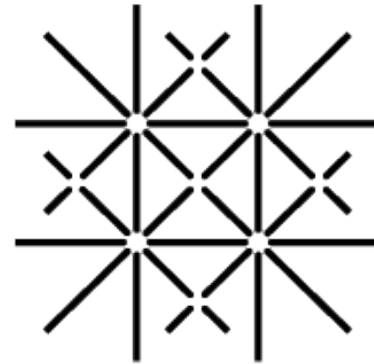


ACHIEVE HIGH-FIDELITY PARALLEL CONTROL IN SPIN QUBITS

Yang Liu
05/10/2026



**University
of Basel**

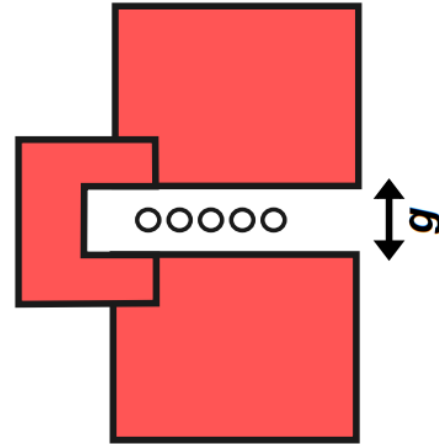
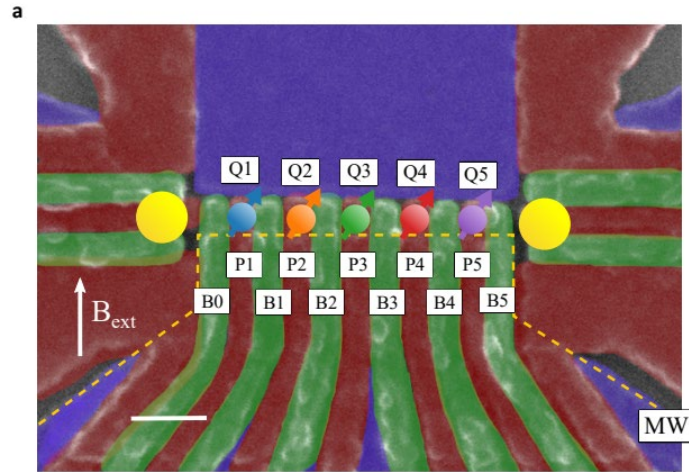
Simultaneous High-Fidelity Single-Qubit Gates in a Spin Qubit Array

Yi-Hsien Wu^{*,1,2,†}, Leon C. Camenzind^{*,1,†}, Patrick Büttler^{1,3}, Ik Kyeong Jin¹, Akito Noiri¹,
Kenta Takeda¹, Takashi Nakajima¹, Takashi Kobayashi⁴, Giordano Scappucci⁵,
Hsi-Sheng Goan^{2,6,7} and Seigo Tarucha^{1,4,†}

Problem:

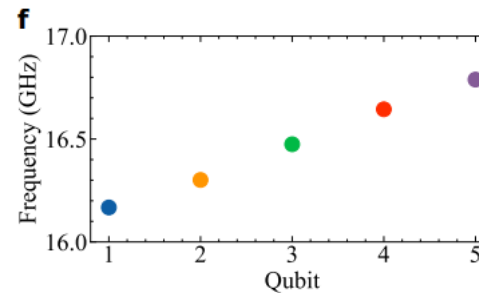
- A shared microwave line introduces off-resonant crosstalk between silicon spin qubits
- Microwave-induced AC-Stark shifts cause unwanted Z rotations
- Simultaneous driving changes the electron's displacement amplitude, causing X-rotation errors

Device and Micromagnet



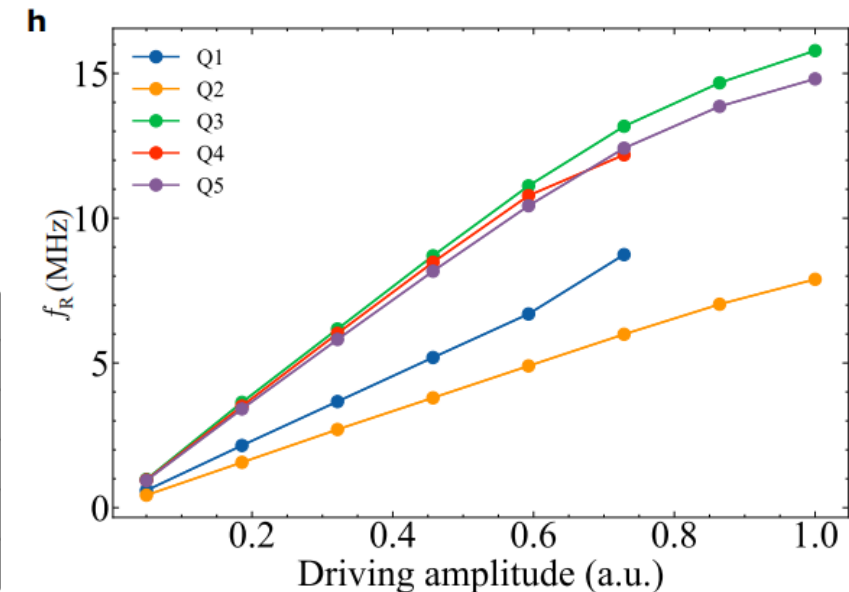
- SEM image of purified Si/SiGe QD device, 1*5 quantum dots + 2 sensors
- Microwave signals are applied to the MW screening gate
- Charge occupation: (3, 1, 1, 3, 1), increase the readout window

- The micromagnet gradient induces an approximate 150 MHz separation
- The driving amplitude shows a linear relationship for all qubits up to $f_{\text{Rabi}} \sim 8$ MHz

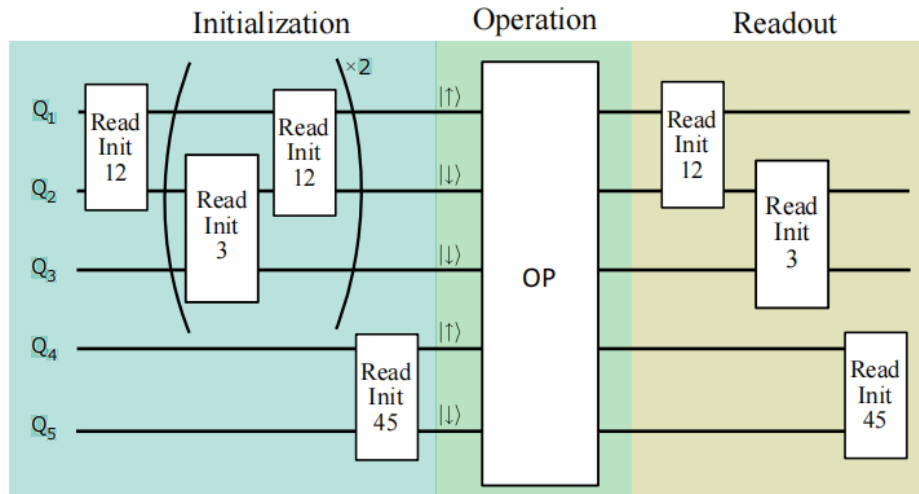


g

	T_2^* (μs)	T_2^{Hahn} (μs)
Q ₁	16.7(4)	60(2)
Q ₂	7.8(2)	36(1)
Q ₃	7.5(3)	63(3)
Q ₄	12.9(3)	97(5)
Q ₅	6.6(2)	44(2)

