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Sensing of cryogenic temperatures by superconducting NbTi(N) thin-film S-shaped Split Ring Resonators

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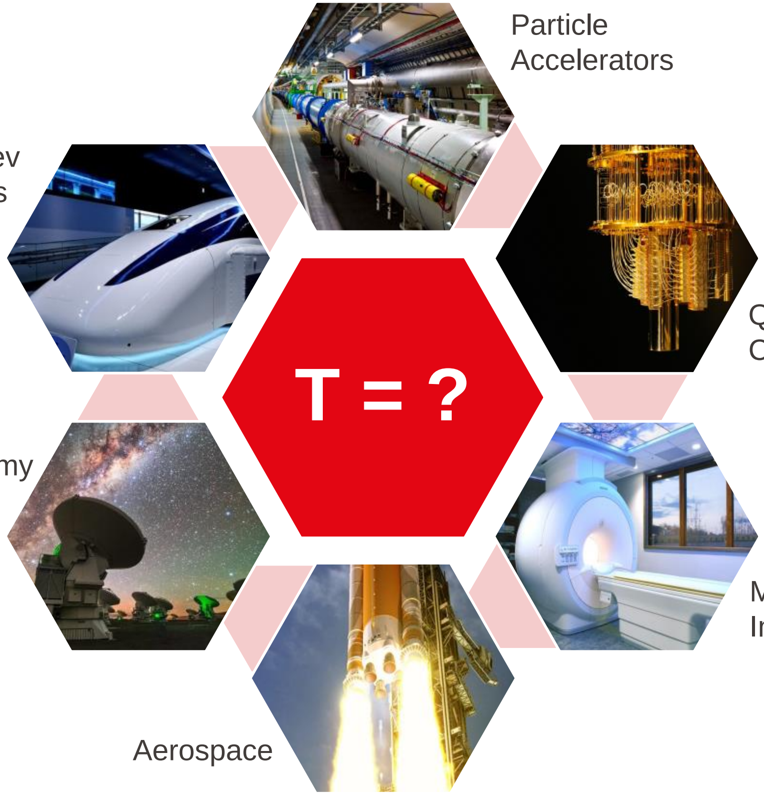
École polytechnique fédérale de Lausanne

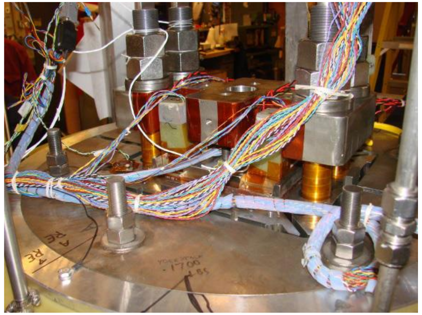
Thermometry for Cryogenic Systems



[1]

- Many wiring issues when dealing with mulit-stages cryogenic environments…

[2]



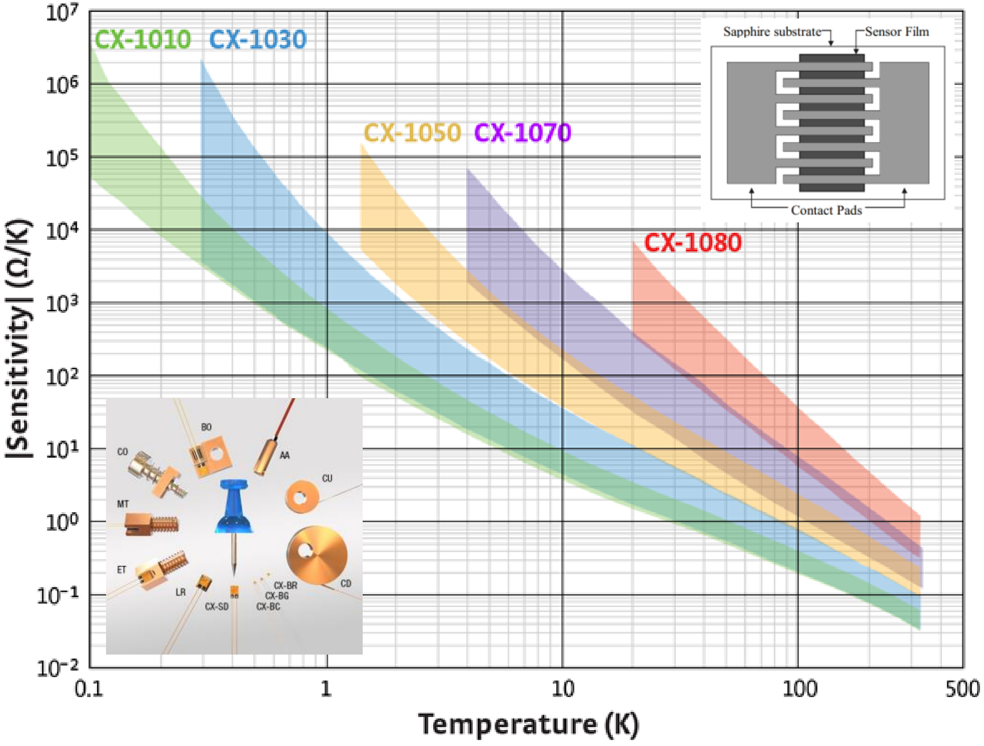
[1] Courtesy of P. Borges de Sousa CERN, TE CRG CI
[2] M. Turqueti et al., *Physics Procedia 67* (2015)

