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Error attribution for singlet-triplet qubits through randomized benchmarking in the presence of temporally correlated noise

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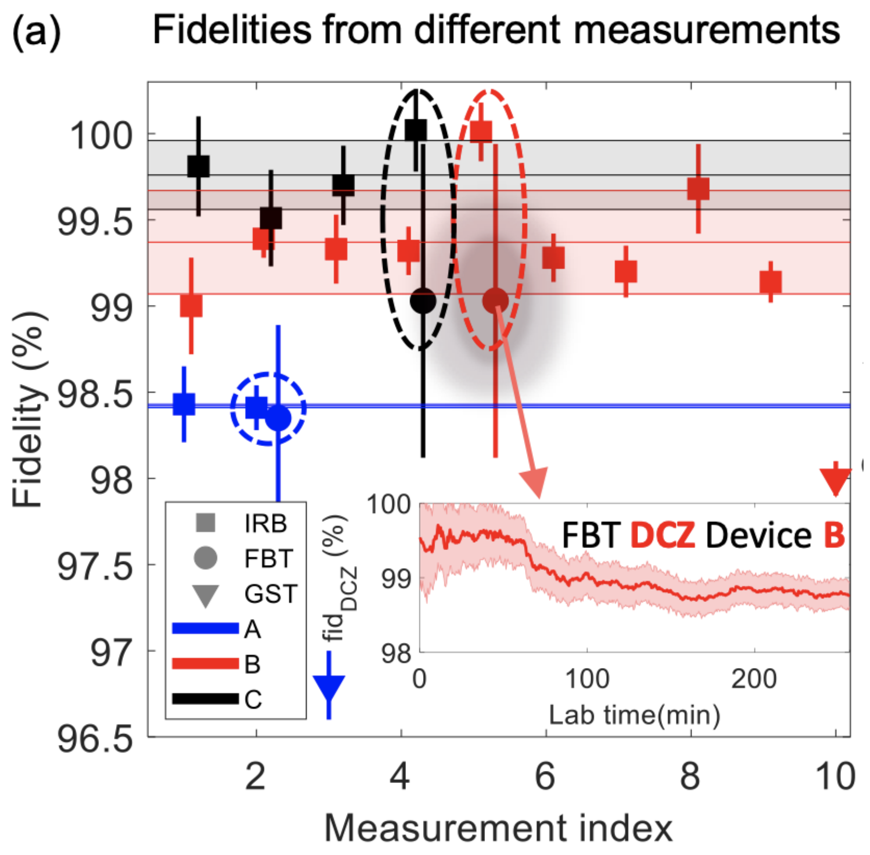
Problem statement

- Qubit fidelity can drift under noisy lab conditions
  - Correlated charge and magnetic noise present
- **Randomized benchmarking (RB) is used to quantify qubit fidelity over time**
  - Apply *L* Clifford operators + inverse

- **Can we simulate drift and use comparison with experiment to learn more about the noise itself or stress test our error models?**
  - ‘Wall-clock’ simulations: replicate laboratory conditions over complete RB experiments
    - **Maintain correlations in background noise over long timescales**
    - Efficient simulations allowing for ‘fast-forwarding’ of noise

Example of drift from Dzurak group (UNSW)



[Tanttu, et al. arXiv:2303.04090 (2023)]

System of interest

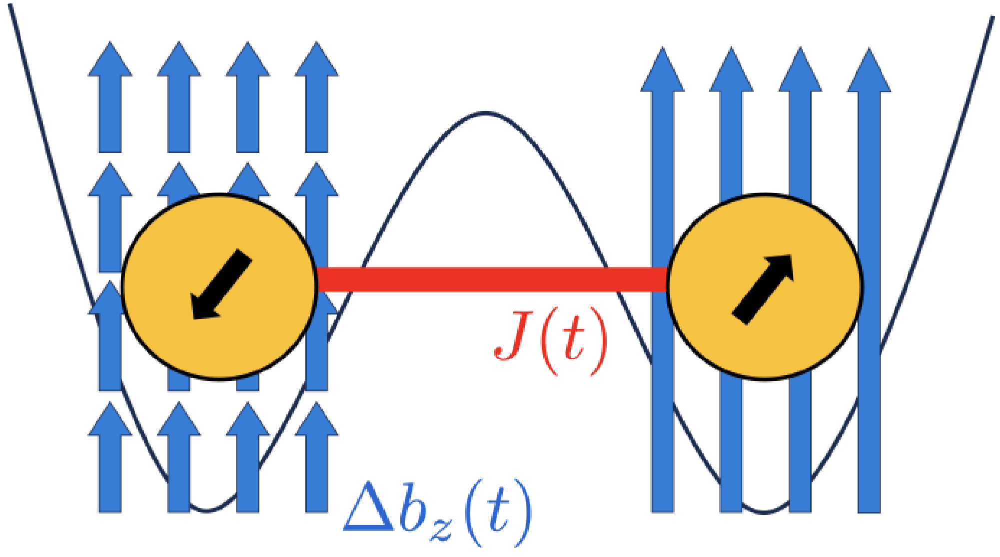
- **Single qubit in the singlet-triplet encoding**
- Hamiltonian:

