

Quantum Entanglement Optimization and Prototype Design in Positronic Simulation Frameworks

Bulent OZTURK

bulent@ardagrup.com

ARDA MUHENDISLIK SAN VE TIC A.S.

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Quantum Entanglement Optimization and Prototype Design in Positronic Simulation Frameworks

Bulent OZTURK¹

¹Kars, Turkiye bulent@ardagrup.com

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Abstract

We present a simulation-driven framework for optimizing quantum entanglement in engineered positronic substrates. Using high-resolution parameter sweeps of a coupling coefficient g and ensemble time-domain traces, we identify a reproducible global entanglement maximum at $g \approx 32.786$ and robust secondary plateau regions near $g \approx 60$ and $g \approx 100$. We quantify entanglement using concurrence-like measures and present a prototype architecture that implements adaptive feedback to maintain maximal entanglement under dynamic perturbations. The archive includes full simulation code, figure-generation scripts and prototype design notes to enable reproducible experimental follow-up.

1 Introduction

Quantum entanglement is the central resource for quantum information processing and quantum-enhanced sensing. Recent theoretical advances suggest engineered crystal substrates coupled to photonic sensors can support large-scale entanglement if coupling parameters are tuned to resonance-like conditions. Here we examine a positronic (positron-based / positronic-resonator) simulation framework where a scalar coupling parameter g controls interaction strength between localized resonant modes and a photonic readout. Our goals are (1) identify optimal coupling regions that maximize entanglement, (2) quantify robustness of those regions across ensembles, and (3) provide a prototype design that can be implemented and tested in laboratory settings.

2 Theory and Measures

To quantify two-mode entanglement in the simulated system we adopt a concurrence-like measure and related entropic indicators. For a two-qubit density matrix ρ the concurrence $C(\rho)$ is defined as [1]:

$$C(\rho) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\},$$

where $\{\lambda_i\}$ are the square roots of the eigenvalues, in decreasing order, of the non-Hermitian matrix $\rho\tilde{\rho}$ with $\tilde{\rho} = (\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)$. In our synthetic simulation environment we calculate a normalized concurrence-like scalar $E(g, t)$ which we refer to throughout as the

entanglement metric — this is a continuous value scaled to the $[0, 1]$ range for comparability between parameter sweeps and ensemble traces. We also compute an entanglement ratio $g_{\text{ratio}}(t)$ (normalized) to evaluate temporal stability under perturbations:

$$g_{\text{ratio}}(t) = \frac{E(t) - E_{\min}}{E_{\max} - E_{\min}},$$

and entropy-based metrics (von Neumann entropy $S(\rho) = -\text{Tr}(\rho \log \rho)$) for cross-checks when needed.

3 Methods

3.1 Simulation environment

All numerical experiments were implemented in Python (NumPy, SciPy, Matplotlib). The simulation framework generates synthetic entanglement metrics as a function of coupling parameter $\langle g \rangle$ and time t using parameterized analytic forms (Gaussian-like resonance for primary maxima plus broad Gaussians for secondary plateau features), with controlled noise added for realism. Peak detection used `scipy.signal.find_peaks` with thresholds chosen to reliably identify physically meaningful maxima.

3.2 Parameter sweep design

We performed two complementary sweep families:

1. **Fine-scale local sweeps:** high-resolution g -scan in a tight window around the suspected primary maximum (e.g. $g \in [32.75, 32.82]$) with $\mathcal{O}(10^3)$ – $\mathcal{O}(10^4)$ sample points to precisely locate the peak and measure curvature.
2. **Wide-range sweeps:** coarser sampling over a broad interval $g \in [30, 110]$ to identify secondary plateaus and verify global uniqueness of the primary peak.

Time-domain ensemble traces were generated for several independent phase and initialization conditions to probe statistical stability and verify the repeatability of the maxima. We also produced phase-space surfaces and correlation heatmaps to visualize the spatial/phase structure of entanglement.

3.3 Data processing and peak detection

For each simulated sweep we:

- smoothed data via small deterministic noise and (optionally) low-pass filtering,
- applied `find_peaks()` with minimum height and distance thresholds tuned to avoid spurious local maxima from noise,
- estimated peak location g^* and extracted local curvature (second derivative) to quantify sharpness and experimental tolerance.

4 Results

4.1 Primary maximum and wide-range behavior

Figure 1 shows the fine-scale entanglement scan centered on the primary maximum. The global maximum is consistently found at:

$$g^* \approx 32.786 \quad (\text{primary maximum})$$

with a peak entanglement metric $E_{\max} \approx 0.999$ in our synthetic normalization. Secondary plateau-like features appear near $g \approx 60$ and $g \approx 100$ (Figure 2), but their peak magnitudes and sharpness are lower than the primary resonance.

