MASTER THESIS IN MATERIAL SCIENCE

Superconducting resonant cavities design and material development for quantum computing and quantum sensing applications

STUDENT:

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DiSC

ACKNOWLEDGMENTS

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ACKNOWLEDGMENTS

The design and fabrication of the superconductive resonant cavities presented has been carried out at:

INFN Legnaro National Laboratories

The characterization of the devices for quantum computing applications has been carried out at:

INFN Frascati National Laboratories with my participation

The characterization of the devices for axion search has been carried with the collaboration of:

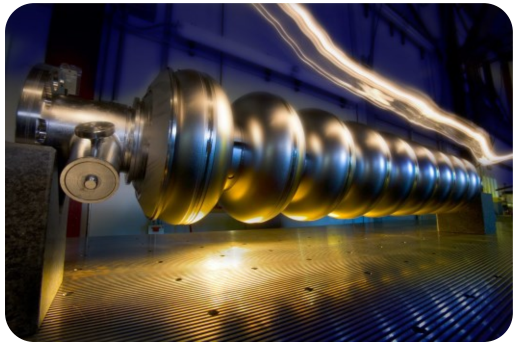
INFN – Frascati National Laboratories,

INFN Salerno,

University of Paris – Saclay,

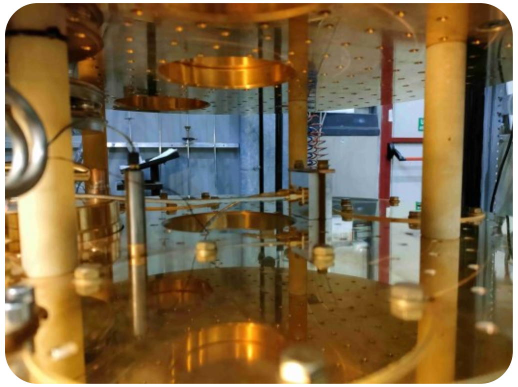
Fermilab (USA)

Superconducting Resonant Cavities



Most common application is particle accelerators

Important parameters:
Cavity Quality factor (Q_0)
Accelerating field
Meissner regime
2 K or 4.2 K operation temperature



Quantum computing and sensing

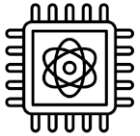
Important parameters:
Both Meissner and Shubnikov regime
mK operation regime
Cavity Quality factor (Q_0)

$$Q_0 = \frac{G}{R_s}$$

G — Depends on shape and frequency

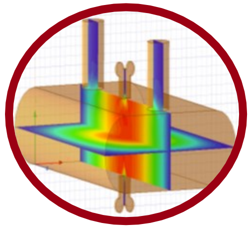
R_s — Depends on material/surface treatments

OUTLINE



Quantum computing

Aluminum cavities for 3D transmon architecture



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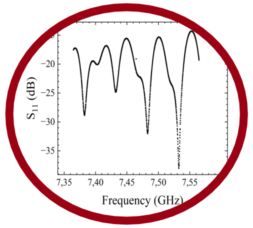
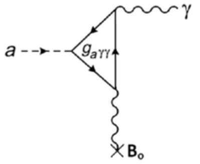


Characterization of the Cavity + Qubit

Axion search



NbTi thin film on Cu cavities as haloscopes

Material selection & Characterization

Fabrication

Characterization at 4 K

OUTLINE

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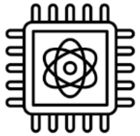

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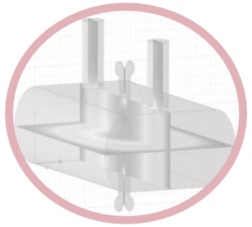

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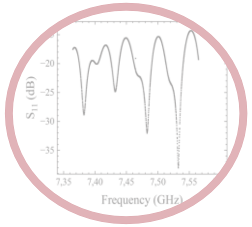

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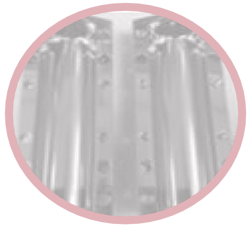
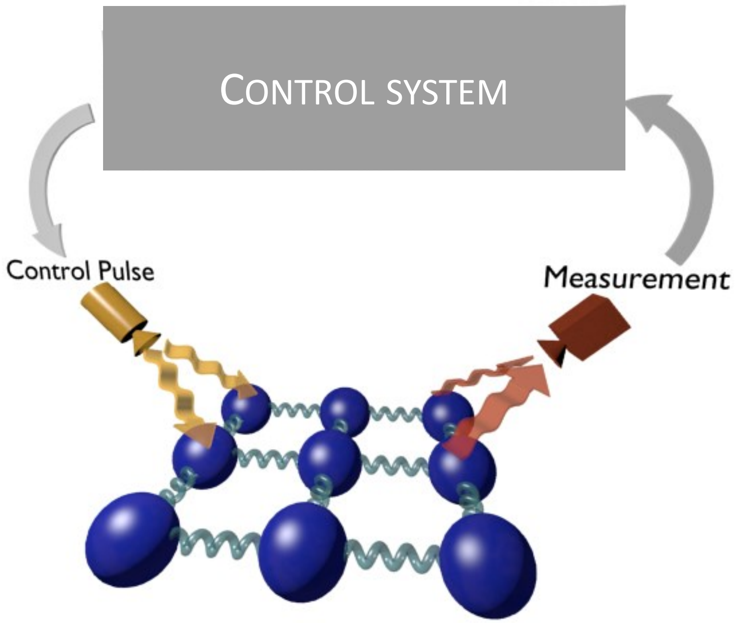


Fabrication

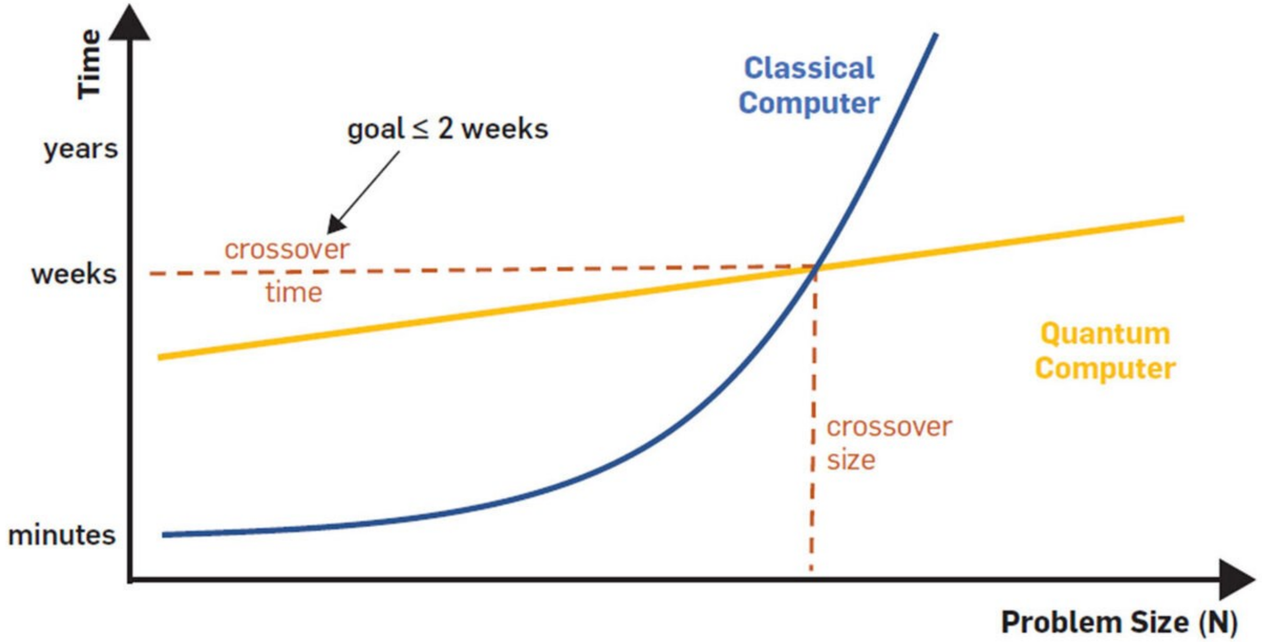
Characterization at 4 K

Why go quantum?

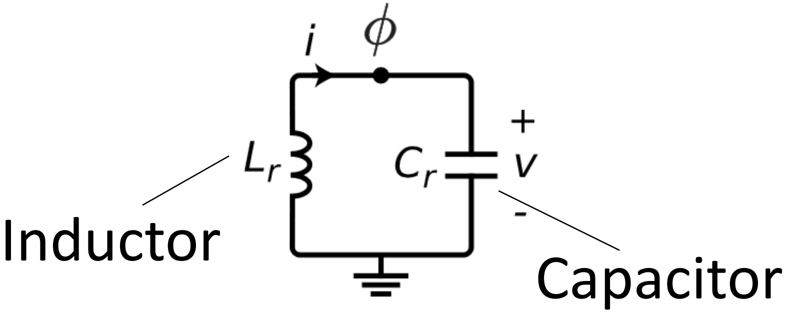
Analogue simulations

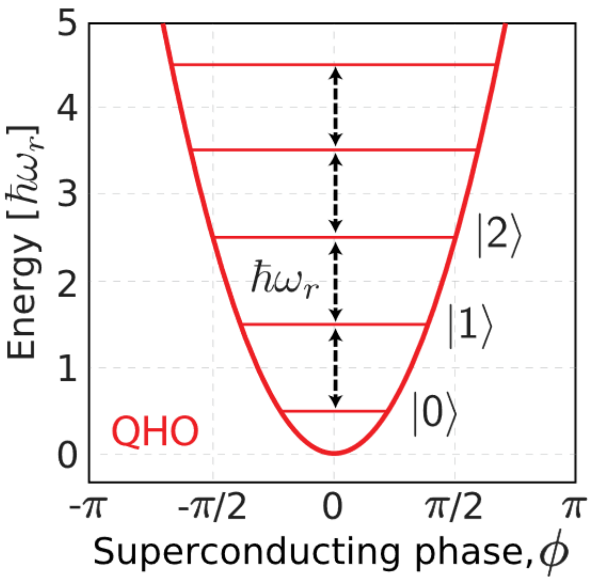


Algorithms implementation



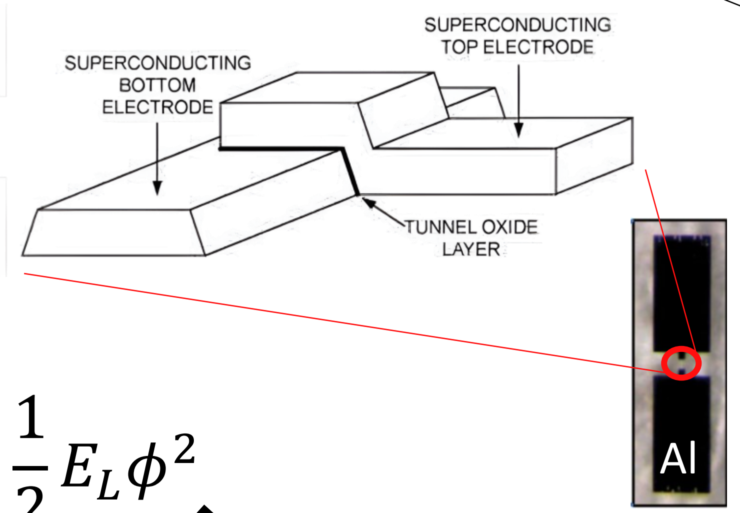
Harmonic resonator





$$H = 4E_C n^2 + \frac{1}{2} E_L \phi^2$$

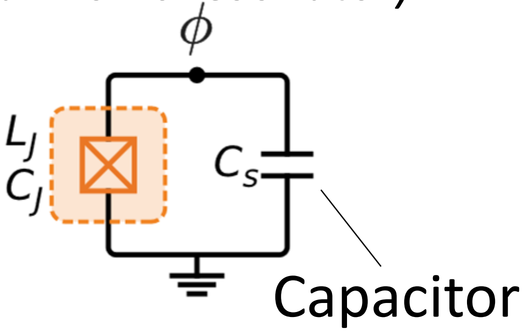
Josephson junction

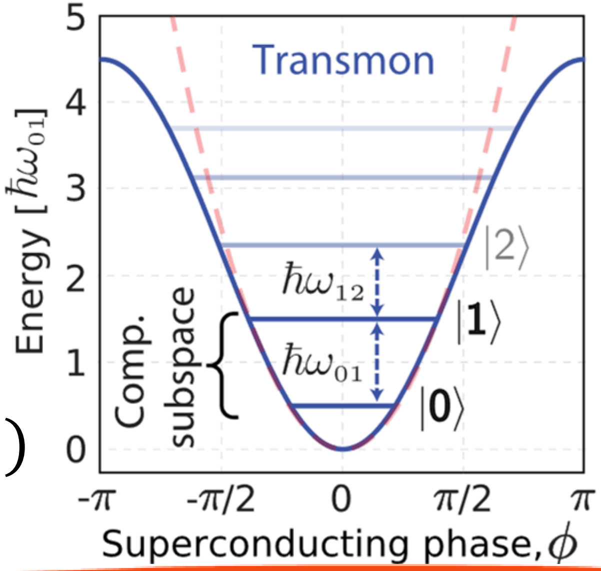


$$H = 4E_C n^2 - E_j \cos(\phi)$$

Transmon qubit

(Anharmonic resonator)

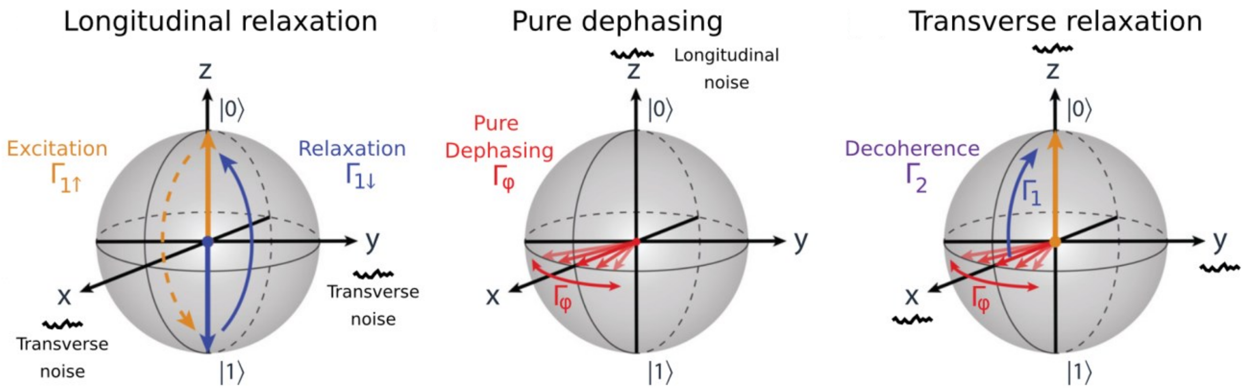




P. Krantz, et al., *Applied Physics Reviews*, vol. 6, fasc. 2, giu. 2019

QUANTUM COMPUTING

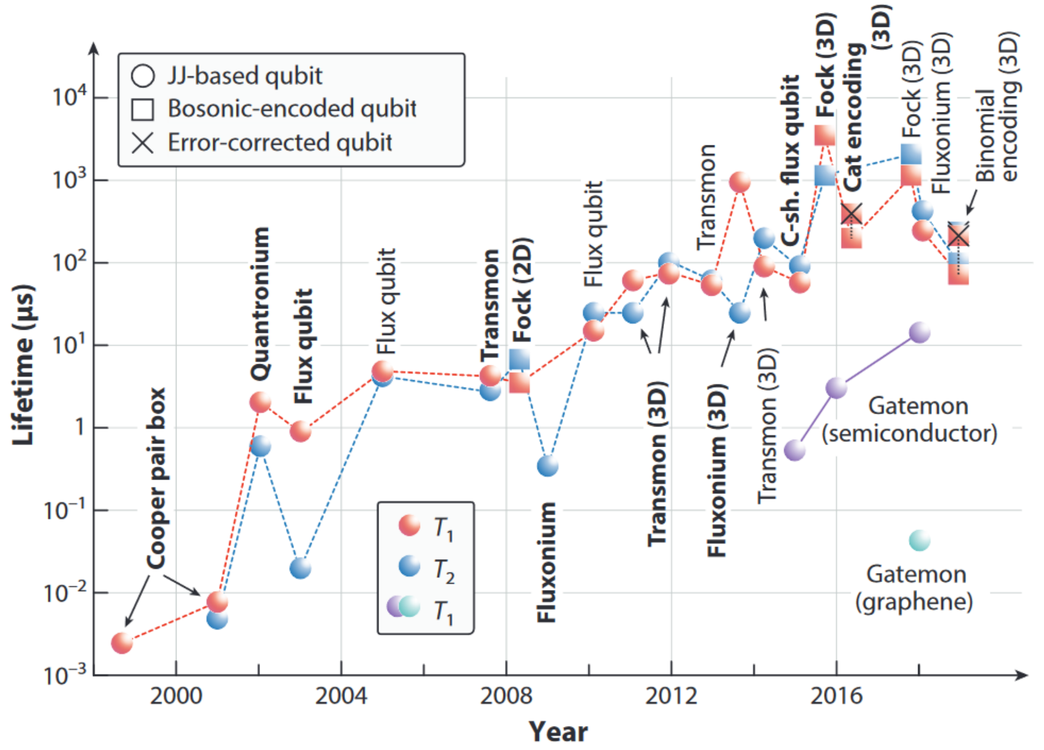
Decoherence



$$\Gamma_1 = \frac{1}{T_1} \qquad \Gamma_\varphi \qquad \Gamma_2 = \Gamma_1 + \Gamma_\varphi = \frac{1}{T_2}$$

