QUANTUM COMPUTING NAPOLI

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

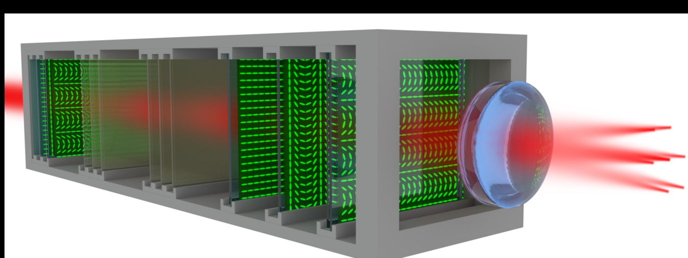
ICSC

PNR 2021-2027 Programma nazionale per la ricerca

NQSTI National Quantum Science and Technology Institute

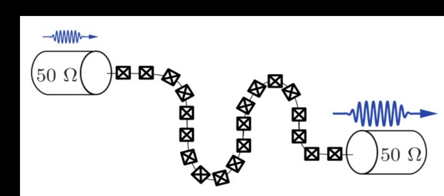
Superconducting quantum technologies

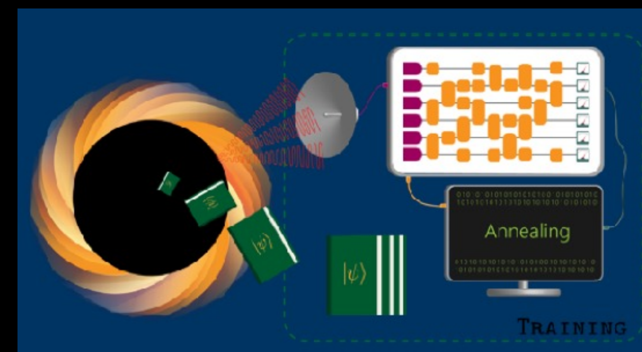
Halima G. Ahmad, Giovanni Ausanio, Ciro Bruscino, Isita Chatterjee, Luigi Di Palma (@SEEQC), Pasquale Ercolano, Martina Esposito (@CNR-SPIN), Raffaella Ferraiuolo, Zafar Iqbal, Anna Levochkina, Davide Massarotti, Pasquale Mastrovito, Alessandro Miano (@Yale), Domenico Montemurro, Loredana Parlato, Roberta Satariano, Giuseppe Serpico, Giampiero Pepe & Francesco Tafuri



Quantum optics and photonics

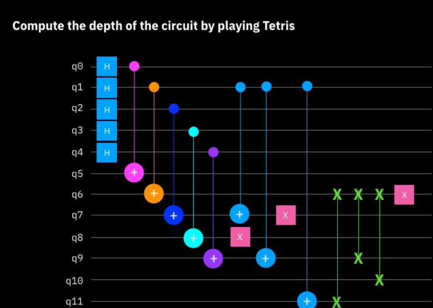
Filippo Cardano, Vincenzo D'Ambrosio, Corrado De Lisio, Lorenzo Marrucci, Bruno Piccirillo, Alberto Porzio



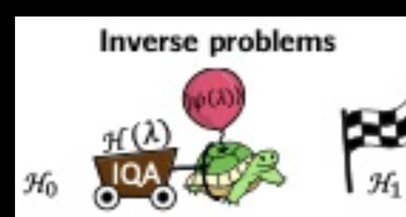


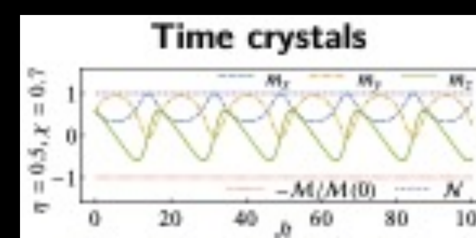
Quantum information theory and quantum algorithms, artificial intelligence and quantum machine learning
Giovanni Acampora, Alioscia Hamma, Massimo Taronna, Patrizia Vitale, Autilia Vitiello

Quantum engineering: quantum communication and network, macroscopic electrodynamics modeling, Quantum Internet
Angela Sara Cacciapuoti, Marcello Caleffi, Carlo Forestiere, Giovanni Miano



Quantum many-body systems
Condensed-matter quantum modeling
Dario Alfé, Vittorio Cataudella, Giulio De Filippis, Rosario Fazio, Procolo Lucignano, Domenico Ninno, Carmine Antonio Perroni





WP10.1. Software (Leader: INFN).
Development and application of high-level quantum software for algorithms solving general purpose problems, scientific and industrial applications.

- T1.1 New algorithms (Pavia, Bologna, IIT, Catania, CINECA, CNR, Pisa, Sapienza, Bari, PoliMI, Padova);
- T1.2 Applications and use cases (IIT, Bologna, CINECA, CNR, INAF, INFN, Pavia, Pisa, Bari, Bicocca, PoliMI, Padova)

WP10.2. Mapping, compilation and quantum computing emulation (Leader: CINECA).
Development of software toolchain for compilation, benchmarking, verification, emulation of quantum computers and algorithms.

- T2.1 Mapping and compilation (Bologna, CNR, Pisa, PoliMI);
- T2.2 Emulation (CINECA, INAF, Bari, Padova)

WP10.3. Firmware and hardware platforms (Leaders: CNR, Catania).
Development of low-level software for the physical operation of quantum computers. Development and support of the quantum computer hardware chain.

- T3.1 Photonic hardware (Sapienza, CNR, Bicocca, Pavia, Napoli);
- T3.2 Superconducting circuits (Napoli, INFN, Bicocca, CNR, Catania, Pisa);
- T3.3 Atomic hardware (CNR, Padova, Pisa);
- T3.4 Models and firmware (Catania, PoliMI, Bari, Padova, Bicocca, CNR, Pisa, Sapienza)

Roadmap on Superconducting Quantum circuits

Superconducting quantum circuits and qubit architectures

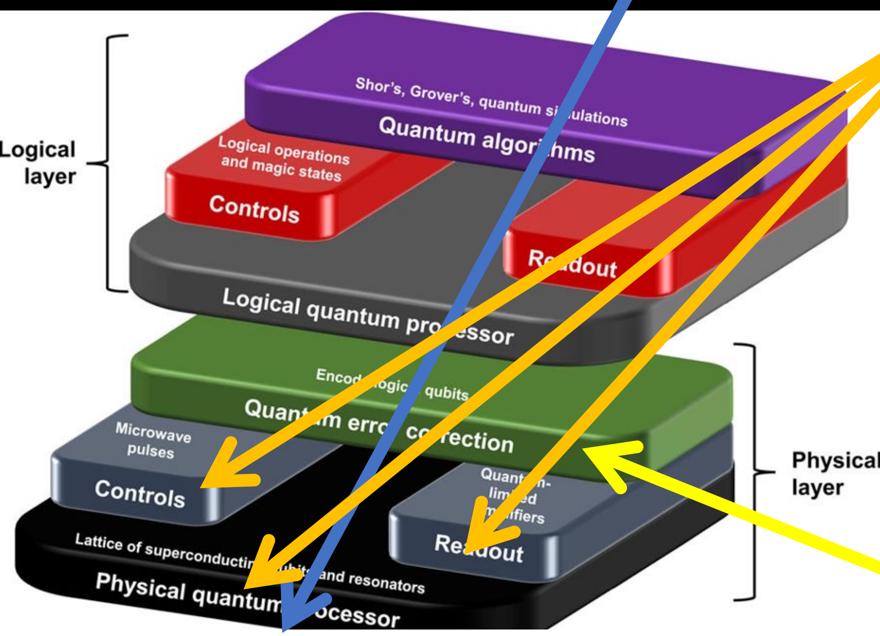
Alternative qubit layouts, transmon

Ferro-transmon, based on JJs with ferromagnetic barriers

Standard approach Al technology

Running a scalable superconducting quantum computer

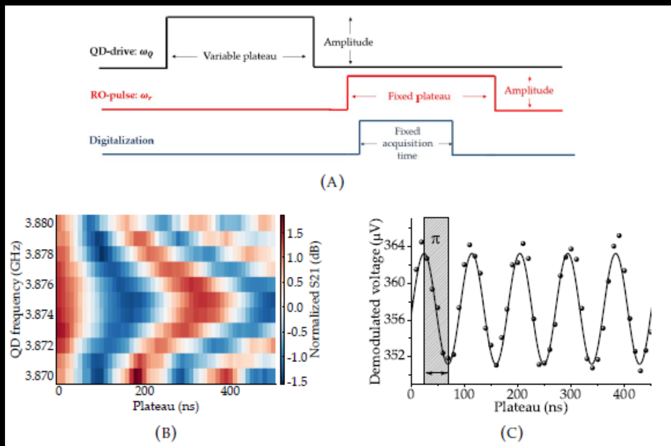
Novel control and read-out, SFQ-circuits and phase-detectors

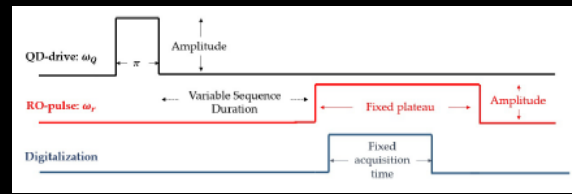


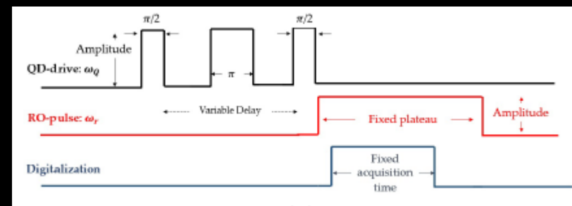
Jay M. Gambetta, Jerry M. Chow & Matthias Steffen
npj Quantum Information **3**, Article number: 2 (2017)

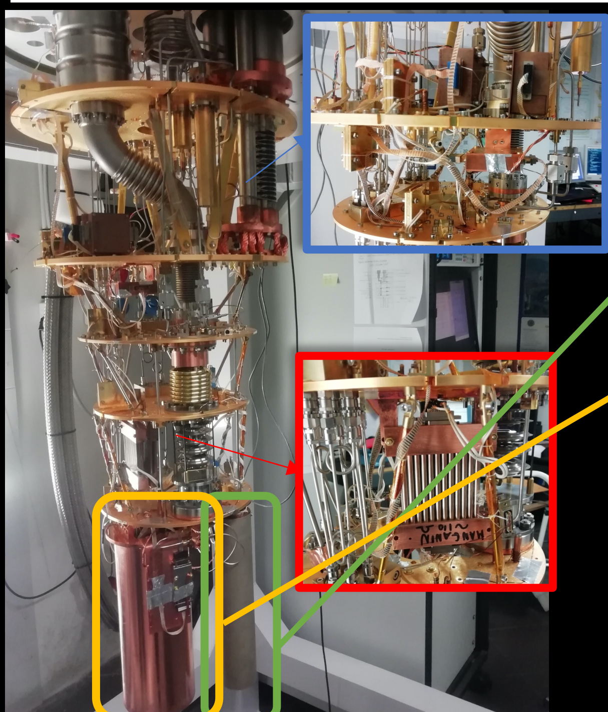
Running classical/quantum algorithms for error mitigation

