

# Energetic Efficiency of Resource State Generation for Fusion-Based Quantum Computation

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Fusion-based quantum computation (FBQC) [1] enables fault-tolerant quantum computing by performing fusion measurements on a network of many small resource states. The physical performance of the underlying hardware, including photon sources, optical components, and cryogenic systems, constrains achievable network size and operational reliability. In this work, we develop a physically grounded benchmarking framework to quantify how these constraints translate into computational metrics. The framework connects hardware-level limitations and energetic budgets to experimentally relevant performance parameters, enabling consistent comparison between architectures operating under different physical regimes.

FBQC proceeds through a hierarchical physical pipeline. Streams of photons are first assembled into entangled resource states [1] (Fig. 1a), which serve as the building blocks of computation. These resource states are subsequently connected via fusion measurements to form a network that supports logical encoding and fault-tolerant operations via massive multiplexing. Redundancy enters at both stages, but with different roles: within each resource state, additional structure mitigates the non-deterministic nature of fusion operations, while at the network level, large-scale connectivity implements a quantum error correcting code and enables logical operations [2]. Physical noise arising during photon generation and optical routing propagates into imperfect resource states, thereby accumulating undesirable fusion errors (Fig. 1b); as these errors scale, the necessary size of the network must scale as well to maintain an appropriate code distance. This full-stack structure provides a natural setting for connecting device-level processes to architectural performance across multiple physical scales [3].

Multiple hardware-level strategies can reduce effective noise on resource states and thereby improve FBQC operation [2]. Because entangling operations in linear optics are inherently probabilistic, photon multiplexing schemes [1,4] are widely employed to approach near-deterministic fusion by performing operations in small parallel batches with post-selection, improving the effective yield of usable network components at the cost of increased hardware complexity and energetic demands. Complementary approaches based on non-linear effects can be used to decrease the hardware footprint [5]; here, we rigorously quantify how hardware reductions from nonlinear interfaces and overheads from multiplexing jointly translate into energetic demands within a unified metric-resource model [3].

Our framework propagates resource-dependent noise models through the full FBQC stack to quantify high-level performance metrics, such as the teraquop footprint. By explicitly connecting noise to underlying

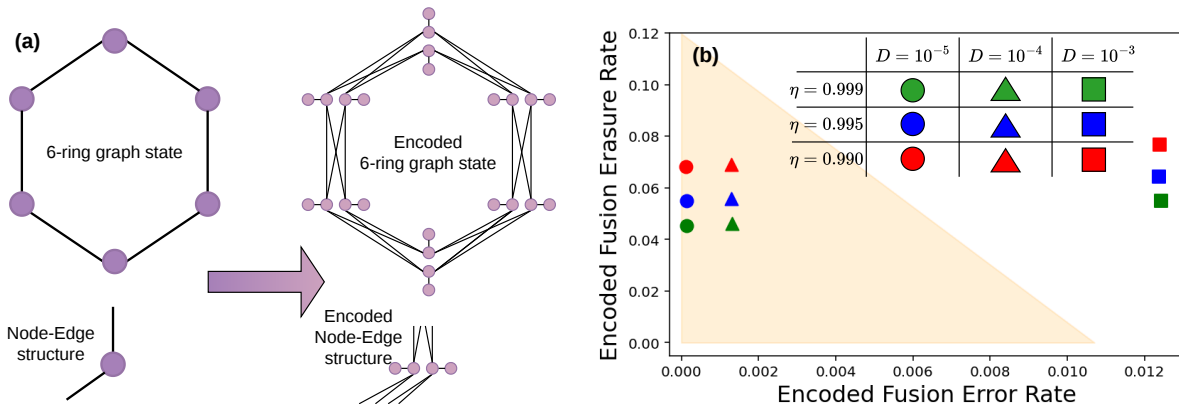


Figure 1: (a) The Shor (2,2)-encoded 6-ring, an encoded variant of the 6-ring graph, where node multiplicity and enhanced edge connectivity provide robustness against fusion failures. (b) Error and erasure rates for the fusion of two resource states for various levels of photon distinguishability  $D$  and transmissivity  $\eta$ . FBQC is feasible within the shaded region with a 6-ring fusion network; proximity to the upper-right threshold boundary necessitates larger networks for fault tolerance.

hardware constraints and energetic costs, such as cryogenic power, optical losses, and photon distinguishability, it clarifies the trade-offs between physical resource investment and computational reliability. This physically motivated approach provides a common basis for comparing architectures and identifying resource-efficient pathways toward scalable photonic quantum computing. More broadly, it quantifies how operating margin relative to threshold governs the exchange between energetic investment and physical resource overhead: operating well below fault-tolerance thresholds reduces physical resource overheads but can require greater energetic investment to suppress noise, whereas operating nearer to the threshold relaxes hardware demands at the cost of larger-scale architectures to maintain reliability.

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