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PIANO NAZIONALE DI RIPRESA E RESILIENZA

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Missione 4 Istruzione e Ricerca

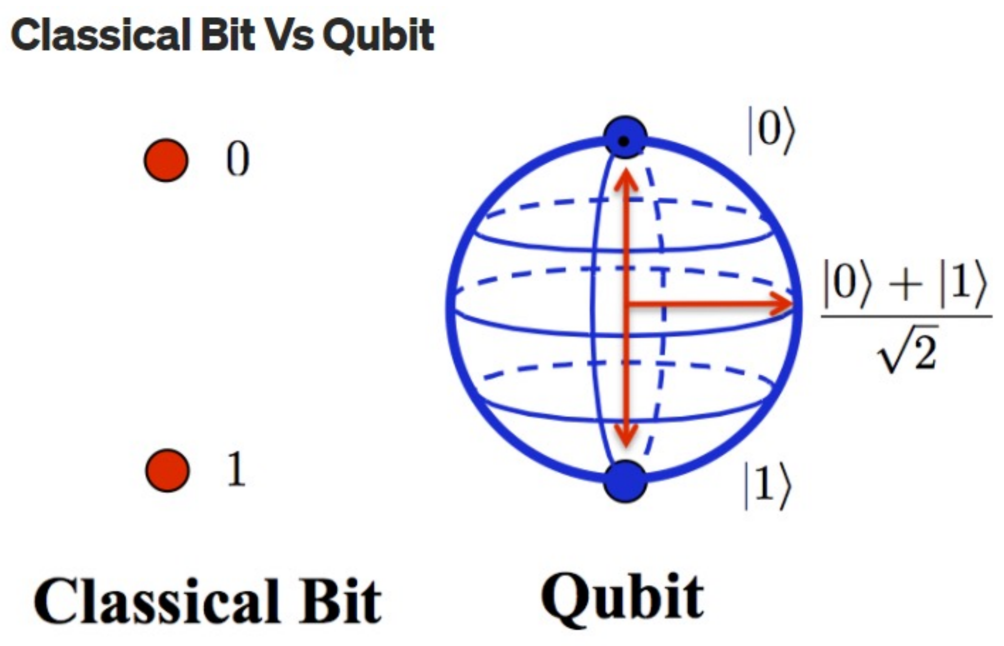
INFN

Superconducting Qubit in a 3D Cavity

Simone Tocci

16 January 2024

Qubit



By Abhishek Dubey

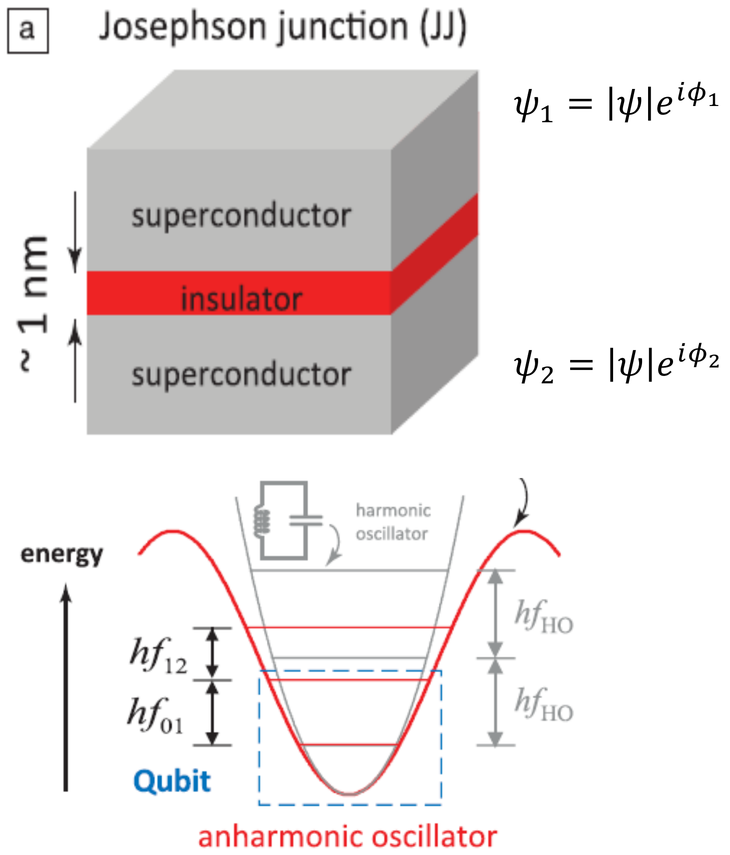
Qubits exploits the states superposition to increase calculation power

A two level quantum system is required

JJ provide a solid state system that is able to mimic the features of an artificial atom with discrete energy levels

Josephson Junction

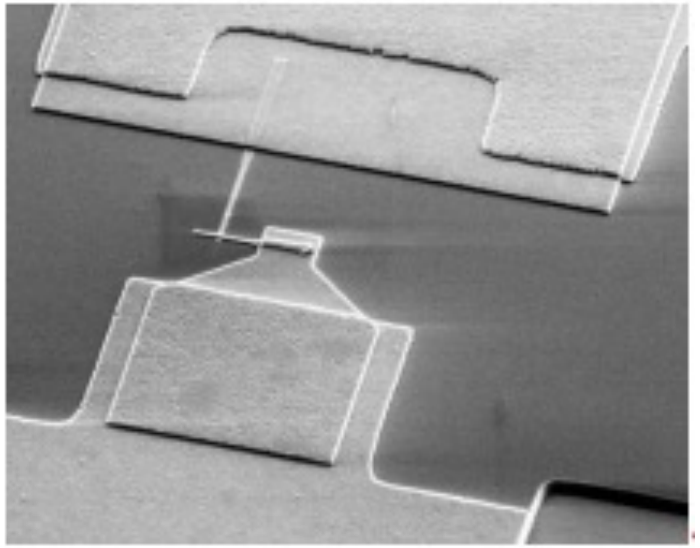
The most widespread qubit type is the transmon.



$$\phi_1 - \phi_2 = \varphi$$

$$I = I_c \sin \varphi$$

$$\frac{d\varphi}{dt} = \frac{2e}{\hbar} V$$



Transmon consists of a small JJ shunted by two large capacitors to reduce the charge noise. Its simple design and high quality performance make the transmon one of the best candidates for large-scale production.

