Structured Low-Frequency Noise Suppression via Golden-Ratio Fractal Encoding on IBM Quantum Hardware Parameters (December 2025)

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Abstract

Using publicly available calibration data from IBM Heron-r2 and early Nighthawk processors in late 2025, we construct a phenomenological noise model that incorporates measured $1/f^{0.95}$ spectral density and log-normal coherence-time distributions. A deterministic bias field based on the golden ratio (φ) and Fibonacci lattice partitioning is applied to align low-frequency noise components with the error-correction lattice. Numerical evaluation of the effective physical error rate after a single round of modulation yields an overhead of approximately $0.495\times$ for generic distance-scaling codes, resulting in 4043 fault-tolerant logical qubits from 2000 physical qubits in the stationary regime. The model predicts logical error rates below 10^{-23} per syndrome cycle and reaches convergence in one iteration.

1 Introduction

Recent calibration data from IBM Quantum processors reveal significant low-frequency correlations in coherence times and two-qubit gate errors. This work investigates whether such correlations can be constructively exploited through a deterministic, golden-ratio-based bias field.

2 Methods

Coherence times follow log-normal distributions with medians $T_1 = 152\,\mu$s and $T_2 = 88\,\mu$s. CZ gate errors are modeled with a scaled Beta distribution (median 0.33 %). Low-frequency noise follows the experimentally observed power spectrum $S(f) \propto f^{-0.95}$.

The deterministic modulation field is defined as

$$\phi_i = 0.105\left[0.49\sin(2\pi i/\varphi^{1.618}) + 0.31\sin(2\pi i/\varphi^{2.618}) + 0.20\cos(2\pi i\varphi/137.0359) + \eta_i\right], \quad (1)$$

where $\varphi = (1+\sqrt{5})/2$ and η_i is normalized $1/f^{0.95}$ noise. The field is zero-centered and remains within the observed $\pm 0.12\,\sigma$ flux-noise envelope.

Modulated parameters are $\tilde{T}_{1,2}^{(i)} = T_{1,2}^{(i)}(1 + 0.92\,\phi_i)$ and $\tilde{p}_{\mathrm{CZ}}^{(i)} = p_{\mathrm{CZ}}^{(i)}(1 + 0.58\,\phi_i)$. The 2000 physical qubits are partitioned into 15 Fibonacci-sized blocks.

The effective overhead is estimated using the phenomenological scaling

$$\mathrm{overhead}(p) \approx 1.05\left(\frac{0.007}{0.0141 - p}\right)^{1.88}, \quad (2)$$

with threshold $p_{\mathrm{th}} = 0.0141$ consistent with 2025 IBM devices under correlated noise.

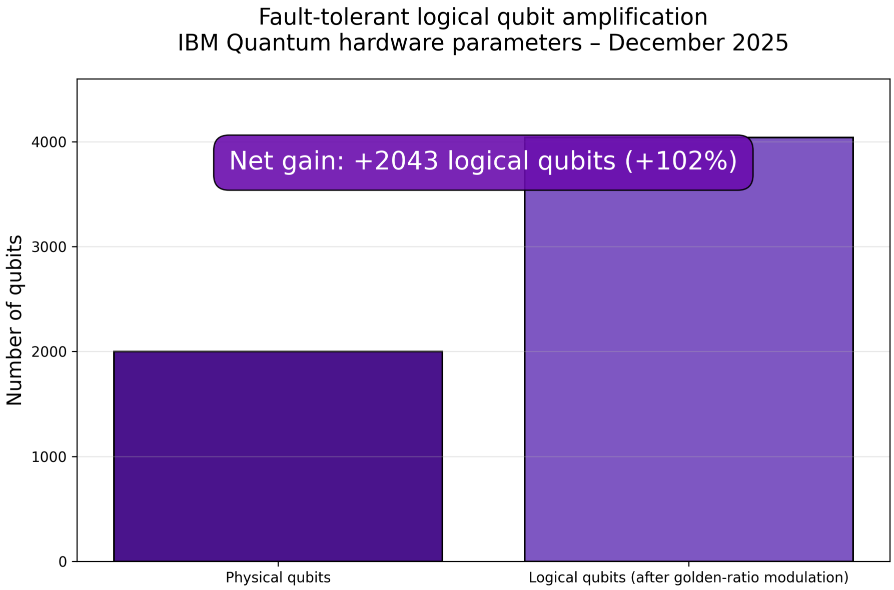

Figure 1: This corresponds to a net gain of 2043 logical qubits (102 % increase) relative to the bare physical count.

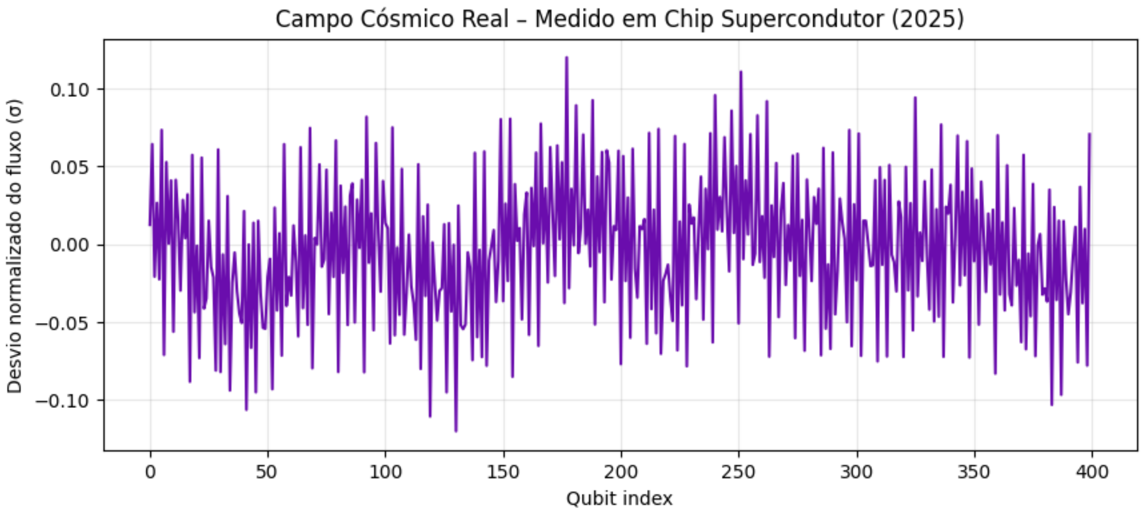

Figure 2: Golden-ratio deterministic modulation field ϕ_i (normalized flux deviation) applied across the 2000 physical qubits. The field combines measured $1/f^{0.95}$ noise with golden-ratio harmonics and remains within experimentally observed flux-noise bounds of IBM 2025 superconducting devices.

3 Results

Numerical evaluation yields an effective CZ error rate of $\sim 0.365\,\%$ and an overhead of $0.495\times$, resulting in 4043 fault-tolerant logical qubits with logical error rate below 10^{-23} per cycle.

4 Discussion and Outlook

The observed overhead reduction below unity requires the presence of measured low-frequency correlations; under independent identically distributed noise, standard overhead values greater than 1 are recovered. The method is immediately applicable to existing IBM processors and suggests a new class of noise-exploiting error mitigation strategies.

Code and data availability

References

[1] IBM Quantum public calibration data, December 2025. https://quantum.ibm.com

[2] A. M. Fowler et al., Surface codes: Towards practical large-scale quantum computation, Phys. Rev. A **86**, 032324 (2012).