P. Krantz, et al., *Applied Physics Reviews*, vol. 6, fasc. 2, giu. 2019

Qubit coherence time evolution



M. Kjaergaard *et al.*, *Annu. Rev. Condens. Matter Phys.*, vol. 11, fasc. 1, mar. 2020

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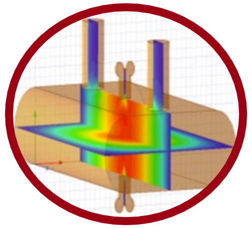

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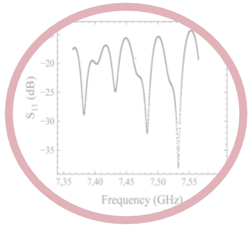

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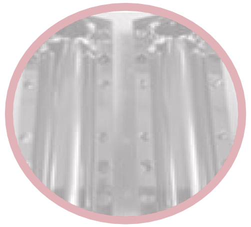

Fabrication

Characterization at 4 K

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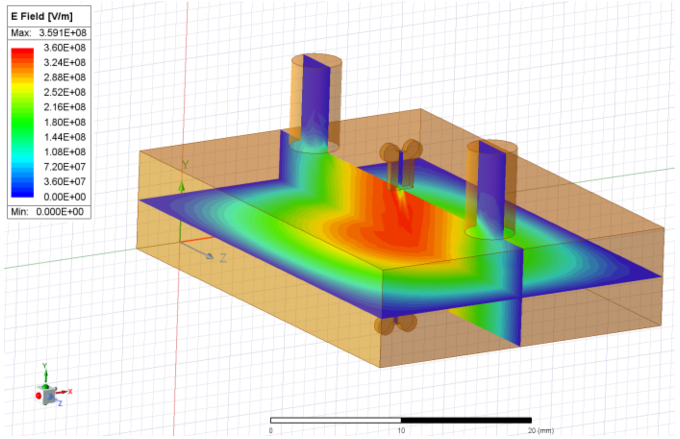
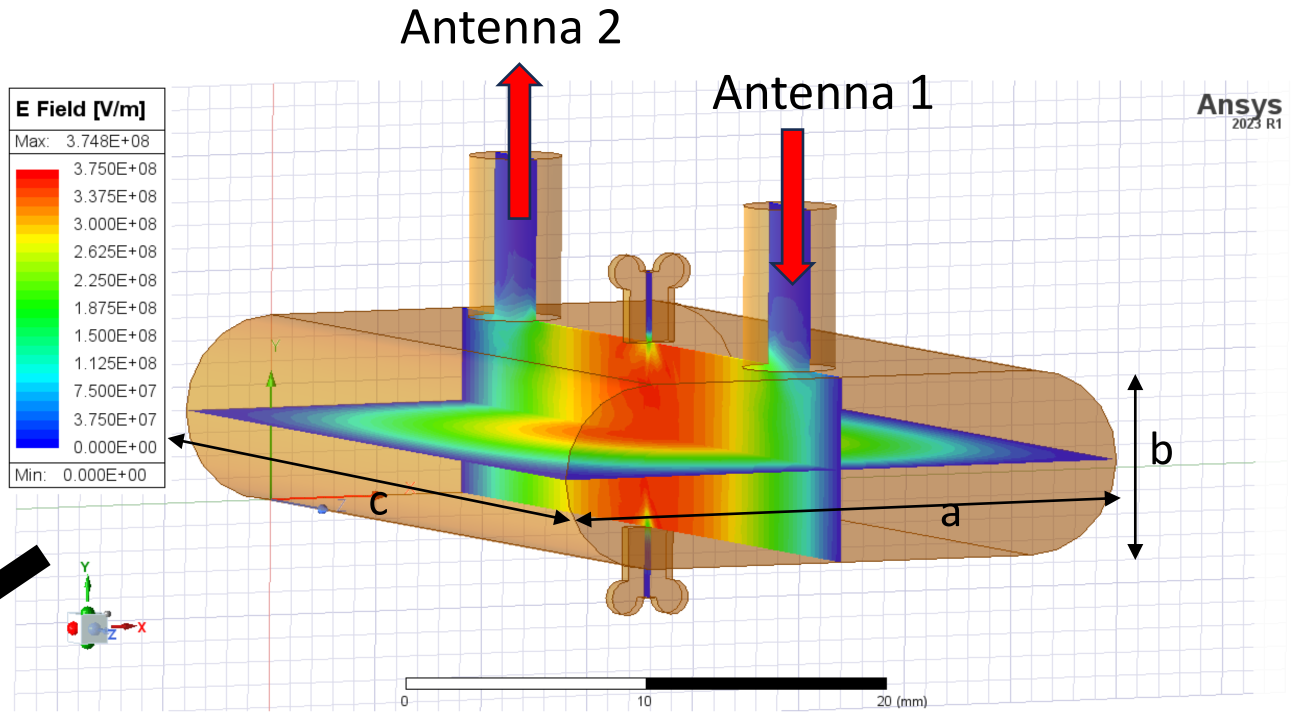
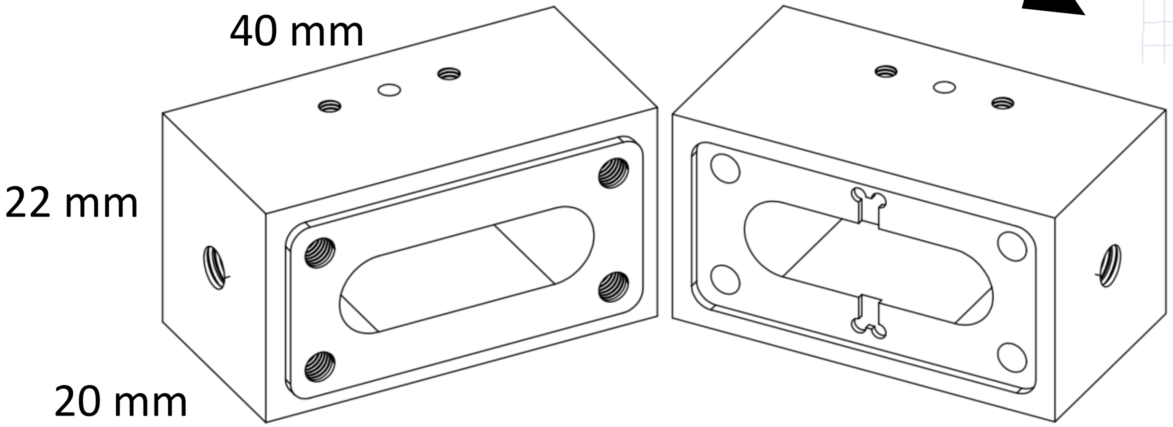
Shape optimization







Width	$a = 26\ mm$
Height	$b = 8\ mm$
Length	$c = 36\ mm$
Resonant frequency	$\omega_0 = 7.46\ GHz$

$\sim 1\ GHz$ detuning from qubit at $\simeq 6.50\ GHz$

Surface resistance estimation

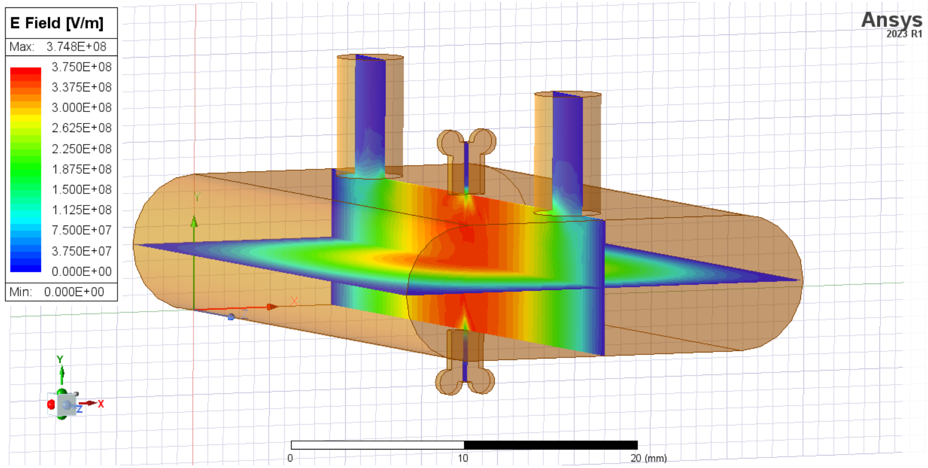
$$G = \frac{\omega_0 \mu_0 \int_V |\bar{H}|^2 dv}{\int_S |H|^2 ds} = 157.30\ \Omega$$

⬇

Using experimental value of Q_0
for the aluminum alloy cavity

⬇

$$R_s = \frac{G}{Q_0} = (730 \pm 40)\ \mu\Omega$$ ➡ $$R_s = R_{BCS} + R_{res}$$



Only experimentally measurable

Cavity Simulation

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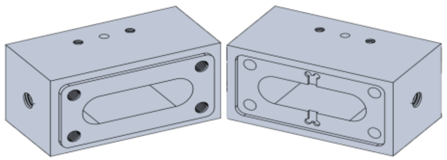
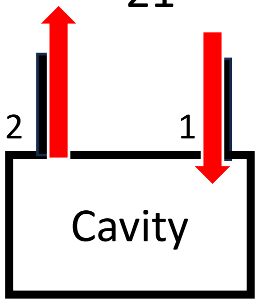
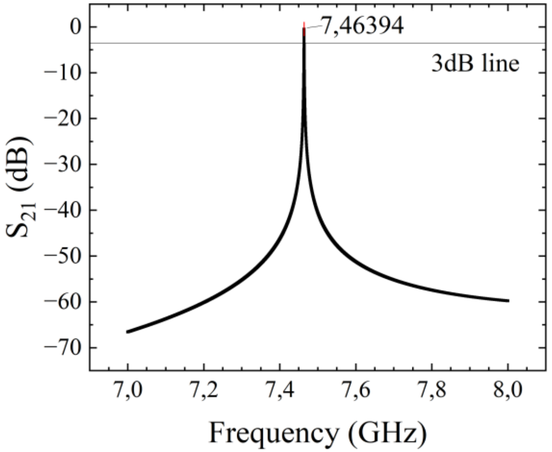
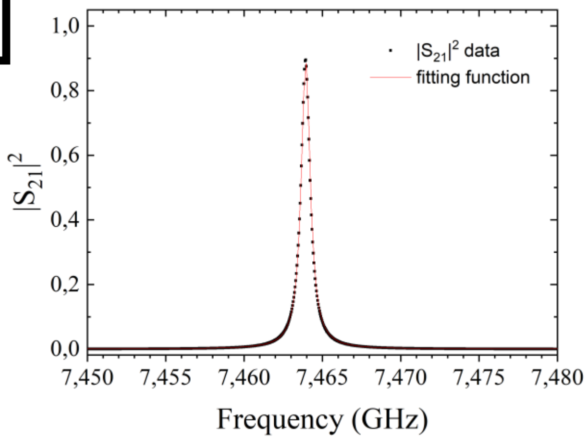
Scattering parameters simulations @7.46 GHz



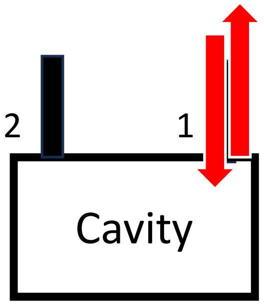
Transmitted power S_{21}

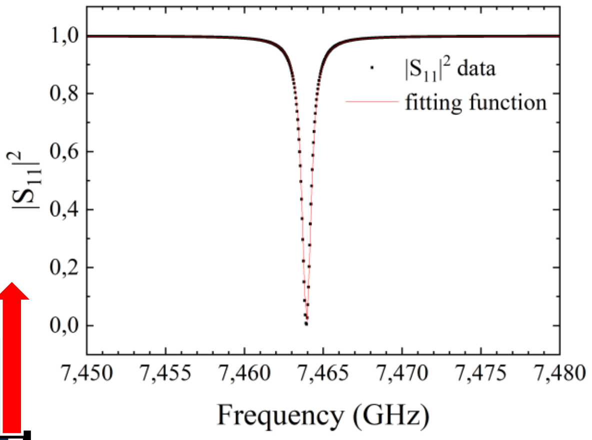


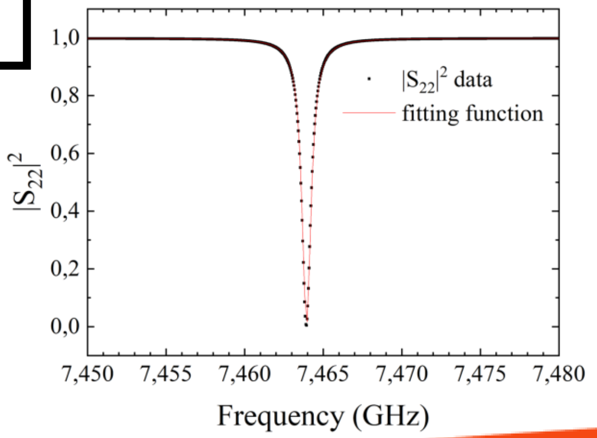




Reflected power S_{11}







Lorentzian fitting function

$$|S_{11}|^2 = A \cdot \left(1 - \frac{k_1(k_2 + k_{int})}{k_{tot}^2 + 4(x - \omega_0)^2}\right)$$

$$|S_{22}|^2 = B \cdot \left(1 - \frac{k_2(k_1 + k_{int})}{k_{tot}^2 + 4(x - \omega_0)^2}\right)$$