W. D. Oliver, P.B. Welander, MRS Bulletin, 2013

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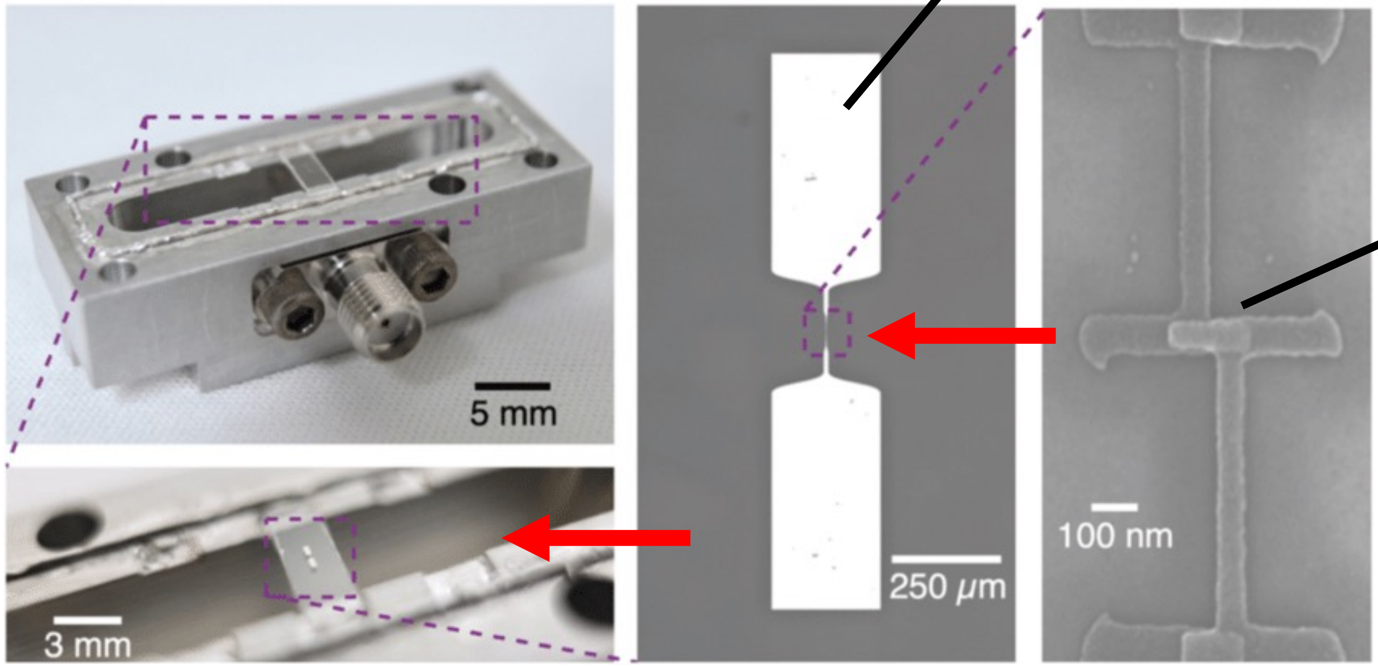
Transmon in a RF cavity

Two metal pads (two large capacitors)

Josephson Junction



Transmon

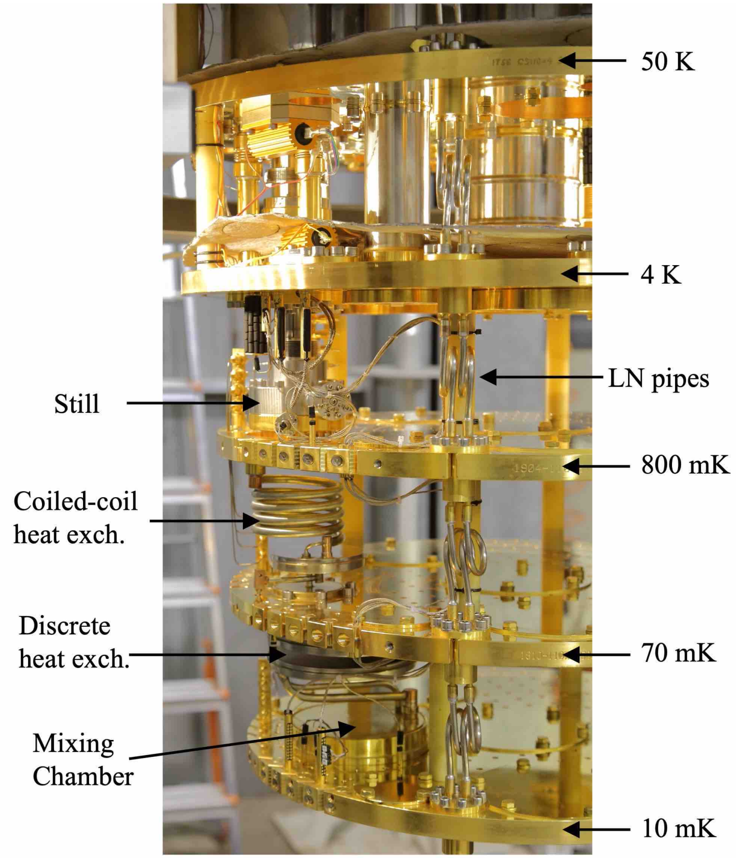
LNF-cryostat

LEIDEN CRYOGENICS

$$T_{base} = 8\ mK$$

Cooling power:

$$500\ \mu W\ \ @\ \ 100\ mK$$



Transmon

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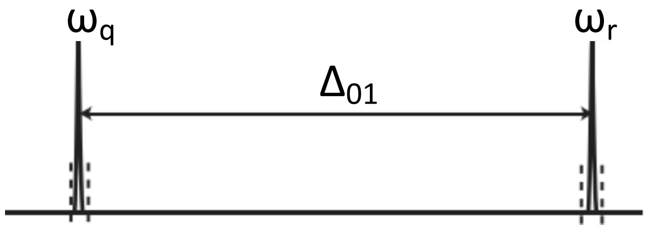
Qubit in 3D cavity

Dispersive regime



$$H_{JC} = \left(\omega_r - \frac{\chi_{12}}{2} + \chi\sigma^z\right)a^\dagger a + \frac{1}{2}(\omega_q + \chi_{01})\sigma^z,$$

$$\chi = \chi_{01} - \frac{\chi_{12}}{2} \qquad \chi_{ij} = \frac{g_{ij}^2}{\Delta_{ij}}$$

$$\Delta_{01} = \omega_q - \omega_r \qquad \omega_q = \omega_{01}$$

Technology Innovation Institute

We read the Qubit state through a cavity measurement

Fabricated @ Technology Innovation Institute, Abu Dhabi

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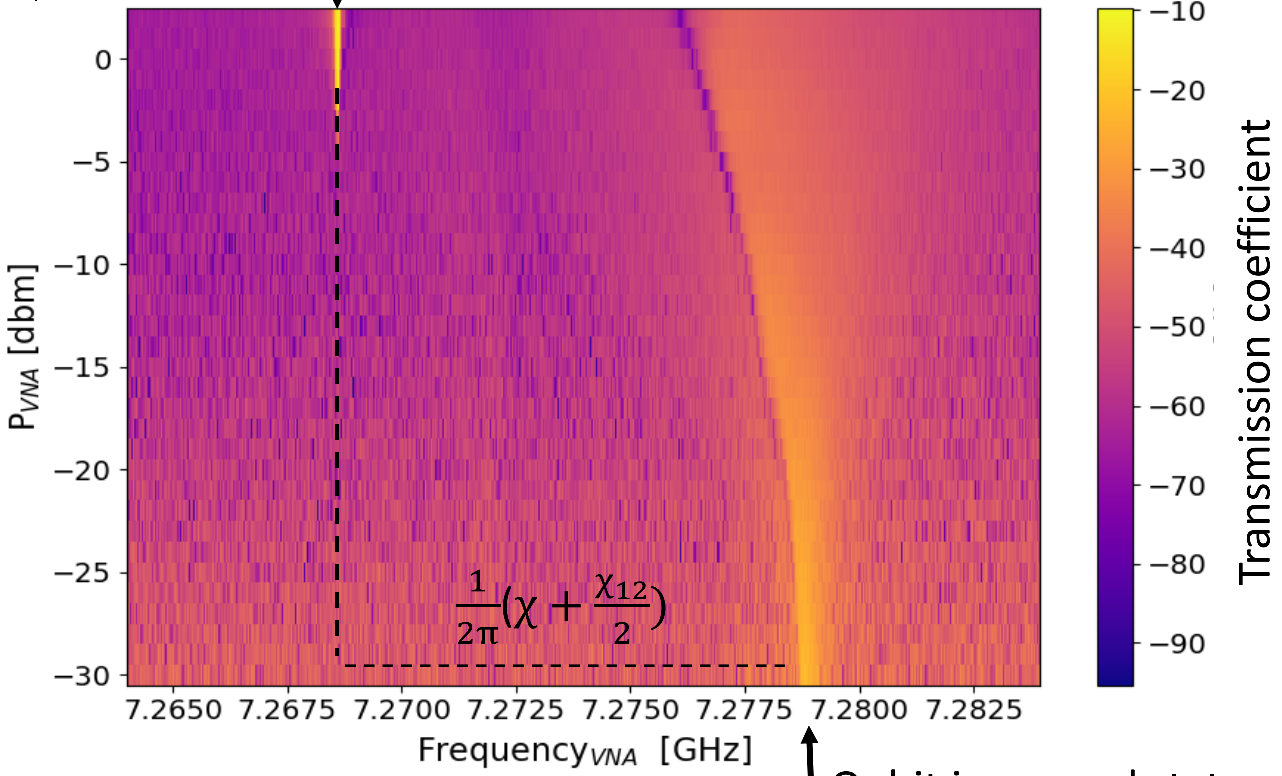
Qubit in 3D cavity: Cavity spectroscopy

