Contributions to the development of photonic and superconducting quantum processors at the University of Milano-Bicocca

Angelo Nucciotti

Physics Department, University of Milano-Bicocca

Bicocca Quantum Technologies center - BiQuTe

ICSC
Centro Nazionale di Ricerca in HPC,
Big Data and Quantum Computing

Outline

- motivations and framework
- quantum processor prototype development status
  - photonic platform
    - quantum dot photon source fabrication
    - quantum dot photon source design optimization
  - superconducting platform
    - single transmon qubit design and simulation
    - qubit readout and control firmware
  - more on quantum algorithms…
- next steps

Motivations and framework / 1

- **ICSC Spoke 10 *Quantum Computing***
- development of the quantum processor supply chain in Italy
  - WP3 - Firmware and hardware platforms: 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
    - T3.2 Superconducting circuits
    - T3.4 Models and firmware
- in strong collaboration with INFN, CNR-IFN and University of Rome Sapienza

Motivations and framework / 2

- **ICSC Spoke 10 *Quantum Computing***
- development of the quantum processor supply chain in Italy
    - WP1 - Software: Development and application of high-level quantum software for algorithms solving general purpose problems, scientific and industrial applications
        - T1.2 Applications and use cases.

Quantum Information Science: simulation, QML, QKD, …

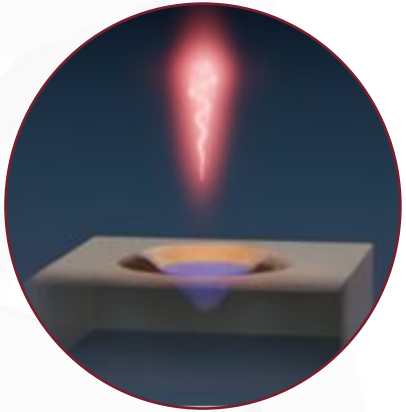
- https://github.com/qismib and https://github.com/biqute

Participation to 2 Innovation Grants within ICSC

- *Serial Code Porting on HPC & Quantum Computing*, with SOGEI
- *Quantum algorithm for the Detection of the Optimal Maximal Clique,* with Unipol SAI

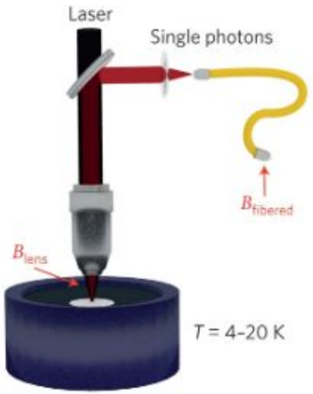
Photonic platform: deterministic indistinguishable single photon sources

- prototype quantum processor based on the LOQC
- fabrication and testing of deterministic single photon sources based on epitaxial semiconductor quantum dots
- QD state engineering via strain free by Droplet Epitaxy
- **in collaboration with Università di Roma Sapienza**

