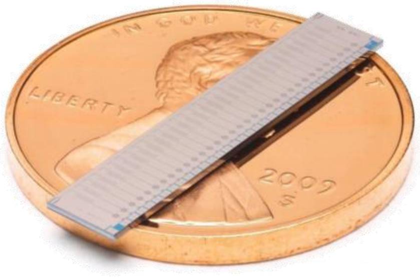
Multiplexing readout schemes for low temperature detectors



Why do we multiplex?

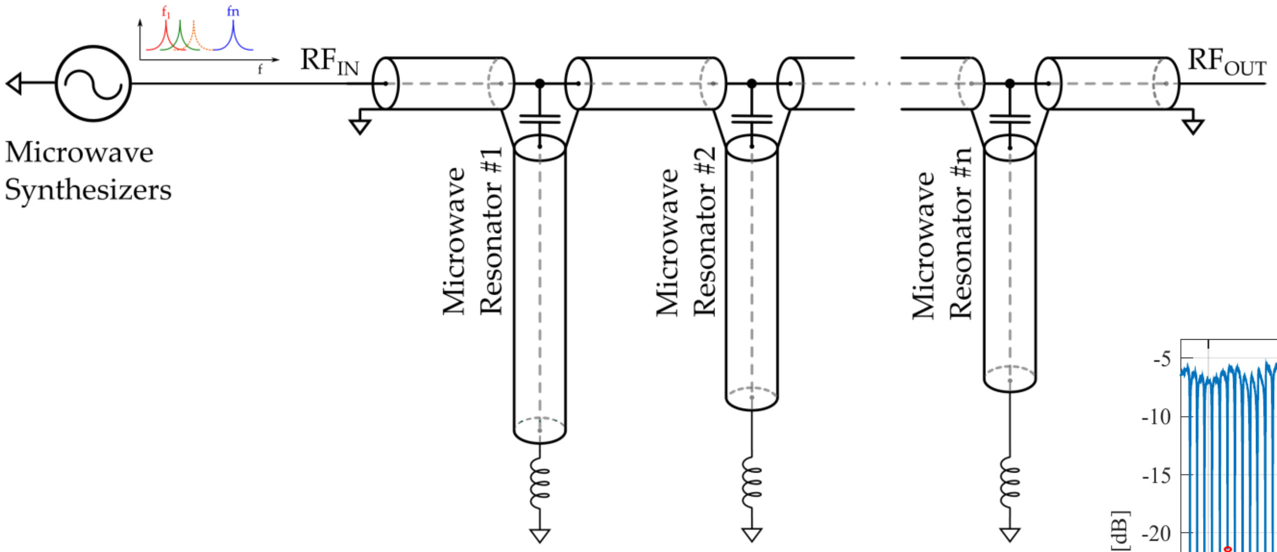
- each LTD requires readout wiring between room temperature and the cold stage of a dilution refrigerator at **tens of mK**
- there are a few multiplexing schemes available for both TESs and MMCs (both rely on a current signal)
- a good candidate needs to provide a large bandwidth and a good multiplexing factor, along with low x-talk
- two are of particular interest
  - microwave SQUID multiplexing (*Appl. Phys. Lett. (2013) 103, 202602*) → already in use for keV detectors by HOLMES
  - Kinetic Inductance Current Sensors (KICS) (*Commun. Eng. 3 (2024) 1, 160*) → demonstrated for NIR TESs, under development for keV TESs

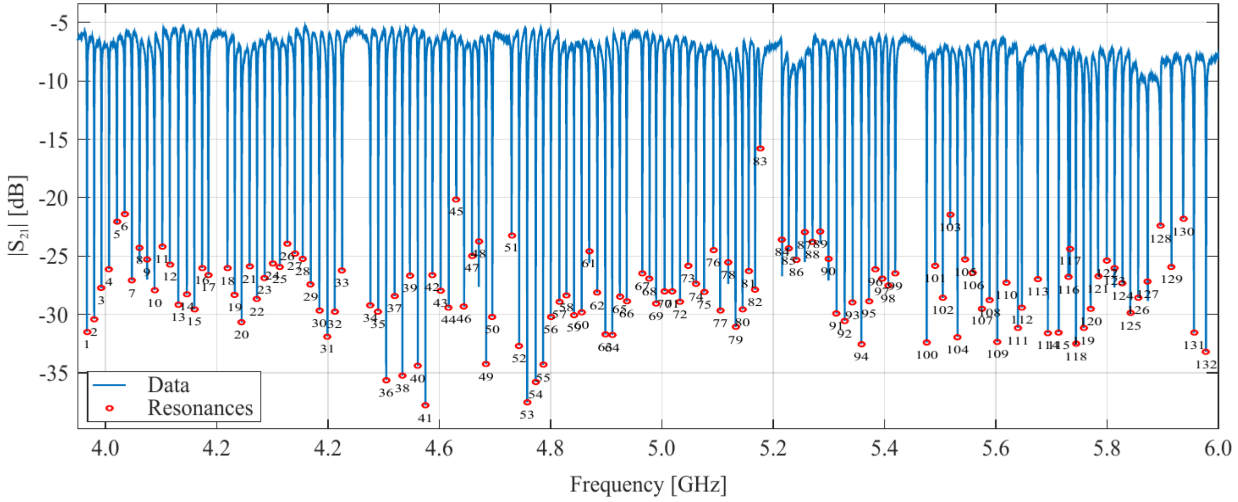
Disclaimer

I’ll refer here to the multiplexing applied to TES, but similar arguments can be made for MMCs (with a few differences)

