Tunable inductive coupler for high-fidelity gates between fluxonium qubits

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Why inductively coupled fluxonium?

- $\alpha > 4GHz$ and atomic-like structure
- $\langle 0|\hat{\varphi}|1\rangle \gg \langle 0|\hat{n}|1\rangle$ achieves $g > 15MHz$
- dielectric limited Q: $\omega_{01} \downarrow \Rightarrow T_1 \uparrow$
- Strong, fast gates and long qubit coherences $\Longrightarrow$ **> 99.9% 2Q gate fidelity**

2Q device Hamiltonians

$$\mathcal{H}_f = -4E_C \frac{d^2}{d\varphi^2} - E_J \cos(\varphi) + \frac{1}{2}E_L\left(\varphi + 2\pi\frac{\Phi_{ext}}{\Phi_0}\right)^2$$

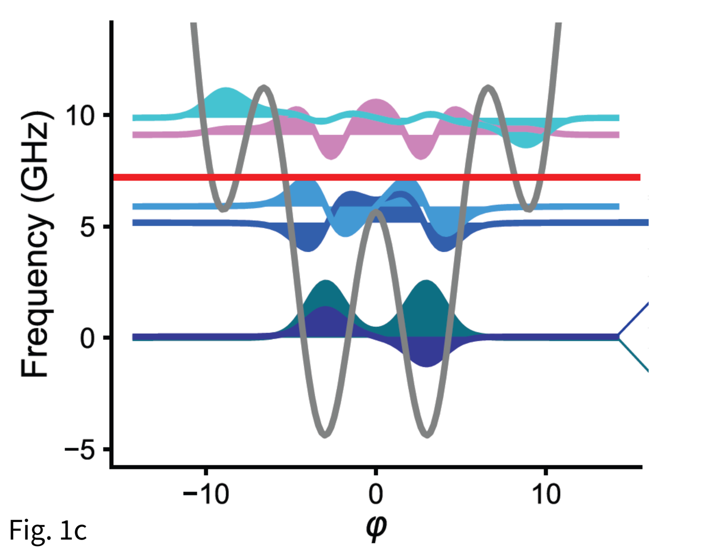


Fig. 1c

- Each fluxonium is capacitively shunted (small E_C), resulting in low $f < 100$MHz
- Although resonator detuning is $\Delta\sim$6GHz, $X\sim$0.7MHz via coupling to plasmon levels

	qubit a	qubit b
f_{10} (GHz)	0.0618	0.0484
α (GHz)	4.41	5.06
T_1 (μs)	180	300
T_2^* (μs)	150	200
T_{2e} (μs)	250	300

Tab. S1

$$\mathcal{H}_{eff} = -\sum_{\mu=a,b}\left(\frac{\omega_\mu}{2}\sigma_z^\mu + \Omega_\mu\sigma_x^\mu\right) + J\sigma_x^a\sigma_x^b + \xi\sigma_z^a\sigma_z^b$$

$\mathcal{H}_{eff}$ is found via perturbation theory near half-integer flux, where:

- ω_μ are dressed qubit freqs, incl. coupler-induced Lamb shifts
- $\Omega_\mu(\Phi_{ext}^\mu, \Phi_{ext}^C)$ executes single-qubit gates
- $J(\Phi_{ext}^A, \Phi_{ext}^B, \Phi_{ext}^C)$ gives the desired XX coupling; tunable to ~0
- ξ is an unwanted ZZ coupling, but is suppressed to be $< 3kHz$