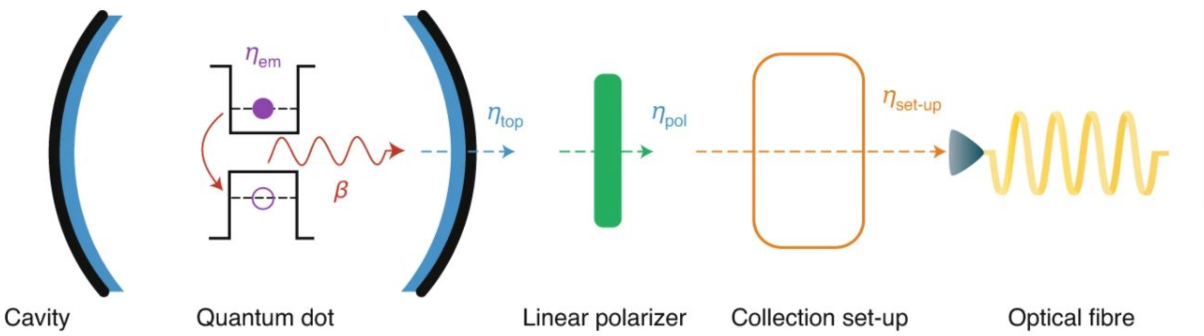


F. Sciarrino slides

Optically pumped SPS

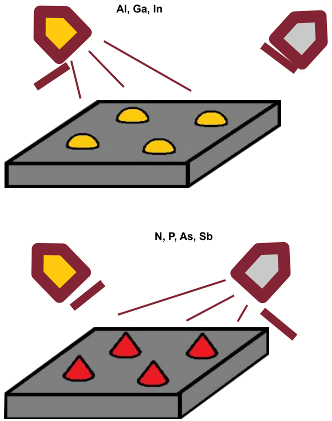


Source Scheme



Photonic platform: Quantum Dots by droplet epitaxy

State-of-the-Art Droplet Epitaxy



Group III reservoir deposition (droplets)
Droplet <u>size</u>, <u>density</u> and <u>size distribution</u> control
III-V crystallization under group V flux
Nanostructure morphology and topology control

ADVANTAGES:

1. Strain independence
2. Shape control
3. Independent size and density control
4. Nucleation site control

nature materials REVIEW ARTICLE
https://doi.org/10.1038/s41563-019-0355-y

Droplet epitaxy of semiconductor nanostructures for quantum photonic devices

Massimo Gurioli[1], Zhiming Wang[2], Armando Rastelli[3], Takashi Kuroda[4] and Stefano Sanguinetti[5*]

https://doi.org/10.1038/s41563-019-0355-y

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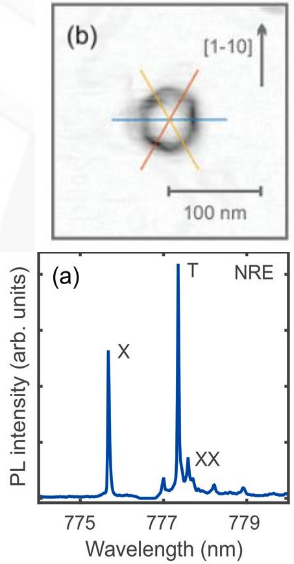
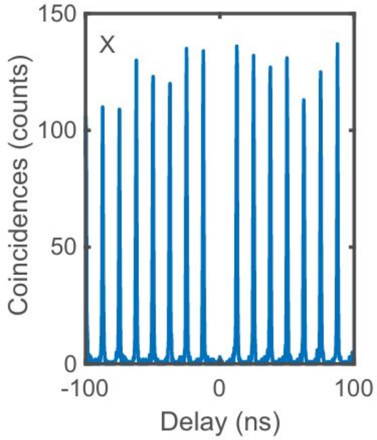
https://doi.org/10.1021/acs.nanolett.7b04472

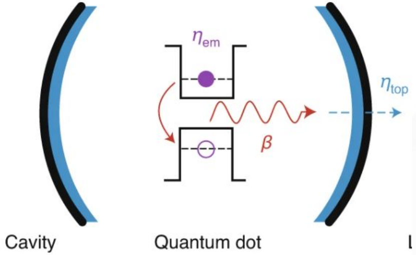
PHYSICAL REVIEW B **107**, 205417 (2023)
https://doi.org/10.1103/PhysRevB.107.205417

