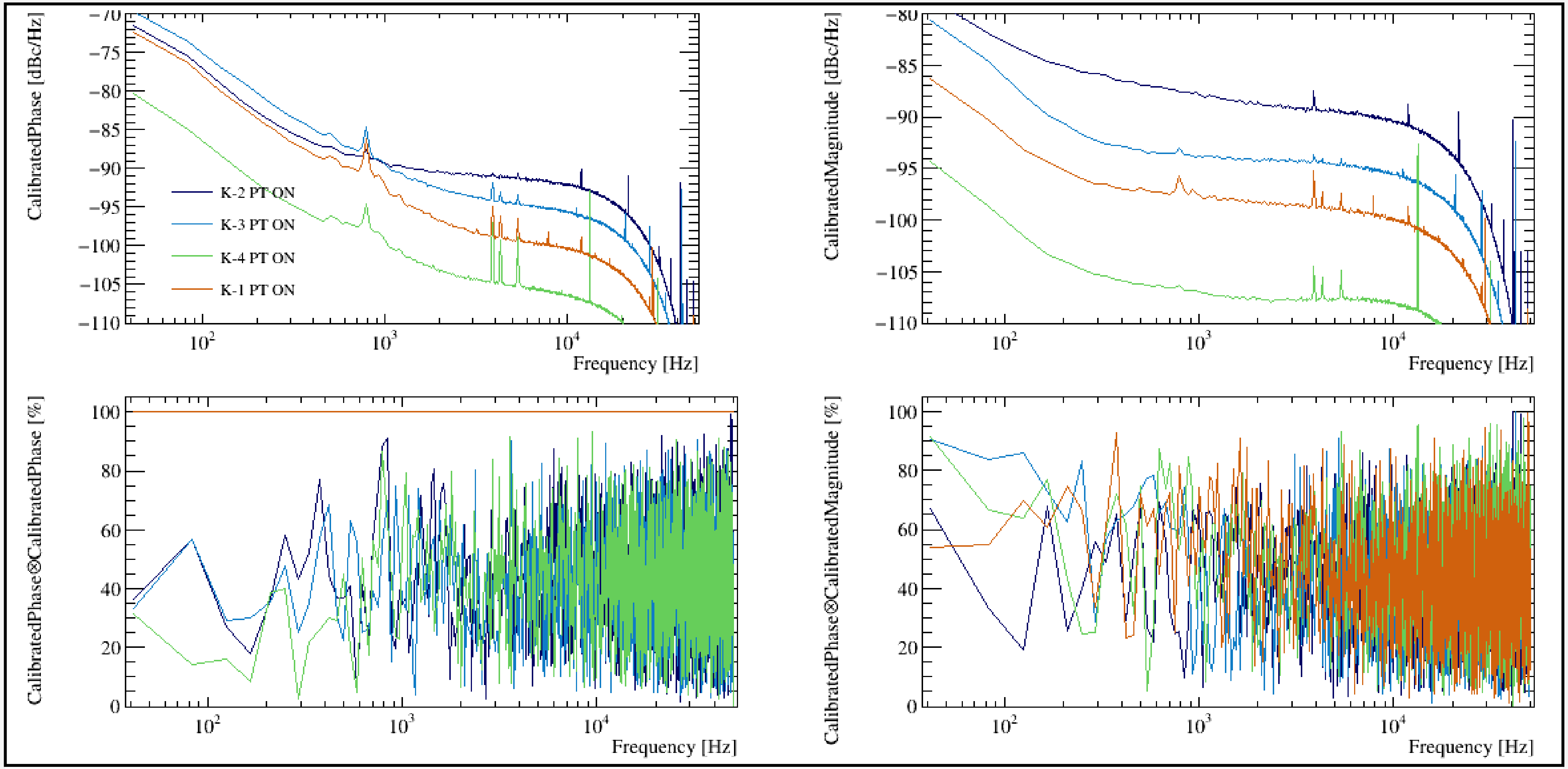
(Extra) Pulse Rise Time



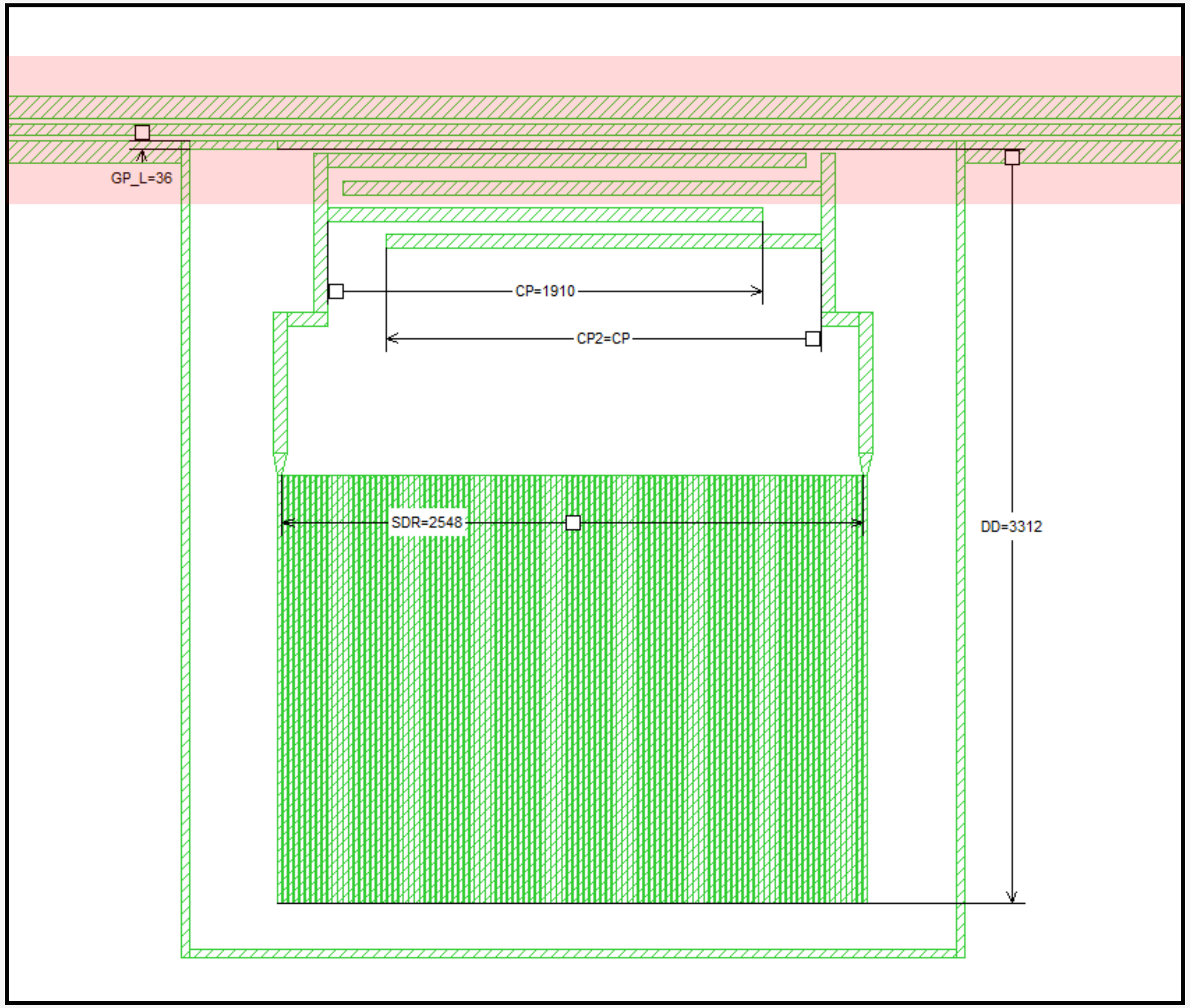
(Extra) GE Noise Power Spectrum

