# Qub-IT

# QUANTUM SENSING WITH SUPERCONDUCTING QUBITS FOR FUNDAMENTAL PHYSICS

DURATA PROPOSTA: 3 ANNI
AREA DI RICERCA: DETECTORS, FUNDAMENTAL PHYSICS, QUANTUM MECHANICS
RESPONSABILE NAZIONALE - CLAUDIO GATTI (LNF)
UNITA' INFN: FERRARA, FIRENZE, LNF, MILANO, MILANO BICOCCA, PISA, SALERNO, TIFPA
ENTI ESTERNI: FBK, CNR-IFN

*ABSTRACT*

Recent progresses in the ability to measure and manipulate individual quanta such as microwave-photons, phonons and magnons are opening new directions in the detection of Dark Matter and of Fifth Forces, in tests of Quantum Gravity and of Quantum Mechanics of macroscopic objects. Superconducting qubits constitute a fundamental building block of this progress. In the last 15 years quantum sensing with superconducting qubits has moved from proof of principle to application to fundamental physics experiments, showing an unprecedent improvement in sensitivity. This was made possible by the ability to engineer and fabricate quantum devices and to manipulate the qubit state with classical fields. Quantum superposition and entanglement have been used to achieve Quantum Non Demolition detection of single photons and detection of itinerant photons, respectively, two fundamental features required by a microwave-photon detector in Axion dark-matter experiments.

The Qub-IT project aims to develop quantum sensing with superconducting qubits for present and future INFN fundamental-physics experiments. The main objective of the project is the realization of an itinerant single-photon counter that surpasses present devices in terms of efficiency and low dark-count rates by exploiting repeated QND measurements of a single photon and entanglement in multiple qubits. This device will find immediate application in light dark-matter searches.

The project goal will be reached through the following specific objectives:

- SO1. Design and simulation of a superconducting qubit coupled to resonators
- SO2. Fabrication of circuits with superconducting qubit
- SO3. Single-shot measurement of superconducting qubit with quantum amplifier
- SO4. Control of superconducting qubit with FPGA board
- SO5. Quantum sensing experiment with entangled qubits

Developing superconducting quantum-devices is a complex process requiring different skills going from theoretical modelling to electromagnetic design, multi-step fabrication with optical and electron lithography, control of qubits with RF pulses and single-shot readout of qubit state with quantum amplifiers, all cooled down in a dilution refrigerator to few mK. The Qub-IT research team succeeded in bringing these skills together through the participation of five INFN cryogenics labs with expertise in radiofrequency and quantum devices, theoretical physicists expert in quantum control theory, open quantum systems and quantum information theory, two engineering departments with expertise in microwave devices, two micro and nano-fabrication facilities, and physicists and engineers experts in quantum-hardward control techniques, quantum applications and FPGA programming. The project will rely on the experience gained with the SIMP project, will be synergistic to DART WARS and its result will have direct application to the QUAX experiment.

# SCIENTIFIC PROPOSAL

## *STATE OF ART*

Recent progresses in the ability to measure and manipulate individual quanta such as microwave-photons [1], phonons [2, 3, 4, 5, 6, 7] and magnons [8, 9] are opening new directions in the detection of Dark Matter and of Fifth Forces [10, 11, 12], in tests of Quantum Gravity [13, 14] and of Quantum Mechanics of macroscopic objects [15, 16].

Superconducting (SC) qubits constitute a fundamental building block of the progresses in quantum sensing. Quantum mechanical effects in Josephson junctions (JJ) were already observed in the '80s [17] while with the advent of SC qubits entanglement has been observed with up to 20 qubits [18, 19, 20] allowing quantum tests such as violation of Bell's inequality [21].

A remarkable property of a quantum system is the ability to encode into its phase the history of the interaction with the surrounding environment. A direct application of this concept is the **Quantum Non Demolition** (QND) detection of a microwave photon [22]. This is exemplified by an experiment with a Rydberg atom passing inside a Fabry-Perot cavity [23]. Before entering the Fabry-Perot cavity (Fig. 1), the atom is prepared in a superposition of excited states with large electric-dipole by a classic resonant field pulse in cavity $R_1$:

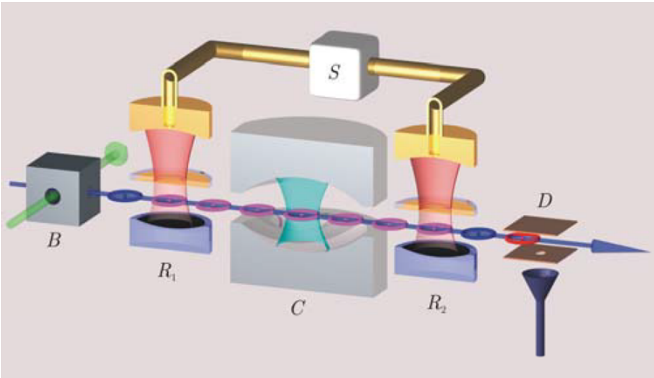



**Figure 1: Rydberg atom in a Fabry Perot cavity.**

$$|+\rangle = |g\rangle + |e\rangle$$

If the atomic frequency is detuned from the cavity mode the atom cannot absorb the photon but accumulates a phase passing in the Fabry-Perot cavity:

$$|\pm\rangle = |g\rangle + e^{i\phi_n}|e\rangle$$

where the phase $\phi_n$ depends on the number *n* of photons in the cavity. A second classical pulse in $R_2$ turns $|+\rangle \rightarrow |g\rangle$ when $\phi_n=0$ or $|-\rangle \rightarrow |e\rangle$ when $\phi_n=\pi$ before the atom state is measured in D. The combination $R_1$, $R_2$ and D is a Ramsey spectrometer that maps the number of photons inside the cavity into the atom state.

Similar schemes are used for the non-destructive measurement of 6 GHz photons [24, 26] where a Transmon qubit [25], used as an artificial atom, is coupled to two resonators: a high-Q resonator is used for storage of the photon and a low-Q resonator for fast readout of

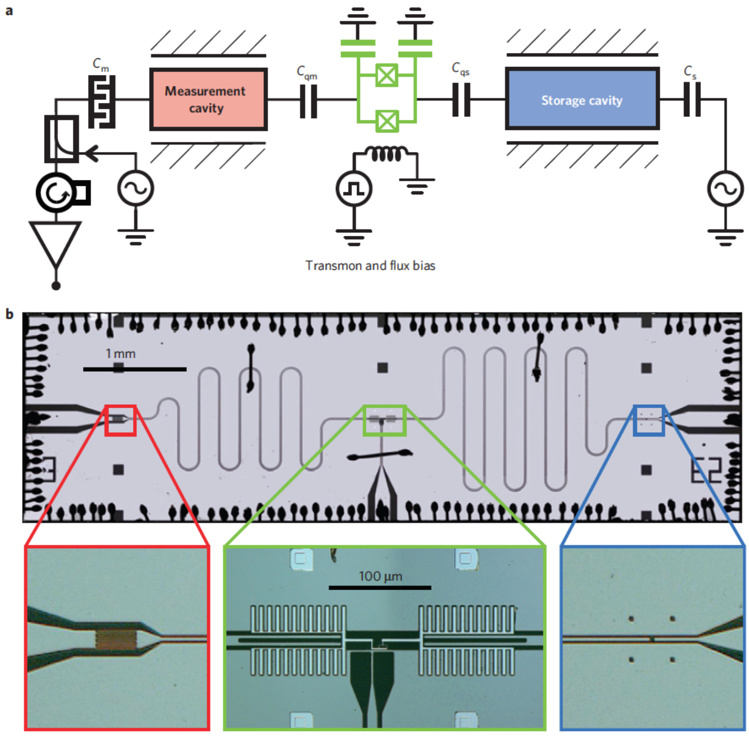



**Figure 2: Circuit schematics and device of the double resonator scheme.**

the qubit (Fig. 2 and 3).

In [26] the Ramsey-type experiment was done in a 3D cavity (Fig. 3) where Transmons are proven to have larger coherence and relaxation times [27].

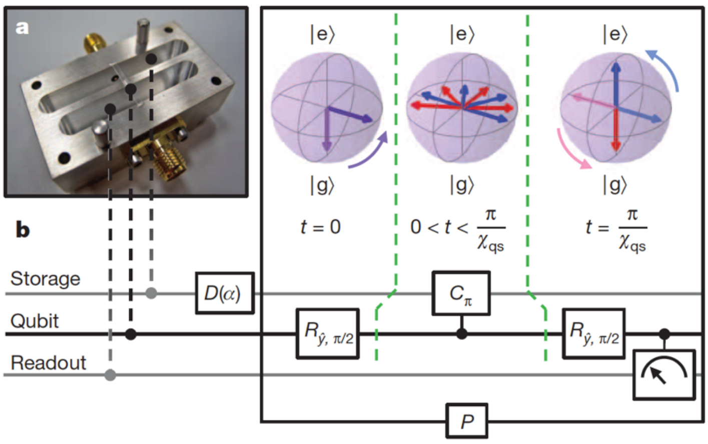



**Figure 3: Ramsey-type experiment for the QND detection of a photon in a 3D cavity.**

The QND nature of this technique, adopted in [11] for the search of dark matter composed of Dark Photons, allowed up to 30 repeated measurements of a 6 GHz photon with a **sensible reduction of readout errors and consequently of the dark counts**.

