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Energy and Power Scaling in Quantum Computers based on Rotated Surface Codes and Silicon Flip-Flop Qubits

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Abstract: Power and energy requirements for quantum computers based on silicon flip-flop qubits are analysed. Using rotated surface codes, scalability and thermal constraints are studied.

Power and energy constraints are among the most critical limiting factors in scaling-up quantum computers. This study examines the energy and power requirements for such systems based on silicon flip-flop (FF) qubits—a unique donor-quantum dot-based qubit design [1,2]. By employing the rotated surface code (SC), a quantum error correction code with one of the highest threshold error rates [3], we estimate the energy consumption of logical qubits implemented on 2D arrays of FF qubits at varying code distances d. Our analysis integrates gate sequences and noise impact on fidelity [4], time constraints, electronics power dissipation, and extends a thermal model for quantum computers [5] that accounts for cryogenic components (T_q =0.1K, T_{cryo}=4 K) and room-temperature electronics (T_0=300K), as illustrated in Fig. 1a.

The results highlight significant scaling challenges, particularly thermal constraints, and estimate a computation power per qubit in the range of 4–400 mW/qubit, depending on the code distance. With state-of-the-art cryo-electronics and cryostat technology, the scaling-up of this quantum computer architecture is mainly limited by the cooling power at T_q, potentially supporting several hundreds logical qubits for specific code distances, as shown in Fig. 1b, and requiring a total power in the kW range.

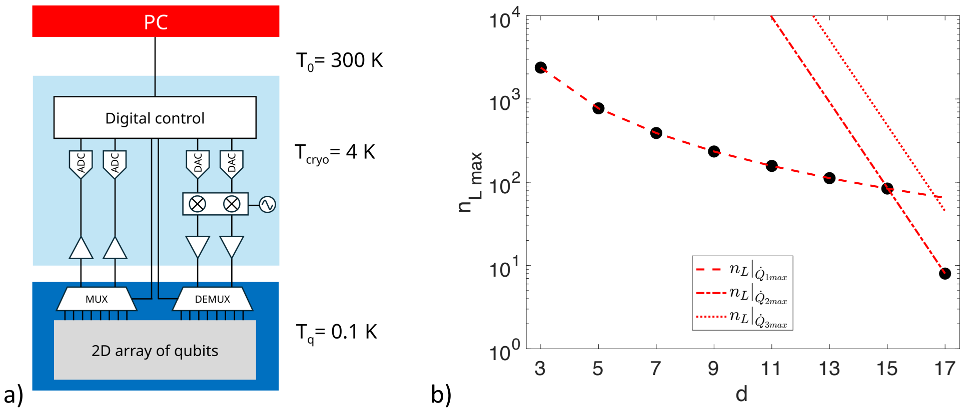

Fig. 1 a) Scheme of the quantum computer architecture. A PC at T_0 controls the entire system, sending signals to and receiving signals from the cryogenic section at T_{cryo}. The cryogenic section is composed by a digital control unit and analog devices. The digital control unit is responsible for SC error syndrome decoding and is implemented using an ASIC, while the analog control part handles input/output operations including DACs, mixers, local oscillators, LNAs, and ADCs. Interconnections extend to the cryogenic base stage at T_q, where analog MUX and DEMUX circuits route input/output signals to interface with the entire 2D array of qubits. b) Symbols represent the largest number of logical qubits n_{Lmax} for which all the power constraints $\dot{Q}_i \le \dot{Q}_{imax}$ for i=1,2,3 at the corresponding temperatures (T_q, T_{cryo}, T_0) are satisfied, vs. the code distance d. The dashed, dot-dashed and dotted red curves indicate the maximum number of logical qubits allowed if only $\dot{Q}_{1max}$ or $\dot{Q}_{2max}$ or $\dot{Q}_{3max}$ holds, respectively.

References

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