State-of-the-Art

- Cryogenic thermometry mainly achieved by **2 and 4-wires thermistors**

- **CERNOX**® thermometers [3-4]:
  - effective over wide T-ranges
  - $\Delta T = 0.1 - 320$ K
  - good sensitivity
  - $dR/dT > 10^3\ \Omega/K$ for $T < 1$ K
  - mechanically robust
  - small and compact
  - insensitive to magnetic field

- **Main issues**:
  - need of 2/4 DC wires for each sensor → feedthrough budget
  - non-linearity
  - heat conduction paths
  - wiring complexity



[3] https://www.lakeshore.com/products/categories/overview/temperature-products/cryogenic-temperature-sensors/cernox
[4] S. S. Courts et al., *AIP Conference Proceedings 684* (2003)

RF Superconducting Thermometry

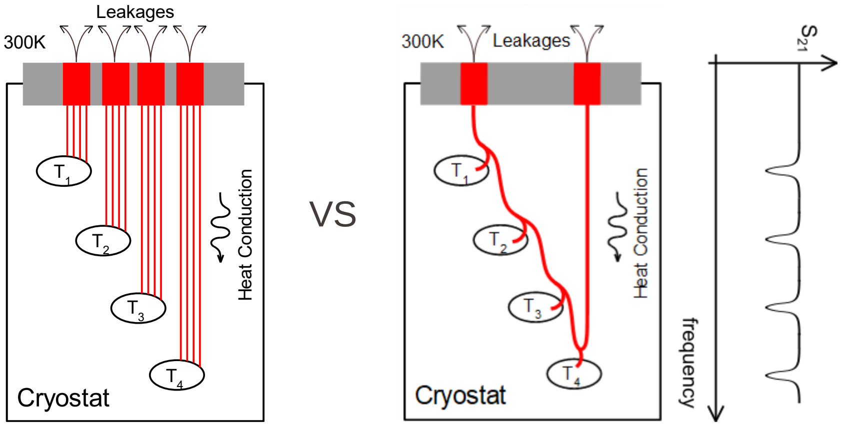
- **Multiplexing is possible in frequency domain** with temperature sensitive resonating systems

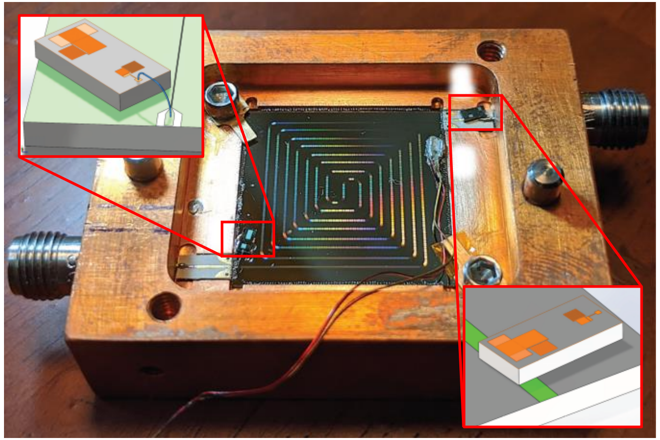
- **RF superconducting resonators** in GHz range can deliver:
  - > 10’000 Q-factors
  - sub-mK resolution
  - single-line parallel readout of several sensors
  - small and compact dimensions

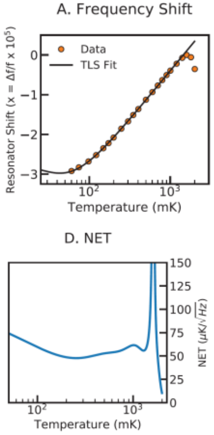
- Several alternative approaches based on different physical phenomena

- 2 GHz Nb lumped elements thin film resonators exploiting **Two-Levels Systems (TLSs)** [5]