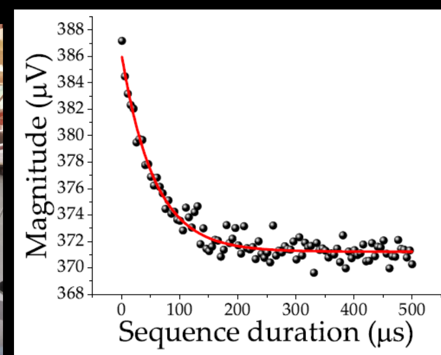
Time-domain heterodyne qubit readout

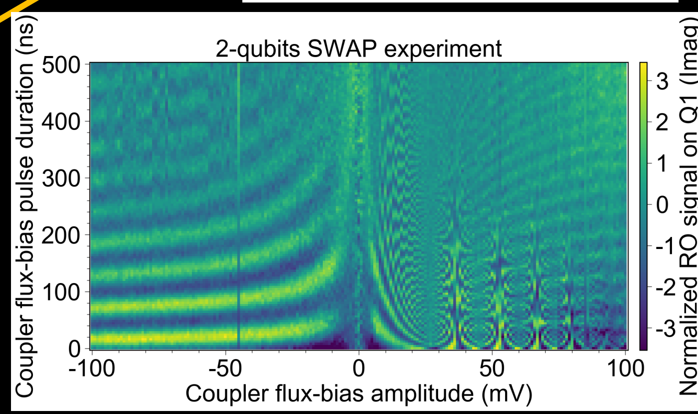


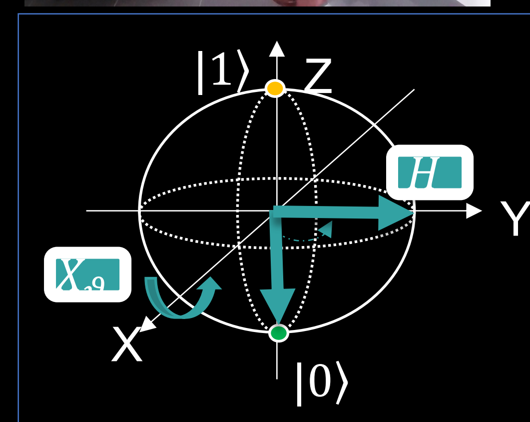


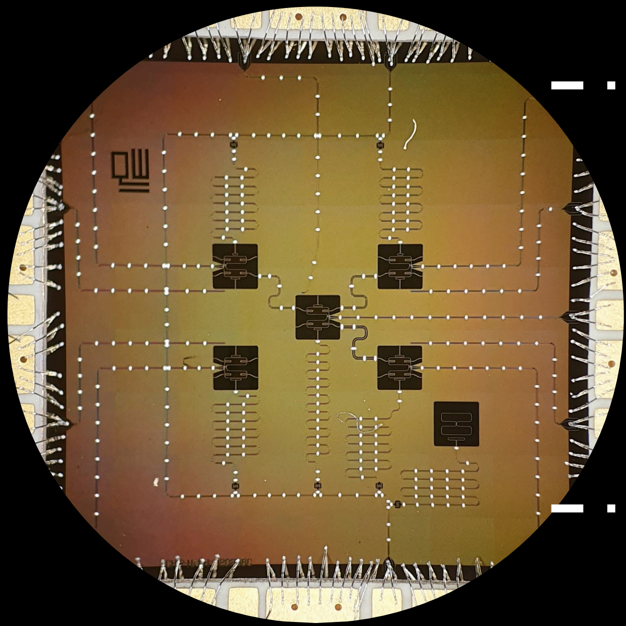


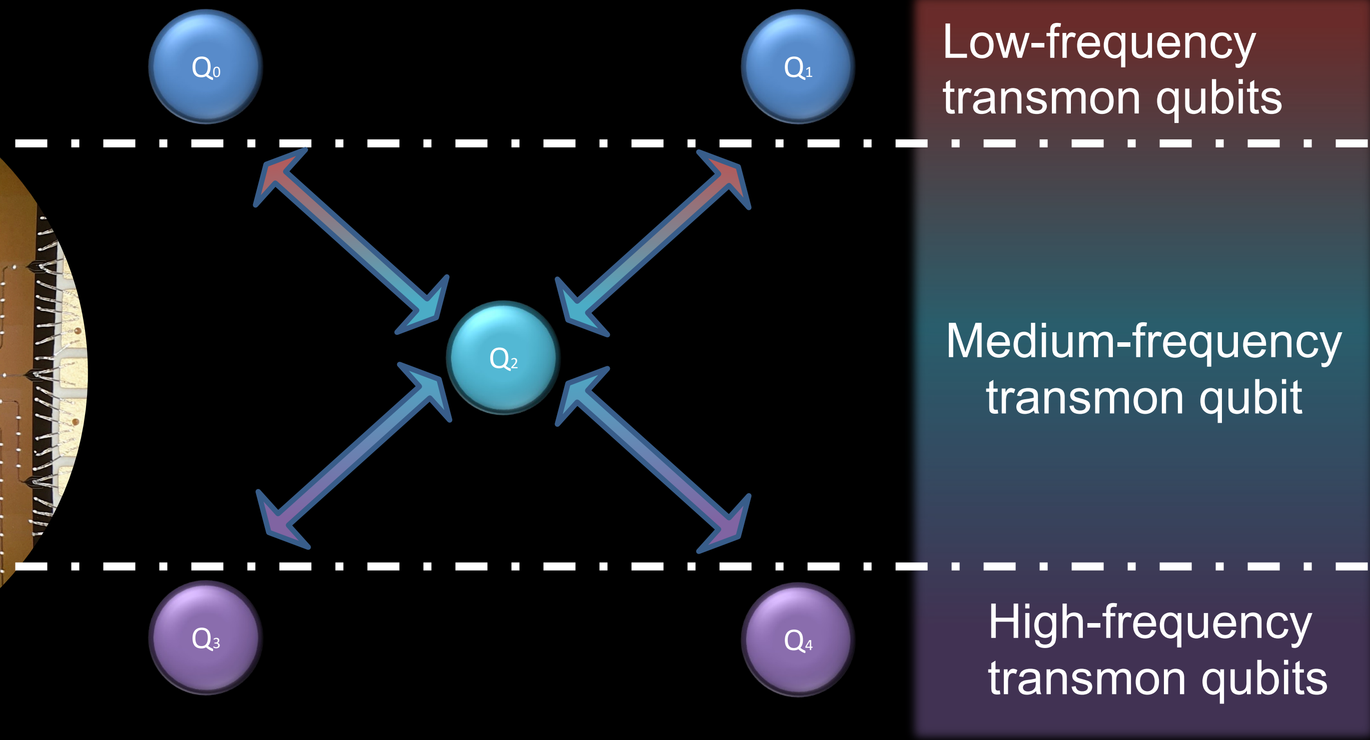






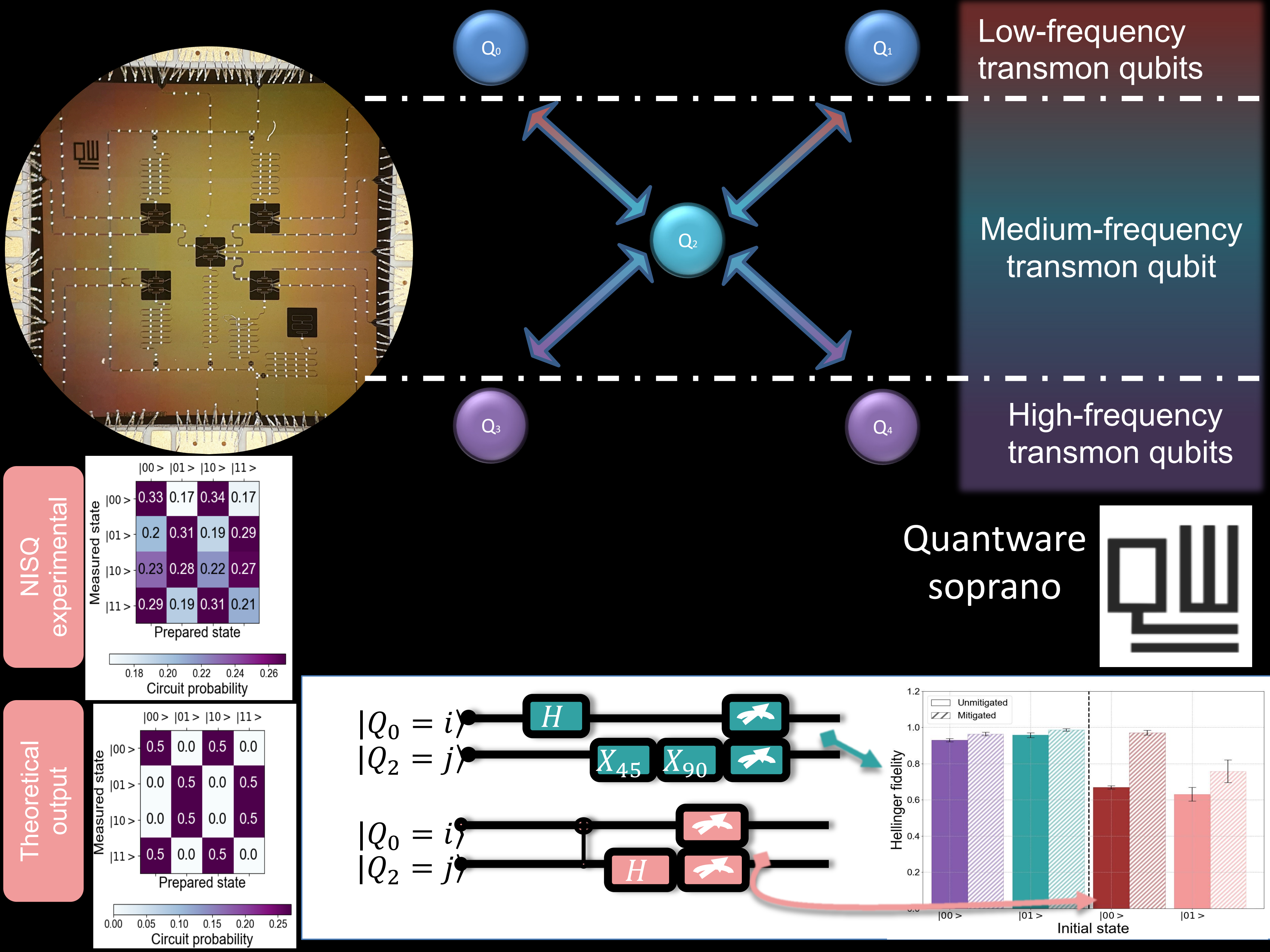






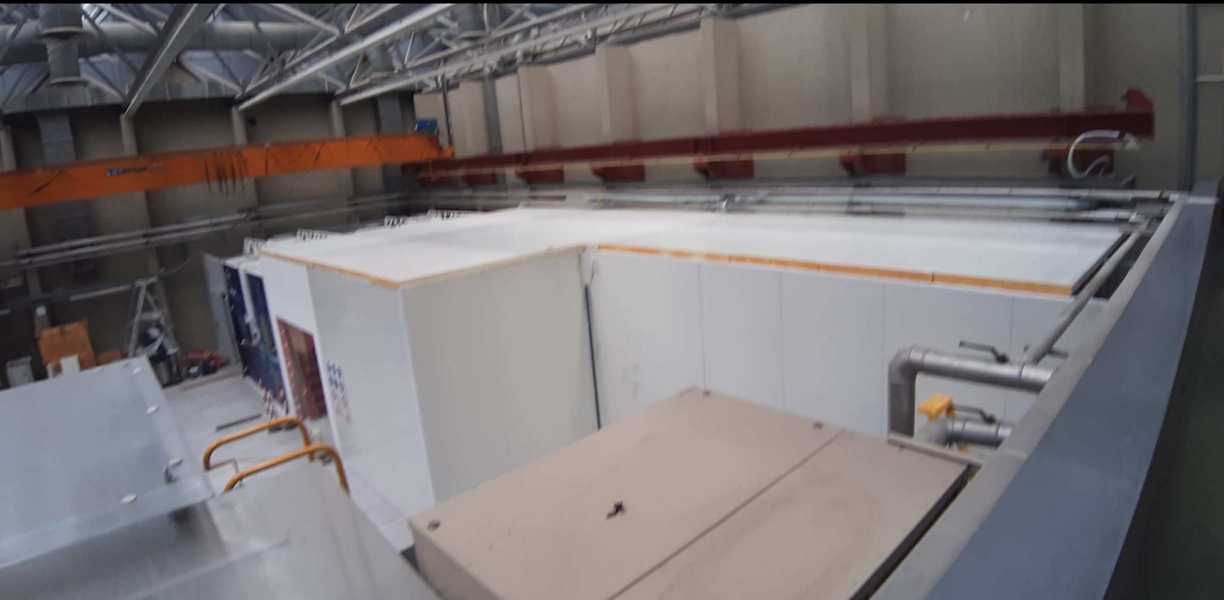
Quantware soprano

- 5-qubit diagnostics
- Entanglement and coupling
- Gate tuning
- State base preparation in |00⟩,|01⟩,|10⟩,|11⟩ and readout fidelity (measurement probability or count vector) for around 1000 single-shot measurements and 10 isolated experiments
- Algorythm: hybrid quantum-classical readout error correction matrix calculation with Fuzzy-C means algorithm

