# QUART&T BO

27/01/2025

G. Bruni

- Quick general review of the project (widely using A. Giachero’s slides)
- Groups and budget
- Working packages
- Kick-off meeting: proposed dates
- Local information

# QUART&T: Goal

A.G.

The QUantum Architectures for Theory & Technology (QUART&T) project aims to develop demonstrator quantum architectures, establishing the foundation for experimental platforms where theoretical models and phenomena of interest to the INFN can be tested.

A ***quartet*** of crucial optimizations:

1. All-to-all connectivity;
2. Tunable couplings;
3. Higher-dimensional systems (Qudits);
4. Circuit Quantum Electrodynamics

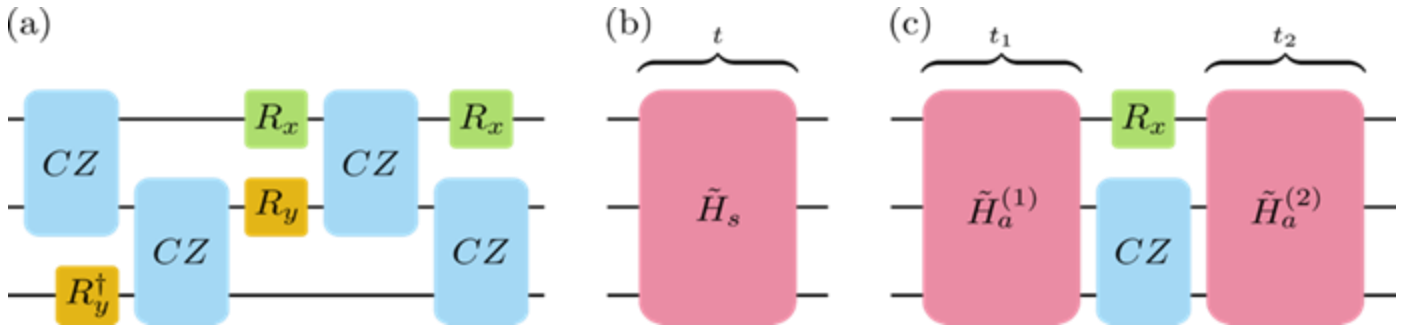
→

The **project goal** and the **crucial optimizations** will be reached through:

1. Simulation and Design of quantum systems in 2D and 3D technologies;
2. Fabrication of circuits with S.C. resonators and qubits;
3. Software and hardware for qubit characterization, measurement, control and readout;
4. Theories and algorithms for quantum simulation, sensing and machine learning.

# QUART&T: Quantum simulations

A.G.




Advances in Physics: X 3(1), 1457981 (2018)

**(a) Digital simulation:**

$$H_s = H_1 + H_2 + ...H_n \;\Rightarrow\; U(t) = e^{-H_1 t/r} \cdot e^{-H_2 t/r} \cdot ... \cdot e^{-H_n t/r}$$

Trotter–Suzuki decompositions: digital sequence tries to reproduce a targeted quantum evolution

**(b) Analog simulation**:

$$H_s = \tilde{H}_s \;\Rightarrow\; U(t) = T \int_0^t dt' H_0 + H_p(t')$$

← **Controllable pulse drive**

Controllable system with evolution $H_s$ mimics almost one-to-one that of the simulated system $H_s$

**(c) Digital Analog Simulation:**

$$H_s = \tilde{H}_a^{(1)} + H_1 + .. + H_n + \tilde{H}_a^{(2)} \;\Rightarrow\; U(t) = \prod \tilde{H}_a^{(i)} \cdot H_j$$

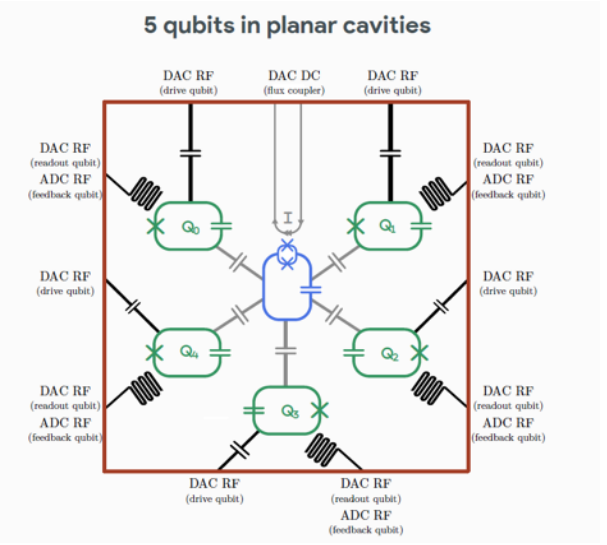
Combines analog blocks that naturally appear in the simulator with digital gates

