Carnot-Guided Warm-Optimization of Dilution Refrigerators: A Reduction in the Electrical and Cost and Material Cost Drivers in Quantum Computing

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The requirement for millikelvin refrigeration is a dominant barrier for scaling quantum computing and unlocking its potential for groundbreaking research across numerous fields. As qubits are thermally hypersensitive, quantum computers require the use of dilution refrigerators to operate at millikelvin temperatures, one of the biggest drivers of capital and operational costs in the field. This project aims to reduce the material and operational cost drivers of these DRs. Thermodynamic limits were evaluated using the Carnot Performance Coefficient (COP). This analysis showed that operating at 25-29mK, rather than the conventional <10mK, increases overall system efficiency. This drastically reduced the power required to circulate helium-3, enabling the dry-vacuum pump to be downsized, in turn reducing pumping costs. Further, components with diminishing returns on material purity or geometry design, such as the cold plates and coaxial cables, were redesigned using alternative materials and optimized geometries. These changes were simulated using FEA software to identify optimal configurations that reduced raw material costs, while simultaneously improving system performance. Further, system cooling was streamlined by removing one pulse-tube cooler, significantly reducing both manufacturing costs and power consumption. These optimization choices were validated through component simulations of the DR, confirming minimal system efficiency tradeoffs alongside ~$100k saved in capital costs and a ~51% decrease in total system power consumption. This project establishes warm-optimization of dilution refrigerators as a practical pathway to lower the dominant cost drivers in QCs, enabling wider access to mK infrastructure for research and development.

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