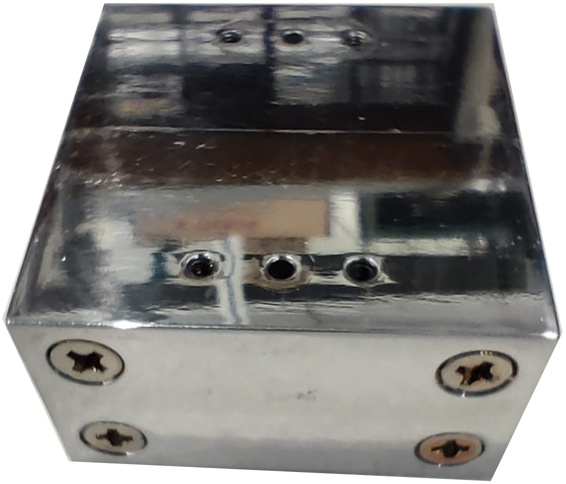
$$|S_{21}|^2 = C \cdot \left(\frac{4k_1k_2}{k_{tot}^2 + 4(x - \omega_0)^2}\right)$$

Cavity Simulation

Source	Q_0
Eigenmode	$(\mathbf{2.16 \pm 1.2}) \cdot \mathbf{10^5}$
Modal Network	$(1.7 \pm 0.2) \cdot 10^5$
Experimental	$(\mathbf{2.17 \pm 1.1}) \cdot \mathbf{10^5}$

Simulation can reproduce experimental values

Lower bound for next cavity performance

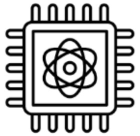


Alloy cavity and qubit fabricated at TII (Arab Emirates)

Al alloy

↓

Move to Al 5N (99.999% purity)



Quantum computing

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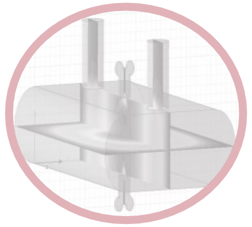

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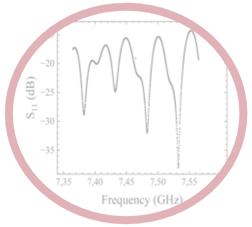

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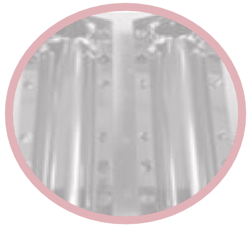
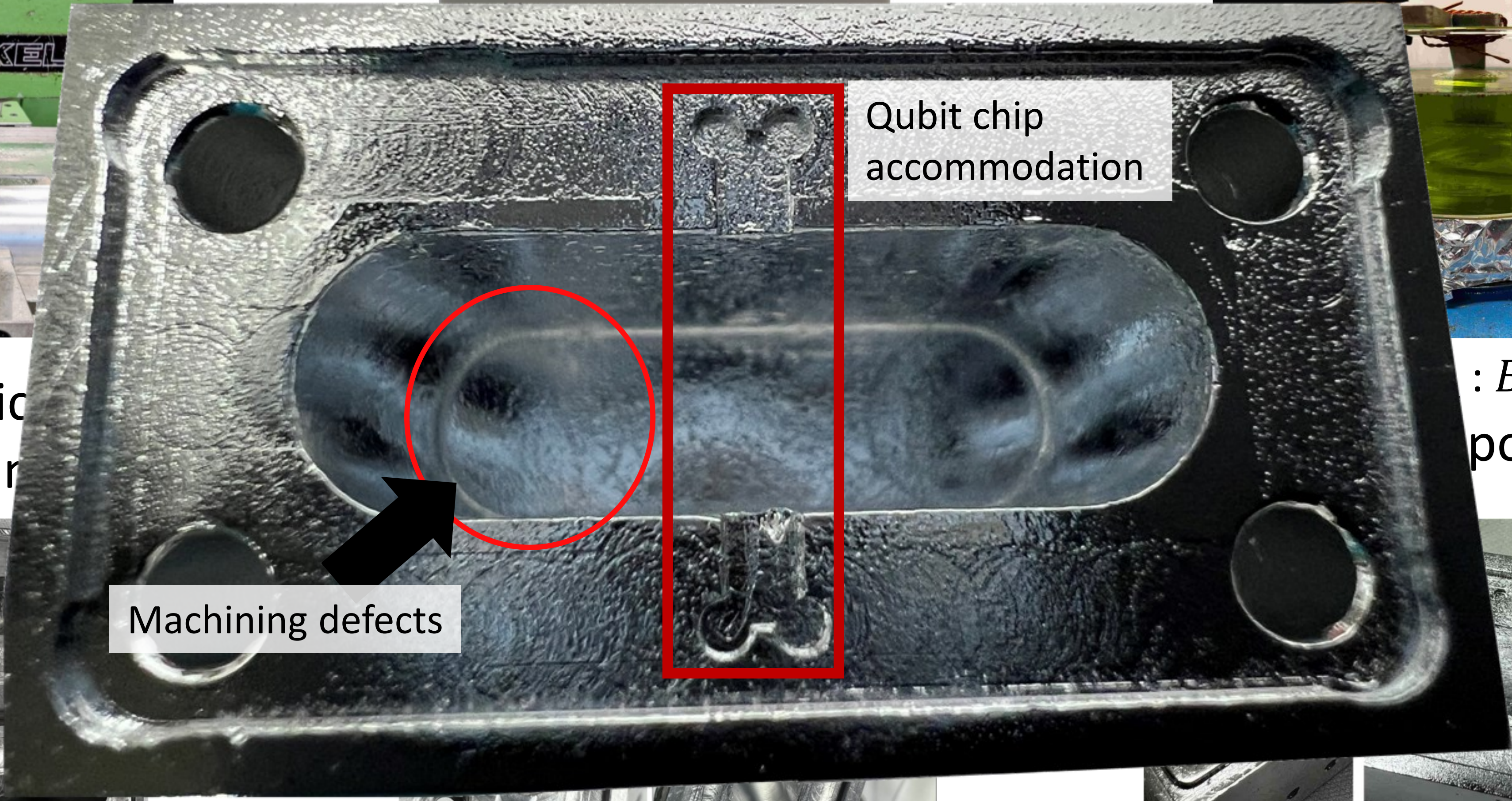


Fabrication

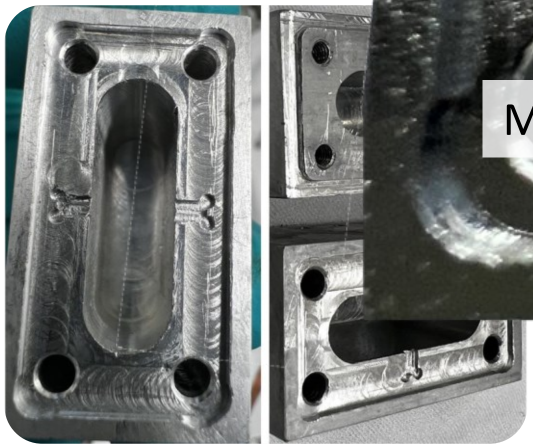
Characterization at 4 K

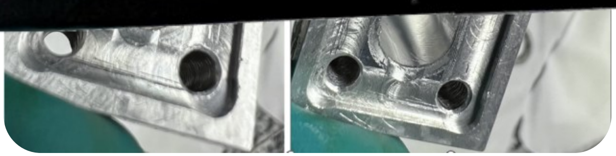
Cavity Fabrication

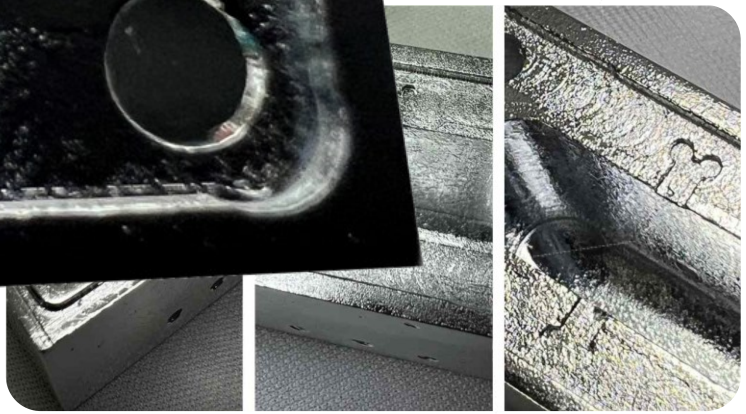


- Mechanic
  Machinin

: $BuAc$
polishing







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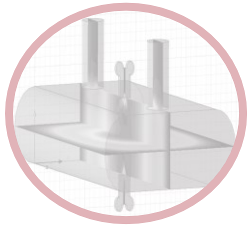

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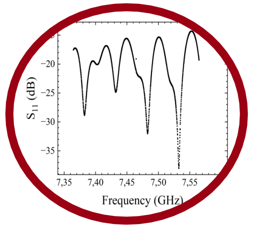

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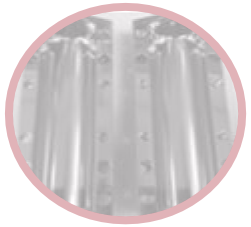

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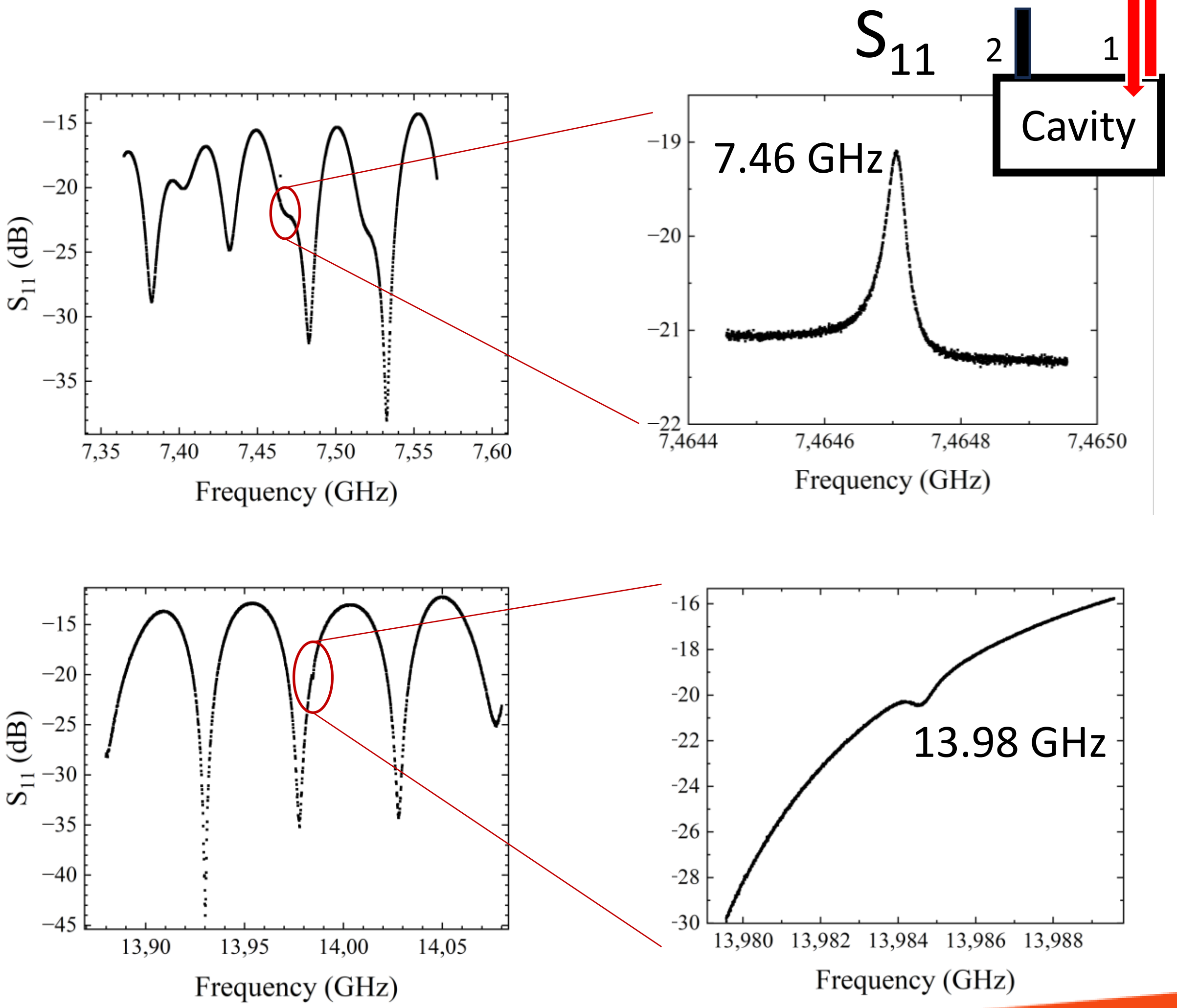
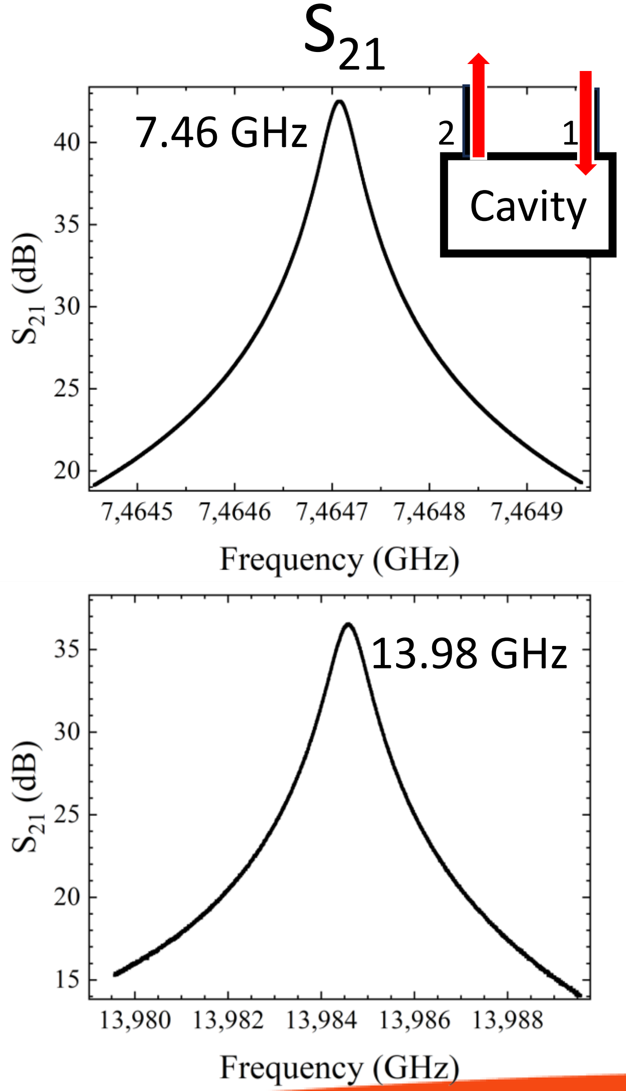
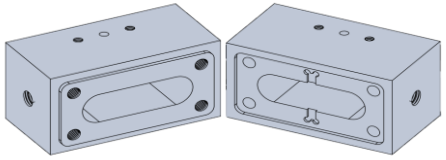
Scattering parameters results







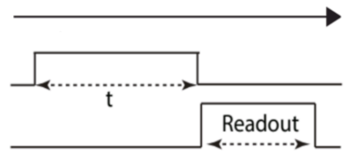
All measures at 30 mK

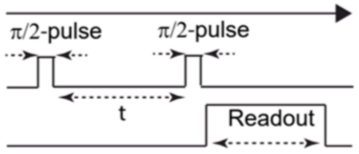
$\boldsymbol{Q_L = (2.2 \pm 1.0) \cdot 10^5}$

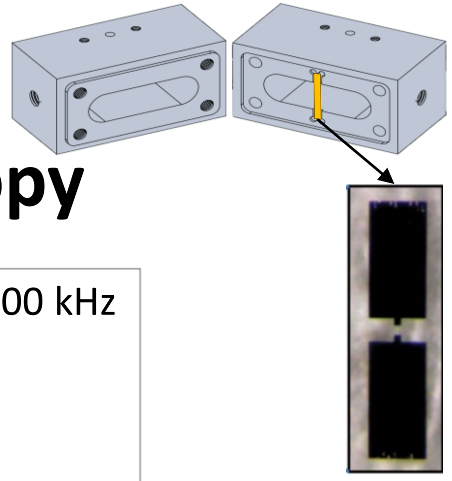
Already better than Al alloy cavity!