Deterministic Single Photon Emitters by GaAs/AlGaAs QDs @ 780 nm



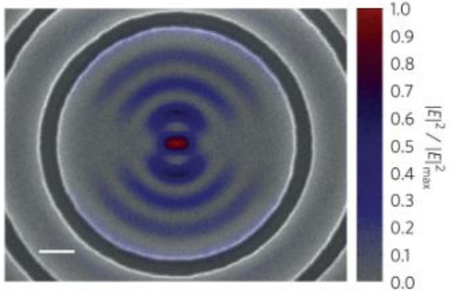


Photonic platform: Quantum Dot photon sources developments

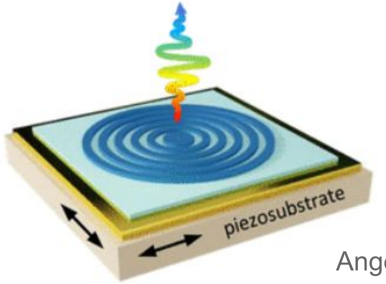


Cavity design

Bullseye Planar cavity



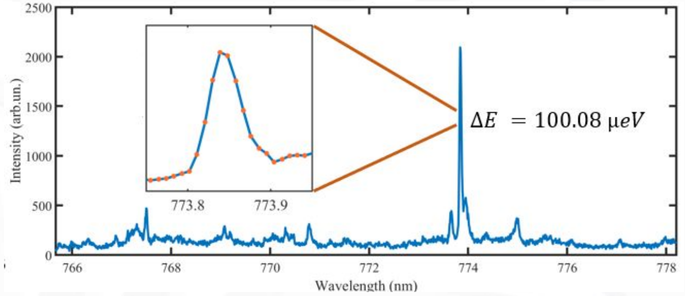
Implementation on a piezoelectric substrate for emission wavelength tuning



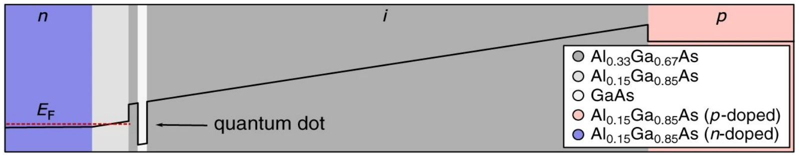
QD design optimization

Reduction of the dynamical Stark noise on the emission linewidth

Heterostructure design: QD on a quantum well



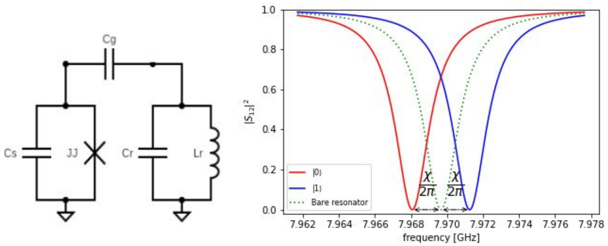
QD in a p-i-n structure



Superconducting circuits: transmons for a quantum processor

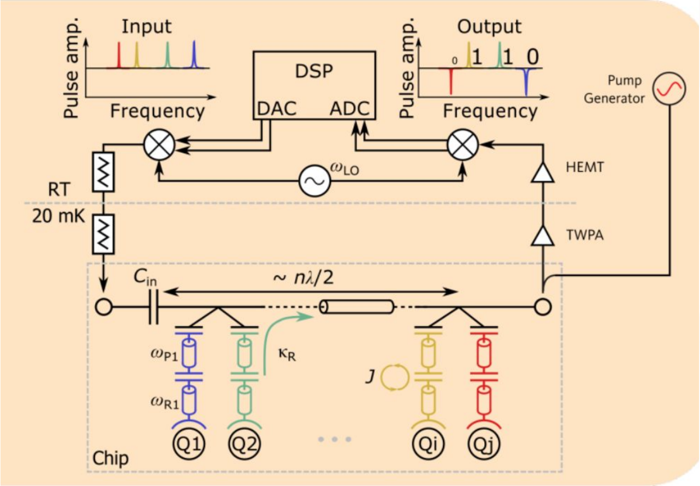
- quantum processor with at least 4 coupled superconducting qubits
  - transmon qubits with dispersive read-out
  - wide-band superconducting parametric amplifiers for quantum-limited multiplexed readout
  - RFSoC FPGA boards for digital control and heterodyne readout
- **in collaboration with INFN and CNR-IFN**
- synergies with DARTWARS and Qub-IT INFN projects and NQSTI