Microwave SQUID multiplexing

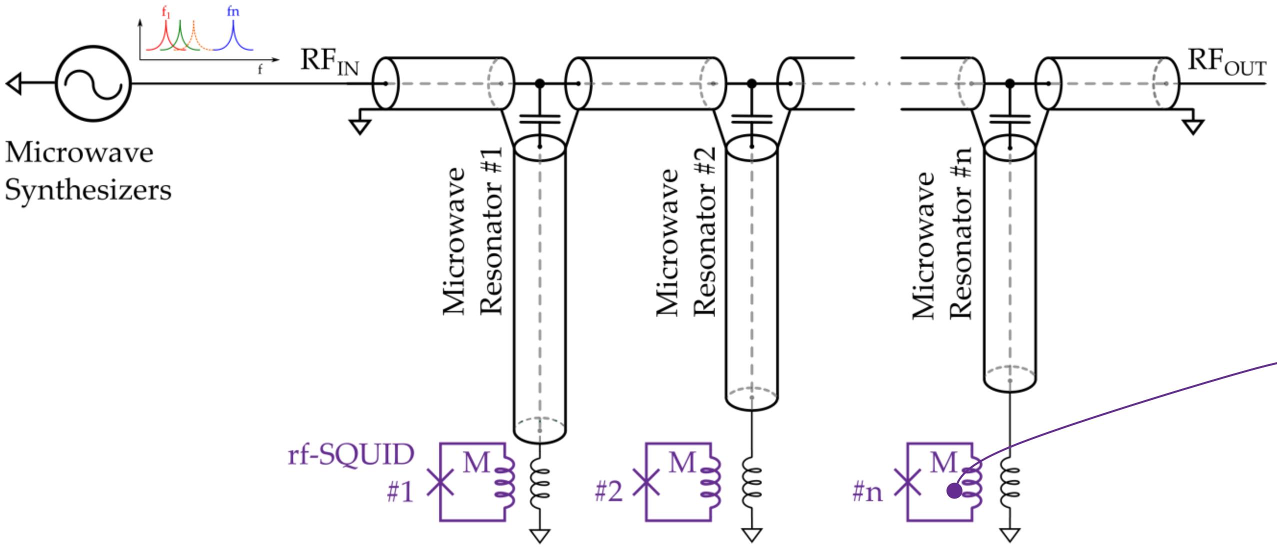
- the multiplexing is naturally achieved with microwave microresonators:

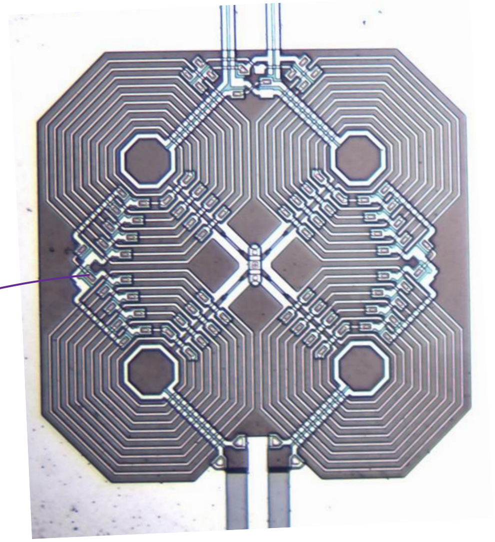


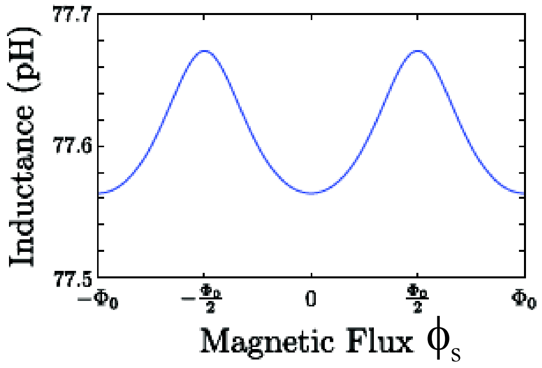

Forward transmission S_{21} of 4 different band chips wired in series

Microwave SQUID multiplexing

- the objective is to detect a current signal: a rf-SQUID translates the current information into magnetic flux, and hence mutual inductance