$Q_L = (1.78 \pm 0.9) \cdot 10^4$

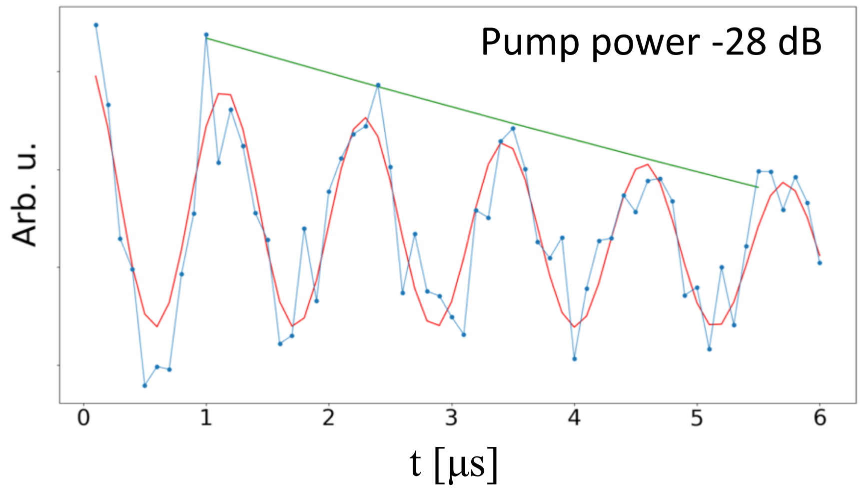
QUBIT CHARACTERIZATION





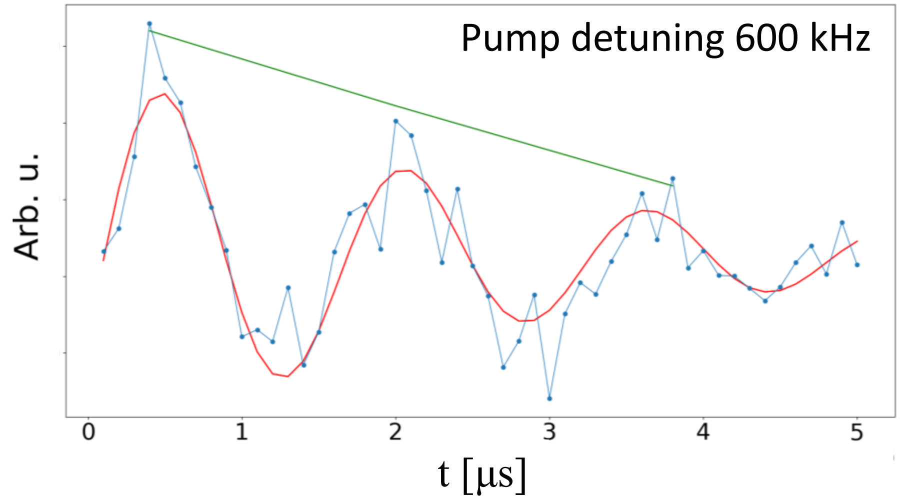


Rabi spectroscopy



$$T_1 = (6.1 \pm 0.3)\mu s$$

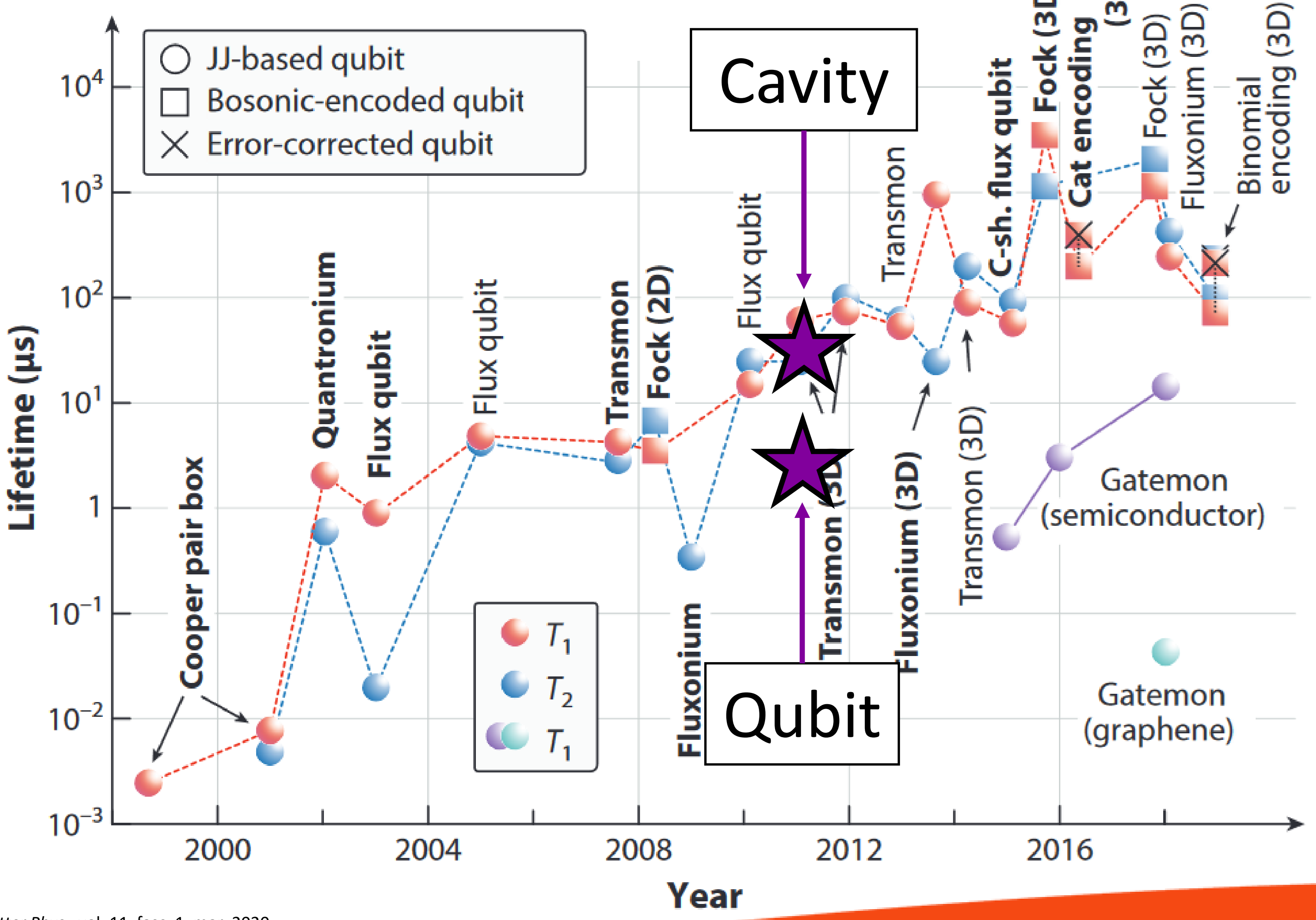
Ramsey spectroscopy



$$T_2 = (2.3 \pm 0.3)\mu s$$

Cavity characteristic time $\tau = \frac{Q_0}{\omega} \simeq 29\ \mu s$

Qubit Characterization



M. Kjaergaard *et al.*, *Annu. Rev. Condens. Matter Phys.*, vol. 11, fasc. 1, mar. 2020

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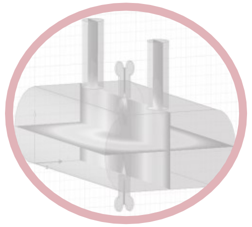

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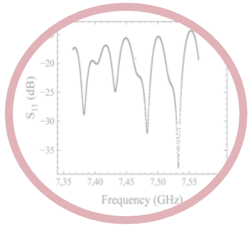

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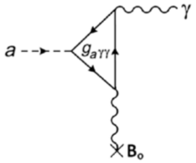

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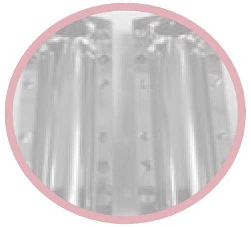

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AXIONS

Axions are a promising dark matter candidate

Axion predicted mass can vary of many orders of magnitude: our range of interest is $10^{-6}\ eV$ to $10^{-3}\ eV$

GHz frequency range

$$P_{a\gamma\rightarrow\gamma} = k \cdot B^2 \omega_0 V \frac{Q_a Q_c}{Q_a + Q_c}$$

Conversion Power

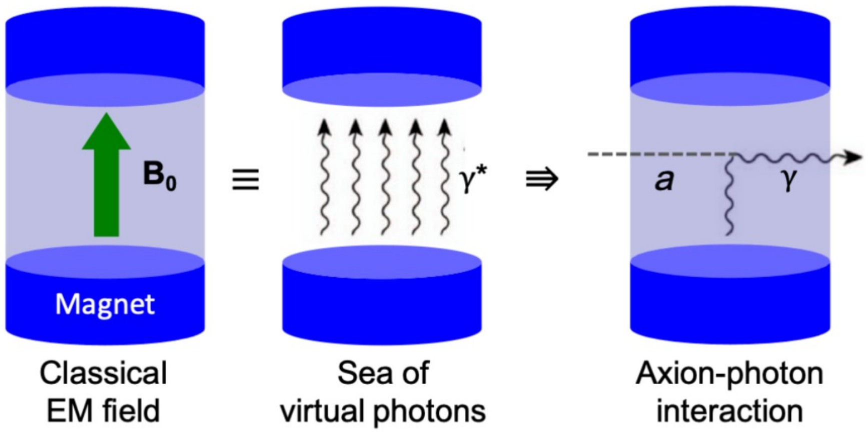
Magnetic Field

Volume

Cavity Quality Factor

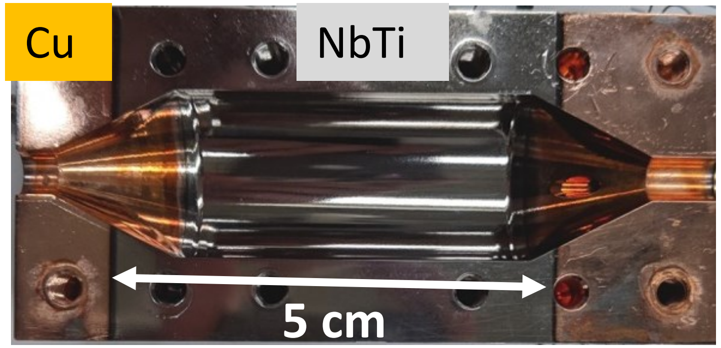
Axion Quality Factor (10^6)

How to detect them?