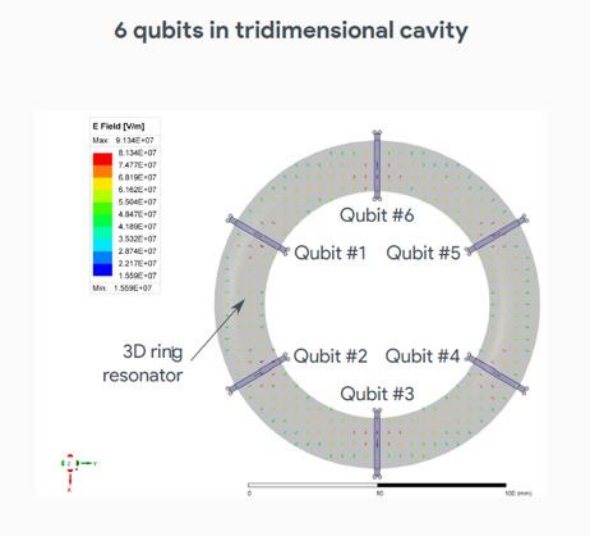
# Examples of quantum simulations of interest

- **Nuclear reactions and dynamics -** Phys. Rev. A 108, 032417 (2023)
  - neutrino-scattering in SN explosion and neutron star cooling
  - cross sections for dark-matter searches and neutrino physics
- **Lattice Quantum Chromo Dynamics (QCD)** - Phys. Rev. Res. 5, 033184 (2023)
- **Circuit Quantum Electrodynamics** – Nat. Comm. 14, 3263 (2023)
  - Simulation of relativistic QM, Dirac equation

# The essential parts

1. **Tunable couplings**
2. **All-to-all connectivity**
   - Qubits coupled to a common bus resonator allow all-to-all coupling
   - Entanglement via tuning near common resonances
3. **Qubits → Qudits**
4. **cQED**

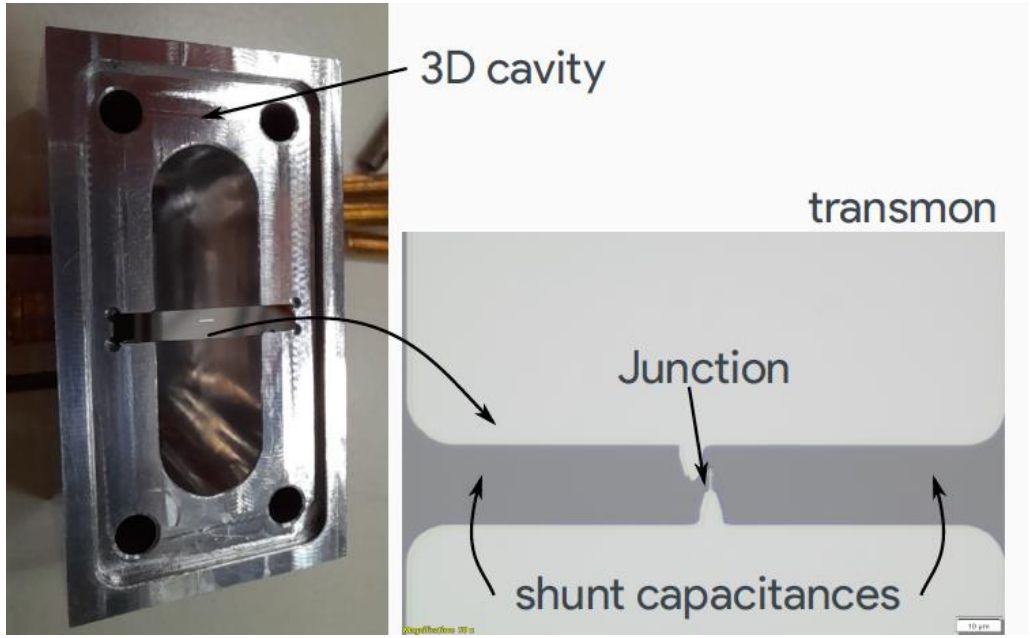




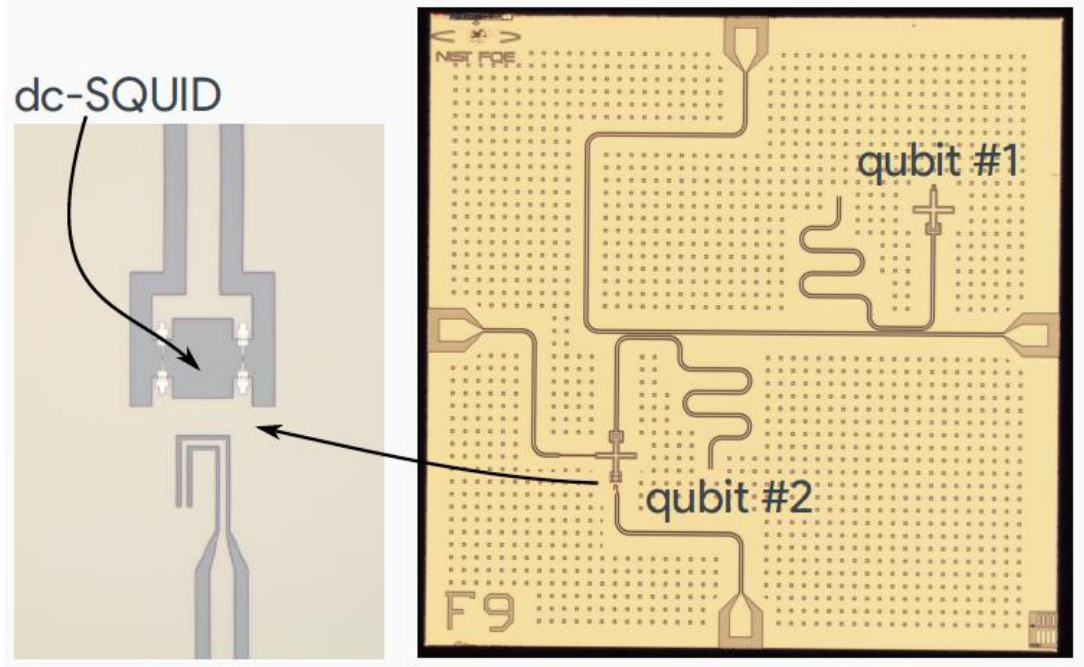
npj Quantum Inf 9, 40 (2023)
Phys. Rev. X 11, 021058 (2021)
arXiv:2405.00873 [quant-ph]