Bare cavity frequency
ν_r= 7.268 GHz



Qubit in ground state

$$\frac{1}{2\pi}(\chi + \frac{\chi_{12}}{2}) = -10.2 \pm 0.1\ MHz$$

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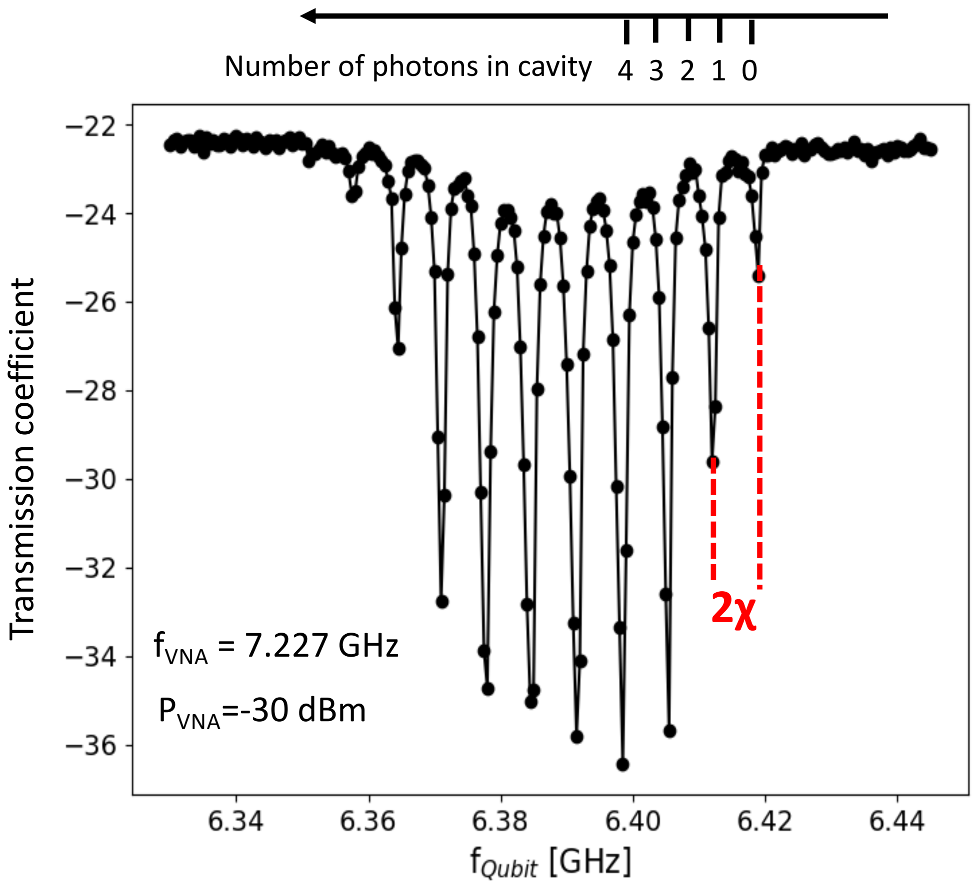
Qubit in 3D cavity: Resolving Photon Number

With a two tone measurement, we measure the qubit frequency



The deep position depends on the number of photons (P_{VNA}) in the cavity

The qubit frequency depends on the number of photons in the cavity

$$\frac{\chi_{12}}{2\pi} = -13.6\pm0.3\text{MHz}$$

$$\frac{\chi_{01}}{2\pi} = -10.2\pm0.2\text{ MHz}$$

$$\frac{\chi}{2\pi} = -\ 3.41\pm0.08\text{ MHz}$$

$$\frac{\omega_{|0\rangle}}{2\pi} = \frac{1}{2\pi}(\omega_q + \chi_{01}) = 6.4194\text{ GHz}$$

$$\frac{\omega_q}{2\pi} = \nu_q = 6.4296\text{ GHz}$$

Estimate of anharmonicity and capacity

$$\frac{\chi_{12}}{2\pi} = -13.6 \pm 0.3\text{MHz}$$

$$\frac{\chi}{2\pi} = -3.41 \pm 0.08 \text{ MHz}$$

$$\frac{\chi_{01}}{2\pi} = -10.2 \pm 0.2 \text{ MHz}$$

$$\frac{\Delta_{01}}{2\pi} = \nu_q - \nu_r = -839 \text{ MHz} \qquad \chi_{01} = \frac{g_{01}^2}{\Delta_{01}}$$

$$\boxed{\frac{g_{01}}{2\pi} = 92.5 \pm 1 \text{ MHz}}$$

$$g_{12} = \sqrt{2} g_{01} \longrightarrow \chi_{12} = \frac{g_{12}^2}{\Delta_{12}} \longrightarrow \Delta_{12} = \omega_{12} - \omega_r \qquad \frac{\Delta_{12}}{2\pi} = -1260 \pm 40 \text{ MHz}$$

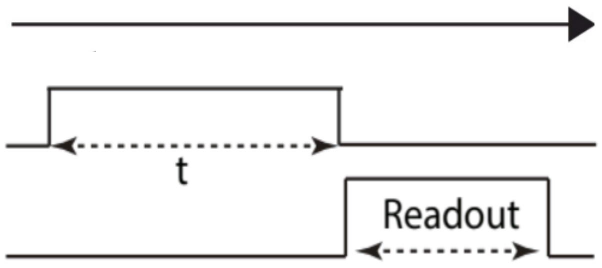
$$\Delta_{01} - \Delta_{12} = \omega_{01} - \omega_{12} = 2\pi\alpha$$

