Quantum algorithm for modeling radiofrequency waves in an inhomogeneous plasma

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Quantum Computing (QC) is now attracting attention as a potential tool for speeding up simulations of classical systems. In plasma physics, particularly promising is the application of QC to high-resolution three-dimensional simulations of radiofrequency waves in fusion plasmas, which has not been possible with classical computers. However, QC research in this area is still in its infancy, with the state-of-the-art being Landau-damping simulations fundamentally limited to homogeneous plasmas [1]. What plasma processes can be simulated with quantum computers efficiently remains an open question, especially for applications beyond toy models.

We show that cold-plasma waves are good candidates. We report the first quantum algorithm for full-wave modeling of a radiofrequency-wave propagation in linear cold inhomogeneous magnetized plasma [2], specifically, X wave, which exhibits reflection, tunnelling, and accumulation of the wave energy near the upper-hybrid resonance. We do this by representing the wave equation as a vector Schroedinger equation with a Hermitian Hamiltonian operator [3] and by solving it using quantum Hamiltonian simulation via so-called Quantum Signal Processing (QSP) [4]. The field amplitudes are stored as the complex amplitudes of quantum states, and the spatial dependence of the fields are encoded into the qubit states.

The quantum circuit is constructed explicitly (Fig. 1), and the simulations are performed on a classical emulator of a quantum computer. The results show agreement with conventional full-wave simulations (Fig. 2).

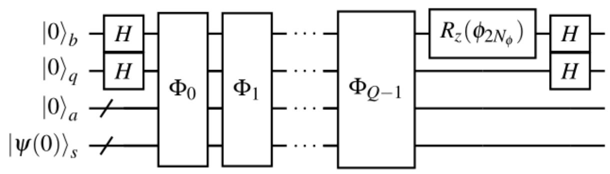

Figure 1: The QSP method solves the Schroedinger equation by approximating the exponential function of the Hamiltonian via a sum of polynomials of opposite parity. In a quantum circuit, this sum is represented by a set of rotations Φ_j with classically precalculated angles. The length of this circuit depends linearly on the simulation time, as the inverse of the approximation error and polylogarithmically on the system spatial size, thus, potentially providing an exponential speedup with respect to classical simulations.

In the course of this work, a numerical library is developed for a broad class of Hamiltonian simulations via QSP [5].

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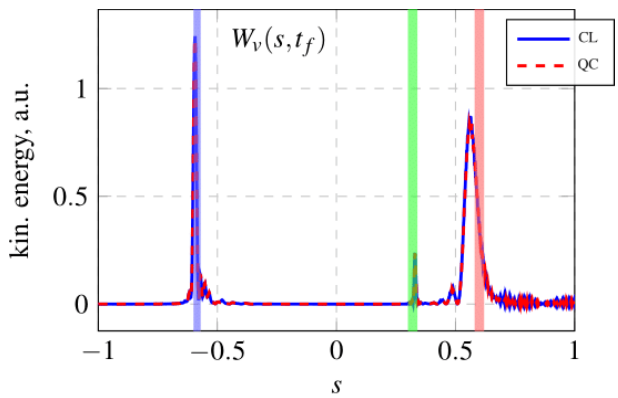

Figure 2: Comparison of the spatial distribution of the wave kinetic energy in classical (CL) and emulated quantum (QC) simulations. The energy is accumulated mainly at the upper-hybrid resonances, whose locations are indicated by the blue and red vertical lines. The QC data are obtained from the classical simulator [5] of quantum circuits without performing actual quantum measurements. On an actual quantum computer, one would need to perform the so-called Amplitude Estimation to extract the wave energy from the quantum simulations.