- For T < 1 K:
  - Q > 35’000
  - $\Delta f_{max} = 60$ kHz
  - NET < 100 μK/Hz$^{1/2}$



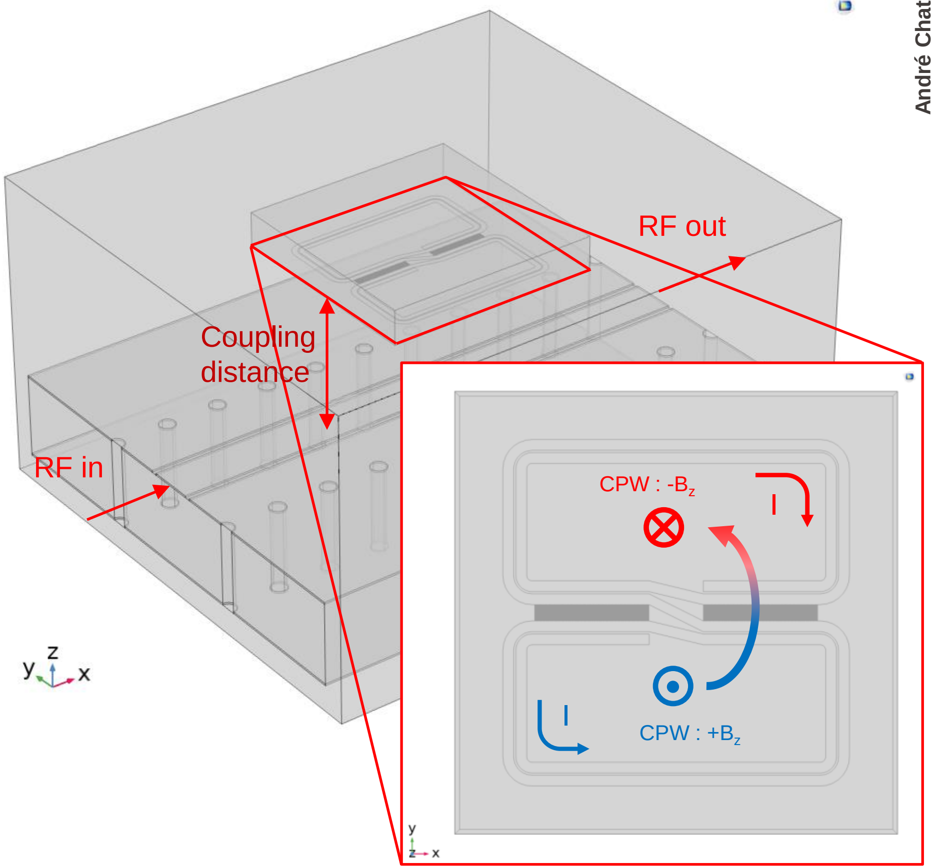




[5] J. Wheeler et al., *Appl. Phys. Lett. 117* (2020)

S-shaped Split Ring Resonator (S-SRR)

- Temperature monitored through variations of the thin film **kinetic inductance L_K(T)**
  - kinetic/inductive energy of Cooper pairs $\frac{1}{2}(2m_e v^2)(n_S(T) l A) = \frac{1}{2} L_K I^2$
  - $L_K(T) = \left(\frac{m_e}{2n_S(T)e^2}\right)\left(\frac{l}{A}\right)$
  - $f_{res}(T) = \frac{1}{2\pi\sqrt{(L_G+L_K(T))\cdot C_G}}$
- **Antisymmetric S-SRRs geometry for optimal electromagnetic proximity coupling** with standard Cu CPWs [6-7]
- Devices designed to resonate ~ 1 GHz



[6] F. Aznar et al., *AIP Journal of Applied Physics 104* (2008)
[7] A. K. Horestani et al., *IEEE Ant. and Wir. Prop. Lett. 13* (2014)

