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NQSTI
National Quantum Science and Technology Institute

Advancing Quantum Sensing through the Development of an Integrated Stack Utilizing Superconducting Devices

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UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

BIQUTE

Outline

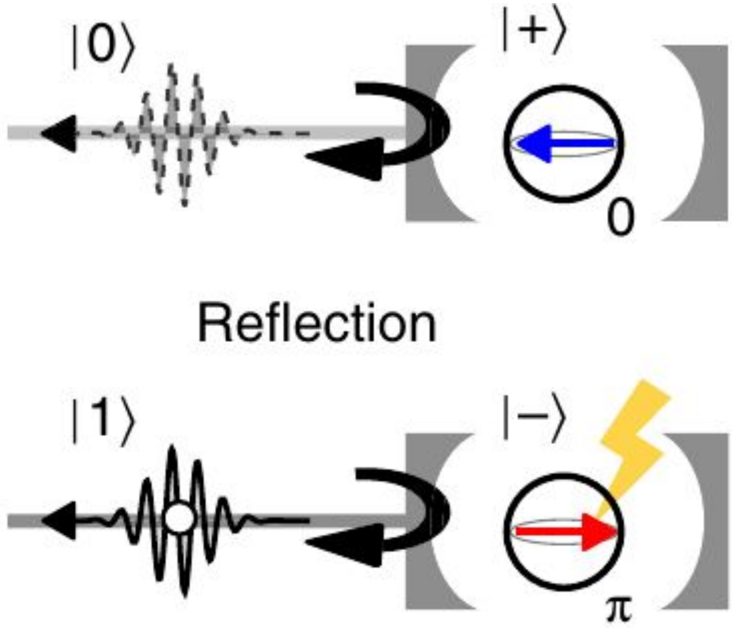
- quantum sensing for microwave photon detection
- the integrated stack development
  - superconducting qubits in CPW and 3D resonators
  - TWPAs for multiplexed readout and for entangled photon generation
  - RFSoC based quantum electronics for control and readout
- conclusions

collaboration among UNIMIB, INFN and FBK partners in **Spoke 6** and

- in collaboration with Spoke 1 (sensing protocols, …) and 5 (TWPA, …)
- in collaboration with CNR-IFN
- in synergy with INFN's DARTWARS and Qub-IT projects, with ICSCI and with more PRIN and EU projects…

Quantum sensing for single microwave photon detection

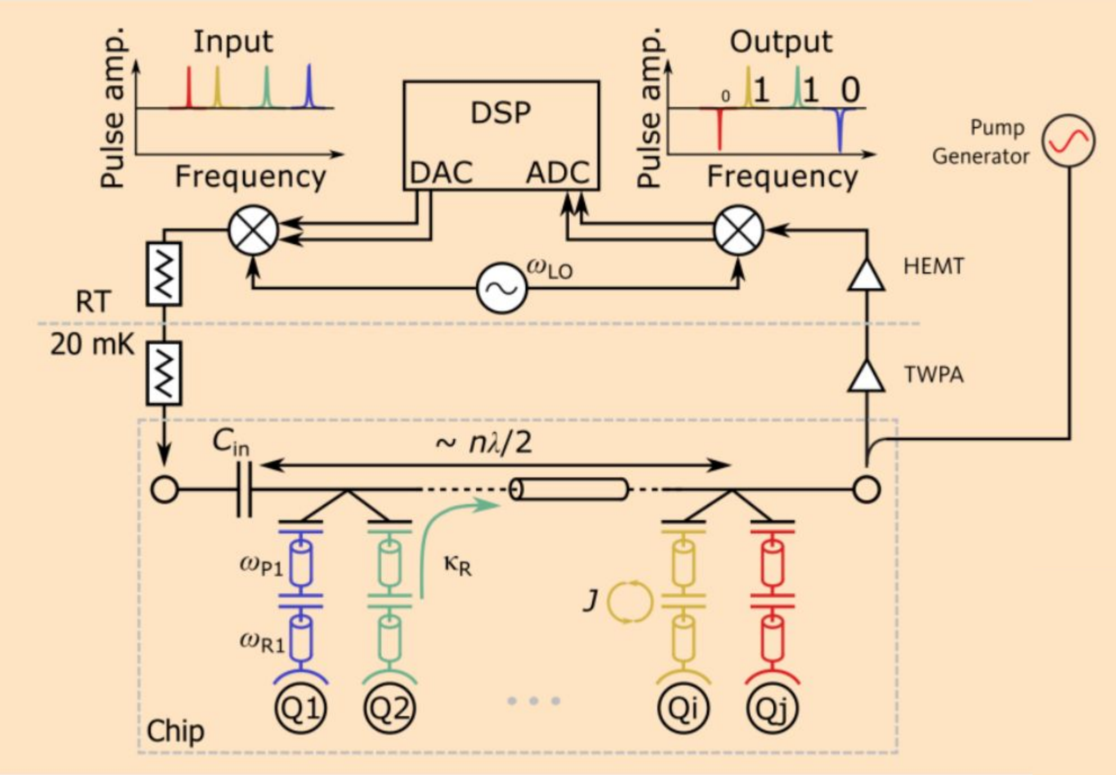
- quantum non-demolition (QND) detection of itinerant microwave photons in CPW
- Ramsey spectroscopy with an array of entangled qubits
  - low dark counts rate (QND) and sensitivity beyond SQL (entangled qubits)
- applications:
  - **searches for axion Dark Matter** (p.e. the QUAX experiment)
    - axions convert into photons in a magnetic field
    - photons propagate through a CPW to the qubit detector
  - searches for hidden photon Dark Matter in 3D resonant cavities
  - remote entanglement protocols in LOQC
  - photon based quantum memories interrogation



Full stack for advanced quantum sensing

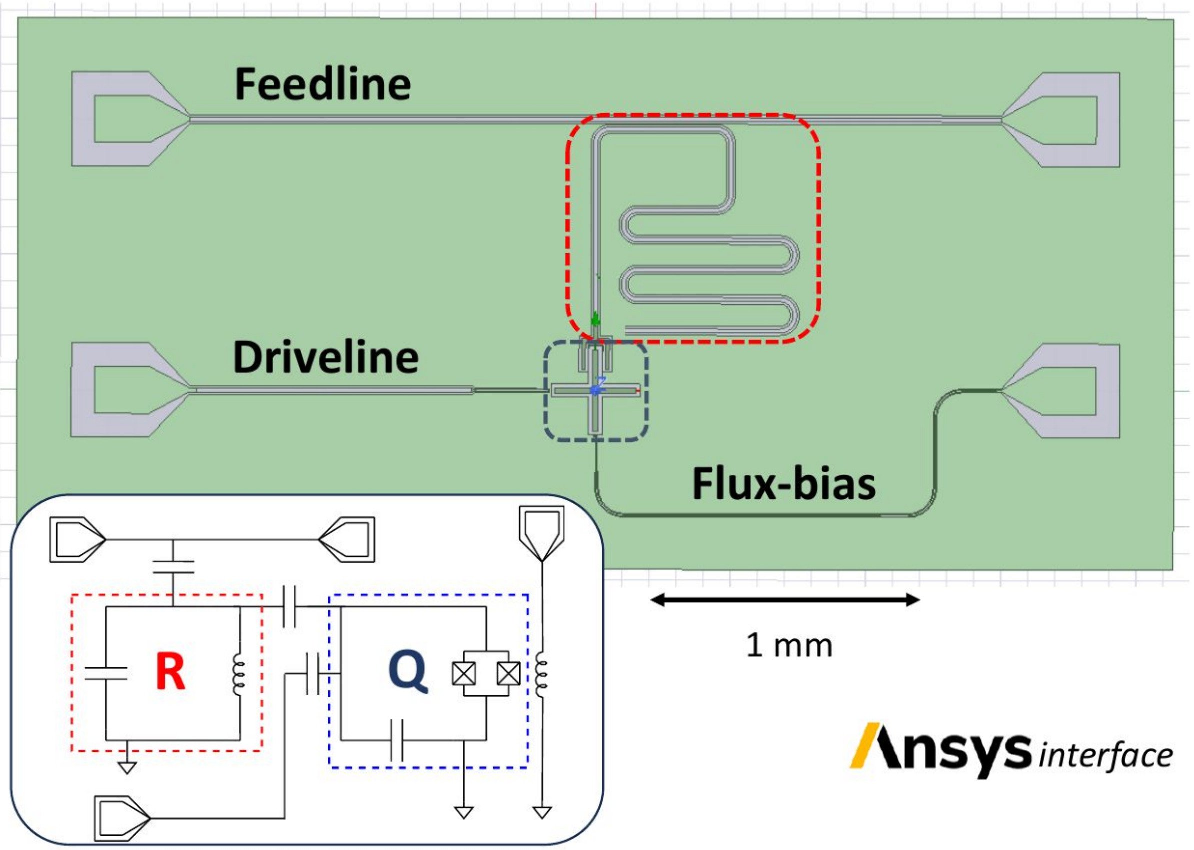
- coupled transmon qubits with dispersive read-out
- wide-band TWPA for quantum-limited multiplexed readout
- RFSoC based quantum electronics

