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Extreme plasma physics with QED effects on a quantum computer

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Quantum Electrodynamical effects are prevalent in the complex, nonlinear dynamics of plasmas in extreme astrophysical environments (neutron stars, pulsars, black-hole accretion disks) and intense laser interaction with matter. Understanding of these systems has advanced in parallel with the development of the particle-in-cell numerical framework, where the electromagnetic fields created by and interacting with the particles are mediated by a grid, thus reducing the computational complexity. This method shares some similarities with the lattice methods used in QCD/QED: both aim to achieve self-consistency in the simulations, they apply discretization/grid-based representation (either of the phase-space or of space-time), and have the ability to capture collective dynamics.

Despite the success of both numerical frameworks, it is believed that quantum computers can provide significant speedups and memory saving when simulating physical systems. However, these computers are naturally applicable only to a certain kind of problems, that can be expressed in a form equivalent to the linear Schrödinger equation. In the last few years many new algorithms have been designed to map problems that do not strictly satisfy this condition to a quantum circuit. Current general public-access quantum computers only allow for $\sim$20 qubits at a time and short circuit depths ($\sim$100 gates before results get corrupted by decoherence). This has restricted simulation capabilities on real quantum computers to testing toy models for most of the problems of interest. Variational algorithms are promising for the near term quantum computers as they present three main advantages: their circuits are shorter than in regular Hamiltonian simulation, they allow for reconstruction of the wavefunction at each timestep and they can be extended to nonlinear dynamics. While quantum algorithms have been successfully applied in areas such as quantum chemistry and quantum field theory, their study in plasma physics is still at its infancy.

In this work we apply quantum computing techniques to extreme plasma physics scenarios where QED phenomena are present and the dynamics is inherently nonlinear. By bridging the gap between traditional simulation methods and quantum frameworks, we aim to advance our understanding of plasma physics and its connection with quantum field theory.

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