Optimizing Readout Fidelity in NV-Centers via Full Photoluminescence Trace Analysis

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Abstract

Realizing practical quantum computing and quantum sensing applications requires overcoming significant gate and measurement infidelities. Nitrogen-Vacancy (NV) centers in diamond offer a robust platform for these tasks due to their exceptional spin coherence and spin-dependent optical transitions. However, maximizing fidelity during state readout remains a critical bottleneck.

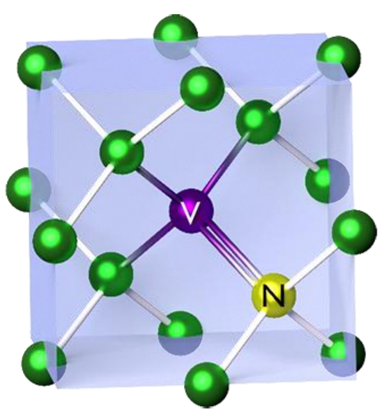
In this work, we explore several strategies to optimize the readout process beyond simple photon counting. We implement various methods based on full photoluminescence (PL) trace analysis. These methodologies are benchmarked using synthetic data designed to replicate experimental data obtained from XeedQ's NV-center-based quantum computing platform. Our results establish an upper bound for readout fidelity in experimental implementations, providing a clear pathway toward more reliable state measurement in diamond-based quantum architectures.

Main Question:
How to improve the readout quality of an NV-center based quantum computer?

- Quality of readout

MSE: $\mathrm{MSE} = \frac{1}{n}\sum_i \left(\mathrm{p}_i^{(true)} - p_i^{(meas)}\right)^2$

fidelity: $\mathrm{F} = \left(\sum_i \sqrt{\mathrm{p}_i^{(true)}\, p_i^{(meas)}}\right)^2$



- Measurements performed on
  - synthetic data produced by a "digital twin"
  - XQ1, XeedQ's NV-center based 2-qubit quantum computer prototype

Applied methods

Photoluminescence traces of four computational basis states: $|01\rangle$ and $|10\rangle$ are barely distinguishable

Fundamental equation:

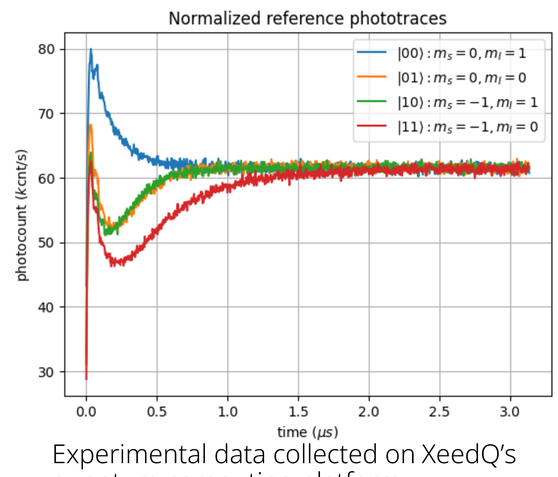
The photoluminescence trace of a state ρ is a linear combination of the pl traces of its diagonal elements:

$$\mathrm{diag}(\rho) = (p_{00}, p_{01}, p_{10}, p_{11})$$

pl trace of basis state

$$L(\rho) = \sum_{i=00,01,10,11} L_i p_i$$

pl trace of measured state



Experimental data collected on XeedQ's quantum computing platform.

Introduce flips: flip the basis states to the "bright" state ($|00\rangle$)

(PhysRevApplied.21.054041, 2024)

- No operation: no transform
- π_{MW2} pulse: $|00\rangle \leftrightarrow |10\rangle$
- π_{RF1} pulse: $|00\rangle \leftrightarrow |01\rangle$
- $\pi_{MW2} - \pi_{RF2} - \pi_{MW2}$ pulse: $|00\rangle \leftrightarrow |11\rangle$

Optimization problem:

$$\min_{\boldsymbol{p}} ||L^{(meas)} - \sum_{i=00,01,10,11} L_i p_i + \sum_{flips} L_{flip}^{(meas)} - L_{flip(i)}\, p_{flip(i)}\,||$$

How to set up parametrization?
- How many flips should be used?
- time resolved / integrated
- Which part of the pl trace to integrate?

Technical reframing of question: Which subset of flip and calibrations is the most effective?