The above scheme represents an example of QND **localized-photon device**. On the contrary, **itinerant-photon devices** are able to detect a photon travelling in a transmission line, a very important feature for Axion dark-matter detectors where the superconductive device must be placed far from the strong magnetic field applied in the interaction region.

A second peculiar property of quantum systems, **entanglement**, allows the realization of itinerant-photon devices. Entanglement is a central resource in quantum information theory and entangled sensors offer enhanced detection sensitivity [22]. In [28] an input pulse mode travelling in a transmission line to the cavity is entangled with a qubit in a far-detuned 3D cavity (Fig. 4). Reflecting on the cavity the photon acquires a $\pi$-phase shift conditioned on the excited state of the qubit (a controlled Z gate):

$$
\begin{aligned}
|0,g\rangle &\rightarrow |0,g\rangle \\
|1,g\rangle &\rightarrow |1,g\rangle \\
|0,e\rangle &\rightarrow |0,e\rangle \\
|1,e\rangle &\rightarrow -|1,e\rangle
\end{aligned}
$$

Preparing the qubit in the sensing state $|g\rangle + |e\rangle$, the reflection of the photon rotates the qubit state to $|g\rangle - |e\rangle$. Performing a Ramsey experiment the photon occupation number is mapped into the qubit state. A similar scheme was used also in [29].

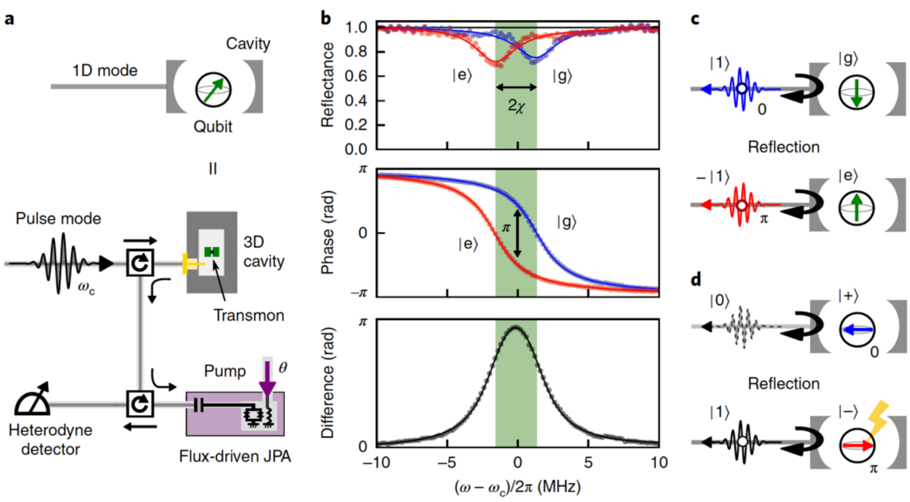



Figure 4: Scheme of QND measurement of an itinerant microwave photon.

The Qub-IT project aims to develop quantum sensing with superconducting qubits for present and future fundamental-physics experiments. It will rely on the experience gained with the SIMP project [46-51], will be synergistic to DART WARS and its result will have direct application to the QUAX experiment [30].

## *OBJECTIVES*

The main objective of the project is the realization of an itinerant single-photon counter that surpasses present devices in terms of efficiency and low dark-count rates by exploiting repeated QND measurements of a single photon and entanglement in multiple qubits. Entangled qubits in a Greenberger-Horne-Zeilinger (GHZ) $|GHZ\rangle = (|ggg \dots ggg\rangle + |eee \dots eee\rangle)/\sqrt{2}$ state increase signal sensitivity [22]: after time evolution the state picks up a phase proportional to the number N of qubits $|GHZ\rangle = \left(|ggg \dots ggg\rangle + e^{-iN\varphi_0}|eee \dots eee\rangle\right)/\sqrt{2}$ enhancing sensitivity (Fig. 5).

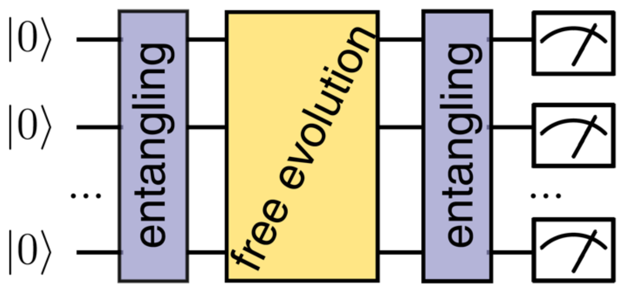



**Figure 5: Entangled Ramsey detection scheme [22].**

Entangled states can reduce the dark counts. In Fig. 6, the passage of an itinerant photon together with a Ramsey pulse sequence, similarly to the scheme in Fig. 4, entangles two qubits in the state $|gg\rangle + |ee\rangle$ resulting in the ability to reject erroneous excitations of single qubit ($|ge\rangle$ states) and in a reduction of dark counts.

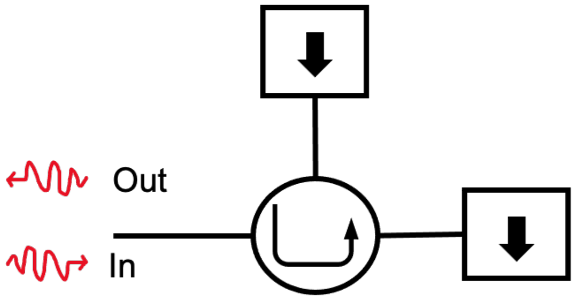



Figure 6: Example scheme of photon detector exploting repeated QND measurement and entanglement.

Such a device will have a direct application to dark-matter axion detection in INFN QUAX experiment [30] and in other light-dark matter or fifth force experiments.

To reach this goal and to profit of the possibilities for new experiments opened by the hybrid quantum-systems obtained by combining different quantum objects, it's necessary to develop theoretical and experimental tools collected in circuit Quantum Electrodynamics (cQED) [31]. Developing superconducting quantum devices is, in fact, a complex process requiring different skills going from theoretical modelling to electromagnetic design, multi-step fabrication with optical and electron lithography, control of qubits with RF pulses and readout with quantum amplifiers, all cooled down in a dilution refrigerator to few mK.

The project goal will be reached through the following specific objectives (SO):

SO1. Design and simulation of a SC qubit coupled to resonators
SO2. Fabrication of circuits with SC qubit
SO3. Single-shot measurement of SC qubit with quantum amplifier
SO4. Control of SC qubit with FPGA board
SO5. Quantum sensing experiment with entangled qubits

## *RESEARCH METHODOLOGY*

SO1. Design and simulation of a SC qubit coupled to resonators (WP1)

The project will focus on Transmon qubits [25] which combine simplicity in fabrication with large anharmonicity of energy levels and low sensitivity to charge noise. Transmon qubits are composed of JJ, non-dissipative non-linear elements, shunted by a capacitor. Their control and readout is obtained via capacitive couplings with resonators and external control lines.

Devices will be designed on IBM's Qiskit Metal [32], Ansys HFSS and Ansys Q3D. Qiskit Metal will be used to link the qubit quantum properties, described by Lagrangian parameters, to the circuit physical structure definined by the layouts of the qubit, the resonators, the coupling capacitors, and the wire-bonding pads. Capacitances will be calculated with Ansys Q3D and the electromagnetic modes will be simulated with Ansys HFSS. The qubit resonant frequency will be set between 5 and 10 GHz, with an anharmonicity on the order of hundreds of MHz. Both schemes with a qubit coupled with a single [1] and two resonators [24] will be designed for single-photon detection experiments. A **two-qubit** device for enhanced detection will be theoretically studied and designed.

Since reduction of dark-count rates is achievable by increasing the relaxation time of the qubit, **3D Transmons**, with longer lifetimes up to 240 microseconds [33], will be considered. A 3D Transmon consists of a JJ coupled with antenna pads inserted in a resonant cavity (Fig. 3). The antenna pads provide the shunt capacitance necesssary to obtain the right anharmonicity and noise insensitivity. Cavity modes, antenna capacitance and qubit coupling to the cavity will be calculated with Ansys HFSS.

