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Quantum Sensing With Superconducting Qubits for Fundamental Physics

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***Abstract*—Quantum Sensing is a research field in rapid expansion and finds one of its applications in Fundamental Physics experiments such as the search for weakly EM-coupled Dark Matter (DM) candidates, namely Axion and Dark Photon. Recent developments in superconducting qubits and fabrication techniques are contributing significantly to driving progress in Quantum Sensing, thanks to their high sensitivity to AC fields and the possibility to leverage detection schemes based on Quantum Non-Demolition (QND) [1] and direct detection [2].**

QND consists of establishing an entangled state between a qubit system and a photon trapped in a cavity, allowing us to infer the presence of the photon without absorbing it, thus enabling multiple measurements that exponentially suppress the dark count rate. Conversely, the direct detection scheme relies on resonant, low-power, Dark Matter-induced AC fields exerting a slow Rabi oscillation of the qubit state, which becomes measurable in high-coherence state- of-the-art transmons and fluxoniums.

This contribution is part of the INFN Qub-IT collaboration, which aims to advance microwave single-photon detection through quantum superconducting devices. The presentation will illustrate the Qub-IT status towards achieving few-hundreds microseconds coherence time and engineering the DM detection setup.

The work investigates the modeling and design optimization of planar transmon qubit chips, leveraging the Lumped Oscillator Model (LOM) [3] and Energy Participation Ratio (EPR) [4] for extracting Hamiltonian parameters. Novel EPR-based strategies are developed to enhance the accuracy of Two-Level System (TLS) losses estimation through finite-element simulations. The possibility to boost DM sensitivity through coupled multi-qubit systems is also discussed, along with the characterization of single-qubit chips fabricated at the National Institute of Standards and Technology (NIST) and a thorough comparison between simulated and measured qubit parameters, like resonant frequencies, anharmonicity and coupling strength to the readout structure.

The preliminary results presented in this work hold promise for further enhancing the sensitivity and reliability of quantum sensing platforms, which could surpass the limitations of current light DM search experiments.

***Keywords (Index Terms)*— Qubit; transmon; axion; dark photon**

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