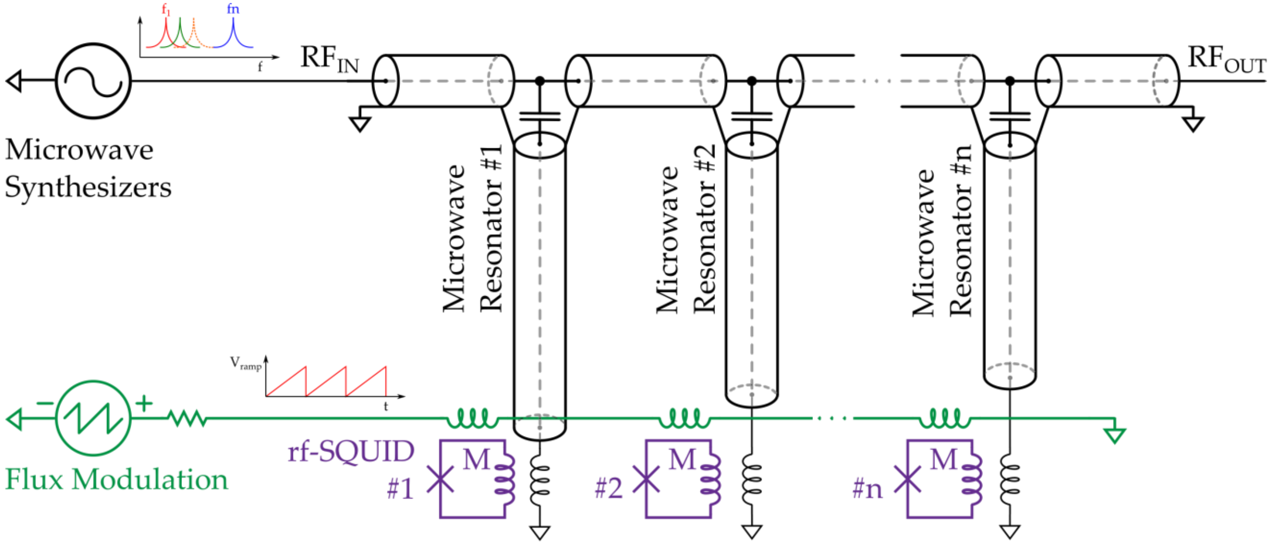


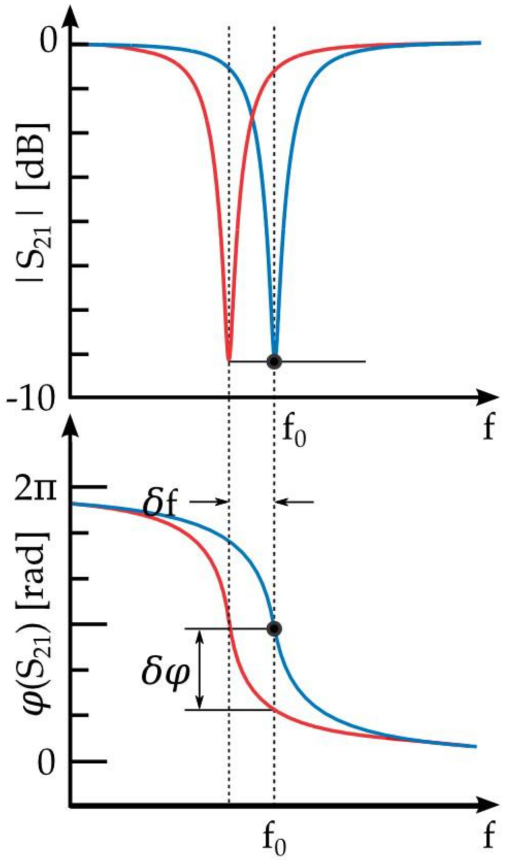


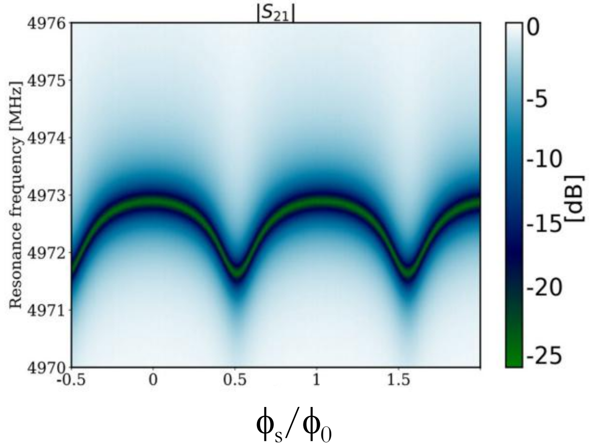
SQUIDs are very sensitive to current signals, but have a non-linear (periodic) response → it is necessary to linearize its response

Microwave SQUID multiplexing

- the objective is to detect a current signal: a rf-SQUID translates the current information into magnetic flux, and hence mutual inductance