Y. K. Semertzidis e S. Youn, *Science Advances*, vol. 8, fasc. 8, feb. 2022

Axion → Photon



$\omega = 9GHz$

D. Kim *et al.* JCAP03(2020)066

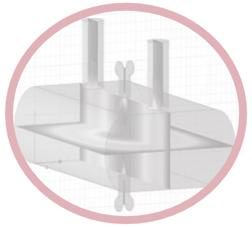
OUTLINE

INFN

UNIVERSITÀ DEGLI STUDI DI PADOVA

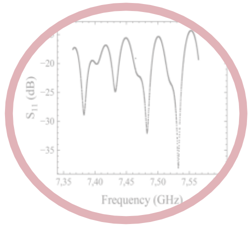
Quantum computing

Aluminum cavities for 3D transmon architecture



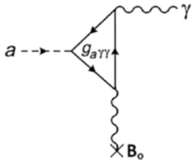
Design of a 7.46 GHz cavity

Fabrication using pure Al vs Al alloy



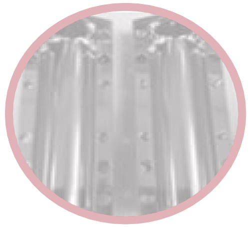
Characterization of the Cavity + Qubit

Axion search



NbTi thin film on Cu cavities as haloscopes

Material selection & Characterization

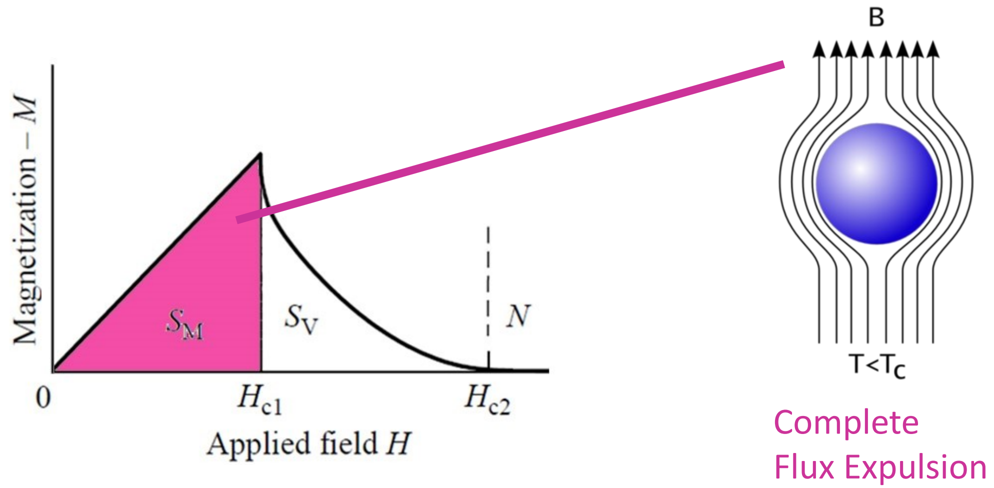


Fabrication

Characterization at 4 K

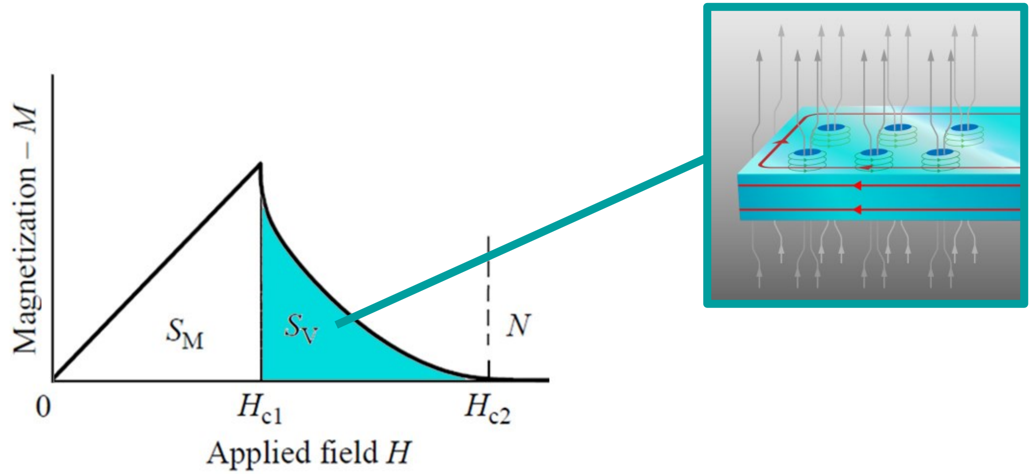
MATERIAL CHOICE

Accelerators Cavities – RF



Meissner state – no magnetic field

Magnets – DC



Mixed state – flux vortex formation

Vortexes are pinned by defects
Flux PINNING

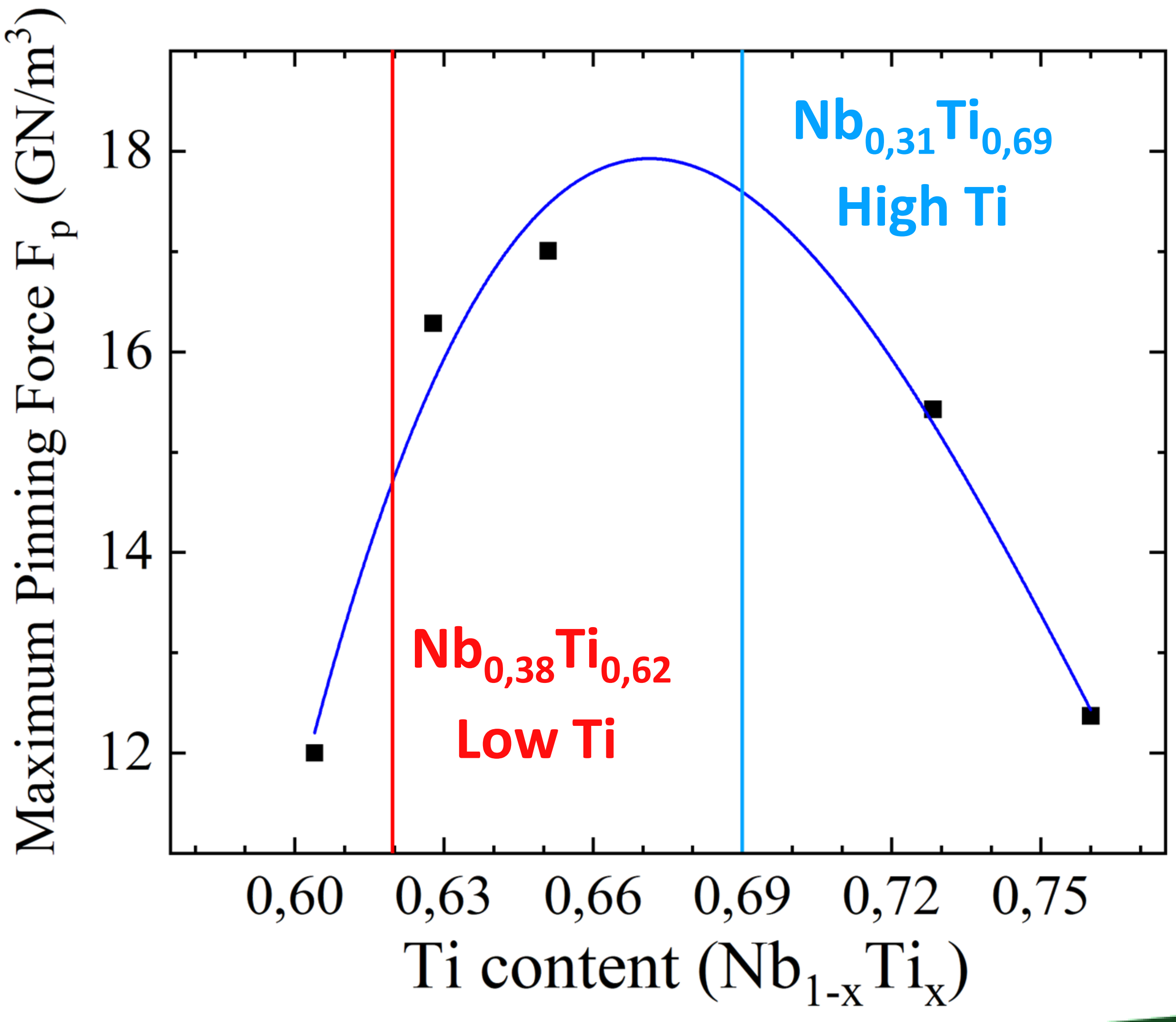
RF + static magnetic field
is a quite new regime for superconductive devices

Material Choice

Material	Tc	Hc2	Note
Nb	9.2 K	**0.4 T**	**Not suitable at high Magnetic field**
NbTi	~ 9.5 K	**~ 14 T**	**Simple preparation**
MgB_2	~ 32 K	**~ 15 T**	**Preparation is a challenge**
Nb_3Sn	~ 18.3 K	**~ 30 T**	**Preparation is a challenge**
REBCO	~ 93 K	**~ 100 T**	**Available in tapes**

NbTi was the obvious choice (although not the best performing) to build and test a SC haloscope **for the first time**

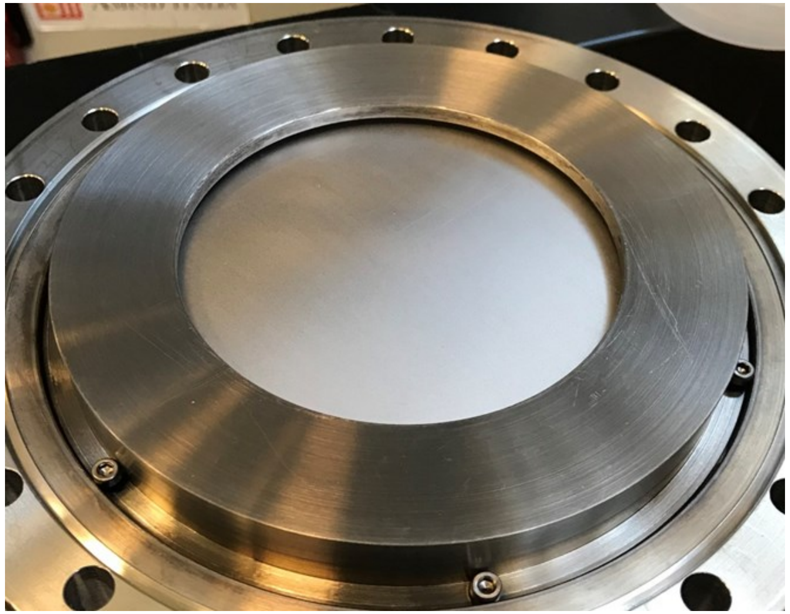
Material Choice



J. C. McKinnell, P. J. Lee, and D. C. Larbalestier,
IEEE Transactions on Magnetics, vol. 25, no. 2, Mar. 1989

Higher Ti content gives higher pinning force $F_p \propto \frac{1}{dissipation}$ up to a maximum

Material Choice



$Nb_{0.38}Ti_{0.62}$
1 mm sheet

$Nb_{0.31}Ti_{0.69}$
5 mm bulk

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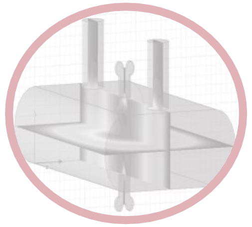
Quantum computing

Aluminum cavities for 3D transmon architecture



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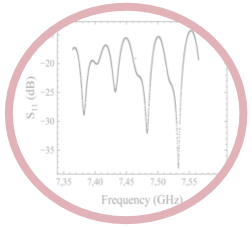

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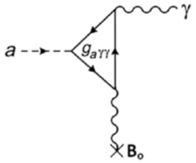

NbTi thin film on Cu cavities as haloscopes

Material selection & Characterization

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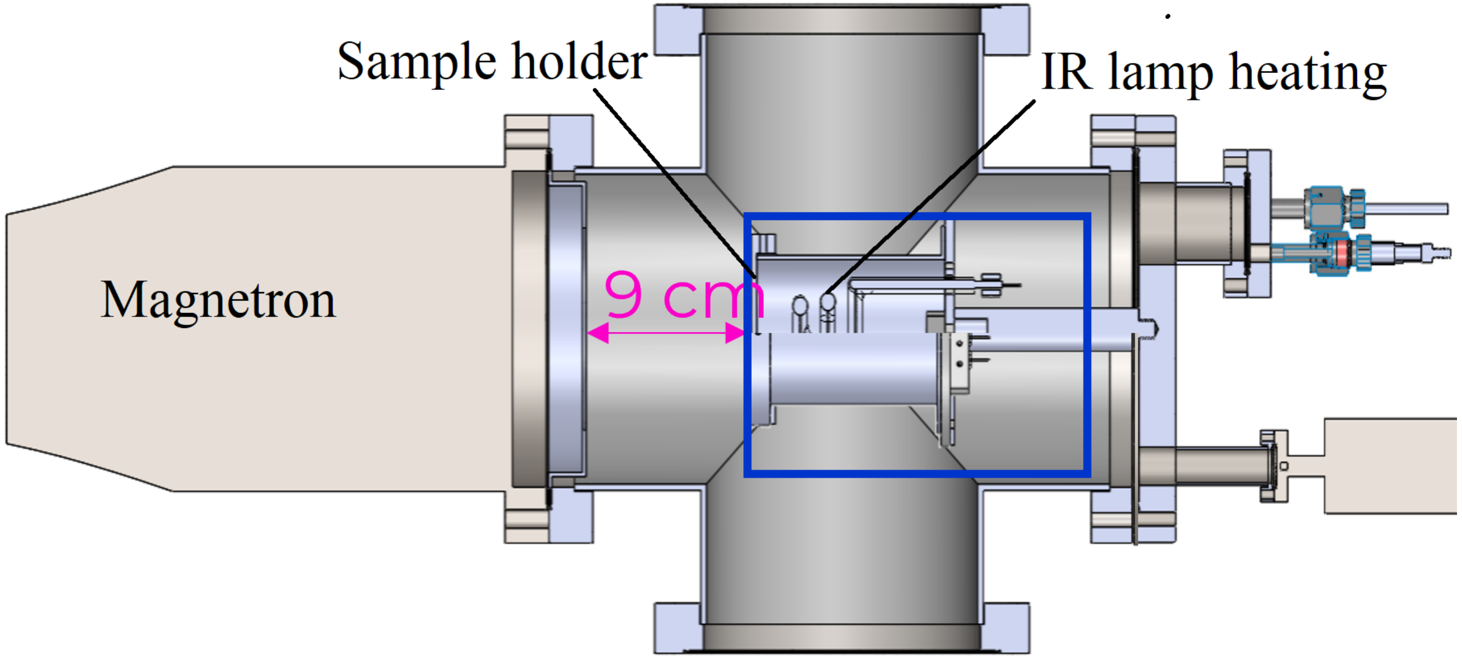
Characterization at 4 K

FABRICATION

DC Magnetron Sputtering

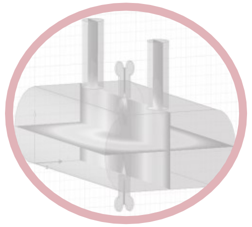


- Single NbTi target
- Ar pressure $6 \cdot 10^{-3}$ mbar
- T substrate 500 °C
- Film thickness 2.5 – 3.5 µm
- No bias voltage

OUTLINE

Quantum computing

Aluminum cavities for 3D transmon architecture



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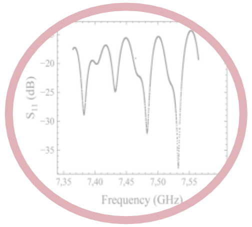

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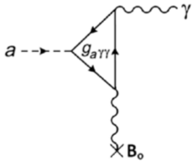

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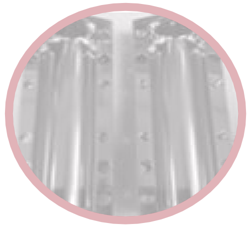

Fabrication

Characterization at 4 K

MATERIAL CHARACTERIZATION

INFN

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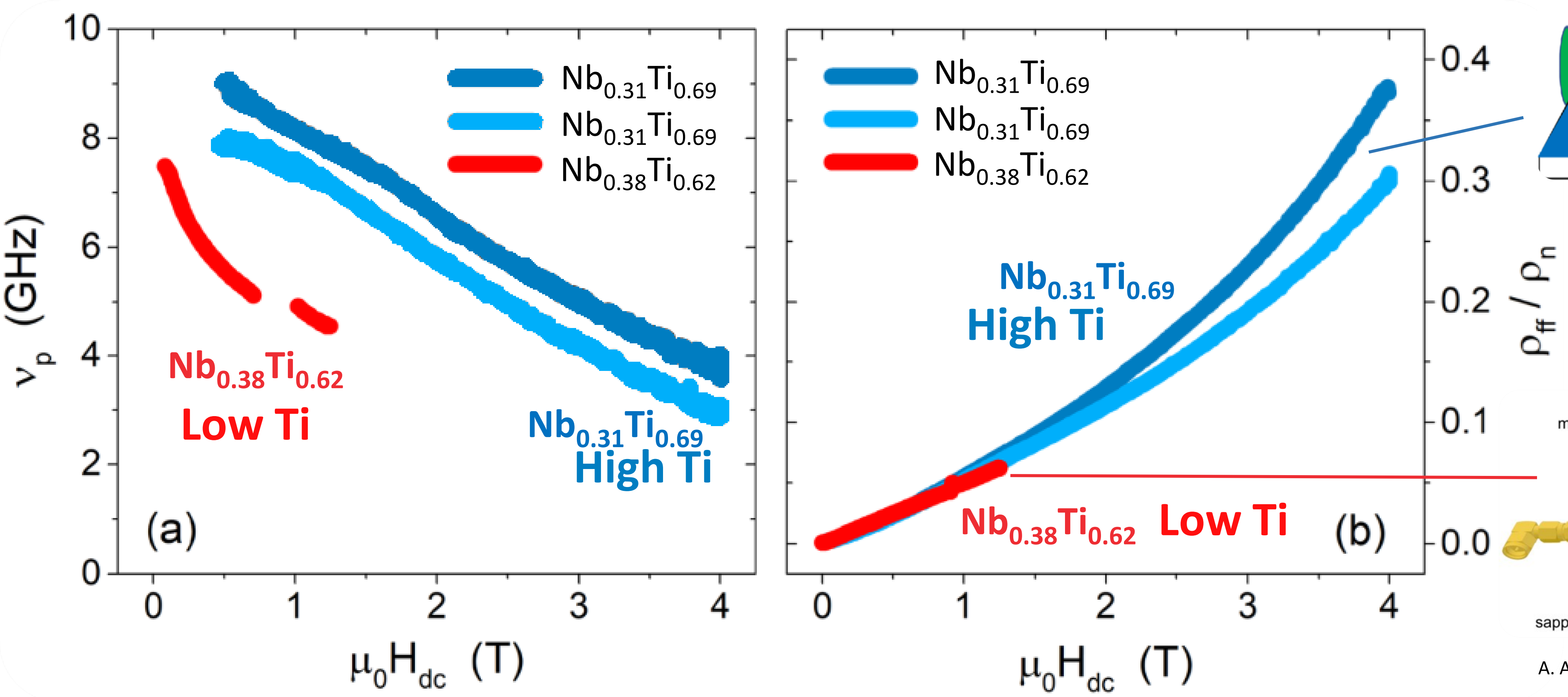
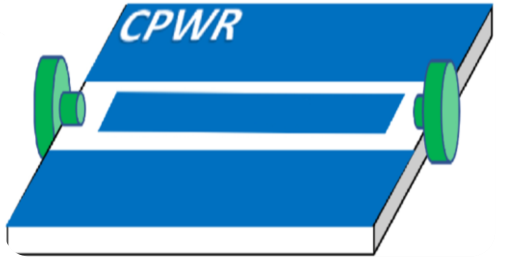
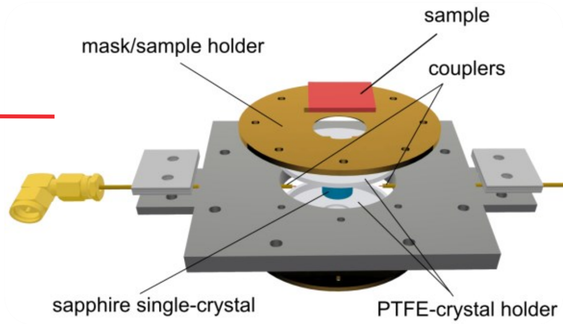