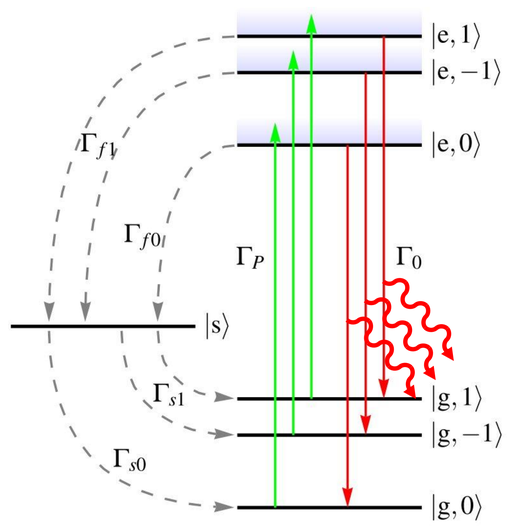
Photophysics of NV-center

2 qubit NV center spin physics under laser illumination:

Lindblad equation

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + \sum_i \Gamma_i D[A_i]\rho$$

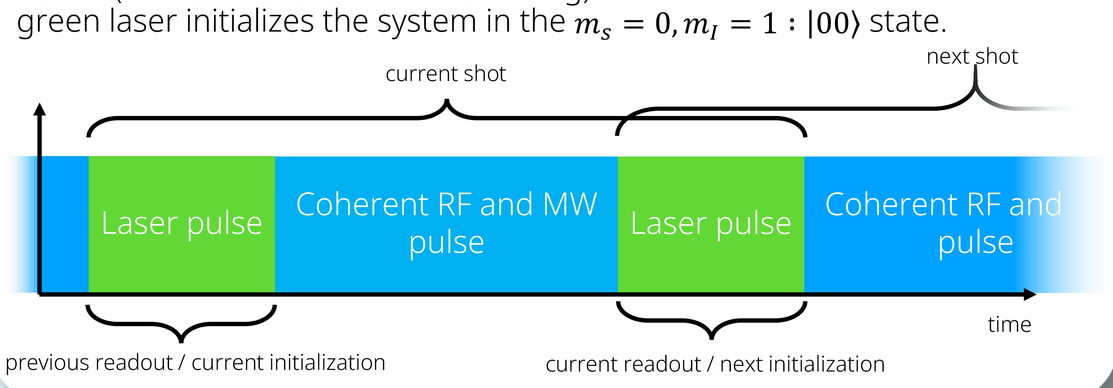
$$D[A]\rho = A\rho A^{+} - \frac{1}{2}\{A^{+}A, \rho\}$$



Hilbert-space:

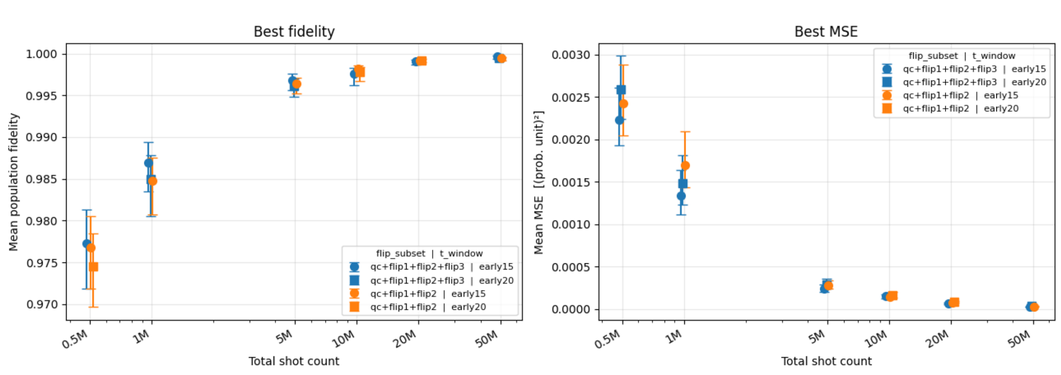
$$\underbrace{\{|g,0\rangle, |g,1\rangle, |g,-1\rangle, |e,0\rangle, |e,1\rangle |e,-1\rangle, |s\rangle\}}_{\text{Electronic spin \& orbit}} \otimes \underbrace{\{|0\rangle, |1\rangle, |-1\rangle\}}_{\text{N-14 nuclear spin}}$$

ESLAC (Excited State Level Anti Crossing):
green laser initializes the system in the $m_s = 0, m_I = 1 : |00\rangle$ state.



Results

- For noisy reference basis states: integration improves SNR ratio
- Only integrate the early section of the photoluminescence trace
- Gives an upper bound for experimental results



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