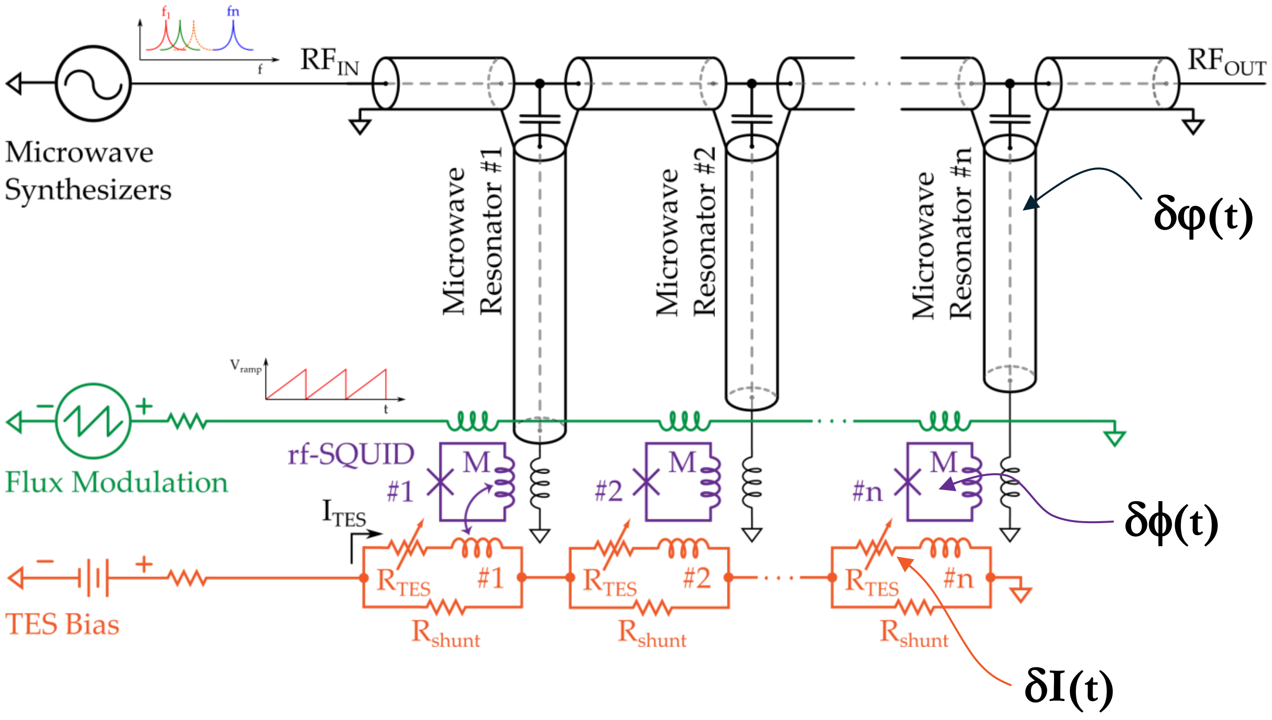


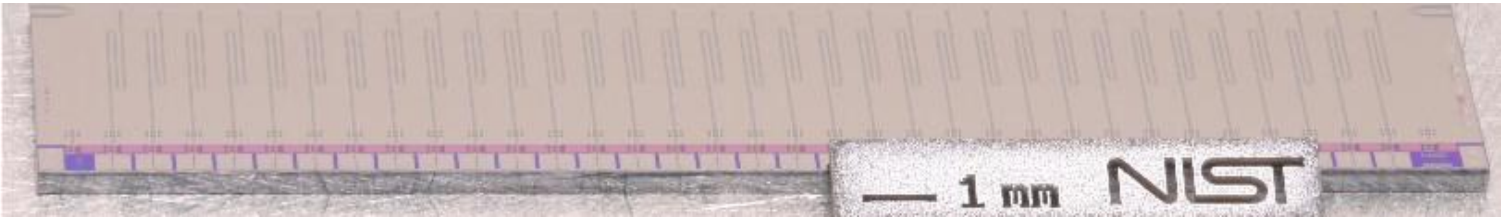
a periodic, linearly increasing, signal (the 'ramp') is applied to the SQUID

→ **the frequencies of the resonators oscillate continuously**

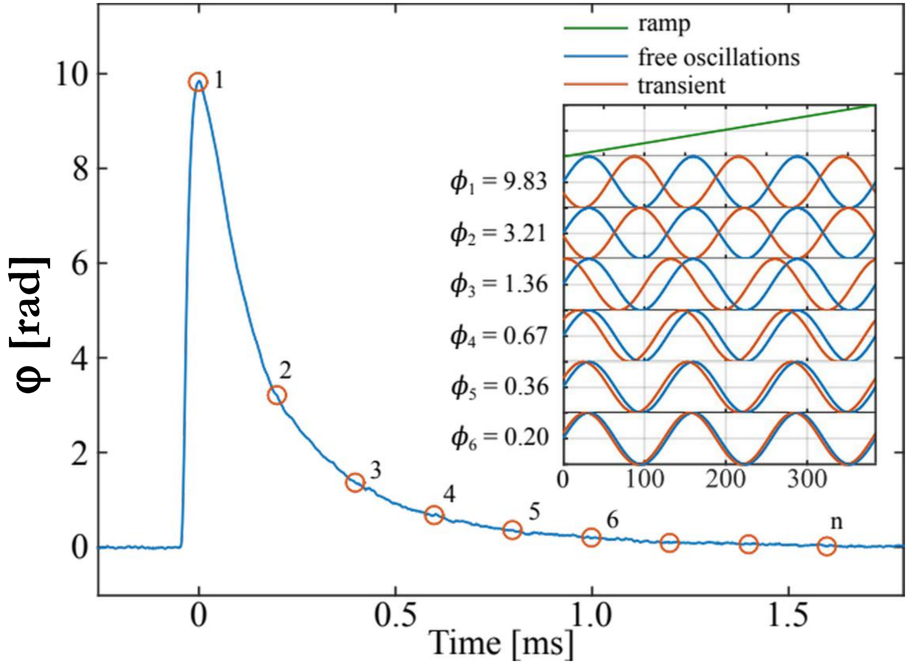
Microwave SQUID multiplexing

- $\delta I(t) \rightarrow \delta\phi(t) \rightarrow \delta\varphi(t)$





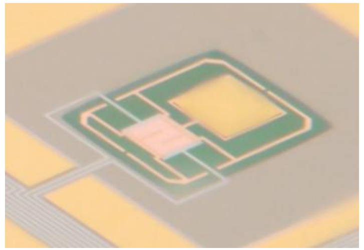
<u>in this scheme the ramp frequency is the signal sampling frequency</u>