Ref App. C

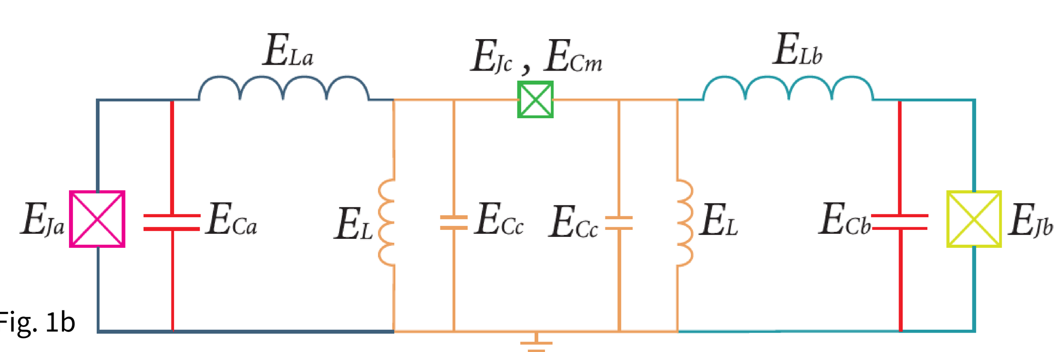


Fig. 1b

- Shared tunable inductor creates a $\varphi_A\varphi_B$ term
- In computational basis (via Schrieffer-Wolff): $\sigma_x^A\sigma_x^B$ [2]

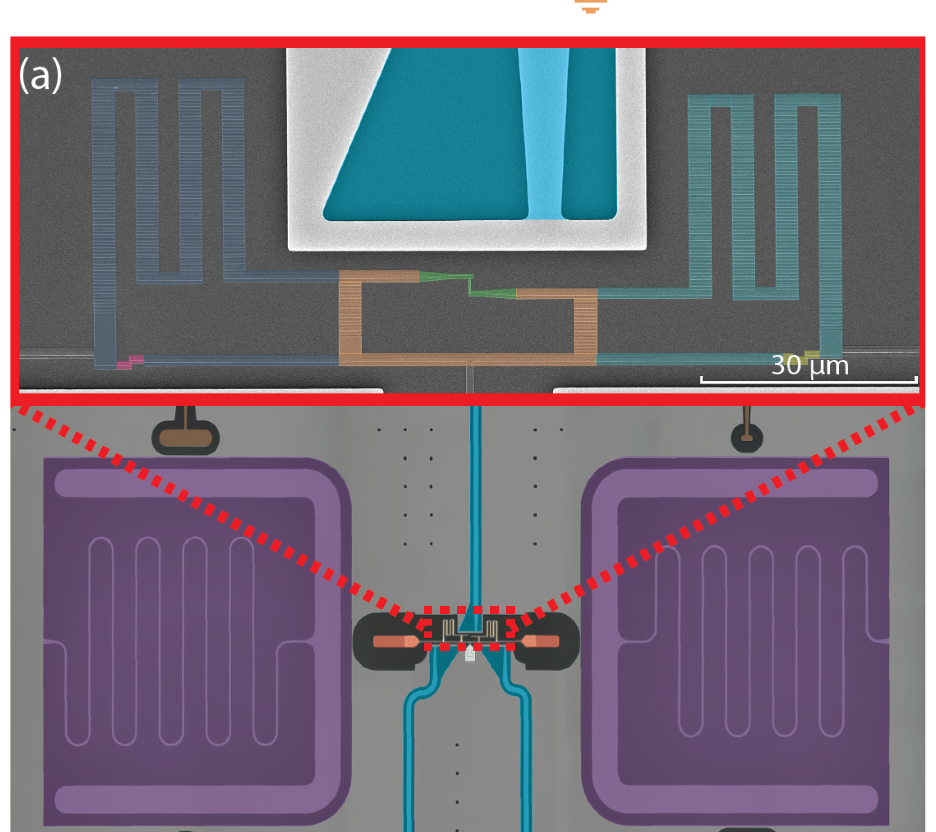


Fig. 1a

- False colors correspond to circuit elements (above)
- Tantalum base metal (200nm) on sapphire substrate (430μm), with aluminum junctions (70nm/90nm)
- Kinetic inductance realized by a chain of 238 Josephson junctions
- Galvanic connection between qubits and coupler is realized by a shared JJ chain, with 36 junctions

Tuning 2Q entangling gates ($\sqrt{bSWAP}$)

$$\sqrt{bSWAP} = \begin{pmatrix} 1/\sqrt{2} & 0 & 0 & i/\sqrt{2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ i/\sqrt{2} & 0 & 0 & 1/\sqrt{2} \end{pmatrix}$$