V. Bonvicini slides



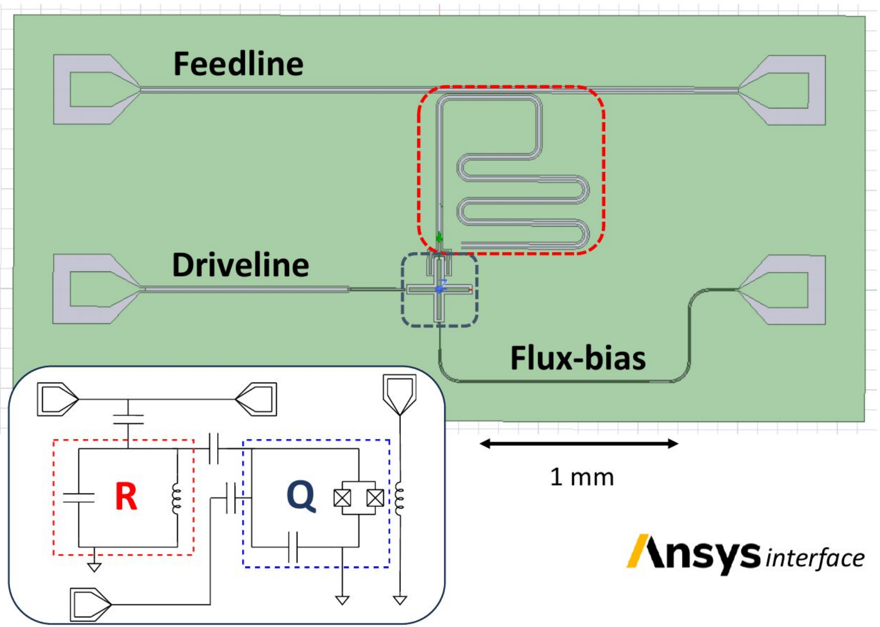
$$H_{JC} \approx \hbar(\omega_r + \chi\sigma_z)a^\dagger a + \frac{\hbar\omega_q}{2}\sigma_z$$

Resonator mode frequency is qubit-state dependent



Superconducting circuits: design of a xmon prototype

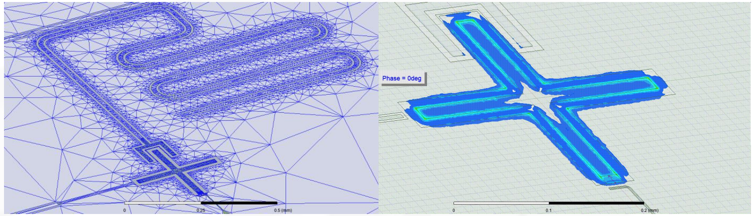
- **grounded xmon-type transmon**
  - λ/4 resonator
  - capacitive resonator/feedline coupling
  - X-shaped shunt capacitance
  - driveline and flux-bias line for control and frequency tuning
- Design: Qiskit Metal (IBM)
  - target Hamiltonian definition
  - qubit-lines layout definition
- EM Simulation: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



Ansys interface

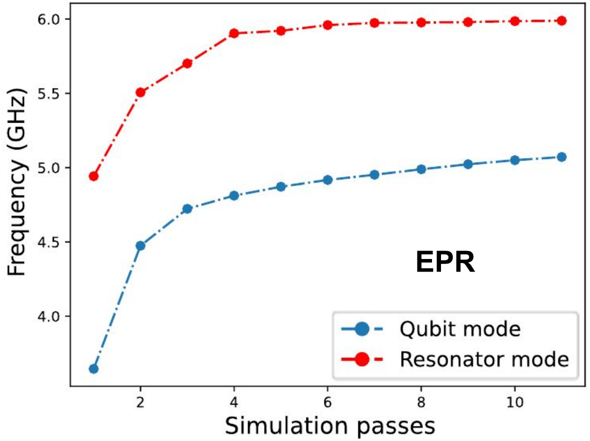
Superconducting circuits: simulations of a xmon prototype