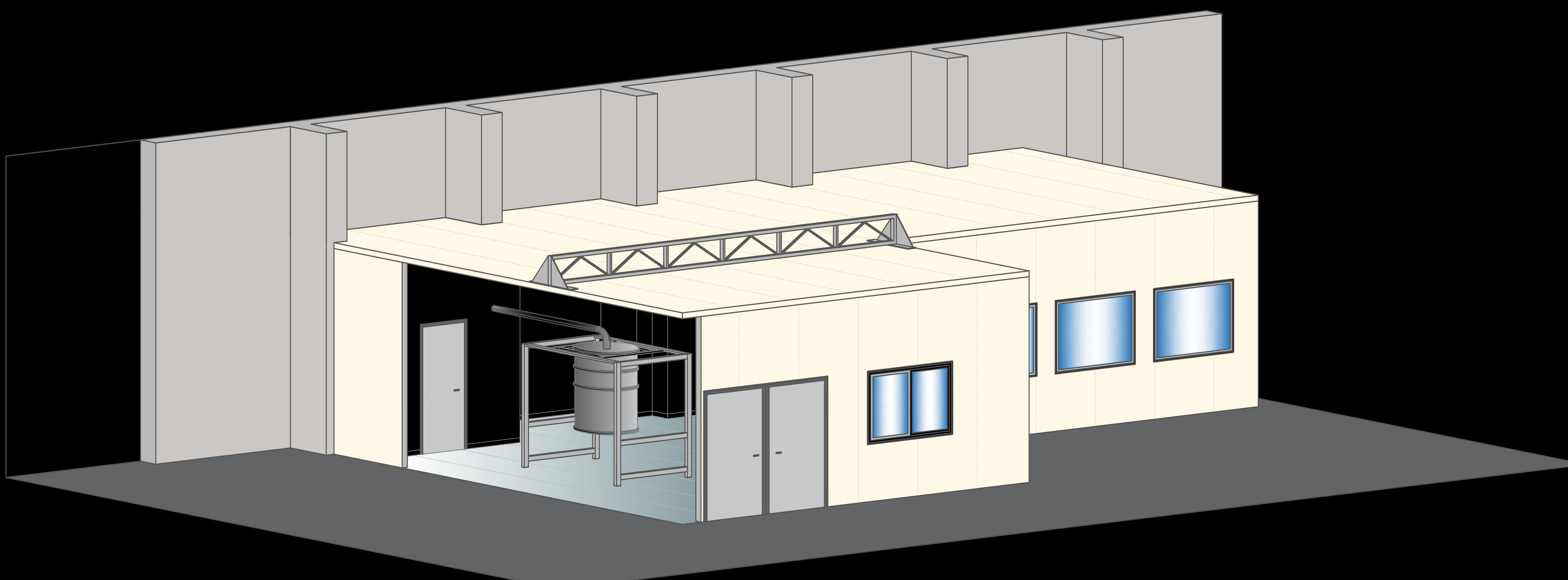


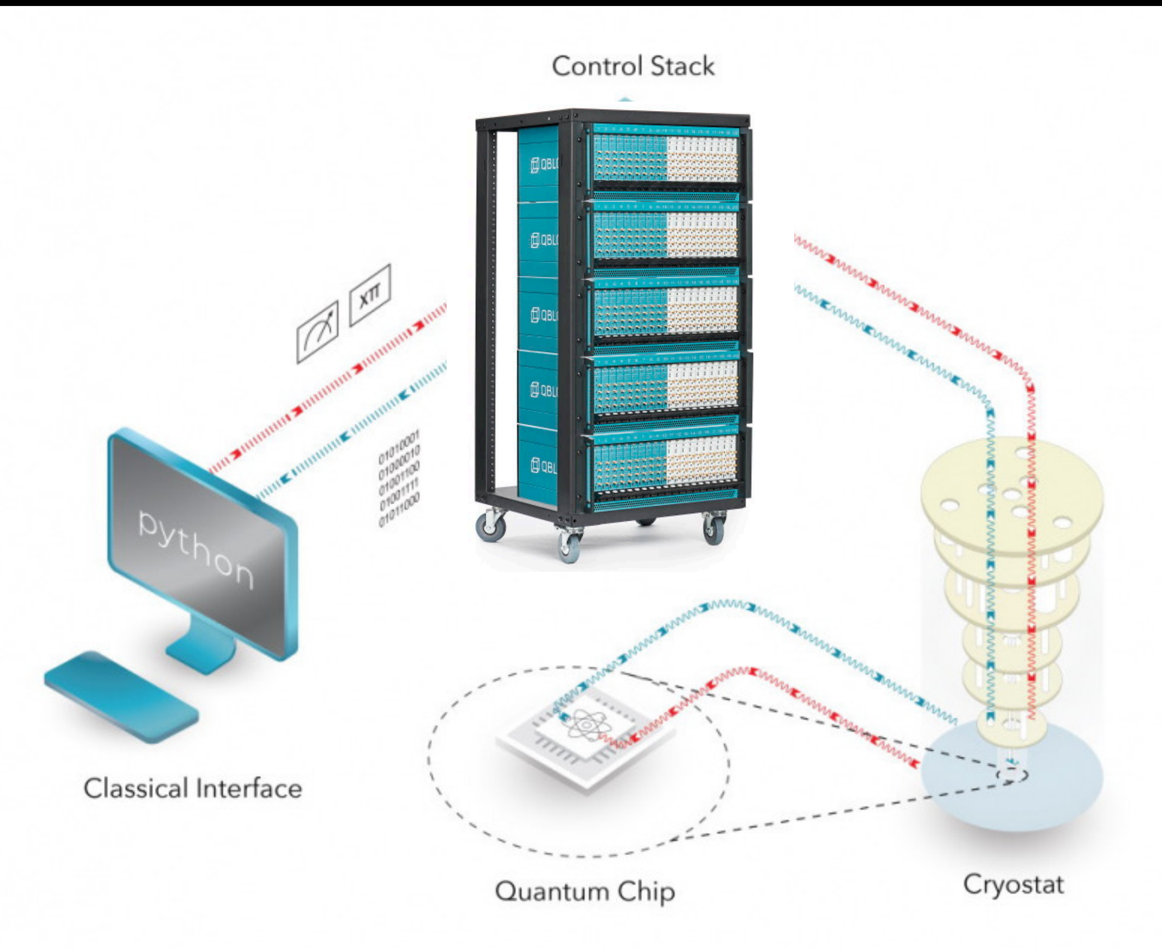
Low-frequency transmon qubits
Medium-frequency transmon qubit
High-frequency transmon qubits
Q0
Q1
Q2
Q3
Q4
Quantware soprano
NISQ experimental
|00 > |01 > |10 > |11 >
|00 > 0.33 0.17 0.34 0.17
|01 > 0.2 0.31 0.19 0.29
|10 > 0.23 0.28 0.22 0.27
|11 > 0.29 0.19 0.31 0.21
Measured state
Prepared state
0.18 0.20 0.22 0.24 0.26
Circuit probability
Theoretical output
|00 > |01 > |10 > |11 >
|00 > 0.5 0.0 0.5 0.0
|01 > 0.0 0.5 0.0 0.5
|10 > 0.0 0.5 0.0 0.5
|11 > 0.5 0.0 0.5 0.0
Measured state
Prepared state
0.00 0.05 0.10 0.15 0.20 0.25
Circuit probability
$|Q_0 = i\rangle$
$|Q_2 = j\rangle$
H
X_{45}
X_{90}
$|Q_0 = i\rangle$
$|Q_2 = j\rangle$
H
Unmitigated
Mitigated
Hellinger fidelity
1.2
1.0
0.8
0.6
0.4
0.2
|00 >
|01 >
|00 >
|01 >
Initial state

QUANTUM COMPUTING NAPOLI



QUANTUM COMPUTING NAPOLI




Control Stack
python
Classical Interface
Quantum Chip
Cryostat

Milestones

- M9-M15: First Tender for Research Infrastructure
- M9-M15. Research activities on Software, Mapping, Compilation, Emulation, Firmware and Hardware at the end of Year 1: Design of quantum algorithms (SW); Classic emulator with 100+ qbits (MW); Report on architectural design of hardware platforms and tools (HW)
- M17-M22: Demonstrators: Use cases implementation and experimentation
- M17-M22: Second Tender for Research Infrastructure
- M22-M26: Research activities on Software, Mapping, Compilation, Emulation, Firmware and Hardware at the end of Year 2: Report on development and validation of quantum algorithms and applications (SW); Report on design of benchmarks for quantum computers and algorithms (MW); Report on design of quantum platforms (HW)
- M25-M36 Use cases: Report on use cases implementation and experimentation

- M25-M36 Research activities on Software, Mapping, Compilation, Emulation, Firmware and Hardware at the end of Year 3: Benchmarking quantum-accelerated applications against classical applications (SW); Test quantum supremacy in industrial setting (MW); Tools and methodologies for design automation and mapping (MW); One platform with 5+ qbits (HW); Photonic sampling machine with 5+ photons and 24+ modes (HW); Report on supporting tools for hardware platforms (HW)

Josephson effect, from primary to secondary quantum effects

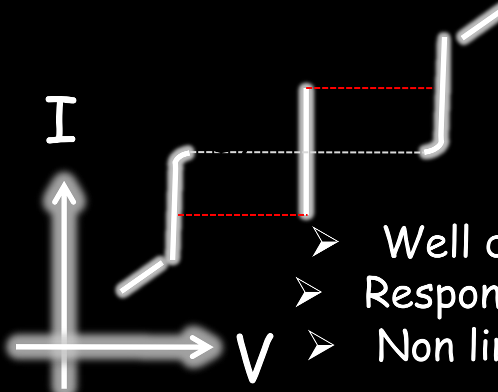
$$\begin{cases} I_S(\varphi) = I_C \sin\varphi \\ \dfrac{\partial\varphi}{\partial t} = \dfrac{2eV}{\hbar} \end{cases}$$

