First operation of the BULLKID array of Kinetic Inductance Detectors.

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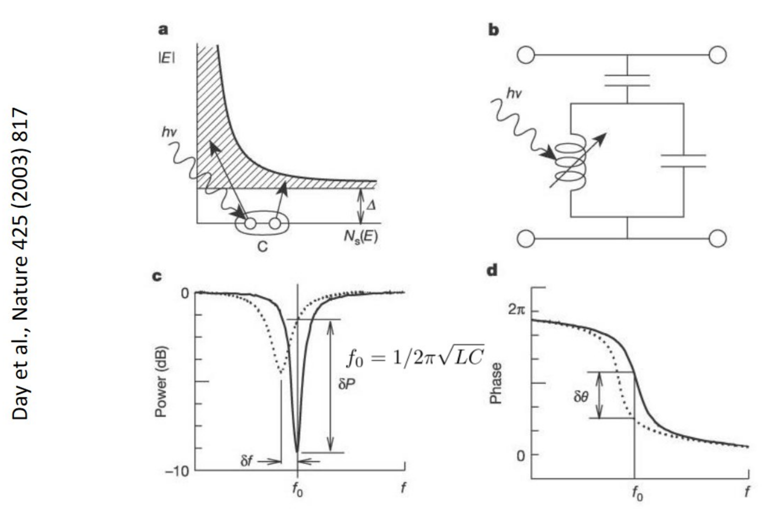
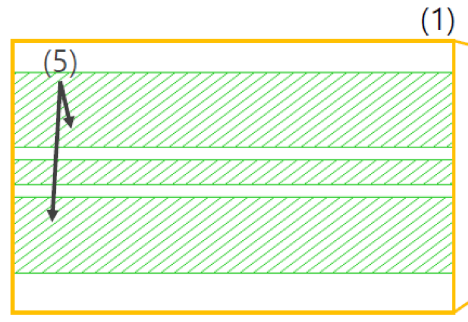
BULLKID is an R&D project which investigates a way of increasing the active volume of cryogenic detectors.
Several cubic silicon absorbers are carved in a 5 mm thick 3-inch diameter wafer. An array of multiplexed Kinetic Inductance Detectors (KIDs) senses the cubes with one KID per cube. When a particle interacts in the silicon it produces phonons which are then detected by the KID. The advantage of using KIDs lies in their natural multiplexing capability which is crucial to scale the technology up to hundreds or thousands of sensors.
The first prototype built consists of 60 cubes, with a measured energy resolution of around 100 eV_{nr}. The response across the array is however not uniform and further refinements of the technology are ongoing.
Further improving the energy resolution is being evaluated as the next step in the R&D and might prove crucial in detecting Coherent elastic neutrino-nucleus scattering (CEvNS) or sub-GeV Dark Matter. If successful several wafers will be produced and stacked to reach the target mass.
In this poster we will describe the BULLKID project and the results from the operation of the first prototype.

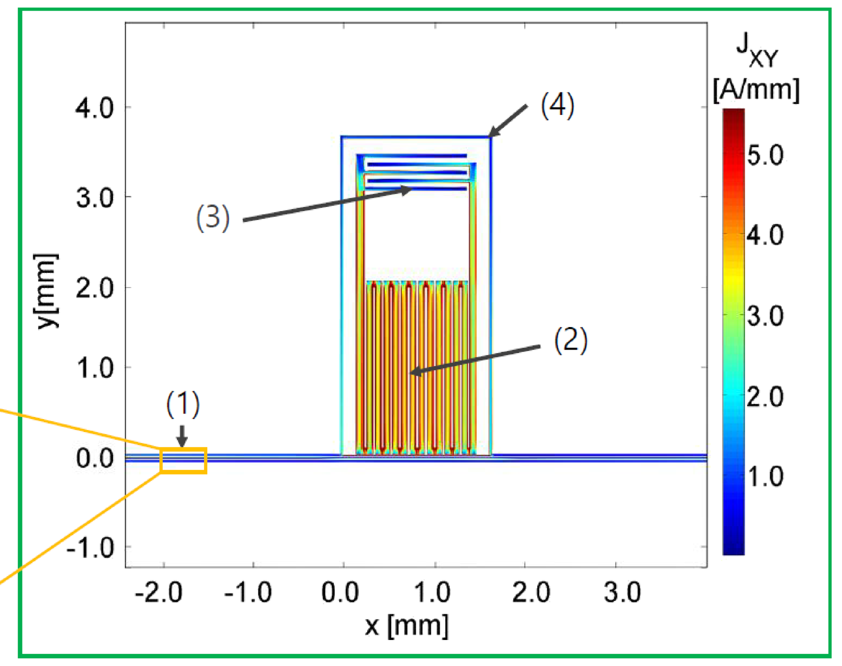
Kinetic Inductance Detectors: The working principle