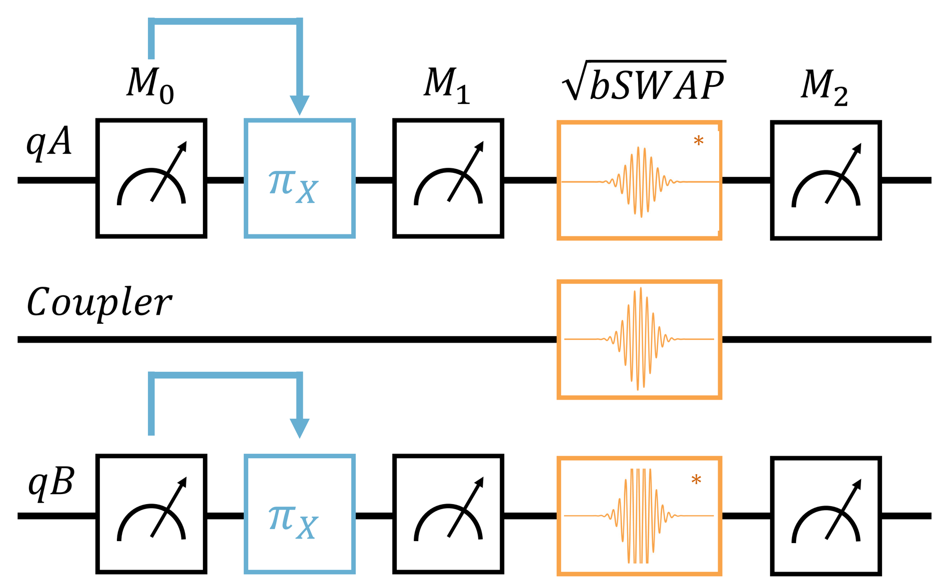
$J(\Phi_{ext}^A, \Phi_{ext}^B, \Phi_{ext}^C)\sigma_x^A\sigma_x^B$

$\Rightarrow A\sin(\omega_d t)\left[\cos(\omega_\pm t)\Sigma_x^\pm + \sin(\omega_\pm t)\Sigma_y^\pm\right]$ (interaction frame)

$\Rightarrow A\left[\sin(2\omega_+ t)\Sigma_x^+ + \cos(2\omega_+ t)\Sigma_y^+\right]$ (RWA: $\omega_d = \omega_A + \omega_B$)

$\Rightarrow \sqrt{\phi_b SWAP}$ ($\phi \propto t$) [2]

Pulse sequence w/ active reset



Correlated oscillations between $|00\rangle \leftrightarrow |11\rangle$

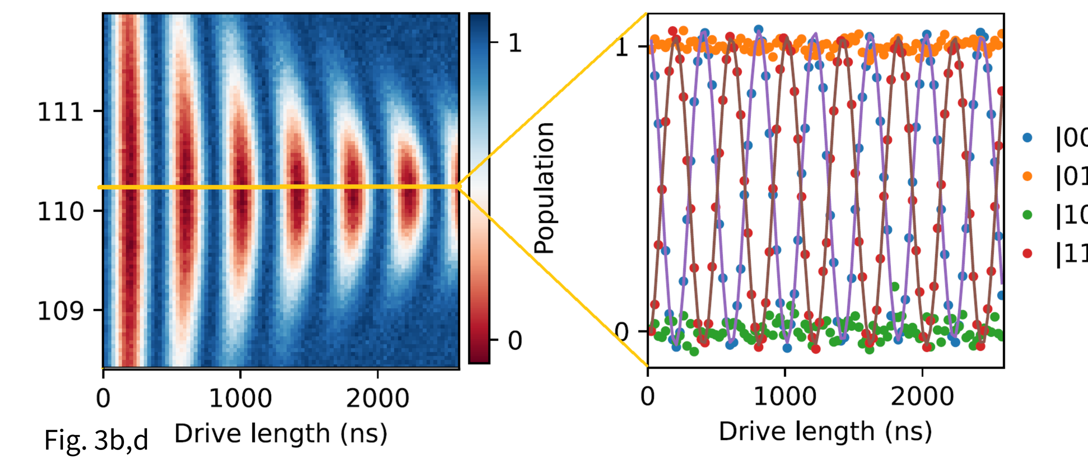


Fig. 3b,d

Drive amplitude: $A = 0.011\ \Phi_0$

Time for one full oscillation: 400ns (2.5MHz)