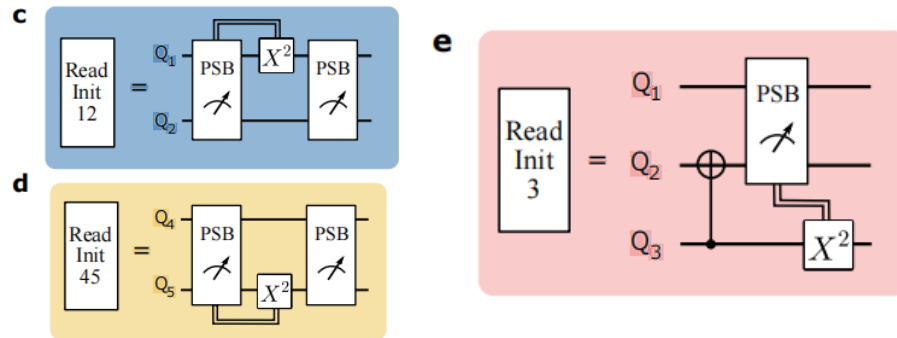


Single Qubit Operation



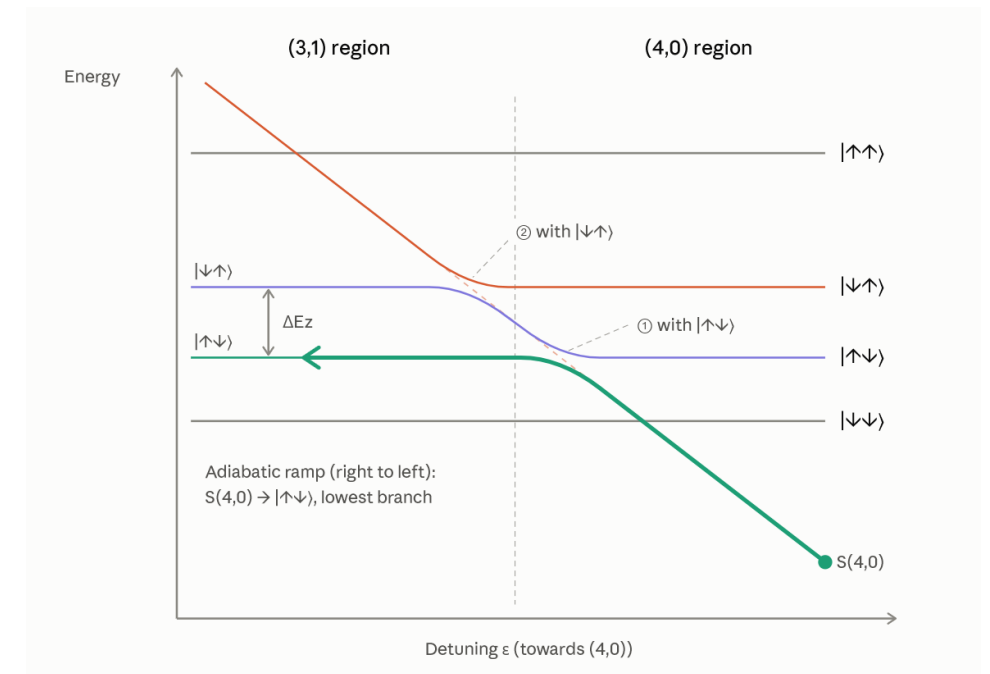
QND readout and initialization of Q3 via Q2:

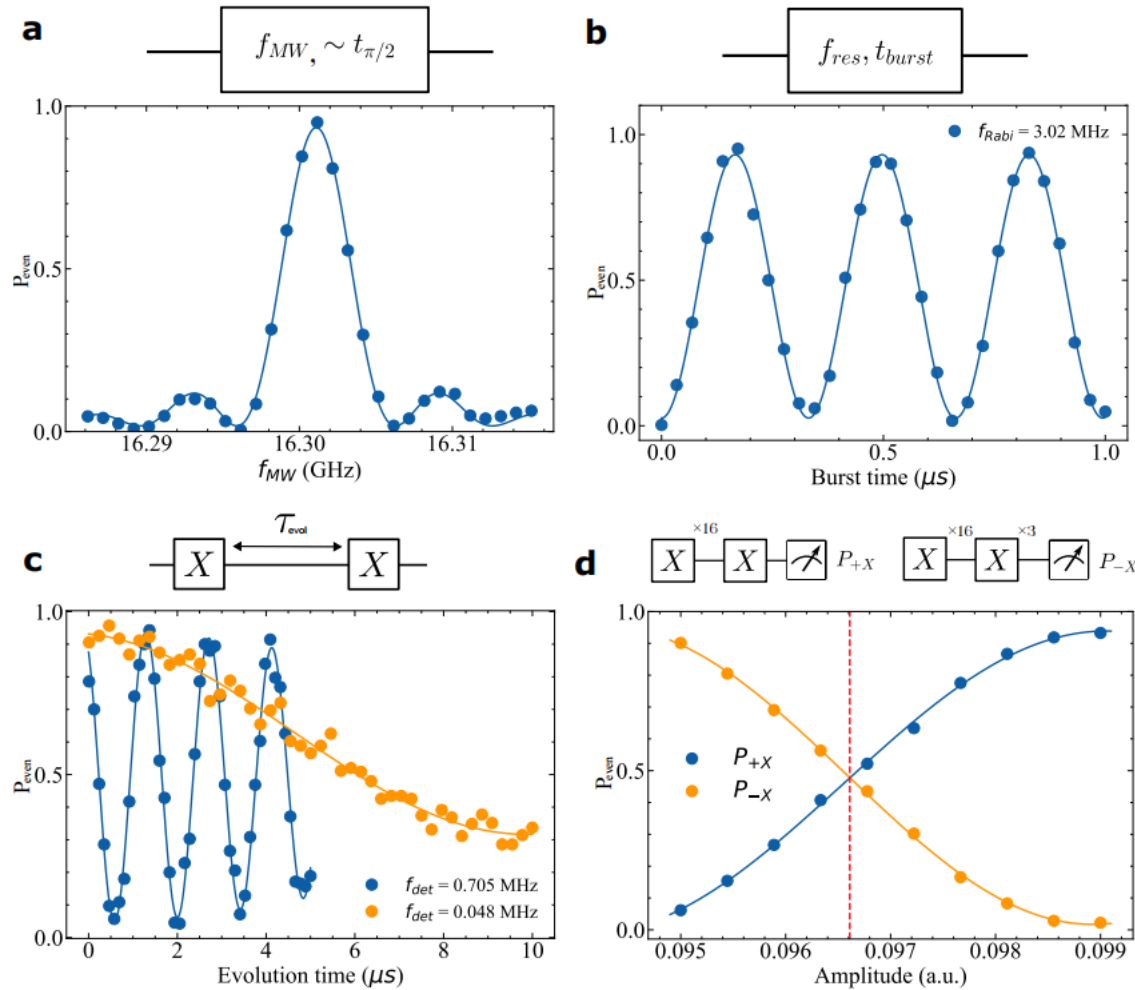
- PSB readout of Q1,2 parity
- CROT gate: Q3 controls, Q2 is the target (Q2 flips if Q3 = $|\uparrow\rangle$, unchanged if Q3 = $|\downarrow\rangle$)
- Conditional $X(\pi)$ gate prepares Q3 in the target state
- QND allows the readout to be repeated twice to boost initialization fidelity
- Initialize all five qubits to $|\uparrow\downarrow\uparrow\downarrow\rangle$ (31131) before gate operations



PSB feedback initialization (Q1,2 / Q4,5):