- Cooper pairs (CP) in a superconductor act as an inductance (L). Absorbed photons change CP density and L.
- High quality factor (Q) resonating circuit biased with a microwave (GHz): Signal from amplitude and phase shift of the wave transmitted past the resonator. [1]

Main components of a KID pixel
1. Feedline
2. Inductive meander
3. Capacitor
4. Guard ring
5. Ground plane





Pulse shape and single pixel response

Once cooper pairs are broken into quasi-particles (QP), their population decays as

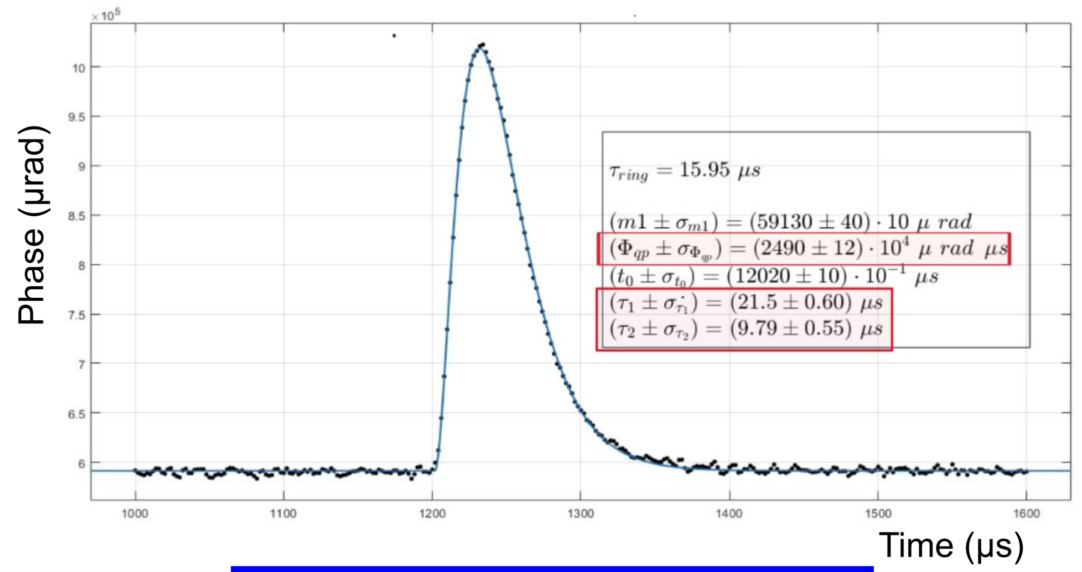
$$N_{qp}(t) = N_{qp}e^{-t/\tau_{qp}}$$

Taking into account also the diluted phonon arrival time and the resonator ring time we have

$$N_{qp}(t) = N_{qp}\tau_{qp}\left[\frac{\tau_{qp}\,e^{-t/\tau_{qp}}}{(\tau_{qp}-\tau_{ph})(\tau_{qp}-\tau_r)} + \frac{\tau_{ph}\,e^{-t/\tau_{ph}}}{(\tau_{ph}-\tau_{qp})(\tau_{ph}-\tau_r)} + \frac{\tau_r\,e^{-t/\tau_r}}{(\tau_r-\tau_{qp})(\tau_r-\tau_{ph})}\right]$$