Decoherence effects will be investigated. Qubits experience different forms of noise due to thermal effects, signal fluctuation or material effects. These will be modeled using Bloch-Redfield or Lindblad-type master equations and simulated.

SO2. Fabrication of circuits with SC qubit (WP2)

A simple technology based on aluminum and its native oxide ($Al/Al_2O_3/Al$) will be used to fabricate JJ and linear circuit elements. The fabrication requires two steps of lithography.

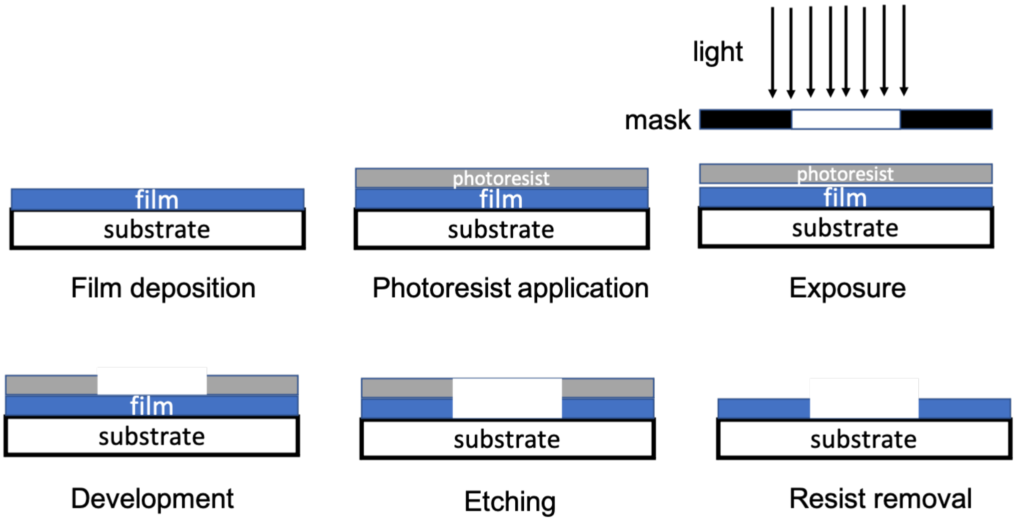



Figure 7: First lithographic step.

The first step is mainly used for the realization of transmission lines, resonators and interdigital capacitors. It consists in depositing 150 nm of aluminum by sputtering, defining it with optical submicron lithography and etching (Fig. 7).

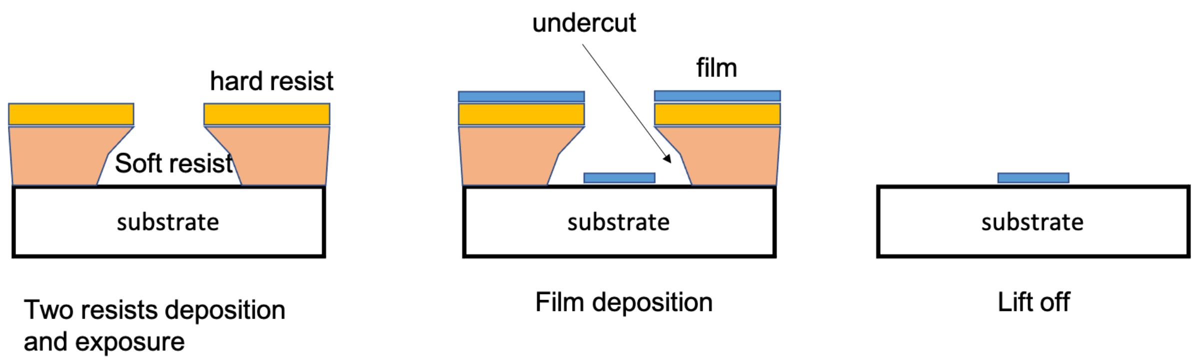



Figure 8: Second lithographic step.

The junctions are formed with a second lithography step and the lift-off technique (Fig. 8). By depositing two different types of resists an undercut is formed that allows the formation of small resist bridges that are used for JJ fabrication with the double-angle evaporation technique (Fig. 9) [34, 35].

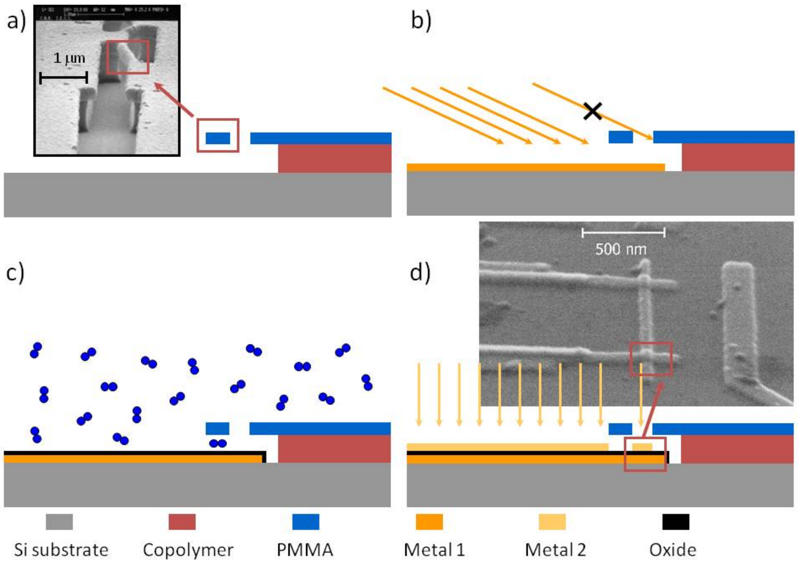



**Figure 9: Double-angle evaporation technique.**

Submicron optical lithography allows the fabrication of minimum junction-areas of about 0.2 x 1 µm$^2$, therefore Transmon qubits, with typical junction areas about 0.1 x 0.1 µm$^2$, require the higher definition obtainable with electron-beam lithography. This technique allows the realization of junctions with area from $\sim 2000\ \mathrm{nm}^2$ to $\sim 100\ \mu\mathrm{m}^2$. A mixed approach combining optical and electron-beam lithography will be used to reduce the fabrication time. Examples of JJ fabricated at CNR-IFN and FBK are shown in Fig. 10.

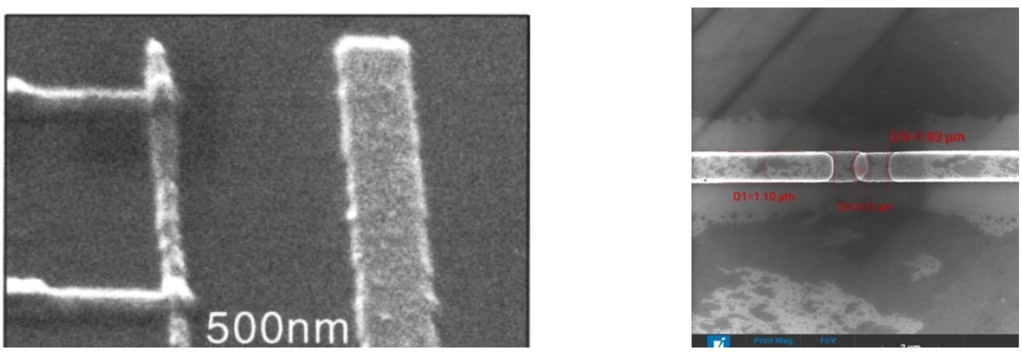



**Figure 10: (Left) SEM image of small area Josephson junction ($100\ \mu m^2 \times 100\ \mu m^2$) fabricated at CNR-IFN [36]. (Right) High resolution image with FIB of 1 micron wide junction obtained at FBK with submicron optical lithography.**

SO3. Single-shot measurement of SC qubit with quantum amplifier (WP1-4)

The qubit state wil be determined with **dispersive readout** obtained by coupling it to a resonator dispersively ($\nu_{qubit} \neq \nu_{resonator}$) and by measuring the transmission coefficient of the resonator. To reach the high fidelity necessary for low-noise and efficient detection-experiment [28], the measurement has to be completed in a time much shorter than the relaxation time $T_1$ and with a power low enough to avoid spurious qubit transitions [37]. Low single-shot fidelity is primarily due to inefficient amplification of the photons leaving the resonator. The noise added by cryogenic semiconductor microwave amplifiers is considerably larger than the signal from the resonator, necessitating repeated measurements to resolve the qubit state [38]. To achieve fast, high-fidelity single-shot readout, Purcell filters [39] and quantum amplifiers are used. Quantum amplifiers such as Josephson parametric amplifiers (JPA) are already employed in INFN experiment QUAX [30]. JJ devices fabricated at CNR-IFN have been succesfully operated as JPA within the INFN-SIMP project at LNF (Fig. 11, Left), and JPA circuits were fabricated at FBK (Fig. 11, right).

