QUART&T: Quantum Architectures for Theory & Technology

Kick-off Meeting

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QUART&T: Goal

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.

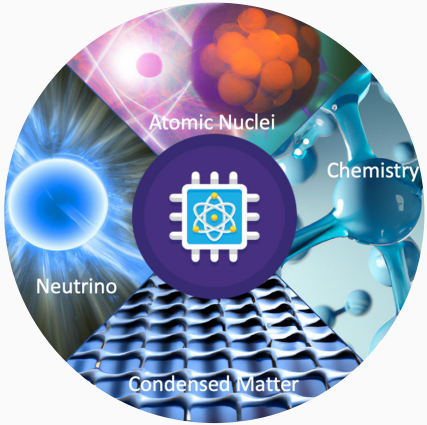
quartet of crucial optimizations:

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

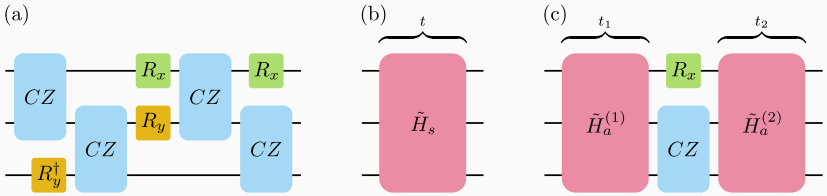
The ***project goal*** and the ***crucial optimizations*** will be reached through:

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

1. Quantum many-body systems are one of the most daunting computational challenge in theoretical physics;
2. This class of problems is characterized by a Hilbert space size that increases steeply when the number of one-body (particle) increases;
3. Many-body systems are relevant in nuclear physics, atomic physics, astrophysics, low dimensional gravity, condensed-matter physics, and quantum chemistry;
4. This large size leads to severe restrictions in the class of many-body systems that one can solve exactly on classical computers;
5. Quantum computers contain an exponential complexity:
   - suitable for tackling many-body;
   - second quantization share many formal aspects with qubits;



Eur. Phys. J. A 59, 227 (2023)



(a) **Digital simulation**: $H_s = H_1 + H_2 + ... + H_n \Rightarrow U(t) = e^{-H_1 t/r} \cdot e^{-H_1 t/r} \cdot ... \cdot e^{-H_n t/r}$
Trotter–Suzuki decompositions: digital sequence tries to reproduce a targeted quantum evolution

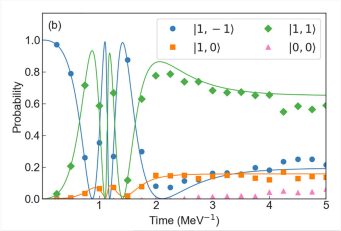
(b) **Analog simulation**: $H_s = \tilde{H_s} \Rightarrow U(t) = T \exp\left[-\int_0^t dt' H_0 + H_p(t')\right]$ where $H_p(t)$ is an external pulse drive;
Controllable system with evolution $\tilde{H_s}$ mimics almost one-to-one that of the simulated system H_s;
The tunable nature allows to to implement external fields and/or interactions;

(c) **Digital Analog Simulation:** $H_s = \tilde{H_a}^{(1)} + H_1 + H_2 + ... + H_n + \tilde{H_a}^{(2)} \Rightarrow U(t) = \prod_i \tilde{H_a}^{(i)} \cdot \prod_j H_j$
Combines analog blocks that naturally appear in the simulator with digital gates

Nuclear Reactions and Dynamics

Ab-initio nuclear dynamics important for:

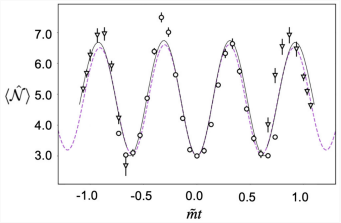
- Nuclear reactions for hot plasmas and nucleosynthesis;
- Nutrino-scattering for supernovae explosion and neutron star cooling;
- Cross sections for dark-matter discovery and neutrino physics



Phys. Rev. A 108, 032417 (2023)

Lattice Quantum Chromodynamics

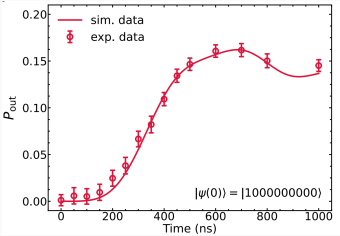
- Real-time dynamics and properties of dense quark matters suffer from the sign problem in classical computations;
- Analog quantum computing hold promise for overcoming the sign problem in quantum many-body simulations;



Phys. Rev. Research 5, 033184 (2023)