Yelding a variation in the complex transmission parameter of

[4] $$\Delta S_{12}(t) = \frac{\alpha Q^2}{Q_c}\frac{N_{qp}(t)}{2N_0 V\Delta}\left(S_1(\omega_0,T) - jS_2(\omega_0,T)\right)$$



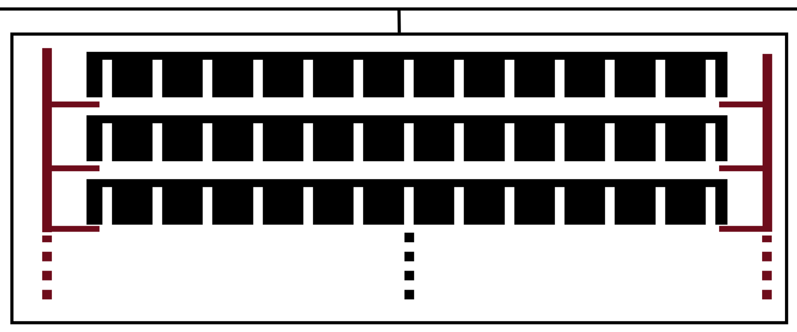
Tau qp	Tau phonon	Tau ring
~ 20 μs	~ 10 μs	10 ÷ 100 μs

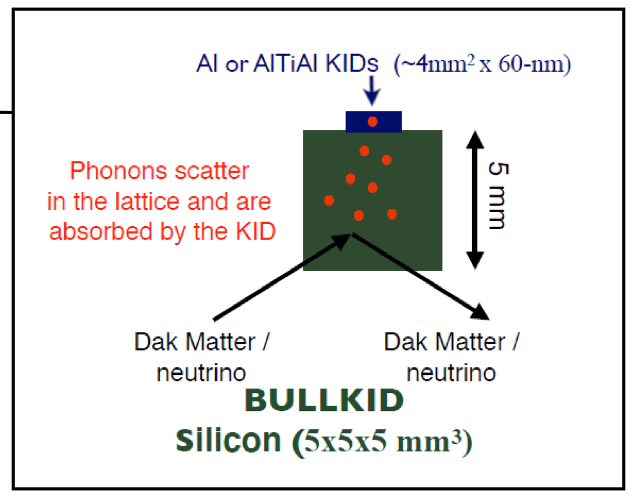
Increasing the active volume of the detector

Usual KID designs are only around 60nm thick.

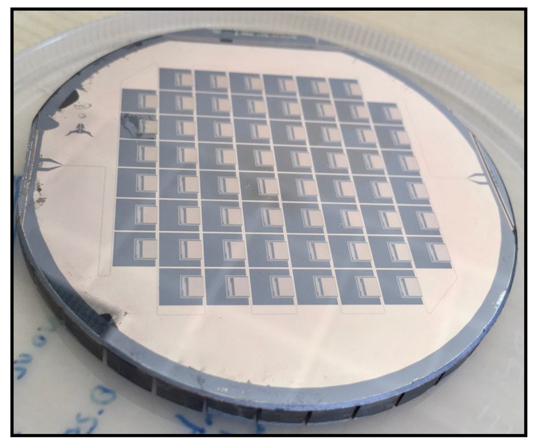
In BULLKID when photons or other particles interact inside the silicon cuebes, part of the energy is converted into phonons. Said phonons then travel inside the silicon and are detected by the KID.

In the two bottom figures it is shown the desired layout for the absorbers: the 5x5x5 mm^3 silicon cubes are carved out of a 3 inch wafer; multiple diced wafers are then stacked to form a cylindrical structure with target volume of 250 cm^3 [4].

