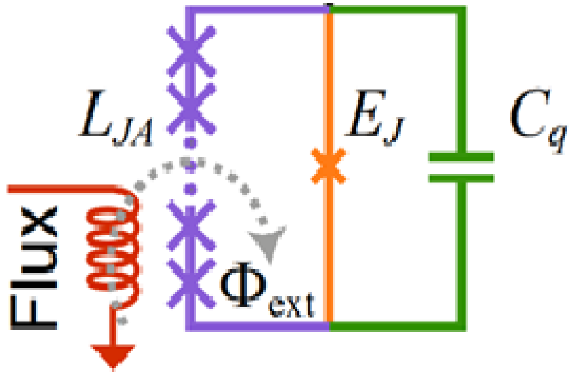
Reconsidering qubit control paradigms for high fidelity fluxonium gates

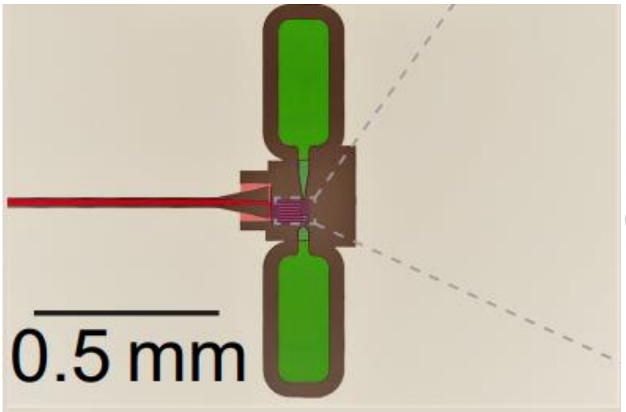
Chunyang Ding, Helin Zhang, Daniel Weiss, Sai Paivan Chitta, Yuwei Ma,

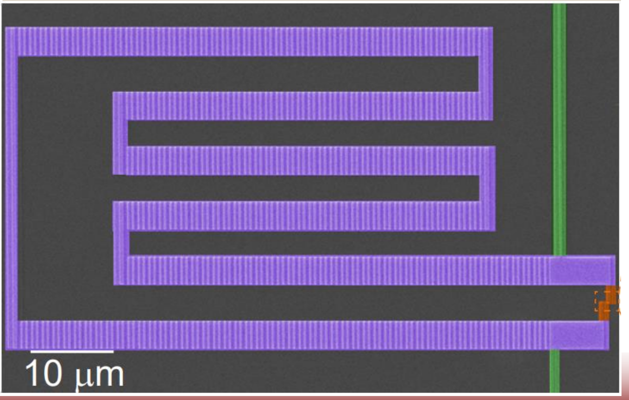
Jens Koch, David Schuster

Fluxonium qubits

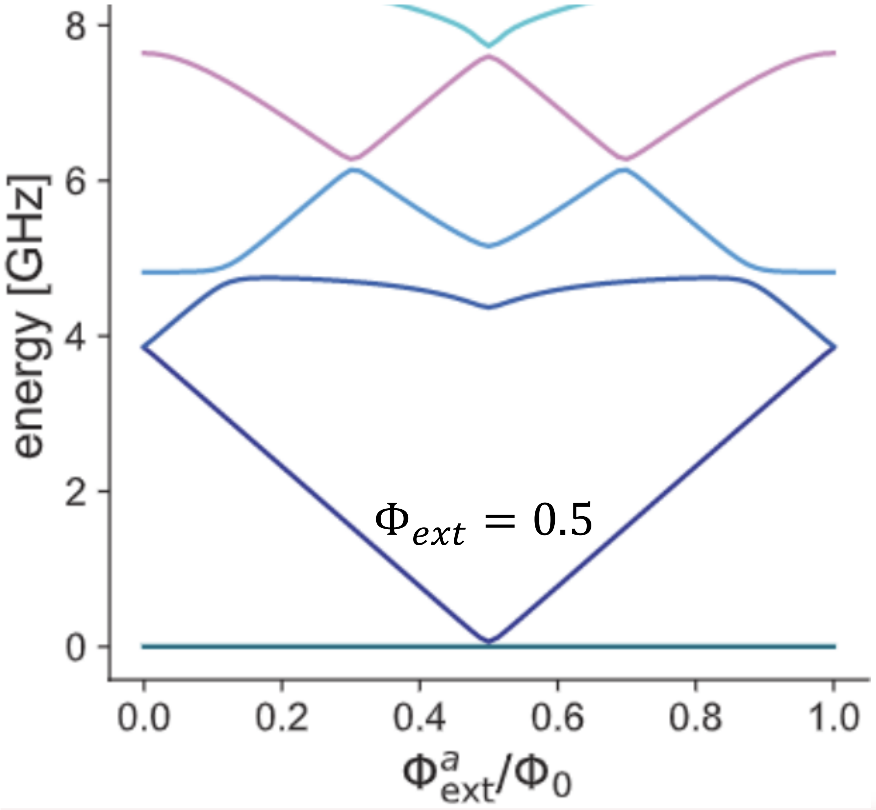


$$H_f = -4E_C \frac{d^2}{d\varphi^2} - E_J \cos(\varphi - 2\pi\Phi_{\text{ext}}/\Phi_0) + \frac{1}{2}E_L\varphi^2$$