$$H_{ST_0}(t) = \underbrace{J_0 e^{\alpha(V_0(t)+\overbrace{\delta V(t)}^{\text{Voltage Noise}})}}_{\text{Exchange Coupling: } J(t)} S^z + \underbrace{(\Delta b_z + \overbrace{\delta b_z(t)}^{\text{Magnetic Noise}})}_{\text{Hyperfine Splitting: } \Delta b_z(t)} S^x$$

  - Exchange coupling is a function of voltage
  - **Temporally correlated voltage and magnetic noise generate classical Hamiltonian noise**

- Unitaries are approximated as

$$U(T) \approx \prod_{k=1}^{T/\Delta t} \exp\left[-\frac{i\overbrace{\Delta t}^{\text{Sampling time } (\Delta t \sim 1\text{ns})}}{\hbar} H_{ST_0}(k\Delta t)\right]$$

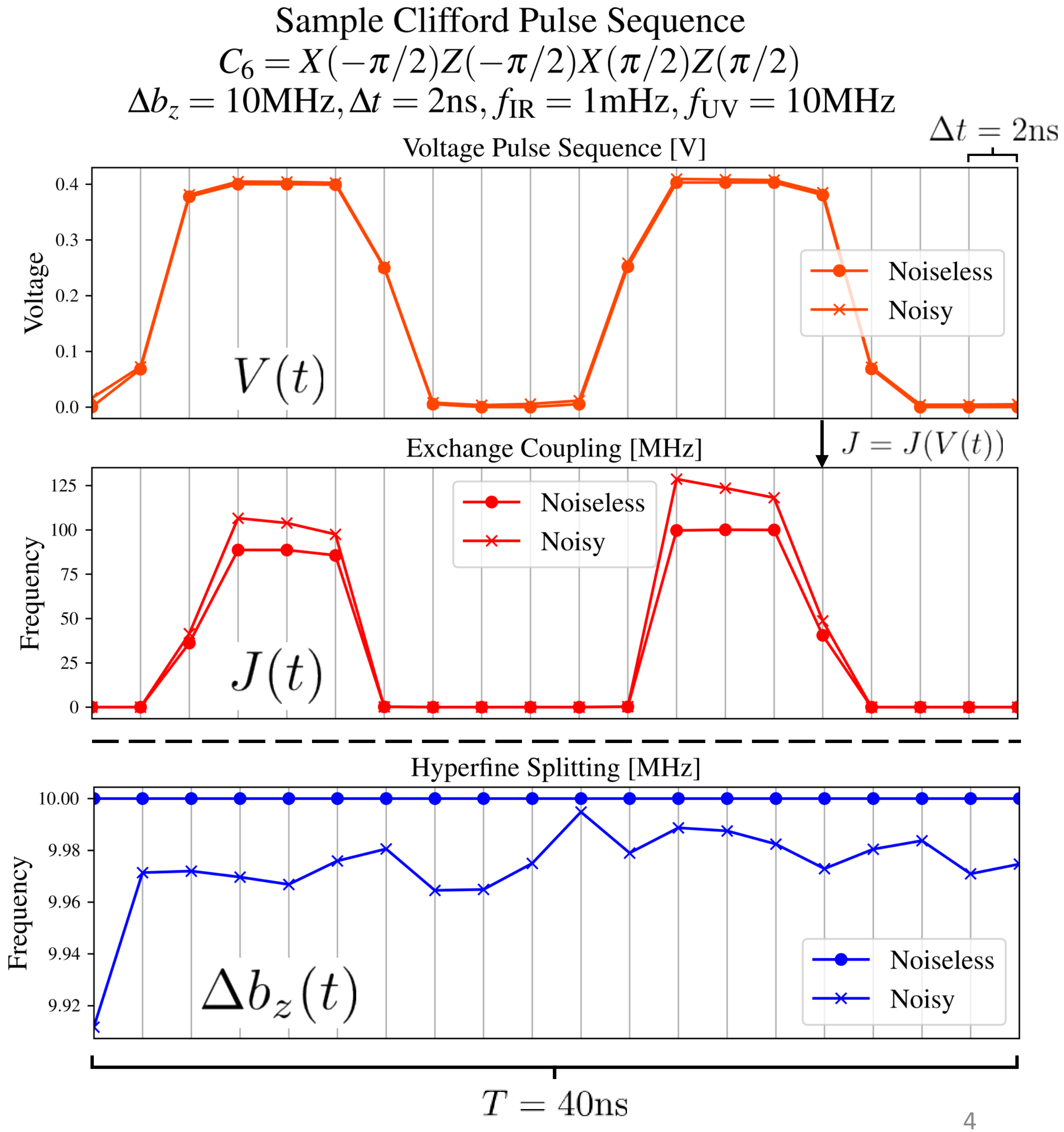


Generating voltage pulses

- **Realistic voltage pulse timings are optimized to generate Clifford operators C_i**
  - Objective function: maximize fidelity of approximated unitary with respect to target Clifford

$$\max\left(\frac{1}{4}\left|\mathrm{Tr}\left[C_i^{\dagger}U(V_0(t),\Delta b_z)\right]\right|^2\right)$$

- Pulse durations, rise/decay times, sampling times, etc. replicate pulses created by waveform generators
- Environment parameters also adjustable