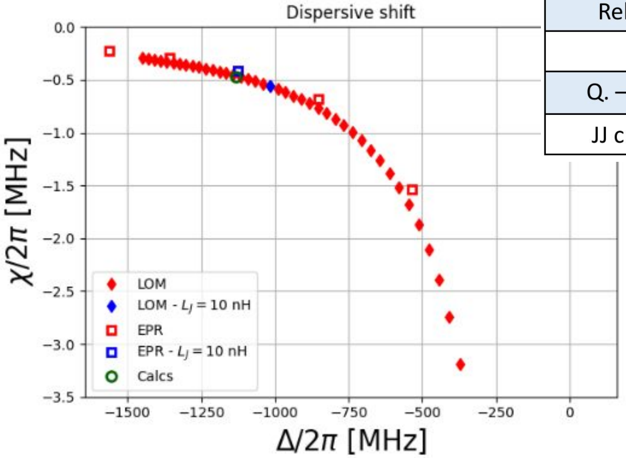
- target values as result of analytical calculations
- two simulation approaches
  - EPR (Energy Participation ratio) – Ansys HFSS
    https://doi.org/10.1038/s41534-021-00461-8
  - LOM (Lumped Oscillator Model) – Ansys Q3D
    https://doi.org/10.48550/arXiv.2103.10344
- EPR and LOM analyses are consistent with theory
  - report here EPR results



		Target	Result
Q. frequency	$\omega_q/2\pi$	4.95 GHz	4.88 GHz
Res. frequency	$\omega_r/2\pi$	6.00 GHz	5.99 GHz
Anharmonicity	$\alpha/2\pi$	202 MHz	214 MHz
Transmon regime	E_j/E_C	> 50	81
Relaxation time	T_1		33 μs
Disp. shift	$\chi/2\pi$	-0.47 MHz	-0.44 MHz
Q. – Res. coupling	C_g	4 fF	3.93 fF
JJ critical current	I_c	33.0 nA	33.0 nA