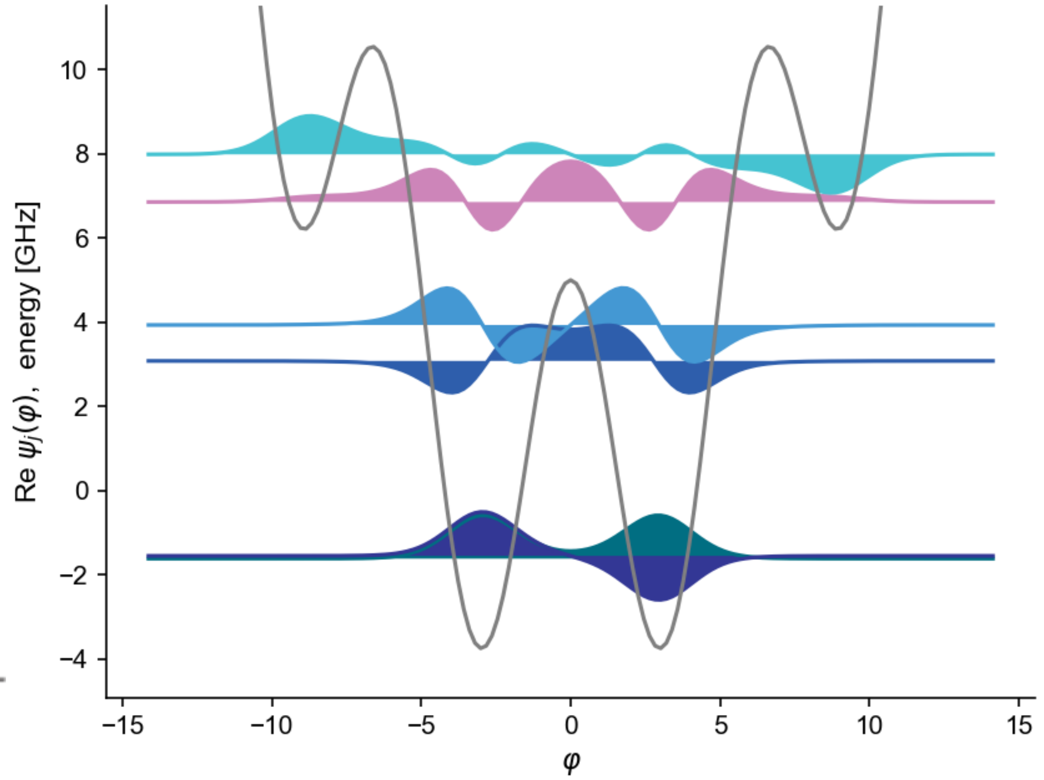




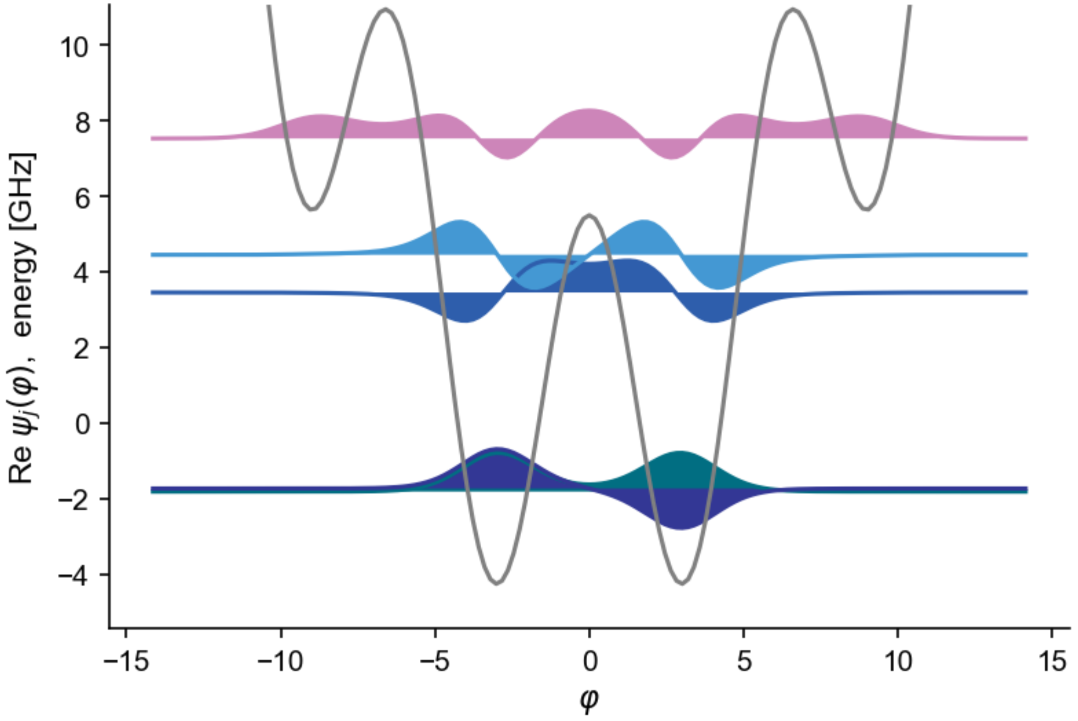
Energy spectrum (Φ_{ext})



$\Phi_{ext} = 0.5$



Why Fluxonium?



Important quantity for most SC qubit gates is:

Gate time / **Coherence time**

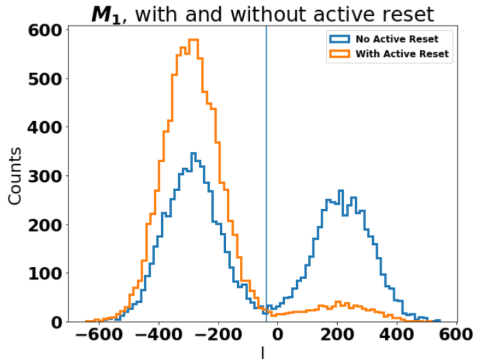
- Coherence (esp. T1) scales inversely with qubit frequency
- Gate time scales like $\min(\omega_{01}, \alpha)$

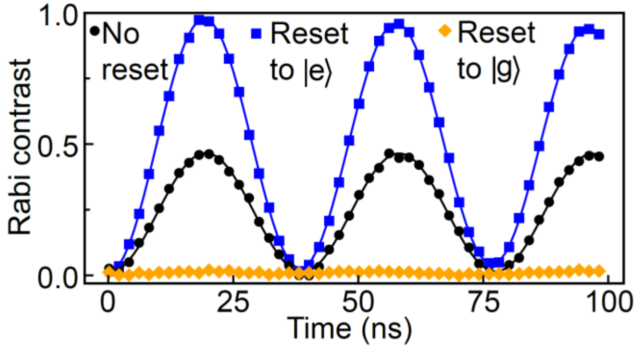
Fluxonium decoherence should be slower, but gates can be faster

