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Efficient verification of quantum computing architectures with bosons

D3.1 – QUBITDYNE PROTOCOL

Version 1.0 – Final
PU

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Qubitdyne Protocol

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Acronyms

SNAPPA	Selective Number-dependent Arbitrary-Phase Photon-Addition
TWPA	Traveling Wave Parametric Amplifier

Publishable Summary

This report outlines the experimental realization of the Qubitdyne protocol. Qubitdyne is a new novel measurement protocol to realize homo- and heterodyne detection of stationary superconducting bosonic modes. The protocol approximates the right statistics by sequentially swap out quantum information from a bosonic mode into an ancilla qubit, measure the qubit along a defined quadrature, reset the qubit and then swap out more information until the bosonic mode is depleted from excitations. The successful implementation of a demonstration of the protocol has been demonstrated on a non-gaussian Fock 1 state, where we obtain the characteristic dip at the centre of in the homodyne statistics.

In the Veriqub project, the Qubitdyne protocol can be used to realize the verification (via balanced heterodyne) and solve a hard sampling problem (via unbalanced heterodyne).

1. QUBITDYNE PROTOCOL

The goal of the Qubitdyne protocol (Figure 1) is to obtain the homo-and heterodyne statistics of a stationary bosonic mode, which we will refer to as the cavity (mode). The theoretical considerations of the Qubitdyne protocol are published in [1], and the experimental realization presented here requires a range of building blocks as mentioned in the introduction:

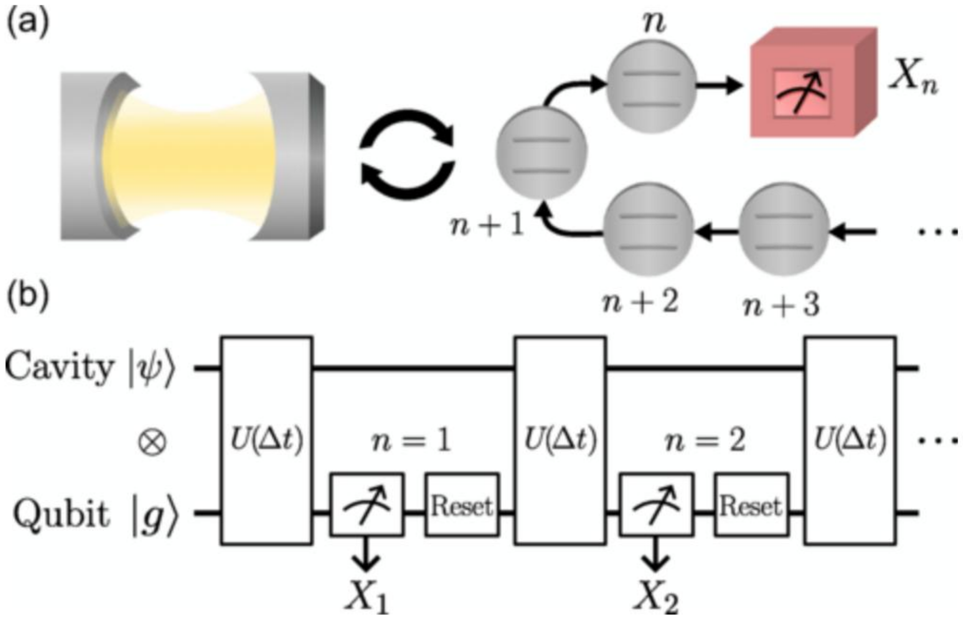

FIGURE 1 QUBITDYNE PROTOCOL SEQUENCE

1) Cavity-qubit SWAP operation

The SWAP operation is realized by driving |n,g> to |n-1, e> transitions (from cavity Fock state n to qubit state g/e) using the four wave mixing capability provided by the (nonlinear) qubit, as in [2]. Scaling to multiple simultaneous transitions can be realized by scaling the number of drives analogously to how it has been done at Chalmers for the SNAPPA transition [3]. In the Qubitdyne protocol, we only want to extract a fraction of a photon in each iteration to approximate the correct statistics. Hence, we calibrate the SWAP rate (Figure 2) and choose a SWAP strength which results in approximately 10% qubit excitation.