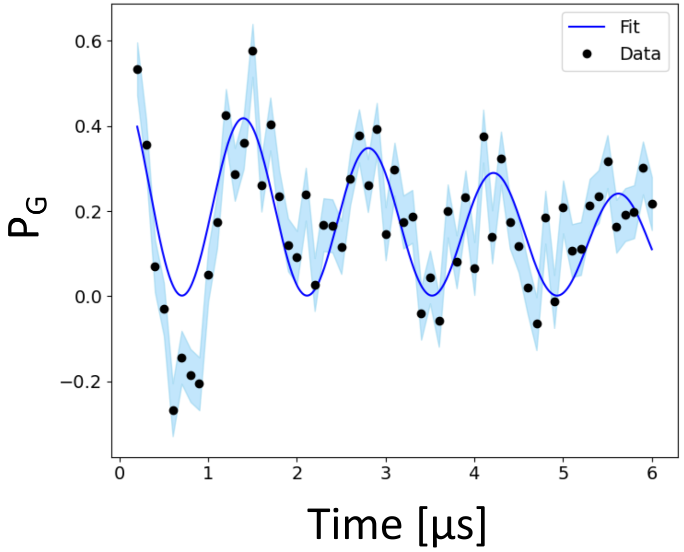
Anharmonicity=α = 421±84 MHz

$$h\alpha = \frac{e^2}{2C} \qquad C = 46 \pm 5 fF \longrightarrow$$ Transmon Capacity

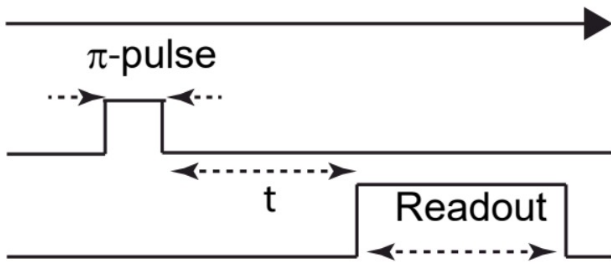
Qubit in 3D cavity: Rabi and T1 measurements

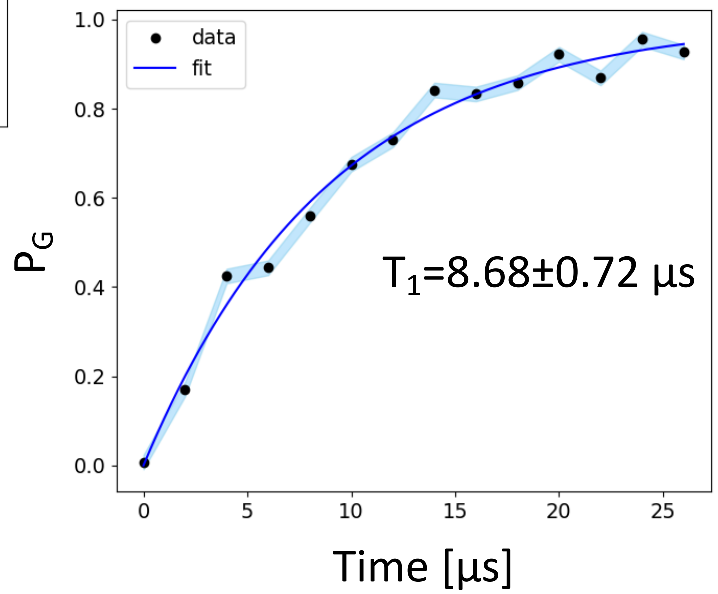
Rabi





T_1





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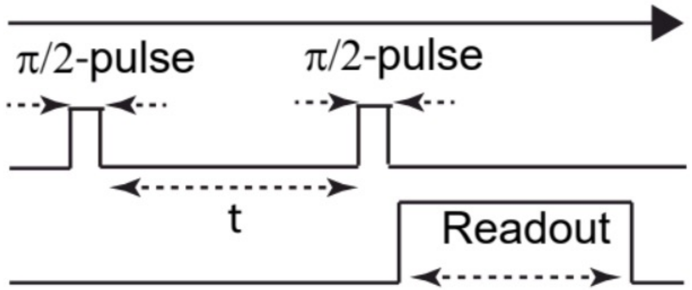
Qubit in 3D cavity: Ramsey spectroscopy