  for digital coherent control and heterodyne readout

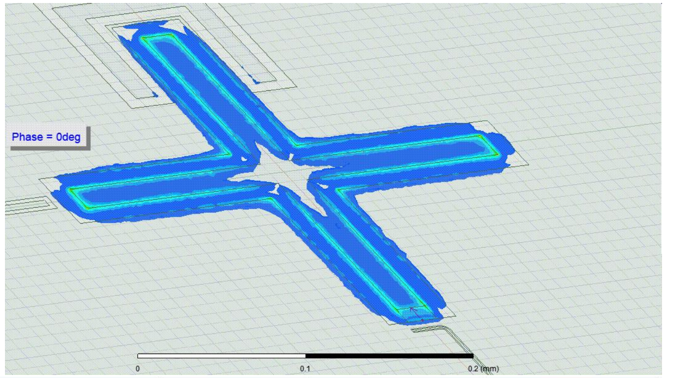


Transmon-type superconducting qubits: design

- grounded **xmon-type transmon**
  - λ/4 resonator
  - capacitive resonator/feedline coupling
  - X-shaped shunt capacitance
  - driveline and flux-bias line for control and frequency tuning
- design: Qiskit Metal (IBM)
  - target Hamiltonian definition
  - qubit-lines layout definition
- EM simulation: Ansys HFSS, Ansys Q3D
- quantization: Energy Participation Ratio (EPR) and Lumped Oscillator Model (LOM)



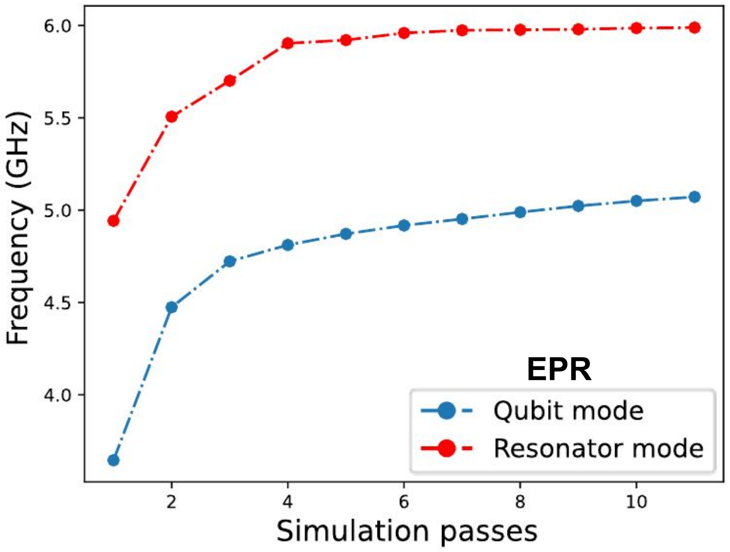
Transmon-type superconducting qubits: prototype simulation

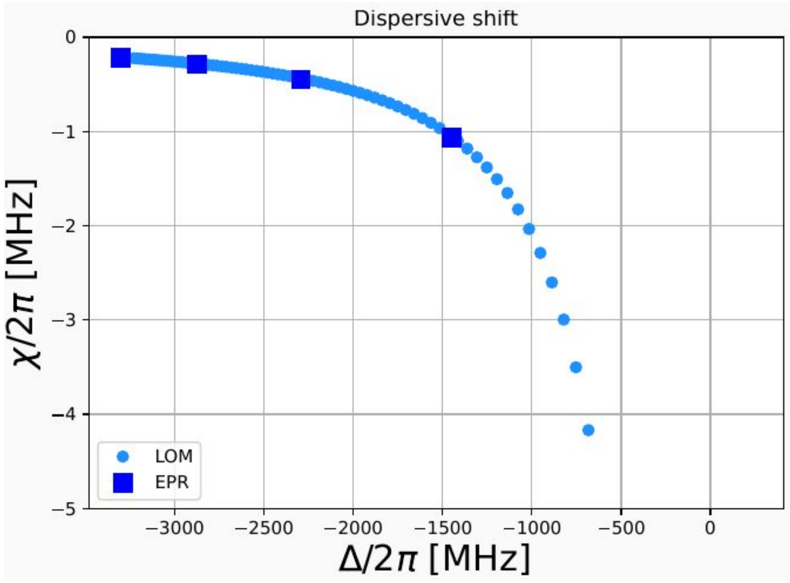


- target values as a result of analytical calculations
- two simulation approaches
  - EPR (Energy Participation ratio) – Ansys HFSS
  - LOM (Lumped Oscillator Model) – Ansys Q3D
- EPR and LOM analyses are consistent with theory

	Target	LOM	EPR
JJ Inductance L_J [nH]	10	10	10
Transmon regime E_j/E_c	>50	78.61	79.96
Anharmonicity $\alpha/2\pi$ [MHz]	202	230.62	216.44
Dispersive shift $\chi/2\pi$ [MHz]	0.30	0.31	0.35
Qubit frequency $\omega_q/2\pi$ [MHz]	5000	4995.79	4893.84
Cavity frequency $\omega_r/2\pi$ [MHz]	7400	7481.04	7435.44
Qubit-res coupling C_g [fF]	4	3.93	–