Device measurement and characterization

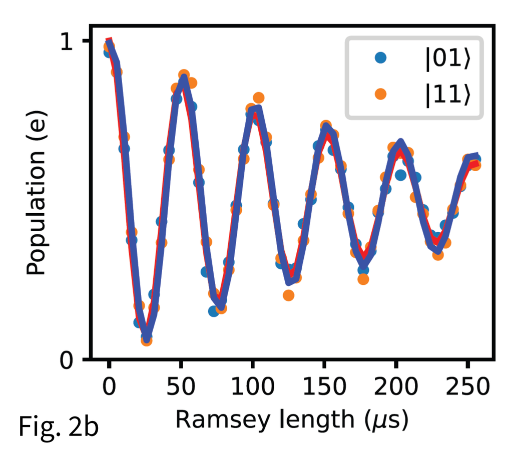


Fig. 2b

- Ramsey exp. of qB at $\Phi_{ext}^C\sim$0.3, the "off position"
- ZZ is found via the freq. diff $(f_{11} - f_{10}) - (f_{01} - f_{00})$ and is measured to be < 100Hz

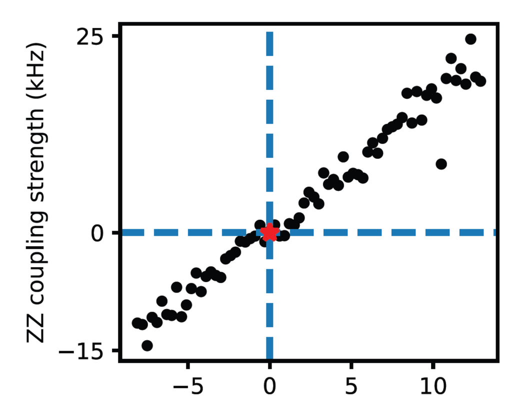


Fig. 2c

- Measured ZZ when tuning away from the "sweet spot contour"
- Used as an indicator for calibrating the "off position"

Qubit parameters, determined by fitting to plasmon spectroscopy lines via `scqubits`

	qubit a	qubit b	coupler φ_-	coupler φ_+
E_J (GHz)	5.65	4.88	4.246	
E_C (GHz)	0.95	0.905	8	12
E_L (GHz)	0.292	0.286	3.52	3.52

XX, ZZ as function of Φ_{ext}^C (sweet spot contour)

