Quantum information science with superconducting platform @ INFN

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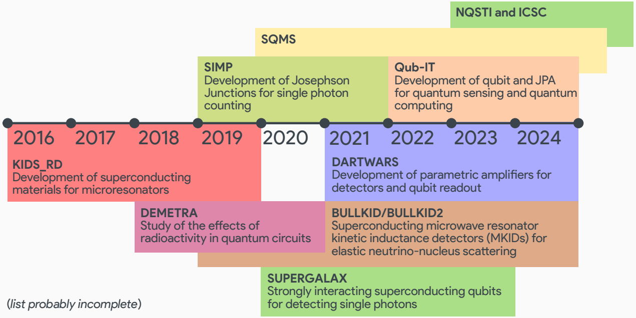
Superconductivity and qubits

Key elements for a superconducting qubits:

- Superconducting materials;
- Josephson junctions;
- rf- and dc-SQUID;
- 2D and 3D cavity resonators;

Different types of superconducting qubits:

- Phase-qubit;
- Flux qubit;
- Cooper Pair Box (CPB)/charge qubit:
  - Transmon (Xmon);
  - Fluxonium (also a flux qubit);
- Cat qubit;
- ...



(list probably incomplete)

- INFN has extensive experience in resonators, Josephson junctions, and cavities developed in the detector field, and more recently, in quantum systems;
- Experience developed in collaboration with other institute in Italy: CNR, FBK, INRiM, etc;
- Member of the newly created The National Quantum Science and Technology Institute (NQSTI) and National Research Centre for High Performance Computing, Big Data and Quantum Computing

Qub-IT Project

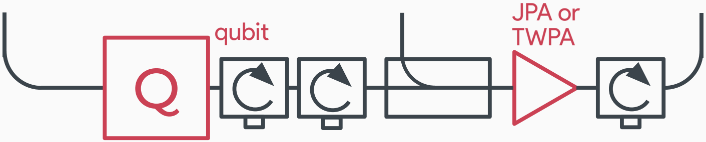
PI: Claudio Gatti, institutes involved: INFN, FBK, CNR, TII   web.infn.it/qub-it

- Development of high fidelity universal 2D and 3D quantum gates for quantum sensing and computing;
- Development of a quantum optimal control system using open source hardware/software;
- Development of a Josephson parametric amplifier for qubit readout and as entangled photons sources;

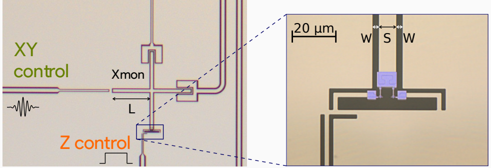
DARTWARS Project

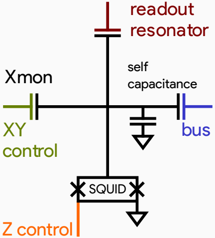
PI: Andrea Giachero, insitutes involved: INFN, FBK, INRiM   dartwars.unimib.it

- Development of broadband quantum limited traveling wave parametric amplifiers (TWPA);
- Multiplexed readout demonstration with qubits, cavities, and detectors (TESs, MKIDs, MMCs);
- Use of TWPA for microwave squeezing and entangled photons generations



- **Transmon qubit** has become the most widely used superconducting qubit *Nature 549, 242–246 (2017)*
  - transmon regime: $E_J/E_C \sim \mathcal{O}(100)$
    E_J: Josephson energy
    E_C: charging energy
  - less sensitive to higher-order effects of the 1/f charge noise;
  - less sensitive to the problem of quasiparticle poisoning;
- **Transmon in Xmon form** *Nature 508, 500–503 (2014)*
  - straightforward connectivity: its four arms allow connections with separate elements.
    - resonator for readout;
    - control to excite the qubit state;
    - control to tune the qubit frequency;
    - quantum bus resonator
  - fast control: separate control line *Phys. Rev. Lett. 111, 080502*
  - long coherence: $T_2 \simeq 500\ \mu s$ *npj Quantum Inf 8, 3 (2022)*



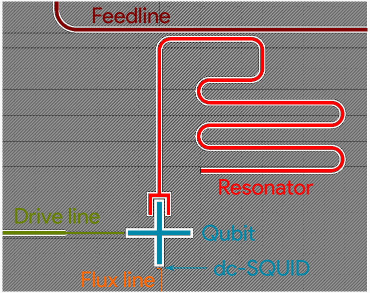


Phys. Rev. Lett. 111, 080502

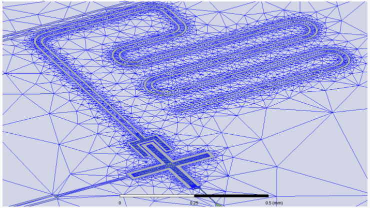
$$E_C = \frac{4e^2}{2C}\ , \quad E_J = \frac{\hbar I_c}{2e}$$