Calibrating our noise model

- **Correlated noise modeled as a sum of Ornstein-Uhlenbeck processes:**

$$S(f) = \sum_j \frac{p_j f_j}{\pi(f^2 + f_j^2)}$$

p_j: Process power

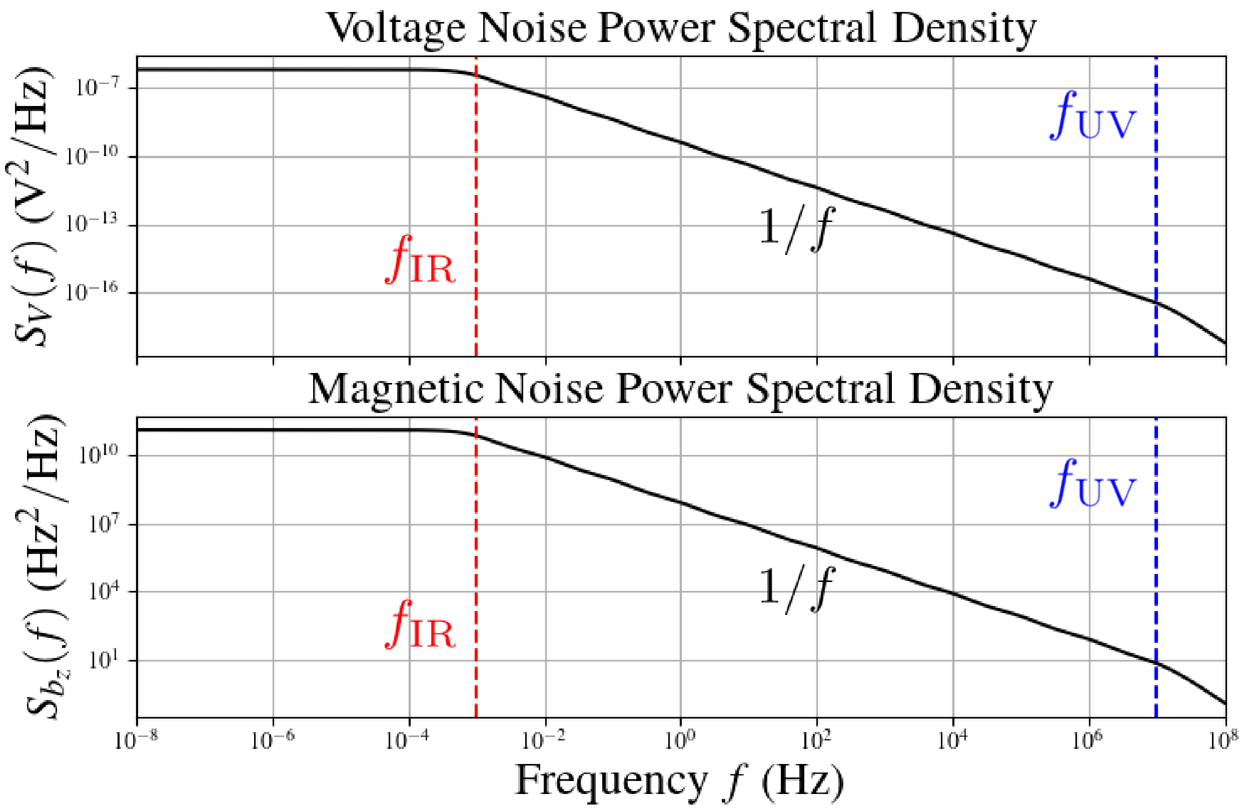
f_j: Characteristic process frequency

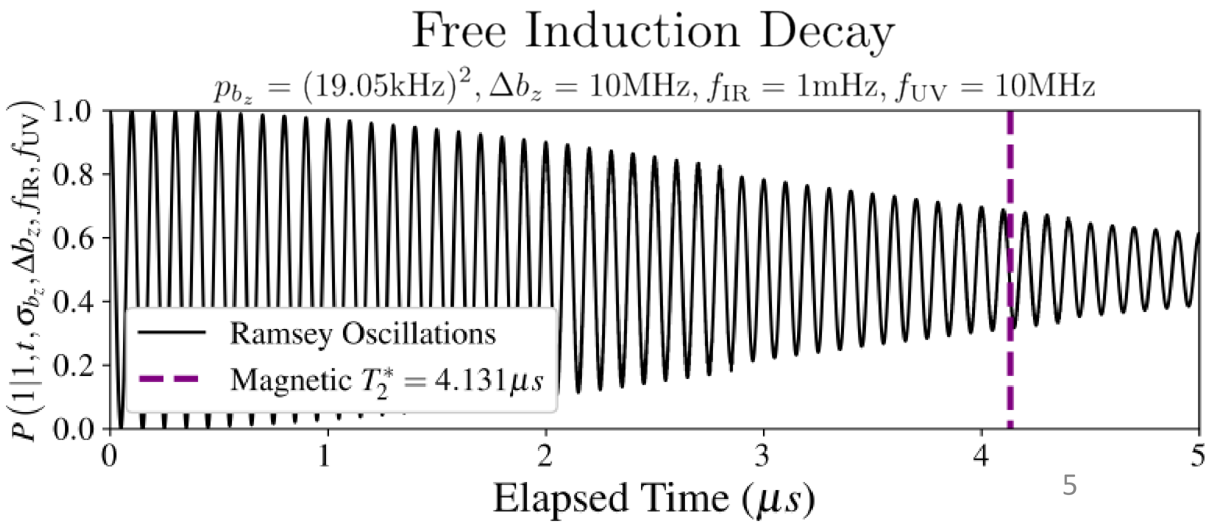
$f_{\mathrm{IR}} = \min_j f_j \qquad f_{\mathrm{UV}} = \max_j f_j$

  - Used to model 1/f power spectral density
  - **Can efficiently fast-forward noise over arbitrarily large time intervals**
  - Sampling frequency sufficiently high such that aliasing effects are negligible