https://arxiv.org/abs/2310.05238



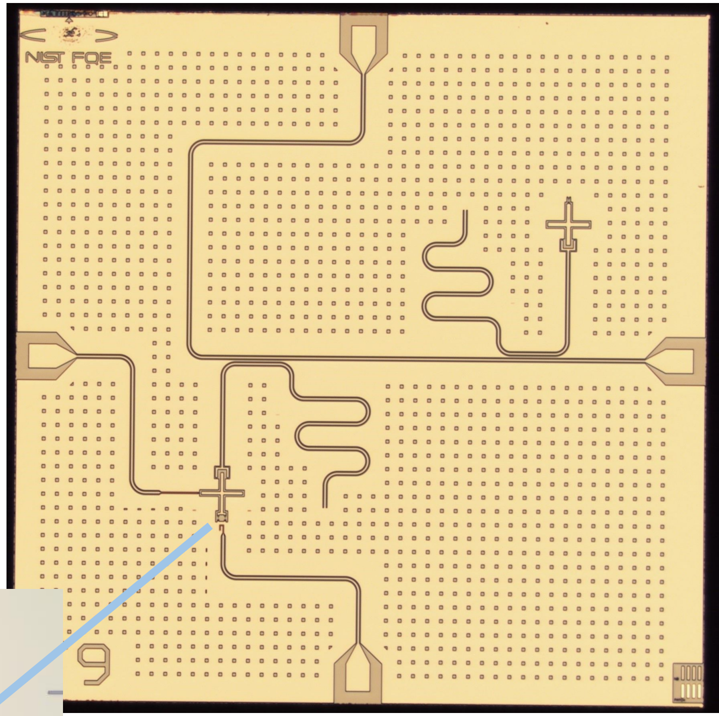


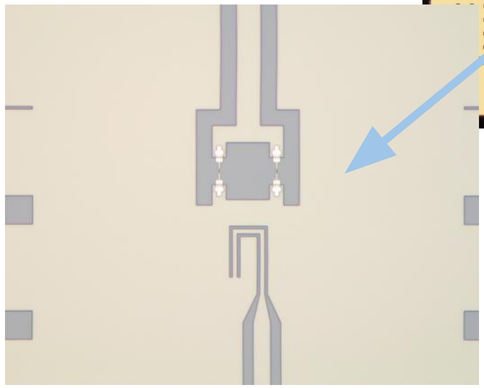
$\Delta = \omega_q - \omega_r$

ω_q varied by flux-bias

Transmon-type superconducting qubits: fabrication of first prototypes

- demonstrative two-qubit chips fabricated at NIST
  - one fixed-frequency, resonator driven transmon
  - one tunable-frequency transmon with dedicated drive-line
  - Niobium with Aluminum junctions by shadow angle evaporation
- main goals
  - calibrate the simulations
  - benchmark for upcoming fabrications at FBK
- low temperature characterisation underway at NIST





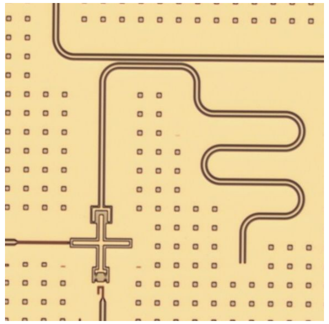
Credit: NIST Superconductive Electronics Group at Boulder (A.Sirois, M.Castellanos, D.Olaya, J.Bieseker, P.Hopkins, S.Benz)

NIST

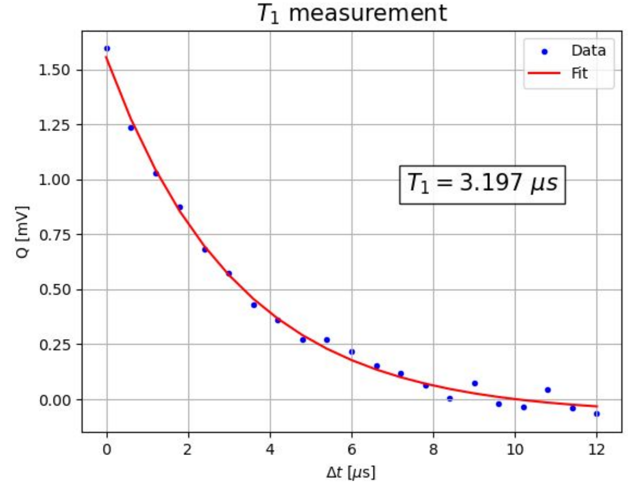
Transmon-type superconducting qubits: preliminary results with NIST prototype

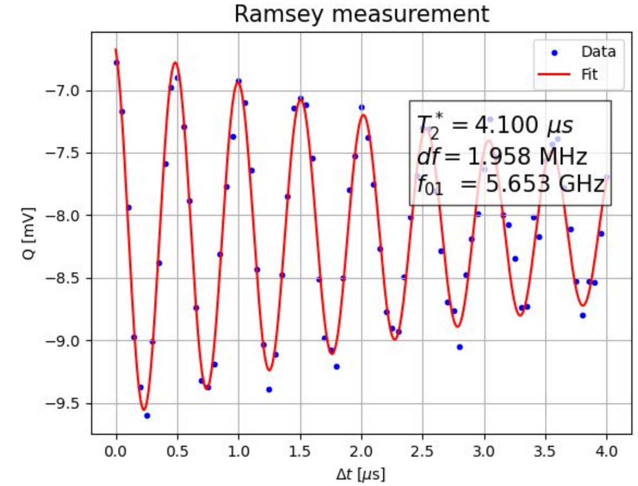
- good agreement with predictions
- poor Q due to a fabrication issue ($Q_i \approx 5 \times 10^4$)
  - short T_1 and T_2^*
- design now adapted for FBK fabrication
  - junction area limited to >3×3μm^2 by photolithography to be reduced by FIB after production