Qubit design and simulations

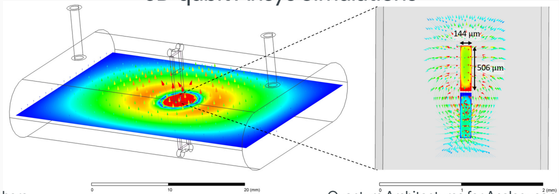
- **Qubit design** created by using qiskit-metal (IBM) and KQCircuits (IQM)
  - target Hamiltonian definition;
  - qubit lines and geometry definition;
- **Electromagnetic Simulations** with commercial tools
  - Ansys HFSS for performing the eigenmode simulation and to compute the resonant frequencies;
  - Ansys Q3D for extracting capacitances and inductances;
- **Quantization** by using dedicated software packages:
  - EPR (Energy Participation ratio) + HFSS *npj Quantum Inf 7, 131 (2021)*
  - LOM (Lumped Oscillator Model) + Q3D *arXiv:2103.10344 [quant-ph]*



2D qubit Ansys Simulations

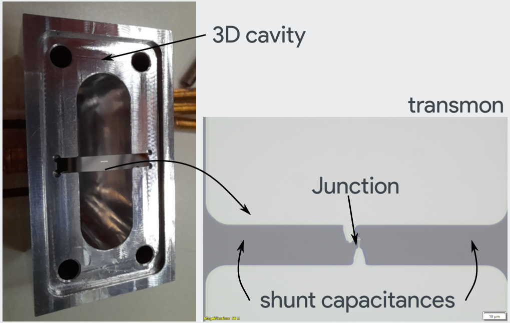


3D qubit Ansys Simulations



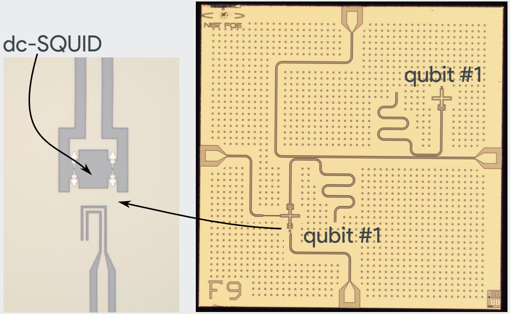
3D and 2D qubit productions

3D Transmon qubit

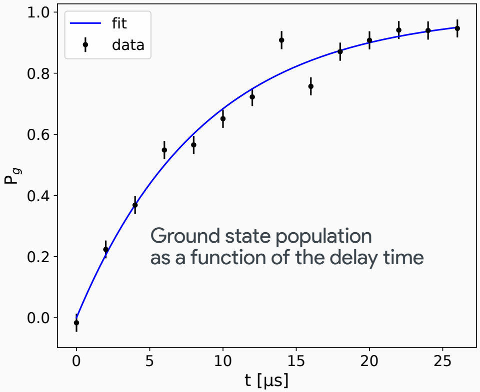


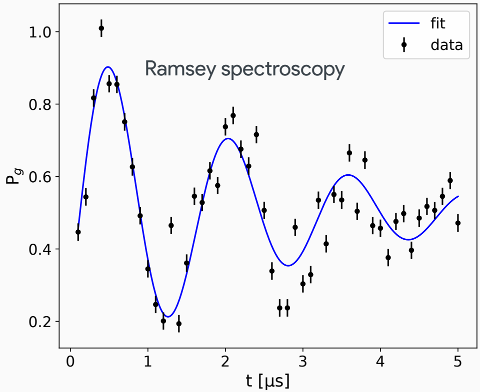
- Transmons in superconducting 3D cavity;
- Alternative approach for longer coherence time;
- First tests with 3D qubit fabricated at TII (Abu Dhabi, EAU);
- New Al cavities are being designed and fabricated by INFN;
- New transmons for 3D cavities are being developed by CNR-IFN;