- First PSB readout determines parity (even/odd)
- Conditional $X(\pi)$ gate flips even-parity pairs into odd parity
- Second PSB readout projects the pair into singlet $S(4,0) \rightarrow |\uparrow\downarrow\rangle$





a. Coarse frequency tuning:

Sweep f_{MW} at fixed pulse duration to locate the resonance frequency

b. Coarse amplitude tuning:

Adjust A_{MW} to reach the target Rabi frequency f_R

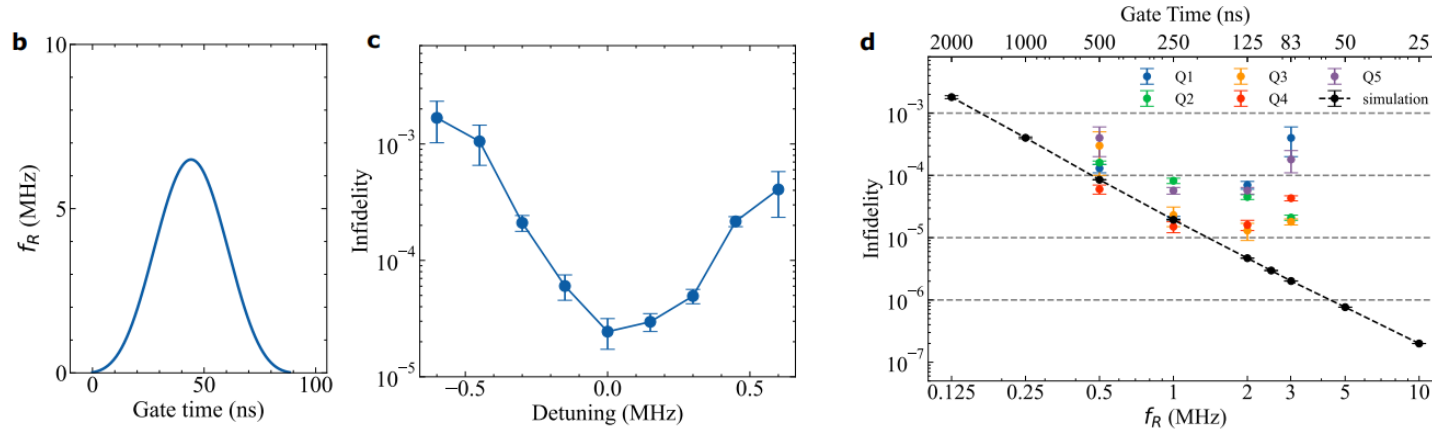
c. Fine frequency tuning (Ramsey):

- Apply intentional detuning to resolve Ramsey oscillations.
- Residual detuning reduced to 48 kHz

d. Fine amplitude tuning (error amplification)

- Apply $16 \times \pi/2$ pulses + 1 or 3 extra X pulses $\rightarrow$ rotate to $+x$ or $-x$ state
- Optimal A_{MW} until $P_{+X} = P_{-X}$

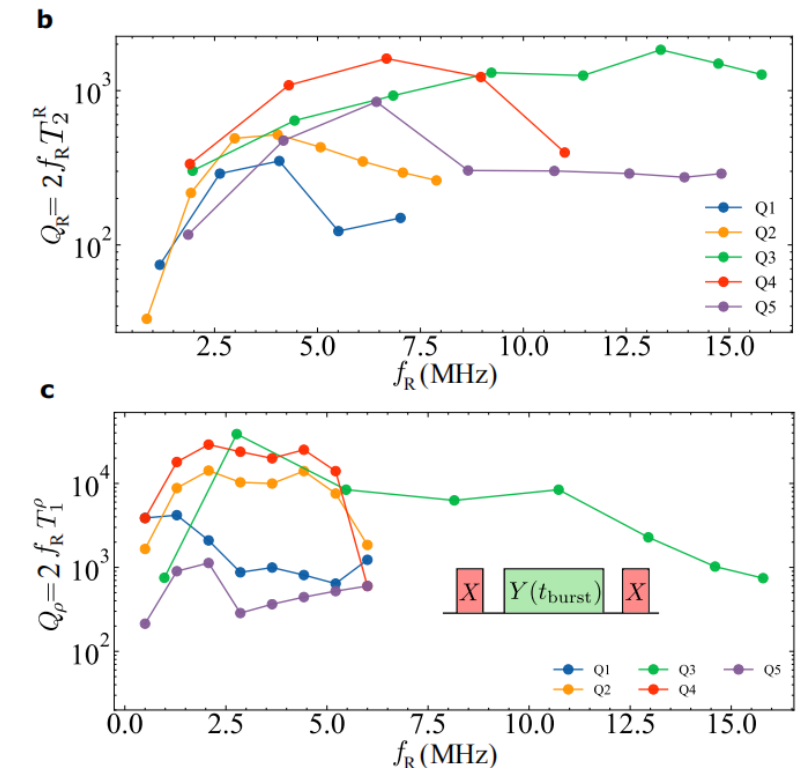
High Fidelity Single Qubit Gate

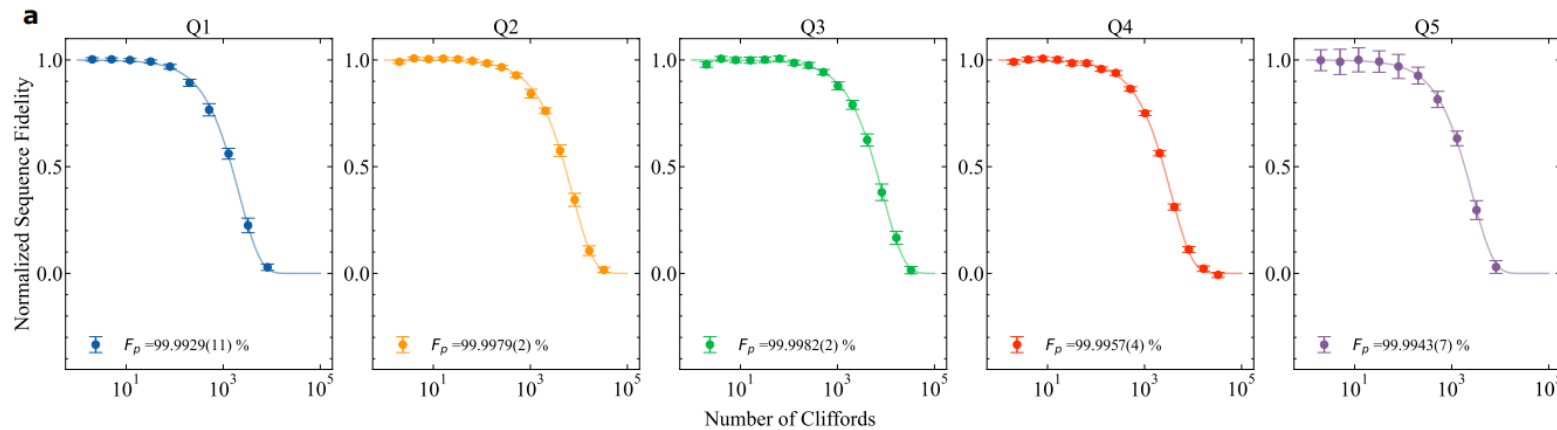


- Kaiser-window pulses suppress direct MW-drive-induced qubit-qubit crosstalk from spectral leakage
- Fidelity remains $> 99.99\%$ over ± 0.4 MHz detuning, exceeding typical charge-noise induced frequency fluctuations (0.1 MHz)
- Low f_R : charge-noise-induced dephasing dominates; high f_R : Microwave-induced noise (decoherence and heating) dominates
- The simulation includes dephasing noise measured under idling conditions $1 - F \propto t_g^2$, fits well in low gate speed region