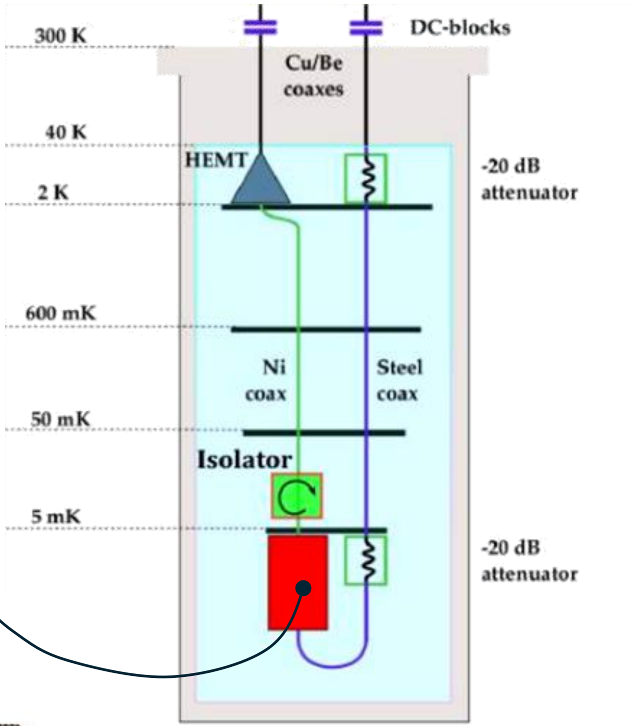
scheme currently <u>in use</u> in HOLMES for acquiring physics data, such as Phys. Rev. Lett. 135 (14), 141801

Microwave SQUID multiplexing

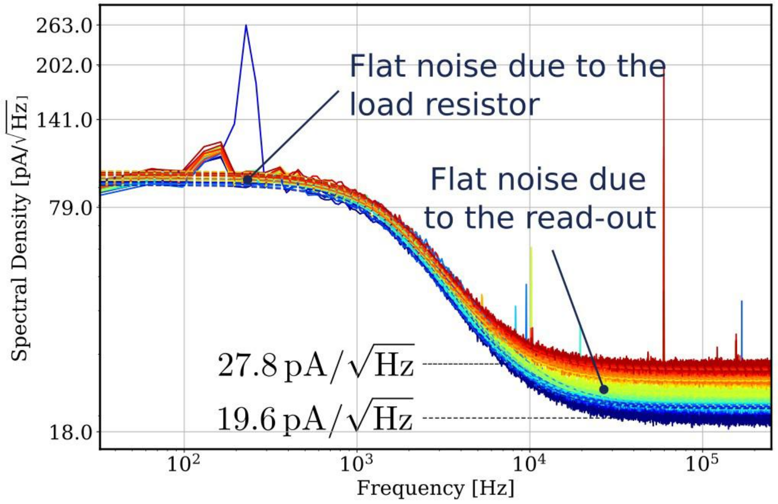
HOLMES



64 TESs

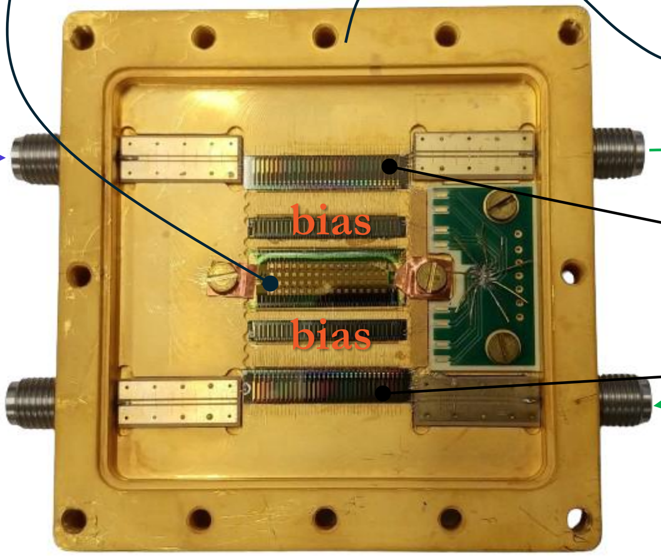


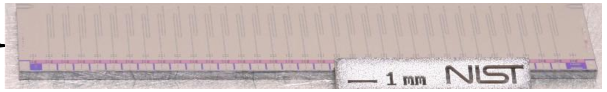
Read out noise
32 Channels, no TES bias applied



RF
probe in

RF (carrier
+ TES
signal) out





Microwave SQUID mux: BW considerations

- $\Delta f_{\mathrm{res}} \geq 2 f_{\mathrm{ramp}} \mathrm{n}_{\phi_0}$ $\mathrm{n}_{\phi_0} = 2$ flux quanta per ramp period
- $f_{\mathrm{ramp}} (= f_{\mathrm{sampl}}) \geq \frac{5}{\tau_{rise}}$ requirement to avoid distortion
- $f_{\mathrm{n}} \geq 8 \Delta f_{\mathrm{res}}$ crosstalk suppression
- each resonator requires a BW equal to $f_{\mathrm{n}} \approx \frac{160}{\tau_{\mathrm{rise}}}$