2D Xmon qubit

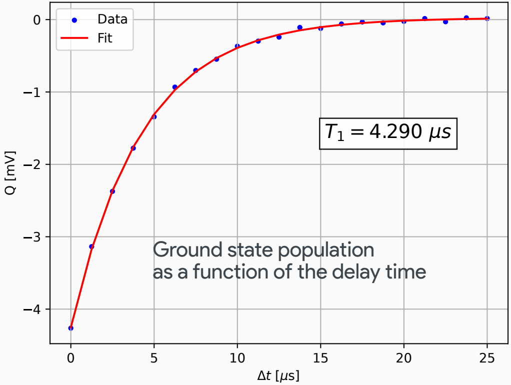


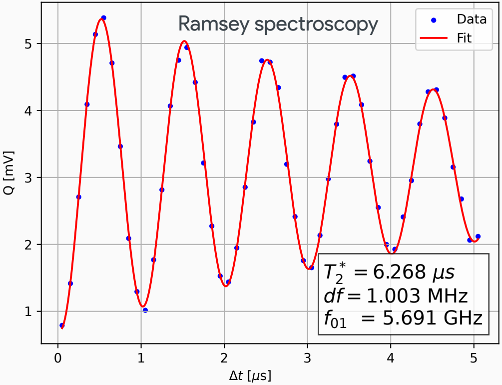
- Transmission/readout line (feedline) through $\lambda/4$ resonator;
- Driveline to enable faster qubit control;
- Flux-bias line to tune the energy spacing between states;
- Production foreseen in 2024 at FBK;
- Demonstrative two-qubit (not coupled) chip fabricated at NIST (Superconductive Electronics Group):





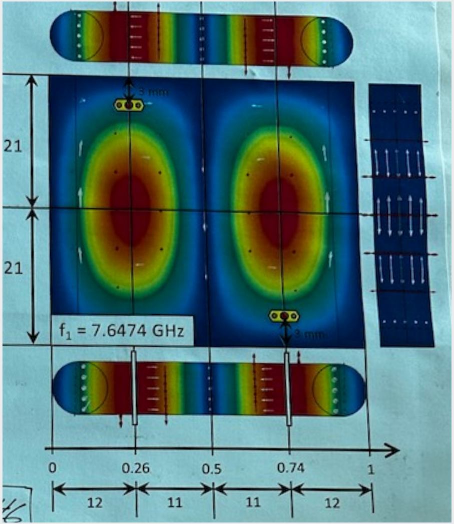
- Simulated resonant frequencies, capacitance, and coupling constant align well with the experimental results;
- Experimental decoherence Times: $T_1 = 8.7\ \mu s$ (relaxation time), $T_2 = 2.3\ \mu s$ (dephasing time);
- Relaxation time from intrinsic lifetime and Purcell effect: $T_1 \sim 42\ \mu s$;
- Underestimation of the participation ratios resulting due to limitations in the numerical mesh resolution.



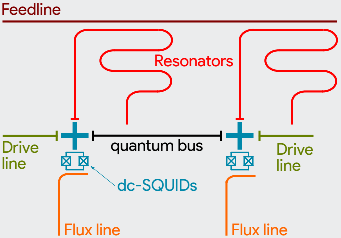


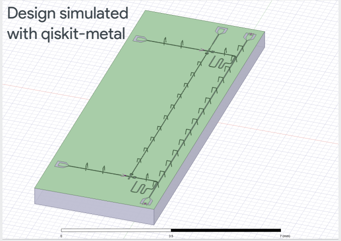
- Qubit and cavity spectroscopy: simulations and measurements are in good agreement;
- Experimental decoherence Times: $T_1 = 4.3\ \mu s$ (relaxation time), $T_2 = 6.3\ \mu s$ (dephasing time);
- Relaxation time from intrinsic lifetime and Purcell effect: $T_1 \sim 24\ \mu s$;
- Low T_1 related to low Q_i measured for readout resonator ⇒ fabrication issue ⇒ new production at NIST during in 2024;
- Same design was adapted for FBK fabrication and produced soon;

Two-qubit gates with 3D design



Two-qubit gates with 2D design





What we learned ...

- Design and simulation of coplanar microresonators and cavities ✔ ☺;
- Design and simulation of 2D and 3D superconducting qubits ✔ ☺;
- Design and simulation of JPA and TWPA ✔ ☺;
- Fabrication of Josephson junction ✔ ☺;
- Fabrication of 3D cavities and coplanar microresonators ✔ ☺;
- Fabrication of qubit and parametric amplifiers (JPA/TWPA) ✔ ☺;
- Readout of qubits with discrete components (AWGs, synthesizer, DAQs) ✔ ☺;
- Readout of qubits with programmable logic device (RFSoC boards) ✔ ☺;
- Design and fabrication of optimized packaging for hosting quantum devices ✔ ☺;

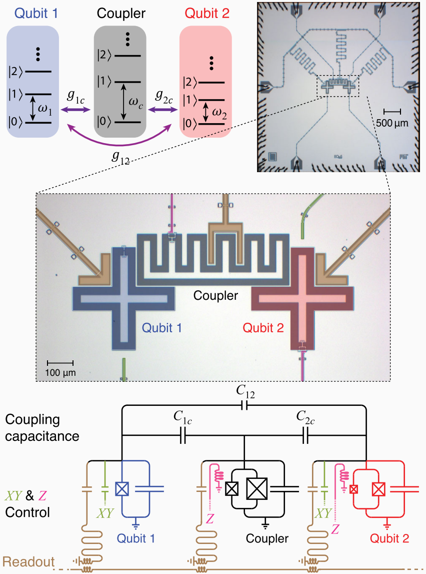
... and what we could do next.