# Achieved in QubIT




**3d Transmon qubit** (TII, Abu Dabi) in SC 3d cavity (INFN-LNL), measured at INFN-LNF

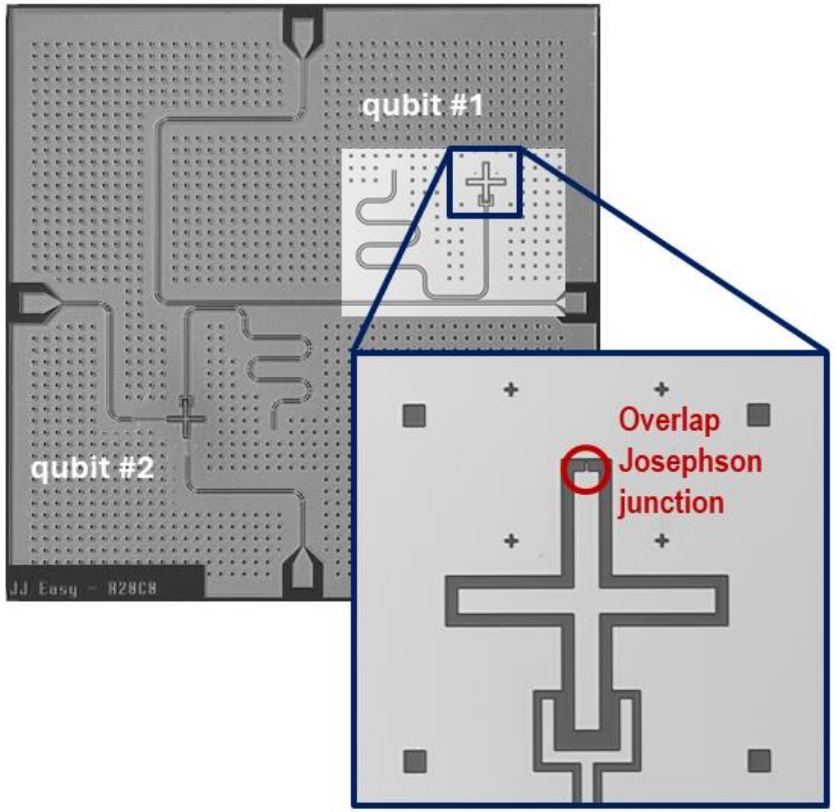
New transmons developed by CNR-INF

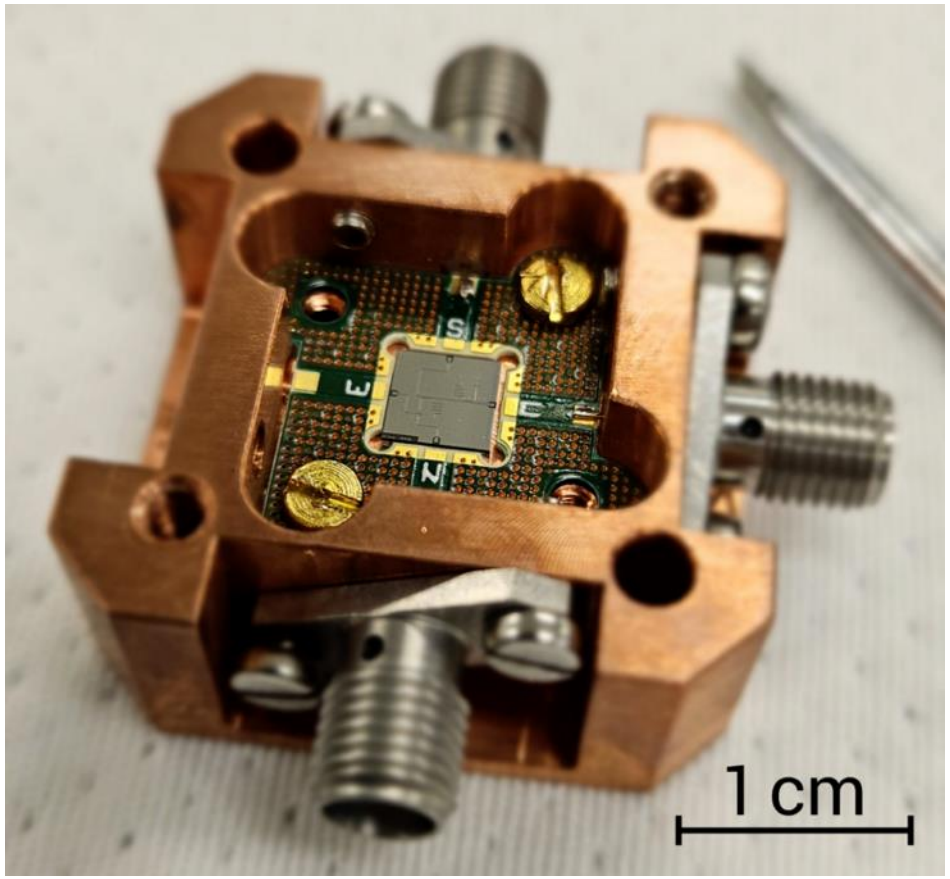



**2d Xmon qubit** (NIST) in SC 3d cavity (INFN-LNL), measured at INFN-MIB cyolab.

Flux-bias line to tune the energy spacing between states

# First italian qubit at FBK – 2d Xmon



# QUART&T: Involved Groups

A.G.