Circuit Quantum Electrodynamics

- Analog quantum computing allows to simulate relativistic quantum physics in circuit quantum electrodynamics;
- Possibility to simulate the dynamics of the Dirac equation and Klein paradox in all regimes;



Nat Commun 14, 3263 (2023)

QUART&T: four essential technological components

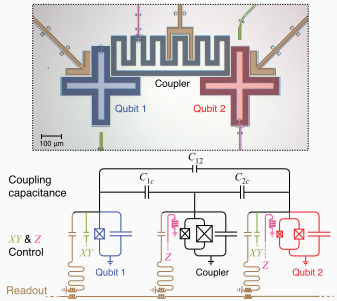
1. **Tunable Couplings**: possibility to implement and control the required couplings between qubit and perform the operation for different lengths of chains and prepared initial states.

2. **All-to-all Connectivity**: Tunable qubits coupled to a common bus resonator have the advantage of all-to-all coupling and can entangle by tuning to near resonance with each other.

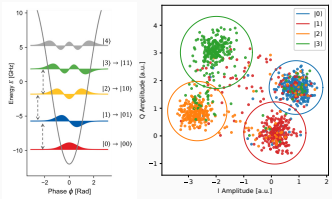
3. **Qudits**: The quantum device developed within the project will also be exploited as higher-dimensional quantum systems (qudits), which offer increased computational power and flexibility

4. **Circuit Quantum Electrodynamics (cQED)**: The integration of cQED principles into the superconducting qubit architecture will be the key approach for enabling the efficient manipulation and measurement of quantum states

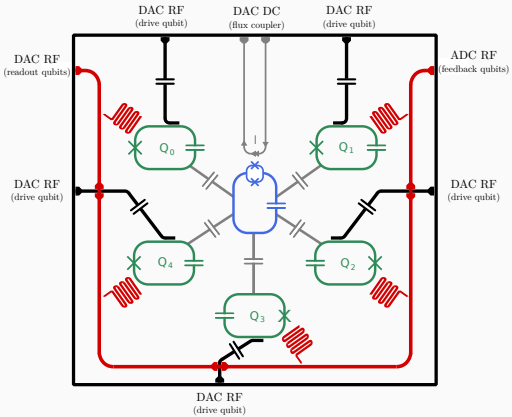
Tunable coupler



Qudit

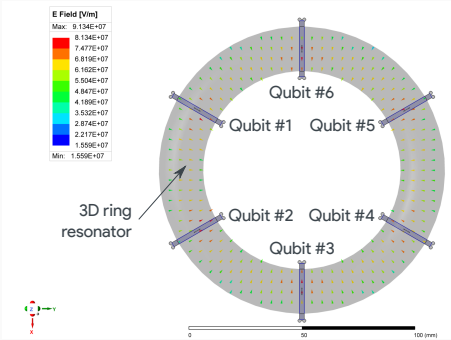


5 qubits in planar cavities



- Planar qubits provide easy scalability;
- Tunable coupling provided by a SQUID or another qubit;
- Suitable for all-to-all connectivity;

6 qubits in tridimensional cavity



- Tridimensional qubits provide higher coherent times;
- More difficult to scale;
- But ideal solution for implementing qudit;

8 INFN Units

- INFN Bologna
- INFN Ferrara
- INFN Firenze
- INFN Lecce
- INFN Milano
- INFN Milano-Bicocca **[RN]**
- INFN Gruppo Collegato di Salerno (INFN Napoli)

2 INFN National Laboratories

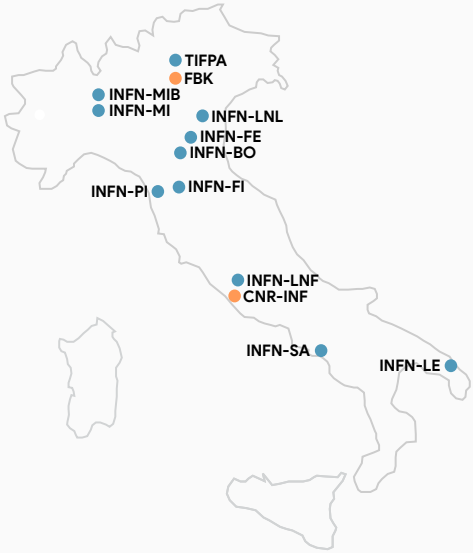
- INFN Laboratori Lazionali di Frascati (LNF)
- INFN Laboratori Lazionali di Legnaro (LNL)

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)



QUART&T: Project Management Board (PMB)