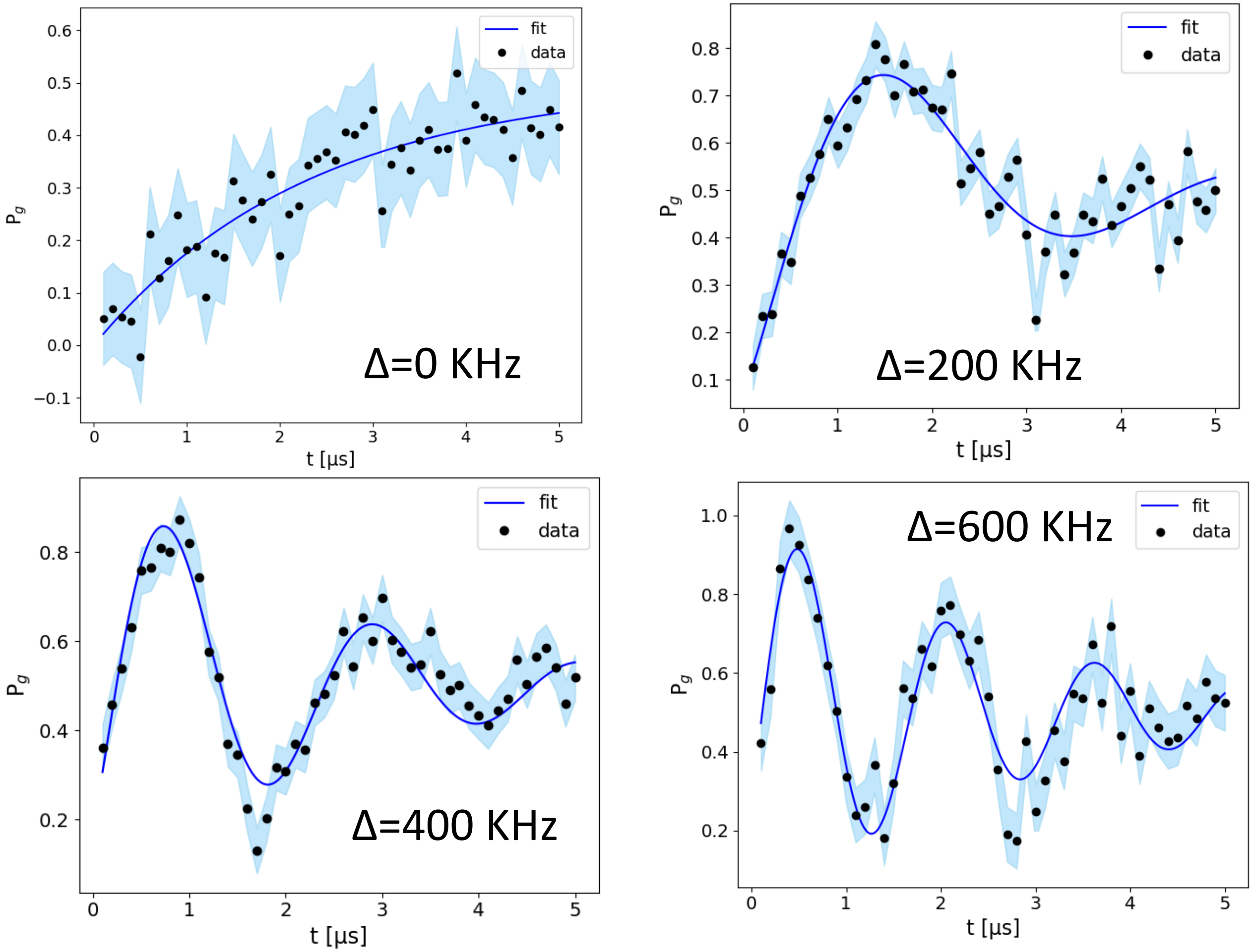
$$P_g = \left(\frac{1}{2} - \sin(2\pi\Delta\times t)\right)e^{-\frac{t}{2T_2}}$$

Averaging over all the T_2 measurements

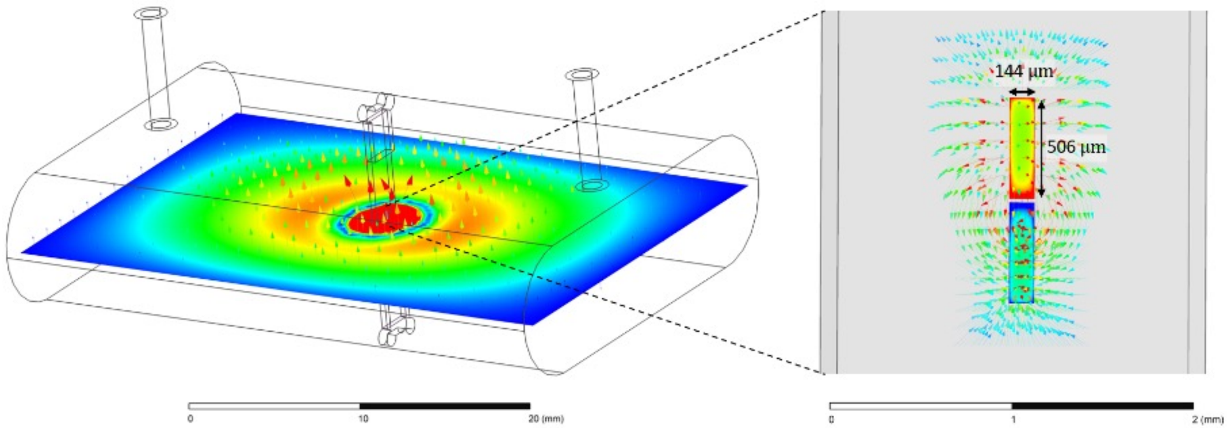
$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\varphi}$$

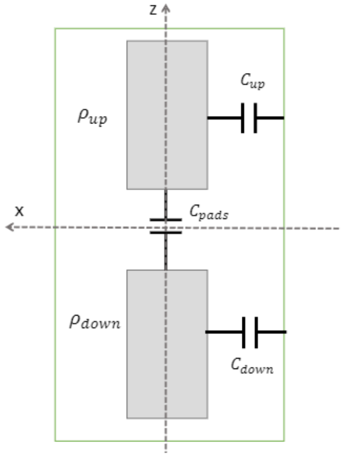
T_2 =2.30±0.11 μs

T_φ= 2.65±0.15 μs



Qubit in 3D cavity: HFSS simulations





$$C = \frac{C_{11}C_{22} - C_{12}C_{21}}{C_{11} + C_{12} + C_{21} + C_{22}}$$

$$d_{\text{eff}} = \int_{A_{\text{up}}} \left(\frac{\rho_{up}(\vec{r})}{|q|} \right) \cdot z \, d\vec{r} + \int_{A_{\text{down}}} \left(\frac{\rho_{down}(\vec{r})}{|q|} \right) \cdot z \, d\vec{r}$$

$$\frac{g_{01}^{sim}}{2\pi} = 97 \text{ MHz} \qquad \frac{g_{01}}{2\pi} = 92.5 \pm 1 \text{ MHz}$$

$$g_{01} = \frac{2e \cdot d_{eff} \cdot E_0}{\hbar} \frac{1}{\sqrt{2}} \left(\frac{E_j}{8E_c} \right)^{\frac{1}{4}}.$$

