cQED@Tn - ”Circuit QED: From Quantum Devices to Analogues on Superconducting Circuits”

Monday, 3 October 2022 - Wednesday, 5 October 2022

FBK (Trento, Italy)

Book of Abstracts

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Circuit QED and analogue simulation of quantum impurities

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Single Microwave Photon Detection with superconducting quantum circuits

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Single Microwave Photon Detection with a Network of Superconducting Qubits

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Testing a Josephson junction as a photon detector with pulsed microwaves measurements

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In fundamental physics, such as in the axion search, linear amplifiers become a limitation when working at frequencies as high as 10 GHz. Reaching sensitivities necessary to the detection of QCD axions at high frequencies, therefore, requires the use of single-photon sensors. The detection of single microwave photons with good efficiency and low dark counts is a hard challenge, but Josephson systems are proved to be particularly suitable for this task. A simple strategy consists in the use of a current-biased Josephson junction as a switching detector.

Within the SIMP project, we are testing Al/AlO_x/Al Josephson junctions to implement this technology. Combining simulations and a first characterization based on escape measurements, we estimate an optimal working point for a Josephson junction-based photon counter, consisting in a current bias of $I_b = 0.65\, I_0$. In this bias condition, the dark count rate would be as low as 1 mHz, only due to macroscopic quantum tunneling.

Then, this contribution will mainly focus on the characterization of a Josephson junction integrated in a single chip with a coplanar waveguide, constituting the simplest prototype of photon detector. The study is based on the switching behavior in the presence of microwaves. When the junction is stressed with continuous microwaves, switching events occur with only one or few photons, thanks to the resonant activation which increases the probability of switching. When pulsed microwaves are applied, we observe that the number of photons required for the junction activation is approximately equal to the number of levels in its potential well, as expected from the simulations. In our experimental conditions, this number is few tens of photons.

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Qub-IT: Quantum sensing with transmon-based itinerant single-photon counter

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Quantum sensing is a rapidly growing field of research which is already improving sensitivity in fundamental physics experiments. The ability to measure physical quantities through quantum devices received a major boost from the application of transmon qubits and the improvements in their engineering and fabrication. The Qub-IT project goal is to realize a transmon-based itinerant single-photon counter able to surpass current devices in terms of efficiency and low dark-count rates. The Qub-IT single-photon counter will perform QND measurements, and exploit entangled qubits to surpass the state of the art performances. Such quantum sensor has direct applications in Axion dark-matter experiments. In this contribution we present the design and simulation of the first transmon of the future single-photon counter realized using Qiskit-Metal (IBM. Qiskit-Metal is a Python package that provides a user-friendly toolkit for quantum chip design and simulation. It comes with different tools to extract the circuit Hamiltonian parameters, such as, qubit resonant frequencies, anharmonicities, qubit-resonator couplings as well as an estimation for qubit decay times (T1). Qiskit-Metal is adopted by the Qub-IT quantum engineering team to tune the quantum sensor parameters in order to obtain the desired Hamiltonian before moving to the manufacturing stage.

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Circuit-QED in non-euclidean geometries

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Analog and digital simulations with small superconducting quantum circuits

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Modeling of the nonlinear dynamics of Josephson Traveling-Wave Parametric Amplifiers

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We discuss the quasiclassical modelling of a Josephson Traveling-Wave Parametric Amplifier (JTWPA). This is a device able to provide parametric amplification through a metamaterial composed by coplanar waveguides embedding several Josephson junctions (JJs), taking advantage of the properties of these nondissipative and nonlinear superconducting components [1, 2].
A JTWPA composed by an array of one thousand JJs was first reported by Yurke *et al.* [3], while an analytical model, including a series of capacitively shunted JJs, was developed by Yaakobi *et al.* [4] and OBrien *et al.* [5], under appropriate assumption, i.e., the first-order approximation of the nonlinear Josephson inductance. Beside the optimistic predictions of these JTWPA models, practical implementations suffer from unwanted behaviors, such as limited gain and dynamic range and strong ripples in the gain vs frequency dependence are found. All these points call for an optimization of the design parameters, and also for a strict control of the cells and transmission line uniformity.
We have addressed these issues by a direct modeling of a JTWPA, without the typical simplifying assumptions of analytical treatments, that indeed were performed considering a lossless electrical circuit consisting of replicas of identical elementary cells. Thus, we can take into account random variation of relevant device parameters, since real devices, consisting of hundreds of Josephson elements, will suffer inevitable fluctuations in the values of the characteristic parameters, such as, in particular, in the junction critical current.
In our work, we analyze how random, or even ad-hoc generated, distributions of the characteristic parameters of the device can influence its response, in terms of the maximum estimated gain and bandwidth. Finally, this work helps in finding the optimal working conditions in a device that aims to get as close as possible to a realistic experimental setting.