Sweet spot for driving:

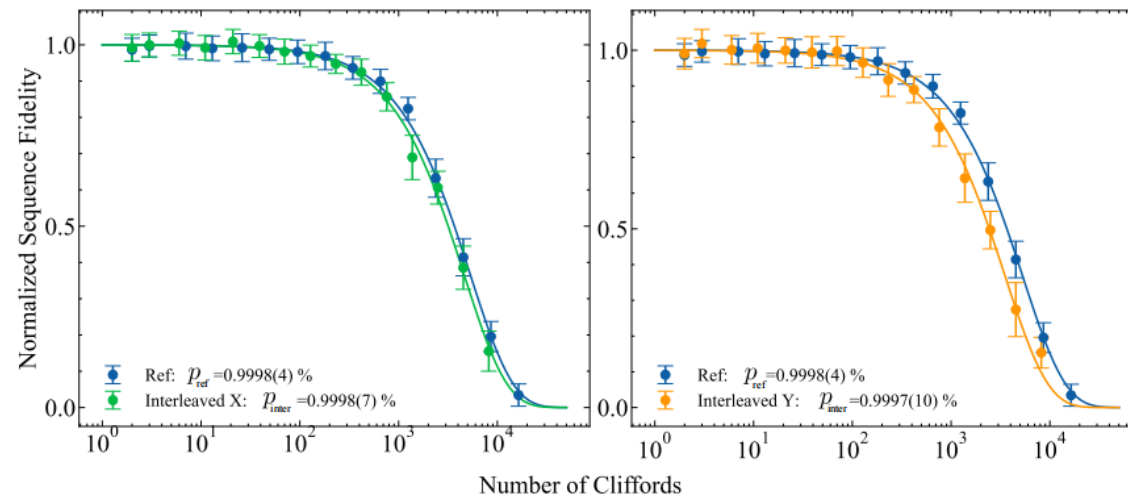
- Rabi quality factor $Q_R = 2f_R T_2^R$
How many X rotation it can do before decoherence
- Spin-lock quality factor $Q_\rho = 2f_R T_1^\rho$
Decoherence induced by driving itself





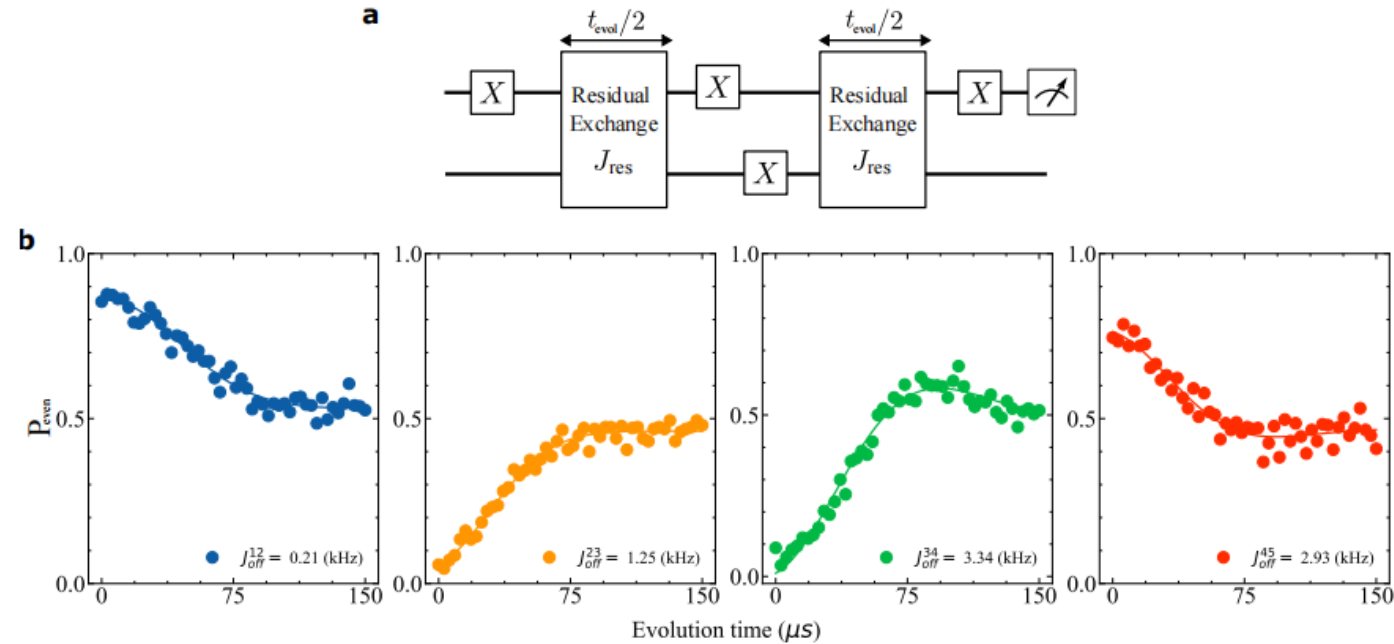
Single-qubit randomized benchmarking (RB):

- Individually address all five qubits through a shared microwave line
- X and Y rotations differ only in the phase of the IQ-generated microwave signal
- Achieve primitive X , Y gate fidelities $F > 99.99\%$ for all qubits



Interleaved RB: X and Y gates:

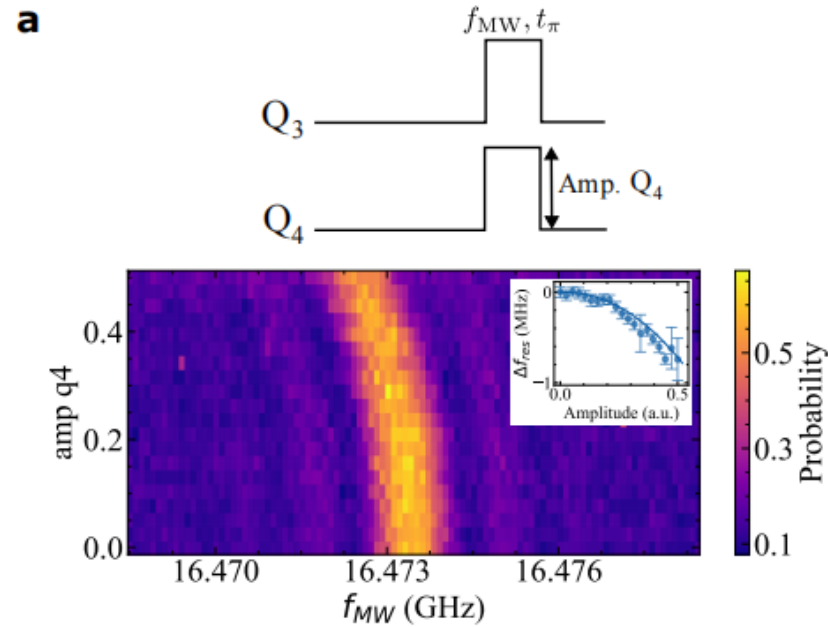
- Both gates achieve fidelities $F > 99.99\%$
- Confirms high fidelity for both rotation axes



$$H = \frac{\delta_1}{2} \sigma_z^{(1)} + \frac{\delta_2}{2} \sigma_z^{(2)} + \frac{J}{4} \sigma_z^{(1)} \sigma_z^{(2)}$$