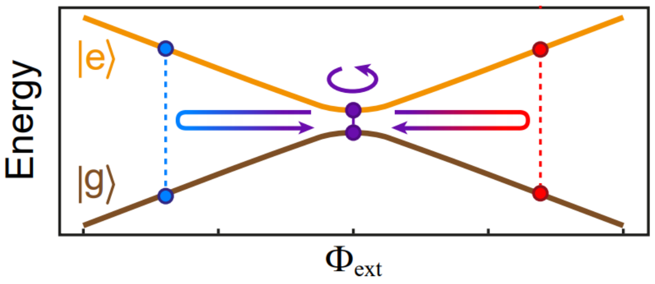
Low frequency is cheaper / easier
Less crowding of transitions

Rethinking paradigms

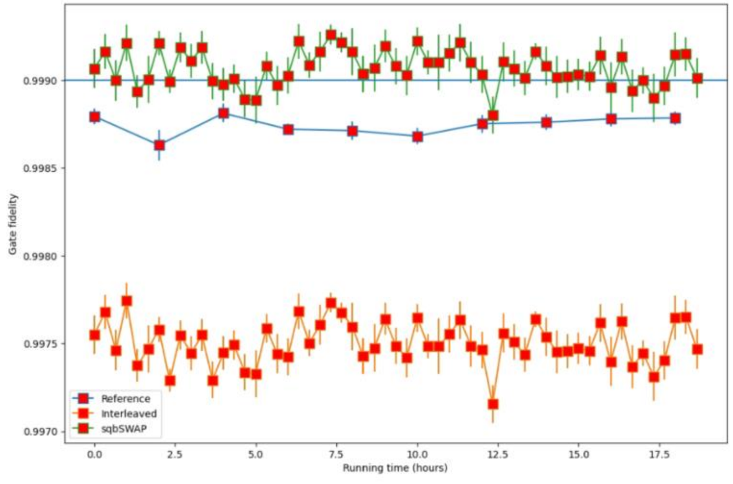
- Initialization via laser cooling
- Initialization via active reset
- Ultrafast single qubit gates
- High fidelity galvanically-coupled two qubit gates







SQBSWAP XEB



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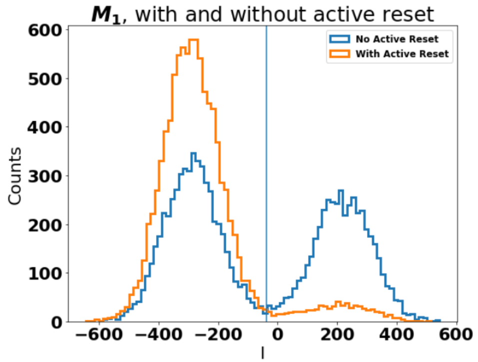