G. Ghigo *et al.*, *Materials*, 2022

Done at INFN Torino



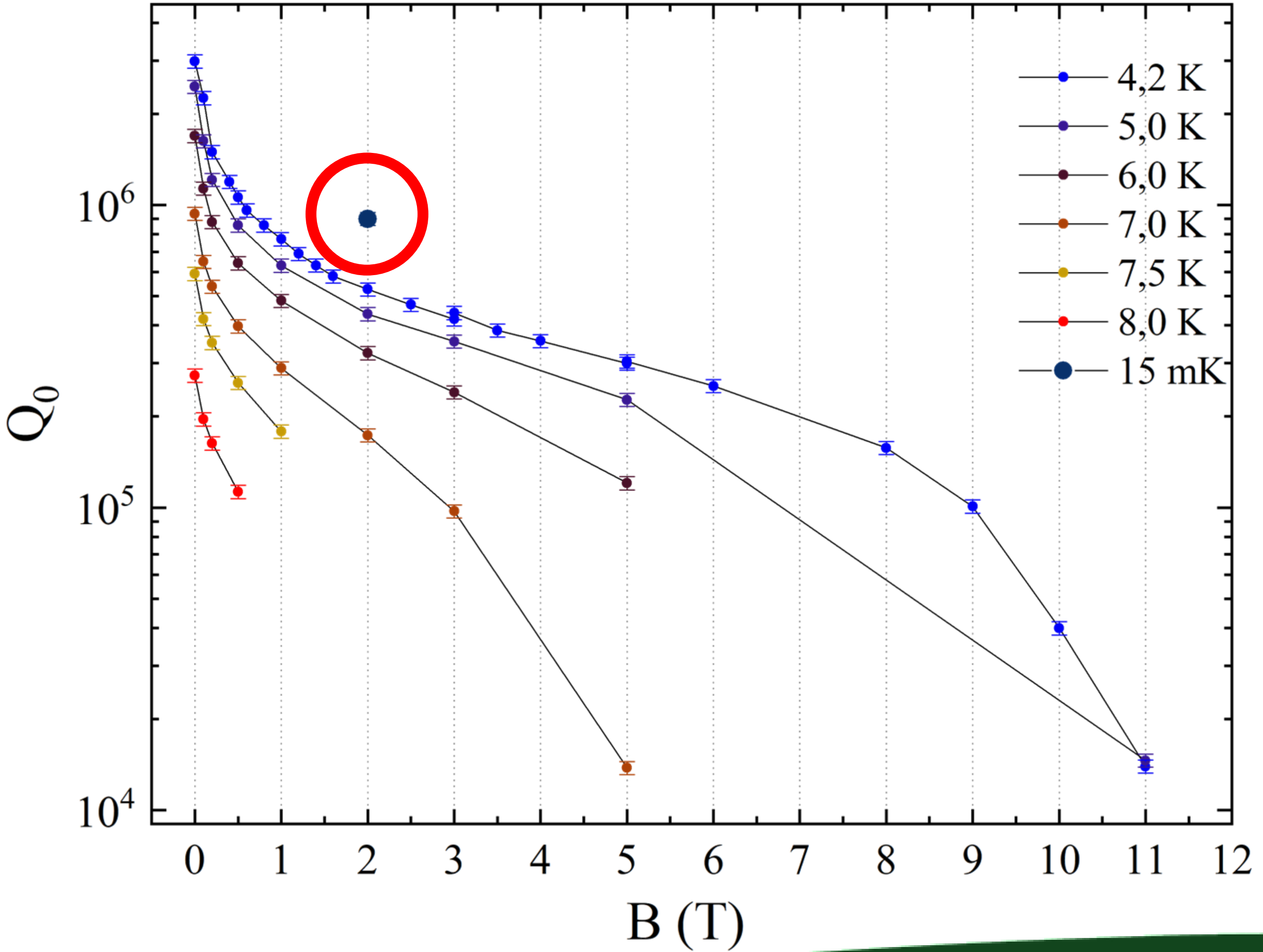
A. Alimenti *et al.*, *Sensors*, 2023

Done at Roma 3 university

$Nb_{0.31}Ti_{0.69}$ is better or similar at most

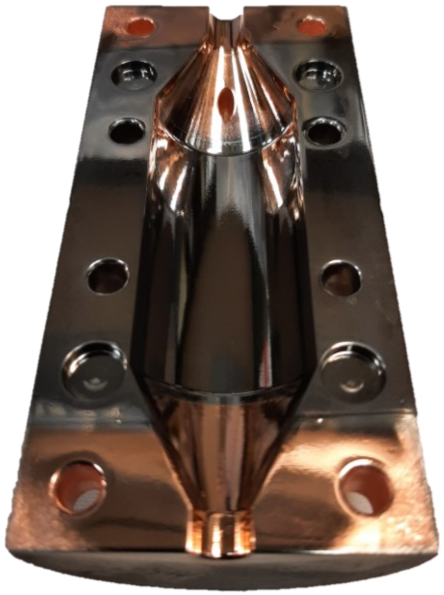
Cavity Characterization

7 GHz

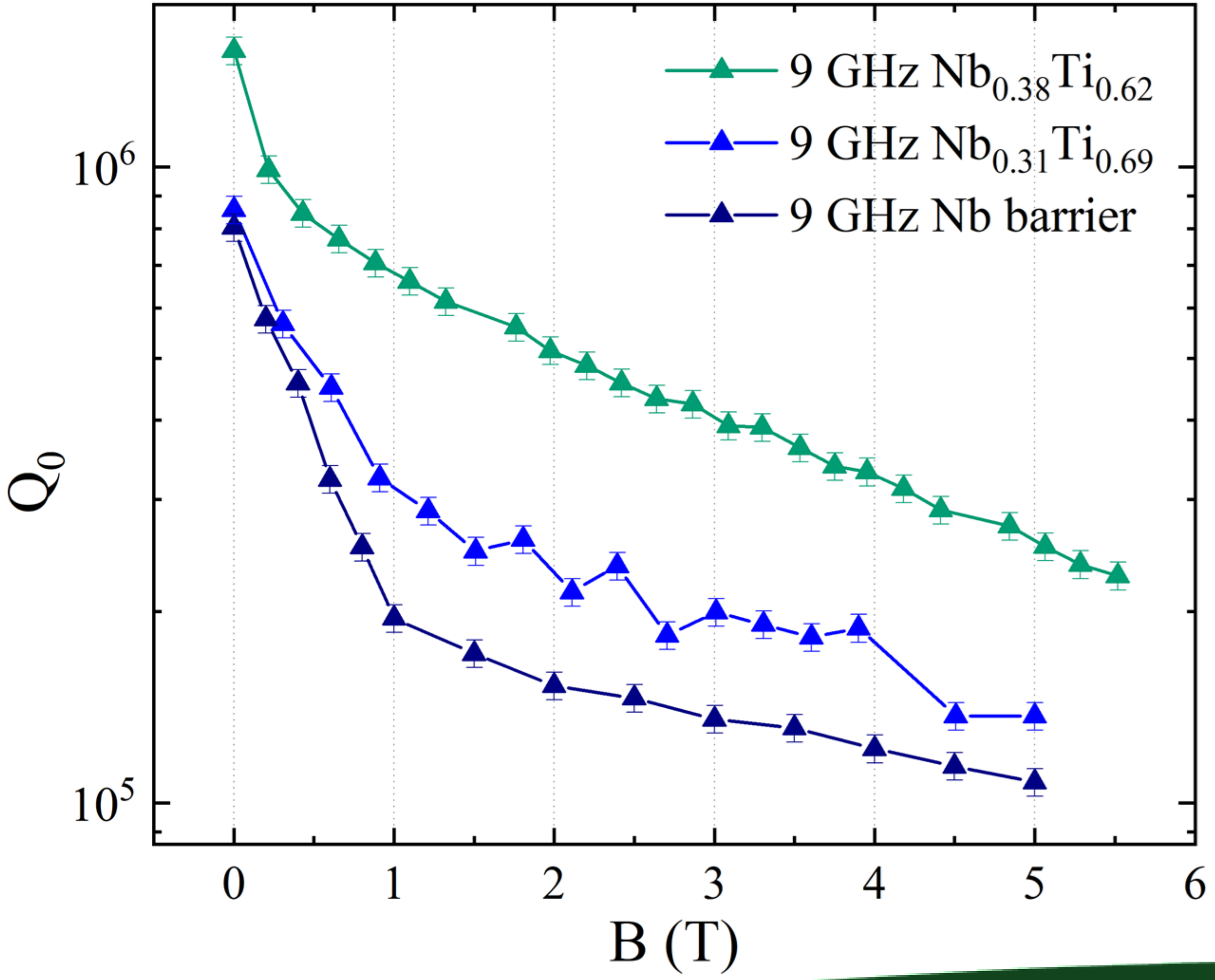


Cavity Characterization

All measures at 4 K



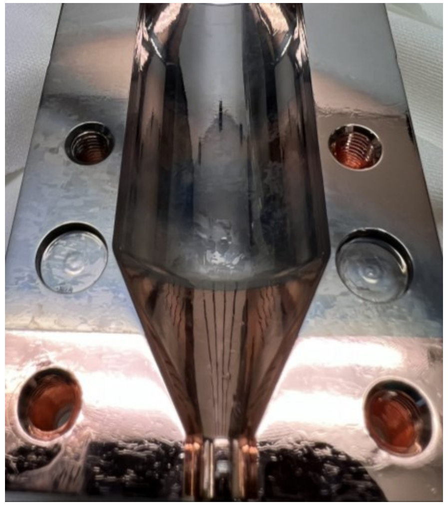
9 GHz



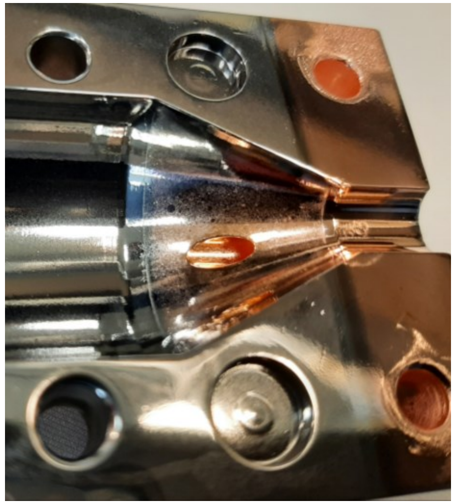
CAVITY CHARACTERIZATION

All measures at 4 K

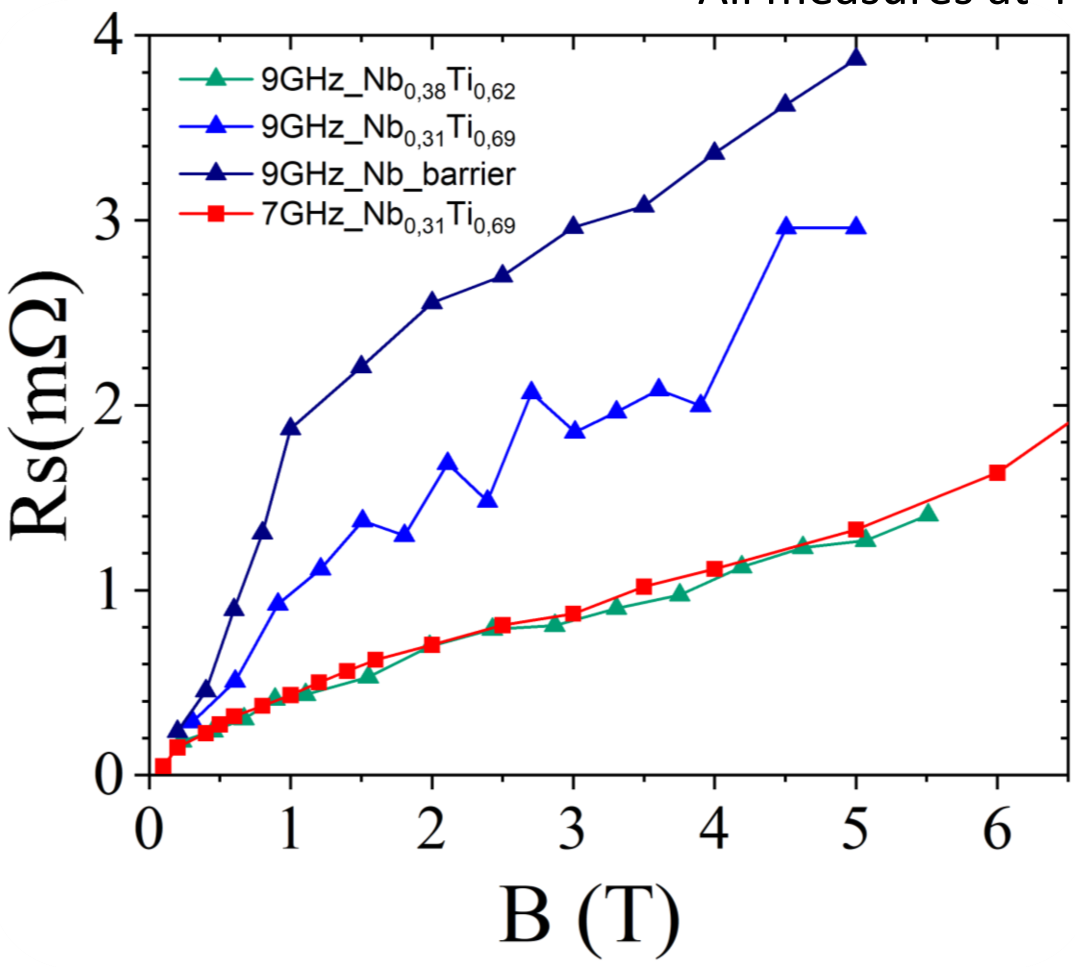
Defects on the cavity surface



Large grain boundaries



Pitting + NbTi coating on Cu cones



CONCLUSIONS

QUANTUM COMPUTING

- The pure Al cavity showed better performances than the Al alloy cavity even with non-optimized surface: $\boldsymbol{Q_L} = (\mathbf{2.2} \pm \mathbf{1.0}) \cdot \mathbf{10^5}$ comparable with state-of-the-art results
- The Qubit was successfully characterized but needs fabrication optimization

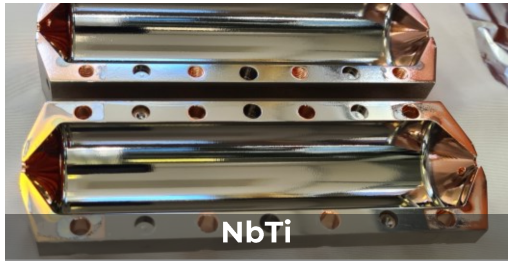
AXION SEARCH

- Four NbTi on Cu cavities have been fabricated and characterized and are ready to be used in axion search experiments. Good performance obtained compared to state-of-the-art at 2 T and 4K

These results have been presented at **SRF 2023** conference in Grand Rapids (June 2023, USA),
HTSHFF workshop 2023 (September 2023, Catania)
and at **Quantum technologies for fundamental physics workshop** (September 2023, Erice) by me

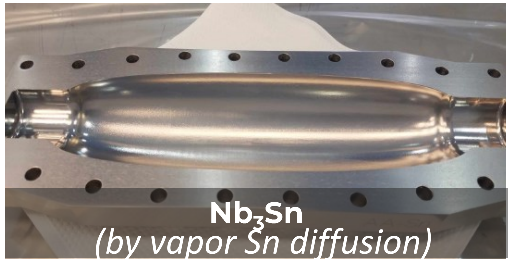
Giovanni Marconato, *Quantum Technologies for Fundamental Physics Workshop, Erice, Italy, Sept 2023*