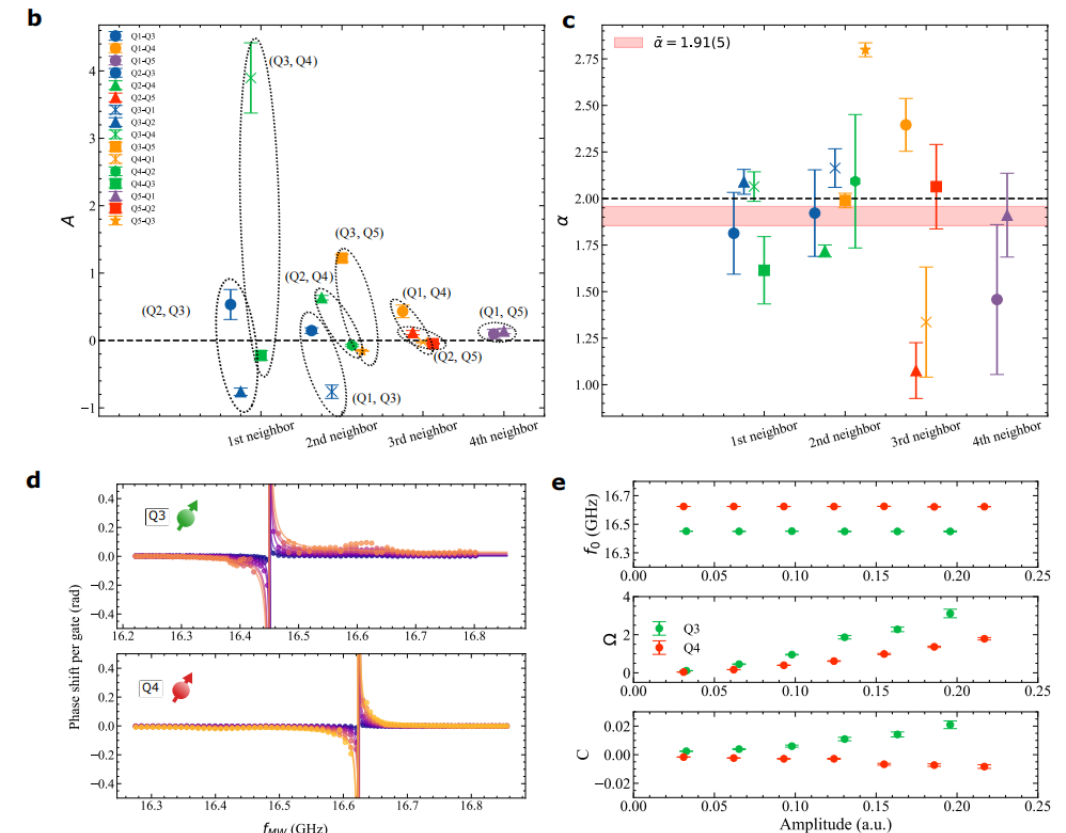
- Interleaved π pulses refocus dephasing while preserving the exchange-induced phase
- No coherent oscillations are observed within the $\sim 30 \mu s$ echo coherence time for any of the four qubit pairs
- Upper bound of residual exchange $J_{off} < 16.6 \text{ kHz}$

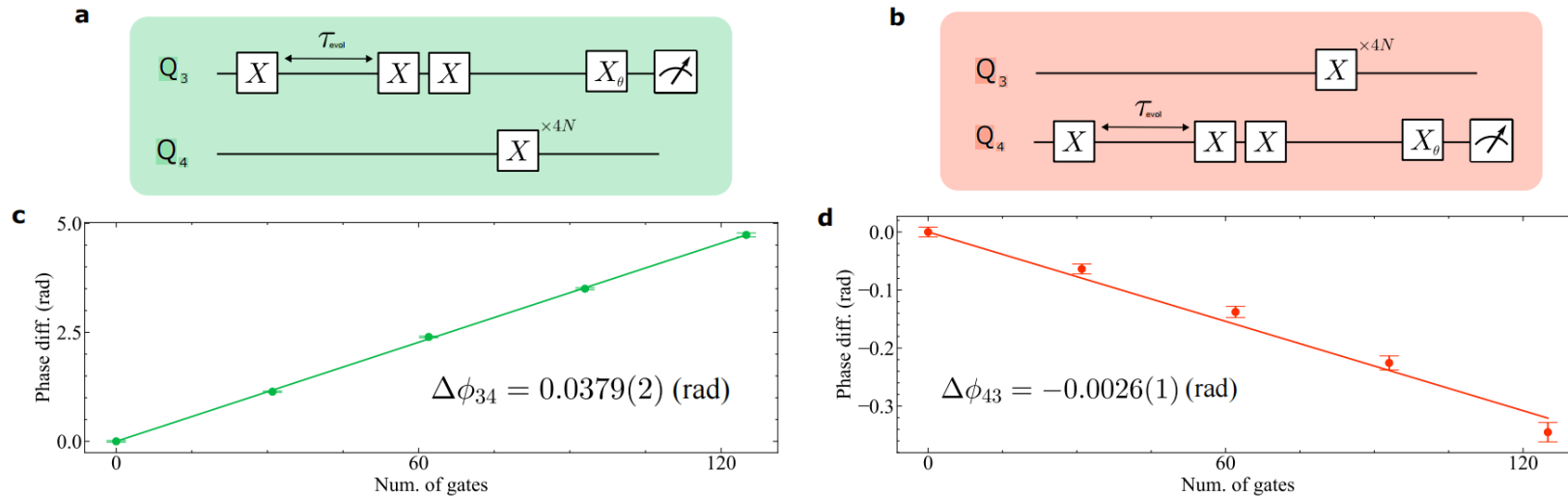
AC stark shift: Z error



- Fit with $A \cdot V_{amp}^\alpha$ for each qubit pairs
- Average exponent $\alpha = 1.91(5)$ agrees with quadratic AC-Stark scaling
- The phase is positive for a higher-frequency driven qubit and negative for a lower-frequency one
- Sweep a second drive tone across resonance; the phase shift reverses sign across resonance
- $\Delta\phi_z \propto \frac{\Omega^2}{f_{MW} - f_0} + C$

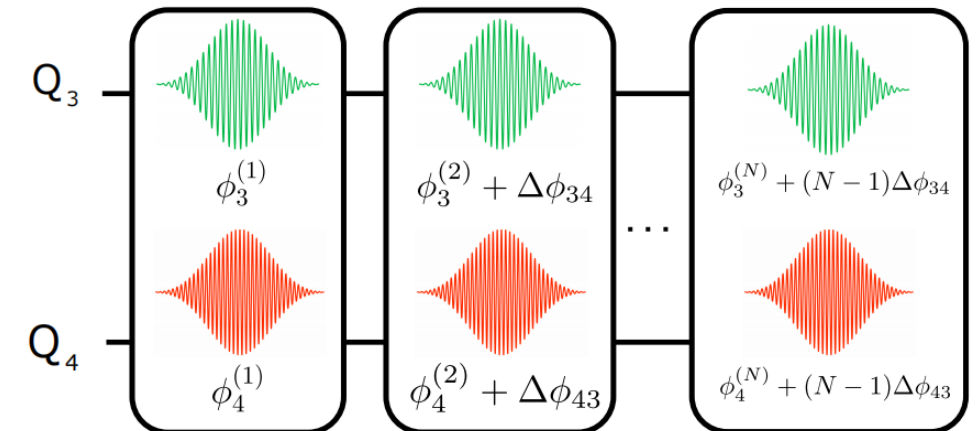
- Amplitude dependence of crosstalk-induced phase shifts between qubit pairs
- $H = \frac{\hbar f_0}{2} \sigma_z + \frac{\hbar \delta f}{2} \sigma_z, \Delta\phi_z = 2\pi \delta f t$
- Simultaneous Q4 drive (X^2 gate): Q3's resonance shifts by **-0.8 MHz**