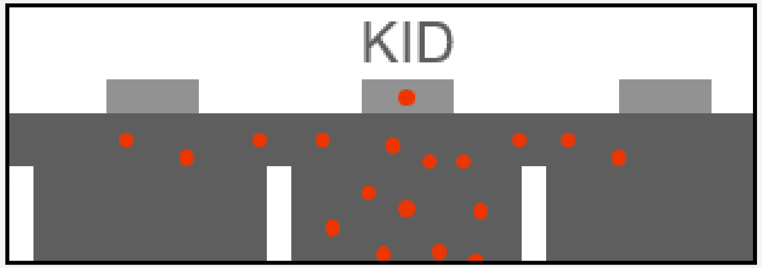


(Extra) BULLKID Noise Power Spectrum



(Extra) Capacitive coupling: meander no longer overlaps grooves

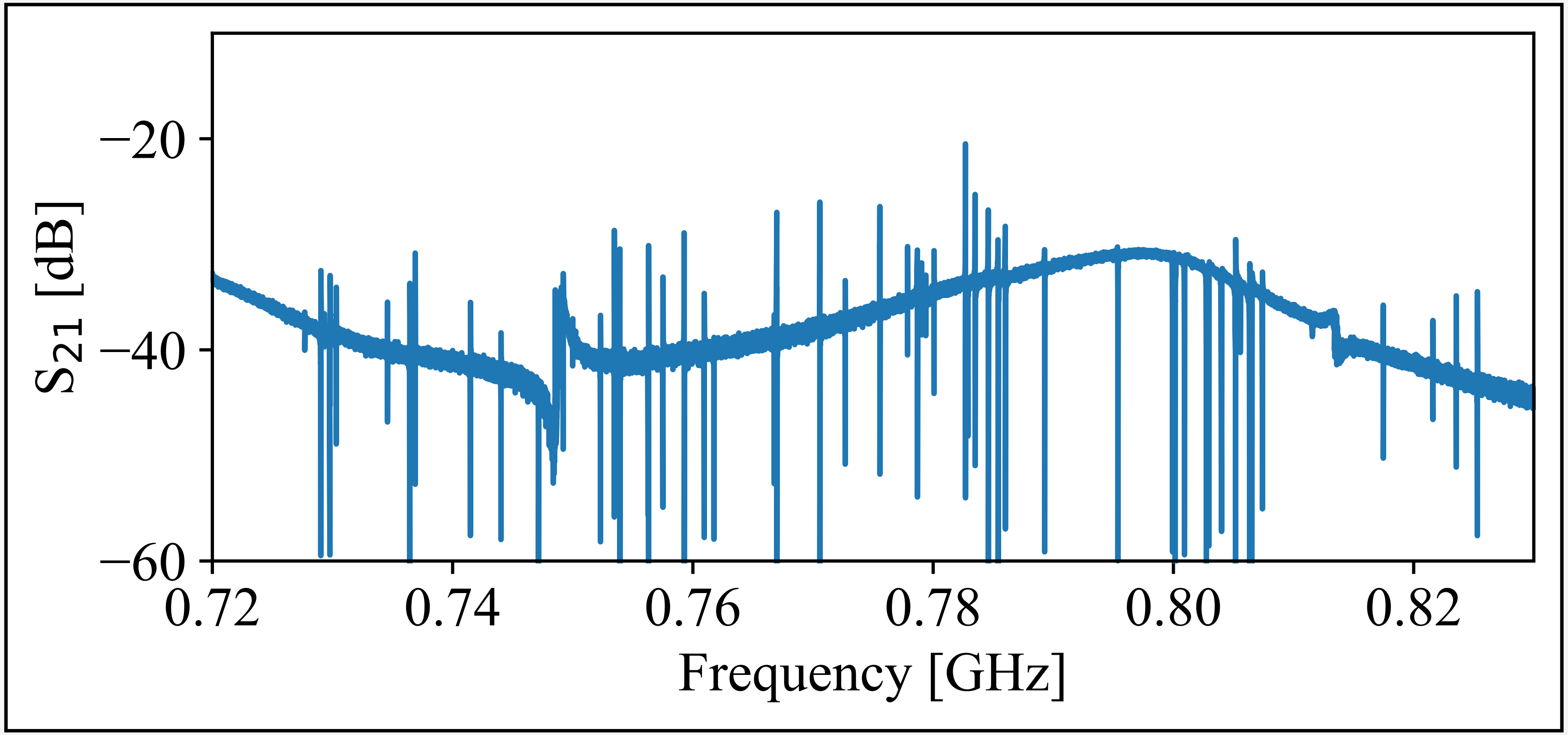




Phonons are less likely to be in the grooved region connecting the dice