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Critical Parametric Quantum Sensing

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Physical systems in proximity of phase transitions develop a diverging susceptibility, and so they represent a compelling tool for sensing applications. Iconic examples of critical sensors of high technological relevance are bubble chambers and transition-edge detectors. Even as they involve quantum processes, these devices are based on a classical sensing strategy. However, critical quantum systems develop highly nonclassical properties that can be exploited to achieve quantum-enhanced sensing. Here, we show that optimal (Heisenberg-limited) sensing can be reached using critical phase transitions taking place in small-scale solid-state quantum technologies, without the need to implement and control complex many-body systems. We then propose a quantum-sensing protocol based on the driven-dissipative phase transition observable in a parametrically-pumped superconducting Kerr resonator. Finally, we propose specific applications for quantum magnetometry, superconducting-qubit readout, and microwave photodetection.

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Continuous quantum gate sets and pulse class meta-optimization

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Quantum gate synthesis and control problems exhibit a vast range of external parameter dependencies, both physical and application-specific.
In this article we address the possibility of learning families of optimal control pulses which depend adaptively on various parameters, in order to obtain a global optimal mapping from the space of potential parameter values to the control space, and hence producing continuous classes of gates.
Our proposed method is tested in particular on superconducting quantum circuit settings for different experimentally relevant quantum gates and proves capable of producing high-fidelity pulses even in presence of multiple variables or uncertain parameters with wide ranges.
See: https://arxiv.org/abs/2203.13594

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Superconducting qubit readout fidelity at the threshold for quantum error correction without a quantum-limited amplifier

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We present a readout scheme for superconducting qubits that combines a shelving technique, to effectively increase the qubit relaxation time, and a two-tone excitation of the resonator to rapidly

distinguish among qubit populations in higher energy levels. Using a machine-learning algorithm to post-process the two-tone measurement results, we further improve the assignment fidelity. We demonstrate single-shot, multiplexed qubit readout, with 140ns readout time, with 99.5% assignment fidelity for two-state readout and 96.9% for three-state readout—without using a quantum-limited amplifier.

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Effects of Radioactivity on Superconducting Qubits

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Environmental radioactivity was recently discovered as a potential limit for superconducting quantum bits. We present recent works proving that ionizing radiation lowers the coherence of singe qubits and induces correlated errors in qubits arrays. We also present preliminary studies showing that operating flux qubits in a low-radioactivity environment improves their performance.

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Evidence of dual Shapiro steps in a Josephson junctions array

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The accuracy with which electromagnetic waves of specific frequencies can be both measured and produced have made frequency the basis for the definition of most physical units, including time, distance, and voltage. The modern primary voltage standard is based on the phenomena of Shapiro steps, where a tone applied to a Josephson junction yields a constant voltage determined by only the frequency of the light and fundamental constants. The duality of current and voltage has long suggested the possibility of dual Shapiro steps—that a Josephson junction device could produce current steps with heights determined only on the applied frequency. In this report, we embed an ultrasmall Josephson junction in a high impedance array of larger junctions to observe dual Shapiro steps resulting directly from microwave synchronised transport of Cooper pairs through the device. For multiple frequencies, we detect the presence of a RF mode in-phase with the tone at frequency f , and the corresponding emergence of flat steps in the IV curve with current 2ef, equal to the tunnelling of a Cooper pair with charge 2e per tone period. The observation of dual Shapiro steps opens a broad range of possibilities for future experiments, e. g. in the field of circuit quantum electrodynamics, many body quantum optics and quantum metrology.