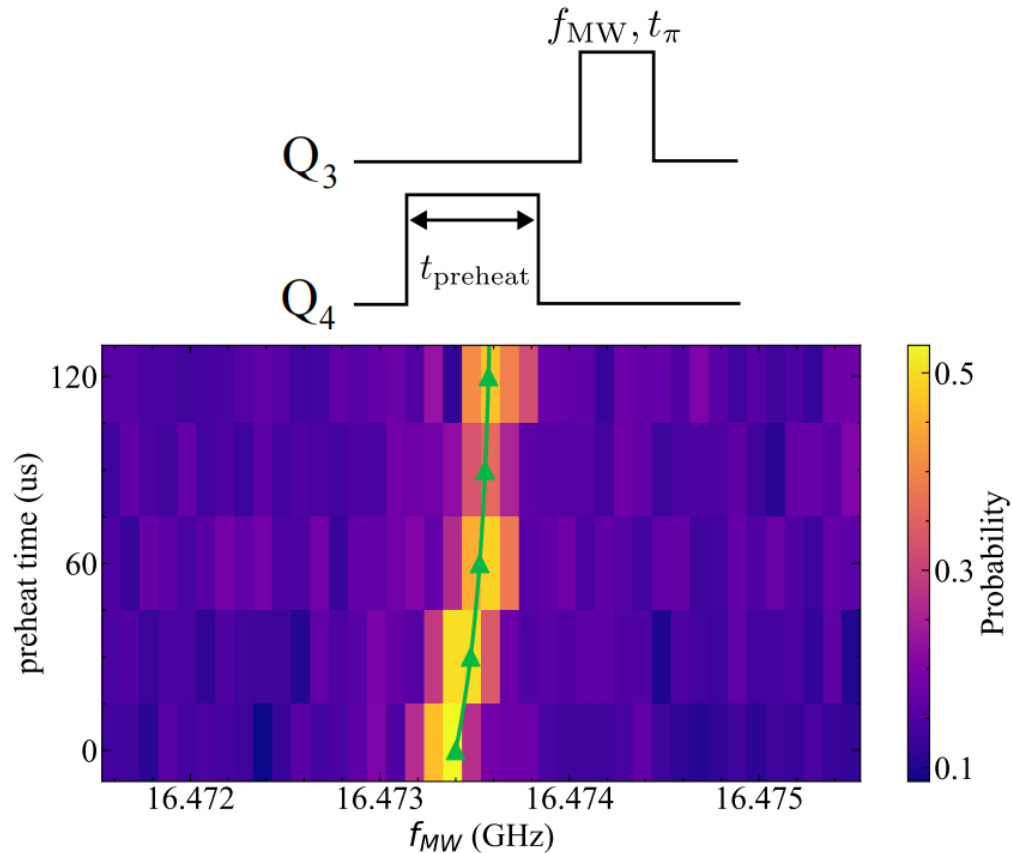


Measuring crosstalk phase:

- Hahn-echo on target qubit + $4N$ repeated X gates on the other qubit
- Asymmetric phase difference comes from different drive power for each qubit $\Delta\phi_z \propto \frac{\Omega^2}{f_{\text{MV}} - f_0} + C$
- Crosstalk phase compensated by shifting MW phase on each subsequent pulse: $\phi_i^{(n)} = \phi_i^{(1)} + (n-1)\Delta\phi_{ij}$



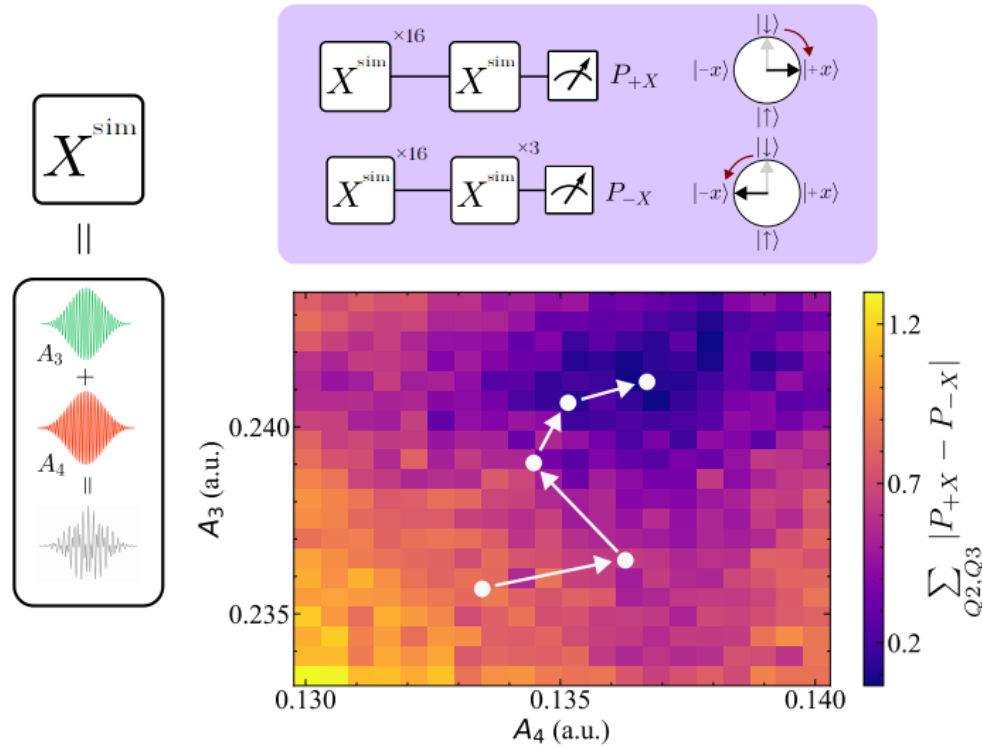
MW-Heating Induced Frequency Shift: X error



- Drive Q4 before probing Q3 to isolate residual frequency shifts consistent with heating
- $T_{\text{mc}} = 120$ mK, matching the RB experimental conditions, frequency shifts reduce
- Q3's resonance shifts by **0.22 MHz** ($f_{\text{Rabi}} = 3$ MHz) after $120 \mu\text{s}$, fitting $f(t) = f_0 + \Delta f_{\text{max}}(1 - e^{-t/\tau})$, $\tau = 60 \mu\text{s}$
- The smaller shift compared with the **0.8 MHz** AC-Stark shift supports heating as a secondary contribution