## 8 INFN Units

- INFN Bologna
- INFN Ferrara
- INFN Firenze
- INFN Lecce
- INFN Milano
- INFN Milano Bicocca
- INFN Gruppo Collegato di Salerno (INFN Napoli)

## 2 INFN National Laboratories

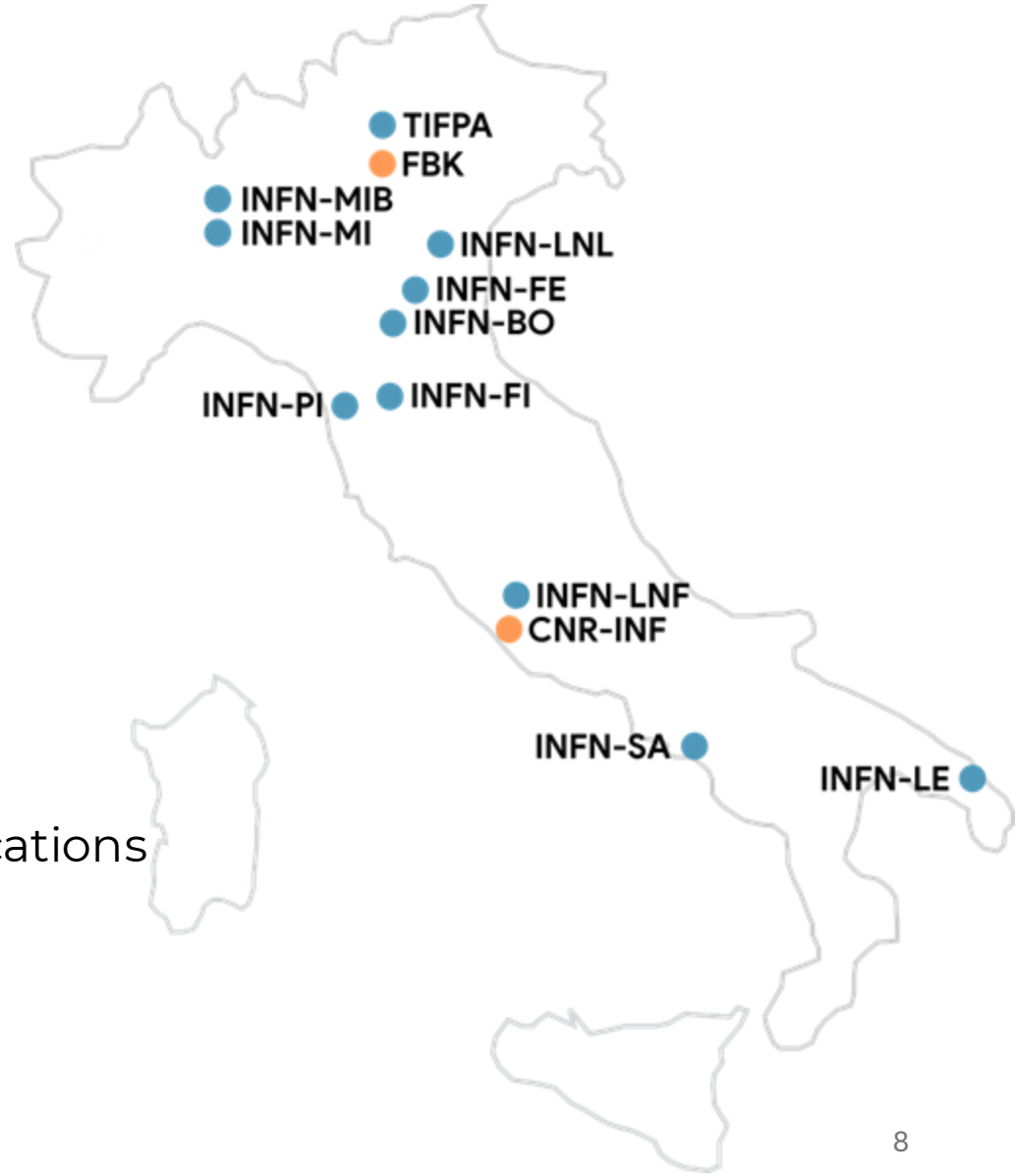
- INFN Laboratori Lazionali di Frascati (LNF)
- INFN Laboratori Lazionali di Legnaro (LNL)

## 1 INFN Research Center

- Trento Institute for Fundamental Physics and Applications (TIFPA).