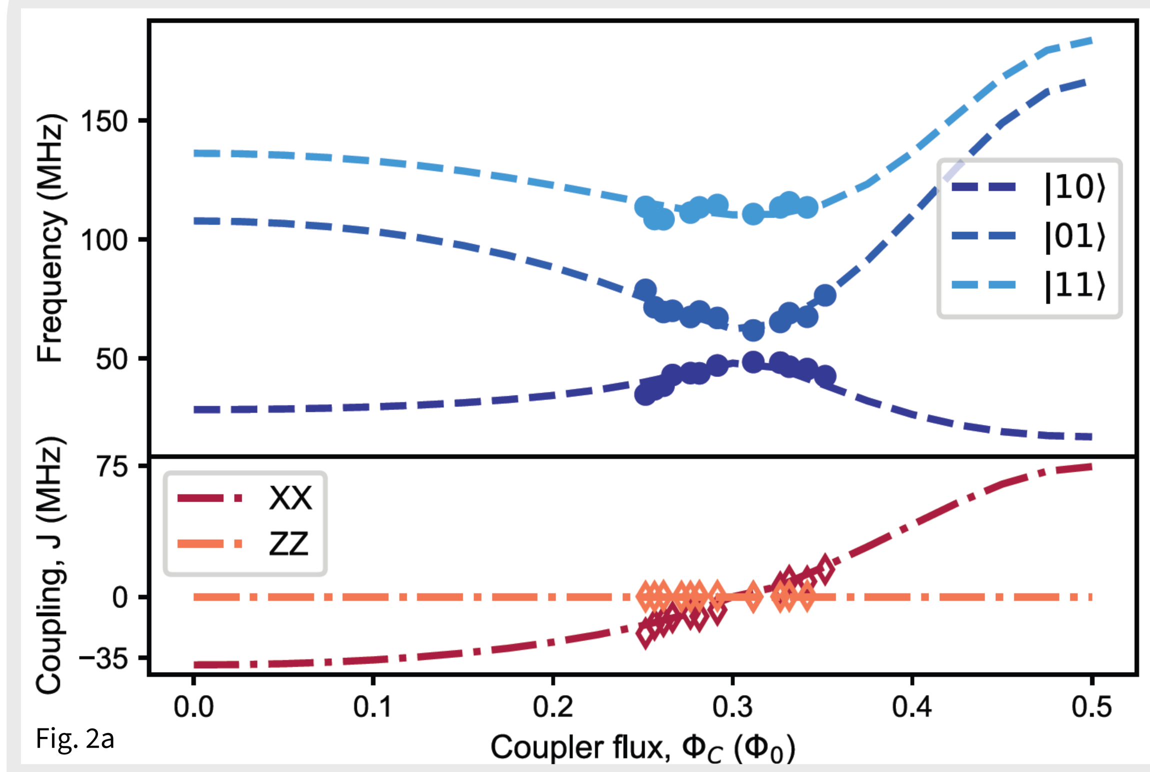


Fig. 2a

- Dots: measured qubit frequencies at various coupler flux
- Diamonds: measured XX and ZZ coupling strengths
- Dashed lines: theory curves using extracted qubit params
- ZZ coupling strength < 3kHz across entire measured range
- XX strength measured between -20 to +15 MHz, with on-off contrast > 10^5

qB spectroscopy ($\Phi_{ext}^C = \Phi_{ext}^B = 0$)