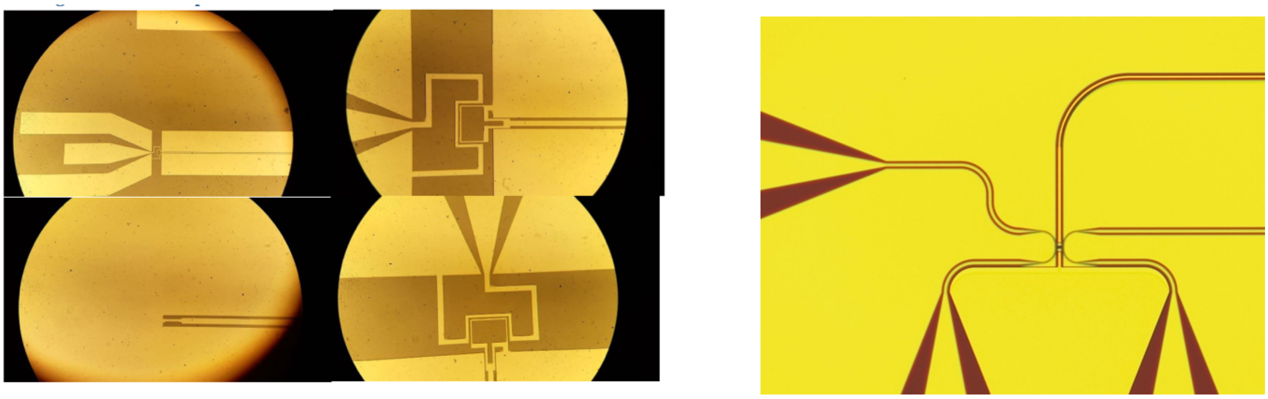


**Figure 11: (Left) JJ devices fabricated at CNR-IFN and operated as JPA. (Right) JPA circuit fabricated at FBK.**

Travelling wave parametric amplifiers (TWPA) developed within the INFN project DART WARS have also been tested (Fig. 12).

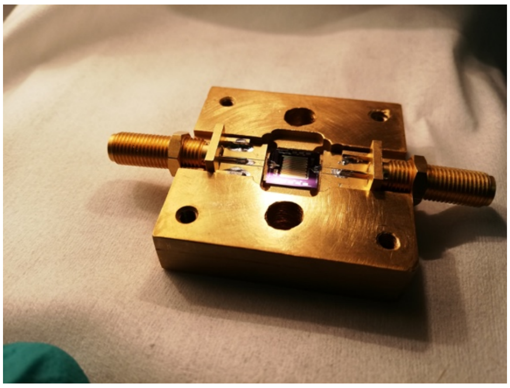


Figure 12: TWJPA from INRiM tested at LNF within the INFN DART WARS project.

SO4. Control of SC qubit with FPGA board (WP3)

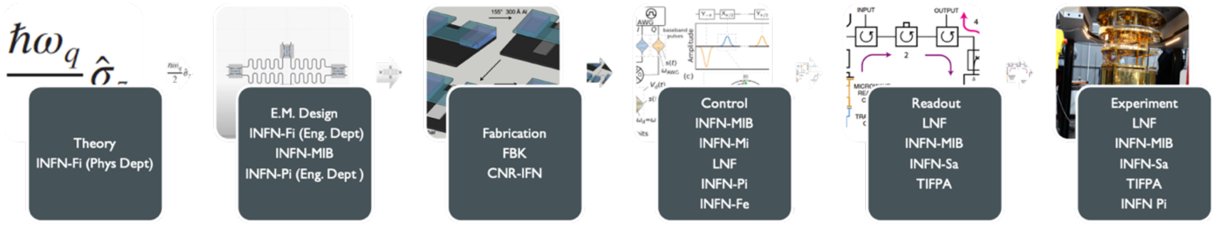
Qubits are controlled with Rabi oscillations driven by resonant RF pulses with appropriate timing and duration [40, 41]. Fast operation and repetition of the measurement will be achieved with SC qubit control and readout platforms built with FPGAs [42]. RF DACs with extra-wide bandwidths will be tested to directly synthesize control pulses [43].

The control system will be developed within the Qibo framework [44] an open-source full-stack operating system, already deployed in another SC qubit experiment, designed to program quantum algorithms and to control quantum devices.

SO5. Quantum sensing experiment with entangled qubits (WP4)

Junction parameters will be characterized experimentally. At room temperature the critical current will be determined from the normal resistance. Junctions and resonators will then be characterized in a dilution refrigerator to calibrate the fabrication process. Qubits will be characterized using one and two tone spectroscopy. Relaxation and dephasing time $T_{1,2}$ will be measured through Rabi and Ramsey spectroscopy [41]. Single photon detection experiments will be done with single and two-resonators devices. Finally, enhanced sensitivity due to entanglement will be shown on a device with two qubits (Fig. 6).

## *PROJECT ORGANIZATION*




The Project is organized in a management (WP5) and 4 work packages (WP1-4) (Fig. 13).

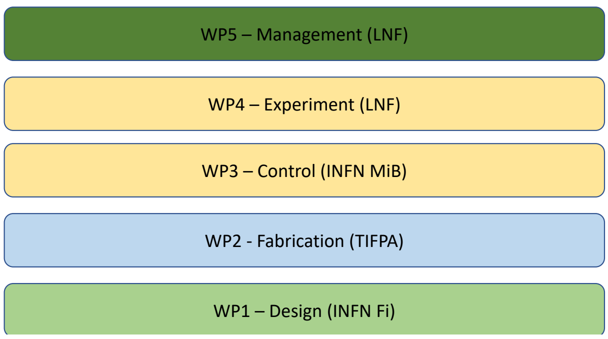



**Figure 13: Project organization in Work Packages.**

**WP1** is dedicated to the **Design** of the quantum devices and it will be led by INFN-Fi.

In **Task 1.1** the theoretical physicists of INFN-Fi will model the devices based on qubits coupled to resonators, define their parameters and investigate the detection scheme based on two entangled qubits. Starting from these parameters, the engineers of Uni-Fi and Uni-Pi together with physicists of INFN-MiB will simulate and define the electromagnetic layout of the superconducting chips. Task 1.1 will deliver the e.m. design for test components (D1.1), for the devices with qubit coupled to one (D1.2) and two resonators (D1.5) based on [1] and [24] respectively, a 3D Transmon based on [26, 27] (D1.3) and for the two-qubits device (D1.6).

In **Task 1.2** LNF, CNR-IFN, FBK and MiB will adapt existing designs of the JPA's [45] to the operation frequency of the quantum devices (D1.4). INFN-Sa will simulate JPA equations to help the characterization and to define the optimal working point.

In **Task 1.3** noise and decoherence effects will be modeled by INFN-Fi using Bloch-Redfield or Lindblad-type master equations and simulated with numerical calculations by INFN-Sa. The task will act as a support to the experimental activity during the whole duration of the project.

**WP2** is dedicated to the **Fabrication** of the quantum devices designed in WP1 and it will be led by TIFPA.

In **Task2.1** FBK and CNR-IFN will fabricate test chips with circuit components such as JJ, resonators and capacitors, for process calibration (D2.1).

In **Task2.2** 2D chips with Transmons coupled to resonators will be fabricated (D2.2 and D2.4). Baseline fabrication process foresee the first step lithography of resonators and capacitors at FBK with optical lithography and the next step with electron beam lithography at CNR-IFN for the deposition of small area JJ.

**Task2.3** is dedicated to the fabrication of the 3D Transmon. INFN-Pi will fabricate the 3D cavity while CNR-IFN will fabricate the Transmon connected to dipole-antenna pads (D2.5).

**Task2.4** is dedicated to the fabrication of JPA's (D2.3).

**Task2.5** is dedicated to the fabrication of the two-qubits device (D2.6).

**WP3** is dedicated to the **Control** of the project quantum-devices and it will be led by INFN-MiB. It aims at authomatize programmatically the execution of specific set of tasks such as the preparation of a quantum circuit architecture with logical gates, its calibration and the measurement of the final state through the development of custom software for control and execution of the proposed qubit system.

In **Task3.1** a new hardware-backend for Qibo [49] will be developed. INFN-MiB and INFN-Mi will take care of the specific implementation of the software in collaboration with the experimental sites. This will include the conversion mechanism from quantum-circuit gates to microwave pulses, the pulse shapes and type, the generation of a pulse sequence through remote connection protocols, scheduling tasks for pulse sequence evaluation, reconstruction of measurement results, and the implementation and automation of qubit calibration algorithms.