## 2 External Research Centers

- Fondazione Bruno Kessler (FBK, Trento)
- Istituto di Fotonica e Nanotecnologie (CNR-IFN, Roma)



# Group’s size

| # | Unit | Number of Researchers | FTE |
|---|---|---|---|
| 1 | INFN-BO | 10 | 2.2 |
| 2 | INFN-FE | 4 | 1.1 |
| 3 | INFN-FI | 4 | 1.4 |
| 4 | INFN-LE | 6 | 1.2 |
| 5 | INFN-LNF | 11 | 4.3 |
| 6 | INFN-LNL | 3 | 1.5 |
| 7 | INFN-MI | 2 | 1.4 |
| 8 | INFN-MIB | 14 | 6.4 |
| 9 | INFN-PI | 16 | 2.55 |
| 10 | INFN-SA | 7 | 2.2 |
| 11 | INFN-TIFPA | 14 | 4.4 |
| | **Total** | **91** | **28.65** |

# Budget – 3 year's plan

| Unit | 1st Y [k€] | 2nd Y[k€] | 3rd Y [k€] | Total [k€] |
|---|---|---|---|---|
| INFN-BO | 20 | 20.5 | 14.5 | **56** |
| INFN-FE | 3 | 3 | 3 | **9** |
| INFN-FI | 9 | 4 | 4 | **17** |
| INFN-LE | 20 | 19 | 14 | **63** |
| INFN-LNF | 46 | 45 | 45 | **136** |
| INFN-LNL | 13 | 9 | 6 | **28** |
| INFN-MI | 15 | 6 | 1 | **15** |
| INFN-MIB | 36 | 23 | 11 | **70** |
| INFN-PISA | 28 | 27 | 21 | **76** |
| INFN-SA | 25 | 24 | 22 | **71** |
| INFN-TIFPA | 35 | 35 | 35 | **105** |
| **Totale** | **250** | **215.5** | **176.5** | **642** |

Chip production (FBK)
25 k€ / year

Chip production (CNR-IFN)
20 k€ / year

Cavity production (INFN-LNL)
5 k€ / year

# Working Packages

| Unit | WP1 | WP2 | WP3 | WP4 | WP5 | WP6 | WP7 | WP8 | WP9 |
|---|---|---|---|---|---|---|---|---|---|
| INFN-BO | ✓ | ✓ | | | ✓ | | | | |
| INFN-FE | | | | | ✓ | | | | |
| INFN-FI | ✓ | ✓ | ✓ | | | | | ✓ | |
| INFN-LE | | | | | | | ✓ | ✓ | |
| INFN-LNF | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| INFN-LNL | | | | ✓ | | | | | |
| INFN-MI | ✓ | | | | ✓ | | | | |
| INFN-MIB | | ✓ | | | ✓ | ✓ | ✓ | | ✓ |
| INFN-PI | ✓ | | ✓ | ✓ | | | | ✓ | |
| INFN-SA | | ✓ | | | | ✓ | ✓ | | |
| INFN-TIFPA | ✓ | | | ✓ | | ✓ | ✓ | | |
| | 6 | 4 | 3 | 3 | 5 | 4 | 5 | 4 | 1 |

- **WP1: Theoretical Background** *led by INFN-TIFPA*
- **WP2: Design and simulations of planar (2D) devices** *led by INFN-TIFPA*
- **WP3: Design and simulations of tridimensional (3D) devices** *led by INFN-LNF*
- **WP4: Microfabrication process for superconducting qubits** *led by INFN-PI and INFN-TIFPA*
- **WP5: Software and readout system** *led by INFN-MI and INFN-MIB*
- **WP6: Quantum Limited Amplifiers** *led by INFN-SA*
- **WP7: Characterization, Measurement and Demonstration** *led by INFN-LNF and INFN-MIB*
- **WP8: Application for quantum sensing and Machine Learning** *led by INFN-FI and INFN-LNF*
- **WP9: Management and Communication** *led by INFN-MIB*