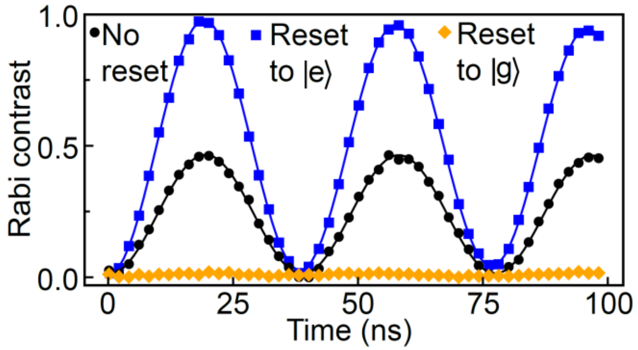

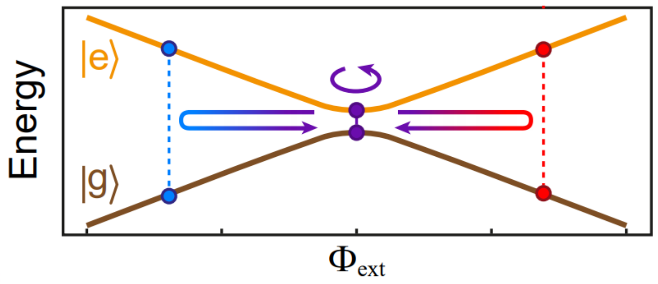

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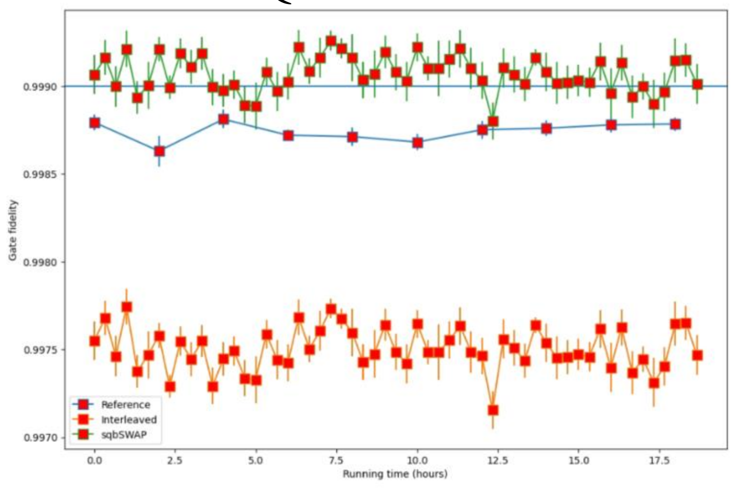
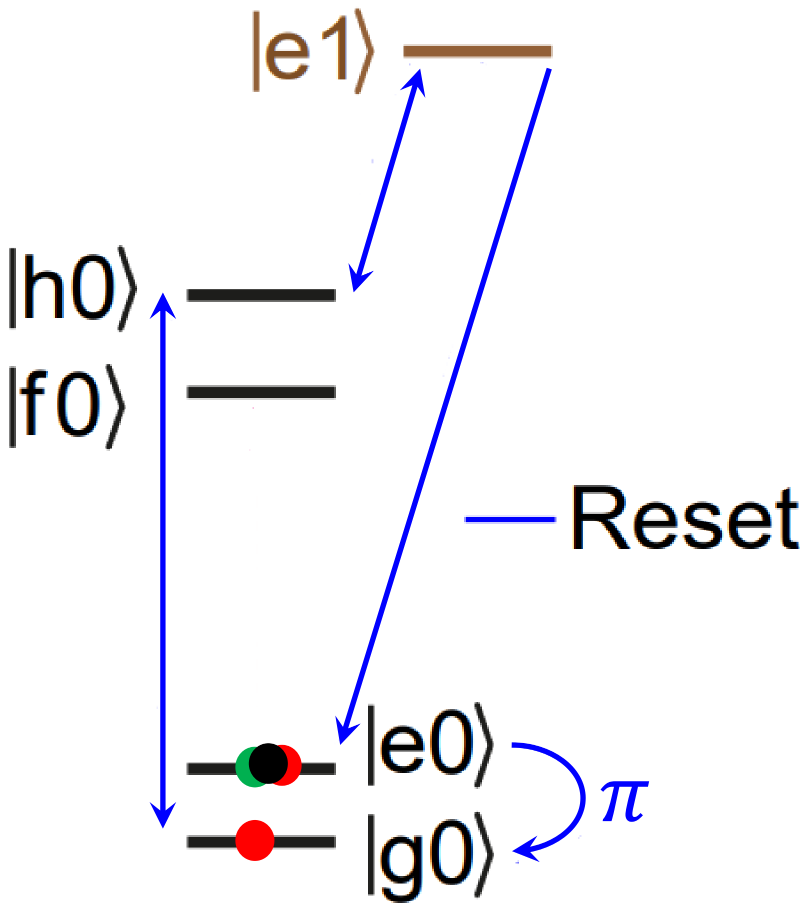
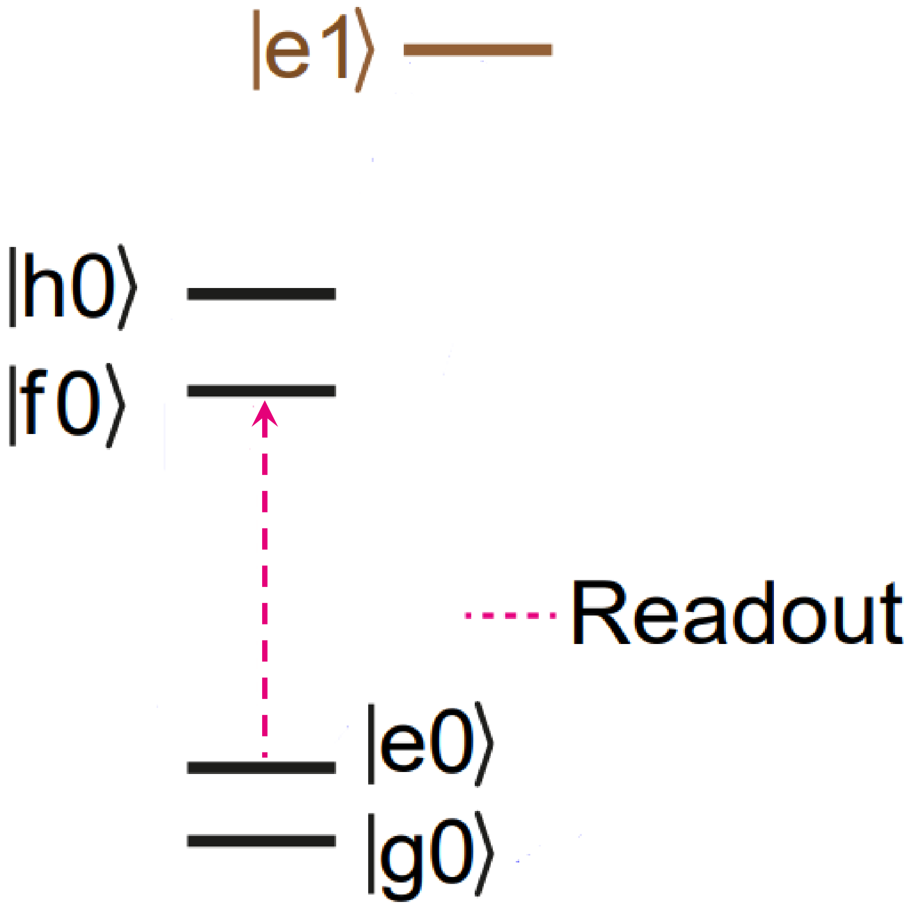