Experimental data are well reproduced by simulations

$$C^{sim} = 56\, fF \qquad C = 46 \pm 5 fF$$

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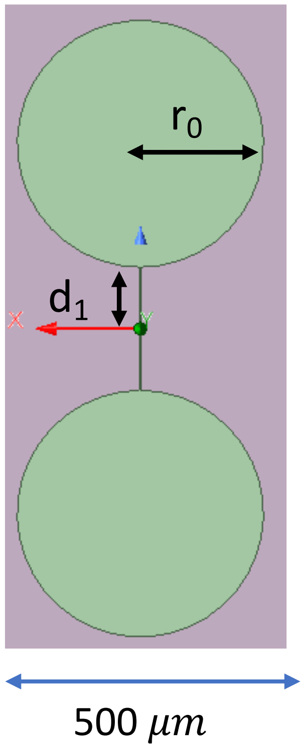
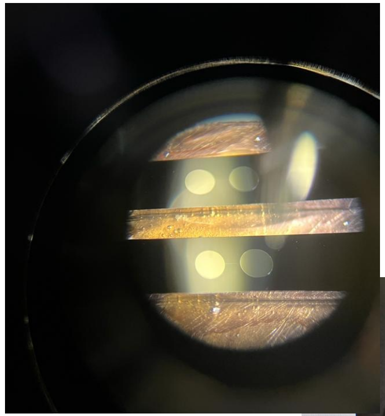
Qubit in 3D cavity: Design and fabrication a new Transmon

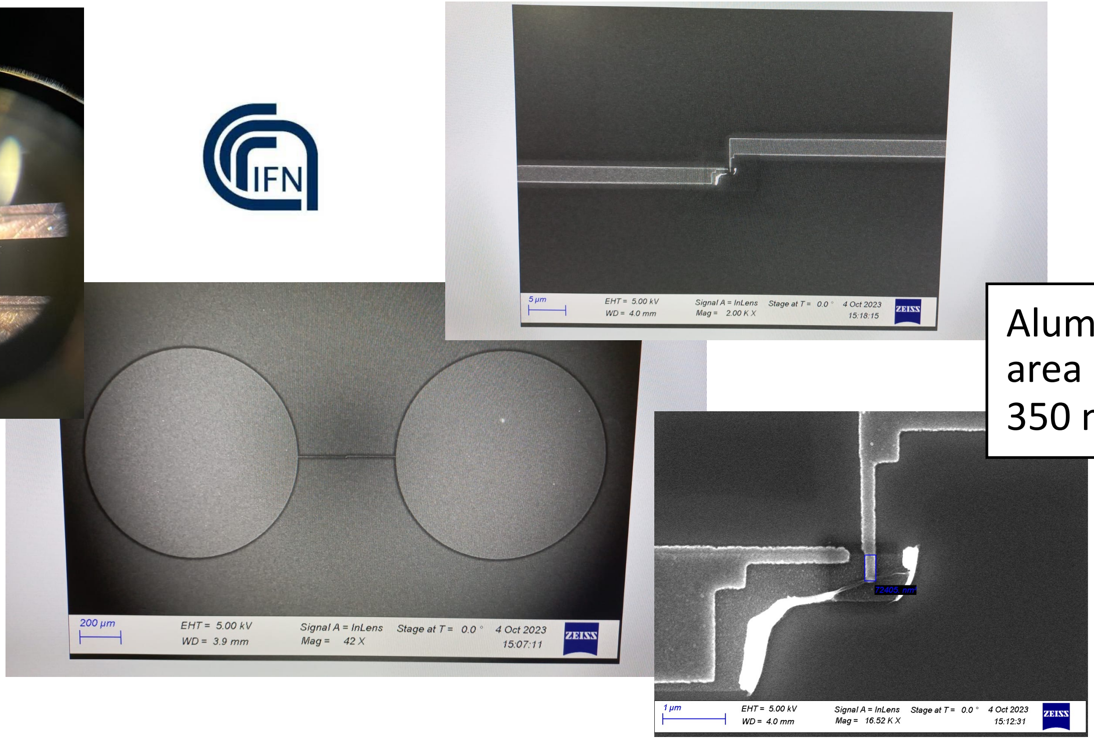


F_q=6.57GHz
C_{tot}=100fF

r_0 [μm]	500
d_1 [μm]	243
d_{eff} [μm]	508

Expected T_1 improvement of $\sim$30%





New design already fabricated and soon to be tested

Aluminum JJ with area about 200 x 350 nm

Manufacturing of 3D qubits with circular pads at IFN CNR

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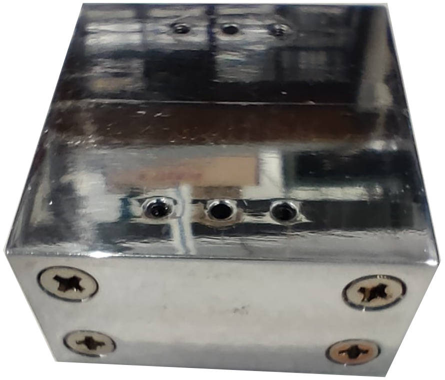
Qubit in 3D cavity: Ultra –pure Al cavity

$$Q = (1.78 \pm 0.9) \cdot 10^5$$



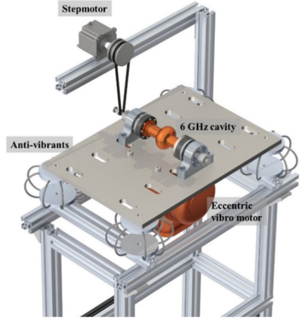
Al alloy

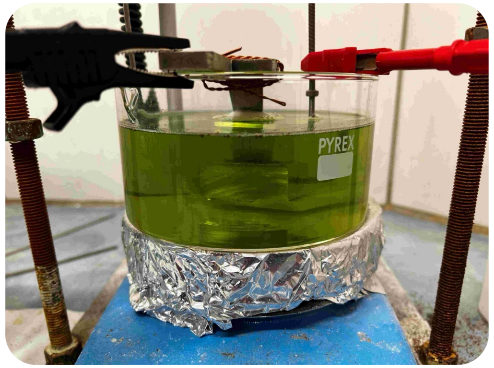
Alloy cavity and qubit fabricated at Technology Innovation Institute, Abu Dhabi