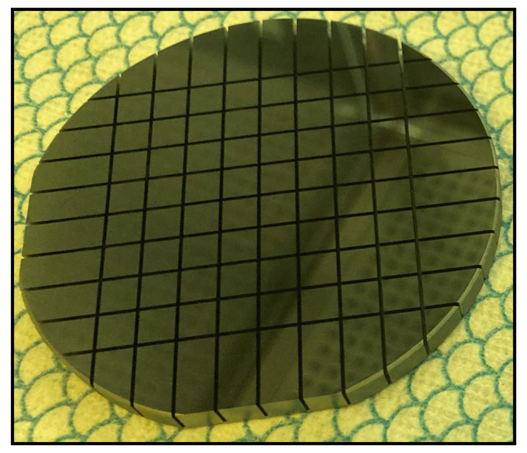


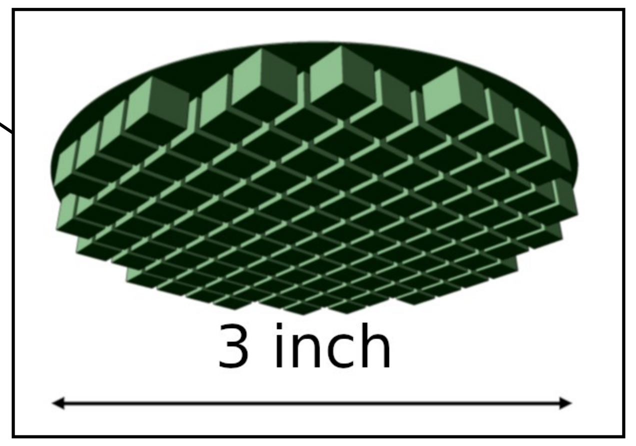


Front side



Back side





Light pulses acquisition: sensitivity and responsivity estimate

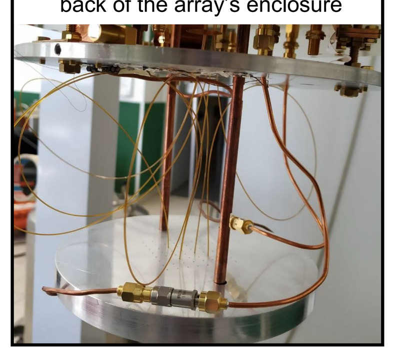
Absolute calibration (400 nm lamp)
- Acquired ramps of optical pulses consisting in 1÷20 cycles
- Each cycle in the ramp can be fitted to a separate gaussian