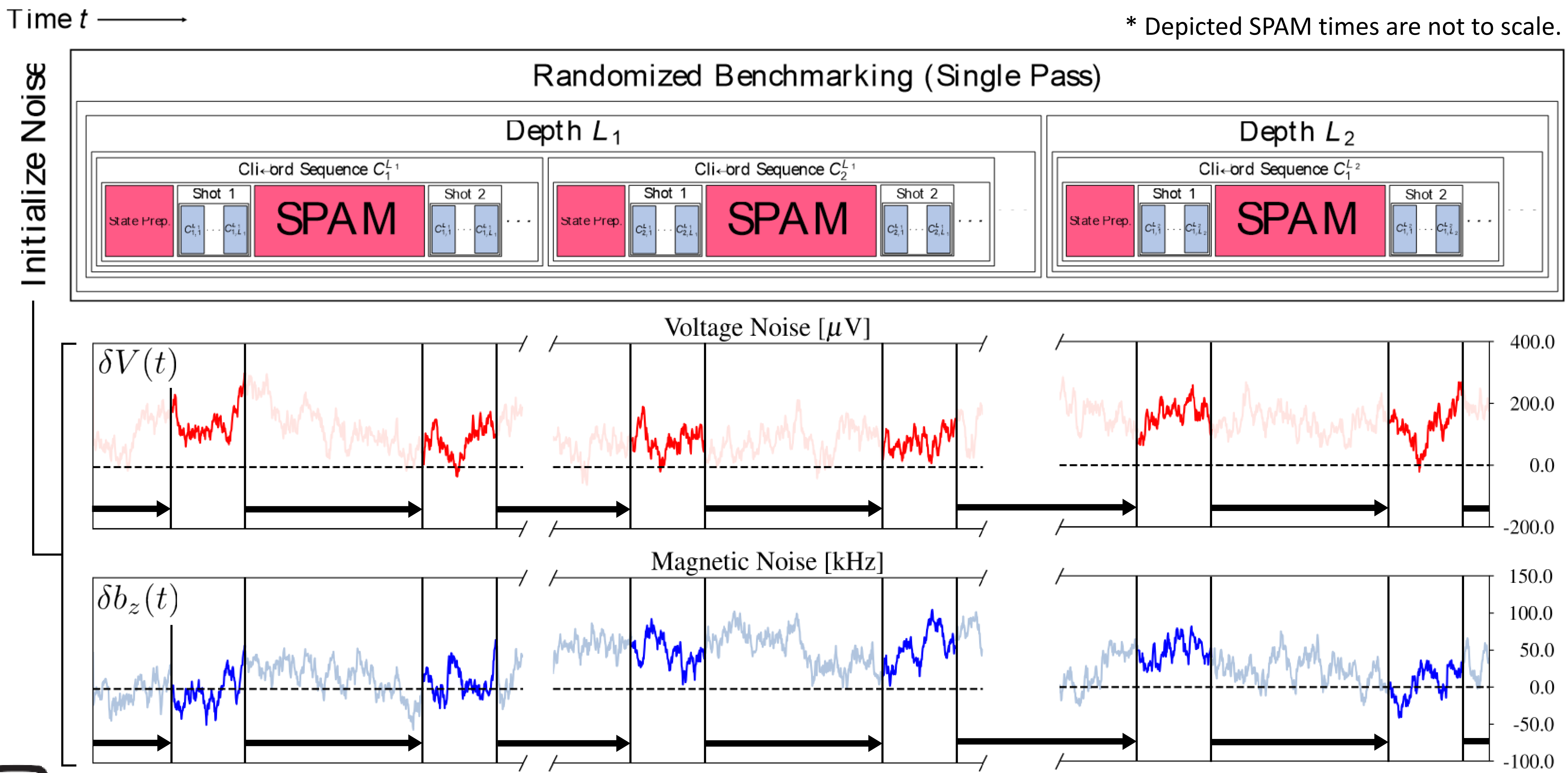
- Magnetic noise process power calibrated by matching simulated T_2^* with device measurement