Qubit initialization and readout



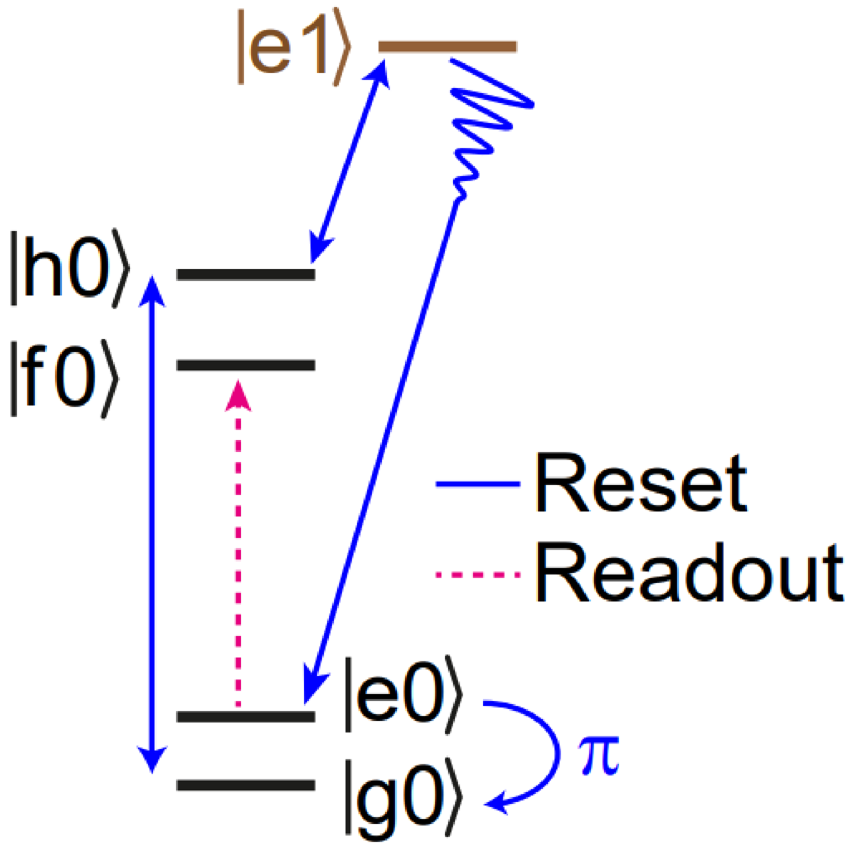
- Reset fidelity limited by cavity & $|f\rangle$ state population

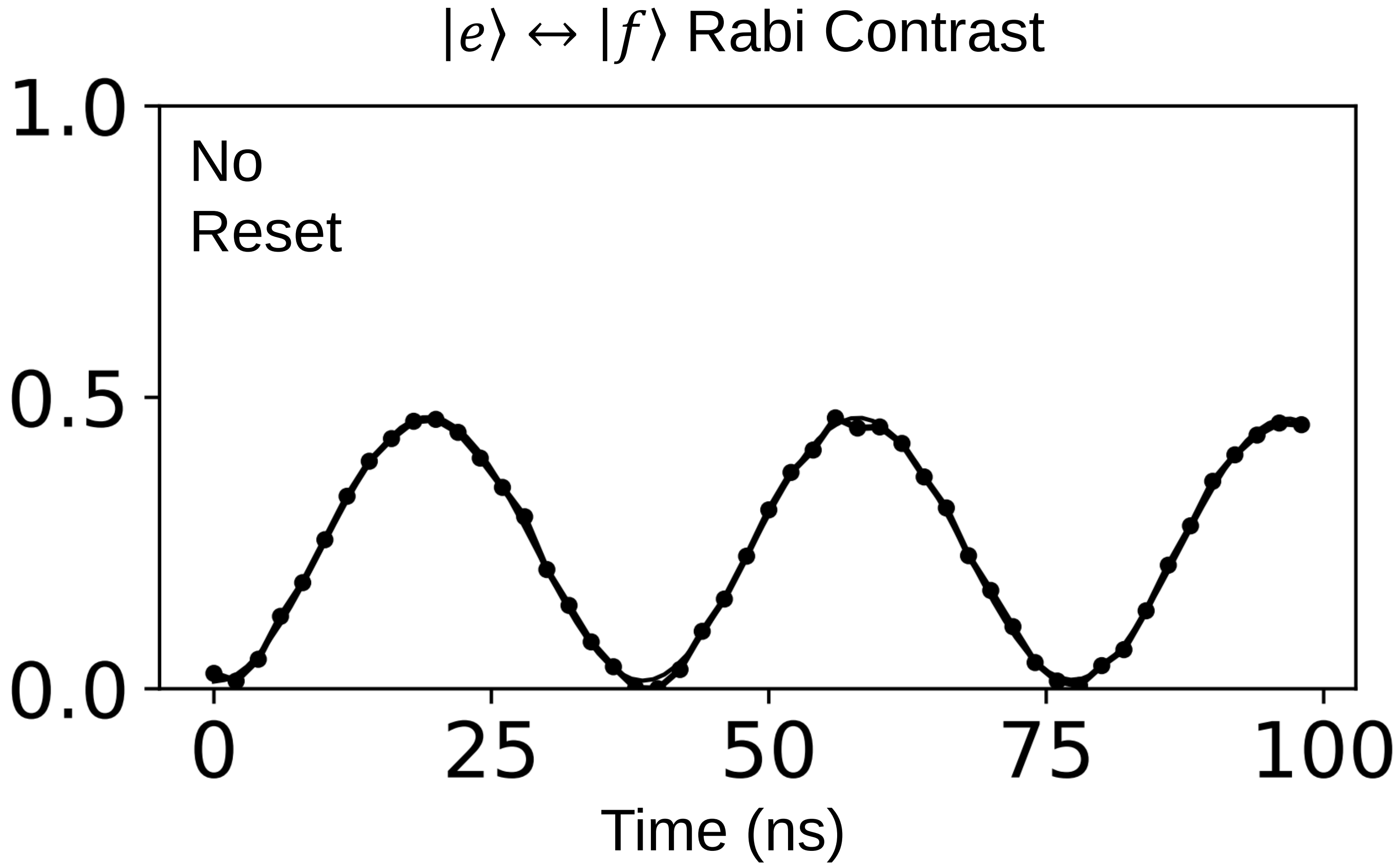
Qubit initialization and readout



- Reset fidelity limited by cavity & $|f\rangle$ state population
- Perform a $|e\rangle \rightarrow |f\rangle$ π pulse before readout
- 50% readout fidelity
- In newer samples no longer necessary to excite for readout