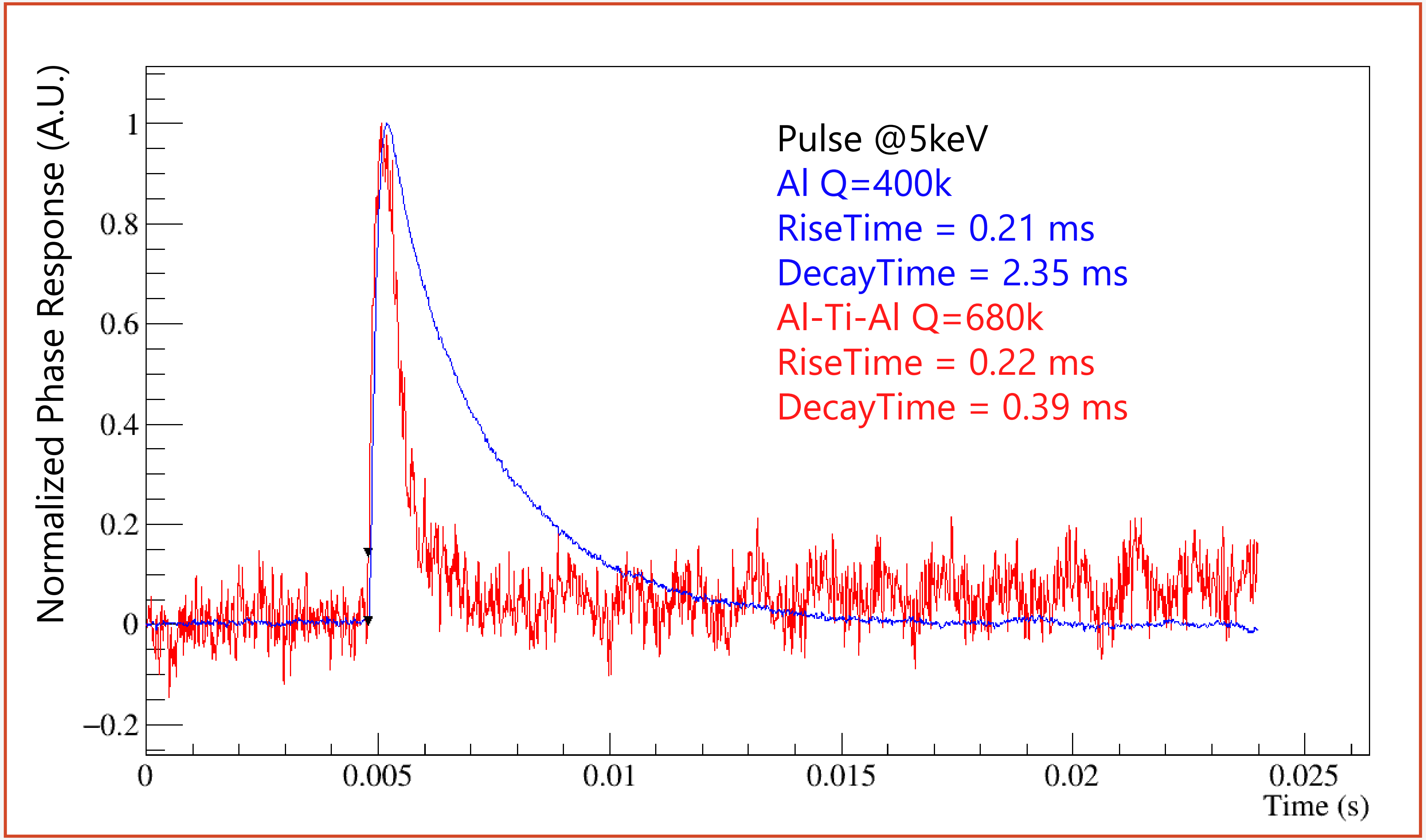
Move inert capacitive fingers over the groove increases phonon collection