# Assegnazioni economiche generali

| Sez. & Suf. | MISS | | | | CON | | | | ALTRICONS | | | | SEM | | | | TRA | | | | PUB | | | | MAN | | | | INV | | | | LIC-SW | | | | APP | | | | SPSERVIZI | | | | TOTALE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. | | Sj | Dot. | Ant. |
| BO | 6.0 | | | | 5.5 | | | | | | | | | | | | | | | | | | | | | | | | 6.0 | | | | 2.5 | | | | | | | | | | | | 20 | | | |
| | 4.0 | | | | 4.5 | | | | | | | | | | | | | | | | | | | | | | | | 6.0 | | | | 2.5 | | | | | | | | | | | | 17.0 | | | |
| FE | 3.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 3 | | | |
| | 3.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 3.0 | | | |
| FI | 4.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 5.0 | | | | | | | | | | | | | | | | 9 | | | |
| | 3.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0.0 | | | | | | | | | | | | | | | | 3.0 | | | |
| LE | 2.0 | | | | 14.0 | | | | | | | | | | | | | | | | | | | | | | | | 4.0 | | | | | | | | | | | | | | | | 20 | | | |
| | 2.0 | | | | 6.0 | | | | | | | | | | | | | | | | | | | | | | | | 0.0 | | | | | | | | | | | | | | | | 8.0 | | | |
| LNF | 5.0 | | | | 25.0 | | | | | | | | | | | | | | | | | | | | 5.0 | | | | | | | | | | | | 11.0 | | | | | | | | 46 | | | |
| | 4.0 | | | | 4.0 | 20.0 | | | | | | | | | | | | | | | | | | | 0.0 | | | | | | | | | | | | 9.0 | | | | | | | | 17.0 | 20.0 | | |
| LNL | 2.0 | | | | 11.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 13 | | | |
| | 2.0 | | | | 8.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 10.0 | | | |
| MI | 5.0 | | | | 10.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 15 | | | |
| | 2.5 | | | | 2.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 4.5 | | | |
| MIB | 6.0 | | | | | | | | 2.0 | | | | | | | | 0.5 | | | | | | | | | | | | 25.0 | | | | 2.5 | | | | | | | | | | | | 36 | | | |
| | 4.0 | | | | | | | | 1.0 | | | | | | | | 0.5 | | | | | | | | | | | | 0.0 | 25.0 | | | 2.5 | | | | | | | | | | | | 8.0 | 25.0 | | |
| PI | 4.0 | | | | 15.5 | | | | | | | | | | | | 0.5 | | | | | | | | | | | | 6.0 | | | | 2.0 | | | | | | | | | | | | 28 | | | |
| | 4.0 | | | | 9.0 | | | | | | | | | | | | 0.5 | | | | | | | | | | | | 0.0 | | | | 2.0 | | | | | | | | | | | | 15.5 | | | |
| SA | 5.5 | | | | 15.0 | | | | 2.0 | | | | | | | | | | | | | | | | | | | | | | | | 2.5 | | | | | | | | | | | | 25 | | | |
| | 4.0 | | | | 7.0 | | | | 2.0 | | | | | | | | | | | | | | | | | | | | | | | | 2.5 | | | | | | | | | | | | 15.5 | | | |
| TIFPA | 2.0 | | | | 33.0 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 35 | | | |
| | 0.0 | | | | 15.5 | 12.5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 15.5 | 12.5 | | |
| TOTALE | 44.5 | | | | 129 | | | | 4 | | | | | | | | 1 | | | | | | | | 5 | | | | 46 | | | | 9.5 | | | | 11 | | | | | | | | 250 | 0 | | |
| | 44.5 | | | | 129 | | | | 4 | | | | 0 | | | | 1 | | | | 0 | | | | 5 | | | | 46 | | | | 9.5 | | | | 11 | | | | 0 | | | | 250 | | | |
| | 32.5 | | 0 | 0 | 56 | 32.5 | 0 | 0 | 3 | | 0 | 0 | | | | | 1 | | 0 | 0 | | | | | 0 | 0 | 0 | | 6 | 25 | 0 | 0 | 9.5 | | 0 | 0 | 9 | | 0 | 0 | | | | | 117 | 57.5 | 0.0 | 0.0 |
| | 32.5 | | | | 88.5 | | | | 3.0 | | | | 0.0 | | | | 1.0 | | | | 0.0 | | | | 0.0 | | | | 31.0 | | | | 9.5 | | | | 9.0 | | | | 0.0 | | | | 174.5 | | | |

# Assegnazioni – dettaglio BO

| Sigla Loc. | Capitolo | Riunione | Note Alla Richiesta | Rich. | Rich. SJ | Assegn. | Assegn. SJ | Assegn. Dot. | Commento Alla Assegnazione |
|---|---|---|---|---|---|---|---|---|---|
| BO | MISS | Assegnazioni | Missioni presso altri laboratori per sessione di lavoro congiunte e misure. Missioni per lavoro congiunto su scheda zcu208 , software e misure sperimentali; test primo prototipo filtro di Purcell in lettura di >=1 qubit | 6.0 | 0.0 | 4.0 | | | |
| | | **Totale MISS** | | **6.0** | **0.0** | **4.0** | **0.0** | **0.0** | |
| | CON | Assegnazioni | Consumo generale per materiale RF (connettori, filtri, cavi ecc.) | 4.0 | 0.0 | 3.0 | | | |
| | | Assegnazioni | 2 mixer RF MM1-0212LS , 2 splitter/combiner RF ZX10-2-183-S+. per up/down conversion analogica | 1.5 | 0.0 | 1.5 | | | |
| | | **Totale CON** | | **5.5** | **0.0** | **4.5** | **0.0** | **0.0** | |
| | INV | Assegnazioni | Scheda VF-100 (v. allegato) per accedere a tutti i canali ADC/DAC della scheda ZCU111 | 6.0 | 0.0 | 6.0 | | | |
| | | **Totale INV** | | **6.0** | **0.0** | **6.0** | **0.0** | **0.0** | |
| | LIC-SW | Assegnazioni | Contributo CNAF per licenza ANSYS - per progettazione elementi 2d quali un filtro di Purcell. | 2.5 | 0.0 | 2.5 | | | |
| | | **Totale LIC-SW** | | **2.5** | **0.0** | **2.5** | **0.0** | **0.0** | |
| **Totale BO** | | | | **20.0** | **0.0** | **17.0** | **0.0** | **0.0** | |