In **Task 3.2** a hardware code will be developed in order to simplify and automate the pulse sequence submission, execution and the retrieve of results from the FPGA boards. This will be achieved by building an open-source codebase of firmware codes for Xilinx and Altera boards that will be employed in the project. The code in Verilog and VHDL will include host-to-FPGA communication routines for request submission and results retrieve from the device memory; specialized bitstreams for ADC and DAC manipulation. INFN-Fe will take care of the interface between QIBO and FPGA, developing Linux drivers, communication protocols between SOC-ARM and FPGA and between high-end PC and SOC-ARM. LNF will take care of the FPGA code in Verilog and VHDL. INFN-Pi will use RF DACs with extra-wide bandwidths to directly synthesize control pulses [43].

Tasks 3.1 and 3.2 will deliver the release of the hardware control package that will be integrated in the experimental sites (D3.1).

**Task 3.3** is dedicated to the test of the control software using emulation software (D3.1) and real quantum hardware (D4.5). Furthermore, INFN-Mi and INFN-MiB provide a full set of benchmark tests and validation procedures that will be implemented systematically in both code repositories in order to periodically check the functionality of the code itself.

**WP4** is dedicated to the test and **Experiments** of the project quantum-devices and it will be led by LNF.

In **Task 4.1** TIFPA and INFN-Sa will test circuit components to calibrate the fabrication process (D4.1).

In **Task 4.2** INFN-MiB and LNF will test and do sensing experiments with 2D Transmon devices coupled to one (D4.2) and two resonators (D4.4). Two important milestones will be reached, the characterization of the first qubit (M4.1) and the detection of single photon in qubit-resonator experiments (M4.3).

In **Task 4.3** INFN-Pi supported by LNF will characterize the 3D Transmon with the goal of showing longer relaxation times (D4.6).

In **Task 4.4** LNF and TIFPA will characterize the JPA's (D4.3). An important milestone will be the single-shot readout of a qubit coupled to a resonator (M4.2) with JPA or TWJPA in synergy with the project DART WARS. INFN-Mi MiB Pi and LNF will test QIBO control system on a real quantum device (D4.5).

In **Task 4.5** LNF and INFN-MiB will do experiments on two-qubits device (D4.7) measuring entanglement in two qubits (M4.4).

**WP5** led by LNF is dedicated to the **Management** of the project. The Responsabile Nazionale (RN) assisted by the WP leaders and the Responsabili Locali (RL) will organize collaboration meetings and prepare periodic reports by CSN V deadlines. Each WP leader with RLs will prepare reports of deliverables. The RN will periodically consult WP leaders and RLs to monitor the progress of the project.

| YEAR | | | Year 1 | | | | Year 2 | | | | Year 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | | | T1 | T2 | T3 | T4 | T1 | T2 | T3 | T4 | T1 | T2 | T3 | T4 |
| WP1 - Design (Fi) | T1.1 | Design | | D1.1 | D1.2 | D1.3 | | D1.5 | | | D1.6 | | | |
| | T1.3 | JPA | | | | | D1.4 | | | | | | | |
| | T1.4 | Simulation | | | | | | | | | | | | |
| WP2 - Fabrication (TIFPA) | T2.1 | Components | | | D2.1 | | | | | | | | | |
| | T2.2 | 2D Tansmon | | | | | D2.2 | | | D2.4 | | | | |
| | T2.3 | JPA | | | | | | D2.3 | | | | | | |
| | T2.4 | 3D Transmon | | | | | | | | | D2.5 | | | |
| | T2.5 | Two qubits device | | | | | | | | | | D2.6 | | |
| WP3 - Control (MiB) | T3.1 | Software | | | | | | D3.1 | | | | | | |
| | T3.2 | Firmware | | | | | | | | | | | | |
| | T3.3 | Test | | | | | | | D3.2 | | | | | |
| WP4 - Experiment (LNF) | T4.1 | Components | | | | D4.1 | | | | | | | | |
| | T4.2 | 2D Transmon | | | | | D4.2 | | | | D4.4 | | | |
| | T4.3 | 3D Transmon | | | | | | | | | | D4.6 | | |
| | T4.4 | Qubit readout | | | | | | | D4.3 | | D4.5 | | | |
| | T4.5 | Two qubits device | | | | | | | | | | | | D4.7 |
| WP5 - Management (LNF) | T5.1 | Collaboration Meetings | | | | | | | | | | | | |

| **Deliverables** |
|---|
| Components |
| Transmon + resonator |
| Transmon +2 resonators |
| JPA |
| 3D Transmon |
| 2 Qubits device |
| Qubit Control |

| **WP1** | **Design** | **WP leader** Leonardo Banchi | |
|---|---|---|---|
| Leader INFN Fi | Fi, MiB, Pi, Sa, LNF, CNR-IFN, FBK | Start month 1 | End month 36 |
| Task 1.1 **Design** (M1-M26) - D1.1, D1.2, D1.3, D1.5, D1.6<br>Task 1.2 **JPA** (M1-M13) - D1.4<br>Task 1.3 **Simulations** (M1-M36) | | | |
| Milestones:<br>M1.1 Realization of first Transmon chip layout (M6)<br>M1.2 First scheme of entangled qubits device (M18) | | | |
| Deliverables:<br>D1.1 Components design (resonators, capacitors, JJ) (M6)<br>D1.2 Design of Transmon coupled to 1 resonator (M10)<br>D1.3 Design 3D Transmon (M12)<br>D1.4 Design of JPA (M13)<br>D1.5 Design of Transmon coupled to 2 resonators (M18)<br>D1.6 Design of two-qubits device (M26) | | | |

| **WP2** | **Fabrication** | **WP leader** Paolo Falferi | |
|---|---|---|---|
| Leader INFN TIFPA | FBK, CNR-IFN, LNF, Pi, TIFPA | Start month 1 | End month 30 |
| Task 2.1 **Components** (M6-M9) – D2.1<br>Task 2.2 **2D Trasmon** (M10-M24) – D2.2, D2.4<br>Task 2.3 **3D Trasmon** (M12-M25) D2.5<br>Task 2.4 **JPA** (M13-M18) - D2.3<br>Task 2.5 **Two Qubits device (M26-M30) -** D2.6 | | | |
| Milestones:<br>M2.1 Start fabrication of first Transmon device (M11) | | | |

| |
|---|
| M2.2 Start fabrication of resonant cavity for 3D Transmon (M20)<br>M2.3 Start fabrication of two-qubits device (M28) |
| Deliverables<br>D2.1 Fabrication of test chip with components, resonators, capacitors and JJ for process calibration (M9)<br>D2.2 Fabrication of 2D chip with Transmon coupled to a single resonator (M13)<br>D2.3 Fabrication of JPA (M18)<br>D2.4 Fabrication of 2D chip with Transmon coupled to two resonators (M24)<br>D2.5 Fabrication of a 3D Transmon (M25)<br>D2.6 Fabrication of two-qubits device (M30) |

| **WP3** | **Control** | **WP leader** Andrea Giachero | |
|---|---|---|---|
| Leader INFN MiB | MiB, Mi, Pi, LNF, Fe | Start month 1 | End month 27 |
| Task 3.1 **Software** (M1-M27) – D3.1<br>Task 3.2 **Firmware** (M1-M27) – D3.1<br>Task 3.3 **Tests** (M18-M27) – D3.2 | | | |
| Milestones:<br>M3.1 Succesful test of software on emulation (M21) | | | |
| Deliverables:<br>D3.1 First release of the Qibo qubit hardware control package (M18)<br>D3.2 Test with emulation (M21) | | | |

| **WP4** | **Experiments** | **WP leader** Claudio Gatti | |
|---|---|---|---|
| Leader LNF | LNF, MiB, TIFPA, Sa, Pi, FBK, CNR-IFN | Start month 9 | End month 36 |
| Task 4.1 **Components** (M9-M12) - D4.1<br>Task 4.2 **2D Transmon** (M13-M30) - D4.2, D4.4 | | | |

| |
|---|
| Task 4.3 **3D Trasmon** (M25-M30) - D4.6<br>Task 4.4 **Qubit readout** (M18-M26) - D4.3, D4.5<br>Task 4.5 **Two qubits device** (M30-M36) - D4.7 |
| Milestones:<br>M4.1 Succesful characterization of first Transmon qubit (M14)<br>M4.2 Single-shot readout of qubit in resonator (M22)<br>M4.3 Detection of single photon in qubit-resonator experiments (M26)<br>M4.4 Succesful measurement of entanglement in two qubits (M36) |
| Deliverables<br>D4.1 Circuit components characterization (M12)<br>D4.2 Experiments with Transmon coupled to one resonator (M14)<br>D4.3 JPA characterization (M20)<br>D4.4 Experiment with Transmon  coupled to 2 resonators (M26)<br>D4.5 Qubit control with FPGA-board (M26)<br>D4.6 3D Transmon  (M30)<br>D4.7 Two-qubits device experiments (M36) |