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Engineering the speedup of quantum tunneling in Josephson systems via dissipation

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It is common sense that when a quantum coherent system is not perfectly isolated from the environment, quantum effects are destroyed and the system fundamentally follows the classical mechanics' rules. This is not always the case. Indeed, the dissipative interaction, namely the interaction between a quantum system and its external bath, can lead to an enhancement of quantum effects.

In this work [1] we show that a such situation can occur in a superconducting Josephson circuit with an extremely simple scheme to achieve the opportune dissipation that plays the desired game. In our proposal, we show that the engineered electromagnetic environment formed by the external impedances and coupled to a current bias Josephson current can enhance the quantum tunneling of the superconducting phase from a metastable state. This environmental assisted quantum tunneling can therefore speed up the relaxation dynamics of the phase towards the absolute energy minimum. This provides a proof of concept opening the route for the promising perspective of using quantum dissipative Josephson circuits as quantum simulators for optimization problems.

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Hybrid architectures and systems with spins

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Microwave optomechanical systems

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Cavity magnonics in strong coupling regime –from magnon-polariton hybrid states to perspectives for quantum sensing

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Cavity magnonics has been rapidly developing based on the hybridization of microwave-frequency cavity modes with collective spin excitations. Recently, the use of quantum systems for the implementation of sensors is attracting remarkable attention. In this respect, cavity magnonics can provide an interesting approach for dark matter detection since axions are expected to be coupled and interact with high spin density materials,such as ferro/ferri-magnets.
Here, investigations on the strong coupling regime among the magnetization precession modes in a small YIG sphere and the MW electromagnetic modes in a 3D cavity will be discussed. Anti-crossing features have been observed in correspondence of various magnetostatic modes, which were excited in the magnetically saturated sample. Time-resolved studies show evidence of Rabi oscillations, demonstrating coherent exchange of energy among photons and magnons modes. Finally, we experimentally show the observation of phenomena related to the presence of non-Hermitian singularities (exceptional points), which result from the travelling-wave induced cooperative external magnon-photon coupling. Such phenomena significantly modify the properties of polaritonic modes and the transmission spectrum.
Because of the rich physics observed, cavity magnon-polaritons provide very interesting means to combine quantum information with spintronics and a relevant resource for quantum enhanced sensing applications,opening perspectives toward exploring nonclassical states. Remarkably, the integration of low-noise superconducting detectors for sensitive readout of the quantum states can further improve the performances and impact, as targeted in DARTWARS collaboration.

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Development of Kinetic Inductance TWPAs with DARTWARS

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In the landscape of superconducting Traveling Wave Parametric Amplifiers, an interesting approach is represented by devices based on the non-linearity of kinetic inductance of superconducting films. In particular, the employment of lumped element artificial transmission lines promises to deliver a parametric amplification over a wide bandwidth along with a high dynamic range, while limiting the gain ripple. In this contribution I will report on the development of a KI-TWPA within the DARTWARS project.

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A preliminary study of Traveling-wave Josephson parametric amplifiers (TWJPA)

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The growing interest in quantum technologies, from fundamental physics experiments to quantum computing, demands for extreme performance and quantum-limited electronics. Superconducting microwave amplifiers, due to their dissipationless nature, exhibit outstanding performances in terms of noise (quantum limited), and gain. However, bandwidth and saturation power still show space for substantial improvement. Within the DARTWARS Project (https://dartwars.unimib.it/), funded by Italian Institute of Nuclear Physics (INFN), the characterization of the performances of traveling-wave Josephson parametric amplifiers (TWJPA) have been studied a 300 mK. This is a device able to provide parametric amplification through a metamaterial composed by coplanar waveguides embedding several Josephson junctions (JJs), taking advantage of the properties of these nondissipative and nonlinear superconducting components.
The characterization of this device at 300 mK aims to evidence the main aspects of their performances. It represents a quick and relatively inexpensive way to test these superconductive devices that can be of helpful to improve the design and fabrication of the TWJPA.

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Josephson TWPAs: from reversed-Kerr amplification to squeezing generation

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Josephson metamaterials: properties and fabrication techniques

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