Phase-Locked Quantum-Plasma Processor: Normalized Hamiltonian and Stability Analysis

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Abstract

We propose a non-algorithmic quantum computation model based on phase resonance, dynamic plasma coupling, and energy-driven convergence. Unlike gate-based or adiabatic quantum computing, this model computes via transition into stable energetic configurations defined by resonance conditions. We present a normalized Hamiltonian formalism, identify stability criteria, define Lindblad dissipation, and demonstrate a prototype numerical convergence scenario.

1 Normalized Formalism

Let the characteristic energy scale be $E_0 = \hbar\omega_q$, time scale $T_0 = 1/\omega_q$, and spatial scale L_0 (e.g., lattice period). Define normalized variables:

$$\tilde{q}_i = \frac{q_i}{L_0}, \qquad \tilde{p}_i = \frac{p_i}{\hbar/L_0}, \qquad \tilde{\rho} = \frac{\rho}{\rho_0},$$
$$\tilde{A} = \frac{A}{E_0}, \qquad \tilde{g} = \frac{g\rho_0}{E_0}, \qquad \tilde{t} = \omega_q t$$

Normalized Hamiltonian:

$$\tilde{\mathcal{H}} = \sum_i \frac{\tilde{p}_i^2}{2} + \tilde{\lambda}(\tilde{t})V(\tilde{q}_i) - \tilde{A}(\tilde{q}_i, \langle\tilde{q}\rangle)\cos\Big(\tilde{t} - \tilde{\phi}(\langle\tilde{p}\rangle)\Big) + \tilde{g}\tilde{\rho}(\tilde{q}_i) + \tilde{\mathcal{H}}_{\text{plasma}} \tag{1}$$

2 Hamiltonian Components

2.1 Task Encoding

$\tilde{\lambda}(t)V(q)$: external problem shape. Choose:

- Adiabatic: $\dot{\lambda}/\lambda \ll \Delta_{\min}/\hbar$
- Floquet: $\lambda(t) = \sum_k \lambda_k \cos(\omega_k t)$

2.2 Resonance Lock

Feedback closure via:

$$\tilde{A}_i = A_0 + \chi \sum_{j \in \mathcal{N}(i)} f(\tilde{q}_j - \tilde{q}_i) \tag{2}$$

$$\tilde{\phi}_i = \phi_0 + \gamma \sum_j g(\tilde{p}_j - \tilde{p}_i) \tag{3}$$

2.3 Quantum-Plasma Coupling

Interaction:

$$\tilde{g}\tilde{\rho}(\tilde{q}_i), \quad \text{with } g = e\varphi(q), \quad \nabla^2\varphi = -\rho/\varepsilon_0 \tag{4}$$

For atomic Rydberg implementations, a typical range is $g \sim 2\pi \times (0.1 - 1)\,\mathrm{MHz}$.

2.4 Plasma Hamiltonian

$$\tilde{\mathcal{H}}_{\text{plasma}} = \int d^3x \left[\frac{\Pi_\rho^2}{2M} + F(\tilde{\rho}, \tilde{v}, T)\right], \quad \{\tilde{\rho}, \Pi_\rho\} = 1 \tag{5}$$

Assuming ideal two-fluid EOS with Debye correction:

$$U = \frac{3}{2}k_B T(\rho_e + \rho_i) + \frac{e^2}{8\pi\varepsilon_0} \cdot \frac{\rho_e \rho_i}{k_B T} \tag{6}$$

2.5 Lindblad Dissipation

We implement dissipative convergence through a Caldeira–Leggett-type operator:

$$\mathcal{L}[\hat{\rho}] = -\frac{i\gamma}{\hbar}[\hat{q}, \hat{p}\hat{\rho}] - \frac{2m\gamma k_B T}{\hbar^2}[\hat{q}, [\hat{q}, \hat{\rho}]] \tag{7}$$

For phase-coupled plasmas, $\gamma \equiv \gamma(\tilde{\rho})$ is density-dependent.

2.6 Readout Operator

Measurement modeled via:

$$\hat{O}_{\text{read}} = \sum_i \kappa_i \hat{q}_i, \quad \text{Solution fixated when } \langle \hat{O}_{\text{read}} \rangle \to 0 \tag{8}$$

3 Stability Criterion

Small perturbations:

$$\tilde{q}_i = \tilde{q}_i^{(0)} + \delta\tilde{q}_i, \qquad \tilde{p}_i = \tilde{p}_i^{(0)} + \delta\tilde{p}_i, \qquad \tilde{\rho} = \tilde{\rho}^{(0)} + \delta\tilde{\rho}$$

Jacobian matrix $\mathcal{J}$:

$$\dot{\boldsymbol{\delta}} = \mathcal{J}\boldsymbol{\delta}, \quad \text{converges if } \operatorname{Re}(\lambda_i) < 0\ \forall i \tag{9}$$

Floquet stability: diagonalize $\mathcal{M}_T = \mathcal{T}\exp\left(\int_0^T \mathcal{J}(t)dt\right)$
Check $|\mu_i| < 1$ for all Floquet multipliers.

4 Computation as Resonant Convergence

$$\text{Solution} \iff |\omega_q - \omega_\phi(t)| \leq \delta\omega_{\text{lock}}, \quad \frac{\mathrm{d}E}{\mathrm{d}t} \to 0^+ \tag{10}$$

5 Numerical Illustration

Figure 1: Simulated 1D phase-locking for $\lambda(t) = t/T_a$, normalized energy convergence, and Floquet eigenvalues showing subunitary decay.

- Initial state: random phase offsets
- Convergence: energy $E(t) \to \min$, $\langle \hat{O}_{\text{read}} \rangle \to 0$

6 Conclusion

This model lays the groundwork for phase-resonant quantum processors with internal energy convergence. It replaces gate logic with dynamic resonance, problem encoding with field shaping, and result extraction with state locking.