Demonstrating quantum error mitigation on logical qubits

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A long-standing challenge in quantum computing is developing technologies to overcome the inevitable noise in qubits. To enable meaningful applications in the early stages of fault-tolerant quantum computing, devising methods to suppress post-correction logical failures is becoming increasingly crucial. In this work, we propose and experimentally demonstrate the application of zero-noise extrapolation, a practical quantum error mitigation technique, to error correction circuits on state-of-the-art superconducting processors. By amplifying the noise on physical qubits, the circuits yield outcomes that exhibit a predictable dependence on noise strength, following a polynomial function determined by the code distance. This property enables the effective application of polynomial extrapolation to mitigate logical errors. Our experiments demonstrate a universal reduction in logical errors across various quantum circuits, including fault-tolerant circuits of repetition and surface codes. We observe a favorable performance in multi-round error correction circuits, indicating that this method remains effective when the circuit depth increases. These results advance the frontier of quantum error suppression technologies, opening a practical way to achieve reliable quantum computing in the early fault-tolerant era.

I. INTRODUCTION

Suppressing errors is a problem that lies at the center of quantum computing technologies. Quantum error correction and mitigation are the two generic methods of error suppression. Error correction promises to reach an arbitrarily high fidelity provided sufficient qubit resources. Recently, experiments have demonstrated a positive gain in the surface code error correction when scaling the code distance up to 7 [1]. However, it is still viewed as a long-term goal to achieve negligible infidelity through error correction, which could need millions or even more qubits and pose a challenge to the experimental technologies regarding scalability [2]. Error mitigation takes different resources, computing time, to suppress errors, being originally designed for the regime that error correction is lacking [3]. Considering the earliest applications of quantum computing, it is highly likely that they will be carried out under strict technology constraints, mainly on the qubit number. In this scenario, error correction can only attain a limited fidelity, and a practical approach taking advantage of the two error suppression methods is necessary [4, 5].

Zero-noise extrapolation (ZNE) is one of the most practical error mitigation techniques, universally applicable to quantum algorithms that evaluate expectation values [6, 7]. The central idea behind ZNE is to amplify the noise in a quantum circuit by a controllable factor r, and then extrapolate the results back to $r = 0$, thereby inferring the behavior of a noiseless circuit. In a recent experiment, ZNE demonstrated substantial error suppression on a superconducting system with more than a hundred qubits [8], making it the only error mitigation technique successfully applied at this scale to date. Given these promising results, we consider ZNE the leading candidate for mitigating errors in quantum error correction circuits. Specifically, we apply ZNE to reduce post-correction logical errors by amplifying noise on physical qubits.

The implementation of ZNE on logical qubits faces two primary experimental challenges. First, it requires a quantum processor with high-fidelity gates and sufficient qubits, which is crucial for executing quantum error correction. Recent progress in qubit fabrication and control technologies have made superconducting qubits a promising platform for investigating quantum error correction and mitigation technologies [1, 8–13]. In this work, we utilize two superconducting quantum processors to experimentally assess residual errors and costs in quantum error correction and mitigation, employing both the repetition code and surface code [14–17]. Second, accurate error mitigation relies on measuring error rates per operation [3, 18]. While measuring logical error rates is feasible for small codes, it becomes increasingly time-consuming for larger codes due to the small logical error rates [19, 20]. Additionally, for high-encoding-rate quantum error correction codes, such as certain qLDPC