| **WP5** | **Management** | **WP leader** Claudio Gatti | |
|---|---|---|---|
| Leader LNF | LNF, MiB, Mi, TIFPA, Sa, Pi, Fe, Fi, FBK, CNR-IFN | Start month 1 | End month 36 |
| Task 5.1 **Collaboration Meetings and Continous Monitoring** | | | |
| Milestones<br>M5.1 Kick off meeting | | | |
| Deliverables: Periodic reports (Consuntuvi, Preventivi) | | | |

| Description | WP | Risk | Mitigation |
|---|---|---|---|
| Low relaxation time of qubit | 1 | Medium | Improve design including Purcell filters to decouple qubit from environment. |
| Excessive aging and oxidation of Al chips | 2 | Low | Increase thickness of deposited Al. Improve cleaning of substrate before Al deposition. |
| A fabrication site offline at critical points of the project | 2 | Medium | Second fabrication site can temporarily replace the first. |
| Impossibility to test the control software on two qubits device for lack of RF hardware | 3 | Low | Isolate the components which can be tested individualy based on their availability. Temporarily move hardware from one experimental site to the other. |
| Excessive noise | 4 | Medium | Improve line filtering with metal powder and Eccosorb filters |
| Critical current suppressed by environment magnetic field | 4 | Medium | Improve magnetic field screening of chips with Cryoperm and SC materials |

## DESCRIPTION OF THE RESEARCH UNITS

The **INFN-Fe** unit contributes to WP3-Control. The team has a long experience in developing interfaces between commodity Linux-based PCs and control cards based on FPGAs, attached via PCI-express bus or gigabit ethernet. The unit will develop mainly the interface between the back-end of the QIBO compiler and the FPGA card.

The **INFN-Fi** unit leads WP1-Design. The team is a collaboration between theoretical physicists and engineers. The physics group has experience in quantum control and quantum information theory, open quantum systems and programming of SC quantum devices via IBM Qiskit and Amazon Braket. The engineering group has experience on microwave electronics, quantum functional devices design and development of Transmon qubits using Qiskit Metal, Ansys HFSS and Q3D.

The **LNF** unit coordinates the project and leads WP4-Experiments. The team has know how in axion physics, resonant cavities, cryogenic devices and development of single-photon detectors based on JJ, and thanks to the skills in FPGA programming will contribute to WP3-Control. The team of COLD lab is involved in QUAX, SIMP (end 2021), DARTWARS and H2020-SUPERGALAX (end 2022).

The **INFN-MIB** unit leads WP3-Control and contributes to WP1-Design and WP4-Experiments. Its cryogenic lab is fully equipped with dilution refrigerators, RF and low noise electronics. The team has more than 20 year of experience in cryogenics techniques (CUORE/CUPID, HOLMES, KIDS_RD, DARTWARS) and has long-lasting scientific collaborations with external institutions (FBK, INRiM, NIST, Caltech, MIT).

The **INFN-MI** units contributes to WP3-Control. The team developed the QIBO framework [44] and has experience in quantum hardware control techniques and quantum applications involving quantum circuit and annealer processing.

The **TIFPA** group leads WP2-Fabrication and contributes to WP4-Experiments. The team has a long experience in experimental activities at mK temperatures, with high-Q mechanical and microwave resonators, electromechanical systems (displacement transducers, feedback cooling, parametric squeezing) and cryoelectronics (JJ, SQUID, TES, KIDs), and collaborates in QUAX, SIMP and DARTWARS.

The **INFN-Pi** unit contributes to all WPs. The team is a collaboration between physicists and engineers of the Electronic and Computer Engineering Department. The physics group gained experience within SIMP in microwave-photon detection with TES and in simulation and realization of antenna for signal collection in 3D structures. The engineering group has know-how on measurements at mK temperatures, development of electronic systems and simulation and design of microwave circuits.

The **INFN-SA** group contributes to WP1-Design and WP4-Experiments. The team has multi-decennial experience in simulation of JJ systems and in their experimental characterization in cryogenic lab. It is working on FEEL, SIMP, DART WARS and VIRGO projects. Simulations will exploit a dual processor workstation equipped with TITAN GPU for parallel computing.

| | | INFN-Fe | INFN-Fi | LNF | INFN-Mi | INFN-MiB | INFN-Pi | INFN-Sa | TIFPA | FBK | CNR-IFN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T1.1 | Design | | ■ | | | ■ | ■ | | | | |
| T1.2 | JPA | | | ■ | | ■ | | ■ | ■ | ■ | ■ |
| T1.3 | Simulation | | ■ | | | | | ■ | | | |
| T2.1 | Components | | | | | | | | | ■ | ■ |
| T2.2 | 2D Transmon | | | | | | | | | ■ | ■ |
| T2.3 | JPA | | | | | | | | | ■ | ■ |
| T2.4 | 3D Transmon | | | | | | ■ | | | | ■ |
| T2.5 | Two qubits device | | | | | | | | | ■ | |
| T3.1 | Software | ■ | | | ■ | ■ | | | | | |
| T3.2 | Firmware | ■ | | ■ | ■ | ■ | ■ | | | | |
| T3.3 | Test | ■ | | ■ | ■ | ■ | ■ | | | | |
| T4.1 | Components | | | | | | | ■ | ■ | | |
| T4.2 | 2D Transmon | | | ■ | | ■ | | | | | |
| T4.3 | 3D Transmon | | | ■ | | | ■ | | | | |
| T4.4 | Qubit readout | ■ | | ■ | ■ | ■ | ■ | | ■ | | |
| T4.5 | Two qubits device | | | ■ | | ■ | | | | | |

| **Experiment sites description** | | |
|---|---|---|
| **Units** | **Refrigerators & cryostats** | **Equipment** |
| **LNF** COLD Lab<br><br>http://coldlab.lnf.infn.it | ▪ large volume cryogen-free dilution refrigerator with at T down to 9 mK, with 5 RF lines and a high field SC magnet<br>▪ liquid Helium cryostat with a plastic dilution refrigerator (CNR-IFN property) operating at T down to 40 mK<br>▪ liquid Helium cryostat operating at T down to 4 K, equipped with a 8 T | ▪ 20 GHz Vector Network Analyzer<br>▪ 20 GHz RF Signal Generator<br>▪ 13 GHz RF Signal Generator<br>▪ 20 GHz Spectrum Analyzer<br>▪ low noise voltage and current amplifiers<br>▪ electronics for SQUID control and measurement<br>▪ Low Noise RF amplifiers |

| | | |
|---|---|---|
| | SC magnet and a tuning system for cryogenic RF cavity testing<br>▪ other liquid Helium cryostats | |
| **INFN MiB**<br>https://holmes0.mib.infn.it/nucriomib/<br>https://sites.google.com/unimib.it/biqute/ | ▪ large volume cryogen-free dilution refrigerator with T down to 10 mK, equipped with several RF lines;<br>▪ N.3 liquid Helium cryostat with a dilution refrigerators operating at T 10 mK equipped with RF lines. | ▪ 19 GHz Vector Network and Signal Analyzer;<br>▪ 20 GHz RF Signal Generator<br>▪ N.5 10 GHz microwave synthesizers;<br>▪ N.5 low noise HEMT amplifiers<br>▪ electronics for dc-SQUID and rf-SQUID control and measurement<br>▪ room temperature amplifiers<br>▪ microwave components. |
| **INFN Pi** | ▪ absorption refrigerator He3-He4, 3 stages down to 300 mK with 20uW refrigerator power<br>▪ Dilution Refrigerator (in acquisition)<br>▪ Dilution Refrigerator Leiden MCK 50-100 | ▪ VNA at 44 GHz<br>▪ Spectrum Analyzers at 14 and 44 GHz<br>▪ 22 and 30 GHz low noise CW Signal Generators<br>▪ x2 frequency duplicator in Q-band<br>▪ RF Shielded Room, 3m x 3m (@INFN)<br>▪ VNA Anritsu 50 kHz-20, 43.5, 92 GHz<br>▪ R&S RTO1014Oscilloscope (4channel, 1GHz,10 GS/s)<br>▪ RF Shielded Room, 2 m x 4 m (@ECE)<br>▪ Zurich lock-in amplifier |
| **INFN Sa** | ▪ Oxford Instruments Heliox VL 3He system with two coax RF lines | ▪ Two18 GHz microwave sources<br>▪ 20 GHz spectrum analyzer<br>▪ 9 GHz non sampling oscilloscope for transient analysis<br>▪ State of the art wedge and ball bonder |
| **TIFPA** | ▪ Large volume cryogen-free dilution refrigerator T 20 mK, with thermometry and RF lines<br>▪ Liquid helium transport and lab dewars<br>▪ Cryogenic Services Facility with equipment for helium gas recovery: two helium liquefiers (total capacity 12 l/h), storage dewar 500 l, gas storage capacity 250 $m^3$ | ▪ 20 GHz Vector Network Analyzer<br>▪ 5.4 GHz RF Signal Generator<br>▪ 18 GHz RF Signal Generator<br>▪ 22 GHz Spectrum Analyzer<br>▪ SQUID electronics<br>▪ Low Noise cryogenic and room temperature RF amplifiers |