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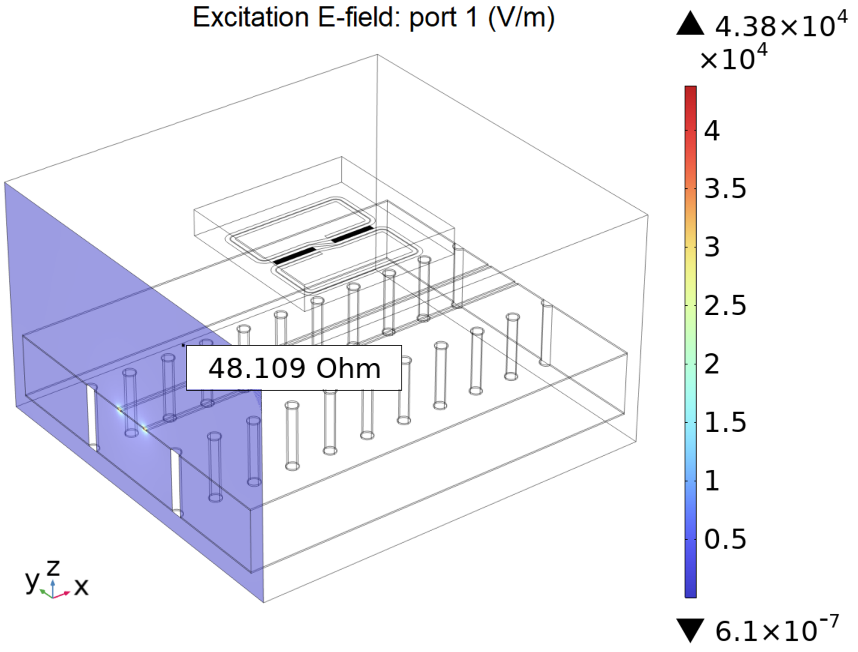

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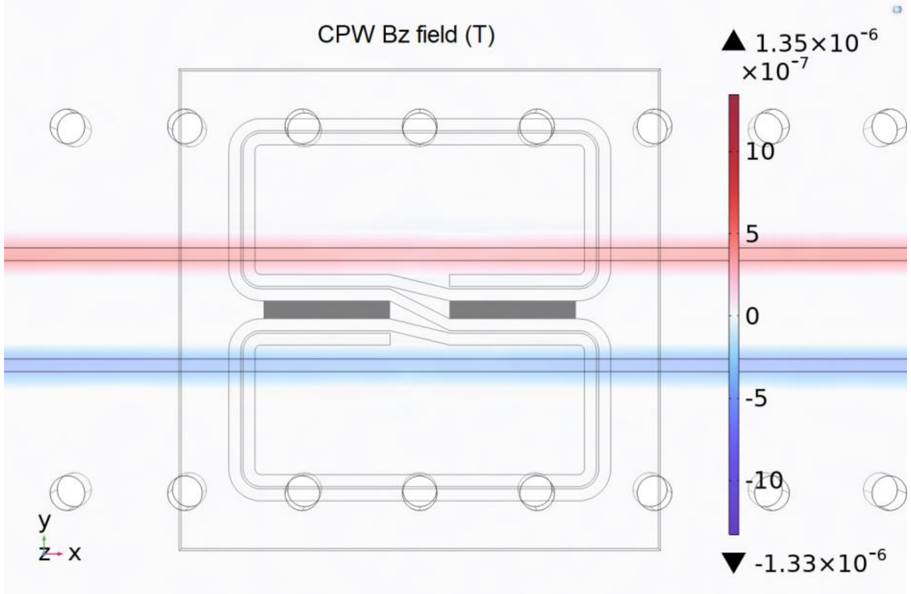

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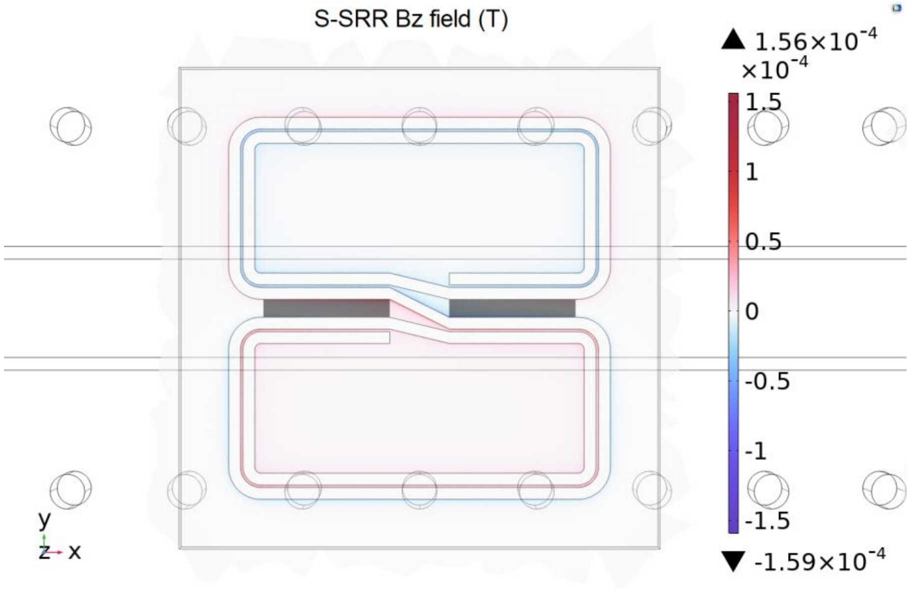