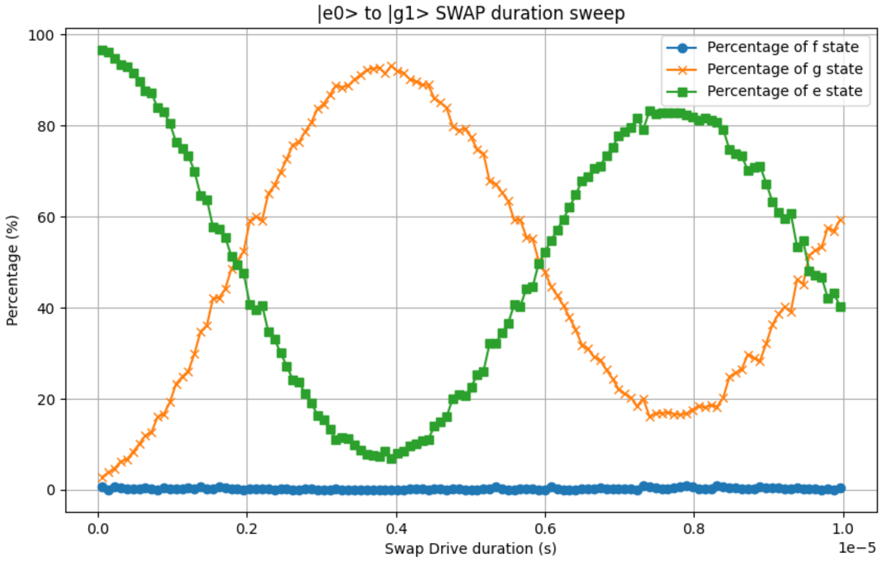

FIGURE 2 CAVITY-QUBIT SWAP

2) Fast high fidelity single-shot readout

High fidelity of the single shot readout is crucial since measurement misassignment leads to imperfections in the Qubitdyne protocol which translate into inaccurate homo- and heterodyne statistics. The single-shot readout fidelity has been optimized using a near-quantum limited TWPA, which is a crucial first amplifier of the readout field to improve the signal-to-noise (SNR) ratio.

Furthermore, we employ ternary readout, meaning that we are able to discriminate between the qubit transmons lowest three states |g>, |e> and |f>. By preparing and measuring the three states we obtain the single-shot state assignment matrix (Figure 3).

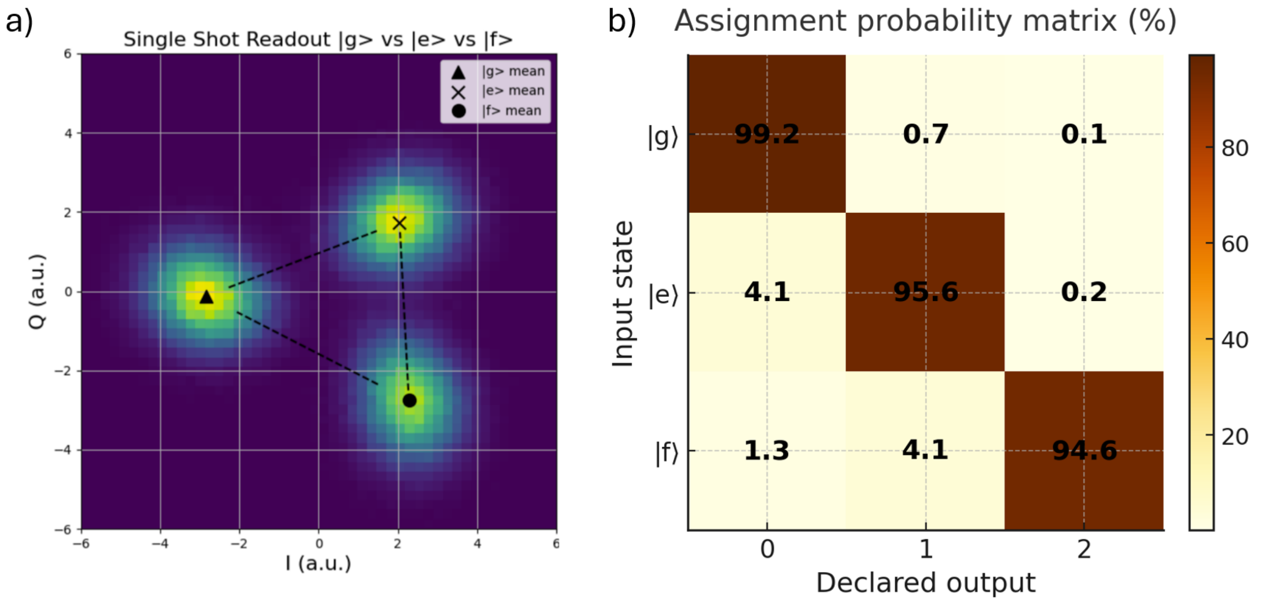

FIGURE 3 SINGLE SHOT READOUT
A) IQ CLUSTERS AFTER PREPARING |G>, |E> OR |F> SEPARATELY (OVERLAY), B) ASSIGNMENT PROBABILITY MATRIX