Qubit initialization and readout





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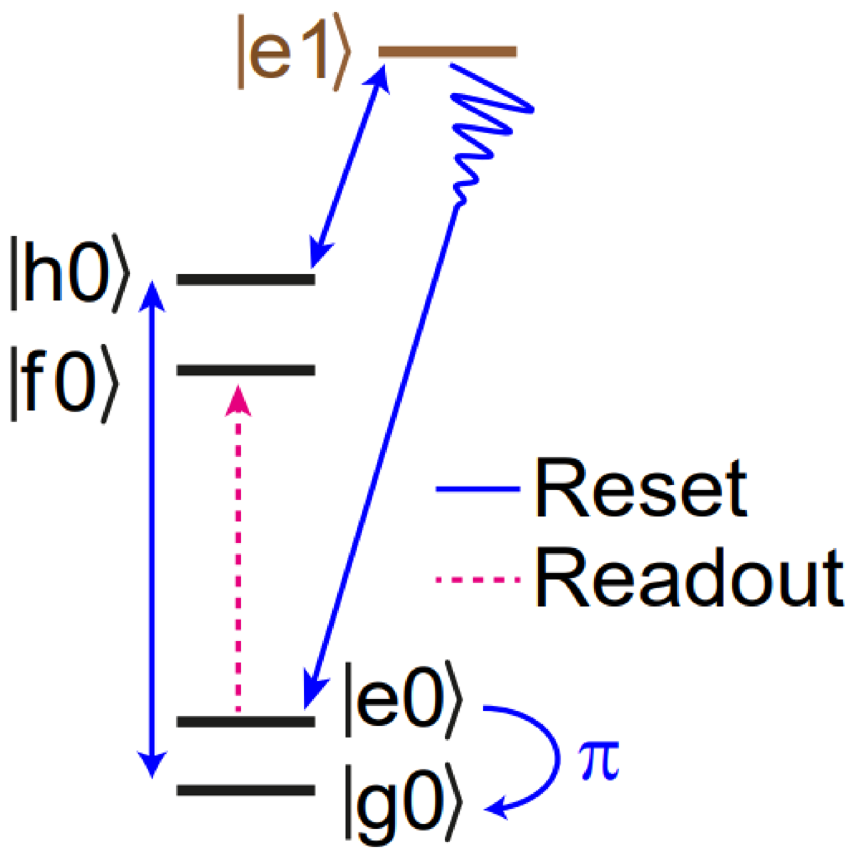