- the current SDR-based DAQ used in HOLMES (ROACH2) has a total BW $f_{\mathrm{ADC}} = 512$ MHz

$$\Rightarrow \frac{f_{\mathrm{ADC}}}{f_{\mathrm{n}}} = \frac{f_{\mathrm{ADC}} \tau_{\mathrm{rise}}}{160} \xrightarrow{\tau_{\mathrm{rise}} = 10 \mu s} = 32 \text{ TESs/ROACH2 board}$$

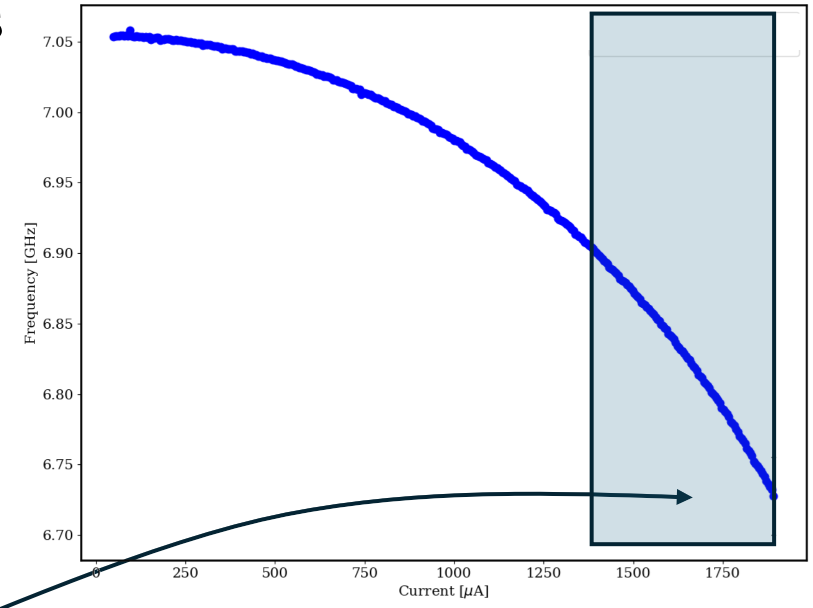
τ_{rise} slowed down electrically on purpose to match the BW of the readout. **The underneath thermal signal is much faster → time resolution limited by the sampling time**

Kinetic Inductance Current Sensors (KICS)

- novel scheme, so far demonstrated for NIR photons
- relies on kinetic inductance vs current flowing in a superconductor:

$$L(I) \approx L_0\left(1+\frac{\mathrm{I}^2}{\mathrm{I}_*^2}+\ldots\right)$$

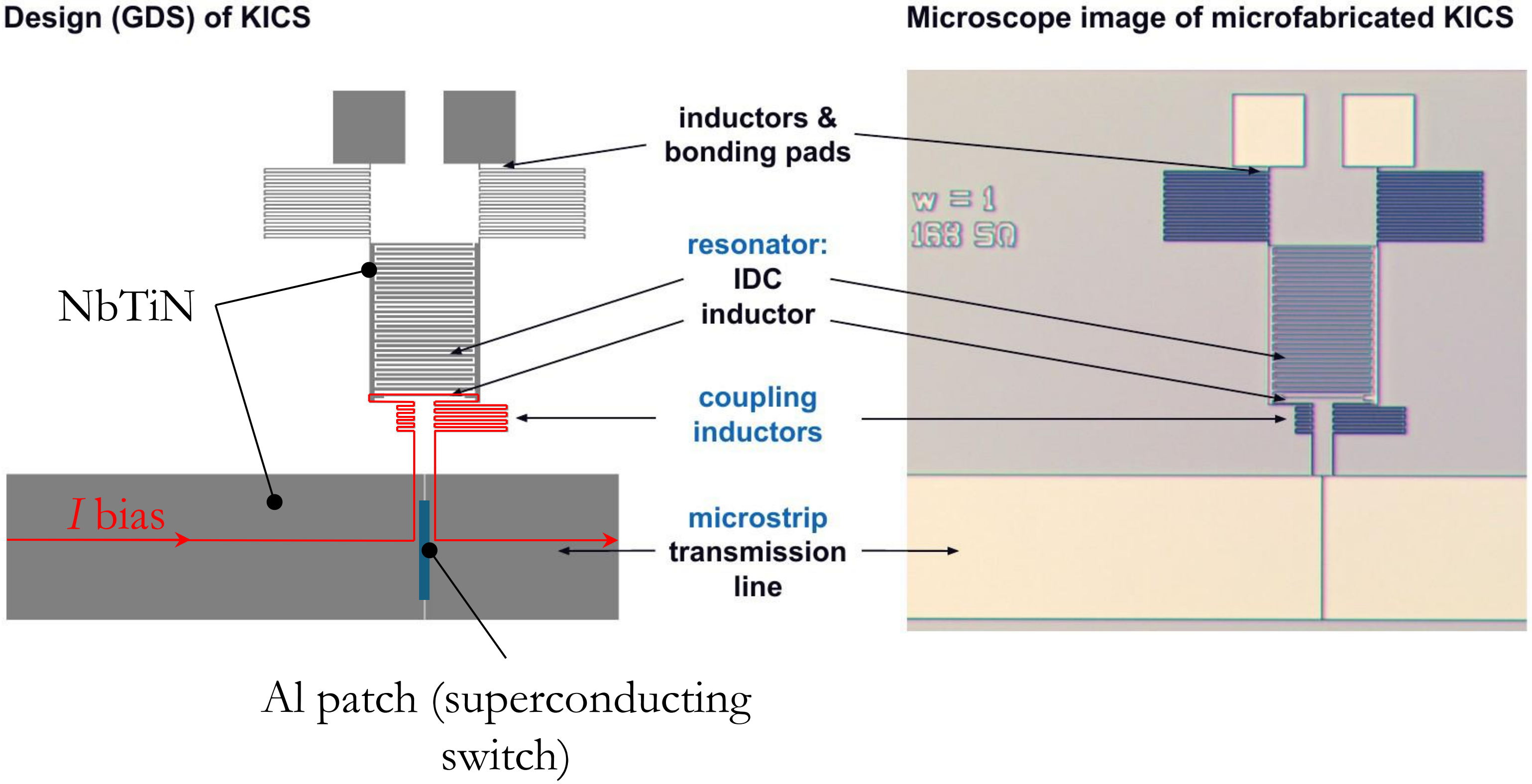
- when patterned into a resonator, f_r depends on the current
- at low currents, the response is basically flat
- to work in the **current-sensitive region**, an additional persistent current is added
- any additional current from the detectors is detected as a frequency shift



