Heat and Entropy Management in Superconducting Devices

Circuit quantum electrodynamics (cQED) is among the most promising platforms for a broad range of quantum-technology applications, involving technology of superconducting qubits. A key challenge for achieving efficient operations, and for scaling these platforms to higher levels of complexity, is the control of thermal properties during operation. Dissipation arises from both qubit readout and control, and from intrinsic sources such as parasitic two-level defects and quasiparticle excitations triggered by device manipulation or by interactions with harmonic environments. Owing to its advanced fabrication maturity, cQED potentially provides a unique setting for experimentally investigating the full scenario of active control of heat generation and entropy production. Building on features as flexible circuit design, tunable couplings, strong driving, and time-resolved thermometry, we will develop and implement protocols for monitoring and controlling the heat dissipated during usual cQED operations.

The CoolPhon Group of MAGTOP will develop novel thermal detection protocols for probing the metastable state of a current-biased Josephson junction (CBJJ). Instead of measuring the post-switching voltage, we will detect the dissipation generated during escape to the normal state. This switching event produces excess quasiparticles (QPs), whose dynamics are sensed by a remote nanothermometer (RNT). After escape, QPs relax via diffusion or recombination with phonon emission. By coupling the RNT to either channel, we directly probe the escape mechanism of the CBJJ. Remarkably, QP-based thermal readout permits independent electromagnetic environments for the CBJJ and RNT, simplifying impedance engineering—essential for studying escape from the zero-voltage state. Interest in these mechanisms has intensified following the 2025 Nobel Prize in Physics for the discovery of macroscopic quantum tunnelling (MQT) [1, 2]. Our protocol represents a paradigm shift: instead of detecting the voltage that develops after switching, we measure the thermal signature of the event. We will implement two architectures: (1) galvanically coupled CBJJ–RNT and (2) galvanically isolated CBJJ–RNT, enabling either QP-mediated or phonon-assisted readout. In both cases, either QP-mediated or phonon-assisted read-out of the CBJJ will be used. The RNT, itself a Josephson junction, will be monitored by switching thermometry, which extracts the temperature-dependent switching probability P(t) and reconstructs the RNT temperature with nanosecond resolution [3, 4].

The developed protocols will be used to investigate temperature of a microwave on-chip resonator – the conceptual arrangement of the experiment is shown in Fig. 1. The displayed architecture eliminates electromagnetic cross-coupling between resonator and RNT. The experiment will verify whether the temperature of the electromagnetic environment of the qubit remains constant while it is manipulated with microwaves. It is a usual silent assumption of experiments done with qubits. It has never been tested experimentally, although it is extremely vital for high-fidelity qubit operations. The experiment will provide direct thermal signatures of defect-related resonator losses producing quasiparticles. Since it is one of dominant decoherence channels in quantum circuits, identifying its thermal footprint is essential for improving a nanodevice performance.

Finally, we will probe how CBJJ switching depends on the temperature of the electromagnetic impedance. Conventional experiments assume identical temperatures for junction QPs and the impedance. We will separate and control these temperatures by heating an on-chip resistor with 5–100 ns pulses to generate gated black-body radiation**.** The fast response of switching thermometry will allow clear discrimination between radiation-induced switching and QPs emitted by the hot resistor.

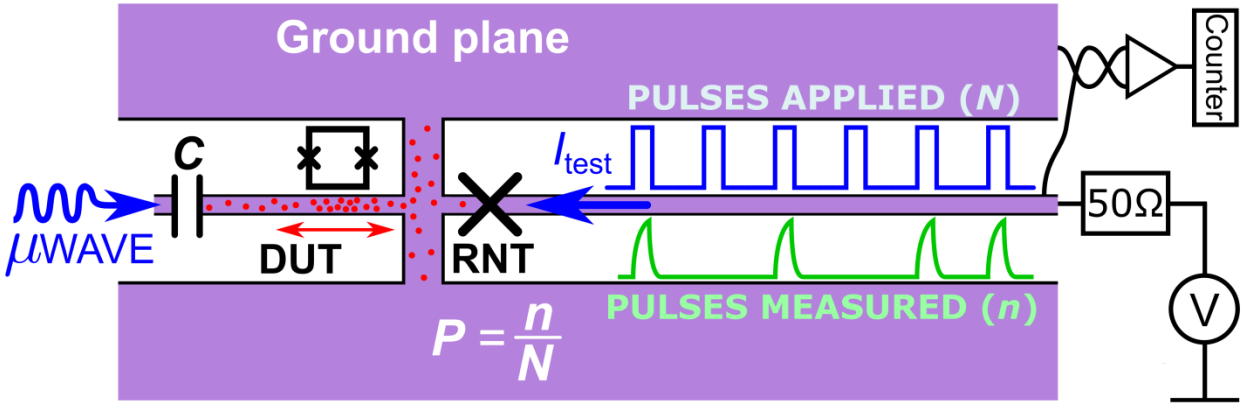

Fig.1: The experimental setup for detecting the temperature of the environment (defined by a resonator, DUT) of a qubit during operations. The remote nanothermometer (RNT) is a Josephson junction tested with current pulses to find its temperature-dependent switching probability *P*. The pulses are synchronized with the microwave signal applied to the resonator yielding the temporal trace of temperature. DUT and RNT are electromagnetically decoupled but they can exchange QPs (red dots).

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Literature

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