Informed noise model mirrors in-lab conditions



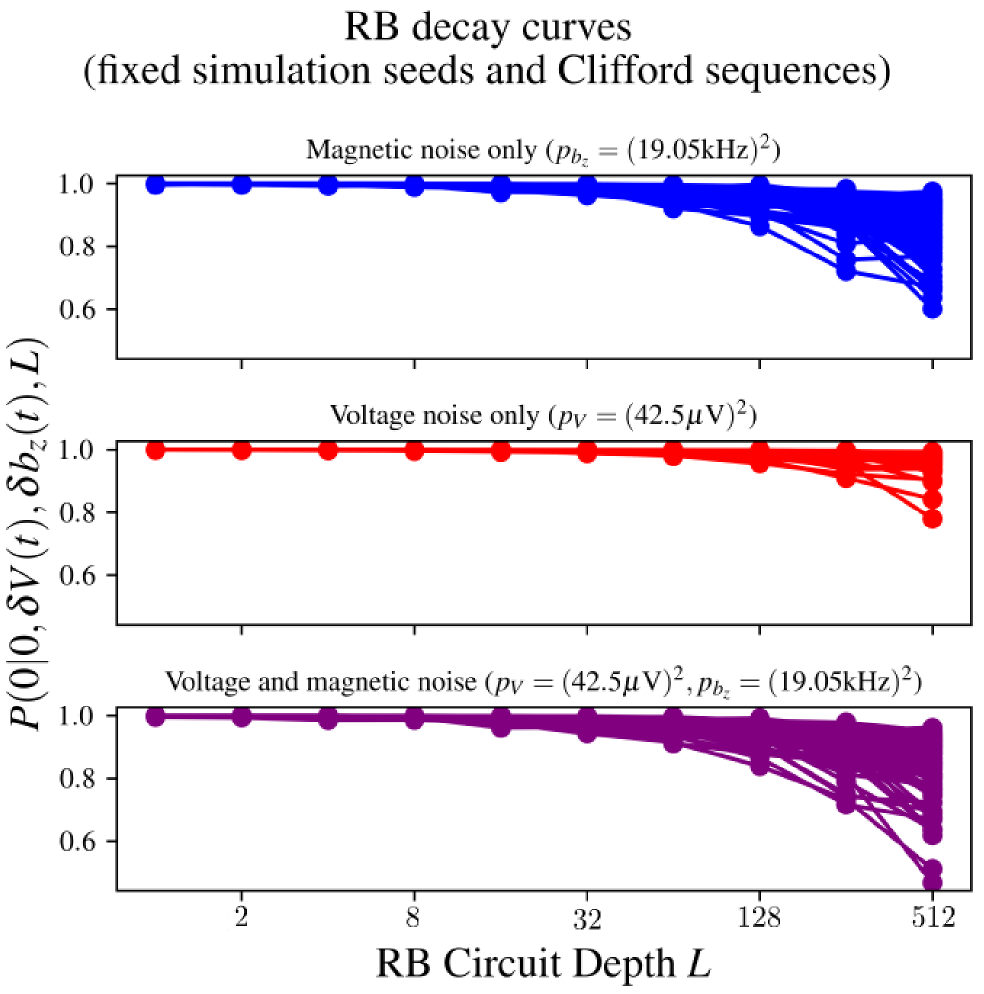


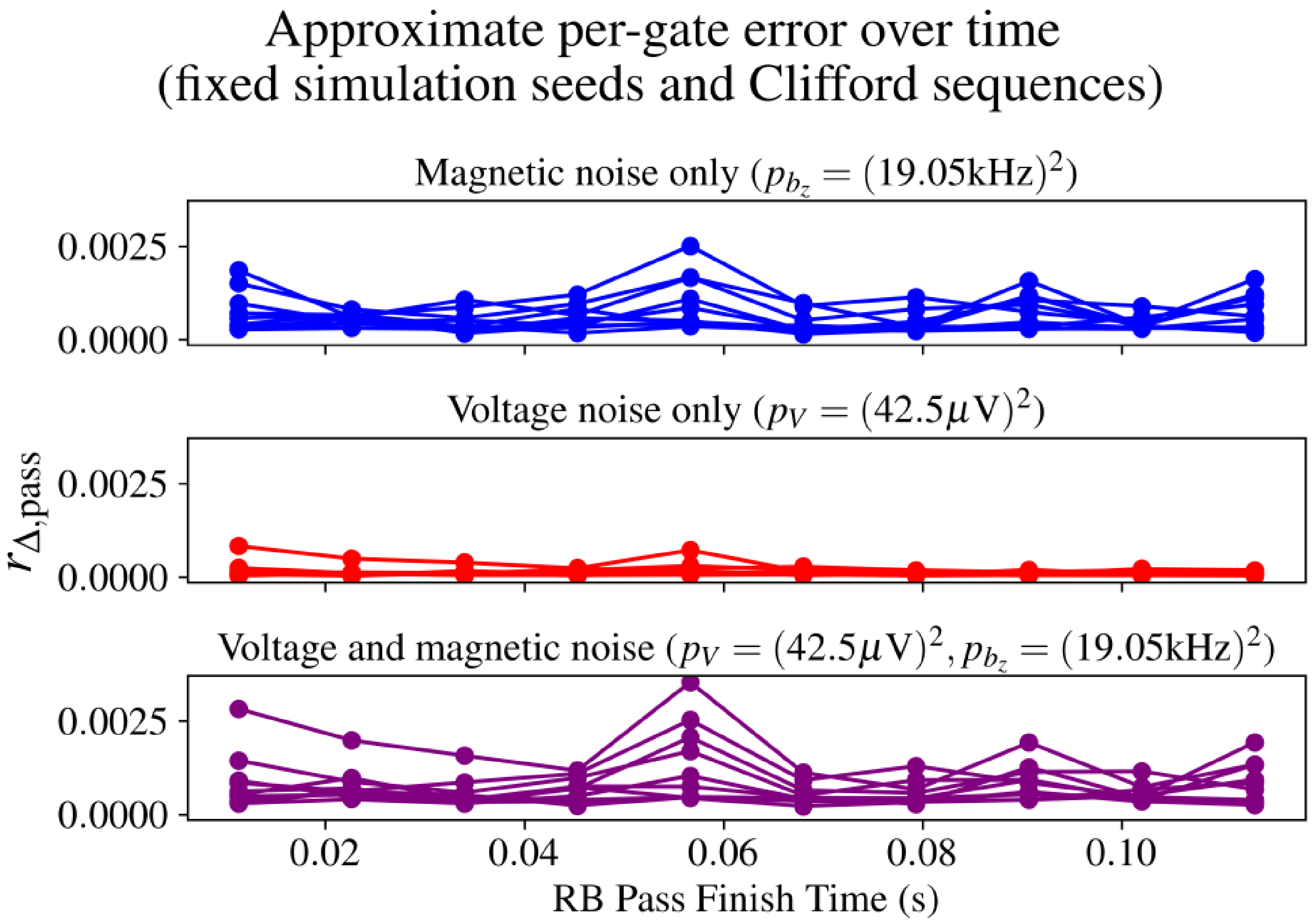
Simulated randomized benchmarking schematic



Noise can be efficiently 'fast-forwarded' during SPAM/idling periods

Simulated drift in randomized benchmarking





Drift in RB number across several experiments is captured

(Fixed $f_{\text{IR}} = 1\text{mHz}$, $f_{\text{UV}} = 10\text{MHz}$)

Error attribution based on per-circuit bitflip probabilities

- Model for characterizing circuit susceptibility to various noise sources:

$$\hat{P}(1|0, p_V, p_{b_z}, U_i) = \frac{p_V}{\alpha_i^2} + \frac{p_{b_z}}{\beta_i^2}$$

U_i: unique Clifford sequence

α_i, β_i: fit parameters (dependent on U_i)