$$f_\mathrm{r}(\mathrm{I})=\frac{1}{2\pi\sqrt{L(I)\mathrm{C}}}$$

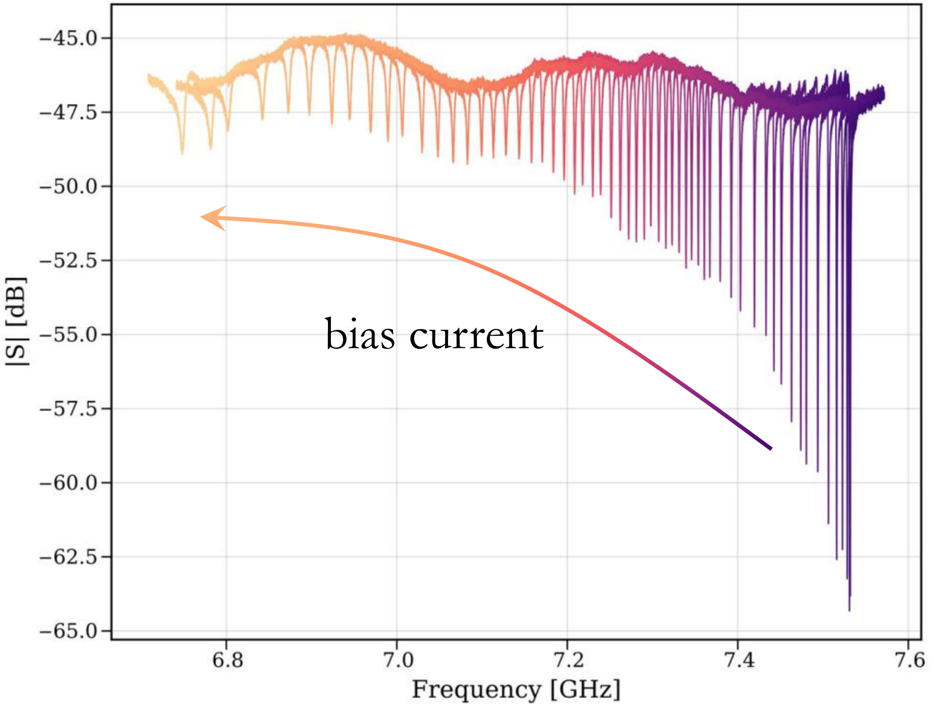
Kinetic Inductance Current Sensors (KICS)

- first prototype produced at FBK within the HOLMES+ collaboration



Design (GDS) of KICS

Microscope image of microfabricated KICS



step 1: apply a bias current while keeping the temperature $T_c^{\text{KICS}} > T > T_c^{\text{switch}}$ of the superconducting switch (in the current prototype: $T_c^{\text{KICS}} \approx 11.8\text{K}$, $T_c^{\text{switch}} \approx 1.2\text{K}$)