NbTi
7 GHz
$\mathbf{9 \cdot 10^5}$



Sam Posen, *Quantum Technologies for Fundamental Physics Workshop, Erice, Italy, Sept 2023*

Nb_3Sn
3.9 GHz
$\mathbf{1 \cdot 10^6}$

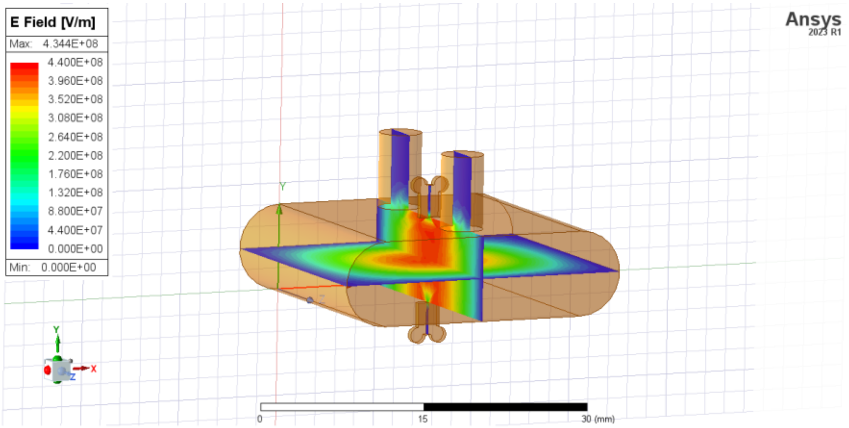


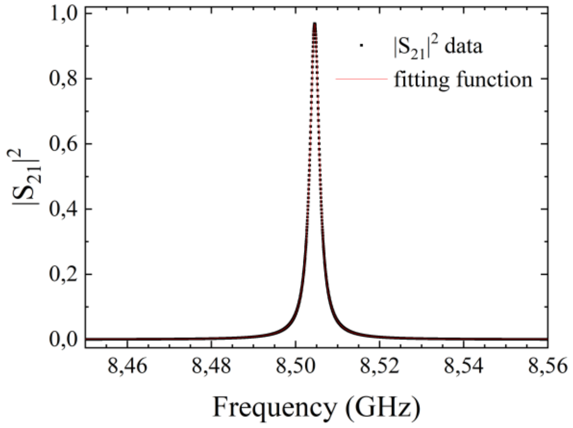
Woohyun Chung, *Quantum Technologies for Fundamental Physics Workshop, Erice, Italy, Sept 2023*

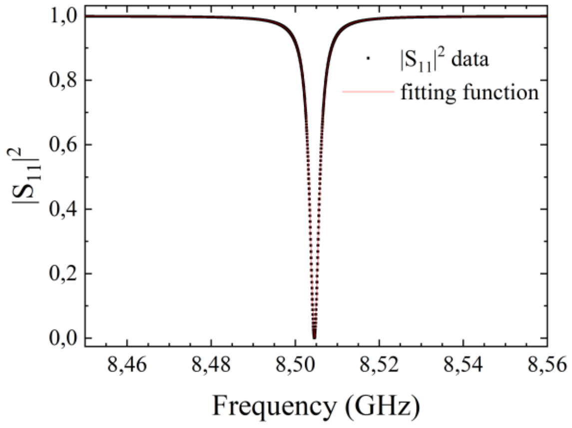
REBCO
5.4 Gz
$\mathbf{1.5 \cdot 10^7}$

Future Developments

- Fabrication and surface treatments improvements on the 7.46 GHz
- Scaling to 8.50 GHz for future developments:







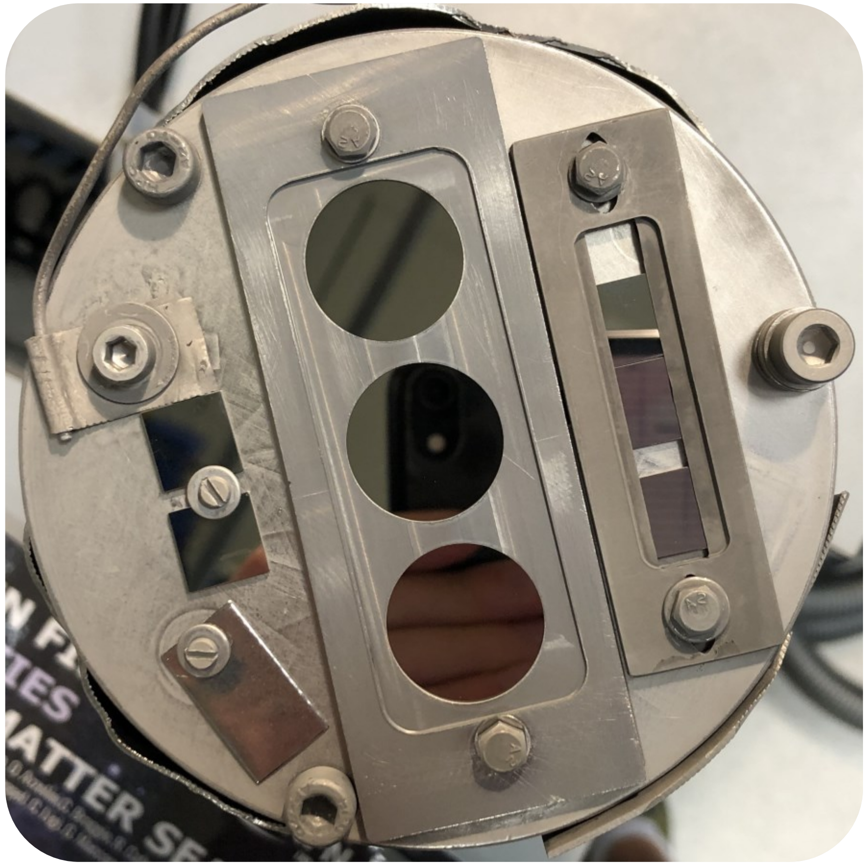
Width	$a = 20\ mm$
Height	$b = 8\ mm$
Length	$c = 23.8\ mm$
Resonant frequency	$\omega_0 = 8.51\ GHz$

$$G = 171.76\ \Omega$$

Source	Q_0
Eigenmode	232000 ± 13000
Modal Network	230000 ± 20000

FUTURE DEVELOPMENTS

- Nb_3Sn by DC Magnetron Sputtering for high Magnetic field applications



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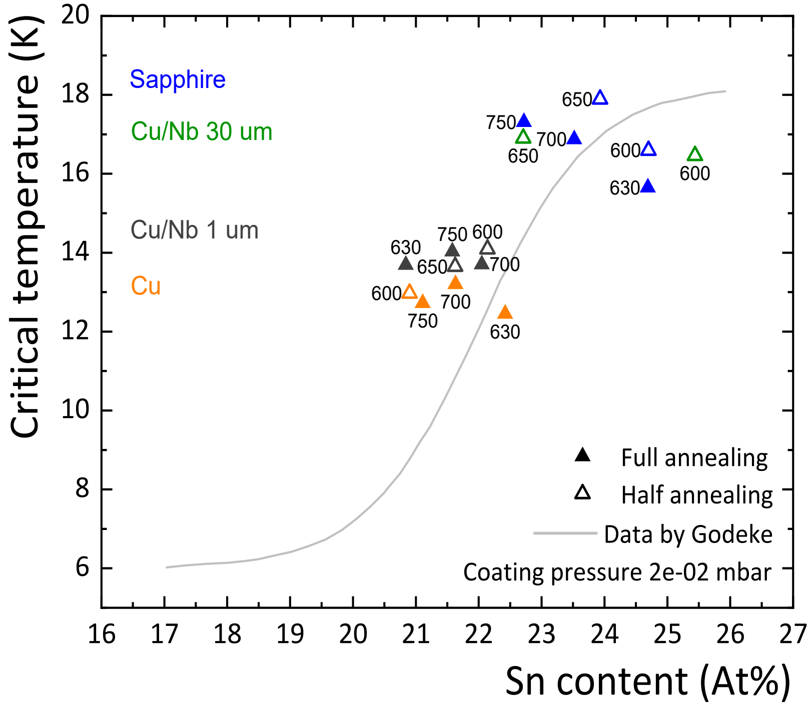

THANK YOU FOR YOUR ATTENTION

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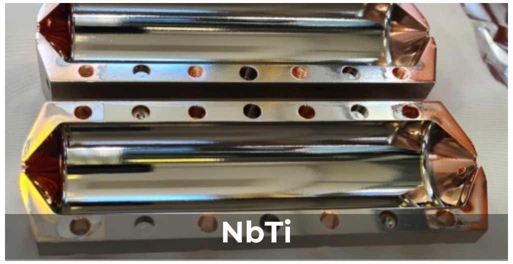
7 GHz

$\mathbf{9 \cdot 10^5}$



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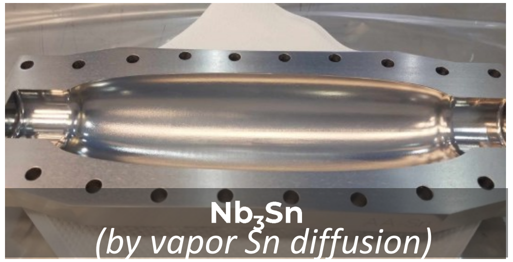

Woohyun Chung, *Quantum Technologies for Fundamental Physics Workshop, Erice, Italy, Sept 2023*

REBCO

5.4 Gz

$\mathbf{1.5 \cdot 10^7}$

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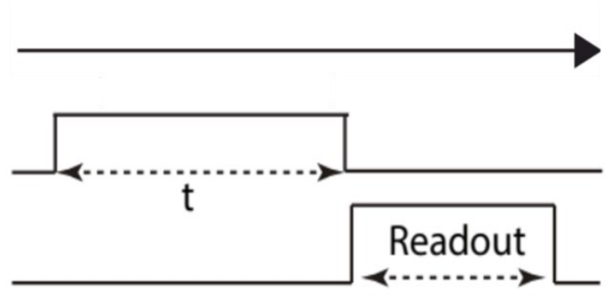
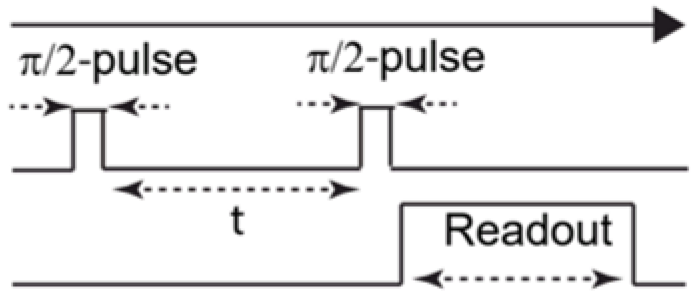
Rabi spectroscopy