drive

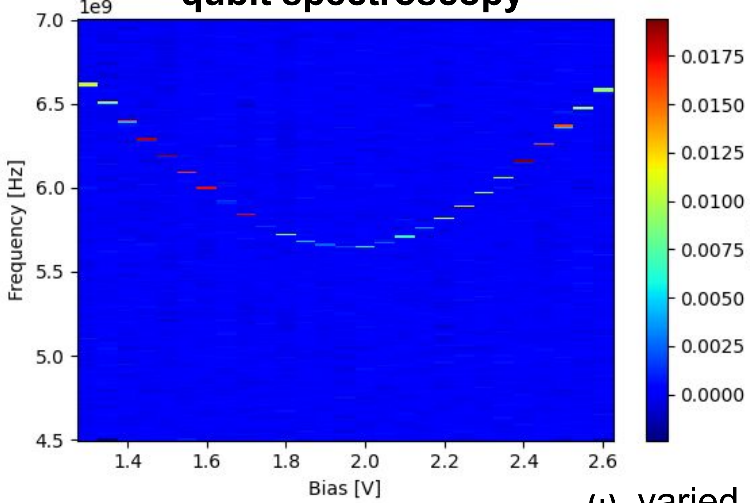


flux-bias

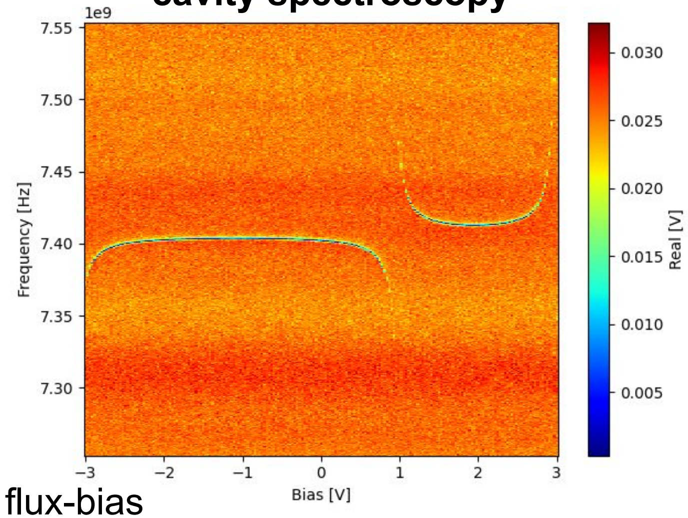




qubit spectroscopy



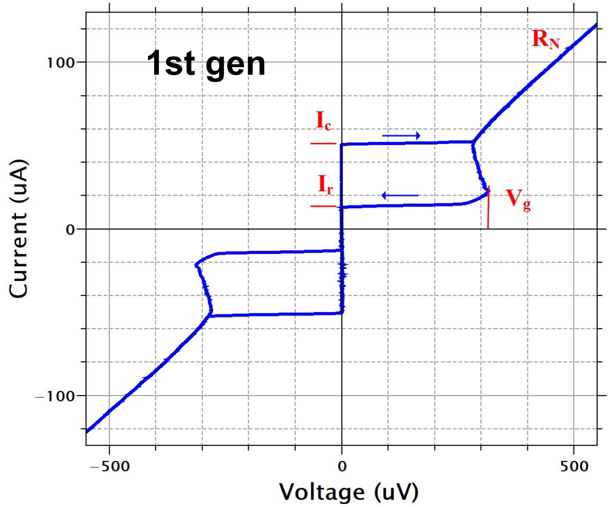
cavity spectroscopy

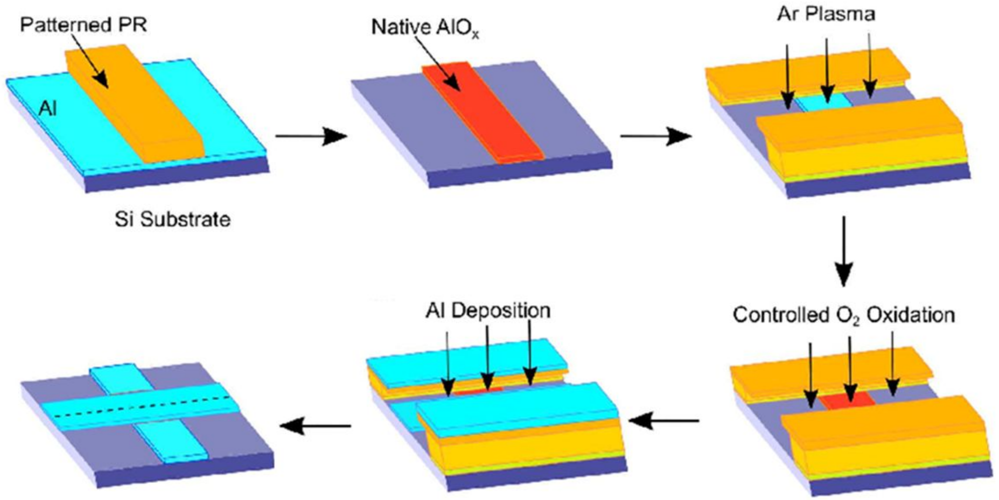


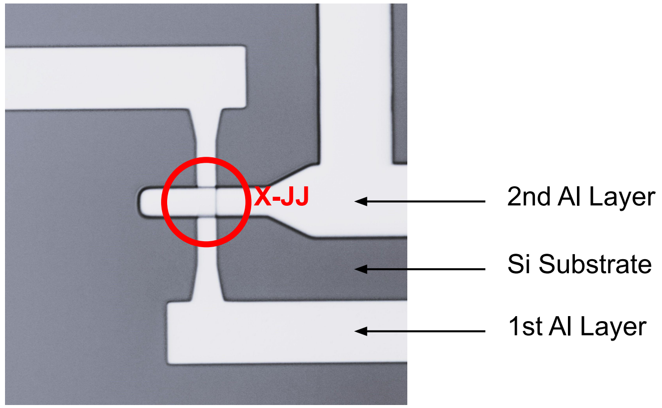
ω_q varied by flux-bias

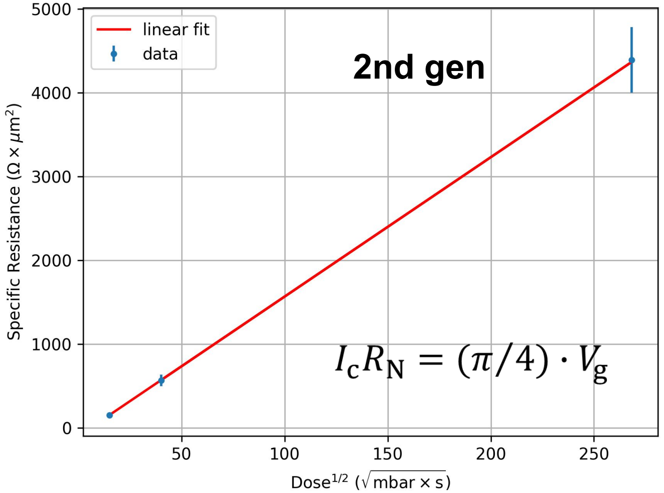
Transmon-type superconducting qubits: progresses for fabrication at FBK / 1

- development of cross **Josephson Junction** fabrication process
  - high control on area and on junction parameters
  - two-layers process
- junction area limited to >3×3μm^2 by photolithography
  - to be reduced by FIB after production
- now tuning oxidation to reduce the critical current $I_c \propto R_N$









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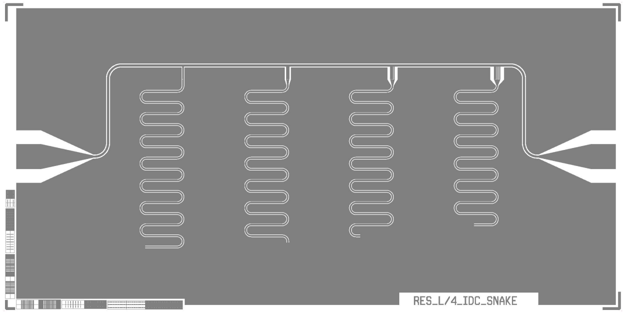
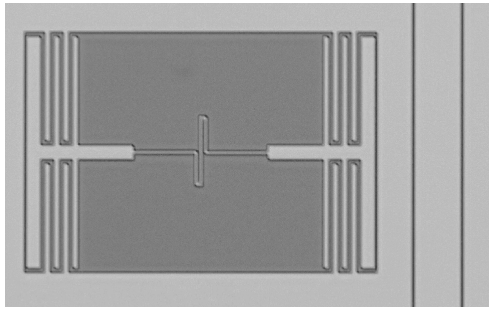
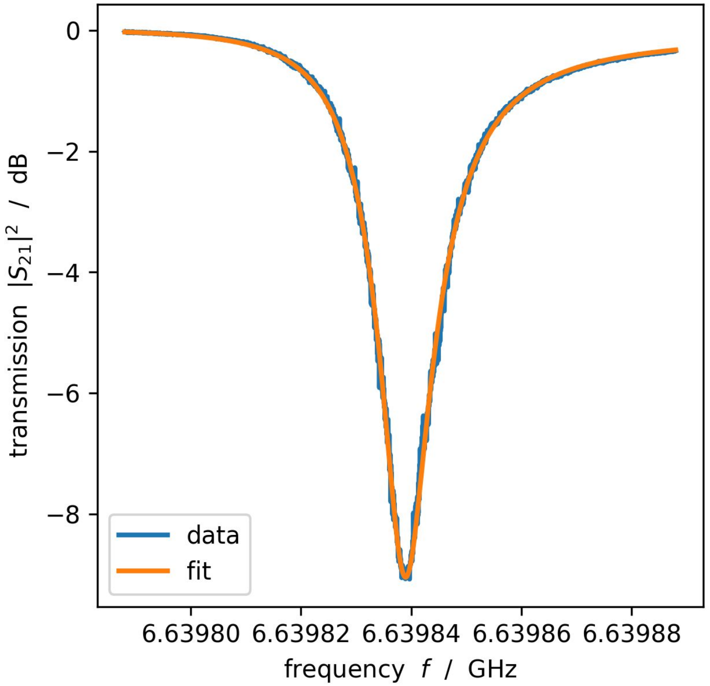
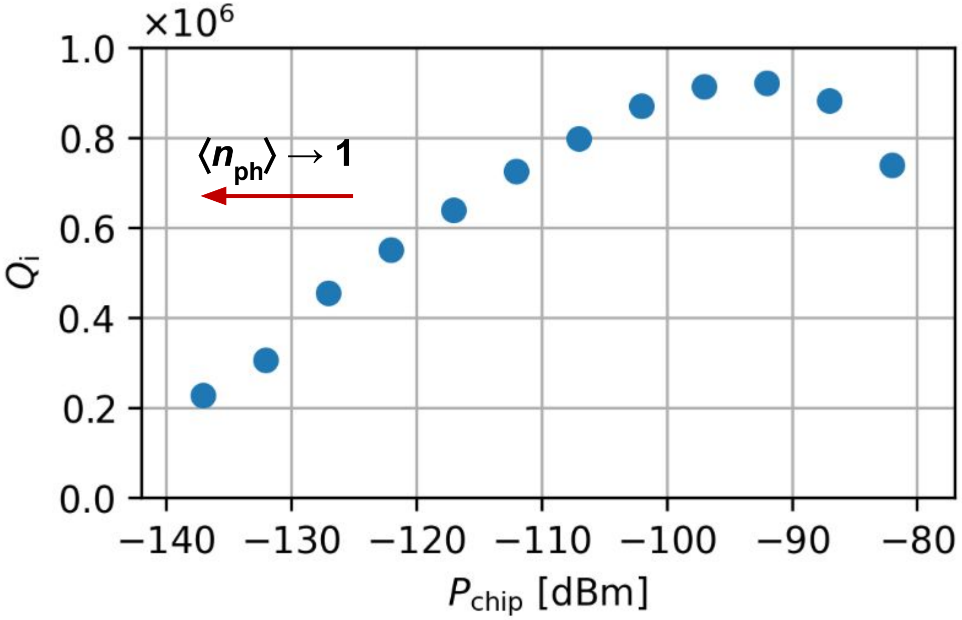
Transmon-type superconducting qubits: progresses for fabrication at FBK / 2