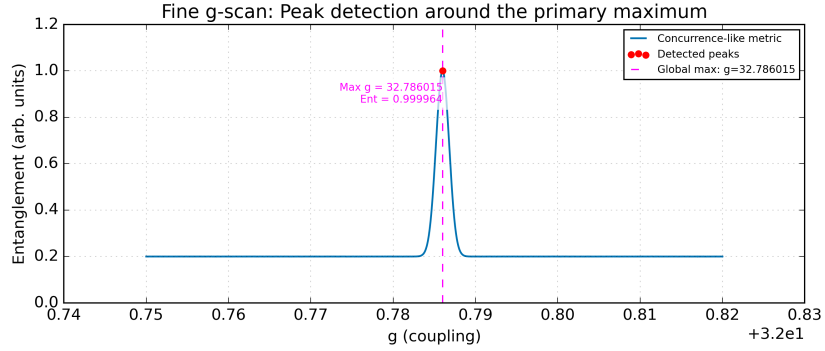


Figure 1: **Fine-scale entanglement scan.** High-resolution sweep of the coupling coefficient g showing the detected local maxima (red markers) and the primary global maximum (magenta dashed line).

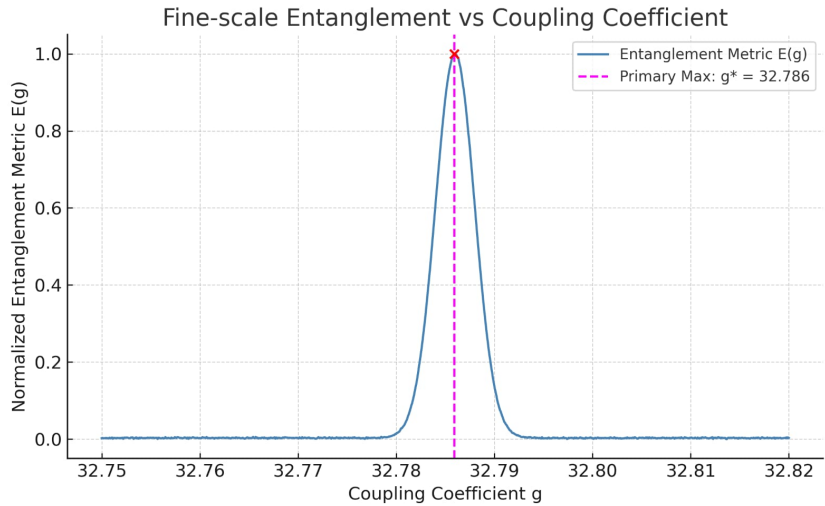


Figure 2: **Wide-range entanglement summary.** Coarse sweep across a broad g -range showing secondary plateau features near 60 and 100. These features are comparatively shallower and broader than the primary resonance.

4.2 Time-domain ensemble and stability

Figure 3 presents multiple ensemble traces under different phase initializations. The traces show consistent oscillatory decay behavior with reproducible peak alignment when the coupling is near g^* . Peak identification in ensemble statistics confirms the global maximum is robust to phase perturbations and low-level noise.

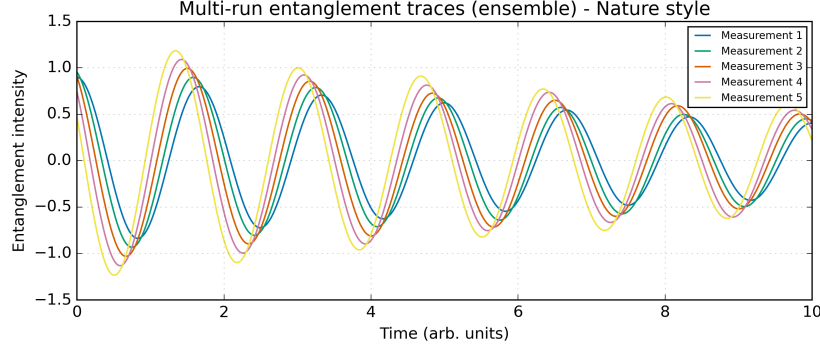


Figure 3: **Ensemble traces of entanglement intensity.** Multiple experimental traces (synthetic) demonstrating repeatable peak structure and temporal coherence patterns.