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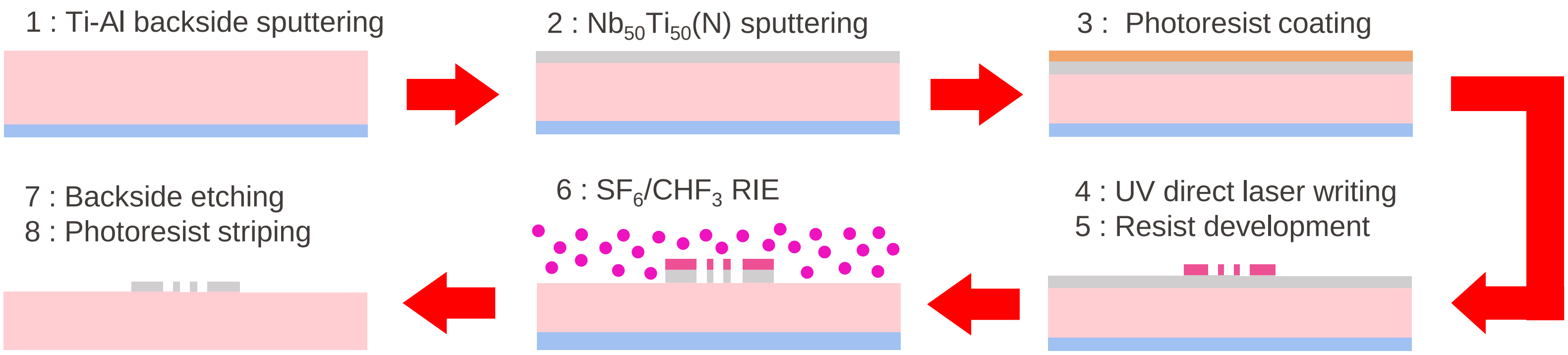
NbTi(N)-over-Sapphire Microfabrication



1 : Ti-Al backside sputtering

2 : $\mathrm{Nb_{50}Ti_{50}}$(N) sputtering

3 : Photoresist coating

4 : UV direct laser writing
5 : Resist development

6 : $\mathrm{SF_6/CHF_3}$ RIE

7 : Backside etching
8 : Photoresist striping

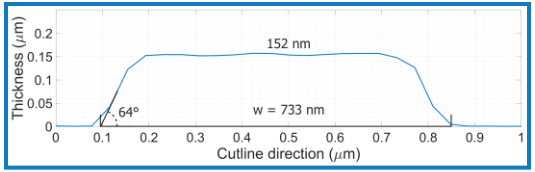
Sapphire

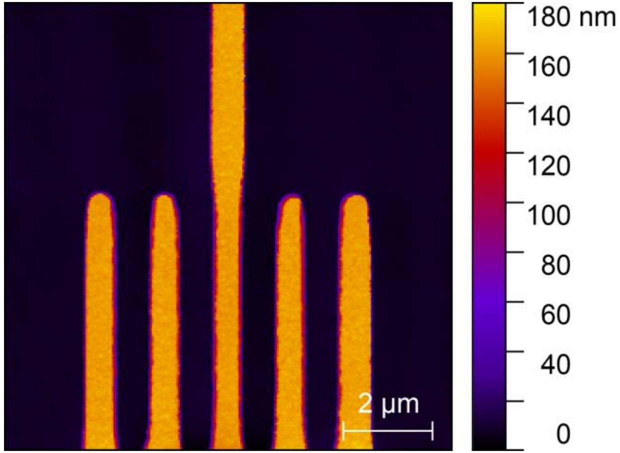
10 nm Ti - 100 nm Al

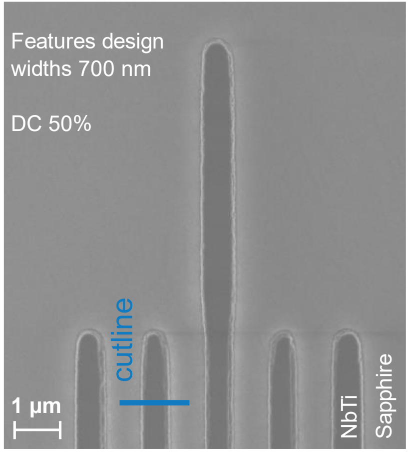
20-150 nm $\mathrm{Nb_{50}Ti_{50}}$(N)