3) High fidelity qubit reset

After the qubit has been measured, we need to immediately reset it to be able to SWAP out more quantum information before the cavity quantum states decays. We use on-board fast (below 300ns) feedback on the FPGA of our Presto control unit. It is crucial to perform ternary readout, since leakage up to |f> also needs to be reset efficiently, otherwise the qubit could get stuck there over several iterations which would skew the measured statistics. When the ternary readout state has been assigned, the corresponding active qubit pulses are applied. If we measure

|g>	no pulse is applied
|e>	a single Pi-pulse from |e> to |g> is applied
|f>	a Pi-pulse from |f> to |e> followed by a Pi-pulse from |e> to |g> are applied

After the reset, we measure the qubit again to verify that the qubit has been reset to |g> with high accuracy. By preparing the three states (Figure 3), performing ternary readout assignment and apply the reset pulses, we obtain a reset fidelity of 98% (Figure 4).

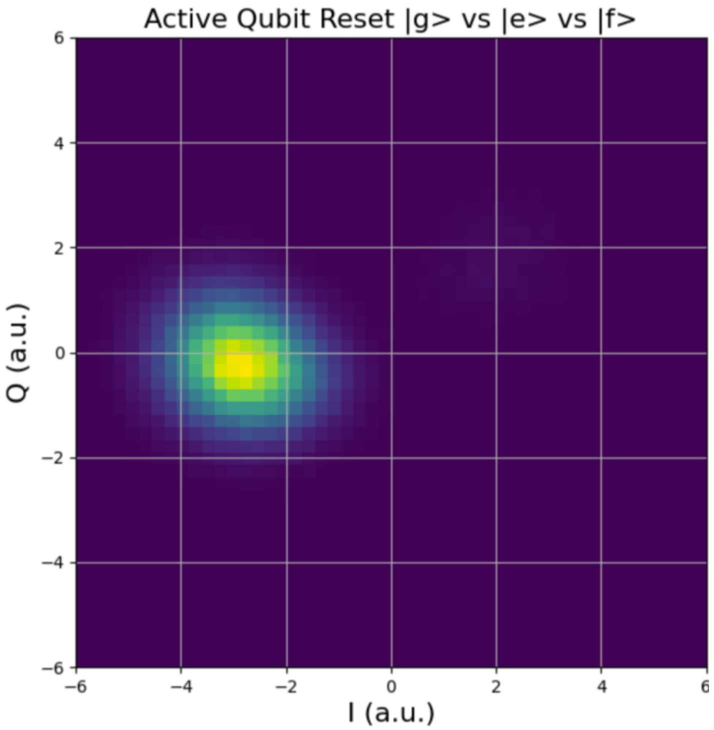

FIGURE 4 QUBIT RESET WHEN PREPARING |E> +|F>

4) Integration of building blocks

Operation of the full Qubitdyne protocol requires many repetitions of the steps 1), 2) and 3) before the cavity state decays by its natural lifetime due to unwanted coupling to its environment. In our experiments, we use 60 iterations to completely deplete the cavity state. Each iteration is approximately 2.8us and the lifetime of the cavity is approximately 350us. The sequence of single-shot outcomes is then summed (with an exponential weighting function) to obtain a single homodyne outcome (if the qubit is always measured along X). Thereafter, the cavity state is re-initialized and another homodyne outcome is pulled by a new Qubitdyne sequence. In an ideal scenario, the statistics of these outcomes corresponds to the homodyne statistics. Experimentally, we demonstrate the homodyne measurement of the non-gaussian Fock 1 state (Figure 5). The data clearly shows the characteristic dip at the origin of the homodyne distribution. However, ideally the dip should go all the way to zero at the origin (Figure 5c), indicating that the experimental realization is not ideal. Some of the discrepancy is due to the decay of the cavity, which can be partly compensated for by standard techniques [4].