(Extra) S21 scan of bonded AlTiAl wafer

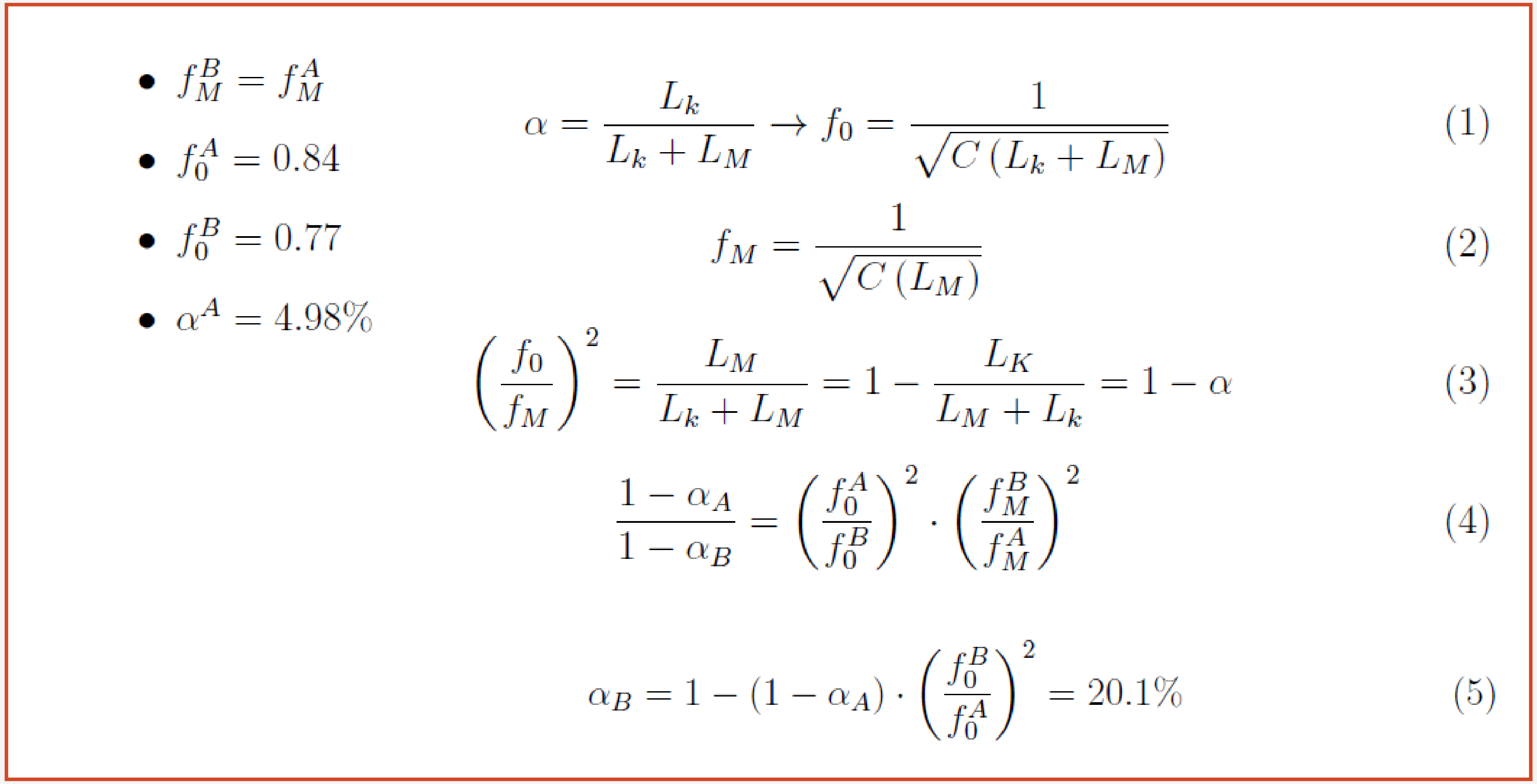


Irregular spacing, excess attenuation (circa -35 dB)
Feedline likely interrupted
57 detected resonators

(Extra) Pulse timings Al vs Al-Ti-Al



(Extra) AlTiAl alpha estimate from frequency shift



- $f_M^B = f_M^A$
- $f_0^A = 0.84$
- $f_0^B = 0.77$
- $\alpha^A = 4.98\%$

$$\alpha = \frac{L_k}{L_k + L_M} \rightarrow f_0 = \frac{1}{\sqrt{C\left(L_k + L_M\right)}} \tag{1}$$

$$f_M = \frac{1}{\sqrt{C\left(L_M\right)}} \tag{2}$$

$$\left(\frac{f_0}{f_M}\right)^2 = \frac{L_M}{L_k + L_M} = 1 - \frac{L_K}{L_M + L_k} = 1 - \alpha \tag{3}$$

$$\frac{1 - \alpha_A}{1 - \alpha_B} = \left(\frac{f_0^A}{f_0^B}\right)^2 \cdot \left(\frac{f_M^B}{f_M^A}\right)^2 \tag{4}$$

$$\alpha_B = 1 - (1 - \alpha_A) \cdot \left(\frac{f_0^B}{f_0^A}\right)^2 = 20.1\% \tag{5}$$