$$\varphi = \varphi_L - \varphi_R$$

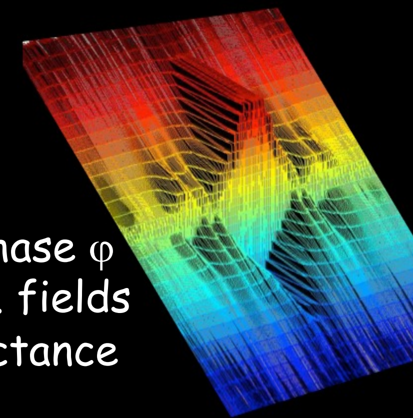
$$E_J >> E_C$$

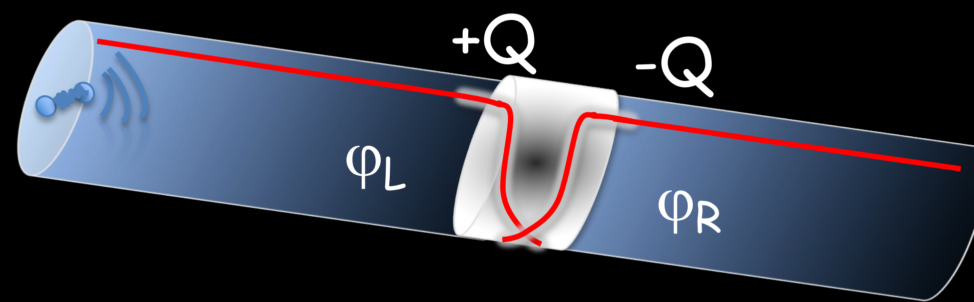
$$E_J = \frac{I_c \phi_o}{2\pi}$$

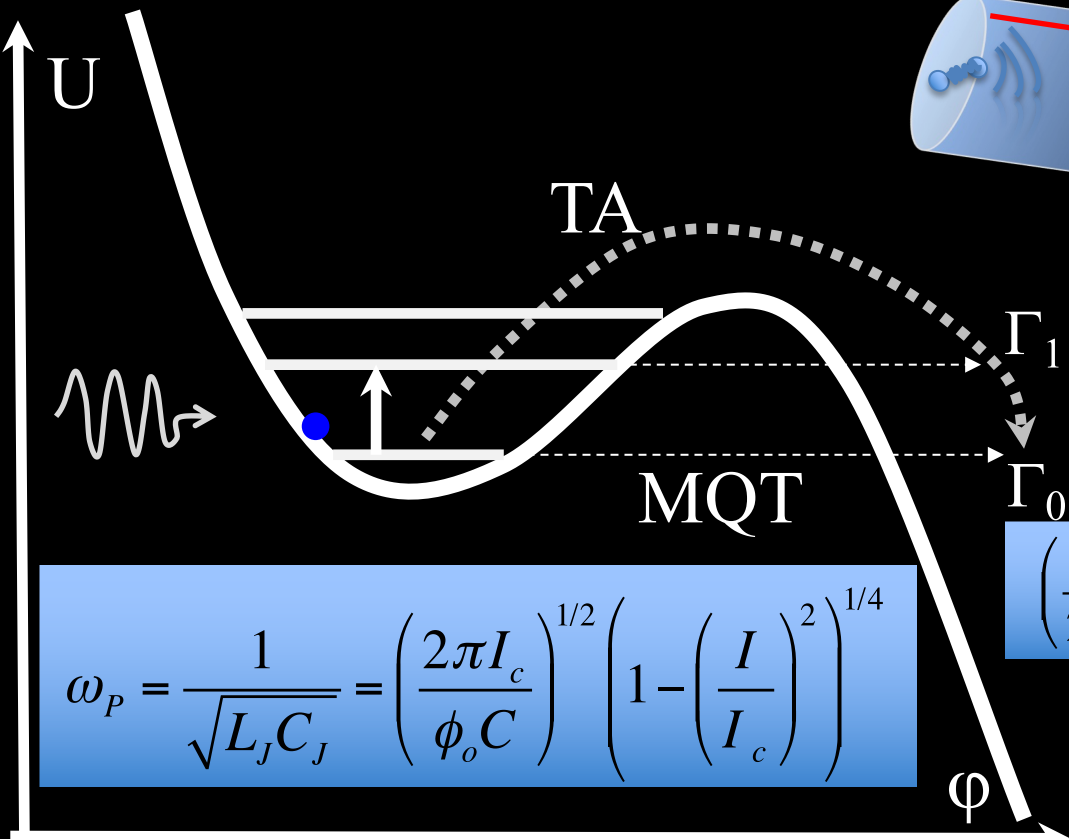
$$E_c = \frac{(2en)^2}{2C}$$



- Well defined phase φ
- Response to e.m. fields
- Non linear inductance







$$\omega_P = \frac{1}{\sqrt{L_J C_J}} = \left(\frac{2\pi I_c}{\phi_o C}\right)^{1/2} \left(1 - \left(\frac{I}{I_c}\right)^2\right)^{1/4}$$

$$I = C\frac{dV(t)}{dt} + GV(t) + I_c \sin\varphi(t)$$

$$\left(\frac{\phi_o}{2\pi}\right)^2 C\frac{\partial^2\varphi}{\partial t^2} + \left(\frac{\phi_o}{2\pi}\right)^2 \frac{1}{R}\frac{\partial\varphi}{\partial t} + \frac{\partial U(\varphi, I)}{\partial\varphi} = 0$$

$$U(\varphi, I) = E_J\left(-\frac{I}{I_c}\varphi - \cos(\varphi)\right)$$

Josephson effect, from primary to secondary quantum effects

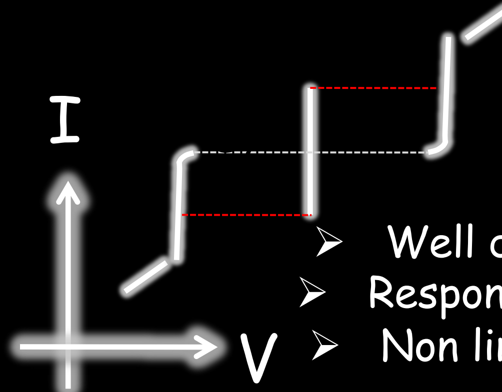
$$\begin{cases} I_S(\varphi) = I_C \sin\varphi \\ \dfrac{\partial\varphi}{\partial t} = \dfrac{2eV}{\hbar} \end{cases}$$

$$\varphi = \varphi_L - \varphi_R$$

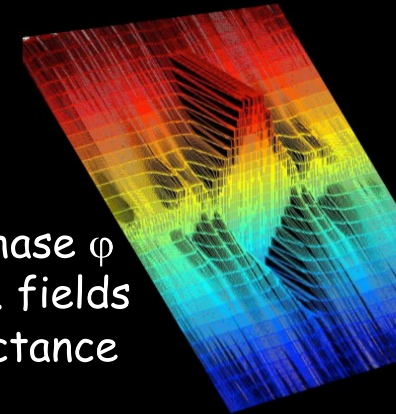
$$E_J >> E_C$$

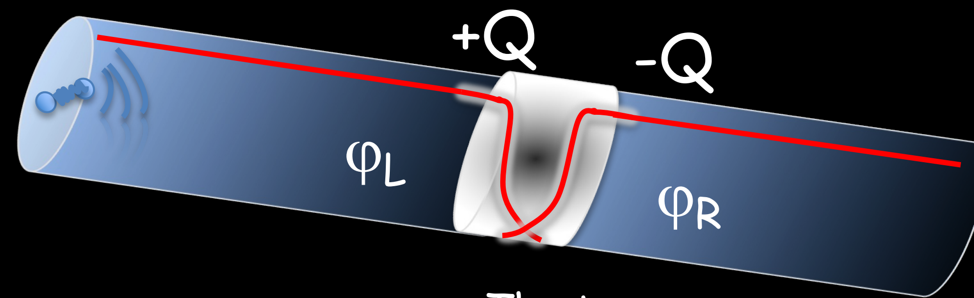
$$E_J = \frac{I_c \phi_o}{2\pi}$$

$$E_c = \frac{(2en)^2}{2C}$$

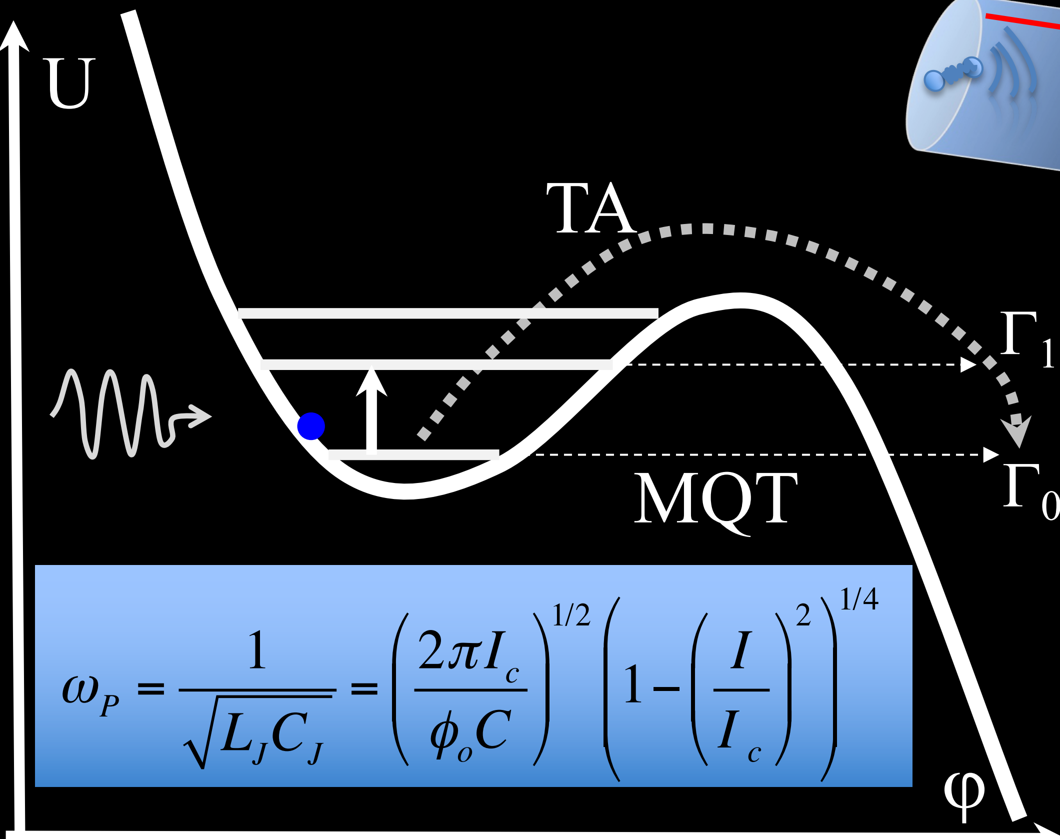


- Well defined phase φ
- Response to e.m. fields
- Non linear inductance

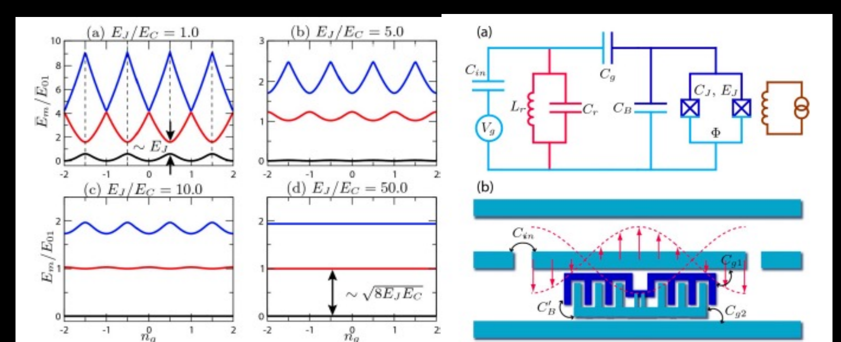




The transmon



$$\omega_P = \frac{1}{\sqrt{L_J C_J}} = \left(\frac{2\pi I_c}{\phi_o C}\right)^{1/2} \left(1 - \left(\frac{I}{I_c}\right)^2\right)^{1/4}$$