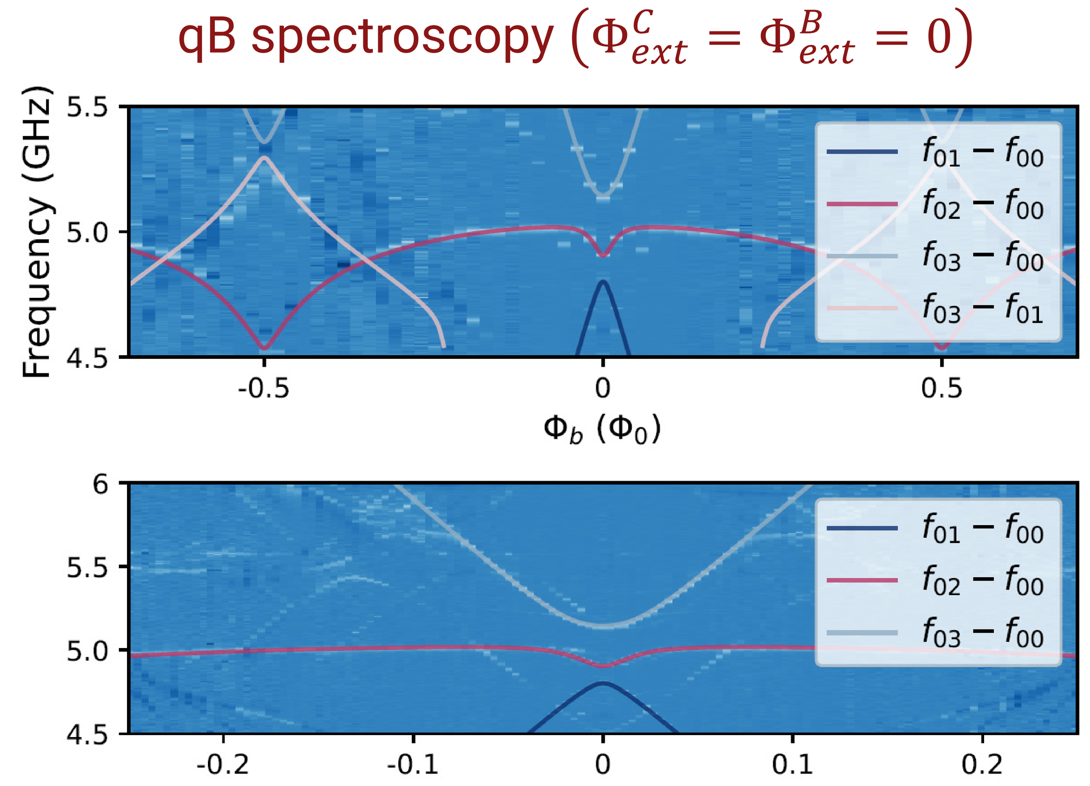
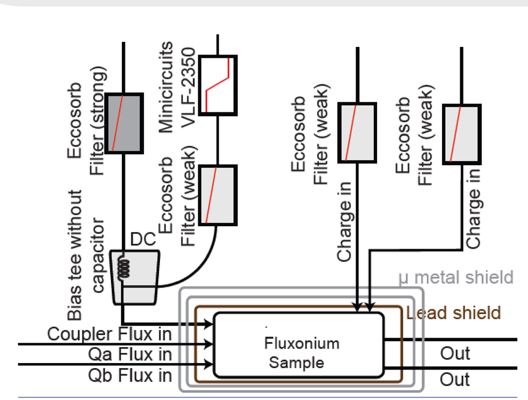
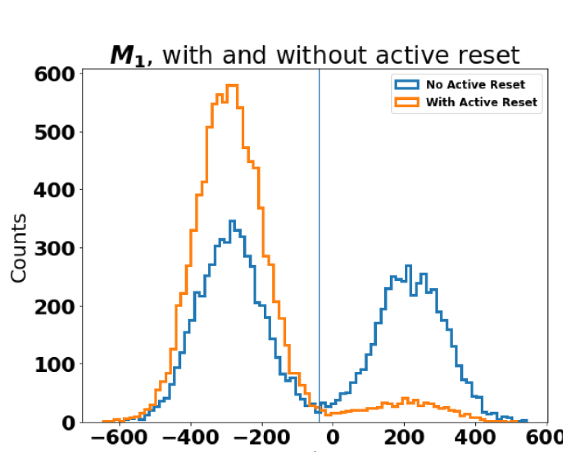


Fig. 5b, c



- Filter qubit lines using Eccosorb IR & K&L lowpass filters
- The qubit's Boltzmann temperature (hf/k_B= 2.8mK) is lower than its environment, measured to be ~50mK



- Active reset and postselection is necessary for initializing the qubit
- Realized using the QICK firmware [3] on a Xilinx ZCU111 rfSoc

Phase & crosstalk calibrations

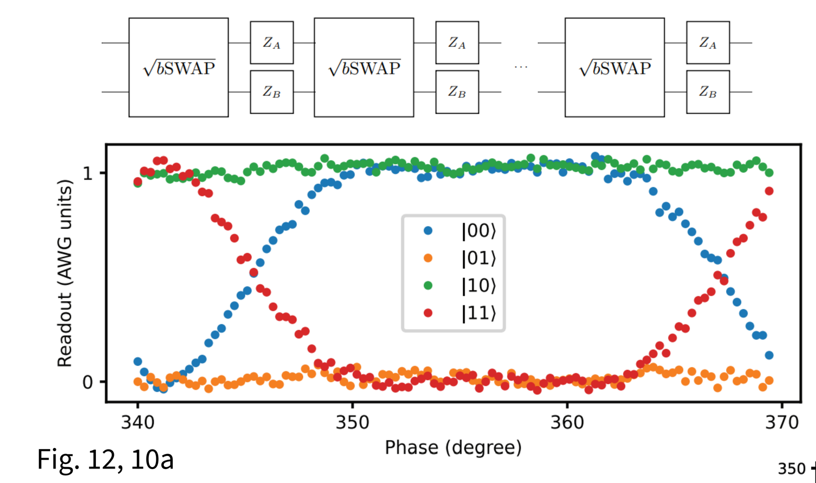


Fig. 12, 10a

Repeatedly playing the pulse amplifies rotation error, allowing phase calibration