https://arxiv.org/abs/2310.05238



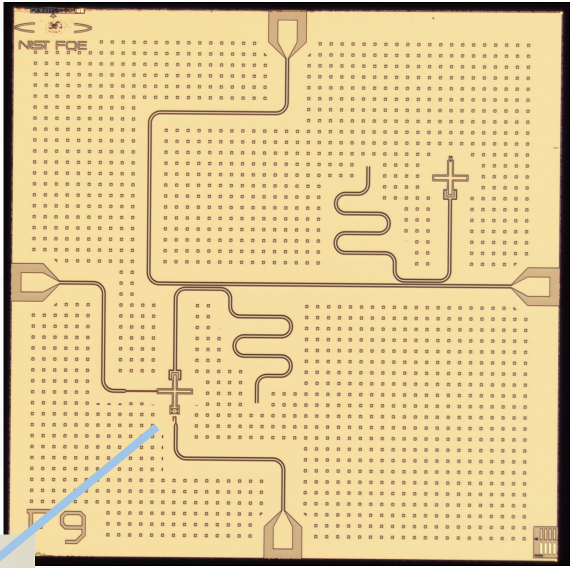


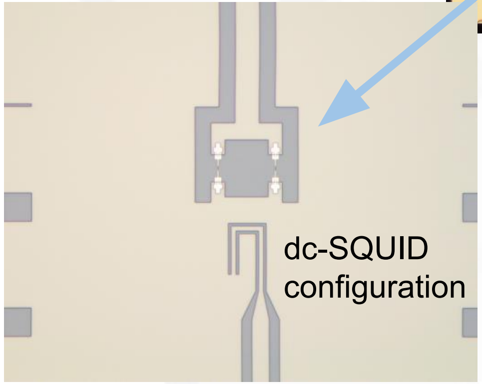
$\Delta = \omega_q - \omega_r$

ω_q varied by flux-bias

Superconducting circuits: fabrication of a first xmon prototype

- demonstrative two-qubit chip fabricated at NIST
  - one fixed-frequency, resonator driven transmon
  - one tunable-frequency transmon with dedicated drive-line
- xmon-type transmons
- Niobium with Aluminum junctions by shadow angle evaporation
- main goals
  - *calibrate* the simulations
  - benchmark for upcoming fabrications in Italy (CNR-IFN, FBK)
- low temperature characterization in progress at NIST

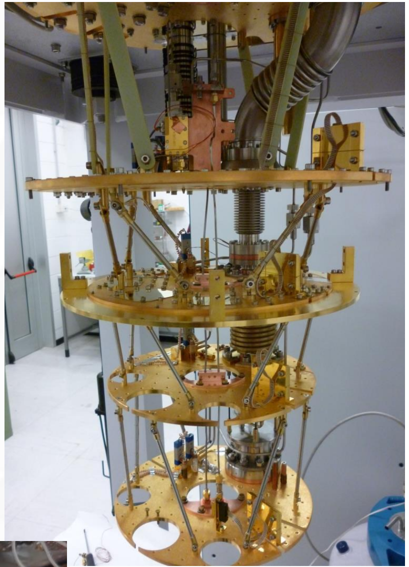




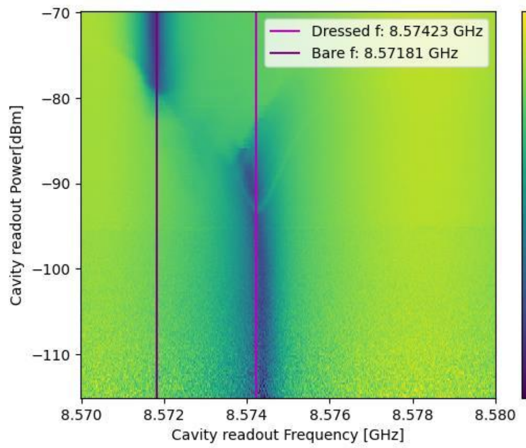
Credit: NIST Superconductive Electronics Group at Boulder (A.Sirois, M.Castellanos, D.Olaya, J.Bieseker, P.Hopkins, S.Benz)

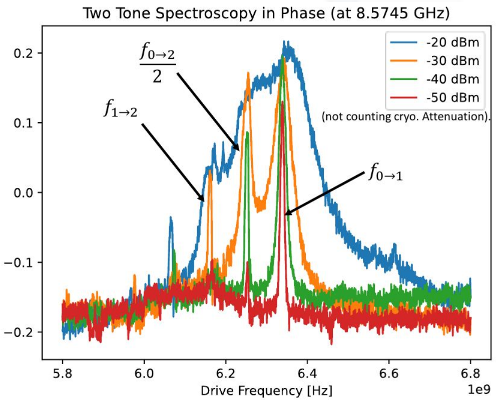
Superconducting circuits: the cryogenic set-up for a quantum processor

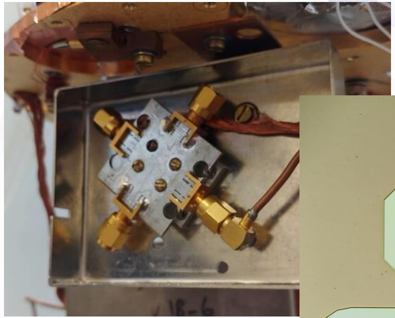
- high access cryogen-free dilution refrigerator at UNIMIB
- tests with concentric transmon qubit provided by NIST
  https://doi.org/10.1063/1.4940230 https://doi.org/10.1103/PhysRevA.97.062334
- low noise HEMT read-out
- preliminary calibration with VNA and AWG
  - single and two tone spectroscopy
- installation of JPA for quantum limited readout in progress (thanks to NIST)