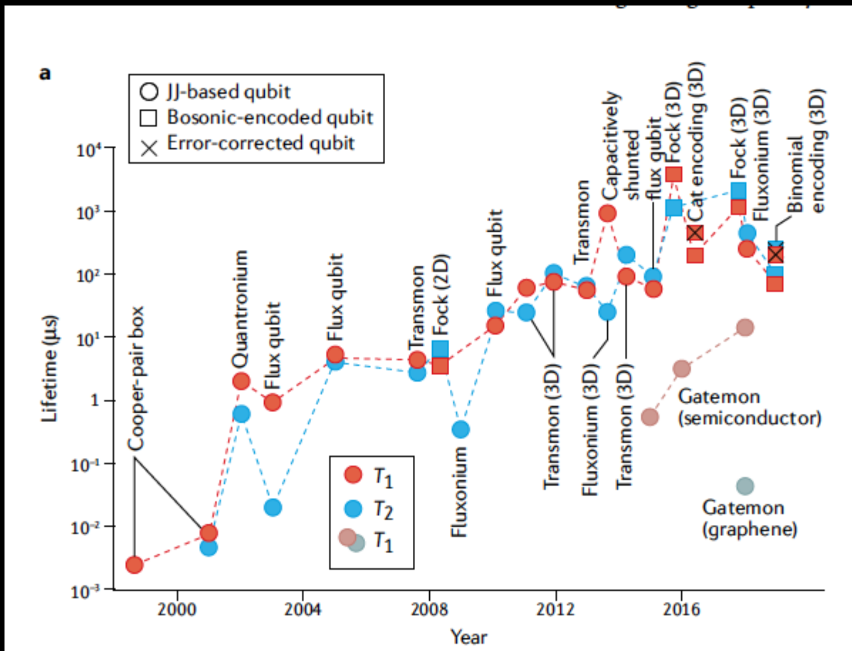


PHYSICAL REVIEW A **76**, 042319 (2007)

Charge-insensitive qubit design derived from the Cooper pair box

Jens Koch,[1] Terri M. Yu,[1] Jay Gambetta,[1] A. A. Houck,[1] D. I. Schuster,[1] J. Majer,[1] Alexandre Blais,[2] M. H. Devoret,[1] S. M. Girvin,[1] and R. J. Schoelkopf[1]

Trends in Superconducting Qubit-oriented hardware activities



- Topology of the circuit
- Optimization of architecture, of every single step in fabrication, including read-out and control
- Quality of the Josephson junctions, reducing noise
- .....

Novel types of qubits

Engineering high-coherence superconducting qubits

Irfan Siddiqi[1,2]

NATURE REVIEWS | MATERIALS
VOLUME 6 | OCTOBER 2021 | 875

REVIEW SCIENCE VOL 339 8 MARCH 2013

Superconducting Circuits for Quantum Information: An Outlook

M. H. Devoret[1,2] and R. J. Schoelkopf[1]*

nature communications

Article https://doi.org/10.1038/s41467-022-34727-2

Engineering superconducting qubits to reduce quasiparticles and charge noise

Received: 3 February 2022
Accepted: 2 November 2022
Published online: 23 November 2022
Check for updates

Xianchuang Pan[1,2,3,8], Yuxuan Zhou[1,2,3,4,8], Haolan Yuan[1,2,3,4], Lifu Nie[1,2,3], Weiwei Wei[1,2,3], Libo Zhang[1,2,3], Jian Li[1,2,3], Song Liu[1,2,3], Zhi Hao Jiang[5], Gianluigi Catelani[6,7], Ling Hu[1,2,3], Fei Yan[1,2,3] & Dapeng Yu[1,2,3,4]

Identifying, quantifying, and suppressing decoherence mechanisms in qubits are important steps towards the goal of engineering a quantum computer or simulator. Superconducting circuits offer flexibility in qubit design; however,

Trends in Superconducting Qubit-oriented hardware activities

nature nanotechnology

Letter https://doi.org/10.1038/s41565-022-01223-z

Quantum-noise-limited microwave amplification using a graphene Josephson junction

Received: 29 March 2022

Accepted: 18 August 2022

A list of authors and their affiliations appears at the end of the paper

nature communications

Article https://doi.org/10.1038/s41467-022-34614-w

Unimon qubit

Received: 4 May 2022

Accepted: 28 October 2022

Published online: 12 November 2022

Check for updates

Eric Hyyppä[1], Suman Kundu[2], Chun Fai Chan[1], András Gunyhó[2], Juho Hotari[1], David Janzso[1], Kristinn Juliusson[1], Olavi Kiuru[2], Janne Kotilahti[1], Alessandro Landra[1], Wei Liu[1], Fabian Marxer[1], Akseli Mäkinen[1], Jean-Luc Orgiazzi[1], Mario Palma[1], Mykhailo Savytskyi[1], Francesca Tosto[1], Jani Tuorila[1], Vasilii Vadimov[2], Tianyi Li[1], Caspar Ockeloen-Korppi[1], Johannes Heinsoo[1,4], Kuan Yen Tan[1,4], Juha Hassel[1,4] & Mikko Möttönen[1,2,3,4]

News & views

Superconducting devices https://doi.org/10.1038/s41565-022-01239-5

Graphene amplifier reaches the quantum limit

Kin Chung Fong

Check for updates

Graphene Josephson junctions enable parametric amplification at the quantum noise limit with gate-tuneable working frequency.

tracking quantum trajectory, and even searching for the rare event when the axion dark matter converts into a microwave photon under a high magnetic field. Writing in *Nature Nanotechnology*, two independent reports by Guilliam Butseraen et. al.[5] and Joydip Sarkar et. al.[6], now

nature materials

Article https://doi.org/10.1038/s41563-022-01417-9

Granular aluminium nanojunction fluxonium qubit

Received: 18 February 2022

Accepted: 20 October 2022

Published online: 8 December 2022

Check for updates

D. Rieger[1,4], S. Günzler[1,2,4], M. Spiecker[1], P. Paluch[1,2], P. Winkel[1,2], L. Hahn[3], J. K. Hohmann[3], A. Bacher[3], W. Wernsdorfer[1,2] & I. M. Pop[1,2]

Mesoscopic Josephson junctions, consisting of overlapping superconducting electrodes separated by a nanometre-thin oxide layer, provide a precious source of nonlinearity for superconducting quantum circuits. Here we show that in a fluxonium qubit, the role of the Josephson

nature physics

Article https://doi.org/10.1038/s41567-022-01929-w

Broadband squeezed microwaves and amplification with a Josephson travelling-wave parametric amplifier

Received: 22 February 2022

Accepted: 16 December 2022

Published online: 9 February 2023

Check for updates

Jack Y. Qiu[1,2], Arne Grimsmo[3,7], Kaidong Peng[1,2], Bharath Kannan[1,2,8], Benjamin Lienhard[1,2], Youngkyu Sung[1,2,8], Philip Krantz[1], Vladimir Bolkhovsky[4], Greg Calusine[4], David Kim[4], Alex Melville[4], Bethany M. Niedzielski[4], Jonilyn Yoder[4], Mollie E. Schwartz[4], Terry P. Orlando[1,2], Irfan Siddiqi[6], Simon Gustavsson[1,8], Kevin P. O'Brien[1,2] & William D. Oliver[1,2,4,8]

Quantum integrated solutions and components

Novel types of qubits

Quantum interfaces

nature physics

Article https://doi.org/10.1038/s41567-023-02071-x

Direct manipulation of a superconducting spin qubit strongly coupled to a transmon qubit

Received: 1 September 2022

Accepted: 26 April 2023

Published online: 22 May 2023

Marta Pita-Vidal[1,9], Arno Bargerbos[1,9], Rok Žitko[2,3], Lukas J. Splitthoff[1], Lukas Grünhaupt[1], Jaap J. Wesdorp[1], Yu Liu[4], Leo P. Kouwenhoven[1], Ramón Aguado[5], Bernard van Heck[6,7], Angela Kou[8] & Christian Kraglund Andersen[1]

simulator. Superconducting circuits offer flexibility in qubit design; however,

Ferromagnetic Josephson junctions among possible proposals for novel types of qubits

PHYSICAL REVIEW B **105**, 214522 (2022)

Hybrid ferromagnetic transmon qubit: Circuit design, feasibility, and detection protocols for magnetic fluctuations

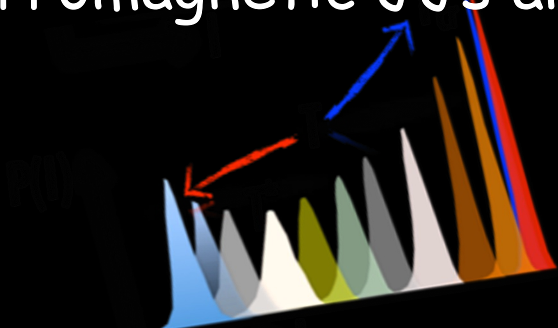
Halima Giovanna Ahmad,[1,2,3,*] Valentina Brosco,[4,5] Alessandro Miano,[1,†] Luigi Di Palma,[1] Marco Arzeo,[2] Domenico Montemurro,[1,3] Procolo Lucignano,[1] Giovanni Piero Pepe,[1] Francesco Tafuri,[1,6] Rosario Fazio,[7,1] and Davide Massarotti[8,3]

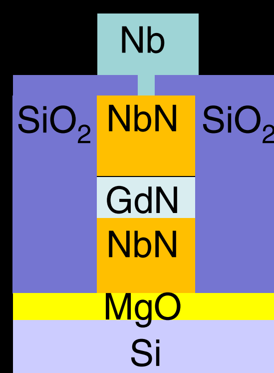
Electrodynamical behavior of ferromagnetic JJs and dissipation

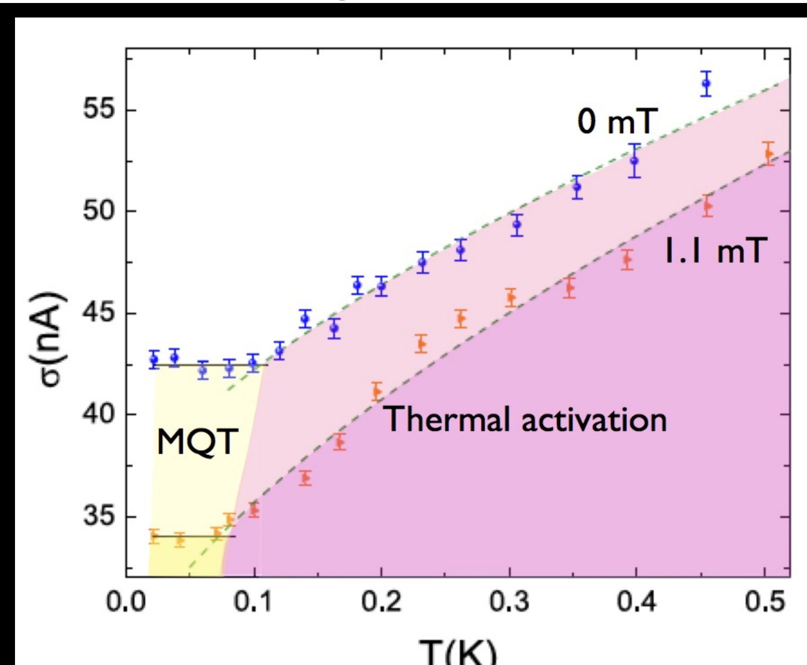
ARTICLE
Received 12 D
nature COMMUNICATIONS
DOI: 10.1038/ncomms8376
OPEN

Macroscopic quantum tunnelling in spin filter ferromagnetic Josephson junctions

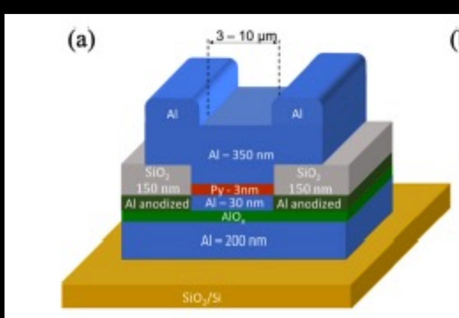
D. Massarotti[1,2], A. Pal[3], G. Rotoli[4], L. Longobardi[4,5], M.G. Blamire[3] & F. Tafuri[2,4]