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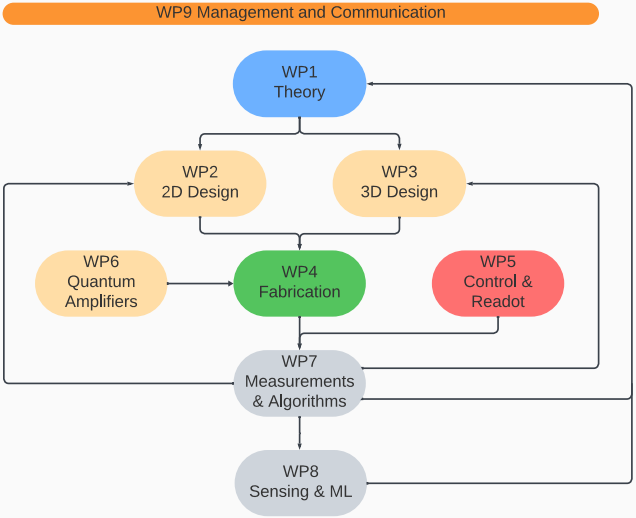
- Defines the overall objectives and milestones of the project;
- Tracks project progress against predefined milestones and deliverables;
- Defines a publication policy, ensuring proper authorship, acknowledgment, and institutional affiliations;
- Defines guidelines for presenting results at conferences, ensuring uniformity and accurate representation of the project;
- E-mail: quartet-pmb@lists.infn.it

QUART&T: Working Packages



- **WP1: Theoretical Background** *led by INFN-TIFPA*
- **WP2: Design and simulations of planar (2D) devices** *led by INFN-MIB and 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 and INFN-TIFPA*
- **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*

QUART&T: WP leaders

	Leader	Unit	e-mail
WP1	Alessandro Roggero	INFN-TIFPA	a.roggero@unitn.it
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IFN-CNR	Francesco Mattioli	francesco.mattioli@cnr.it
FBK	Federica Mantegazzini	fmantegazzini@fbk.eu

QUART&T: Allocated Funds for 2025

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		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			
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FE	3.0																																													3			
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FI	4.0																												5.0																9			
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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			
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MI	5.0				10.0																																									15			
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MIB	7.0								2.0								0.5												25.0				2.5												37			
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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			
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TIFPA	2.0				33.0																																								35			
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TOTALE	45.5				129				4								1								5				46				9.5				11								251	0		
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	33.5		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					118	57.5	0.0	0.0
				33.5				88.5				3.0				0.0				1.0				0.0				0.0				31.0				9.5				9.0				0.0				175.5

- 118 k€ assigned
- 57.5 k€ sub-judice (12.5k€ at TIFPA for production at FBK and 20k€ at LNF for for production at IFN-CNR)

2025.M1 30-06-2025	Simulations and design of the elementary components required for implementing tridimensional (3D) coupled qubits.
2025.M2 30-06-2025	Simulations and design of the elementary components required for implementing planar (2D) coupled qubits.
2025.M3 30-09-2025	Production of the elementary components for implementing 2D and 3D coupled qubits.
2025.M4 31-12-2025	Characterization of the produced elementary components for implementing 2D and 3D coupled qubits.
2025.M5 31-12-2025	First version of the software and firmware for controlling and reading out coupled qubits.

QUART&T: endorsement

#	Institute	Contact Person
1	Chalmers University of Technology, Göteborg, Swede,	Prof. Simone Gasparinetti
2	Charles University, Prague, Czech Republic	Prof. Alfredo Iorio
3	Istituto Nazionale di Ricerca Metrologica, Torino, Italy	Dr. Emanuele Enrico
4	National Institute of Standards and Technology, Boulder, CO, USA	Dr. Raymond Simmonds
5	Planckian, Pisa, Italy	Dr. Michele Dallari (CEO)
6	Politecnico di Torino, Torino, Italy	Dr. Fabrizio Riente
7	QuTech Quantum Computing Research Center, Delft, Netherlands	Prof. Christian Andersen
8 (new)	Institute for Quantum Computing (IQC), Waterloo, Canada	Prof. Christopher Wilson

QUART&T: Conclusion

- Analog quantum simulation is a fundamental tool for theoretical computation in fields of interest to the INFN;
- Superconducting planar (2D) and three-dimensional (3D) qubits coupled by a tunable coupler can be used to implement analog quantum simulations;
- The implemented architecture will be exploited for applications in quantum sensing and quantum machine learning;
- Several challenges will need to be addressed, but the collaboration can rely on the expertise from two INFN National Laboratories, nine INFN Units, and two of the main micro and nano-fabrication facilities in Italy (FBK and CNR-IFN).
- Qub-IT and DARTWARS helped to introduce superconducting quantum technologies into the INFN.
- QUART&T will consolidate this acquired knowledge and open up new opportunities for quantum simulation and fundamental physics experiments.