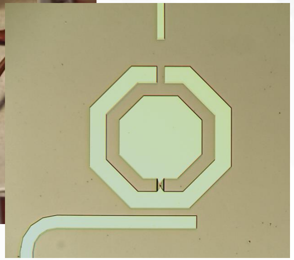


HOLMES neutrino mass experiment set-up









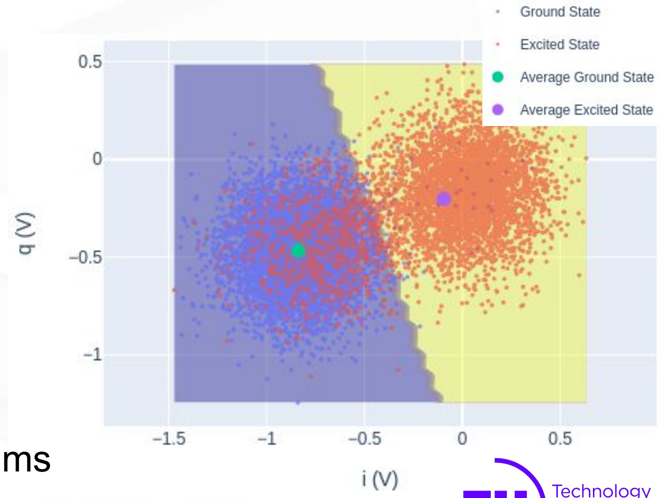
Superconducting circuits: firmware and hardware for qubit control

RFSoC FPGA board

- High-performance DACs and ADCs for signals up to 10 GHz

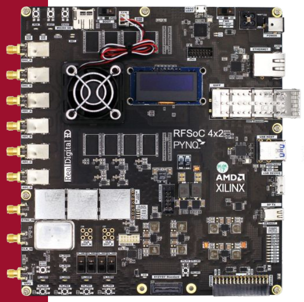
Firmware and software

- 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
  - multiplexed readout for up to 3 flux tunable qubits at TII

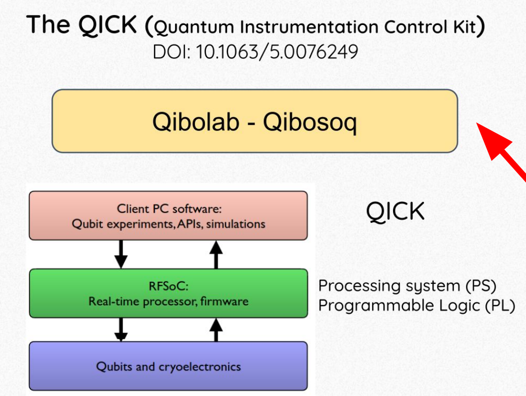


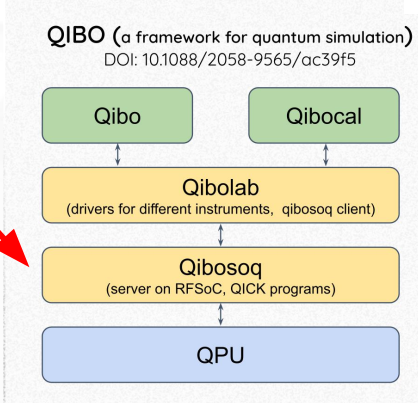
Technology Innovation Institute

RFSoC4x2 from Xilinx



RFSoC ZCU111 from Xilinx





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Superconducting circuits: next steps

- design of coupled transmons (in progress)
  - simulation upscaling using Reinforcement Learning, Genetic Algorithms, etc ...
- implementation of RFSoC based qubit control and readout at UNIMIB lab
- low temperature characterization of superconducting quantum devices:
  - tests at UNIMIB lab of NIST xmon samples
  - tests with first TWPA produced within DARTWARS project
- fabrication of revised xmon transmons at CNR-IFN
- work to improve coherence time