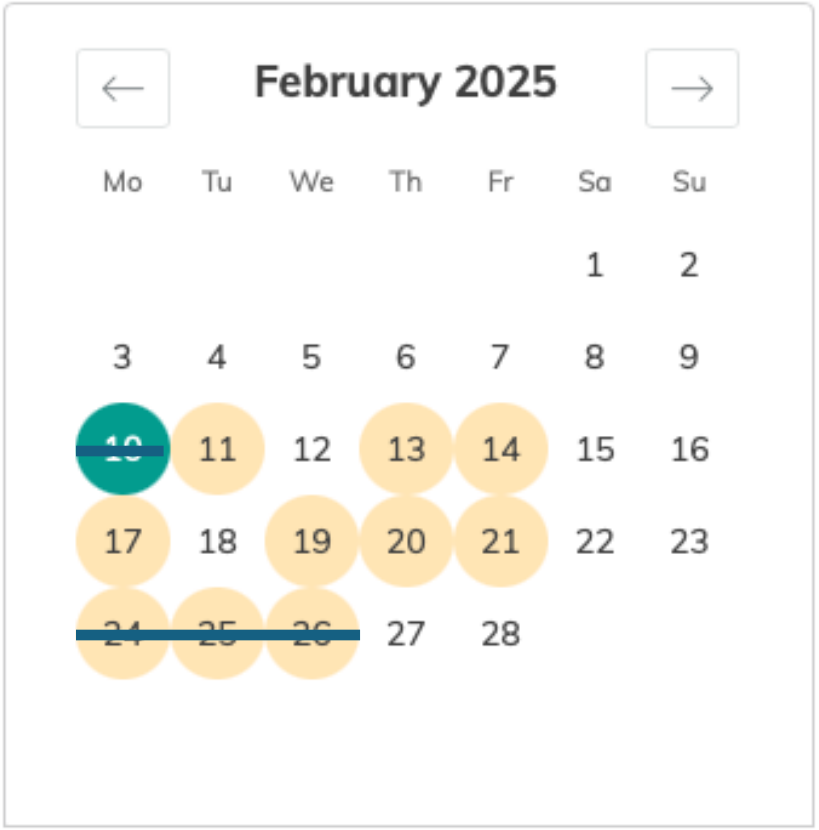
| Totale Generale QUARTET | 20.0 | 0.0 | 17.0 | 0.0 | 0.0 | |
|---|---|---|---|---|---|---|

# Working packages - aggiornati

| QUART&T WP leaders | |
|---|---|
| **WP1: Theoretical Background** | |
| Alessandro Roggero (TIFPA) | a.roggero@unitn.it |
| **WP2: Design and simulations of planar devices** | |
| Danilo Labranca (MIB) | danilo.labranca@mib.infn.it |
| Felix Ahrens (TIFPA) | fahrens@fbk.eu |
| **WP3: Design and simulations of three-dimensional (3D) devices** | |
| Alessandro D'Elia (LNF) | alessandro.delia@lnf.infn.it |
| Simone Tocci (LNF) | simone.tocci@lnf.infn.it |
| **WP4: Design and simulations of three-dimensional (3D) devices** | |
| Claudio Puglia (PI) | claudio.puglia@pi.infn.it |
| Federica Mantegazzini (TIFPA) | fmantegazzini@fbk.eu |
| **WP5: Hardware and Software development** | |
| Stefano Carazza (MI) | stefano.carrazza@unimi.it |
| Andrea Giachero (MIB) | andrea.giachero@mib.infn.it |
| **WP6: Quantum Limited Amplifiers** | |
| Sergio Pagano (SA) | spagano@unisa.it |
| Nicolò Crescini (TIFPA) | ncrescini@fbk.eu |
| **WP7: Characterization, Measurement and Demonstration** | |
| Alessio Rettaroli (LNF) | alessio.rettaroli@lnf.infn.it |
| Marco Faverzani (LNF) | marco.faverzani@mib.infn.it |
| **WP8: Application for Quantum Sensing and Machine Learning** | |
| Leonardo Banchi (FI) | leonardo.banchi@unifi.it |
| Claudio Gatti (LNF) | claudio.gatti@lnf.infn.it |

| **External Institutions** | |
|---|---|
| **FBK** | |
| Federica Mantegazzini (FBK) | fmantegazzini@fbk.eu |
| **CNR** | |
| Francesco Chiarello (IFN-CNR) | francesco.mattioli@cnr.it |

