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Exploration of Quantum Computing for Fusion Energy Science Applications

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Quantum computing promises to deliver large gains in computational power that can potentially have a beneficial impact on a number of Fusion Energy Science (FES) application areas that rely on either intrinsically classical or intrinsically quantum calculations. This work presents an overview of our recent efforts [1] to develop and extend quantum algorithms to perform FES-relevant calculations and perform concrete examples of quantum computations on present-day quantum computing hardware platforms. We have developed quantum algorithms that can: (1) exactly simulate the Liouville equation [2], even for nonlinear non-Hamiltonian, e.g. dissipative, classical dynamics; (2) perform efficient eigenvalue estimation for generalized eigenvalue problems common in plasma physics and MHD theory [3]; (3) efficiently implement nonlinear wave-wave interactions [4]; and (4) efficiently explore chaotic quantum and classical dynamics [5,6].
Simplified versions of these quantum algorithms have been implemented on state-of-the-art cloud-based superconducting architectures such as the IBM-Quantum Experience and Rigetti Quantum Cloud Services platforms to test the fidelity of emerging quantum hardware capabilities. We have also implemented some of these algorithms on the LLNL Quantum Design and Integration Testbed (QuDIT), which has novel capabilities such as the ability to work with more than two energy levels per transmon and the ability to synthesize arbitrary unitary gates (for small qubit numbers) using optimized control pulses. These hardware platforms have been used to simulate a nonlinear three-wave interaction problem [4] and a three-level Grover's search algorithm. We have also explored the ability of the IBM-Q platform to simulate chaotic dynamics through the quantum sawtooth map [5,6], as well as a number of the building blocks of the quantum variational eigensolver algorithm. The fidelity of the experimental results matches noise models that include decay and dephasing processes and highlights key differences between state-of-the-art approaches to quantum computing hardware platforms.

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