↓

Move to Al 5N (99.999% purity) to reduce surface loss and improve the quality factor

3D Cavity Fabrication





Mechanical machining

▸ Vibro-tumbling

▸ Electropolishing

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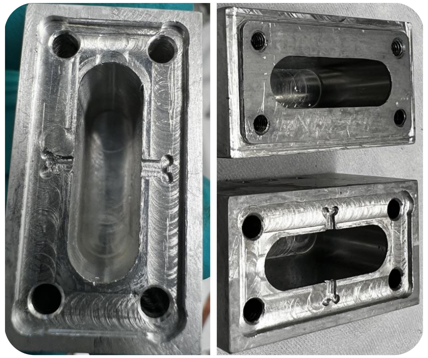
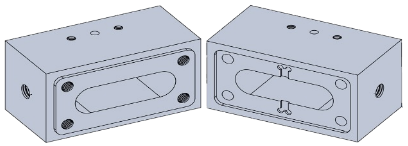
Laboratori Nazionali di Legnaro



Qubit in 3D cavity: pure Al cavity measurement

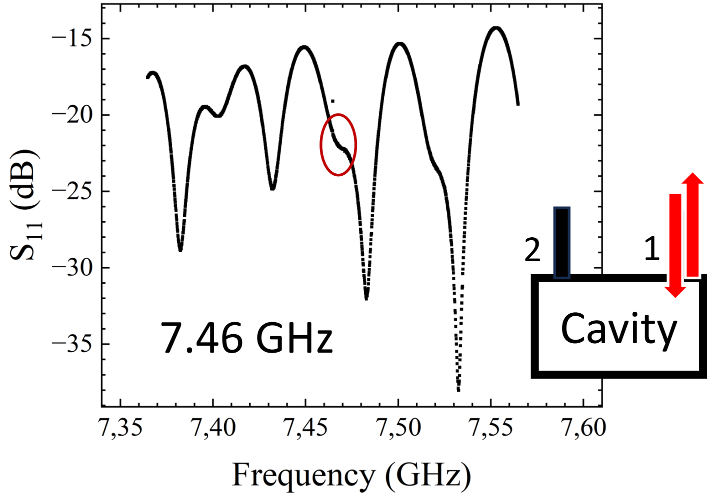


The first new cavity in ultra-pure Al

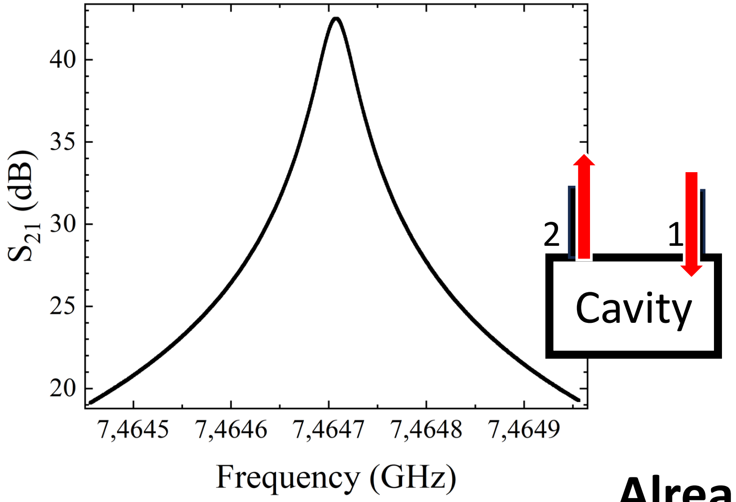
Scattering parameters results

All measurements at 30 mK

S_{11}



S_{21}



Al alloy

$$Q = (1.78 \pm 0.9) \cdot 10^5$$

Al 5N

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

Already improved with respect to previous Al alloy cavity!

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Conclusion:

In conclusion, we showed our characterization of a dispersively coupled qubit-cavity system.

- We measured all the relevant parameters of the Hamiltonain and the coherence properties of the qubit.
- The simulations reproduce the measured parameters very well.
- A superconducting qubit with circular pads has been designed and fabricated.
- We fabricated and tested the superconducting cavities with pure Al

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People involved in this work

Boulos Alfakes, Anas Alkhazaleh, Leonardo Banchi, Matteo Beretta, Stefano Carrazza, Fabio Chiarello, Alessandro D'Elia, Daniele Di Gioacchino, Claudio Gatti, Andrea Giachero, Felix Henrich, Alex Stephane Piedjou Komnang, Carlo Ligi, Giovanni Maccarrone, Massimo Macucci, Federica Mantegazzini, Giovanni Marconato, Francesco Mattioli, Angelo Nucciotti, Emanuele Palumbo, Andrea Pasquale, Luca Piersanti, Cristian Pira, Florent Ravaux, Alessio Rettaroli, Matteo Robbiati.

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UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

A. D'Elia et al., "Characterization of a Transmon Qubit in a 3D Cavity for Quantum Machine Learning and Photon Counting," submitted to Applied Sciences.

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Thank you for your attention