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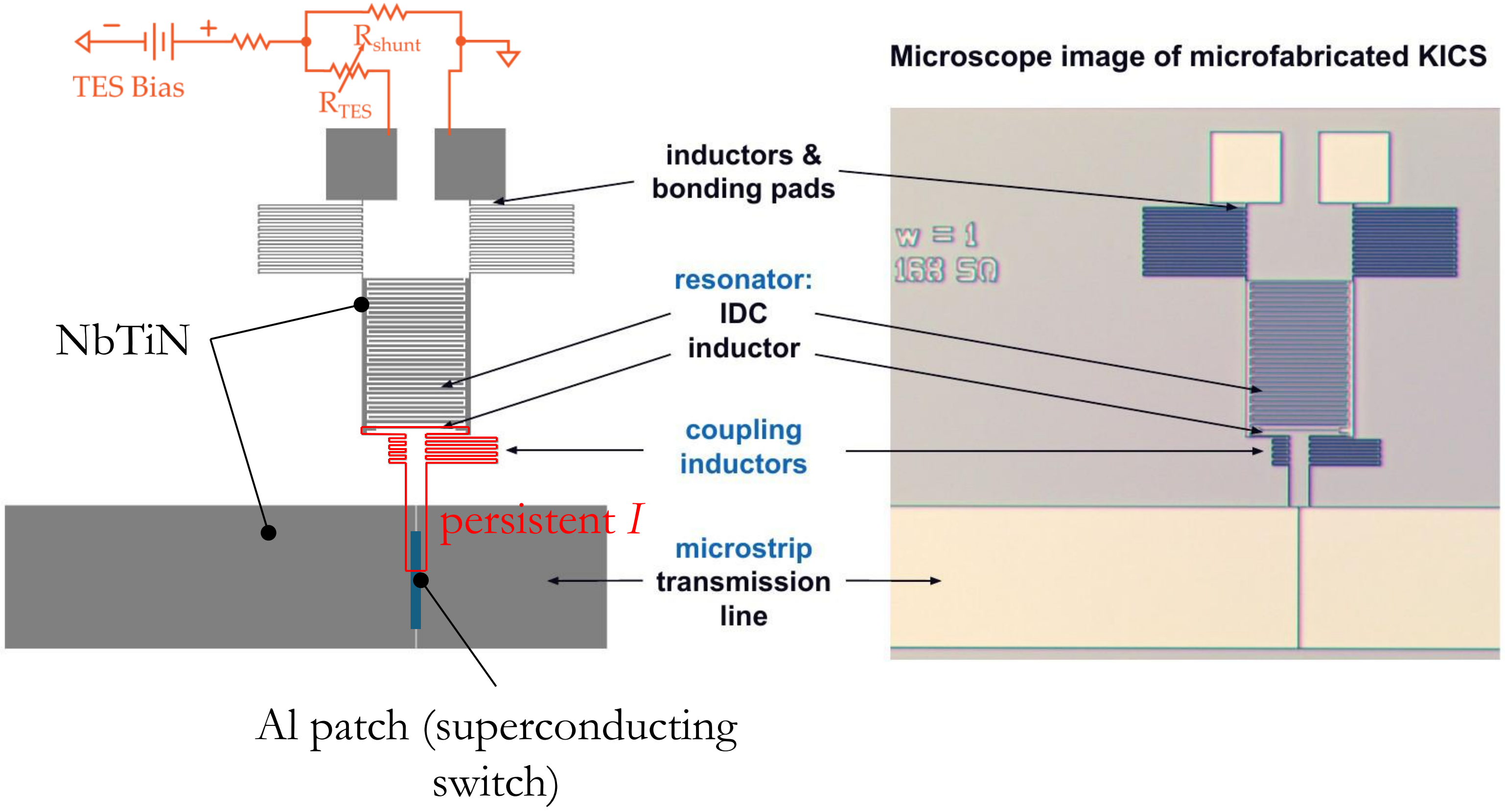

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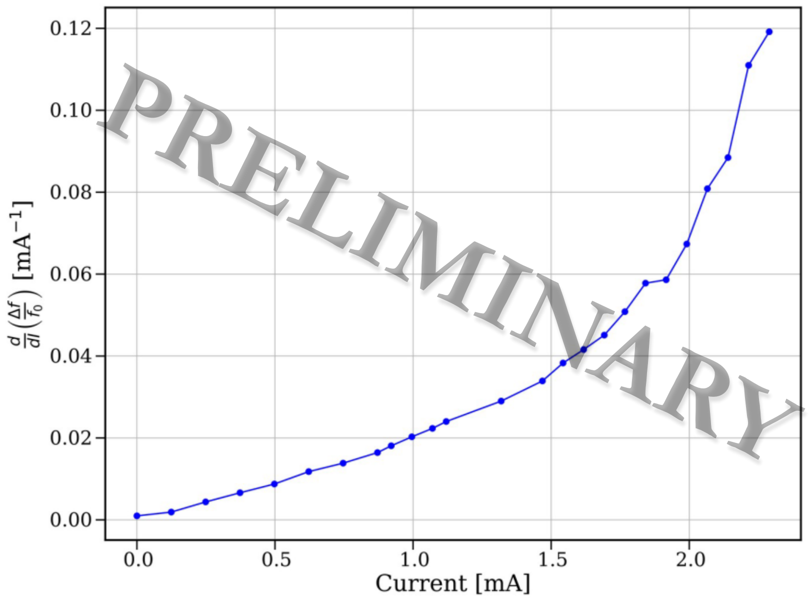

step 2: lower T below T_c^{switch} and remove the bias: the resonator will detect a current signal from a TES w/o ramp modulation

→ **current prototypes successfully tuned with persistent current**

KICS: BW considerations

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- $\Delta f_{\mathrm{res}} \geq \frac{1}{\pi \tau_{rise}}$ requirement to avoid distortion
- $f_{\mathrm{n}} \geq 8 \Delta f_{\mathrm{res}}$ crosstalk suppression
- each resonator requires a BW equal to $f_{\mathrm{n}} \approx \frac{8}{\pi \cdot \tau_{\mathrm{rise}}} \Rightarrow$ **a factor 60**

increase in the mux factor respect to SQUID mux

- additional benefit from new RF-SoC boards, with larger BW
- sampling time 0.1 µs → lower pup contribution