| Unit | INFN-Fe | INFN-Fi | LNF | Mi | MiB | INFN-Pi | INFN-Sa | TIFPA | TOT |
|---|---|---|---|---|---|---|---|---|---|
| FTE | 1.4 | 1.4 | 2.65 | 0.2 | 1 | 2 | 1.4 | 1.2 | 11.25 |

| INFN-Fe | | FTE |
|---|---|---|
| Calore Enrico | Ric [UNIFE] | 0.9 |
| Schifano Fabio | Prof Assoc [UNIFE] [RL] | 0.4 |
| Tripiccione Raffaele | Prof Ord [UNIFE] | 0.1 |
| TOT | | **1.4** |

| INFN-Fi | | FTE |
|---|---|---|
| Banchi Leonardo | RTDb [**RL**] [UNIFI] | 0.2 |
| Cidronali Alessandro | Prof Assoc [UNIFI] | 0.1 |
| Corti Hervé | PhD [UNIFI] | 1 |
| Cuccoli Alessandro | Prof Assoc [UNIFI] | 0.1 |
| TOT | | **1.4** |

| LNF | | FTE |
|---|---|---|
| Babusci Danilo | Primo Ric | 0.4 |
| Beretta Matteo Mario | Tec | 0.1 |
| Buonomo Bruno | Primo Tec | 0.2 |
| Chiarello Fabio | Ric [CNR-IFN] | 0.3 |
| Di Gioacchino Daniele | Ric | 0.2 |
| Felicetti Simone | Ric [CNR-IFN] | 0.2 |
| Felici Giulietto | Dir Tec | 0.05 |
| Gatti Claudio | Primo Ric [**RN**] | 0.3 |

| | | |
|---|---|---|
| Foggetta Luca Gennaro | Tec | 0.2 |
| Ligi Carlo | Tec [**RL**] | 0.2 |
| Mattioli Francesco | Ric [CNR-IFN] | 0.2 |
| Piersanti Luca | Ric | 0.1 |
| Torrioli Guido | Primo Ric [CNR-IFN] | 0.2 |
| TOT | | **2.65** |

| **INFN-Mi** | | **FTE** |
|---|---|---|
| Carrazza Stefano | RTDb [**RL**] [UNIMI] | 0.2 |
| TOT | | **0.2** |

| **INFN-MiB** | | **FTE** |
|---|---|---|
| Borghesi Matteo | PhD [UNIMIB] | 0.2 |
| Fanciulli Marco | Prof Ord [UNIMIB] | 0.2 |
| Faverzani Marco | Ric Univ [UNIMIB] | 0.2 |
| Giachero Andrea | Ric Univ [**RL**] [UNIMIB] | 0.2 |
| Sanguinetti Stefano | Prof Ord [UNIMIB] | 0.2 |
| TOT | | **1** |

| **INFN-Pi** | | **FTE** |
|---|---|---|
| Costa Filippo | RTDb [UNIPi] | 0.2 |
| Di Pascoli Stefano | Prof Assoc [UNIPi] | 0.2 |
| Giazotto Francesco | Dir Ric [CNR-Nano] | 0.2 |
| Lamanna Gianluca | Prof Assoc [UNIPi] | 0.2 |
| Macucci Massimo | Prof Ord [UNIPi] | 0.2 |
| Manara Giuliano | Prof Ord [UNIPi] | 0.2 |
| Marconcini Paolo | Prof Assoc [UNIPi] | 0.2 |

| | | |
|---|---|---|
| Paolucci Federico | Ric [CNR-Nano] | 0.2 |
| Spagnolo Paolo | Primo Ric [**RL**] | 0.2 |
| Toncelli Alessandra | Prof Assoc [UniPi] | 0.2 |
| TOT | | **2** |

| **INFN-Sa** | | **FTE** |
|---|---|---|
| Barone Carlo | Ric [UNISA] | 0.3 |
| Carapella G | Ric [UNISA] | 0.3 |
| Filatrella Giovanni | Prof Assoc [UNISannio] | 0.3 |
| Mauro Costantino | AdR | 0.2 |
| Pagano Sergio | Prof Ord [**RL**] [UNISA] | 0.3 |
| TOT | | **1.4** |

| **TIFPA** | | **FTE** |
|---|---|---|
| Cian Alessandro | Ric [FBK] | 0.2 |
| Falferi Paolo | Primo Ric [**RL**] [CNR-IFN] | 0.3 |
| Giubertoni Damiano | Primo Ric [FBK] | 0.2 |
| Margesin Benno | Dir Ric [FBK] | 0.2 |
| Vinante Andrea | Ric [CNR-IFN] | 0.3 |
| TOT | | **1.2** |

## *EXTERNAL COLLABORATIONS*

**Fondazione Bruno Kessler**

**FBK** is a non-profit research organization founded in 2006 by Provincia Autonoma di Trento and is a member of the TIFPA Center. The FBK Centre for Sensors and Devices has a long-lasting experience in fabricating KID detectors and bolometers and, in recent years, sub 1 $\mu m^2$ JJ based on the double angle evaporation technique. For this the group exploits the capabilities of the 6” CMOS pilot microfabrication line of FBK that comprises optical lithography with submicron resolution and e-beam lithography as well as additional equipment for micromachining. The process allows for the fabrication of JPA’s, transmons and qubits.

**CNR Institute for Photonics and Nanotechnologies**

The **IFN-CNR** in Rome is active in the design, fabrication, characterization and use of nanostructures and nanodevices for quantum electronics. It exploits a class 100/1000 clean room of 300mq equipped with electron beam lithography (Raith Voyager EBL system 50 kV, minimum linewidth 8nm), optical lithography, atomic force microscope and scanning electron microscopy, thin films deposition systems for metals and insulating materials and systems for patterning metals, semiconductors and insulators.

A future collaboration is forseen also with the **Quantum Research Centre** of the **Technology Innovation Institute** in Abu Dhabi which conducts theoretical and experimental research and is building the first quantum computer in the region. Common work will focus on control of quantum devices.

## *ONGOING PROJECTS ON SIMILAR TOPICS*

**SQMS**: the SC Quantum Materials and Sysytem Center aims at improving the coherence time of qubits and develop new quantum sensors. The SQMS Center comprises 20 partners including the host institution Fermilab and INFN. Cross-fertilization of ideas expected between Qub-IT and SQMS. Ferrara is the INFN responsible of the project.

**SIMP**: Single Microwave Photon Detection is a project funded by CSN5 aiming at developing single microwave-photon detectors with two technologies: Josephson Junctions and Transition Edge Sensor [46-51]. LNF(RN), PI, TIFPA and SA are involved in the project .

**SUPERGALAX**: H2020-FET project for the detection of single microwave photons with coherent quantum network of SC qubits. LNF is the INFN responsible of the project.

**HOLMES**: is a project funded by the ERC (ERC-2013-AdG no. 340321) and by CSN2 with the aim to measure the neutrino mass by deploying a large array of low temperature 163Ho-implanted microcalorimeters sensed by Transition Edge Sensor and read out by microwave rf-SQUID multiplexing. MIB is responsible for the project.

**DART WARS**: is a project funded by the CSN5 with the aim to boost the sensitivity of experiments based on low-noise SC detectors and qubits, by developing and testing wideband SC amplifiers with noise at the quantum limit. MiB(RN), LNF, SA and TIFPA are involved in the project.

**QUAX**: is an experiment funded by CSN2 searching for galactic axions with two haloscopes at LNL and LNF [30]. LNF and TIFPA are involved in the project.

## *IMPACT*

The strong evidence that the matter in the Universe is mainly nonbaryonic dark matter [52-54], the accelerating expansion of the Universe suggesting the existence of dark energy [55] and the lack of empirical evidence of quantum aspects of Gravity pose some of the unanswered questions of modern physics. New experimental techniques based on higly-sensitive quantum-sensors are emerging to investigate these fields.
Quantum sensing with SC qubits is a game changer in axion experiments since the high sensitivity of light dark-matter searches with photon [11] and magnon [12] sensing with qubits was established. Less mature is phonon sensing with qubits. String Theory moduli, causing a variation of the fine-structure constant and of the electron mass, may induce the oscillation of resonators [56], such as bulk acoustic wave resonators (BAW) [57], detectable with quantum sensor based on qubits [7]. Dark energy, showing itsef as a fifth force acting on matter, could be detected similarly. More intriguing is the idea to amplify and observe minuscule quantum gravitational effects in a table-top BMV experiment [13, 58, 59]: the growth of entanglement between two mesoscopic test masses of tens of picograms can be used to certify the quantum character of the gravitational interaction. This is even more suggestive considering that micrometric mechanical-resonators with 70 pg mass have been recently observed in macroscopic entanglement [15-16]. Quantum sensing and control of mechanical resonators coupled to SC qubits [2,4,5,7] will play a decisive role in these experiments.