- Design, simulation and fabrication of two-qubit gates based on 2D and 3D transmon;
- Preliminary study on fluxonium qubit (longer coherence times, higher anharmonicity, lower frequencies, which reduces noise and improves stability);
- Design, simulation and fabrication of array of interconnetect qubits;
- Optimal control of array of qubit using last generation of programmable logic device;
- ... and then the sky is the limit;

Enabling technologies for future projects

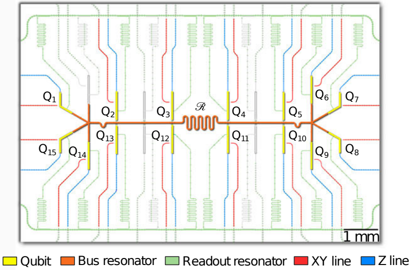
- Modular and versatile quantum interconnect hardware is a key next step in the scaling of quantum information platforms to larger size and greater functionality;
- Tunable couplers use an external control parameter to turn on and off an effective coupling;
- In superconducting circuits an external control parameters can be implemented through SQUID or qubit;
- Tunable couplers that dynamically control the qubit-qubit interaction, are an architectural breakthrough that helps resolve many scalability issues;

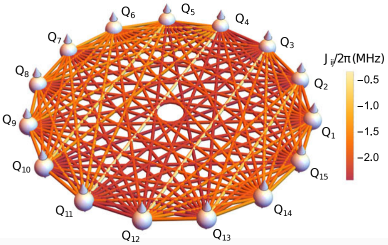
npj Quantum Inf 9, 40 (2023)
Phys. Rev. X 11, 021058 (2021)
Phys. Rev. Lett. 113, 220502 (2014)



- Highly connected networks of qubits allow for entangling qubits with reduced circuit depth;
- Single qubits can be coupled together by using an intermediate electrical coupling circuit (*coupler*);
- Couplers can be implemented as fixed (resonators), tunable (dc-squid, qubit) or parametric (dc-squid) elements;
- All-to-all connectivity between qubits allows two-qubit gates to be executed between any qubit pair;

Quantum Sci. Technol. 6 033001 (2021)
PRX Quantum 3, 040322 (2022)
Phys. Rev. Lett. 119, 180511 (2017)

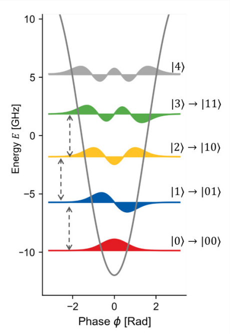


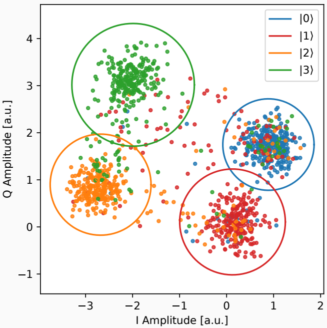


INFN Istituto Nazionale di Fisica Nucleare — CSN5 Technological research — Università degli Studi di Milano Bicocca — BIQUTE

- Multi-level computational unit alternative to the conventional 2-level qubit.
- Compared to qubit, qudit provides a larger state space to store and process information'
- Provide reduction of the circuit complexity, simplification of the experimental setup;
- The accuracy and efficiency of simple quantum circuits and algorithms can be enhanced by qudit-based architecture
- Possibility of driving higher-order transitions in a transmon or fluxonium qubit;

Nat Commun 14, 1971 (2023
Phys. Rev. X 13, 021028 (2023)
arXiv:2303.04261 [quant-ph]





PHYSICAL REVIEW D **108,** 023013 (2023)

Simulating neutrino oscillations on a superconducting qutrit

Ha C. Nguyen[1,2] Bao G. Bach[3] Tien D. Nguyen[1,4] Duc M. Tran[1,5] Duy V. Nguyen[2,6] and Hung Q. Nguyen[1,*]

arXiv:2306.14537v1 [quant-ph] 26 Jun 2023

Qutrit quantum battery: comparing different charging protocols

Giulia Gemme[1], Michele Grossi[2], Sofia Vallecorsa[2], Maura Sassetti[1,3] and Dario Ferraro[1,3]