Final pulse parameters:
- f_{sqb} = 110.2MHz
- t_{sqb} = 101.6ns (5 qubit Larmor periods)
- ϕ_A = 357°

To cancel RF crosstalk, play same coupler pulse on $\Phi_{ext}^A, \Phi_{ext}^B$ with calibrated A, ϕ

Sweep $A(0.7, 1.5\ A_0), \phi(224°, 182°)$ of pulse to observe max oscillation contrast

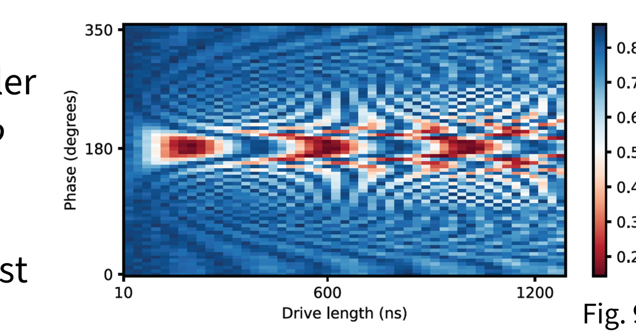


Fig. 9a

Benchmarking Results

Simul. 1Q RB

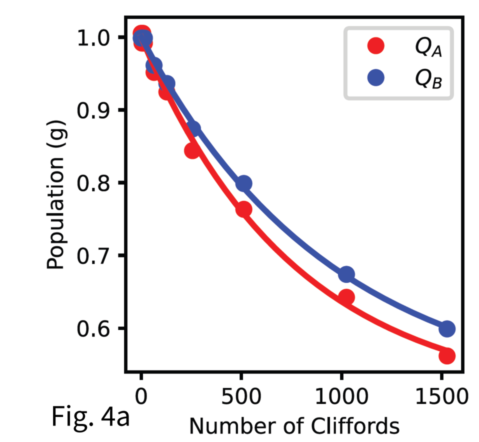


Fig. 4a

DRAG shaping for both 1Q, 2Q gates, optimized via RL

$\sqrt{bSWAP}$ compiled with 2 virtual Z gates and crosstalk cancellation

Fidelity: qA: 99.94%; qB: 99.95%

Gate lengths: qA: 83.3ns; qB: 65.1ns

2Q XEB

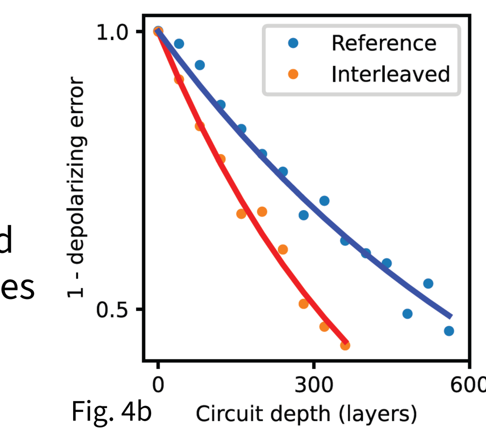