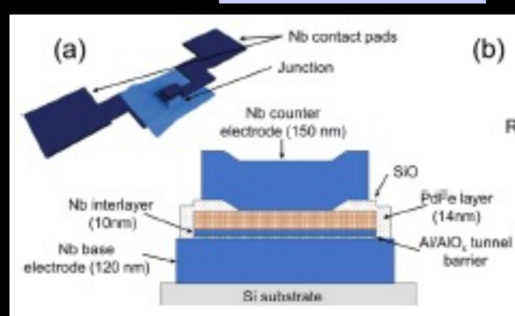






A path through different types of ferromagnetic JJs

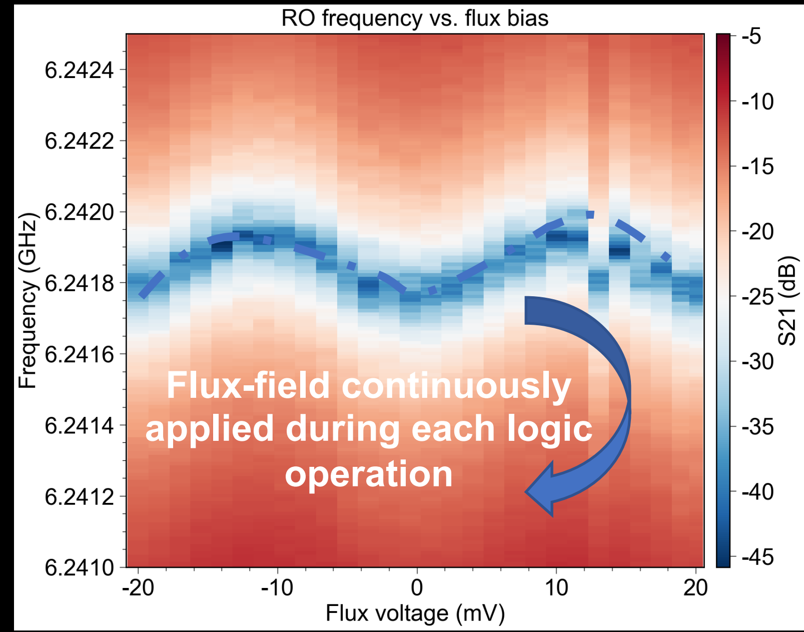




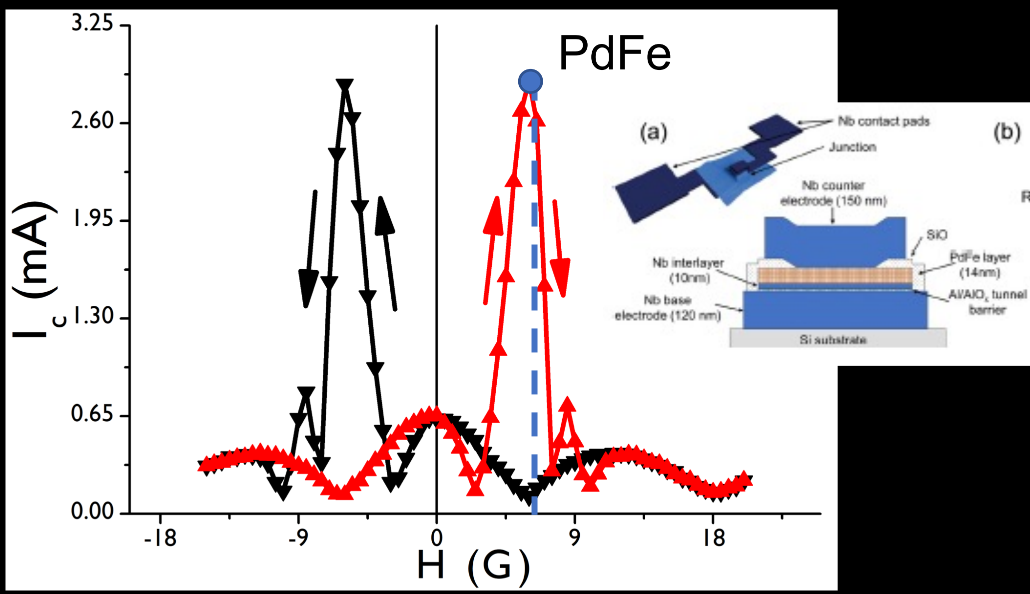
Qubit frequency tuning in standard transmon

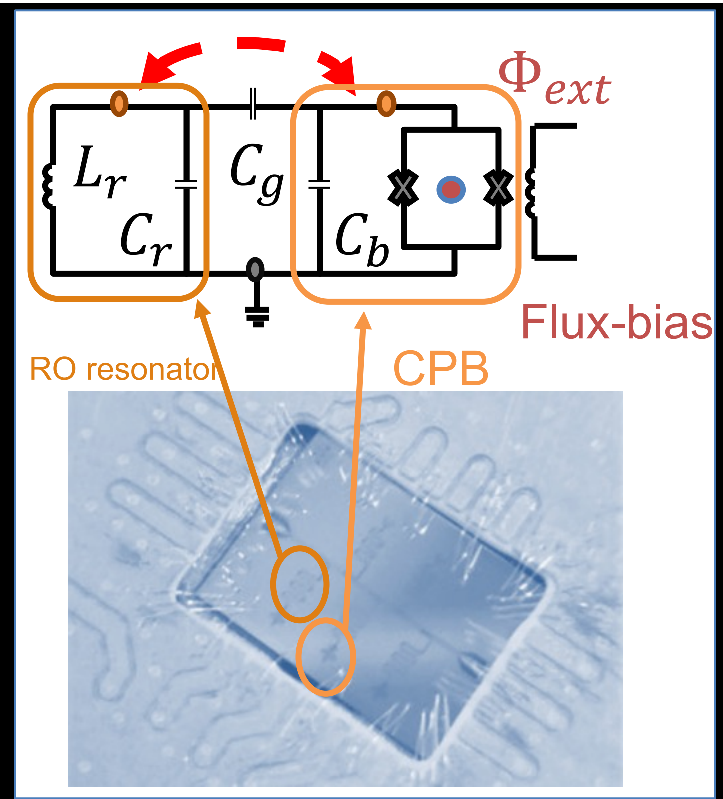
Tunable qubit frequency

$$\omega_Q = \sqrt{8E_J(\Phi_{ext})E_c}$$

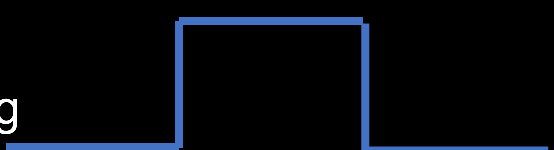


$E_J(\Phi_{ext})$-tuning in SIsFS tunnel JJs





Saturation field

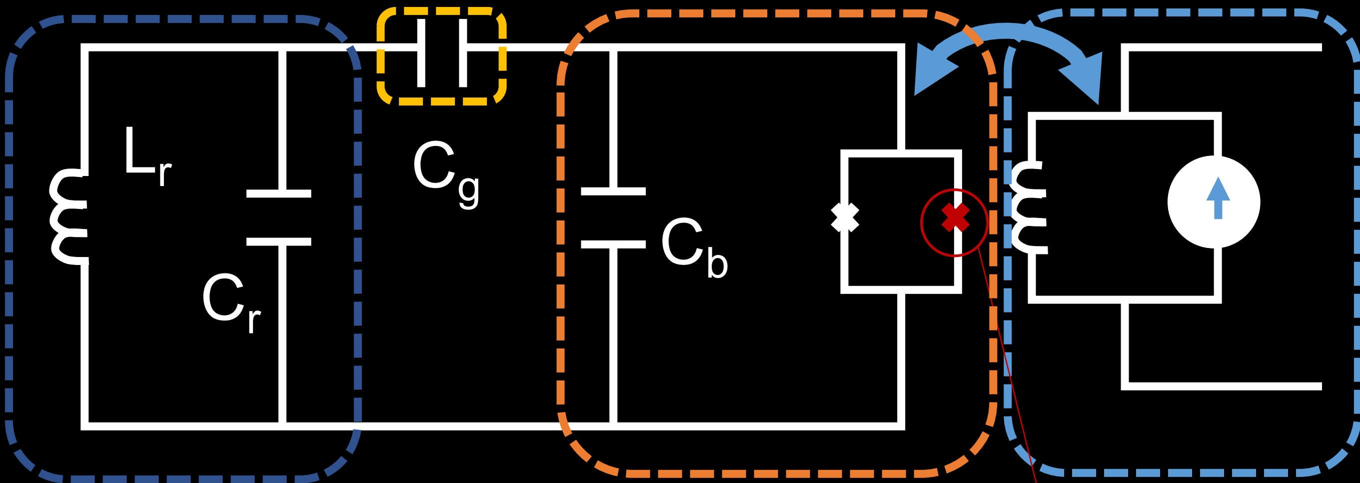


Working point

Transmon qubit based on ferromagnetic JJs-ferrotransmon

Capacitive coupling

Inductive coupling



Transmission line ~ resonator

Split-CPB qubit

Flux drive

Tunnel Ferromagnetic Josephson Junction

- Spin-filter JJs based on GdN insulating ferromagnetic barriers
- SIFS-like Josephson junctions

- Tuning of E_J by using magnetic field pulses
- Qubit as quantum sensor

Tunable qubit frequency

$$\omega_Q = \sqrt{8E_J(\Phi_{ext})E_c}$$

PHYSICAL REVIEW B **105**, 214522 (2022)

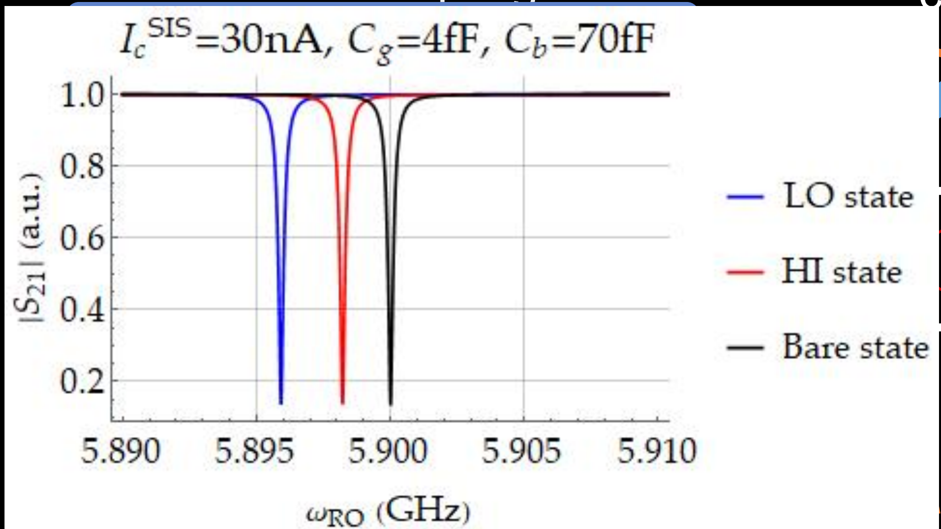
Hybrid ferromagnetic transmon qubit: Circuit design, feasibility, and detection protocols for magnetic fluctuations