- tuning process to fabricate **high quality Al resonators** for low photon number occupancy regime
- tests with CPW λ/4 and lumped element resonators
- Q_i=1/δ dominated by TLS for low read-out power, but close to target value ($Q_i \gtrsim 10^6$)









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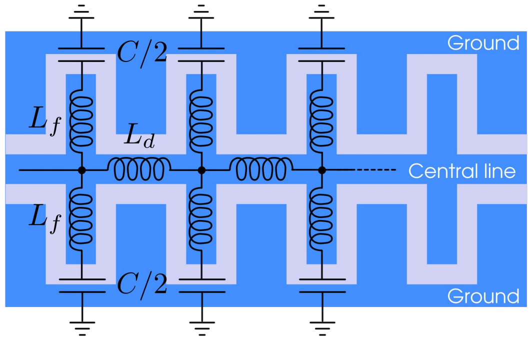
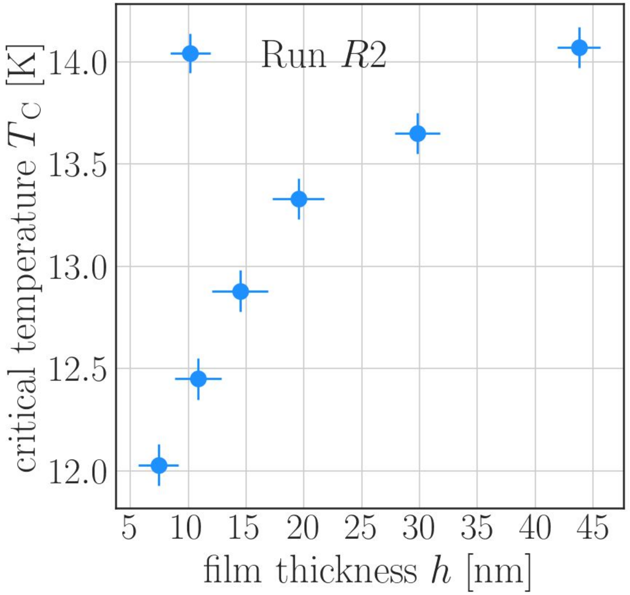
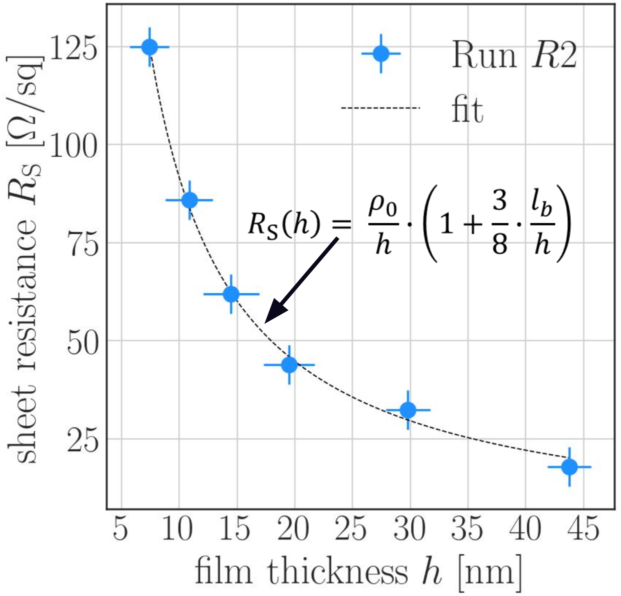
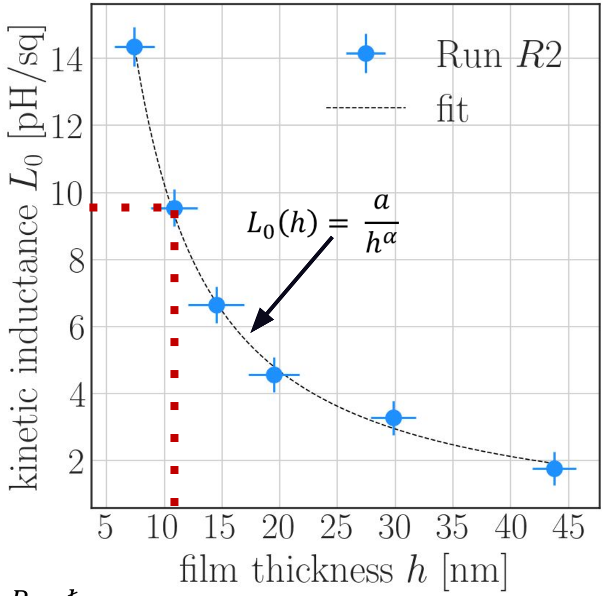
Travelling wave parametric amplifiers: material development



- KI-TWPA: non-linear kinetic inductance material patterned in an artificial transmission line
- **NbTiN**: high T_c, high sheet resistance R_s (→ high kinetic inductance L_0)
- NbTiN recipe successfully developed at FBK https://doi.org/10.1088/1402-4896/ad070d
  - film thickness h can be used for L_0 tuning