Photoresist

Developed Resist



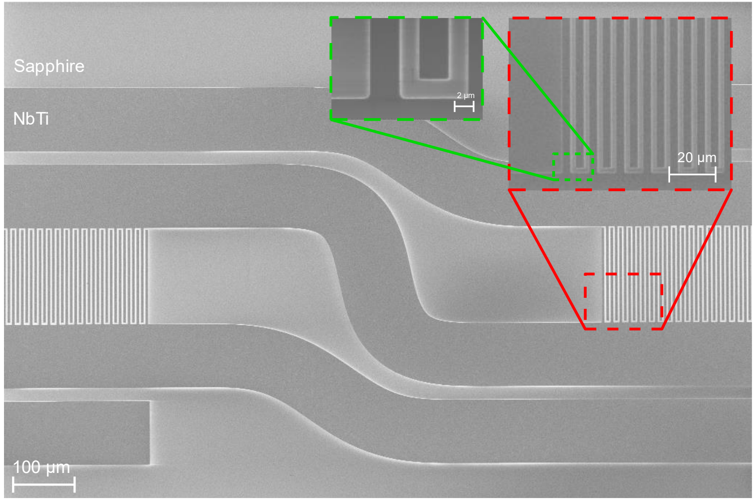


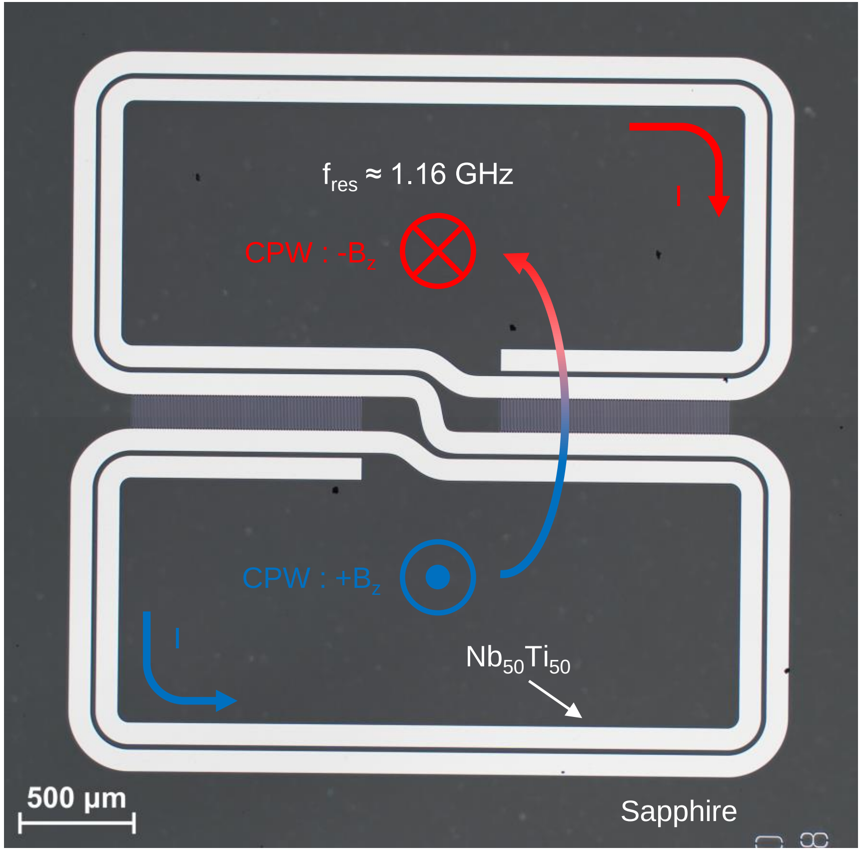


Final Devices

- 100 µm wide **loop-inductance** lines
- 4 µm wide and 2 µm spaced **interdigitated fingers capacitance**
  - lower resonance frequency → lower RF losses
  - keeping the sensor compact