Applications of this technology are innumerable and range from quantum information and metrology or transducers for measuring and connecting different types of quantum systems.

The intellectual property will be regulated by specific collaboration agreements. Each party will remain the exclusive owner of background knowledge and any patenting of the results achieved will be the subject of a separate agreement.

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Dr. Claudio Gatti (gender male)

Claudio Gatti obtained his degree in Physics at Rome University "La Sapienza" and the Ph.D. in Physics at Pisa University in 2003. He is Senior Researcher at LNF. His background is in experimental Particle Physics. He collaborated with the KLOE and ATLAS experiments. In ATLAS he was the Analysis Coordinator of the Italian Community. He is Local Coordinator of the LNF unit of QUAX, leading the installation of a haloscope. He proposed the experiment KLASH for the search galactic-axions with sub micro-eV mass. He is National Coordinator of SIMP and INFN Coordinator of H2020-SUPERGALAX, projects aiming to develop single microwave photon detectors. He contributed to create COLD the CryOgenic Lab for Detectors at LNF. He supervised several students for their thesis and his group includes 2 Post Docs and 1 Ph.D. student. He reviewed projects for US-Israel BSF and papers for Nature Physics, Physics of Dark Universe, NIM A and IEEE Access. He signed more than 700 papers and has h-index 158.

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## RICHIESTA FINANZIARIA

| INFN-FE | | | | | |
|---|---|---|---|---|---|
| **Tipo** | Descrizione | 2022(k€) | 2023 (k€) | 2024 (k€) | Total (k€) |
| **Consumi** | | | | | |
| **Inventario** | PC Server per sintesi | 5.0 | | | 5.0 |
| **Missioni** | Meeting di collaborazione | 1.5 | 1.5 | 1.5 | 4.5 |
| **Licenze** | Licenza Xilinx Vivado | 0.5 | 0.5 | 0.5 | 1.5 |
| **Total (k€)** | | 7.0 | 2.0 | 2.0 | 11.0 |

| INFN-FI | | | | | |
|---|---|---|---|---|---|
| **Tipo** | Description | 2022(k€) | 2023 (k€) | 2024 (k€) | Total (k€) |
| **Consumi** | | 0 | 1 | 1 | 2 |
| **Inventario** | Workstation | 3.5 | | | 3.5 |
| **Missioni** | Missioni siti sperimentali | 3 | 3 | 3 | 9 |
| **Licenze** | Ansys | 2.5 | 2.5 | 2.5 | 7.5 |
| **Total (k€)** | | 9 | 6.5 | 6.5 | 22 |

| LNF | | | | | |
|---|---|---|---|---|---|
| **Tipo** | Descrizione | 2022(k€) | 2023 (k€) | 2024 (k€) | Total (k€) |
| **Fabbricazione** | CNR | 15 | 15 | 15 | 45 |
| **Consumi** | 2nd output line (1 acc dir 1 k+ circ 3k+ 1 HEMT 5k+ 1 LNA 3k + filters 1k + SC cables 2k ) | 4 | 15 | | 19 |
| **Inventario** | DC Power Supply<br>WFG 20GHz | | 1 | <br>30 | 31 |
| **Missioni** | travel | 1 | 2 | 2 | 5 |
| **Licenze** | - | | | | |
| **Total (k€)** | | 15+5 | 15+18 | 15+32 | 45+55 |

| INFN-MI | | | | | |
|---|---|---|---|---|---|
| **Tipo** | Description | 2022(k€) | 2023 (k€) | 2024 (k€) | Total (k€) |
| **Consumi** | | | | | |
| **Inventario** | Workstation | 3 | | | 3 |
| **Missioni** | Viaggi siti sperimentali | 1 | 2 | 2 | 5 |
| **Licenze** | | | | | |
| **Total (k€)** | | 4 | 2 | 2 | 8 k |

| INFN-MIB | | | | | |
|---|---|---|---|---|---|
| **Tipo** | Descrizione | 2022(k€) | 2023 (k€) | 2024 (k€) | Total (k€) |
| **Consumi** | Microwave Components; consumables | 5 | 10 | 11 | 26 |
| **Inventario** | Scheda Xilinx | 10.5 | | | 10.5 |
| **Missioni** | Run sperimentali presso altri laboratori | 2 | 3 | 4 | 9 |
| **Licenze** | Contributo Ansys | 2.5 | 2.5 | 2.5 | 7.5 |
| **Total (k€)** | | 20 | 15.5 | 17.5 | 53 |

| INFN-PI | | | | | |
|---|---|---|---|---|---|
| **Tipo** | Descrizione | 2022(k€) | 2023 (k€) | 2024 (k€) | Total (k€) |
| **Consumi** | RF outpu-line: HEMT, circulator, LNA, mixer, filters.<br>3D resonant cavity | 7 | 10<br>5 | 10 | 32 |
| **Inventario** | Scheda Xilinx EK-U1-ZCU208-ES1-G(Ferrara)<br>RF DAC | 12 | 15 | | 27 |
| **Missioni** | Run sperimentali presso altri laboratori | 1 | 2 | 2 | 5 |
| **Licenze** | Contributo Ansys | 1 | 1 | 1 | 3 |
| **Total (k€)** | | 21 | 33 | 13 | 67 |

| INFN-SA | | | | | |
|---|---|---|---|---|---|
| **Tipo** | Descrizione | 2022(k€) | 2023 (k€) | 2024 (k€) | Total (k€) |
| **Consumi** | LHe, componenti elettronici e meccanici | 7 | 8 | 5 | 20 |
| **Inventario** | GPU NVIDIA per qubit modeling | 3 | 0 | 0 | 3 |
| **Missioni** | Partecipazione esperimenti LNF | 2 | 2 | 3 | 7 |
| **Licenze** | Contributo sez Napoli Ansys | 1 | 1 | 1 | 3 |
| **Total (k€)** | | 13 | 11 | 9 | 33 |

| TIFPA | | | | | |
|---|---|---|---|---|---|
| **Tipo** | Descrizione | 2022(k€) | 2023 (k€) | 2024 (k€) | Total (k€) |
| **Fabbricazione** | FBK | 10 | 20 | 15 | 45 |
| **Consumi** | | 2 | 1 | 0 | 3 |
| **Inventario** | MW generator 20GHz | 22 | 4 | 2 | 28 |
| **Missioni** | | 0 | 1 | 1 | 2 |
| **Licenze** | | | | | |
| **Total (k€)** | | 10+24 | 20+6 | 15+3 | 45+33 |

| | 1st year | 2nd year | 3rd year | Total |
|---|---|---|---|---|
| **Ferrara** | 7 | 2 | 2 | 11 |
| **Firenze** | 9 | 6,5 | 6,5 | 22 |
| **LNF** | 5 | 18 | 32 | 55 |
| **MiB** | 20 | 15,5 | 17,5 | 53 |
| **Mi** | 4 | 2 | 2 | 8 |
| **Pisa** | 21 | 33 | 13 | 67 |
| **Salerno** | 13 | 11 | 9 | 33 |
| **TIFPA** | 24 | 6 | 3 | 33 |
| **CNR (LNF)** | 15 | 15 | 15 | 45 |
| **FBK (TIFPA)** | 10 | 20 | 15 | 45 |
| **Total** | 128 | 129 | 115 | 372 |

| Anno | Missioni | Consumo | Fabbricazione | Inventario | Licenze SW | Totale |
|---|---|---|---|---|---|---|
| **2022** | 11.5 | 25 | 25 | 59 | 7.5 | 128 |
| **2023** | 16.5 | 50 | 35 | 20 | 7.5 | 129 |
| **2024** | 18.5 | 27 | 30 | 32 | 7.5 | 115 |
| **Totale** | 46.5 | 102 | 90 | 111 | 22.5 | 372 |

| | |
|---|---|
| **Missioni** | Missioni verso siti sperimentali, in particolare per studenti PhD di Università |
| **Consumo** | Prevalentemente per strumentazione linee RF refrigeratori a diluizione |
| **Fabbricazione** | Fabbricazione dispositivi superconduttivi CNR-IFN e FBK |
| **Inventario** | Workstations alta prestazione per simulazioni; Generatori RF; Schede FPGA |
| **Licenze** | Contributo per licenze Ansys e Xilinx |