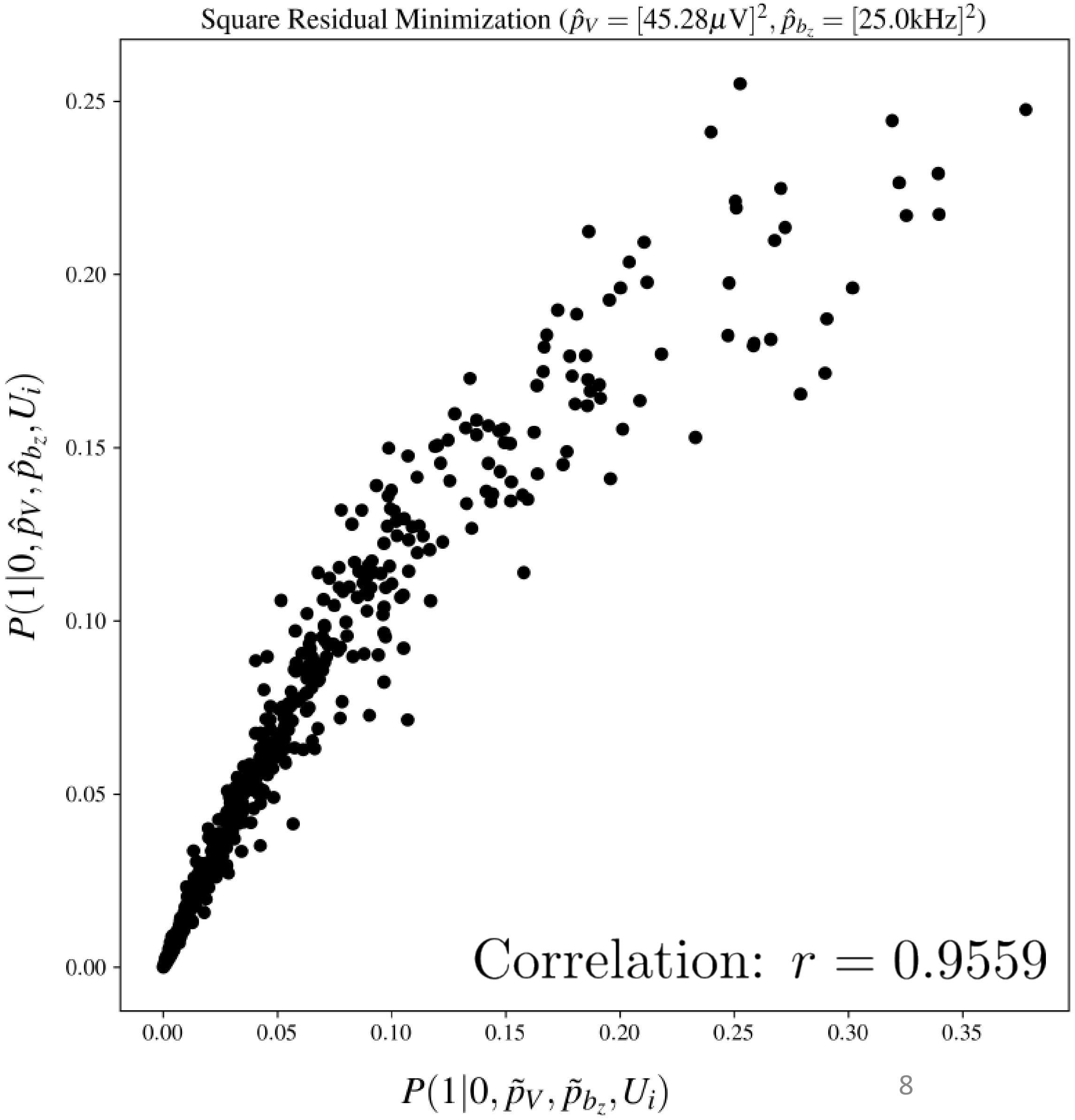
$(\tilde{p}_V, \tilde{p}_{b_z})$: unknown noise parameters

$(\hat{p}_V, \hat{p}_{b_z})$: inferred noise parameters

- Noise parameters can be estimated as

$$(\hat{p}_V, \hat{p}_{b_z}) = \underset{(p_V, p_{b_z})}{\arg\min} \sum_i \Big[\underbrace{P(1|0, \tilde{p}_V, \tilde{p}_{b_z}, U_i)}_{\text{Actual}} - \underbrace{\hat{P}(1|0, p_V, p_{b_z}, U_i)}_{\text{Estimated}}\Big]^2$$

Actual vs. predicted bitflip probabilities under inferred noise conditions $\tilde{p}_V = [42.5\mu\text{V}]^2, \tilde{p}_{b_z} = [19.05\text{kHz}]^2$



Model effectively estimates underlying noise parameters

Summary

- Singlet-triplet qubits subject to correlated noise
- **Wall-clock simulations can be used to calibrate circuit-specific bitflip probability estimators**
    - Relative sensitivity of individual Clifford sequences can be deduced from fit parameters
- **Calibrated estimators can be used to infer unknown background noise levels**

- **Developed computationally efficient means to simulate realistic device conditions across several RB experiments (lab time)**
    - Computationally cheap ‘fast-forwarding’ of *1/f* noise without losing correlations
    - Pulses, noise parameters, etc. tunable to model realistic device/laboratory conditions
    - Can capture the effects of slow drift in noise

- Future work
    - Multi-qubit analysis
    - Alternate qubit encodings (e.g., exchange-only qubit encoding)

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