$$f_{res}(T) = \frac{1}{2\pi\sqrt{L \cdot C_G}}$$

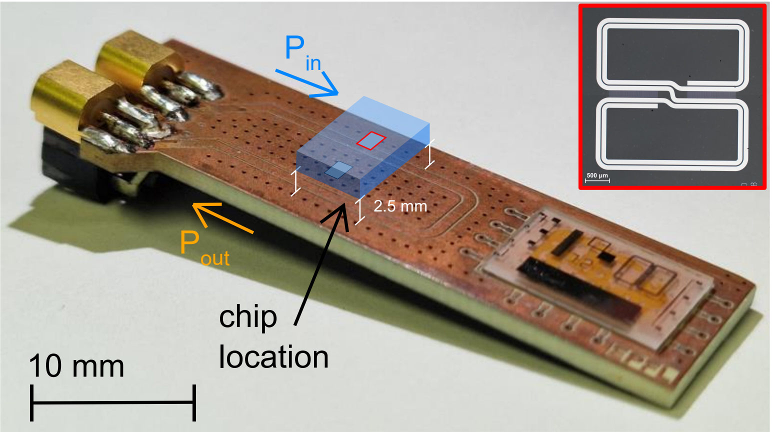


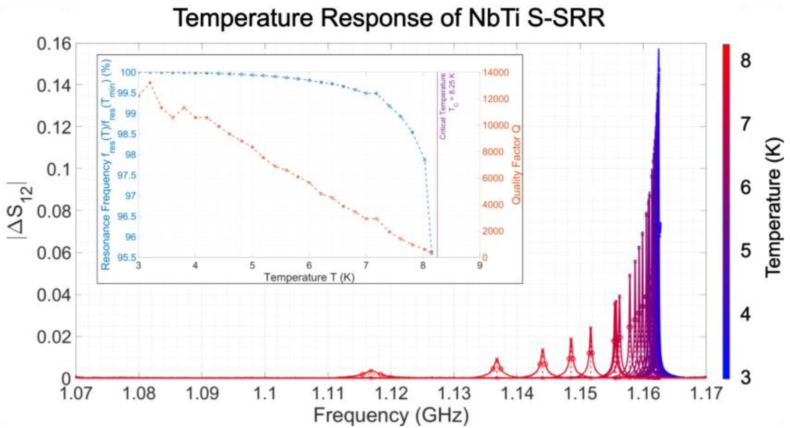


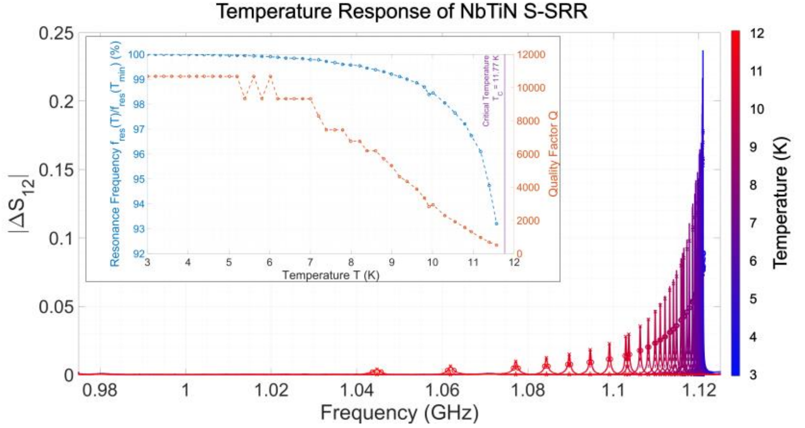
Temperature Responses

- 100 nm thin S-SRRs tested in the **VTI of a closed loop dry cryomagnet** at 0 T magnetic field
- -18 dBm excitation power

	NbTi	NbTiN
f_{res} (3 K)	1.16 GHz	1.12 GHz
Δf_{MAX}%	4.5% (~ 53 MHz)	7% (~ 78 MHz)
T_C	8.3 K	11.8 K
Q_{MAX}	> 13’000	> 11’000




Temperature Response of NbTi S-SRR


Temperature Response of NbTiN S-SRR

Estimation of NET

- Ultimate **S-SRR T-resolution** can be estimated by analyzing 2 physical parameters:
  - **noise spectral density →** S_{xx}
  - **device responsivity →** $\frac{dS_{21}}{dT}$

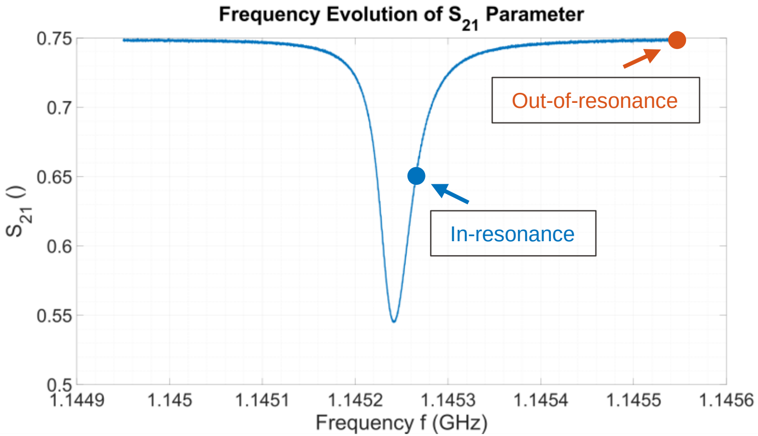
- Experiments performed for a NbTi 150 nm thin S-SRR:
  - @ 3 K (minimum reachable VTI T)
  - @ 0 T B-field
  - @ -18 dBm RF excitation power
  - CW mode scanning for 5 s at 2 kHz rate