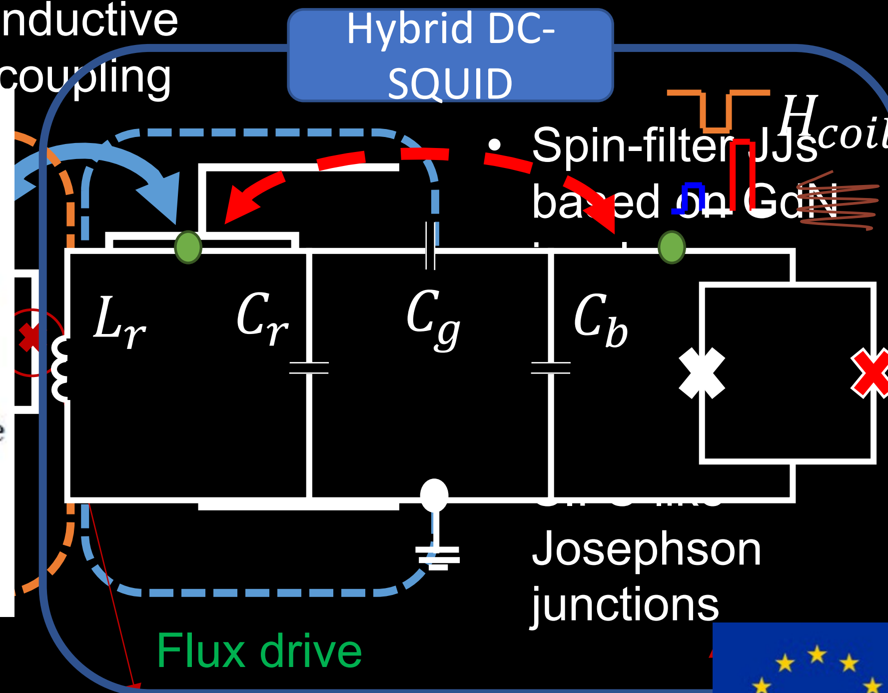
Halima Giovanna Ahmad,[1,2,3,*] Valentina Brosco,[4,5] Alessandro Miano,[1,†] Luigi Di Palma,[1] Marco Arzeo,[2] Domenico Montemurro,[1,3] Procolo Lucignano,[1] Giovanni Piero Pepe,[1] Francesco Tafuri,[1,6] Rosario Fazio,[7,1] and Davide Massarotti[8,3]

Transmon qubit based on ferromagnetic JJs-ferrotransmon

Capacitive coupling

Inductive coupling





- Spin-filter JJs based on GdN

SFS-like Josephson junctions

Transmission line ~ resonator

Split-CPB qubit

Tunnel Ferromagnetic Jo…

FERRO-TRANSMON CIRCUITAL DESIGN AND SIMULATIONS

HORIZON-EIC-2022-PATHFINDERCHALLENGES-01
101115548
FERROMON

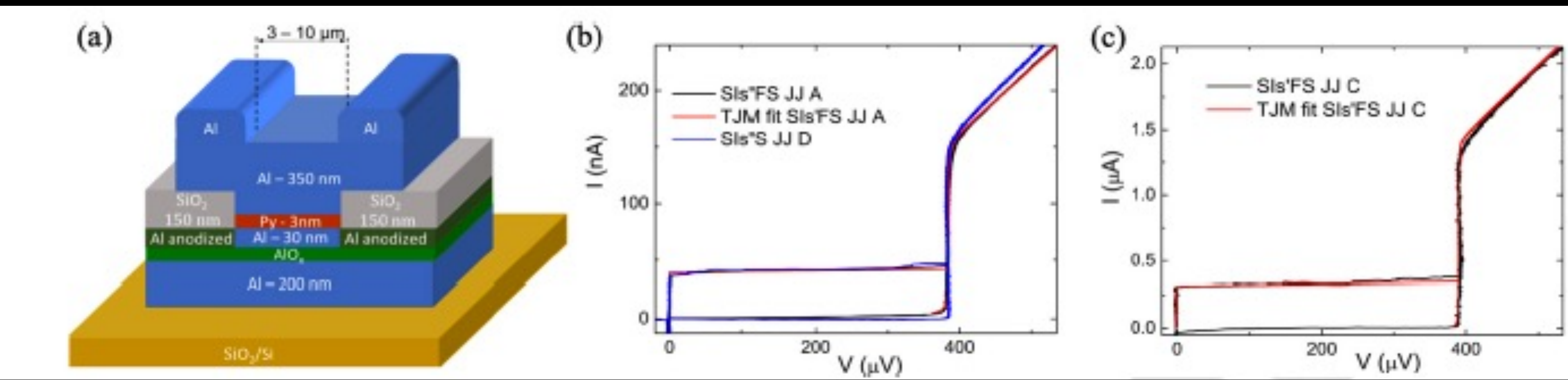
- Tuning of E_J by using magnetic field pulses
- Qubit as quantum sensor

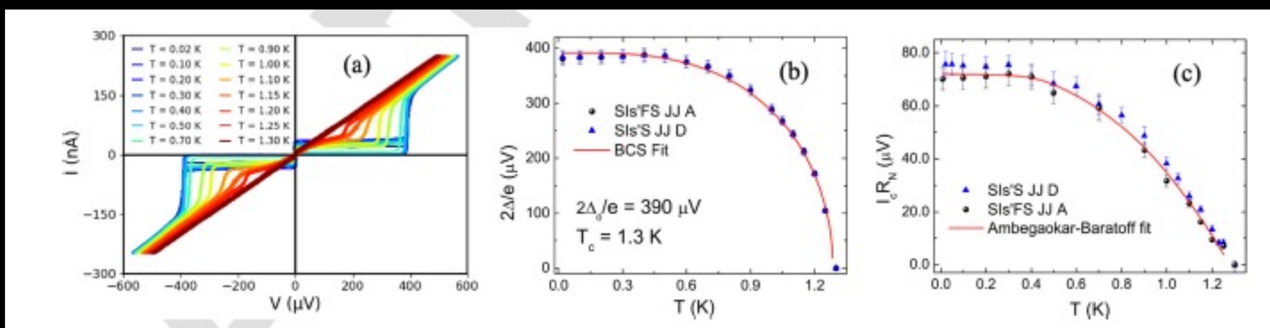
Tunable qubit frequency

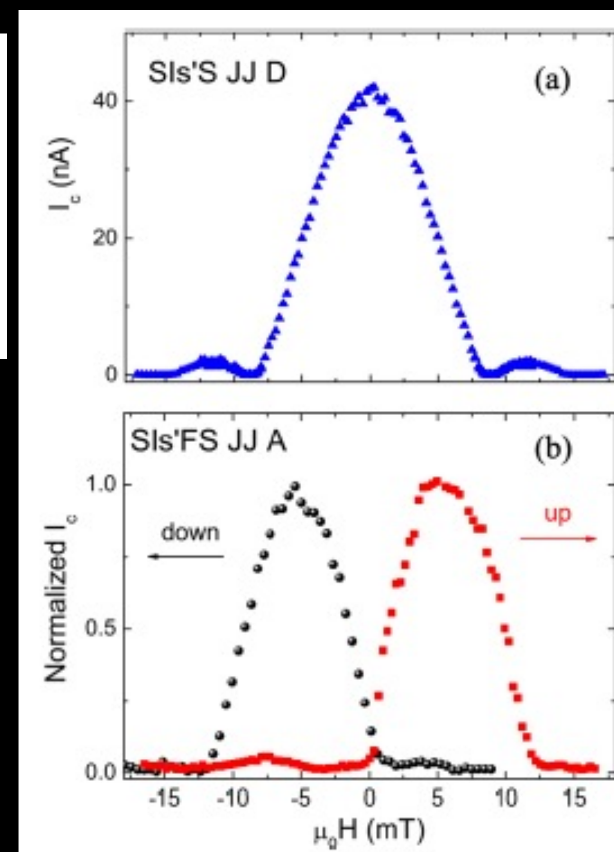
$$\omega_Q = \sqrt{8E_J(\Phi_{ext})E_c}$$

for magnetic fluctuations

Ha… …id[1,2,3,*] Valentina Brosco[4,5] Alessandro Miano[1,†] Luigi Di Palma[1] Marco Arzeo[2]
Domenico Montemurro[1,3] Procolo Lucignano[1] Giovanni Piero Pepe[1]
Francesco Tafuri[1,6] Rosario Fazio[7,1] and Davide Massarotti[8,3]







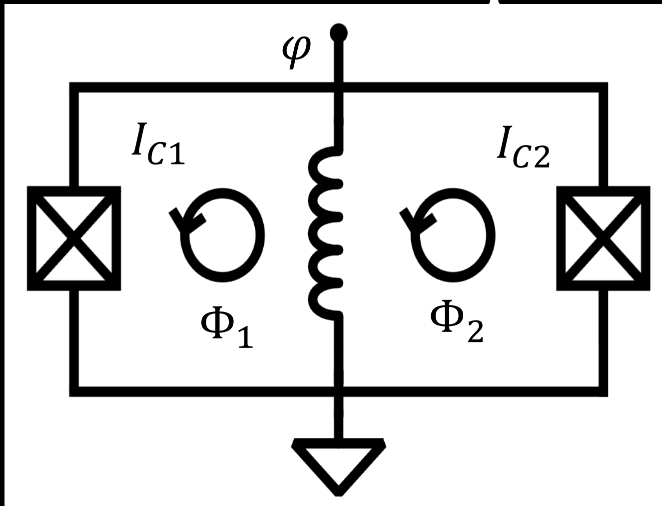
Aluminum-ferromagnetic Josephson tunnel junctions for high quality magnetic switching devices

Cite as: Appl. Phys. Lett. **120**, 000000 (2022); doi: 10.1063/5.0101686
Submitted: 2 June 2022 · Accepted: 12 June 2022 ·
Published Online: 0 Month 0000

View Online Export Citation CrossMark

A. Vettoliere,[1] R. Satariano,[2] R. Ferraiuolo,[2,3] L. Di Palma,[2,3] H. G. Ahmad,[3,4] G. Ausanio,[2,3] G. P. Pepe,[2,3] F. Tafuri,[2,5] D. Montemurro,[2,3] C. Granata,[1] L. Parlato,[2,3] and D. Massarotti[3,4,a)]

Josephson digital phase detector



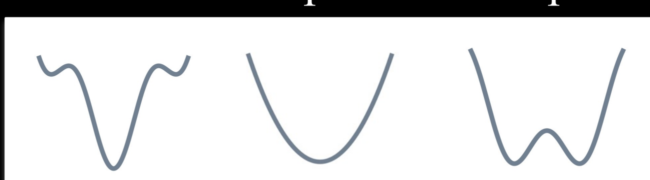
The JDPD is composed by two RF SQUIDs that share an inductive load.
Potential energy:

$$U(\varphi) = \frac{E_l}{2}\varphi^2 \underbrace{- \frac{\Phi_0}{2\pi}\left[I_{c+}\cos(\phi_+)\cos(\varphi+\phi_-) + I_{c-}\sin(\phi_+)\sin(\varphi+\phi_-)\right]}_{2E_j}$$

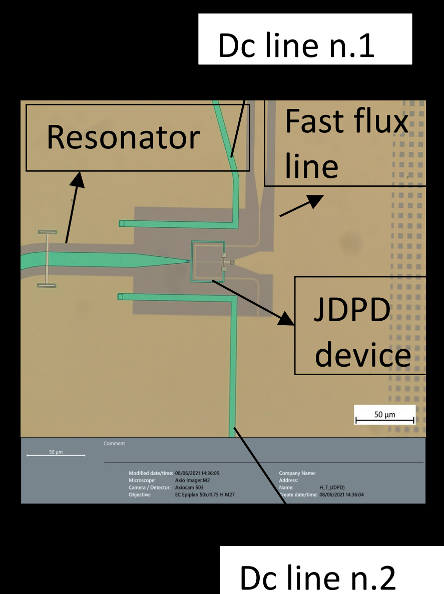
Two degrees of freedom given by Φ_1 and Φ_2

$$\Phi_+ = \Phi_1 + \Phi_2$$
$$\Phi_- = \Phi_1 - \Phi_2$$

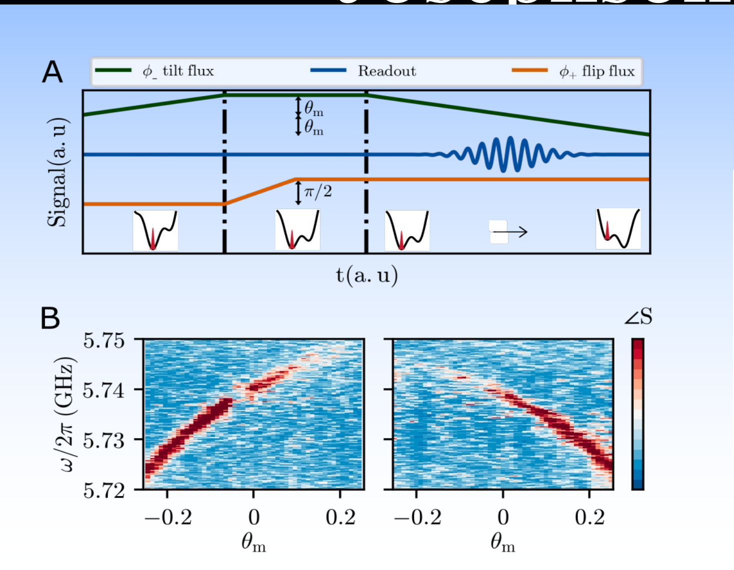
Modifies the potential shape



Provides the tilt



Josephson digital phase detector



PHYSICAL REVIEW APPLIED 19, 064025 (2023)