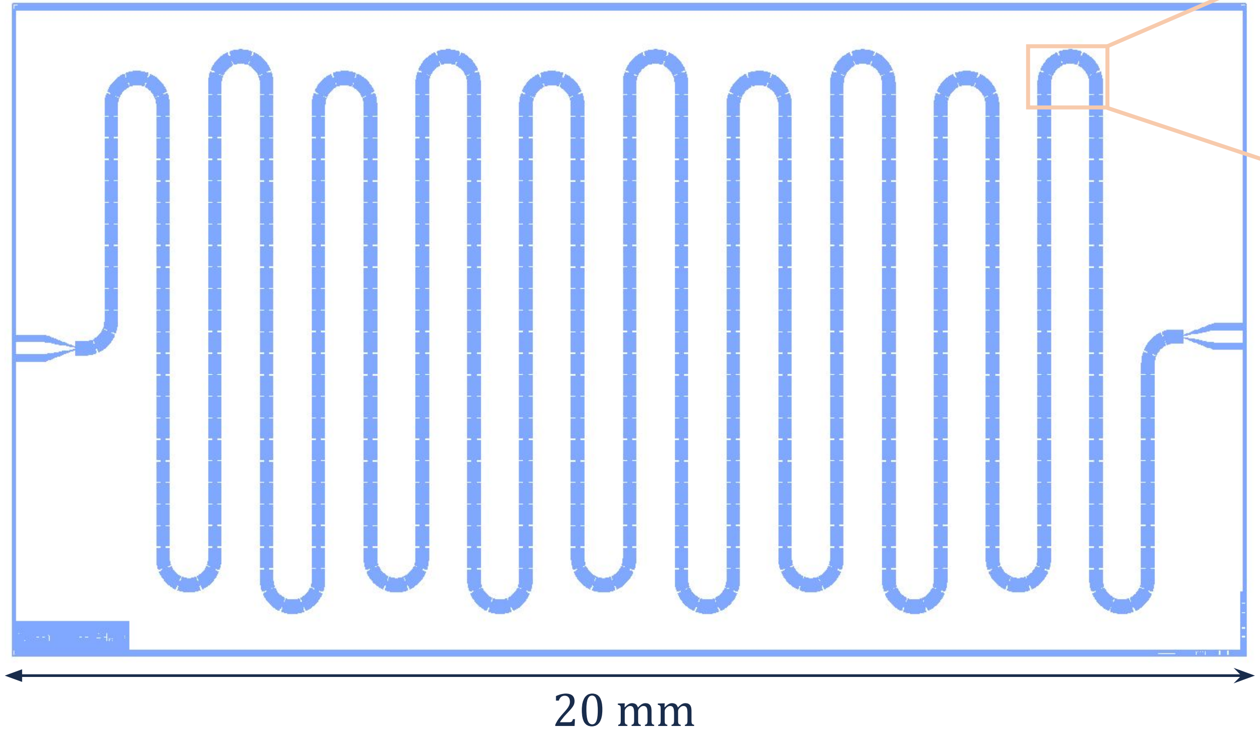


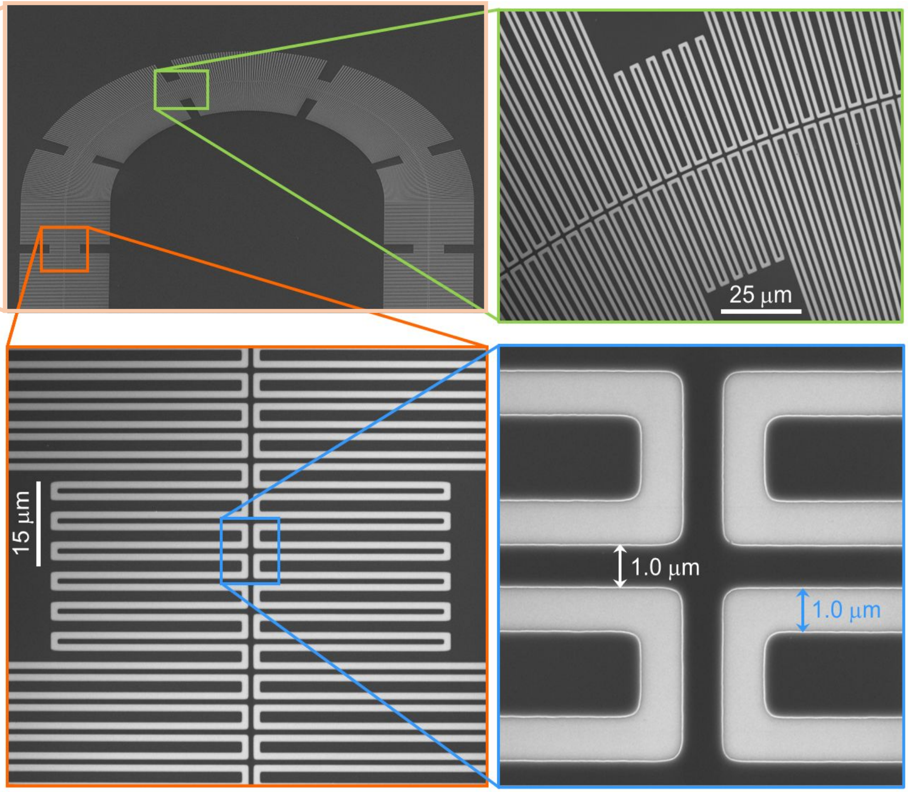


$$L_0 = \frac{R_S \cdot \hbar}{\pi \cdot T_C \cdot k_B \cdot 1.762}$$

Travelling wave parametric amplifiers: design and fabrication

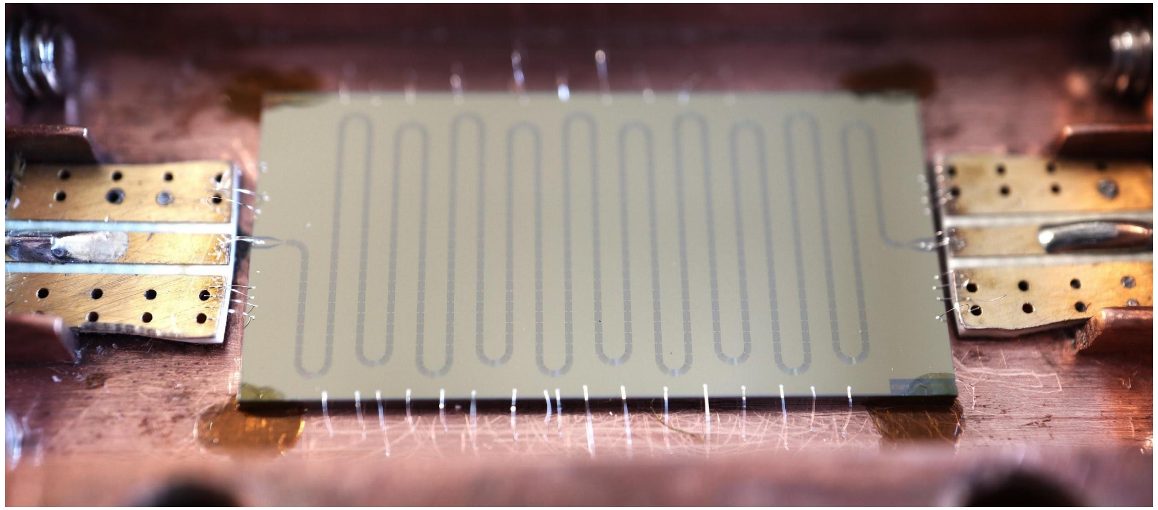
- prototype KI-TWPA with 17 cm long NbTiN transmission line fabricated at FBK
    - 13nm NbTiN thickness
    - 10 dB expected gain

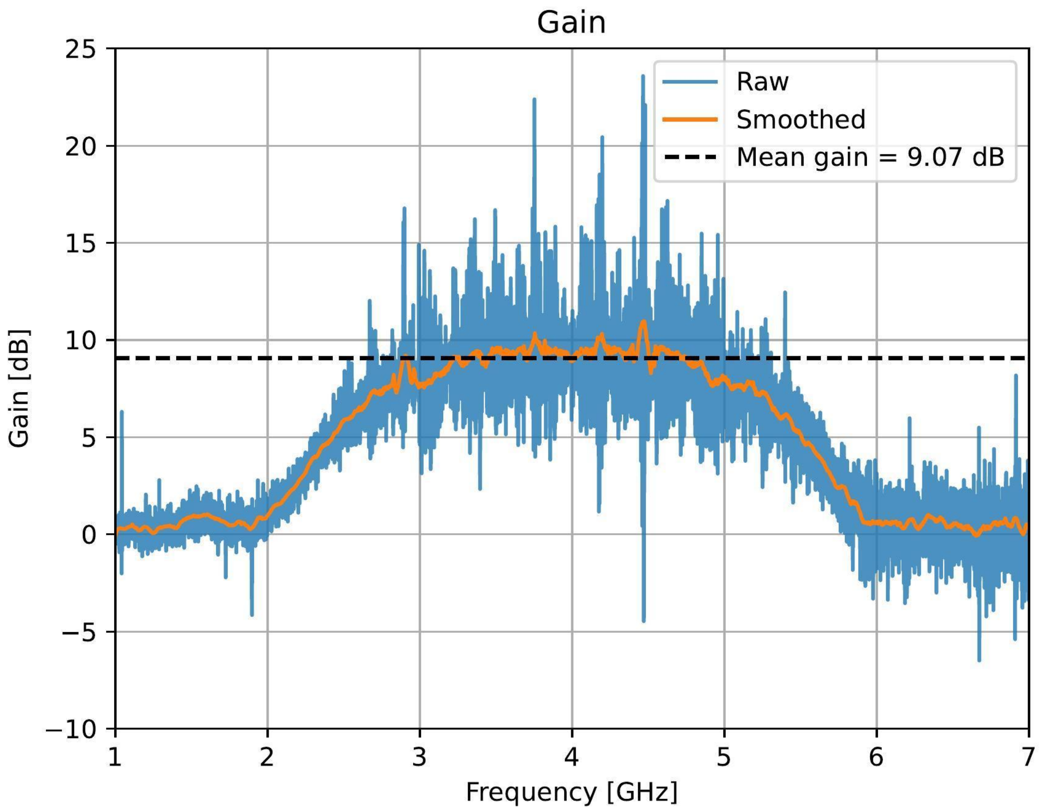




Travelling wave parametric amplifiers: prototype characterization

- prototypes gain: 9-11 dB (as expected from design)
- frequency band: 3-5 GHz (too low: target 4-8 GHz)
- next fabrication run has modified design to shift frequency band
- plans for further fabrications in 2024:
  - 33 cm long transmission line for 15 dB gain and SQL
  - inverted microtrip design for better yield and higher gain