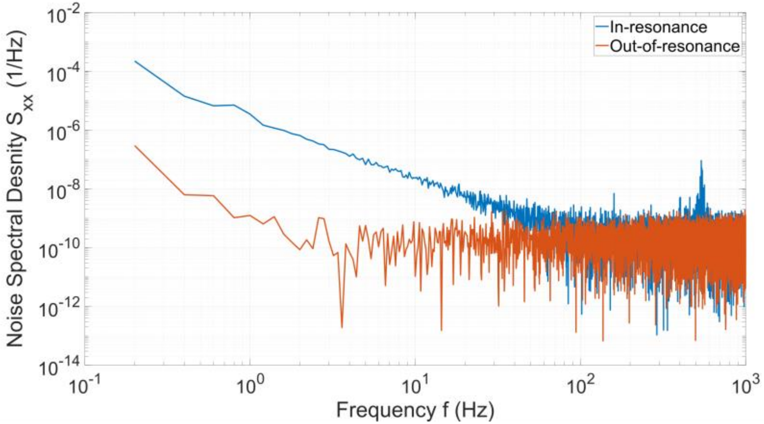
$$\frac{df_0}{dT} \approx \frac{\Delta f_0}{\Delta T} = \cdots = 0.66\ \frac{MHz}{K}$$

$$\frac{dS_{21}}{df} \approx \frac{\Delta S_{21}}{\Delta f} = \cdots = 4.29\ \frac{1}{MHz}$$

$$S_{xx}(1\ Hz) \approx 3.48 \times 10^{-6}\ \frac{1}{Hz}$$

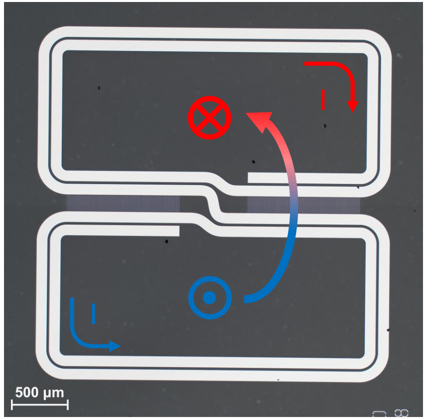
$$\boldsymbol{NET(1\ Hz) = \frac{\sqrt{S_{xx}(1\ Hz)}}{\frac{dS_{21}}{dT}} \approx \cdots \approx 655\ \frac{\mu K}{\sqrt{Hz}}}$$

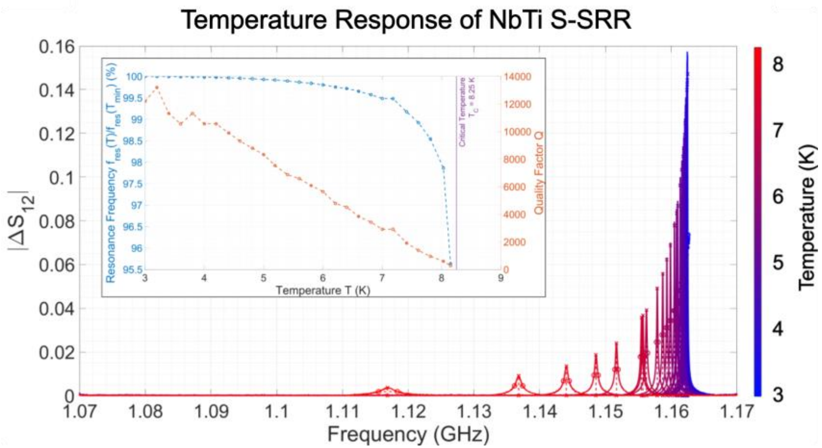




Conclusions and Future Perspectives

- **S-SRR kinetic inductance superconducting thermometer demonstrated:**
  - wire-free cryogenic temperature measurement by EM coupling to an RF line
  - multi-location monitoring possible (frequency range tagging)
- **Sensing properties:**
  - high Q-factors > 10’000 @ 3 K
  - frequency-shifts as large as 7% from 3 to 12 K
  - sensitivity 0.2 MHz/K @ 3 K
  - resolution < 1 mK/Hz$^{1/2}$ @ 3 K
- **Improvements ongoing:**
  - material choices for T-range definition (Al for T < 1 K, HTS for T > 50 K, etc.)
  - low-T sensitivity increase by surface modification of the thin films





Thank you for the attention!

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