Discriminating the Phase of a Coherent Tone with a Flux-Switchable Superconducting Circuit

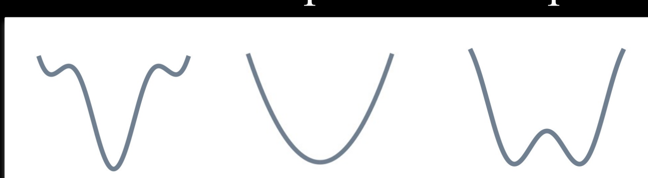
L. Di Palma,[1,2,*] A. Miano,[3] P. Mastrovito,[1] D. Massarotti,[4,5] M. Arzeo,[2] G.P. Pepe,[1] F. Tafuri,[1,6] and O. Mukhanov[7]

$$U(\varphi) = \frac{E_l}{2}\varphi^2 - \frac{\Phi_0}{2\pi}\underbrace{\left[I_{c+}\cos(\phi_+)\cos(\varphi+\phi_-) + I_{c-}\sin(\phi_+)\sin(\varphi+\phi_-)\right]}_{2E_j}$$

Two degrees of freedom given by Φ_1 and Φ_2

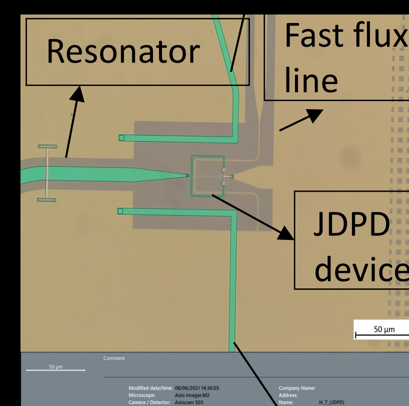
$$\Phi_+ = \Phi_1 + \Phi_2$$
$$\Phi_- = \Phi_1 - \Phi_2$$

Modifies the potential shape



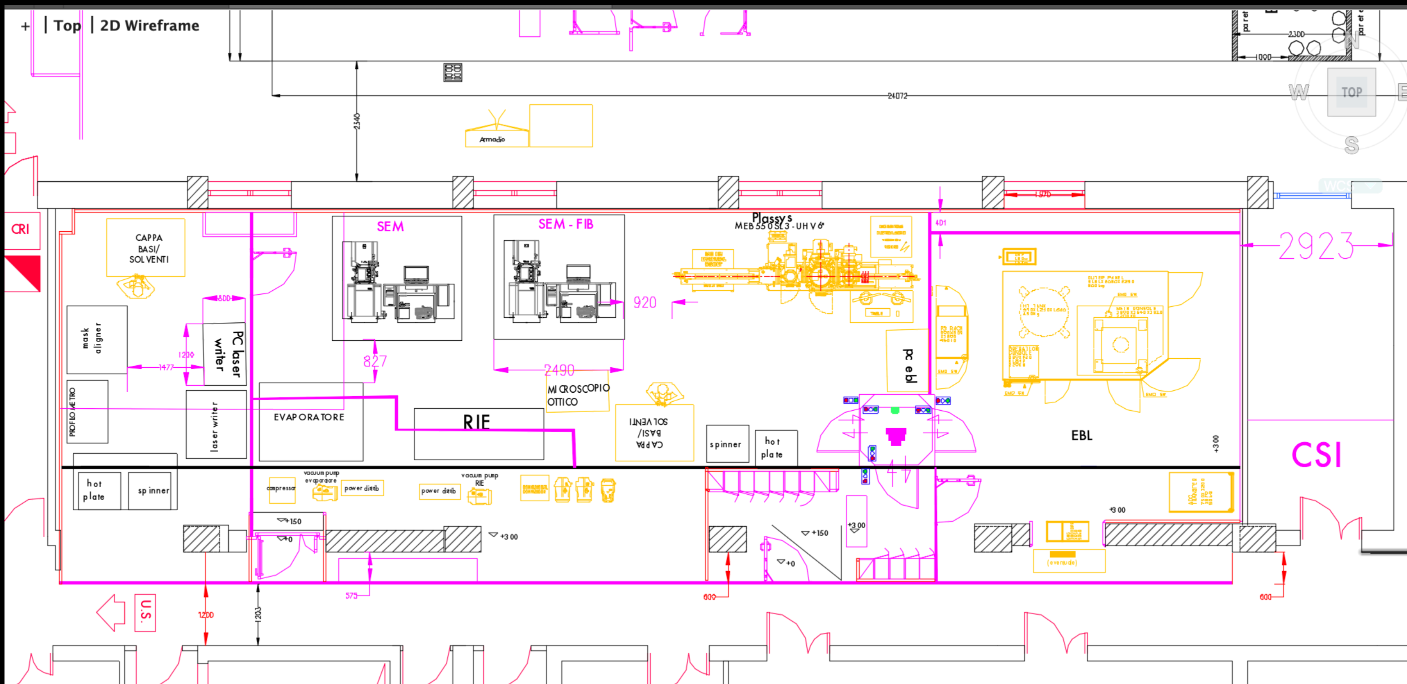
Provides the tilt

Dc line n.1

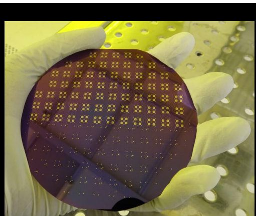


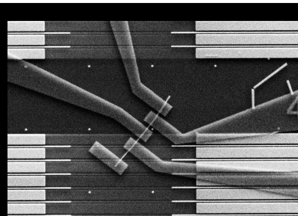
Dc line n.2

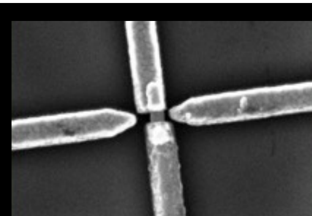
UniNAno: Nanotech facility

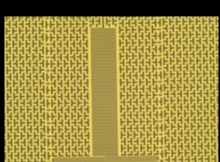


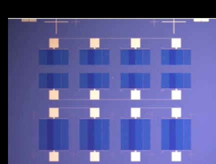
Layout macchine di processo

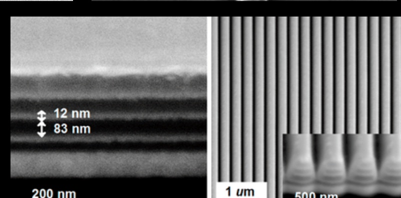




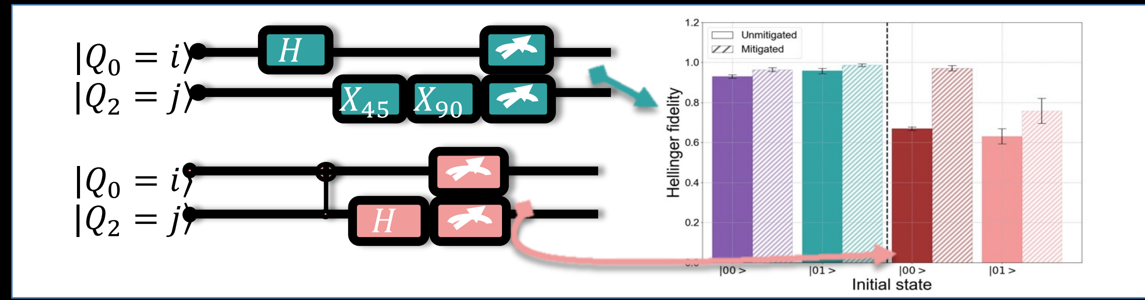




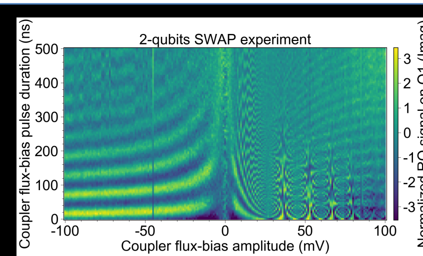


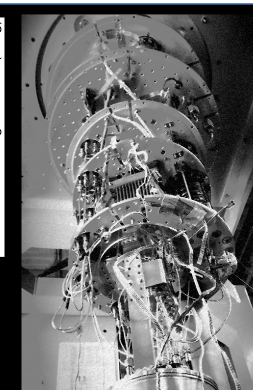


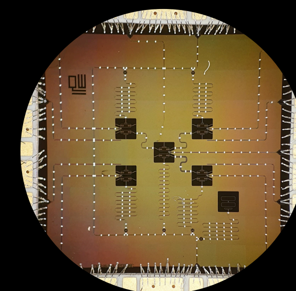
Epilogue



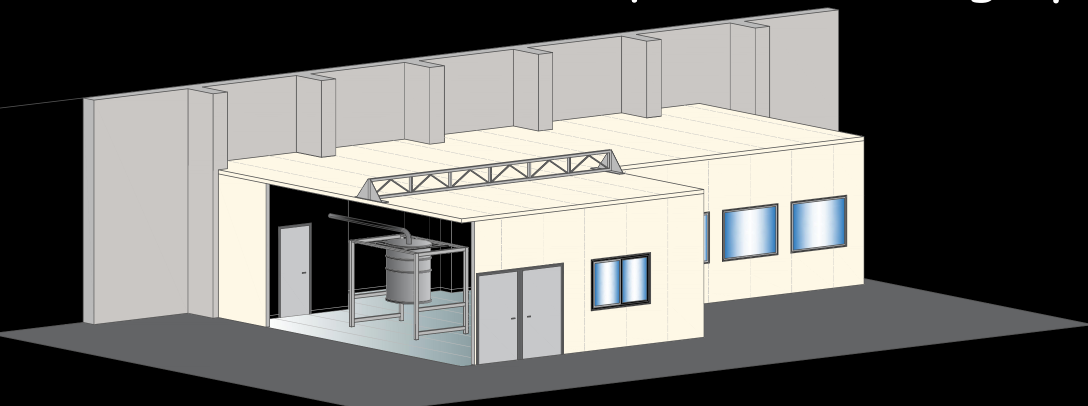
To program a 5-qubit superconducting quantum computer



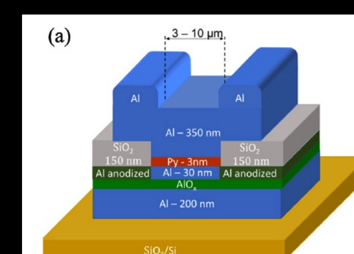




More than 30 qubits, coming up



Alternative qubit design: Ferromagnetic Josephson junctions, Ferrotrasmon



Flexibility in building Hamiltonians, Hamiltonian Engineering, JDPD

because ot its versatilty and electrical properties