# Date kick-off





**h 9-13, 14-18**

il 10/2
h 8-12, 14-18

# Info ANSYS

- Piattaforma disponibile
- Istruzioni (datate): https://web.pd.infn.it/CCR/6-ansys-enab
- Bisogna registrarsi poi indirizzare il license server lm-ansys.infn.it
  - Si usano sempre le porte standard dei vari licence manager, per cui è sufficiente istruire l'installazione con il solo nome del server
- Ansys CFD, EM ed HFSS
- Anche licenze di  Granta, Lumerical e Zemax
- Da Ingegneria serve una VPN INFN
  - Il controllo viene fatto anche sullo user id di chi si registra (un utente non registrato non può accedere al software)

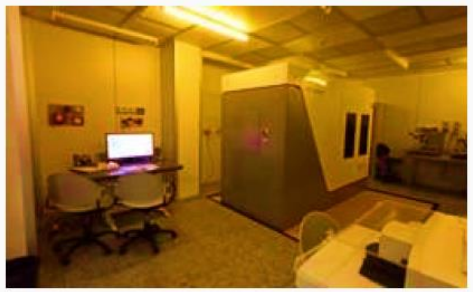
# Attività BO

- Manipolazione/readout tramite Xilinx/AMD ZCU111 (gen.1) + ZCU208? (gen.3)
  - Matteo Franchini
- Filtro di Purcell
  - Simona Zaccaria

- Sarà possibile anche partecipare a WP diversi da quelli in cui formalmente ci si trova
- Definire un giorno/ora che vada bene a tutti per briefing regolari (al momento opportuno)

# CNR-IFN Rome Nanofabrication Facility

The Nanofabrication facility is located in a 500 square meters, 100-1000 class (ISO5 – ISO6) clean room, in the Rome ARToV (Area della Ricerca di Tor Vergata) Research Area.

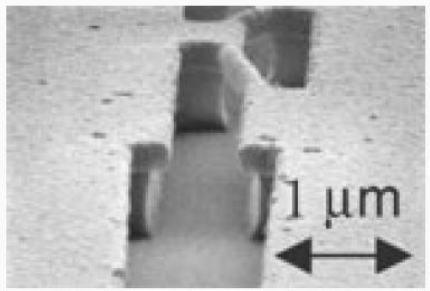


**Voyager Raith Electron Beam Lithography system**

Resolution up to 10 nm, sample sizes up to 6”, realignment on markers

**Balzers 510 evaporation system**

Load lock for on site oxidation, tilted angle evaporation




**SEM image of a suspended bilayer bridge**

for the fabrication of Al/AlOx/Al junctions using double angle shadow evaporation

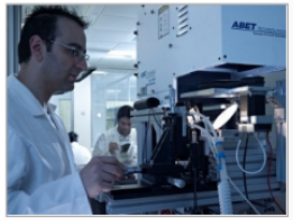
Succesfully produced Josephson junctions for the INFN Project Qub-IT and SIMP;

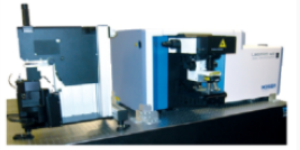
**Main Tools:**

E-Beam microfabricator
Mask aligner
Sputtering
Evaporator (tilted angle)
RIE (Reactive Ion Etching)
ICP (Inductively Coupled Plasma)
SEM (Scanning Electron Microscope)
AFM (Atomic Force Microscope)
Optical microscopes
Ultrasonic bonder
Profilometer
Scriber
Resist spinner
Ovens
Chemicals

# FBK Micro and Nano Fabrication Facility







- **CR-D**: 700 $m^2$, Class 10/100, 0.8 $\mu$m CMOS pilot line: Ion Implantation, Oxidation, Diffusion, RIE, Deep RIE (silicon and oxide), Lithography (0.35 $\mu$m + mask aligner + EBL), metal sputtering, optical profilometry;
- **CR-M**: 500 $m^2$, Class 100/1000, diffusion, lithography (mask aligner + laser writer), wafer bonding, electroplating, Si bulk micromachining, metal evaporation, rf magnetron sputtering, RIE, mechanical and optical profilometry;
- **CR-3D**: $m^2$, Class 10/100, CMP, thinning, bonding, ALD, metrology;
- **Testing Area**: 300 $m^2$; manual parametric testing, automatic parametric/functional testing, optical testing (spectral responsivity, quantum efficiency), solar cells efficiency characterization, gas and pressure sensors test benches;
- **Integration Area**: 100 $m^2$, Class 1000 Microassembly station; screen printing, bonding (ball & wedge bonder), Shear-Pull, Tester, reflow oven, CNC micro-mill, pick and place
- **Nano- and Micro- Analytical Facility**: Nano Ramen, FIB-SEM-EDX-EBSD, D-SIMS, TOF-SIMS, XPS, AFS, XRD/XRF;

Succesfully produced Josephson junction for the JPAs and qubits within the NQSTI and Qub-IT project;