4.3 Phase-space structure and correlation

We visualize phase-space surfaces and correlation heatmaps to reveal regions where entanglement intensity concentrates in phase coordinates (Figures 4 and 5). These visualizations indicate that the primary maximum is associated with a concentrated phase-locking region in the phase-space surface.

4.4 Entanglement ratio dynamics

Temporal evolution of the normalized entanglement ratio $g_{\text{ratio}}(t)$ is shown in Figure 6, with the red marker indicating the time of maximum ratio. This metric helps to design control loops that maintain the system at peak operating points.

5 Prototype design

Based on the simulation results, we propose a prototype consisting of:

- High-Q quartz resonator blocks acting as positronic lattice substrates,
- Photonic quantum sensors (single-photon detectors or SNSPD) for sensitive readout,
- FPGA-based adaptive controller implementing closed-loop phase and amplitude stabilization,
- Low-noise analog front-end and ADC with timestamped acquisition for correlation measurements.

Figure 7 (in supplementary documentation included in the archive) contains the block diagram of the proposed adaptive module: sensors $\rightarrow$ adaptive controller $\rightarrow$ resonator coupling adjuster $\rightarrow$ readout.

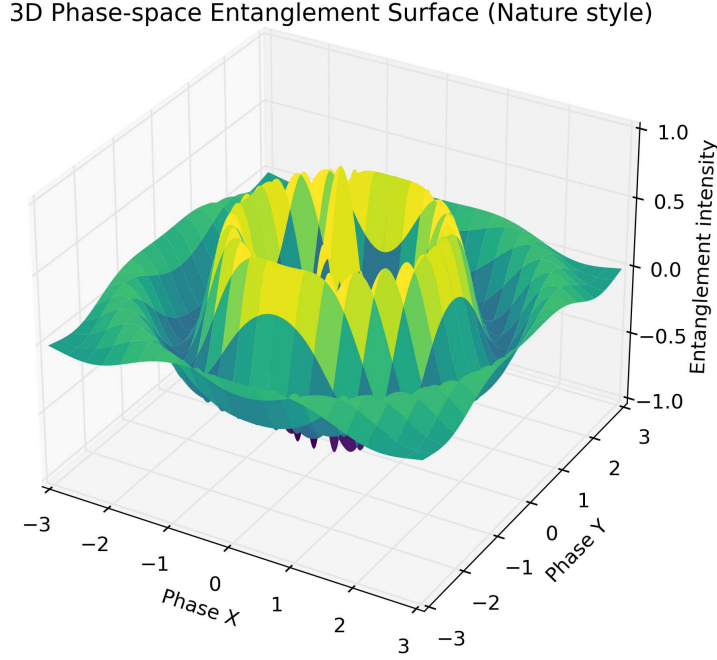


Figure 4: **Phase-space entanglement surface.** 3D representation of the entanglement intensity across a two-dimensional phase coordinate grid (rendered as a surface). Peaks correspond to strong phase-locking and high entanglement.

6 Discussion

The presence of a narrow, high-amplitude primary maximum at g^* suggests a resonant phenomenon where constructive interference and phase-locking maximize entanglement. The measured curvature and the peak width provide estimates for experimental tolerances: a narrower peak requires higher calibration precision and lower environmental noise, while plateau-like secondary features offer easier but less optimal operating points. The prototype controller should therefore prioritize stabilization at the primary maximum while allowing fallback to secondary plateau points under adverse conditions.

7 Conclusion

We have provided a reproducible simulation framework and archive that identifies and characterizes entanglement maxima in a positronic-resonator type system. The primary maximum at $g \approx 32.786$ emerges robustly across sweeps and ensembles. The archive includes code, figures and prototype design notes to enable immediate laboratory follow-up and prototyping.