$$\sigma = \sqrt{\sigma_0^2 + \epsilon_{ph}\cdot R\cdot\mu}$$

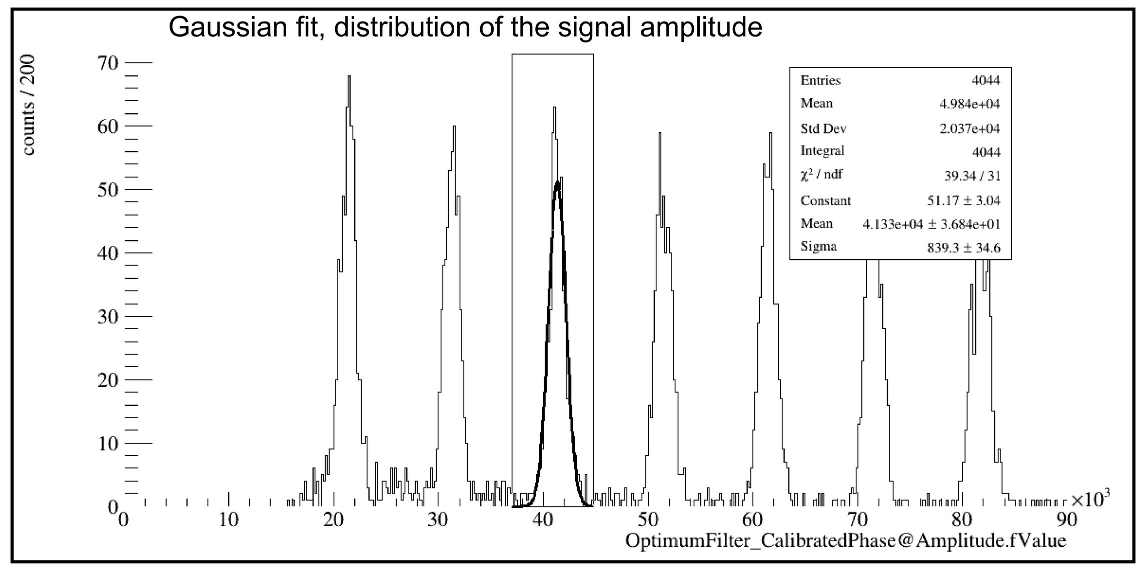
Fit parameters: σ_0, R

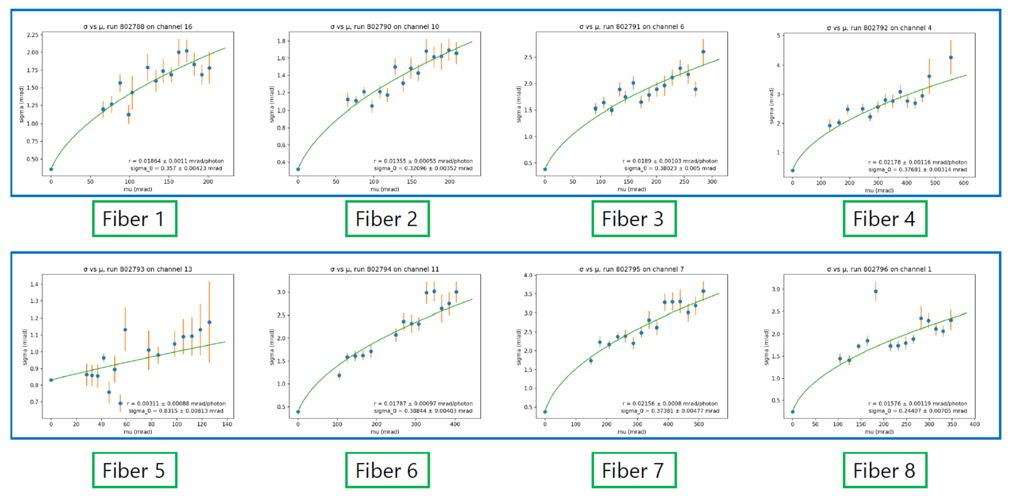
Average sensitivity (σ_0)	Average respositivity (R)
~ 100 eV	~ 5 mrad/keV

Optical fibers shining on the back of the array's enclosure



Gaussian fit, distribution of the signal amplitude



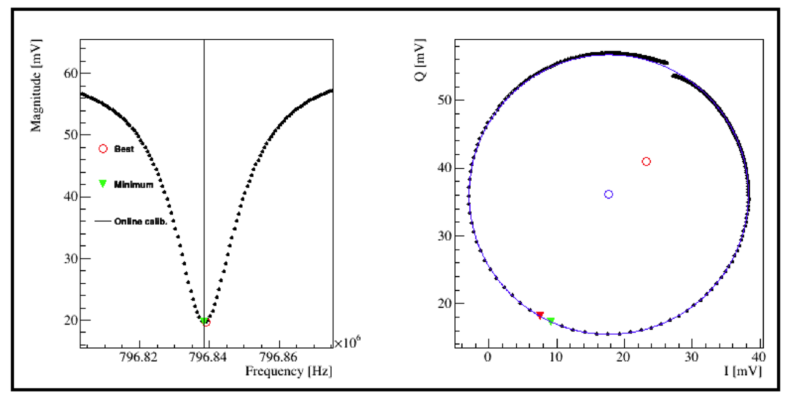


Array readout procedure

- Acquisition is done using a software defined radio (SDR), the data is then streamed to a GPU which handles the demodulation. [5]