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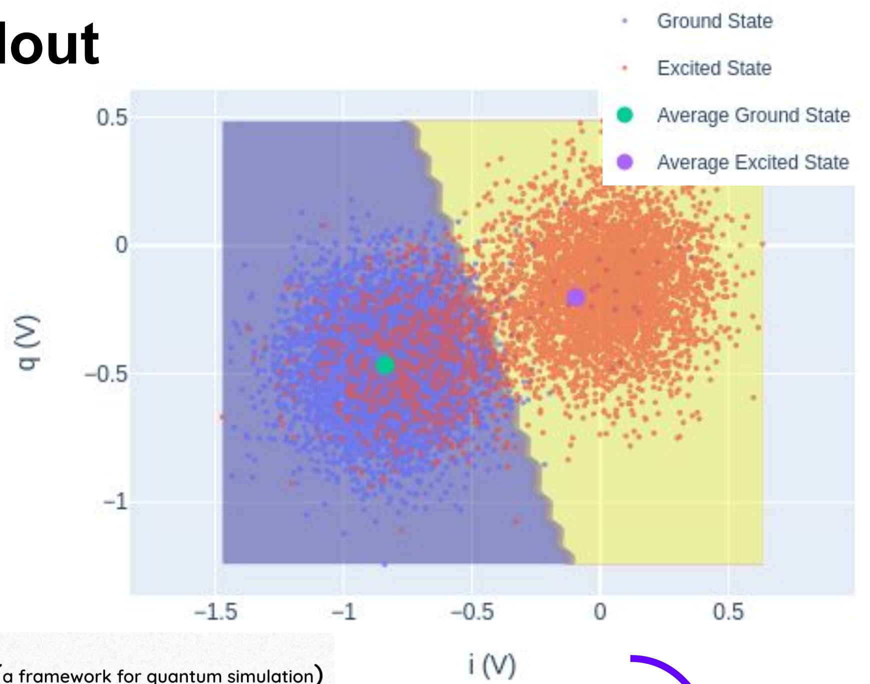
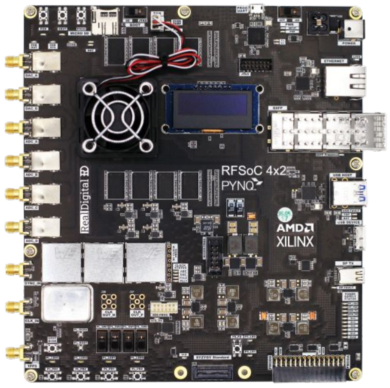
RFSoC FPGA boards for digital control and heterodyne readout

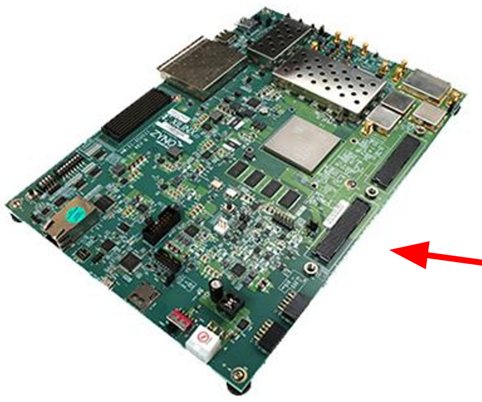
- high-performance DACs and ADCs for signals up to 10 GHz
- QICK: firmware for RFSoC developed by Fermilab
- Qibosoq server on RFSoC for QICK integration in Qibo
  https://arxiv.org/abs/2303.10397
  - full-stack quantum control and readout
  - execution of arbitrary pulse routines and quantum algorithms
  - achieved multiplexed readout for up to 3 flux tunable qubits at TII