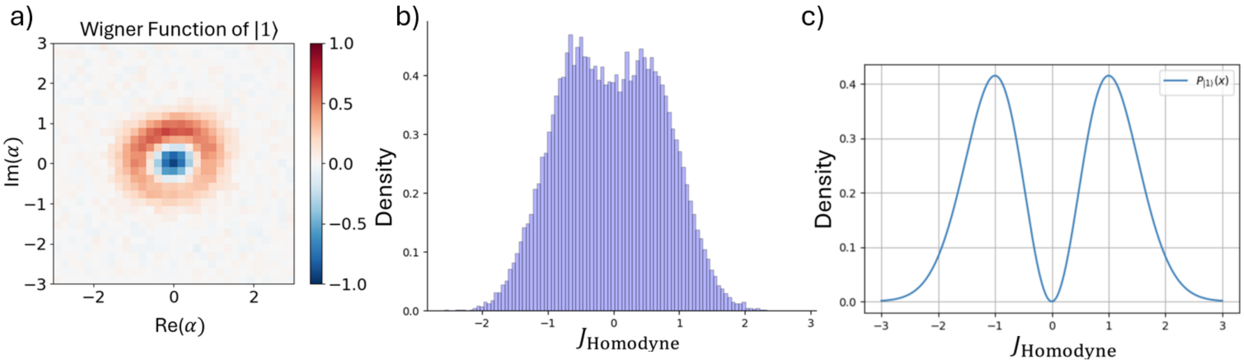

FIGURE 5 QUANTUM STATE CHARACTERIZATION OT THE PREPARED FOCK 1 QUANTUM STATE:
A) WIGNER TOMOGRAPHY, B) QUBITDYNE MEASUREMENT, C) THEORY OF PERFECT HOMODYNE

To summarize, we have demonstrated that the Qubitdyne measurement protocol is able to characterize non-classical quantum states. The performance can be further improved by optimizing each individual building block.

2. HARDWARE PLATFORM

The device employed in this work is a three-dimensional (3D) aluminium microwave cavity coupled to a transmon qubit and a dedicated readout resonator, as depicted in Fig. 6. The transmon qubit is capacitively coupled to the cavity via an antenna pin, and the system operates in the strong dispersive regime where the dispersive interaction strength χ greatly exceeds the cavity decay rate κc (i.e., $\chi \gg \kappa c$). In this regime, the qubit imparts a readily resolvable frequency shift on the cavity conditioned on its state, enabling precise quantum control and high-fidelity readout. A separate readout resonator enables rapid qubit state discrimination without compromising the coherence of the cavity mode. This architecture is a well-established platform for bosonic-mode quantum information processing, and with this demonstrator report, we show that the qubitdyne protocol can be readily implemented on it without modification to the underlying hardware.

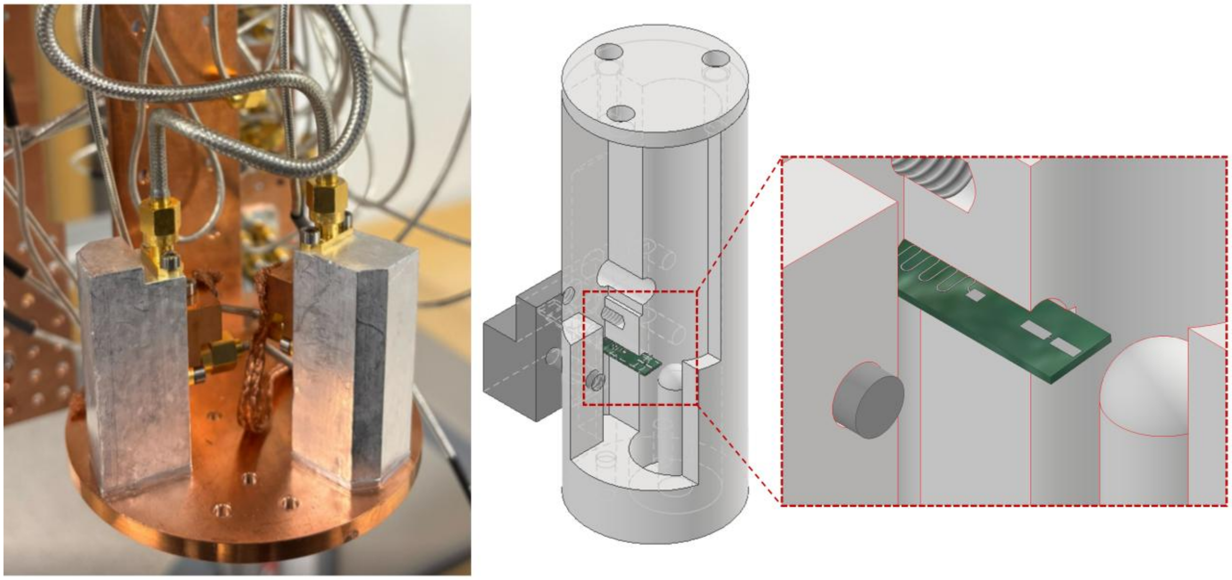

FIGURE 6 PHYSICAL QUANTUM HARDWARE USED TO DEMONSTRATE THE QUBITDYNE PROTOCOL CONSISTING OF A SUPERCONDUCTING 3D CAVITY AND A SUPERCONDUCTING TRANSMON QUBIT.

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