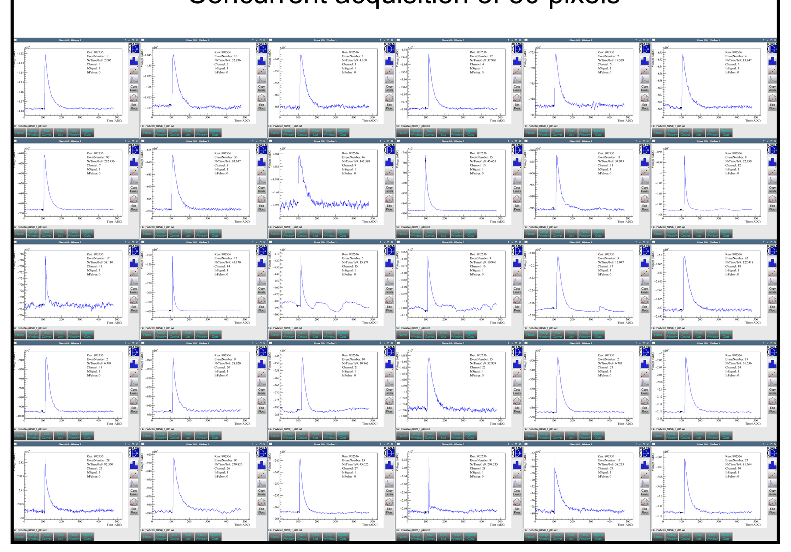
The USRP x300 SDR

1) VNA Scan:
- Resonance identification across the whole array (span of LO ± 80 MHz @ 200 Msps)
- Each pixel is fitted to a circle (in IQ) so that centre position and radius are known



2) Data acquisition:
- TX: While the LO is fixed, tones are generated to match the resonance frequency of the desired channels
- RX: data is streamed from the SDR to the gpu where demodulation takes place (DIRECT or POLIPHASE FILTER BANK modes are available).