Pairwise Amplitude Calibration

f

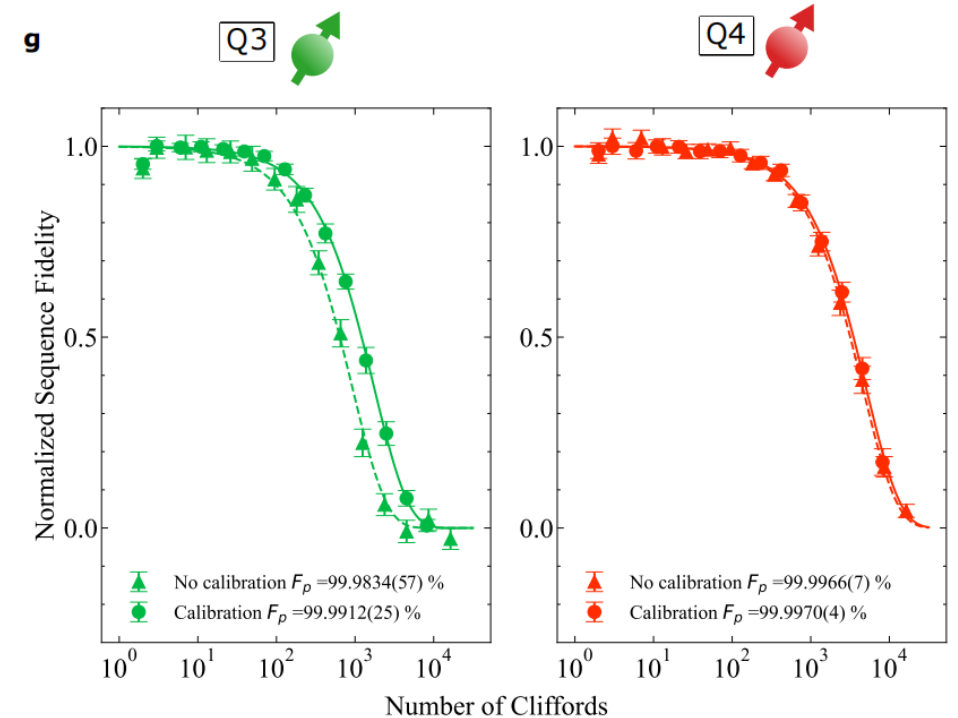


Two-Qubit SRB:

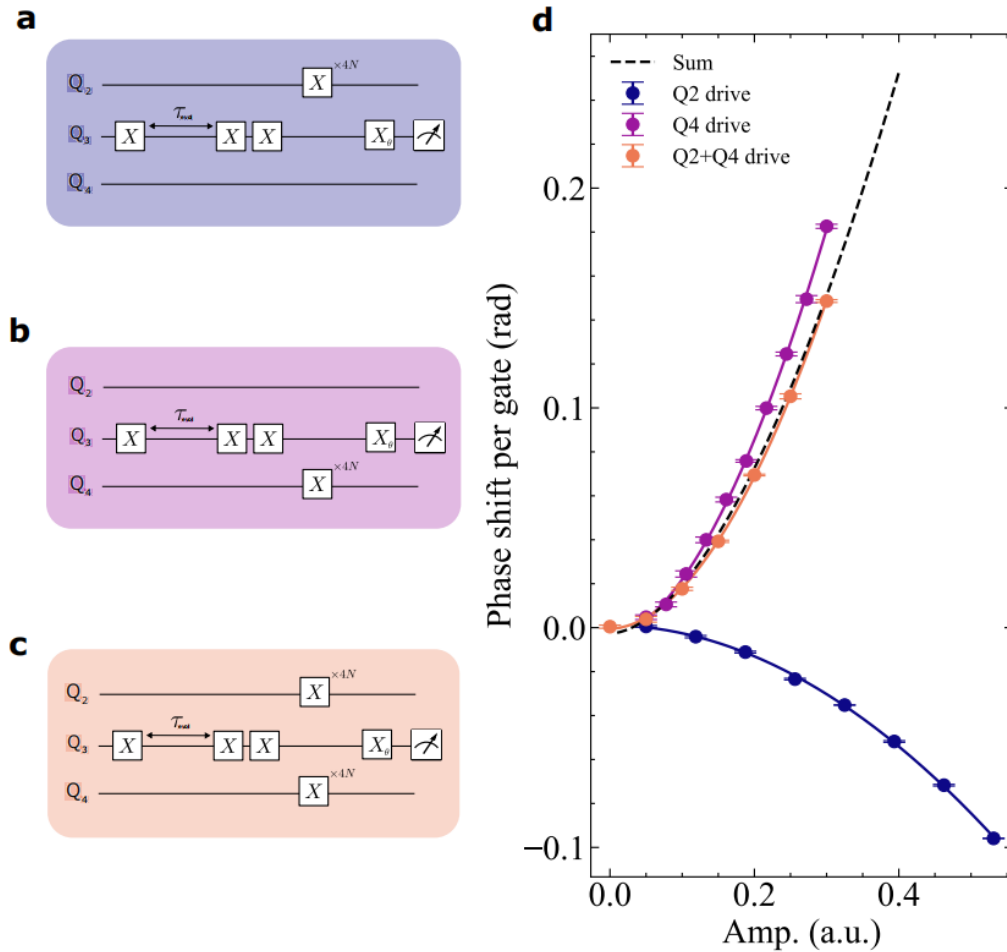
- Without calibration: Q3 reaches 99.9%, while Q4 exceeds 99.99%
- Asymmetric crosstalk: the larger $\Delta\phi_{34}$ limits Q3's uncalibrated fidelity, while the smaller $\Delta\phi_{43}$ leaves Q4 less affected
- With calibration: both qubits exceed 99.99%

Amplitude Calibration:

- Apply 16 X gates followed by 1 or 3 additional pulses to prepare $|+x, +x\rangle$ or $|-x, -x\rangle$
- At optimal amplitude $P_{+X} = P_{-X}$
- Optimize (A_3, A_4) by minimizing $\sum |P_{+X} - P_{-X}|$



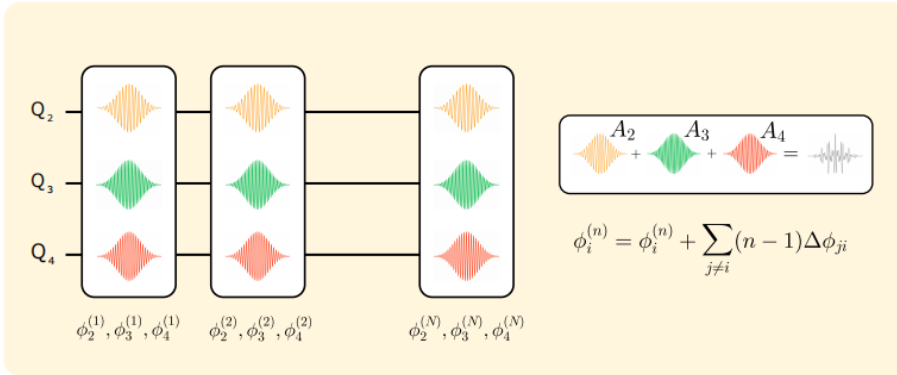
Validating Linear Superposition of Crosstalk



- Measure the crosstalk phase on Q3 while driving Q2, Q4, or both
- The sum of individually fitted phases matches the simultaneous-drive data
- Crosstalk phase can be measured pairwise and summed linearly without detectable higher-order effects

Three-Qubit Calibration and SRB

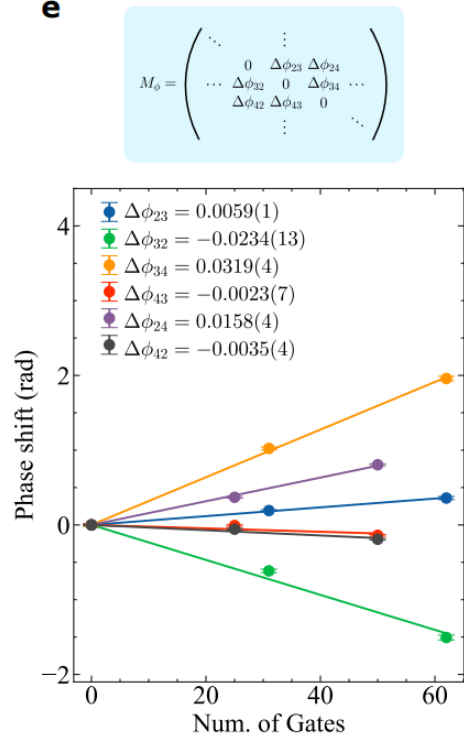
f



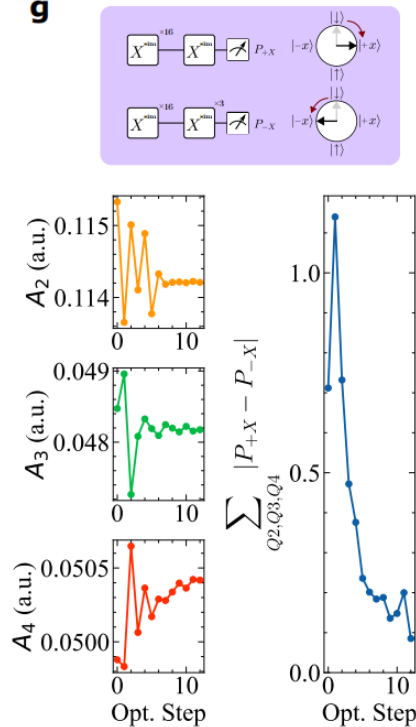
Extending to three qubits (Q2, Q3, Q4):