$$p \propto \cos^2\left(\pi\tilde{\Omega}_R t + \phi\right)e^{-\frac{t}{T_1}}$$

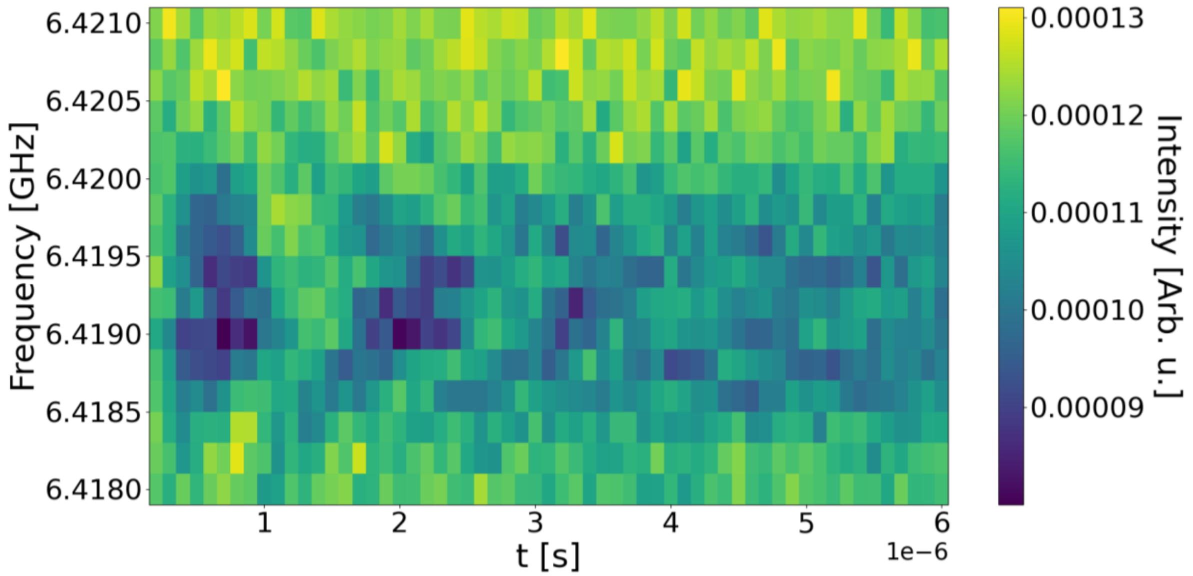
Ramsey spectroscopy

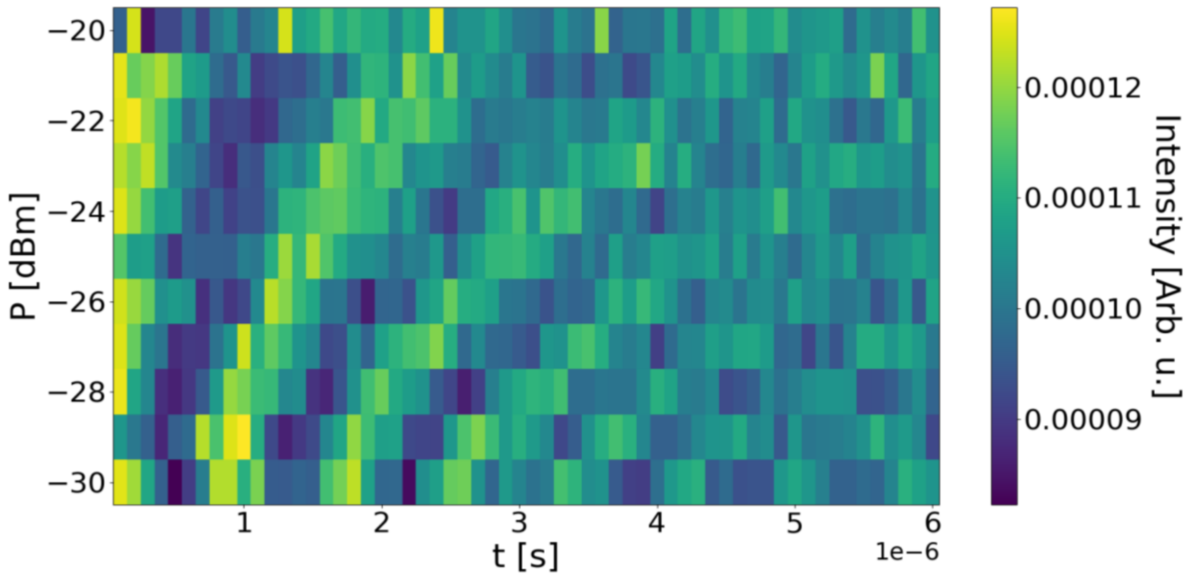


$$p \propto \frac{1}{2} - \sin\left(2\pi k t + \phi\right)e^{-\frac{t}{T_2}}$$

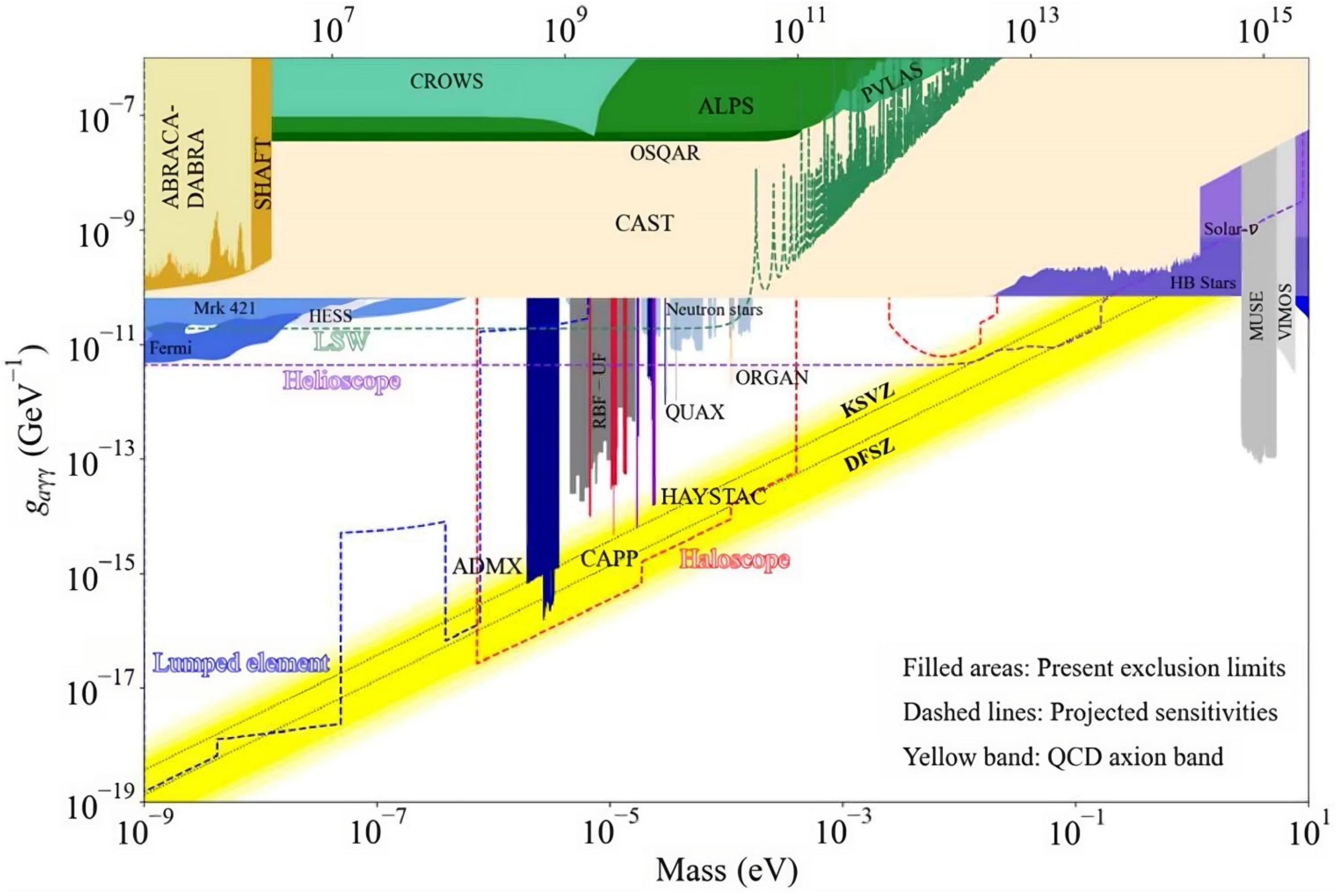
Università degli Studi di Padova

$$p \propto \cos^2\left(\pi\tilde{\Omega}_R t + \phi\right)e^{-\frac{t}{T_1}}$$





Backup



Semertzidis and Youn, *Sci. Adv.* **8**, eabm9928 (2022)

Conversion Power

$$P_{a\gamma\to\gamma} = g^2_{a\gamma\gamma}\frac{\rho_a}{m_a}B^2\omega_0 V C \frac{Q_a Q_c}{Q_a + Q_c}$$

Coupling Constant; Dark Matter Axion Density; Volume; Cavity Quality Factor; Axion Mass; Magnetic Field; Resonant Frequency; Axion Quality Factor (10^6)

D. Kim *et al*. JCAP03(2020)066

Scan Rate

$$\frac{df}{dt} \propto \frac{B^4 V^2 C^2}{K_B^2 T_{sys}^2} Q_a Q_c \frac{1}{1 + Q_a/Q_c}$$

Magnetic Field; Volume; Cavity Quality Factor; System Noise; Axion Quality Factor (10^6)

Fluxon Dissipation

Fluxon viscosity

$$\eta = \frac{\phi_o B_{c2}}{\rho_n}$$

Pinning force

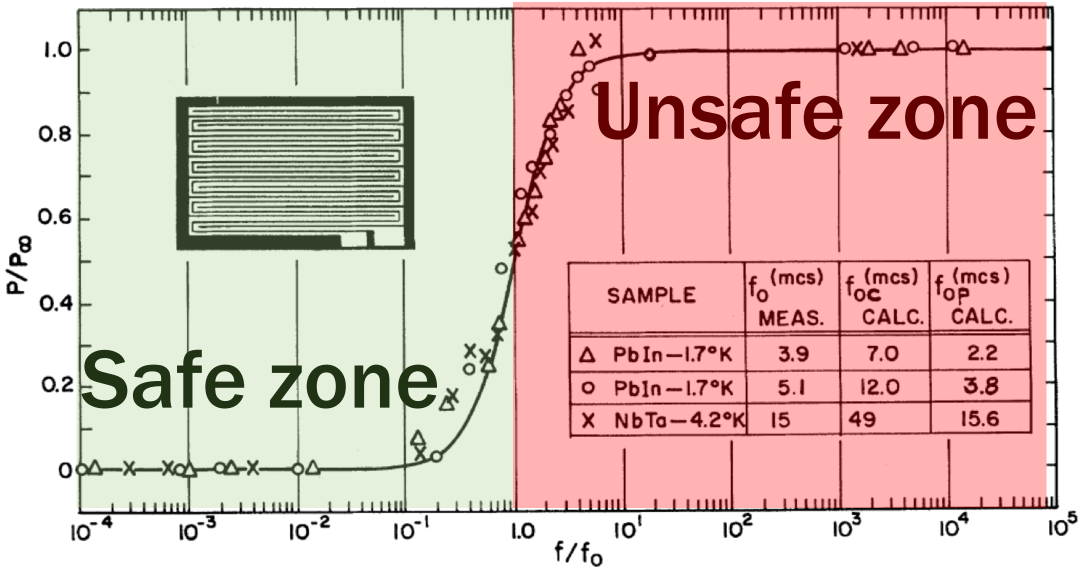
$$k = \frac{2\pi J_c \phi_0}{d}$$

$$m\ddot{x} + \eta\dot{x} + kx = J_{rf}\phi_O$$

$$\omega_o = \frac{k}{\eta}$$

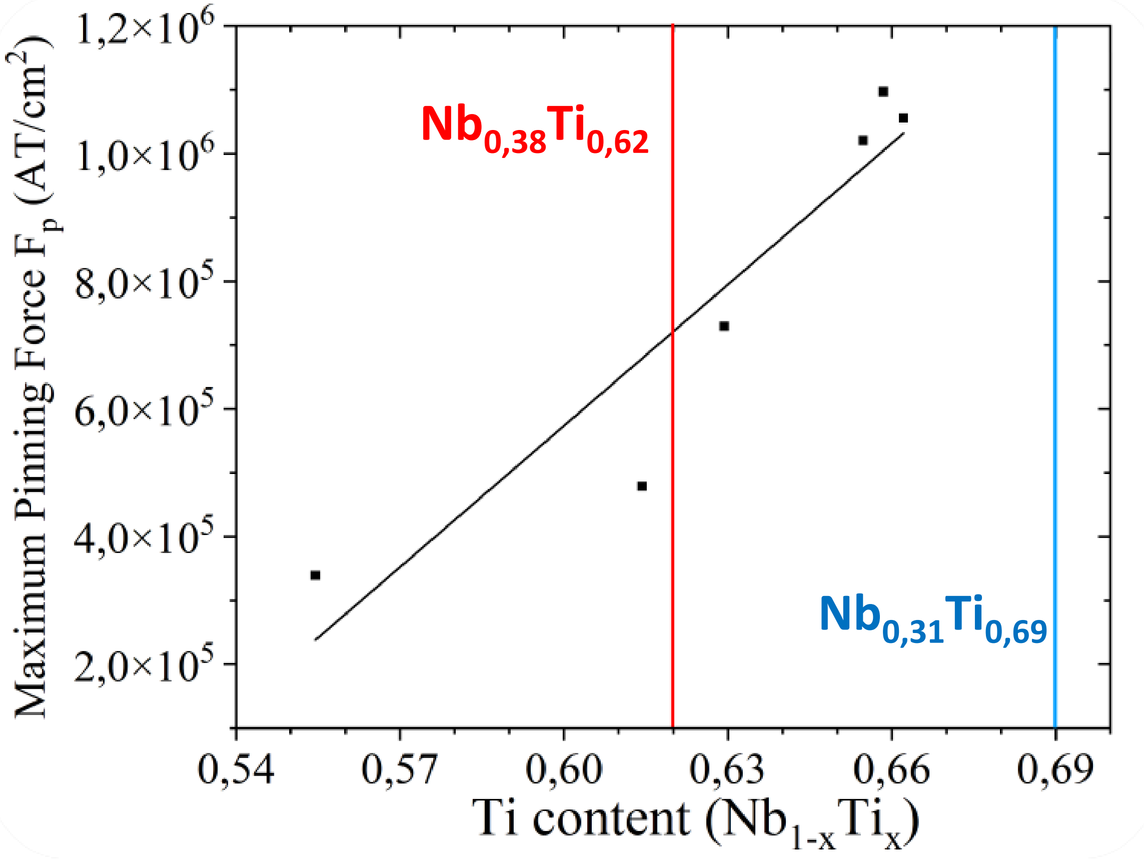
$$f_o(B_o) = \frac{\omega_o(B_o)}{2\pi} = \frac{\rho_n \sqrt{B_o} J_c(B_o)}{\sqrt{\varphi_o} B_{c2}}$$

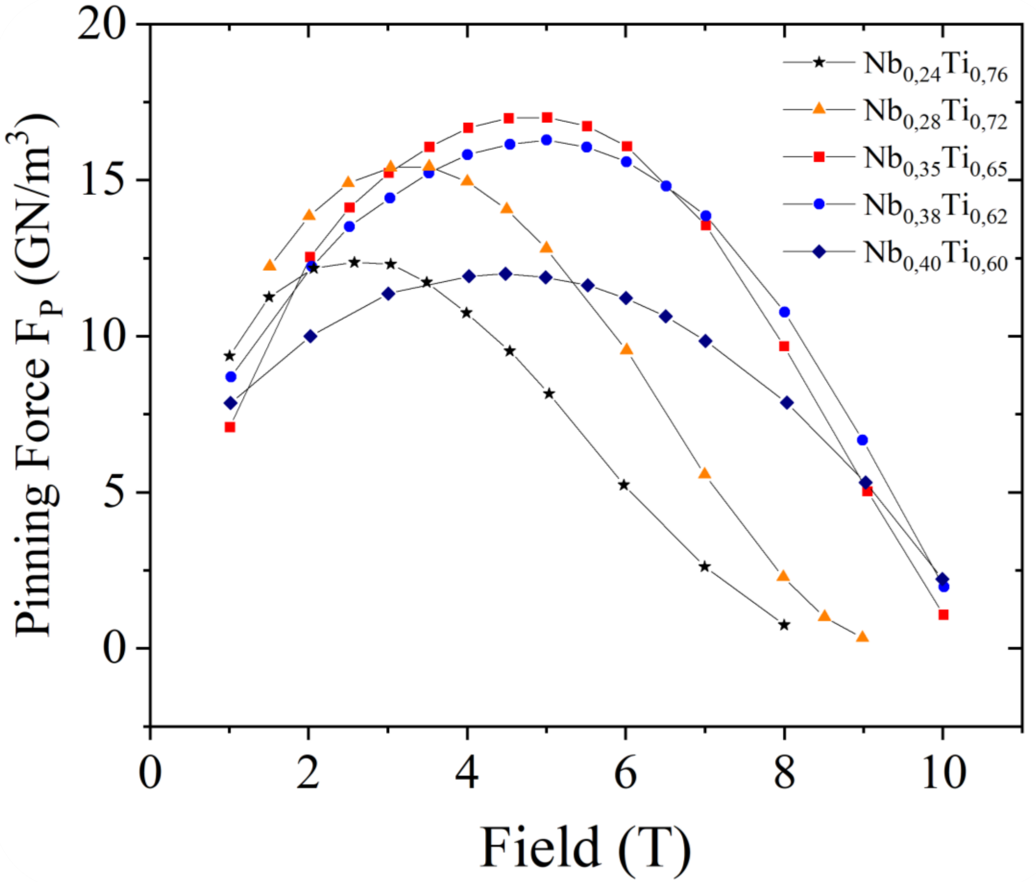
Depinning frequency



NbTi pinning force dependency on Ti content

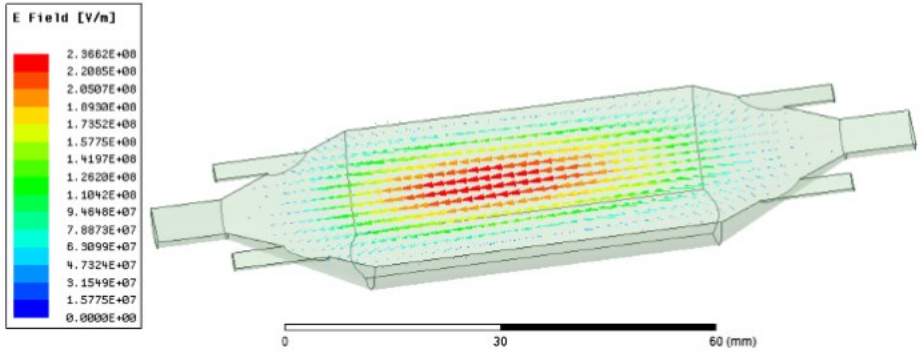
J. C. McKinnell, P. J. Lee, and D. C. Larbalestier, *IEEE Transactions on Magnetics*, 1989

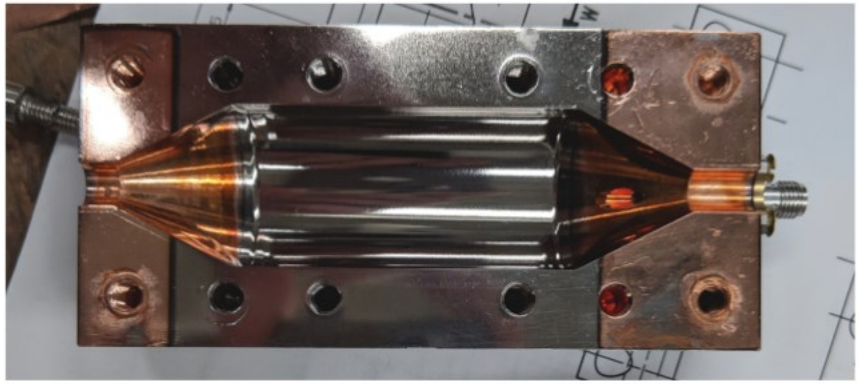




H. Hillmann and K. Best,
IEEE Transactions on Magnetics, 1977

Hybrid structure advantages





Using copper ends the quality factor is limited

$$Q_0^{max} \simeq 1{,}3 \cdot 10^6$$

But less dissipation due to fluxon movement!