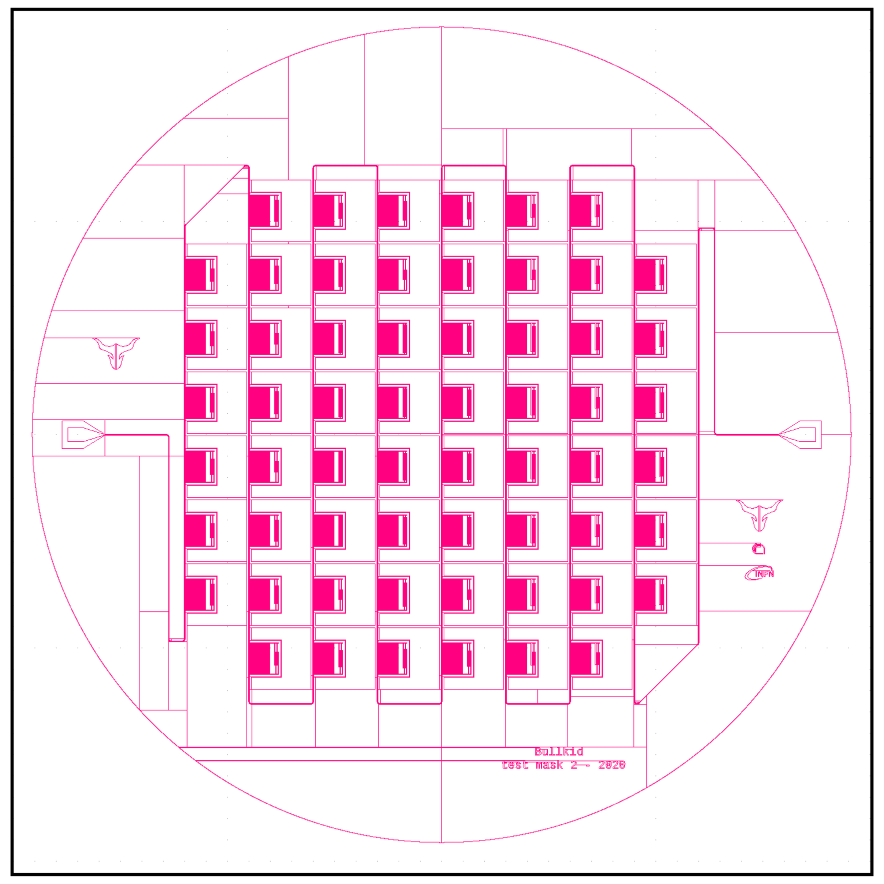
Concurrent acquisition of 30 pixels

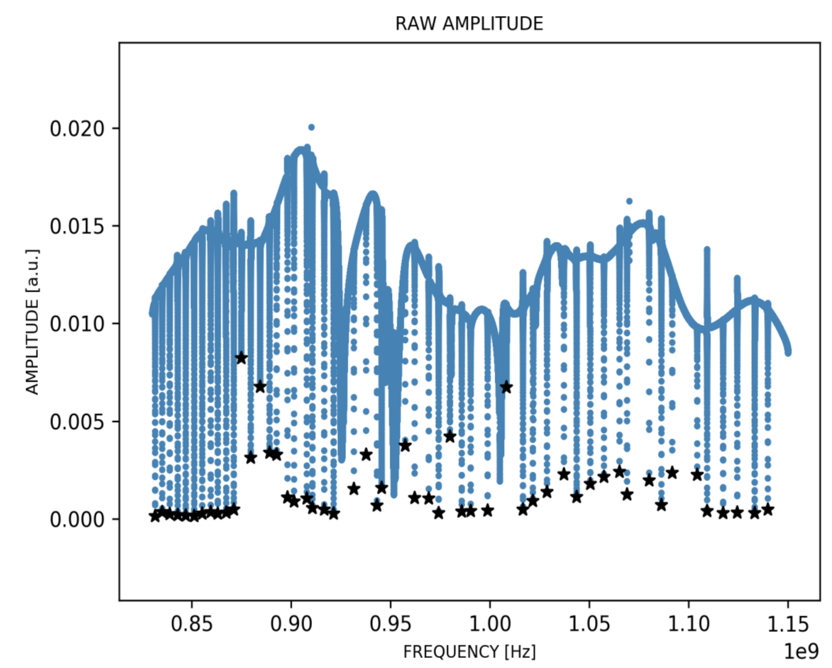


3) Triggering:
- Data is calibrated: using the fits from the VNA scan Amplitude and Phase are calculated with respect to the centre of the resonance.
- Calibrated data is filtered to increase the SNR, then triggered to select only pulses.

4) Data storage:
- After the pulse selection is done data and its respective metadata are saved to disk for offline analysis

Pixel multiplexing





- **Natural multiplexing**: many resonators can be coupled to the same feedline with slightly different resonant frequency
- **No electrical cross-talk**: if enough spaced in frequency the pixels work independently from one another

REFRENCES

1. Jiansong Gao. «The Physics of Superconducting Microwave Resonators, PhD thesis» (2008).
2. L. Cardani et al. «Final results of CALDER: kinetic inductance light detectors to search for rare events» (2021).
3. M. Capeccia. «Rivelatori KID per rinculi nucleari di bassa energia» (2021).
4. S. Manthey Corchado. «BULLKID. Analysing Microwave Kinetic Inductance Detectors (MKIDs) for Dark Matter research»
5. L. Minutolo et al. «A flexible GPU-accelerated radio-frequency readout for superconducting detectors» (2018).