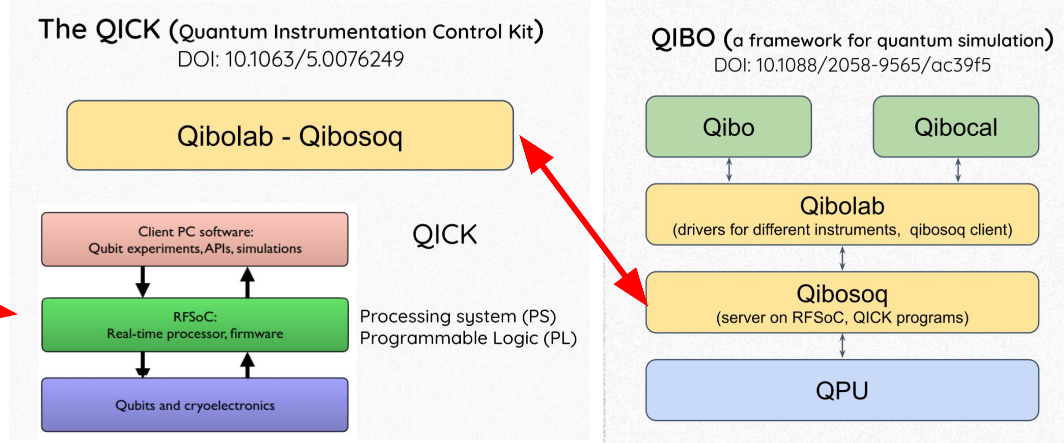


RFSoC4x2
from Xilinx



RFSoC ZCU111
from Xilinx

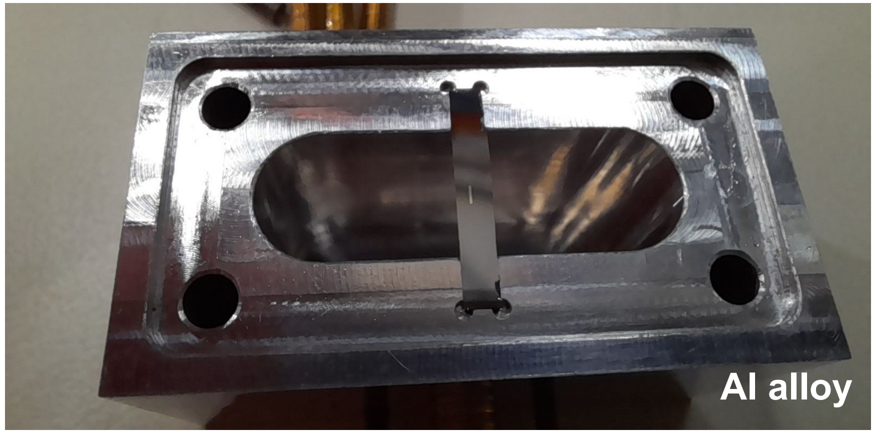




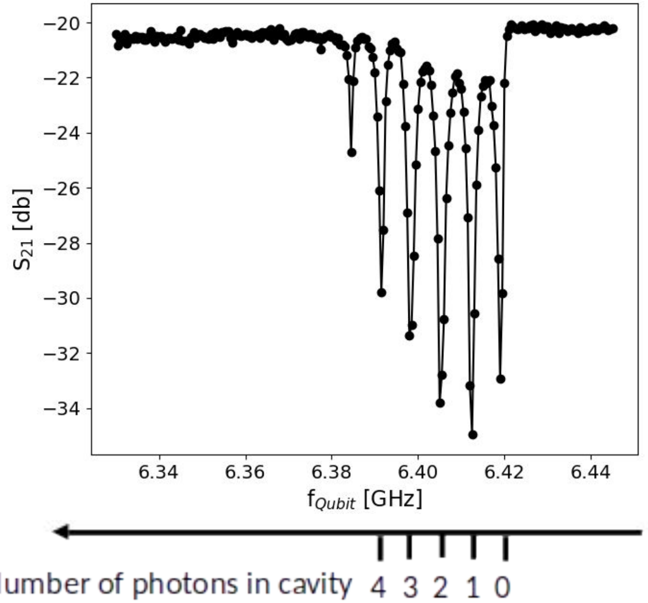
TII Technology Innovation Institute

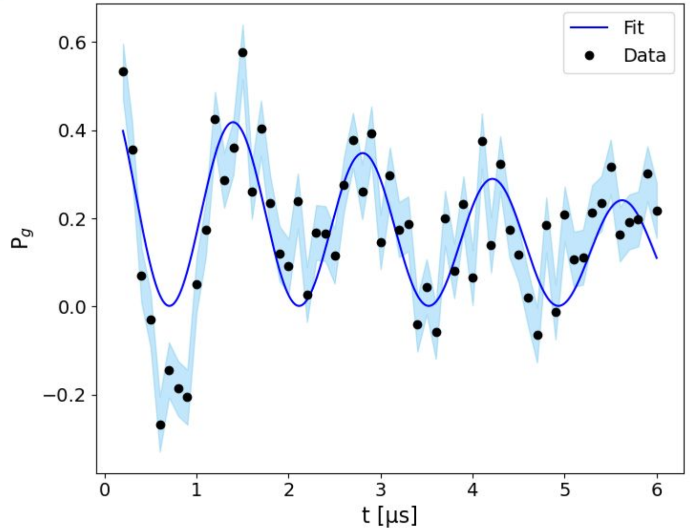
3D qubits

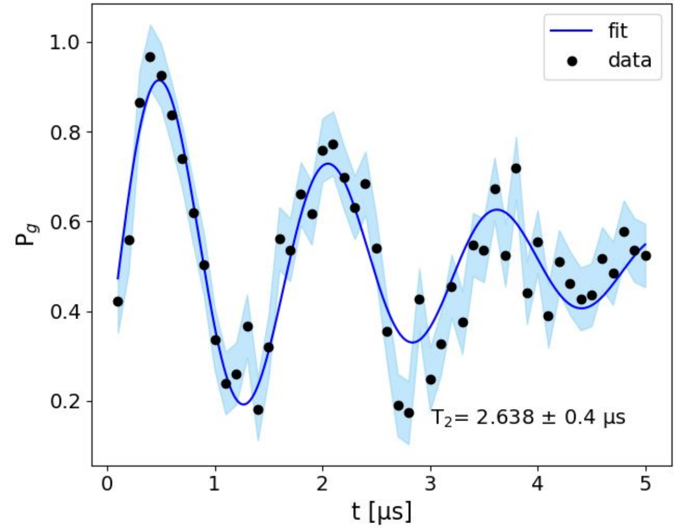
- transmons in superconducting 3D cavity
- alternative approach for longer coherence time
- first tests with 3D qubit fabricated at TII (Abu Dhabi, EAU)
- new Al cavities are being designed and fabricated by INFN
- new transmons for 3D cavities are being developed by CNR-IFN



Technology Innovation Institute



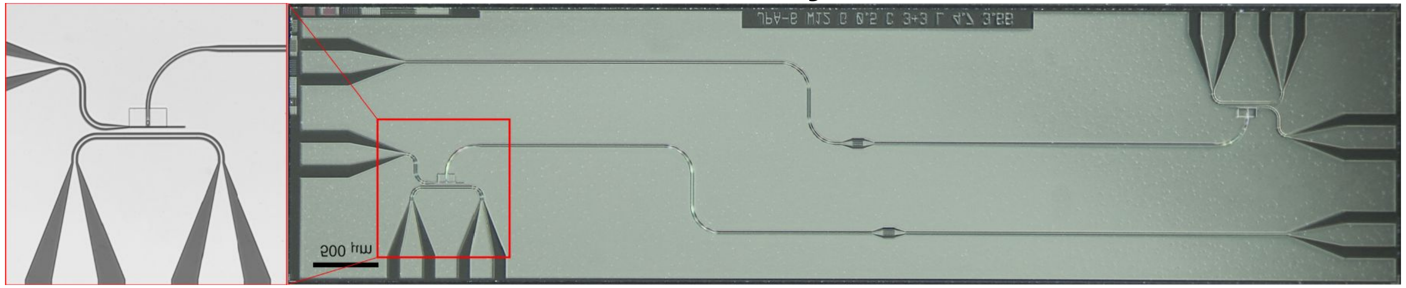


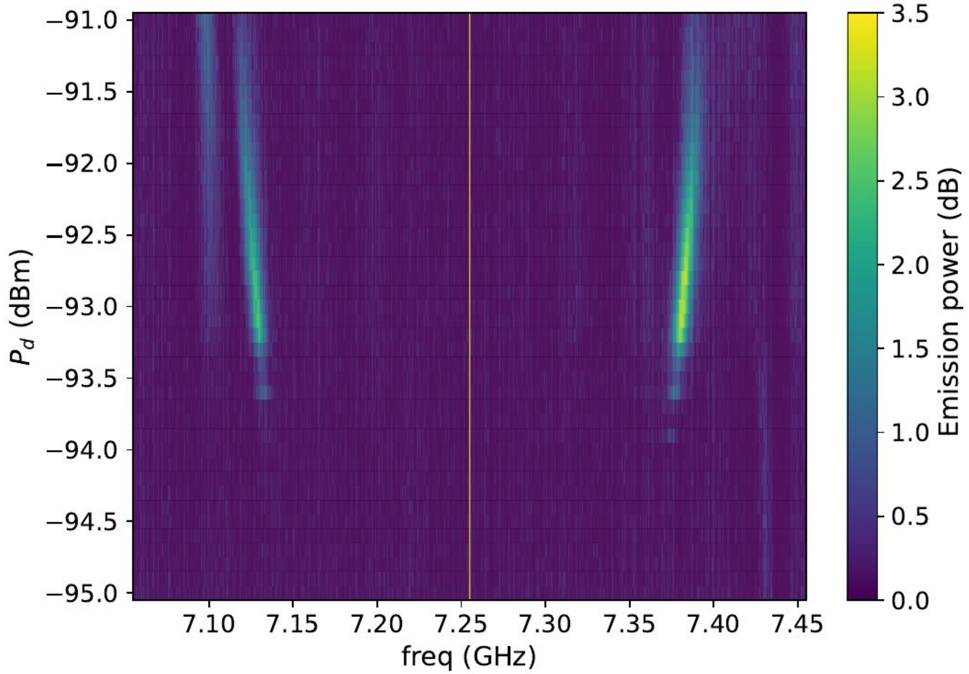


Non-classical photon sources: JPA, TWPA, …

- entangled microwave photon source to be used also for testing the itinerant photon detector
- preliminary investigations with superconducting circuits: SQUID, JPA and J-TWPA
  - correlated photon emission observed and modeled as dynamical Casimir radiation and Autler–Townes fluorescence https://doi.org/10.3390/instruments7040036
- more investigations to characterize the emission are planned

JPA fabricated by FBK





Conclusions

- **xmon-type transmon**
  - single transmon qubit design completed
  - fabrication of first qubits at FBK in preparation
  - coupled qubit design is underway
- **KI-TWPA**
  - high kinetic inductance NbTiN recipe ready
  - first prototype shows near-quantum-limited noise in the 3-5 GHz band
  - improved design TWPA fabrications planned for 2024
- **quantum electronics** for readout and control
  - RFSoC boards successfully used
- progresses made on designing, characterizing and modeling
  - 3D resonator coupled qubits
  - non-classical photon sources based on superconducting circuits

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