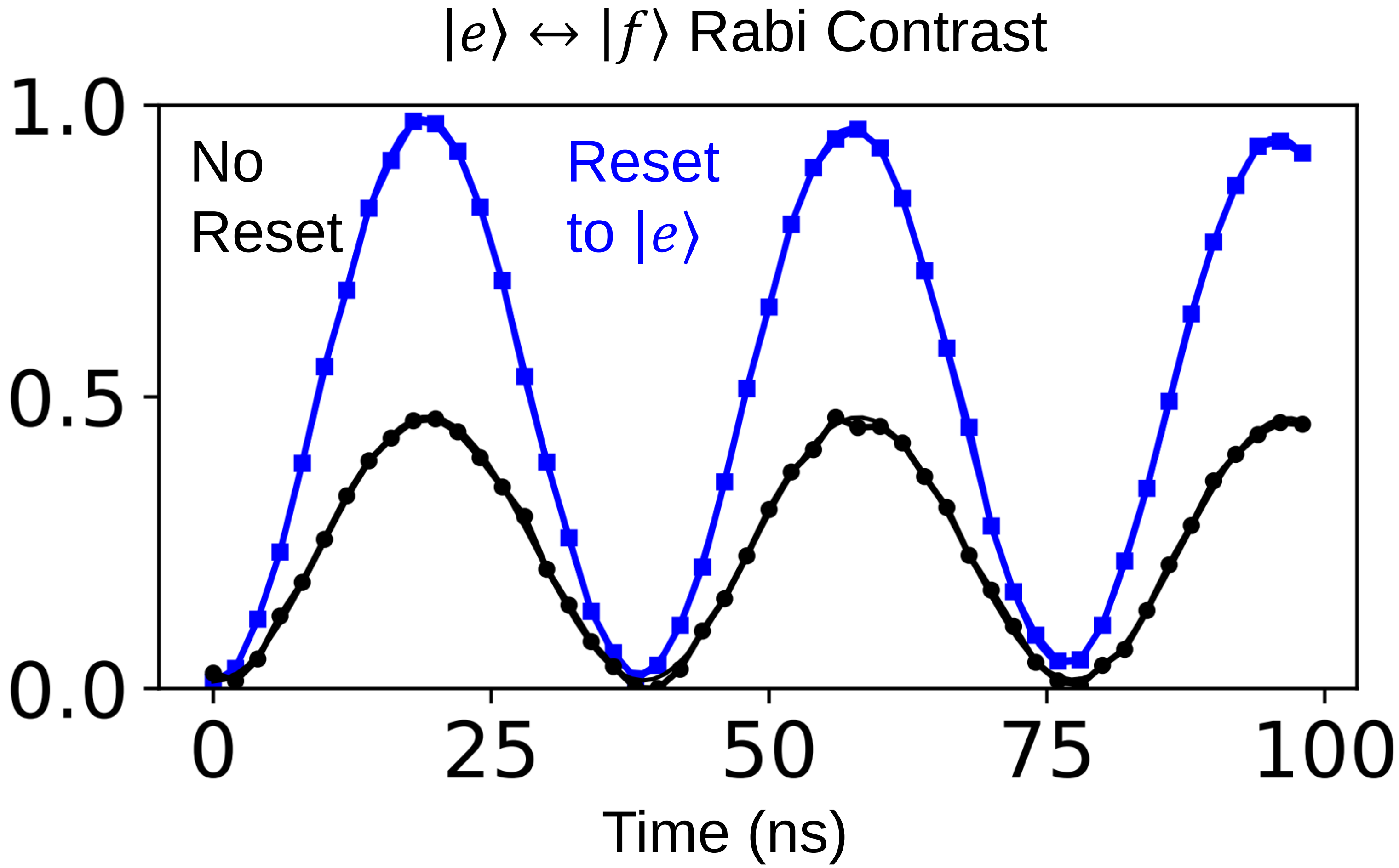

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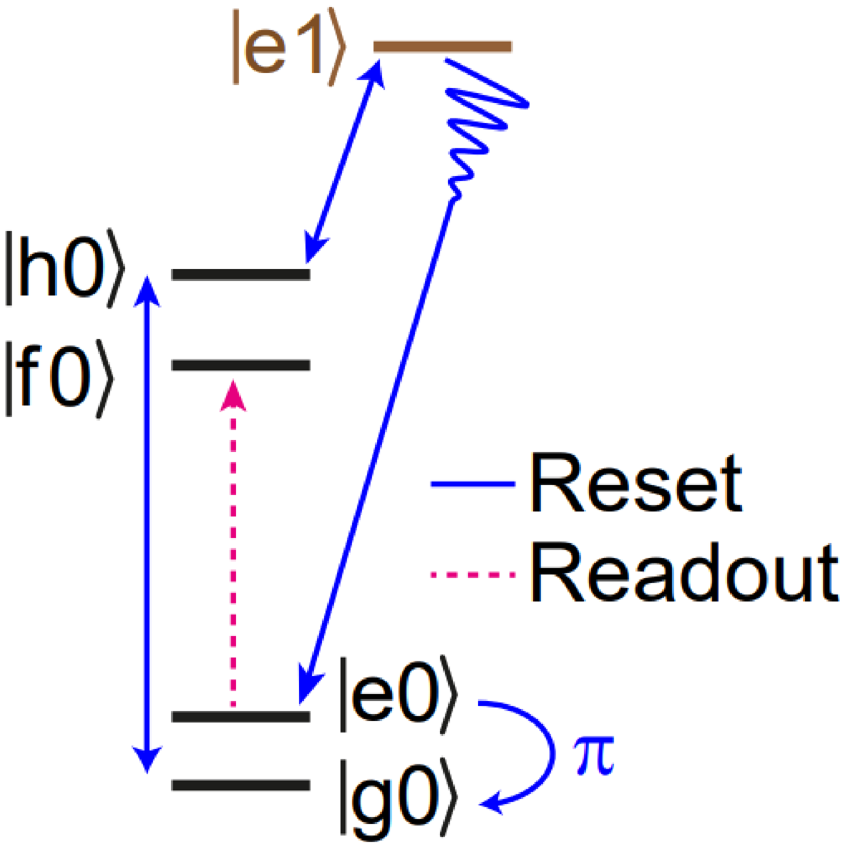