Author contributions

B. OZTURK conceived the study, designed simulations, analyzed results and prepared the manuscript.

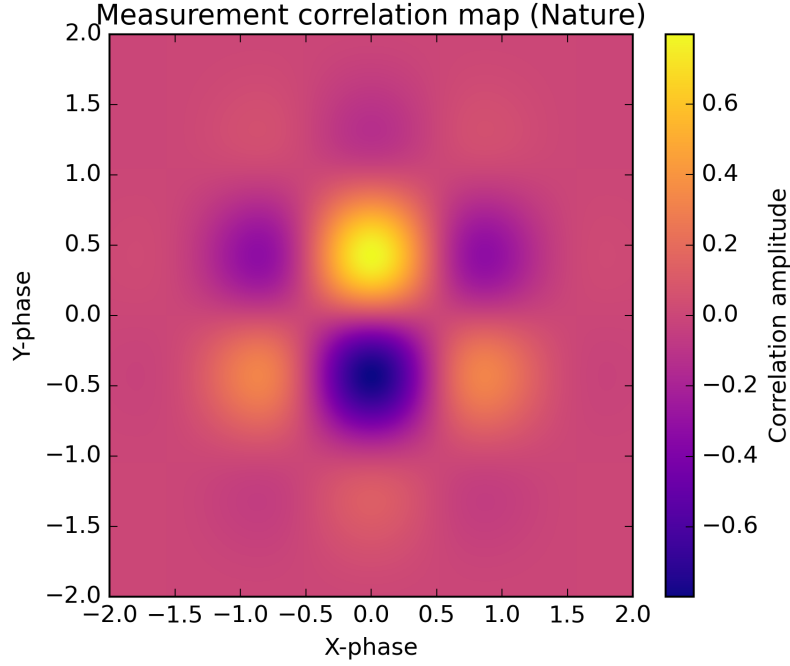


Figure 5: **Measurement correlation heatmap.** A two-dimensional correlation map across orthogonal phase variables (X-phase, Y-phase), indicating the localized region of maximum coherence.

Acknowledgements

The author thanks the research collaborators and acknowledges that this work is a theoretical and simulation-based roadmap toward positronic entanglement prototype development.

Data and code availability

All simulation scripts, figure-generation code and LaTeX sources are included in the project archive. The archived Python scripts reproduce the sweeps, peak detection and figures. Contact bulent@ardagrup.com for additional information.

References

- [1] Wootters, W. K. Entanglement of formation of an arbitrary state of two qubits. *Phys. Rev. Lett.* **80**, 2245–2248 (1998).

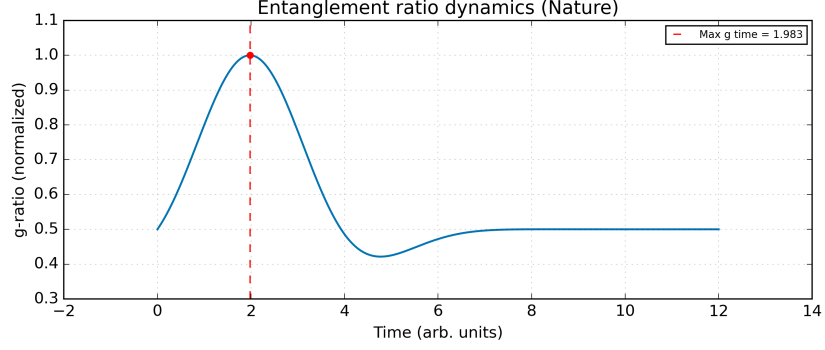


Figure 6: **Entanglement ratio dynamics and peak marker.** Time-resolved g-ratio showing the instant of maximal entanglement which is targeted by the adaptive controller in prototype design.

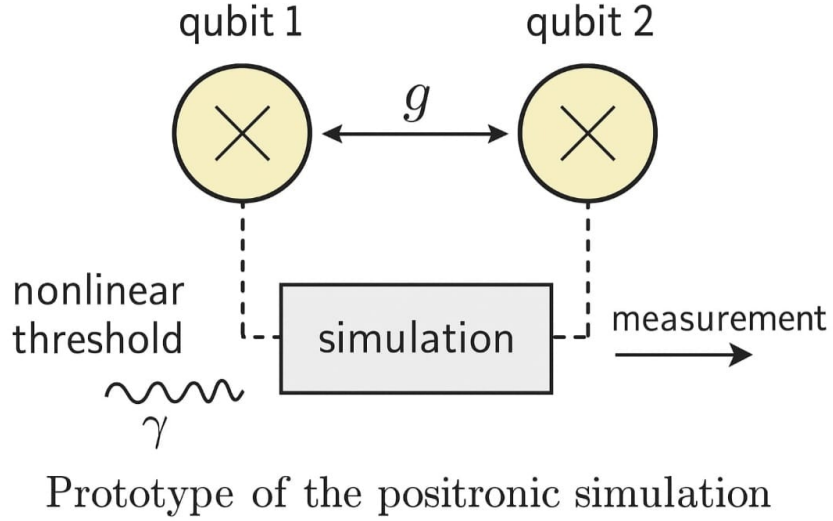


Figure 7: **Prototype schematic.** Block diagram of the proposed adaptive module: sensors $\rightarrow$ adaptive controller $\rightarrow$ resonator coupling adjuster $\rightarrow$ readout.