- Measure all pairwise crosstalk phases $\Delta \phi_{ij}$ individually
- Compensate each qubit's phase by summing contributions from simultaneously driven partners: $\phi_i^{(n)} = \phi_i^{(1)} + \sum_{j \neq i} (n-1) \Delta \phi_{ij}$
- Jointly optimize (A_2, A_3, A_4) , converging within ~ 10 iterations

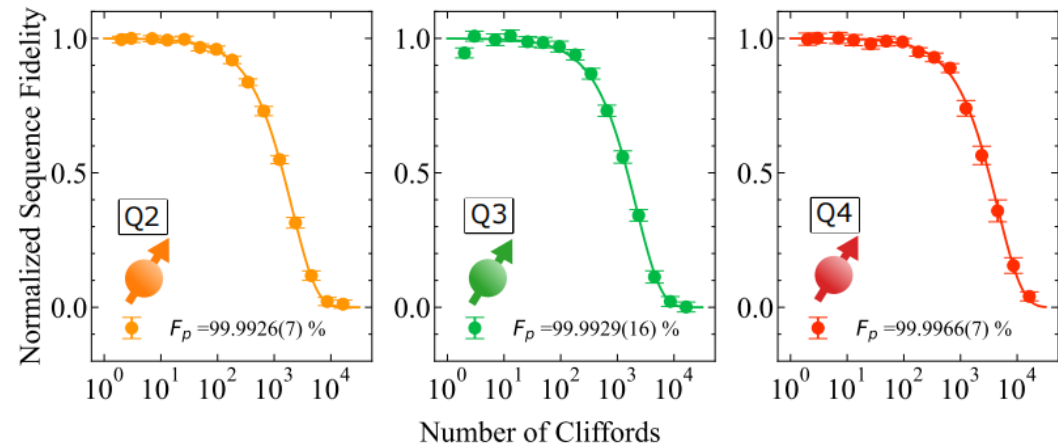
e



g



h

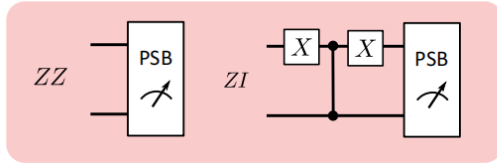


Three-qubit SRB:

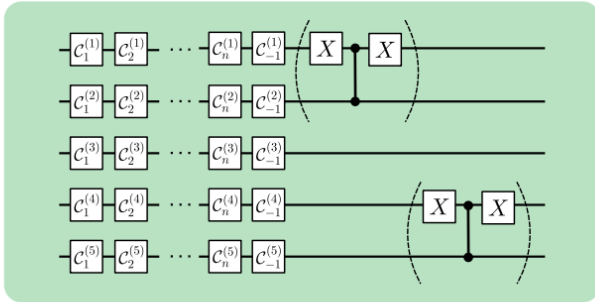
- Primitive $\pi/2$ gate fidelities exceed 99.99% for all three qubits
- Pairwise calibration extends beyond two qubits

Five-qubit simultaneous operation

a



b



$$P_{\uparrow\uparrow} = (s_{ZZ} > v_{\text{thres}}) \& (s_{ZI} > v_{\text{thres}}),$$

$$P_{\downarrow\uparrow} = (s_{ZZ} < v_{\text{thres}}) \& (s_{ZI} < v_{\text{thres}}),$$

$$P_{\uparrow\downarrow} = (s_{ZZ} < v_{\text{thres}}) \& (s_{ZI} > v_{\text{thres}}),$$

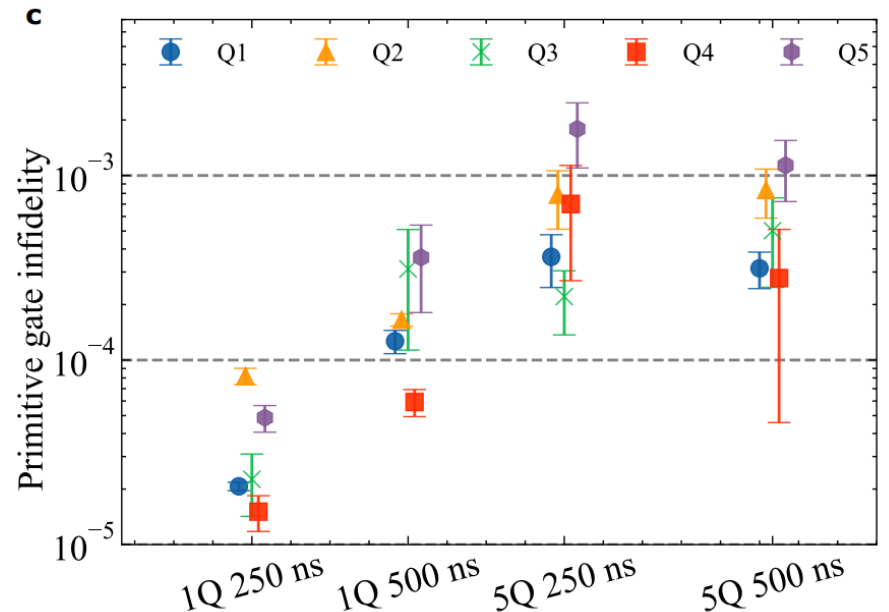
$$P_{\downarrow\downarrow} = (s_{ZZ} > v_{\text{thres}}) \& (s_{ZI} < v_{\text{thres}}).$$

Reconstruct the full five-qubit state:

- Each cycle yields only 3 bits (2 parity + 1 QND), insufficient for individual readout in five-qubit SRB
- Repeat the sequence with two readout settings: ZZ (direct PSB) and ZI (CNOT before PSB)
- Combine both settings to extract each qubit's individual spin-up probability

Competing error mechanisms:

- $t_g = 250$ ns: higher microwave power increases microwave-induced noise and heating
- $t_g = 500$ ns: lower power but longer gate duration increases dephasing
- Both yield similar fidelities: four qubits exceed 99.9%; Q5 reaches ~99.9%
- Total microwave power appears to limit performance, suggesting comparable fidelity may be achievable for ten qubits at $t_g = 500$ ns



Key finding & method:

- Microwave-induced AC-Stark shifts dominate crosstalk
- Pairwise calibration requires only $N(N - 1)$ calibrations

Gate fidelities:

- Single qubit & 3-qubit parallel > 99.99%
- 5-qubit parallel gates: four qubits > 99.9%; Q5 > 99.5%

Limit & outlook:

- Fast gates increase microwave-induced decoherence; slow gates increase dephasing
- Improved micromagnets could enable faster, lower-power gates approaching 99.999%
- Comparable total microwave power may enable ten-qubit operation at 500 ns