Fig. 4b

Avg. depolarizing error:
Reference: 1.3×10^{-3}
Interleaved: 2.4×10^{-3}

$\sqrt{bSWAP}$ XEB: $F_{Avg} = 99.91 \pm 0.02\%$

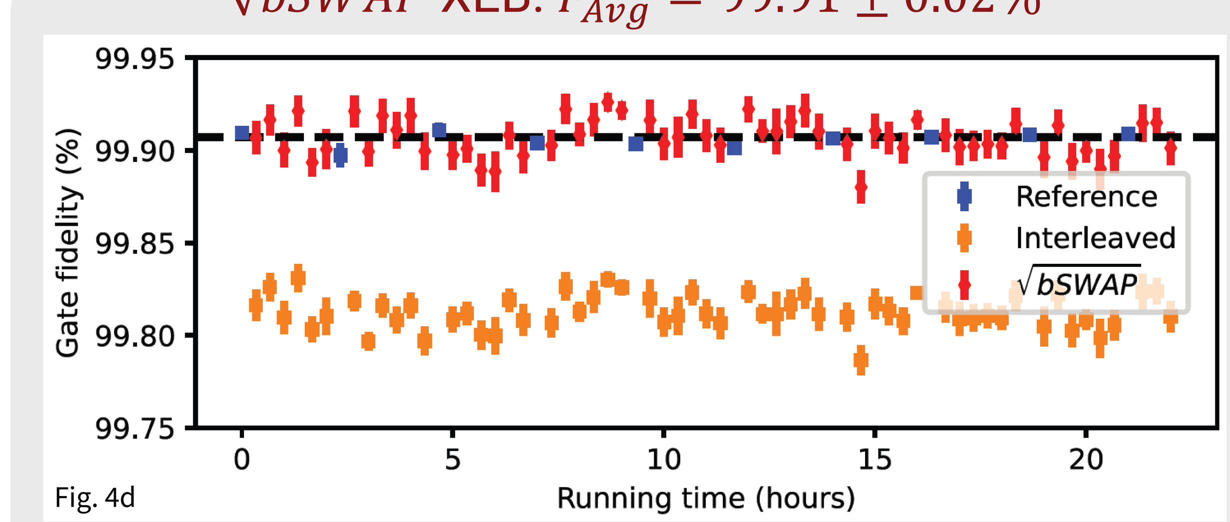


Fig. 4d

Dominant error source: **qubit decoherence**; *not* limited by RWA/carrier envelope. Full error budget here:

Ref App. J

QST

$\rho = |gg\rangle + i|ee\rangle/\sqrt{2}$

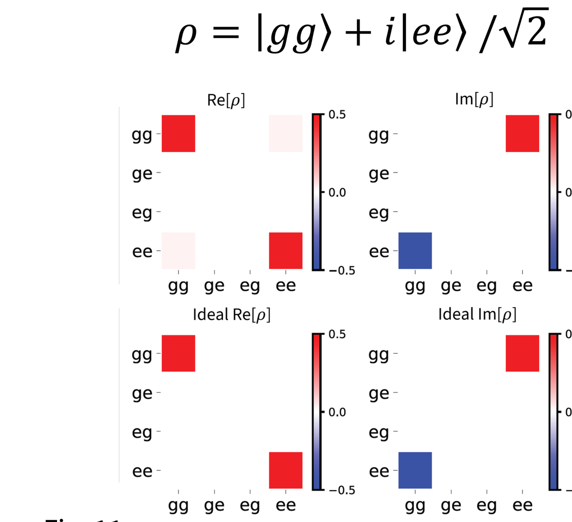


Fig. 11

QPT

$X = \sqrt{bSWAP}$

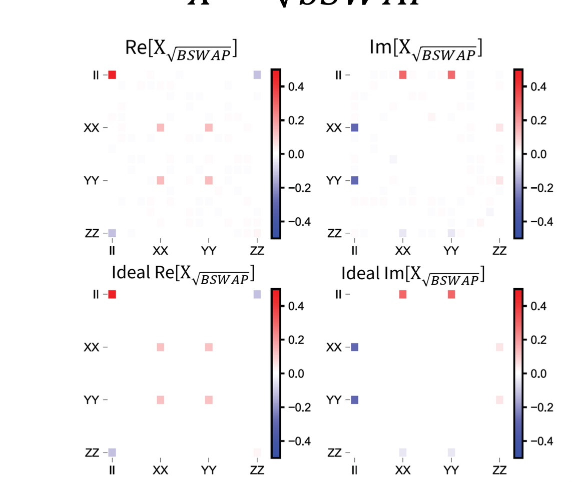


Fig. 14

QST and QPT show fidelity of **95%**, limited by SPAM errors

Bibliography

[1] Zhang and Ding, *arXiv* (2023)
[2] Weiss, *PRX* (2023)
[3] Stefanazzi, *RSI* (2022)