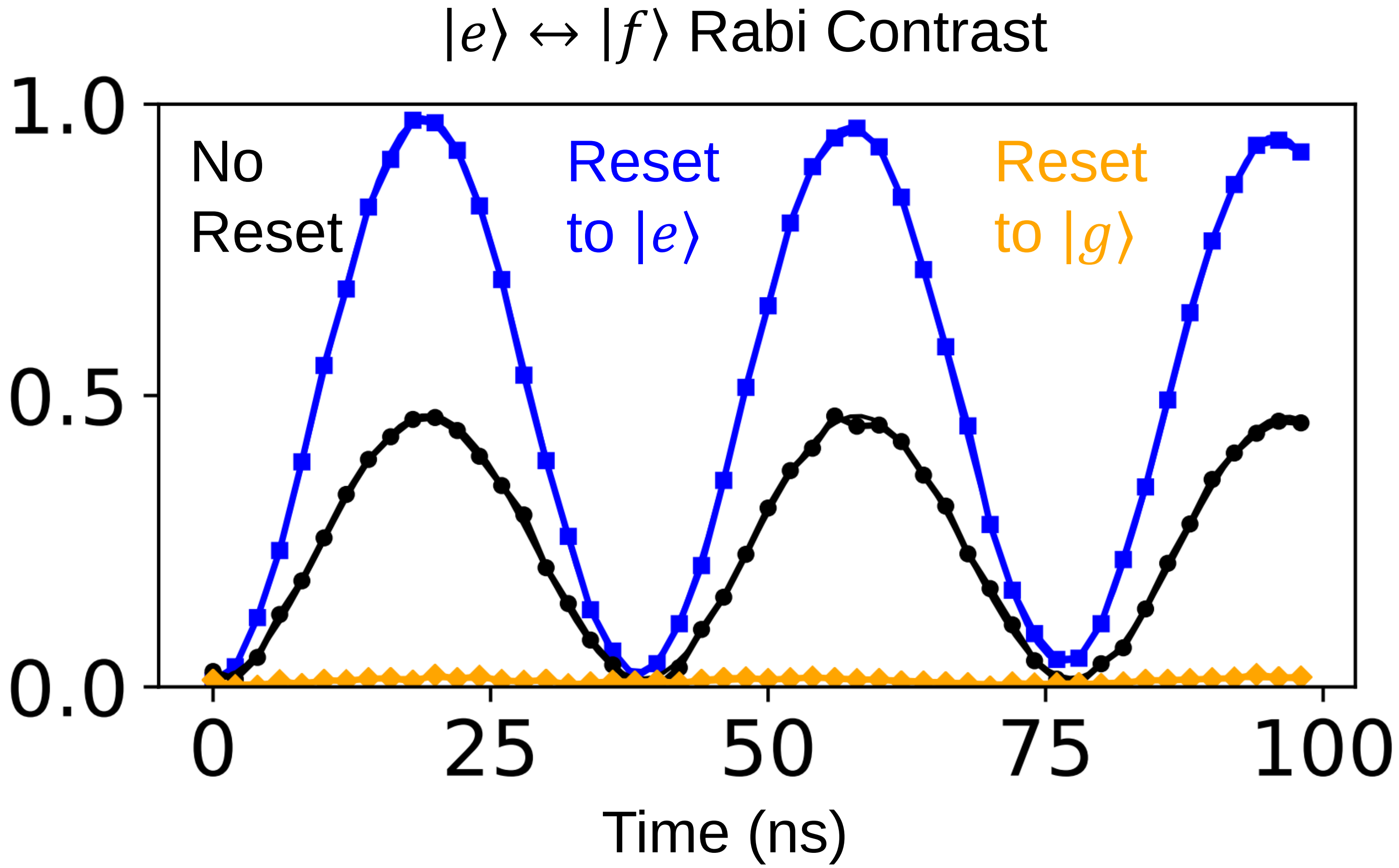

97% initial state fidelity, $T_q = 190\ \mu K$

Rethinking paradigms

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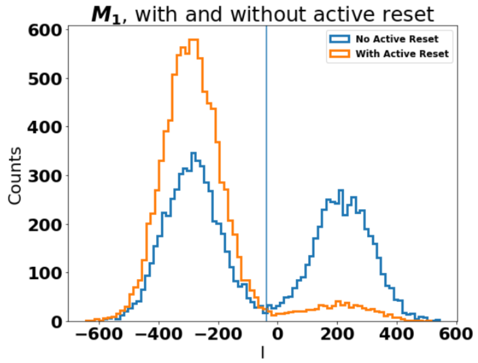
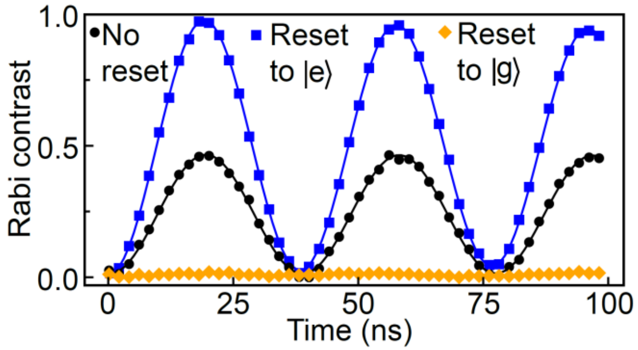
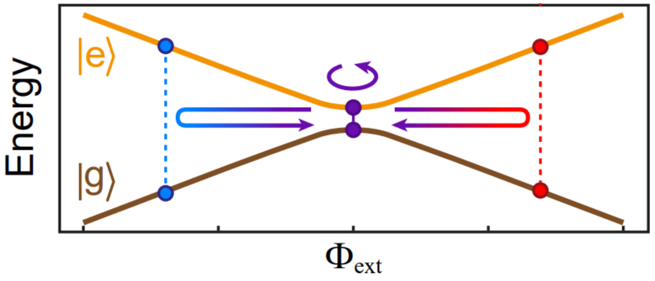
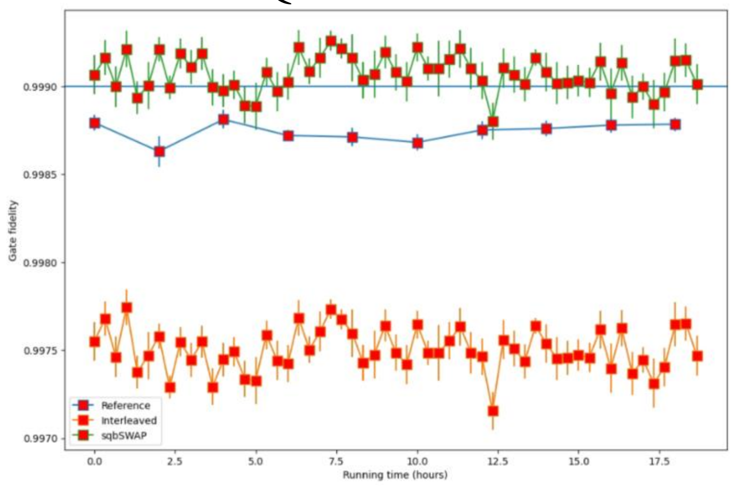
- **Initialization via active reset**
- Ultrafast single qubit gates
- High fidelity galvanically-coupled two qubit gates



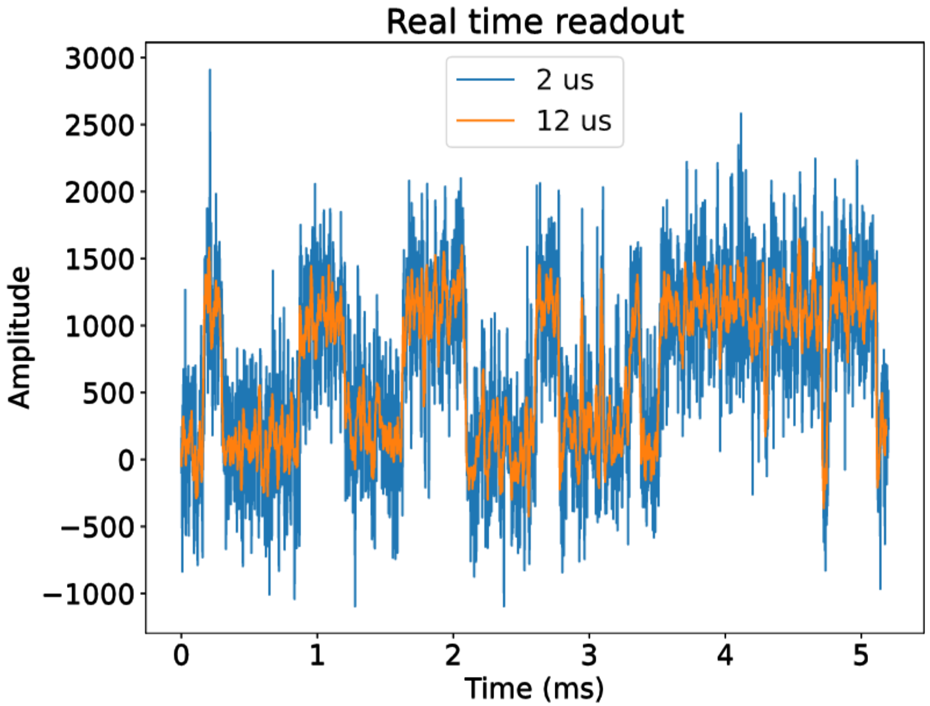


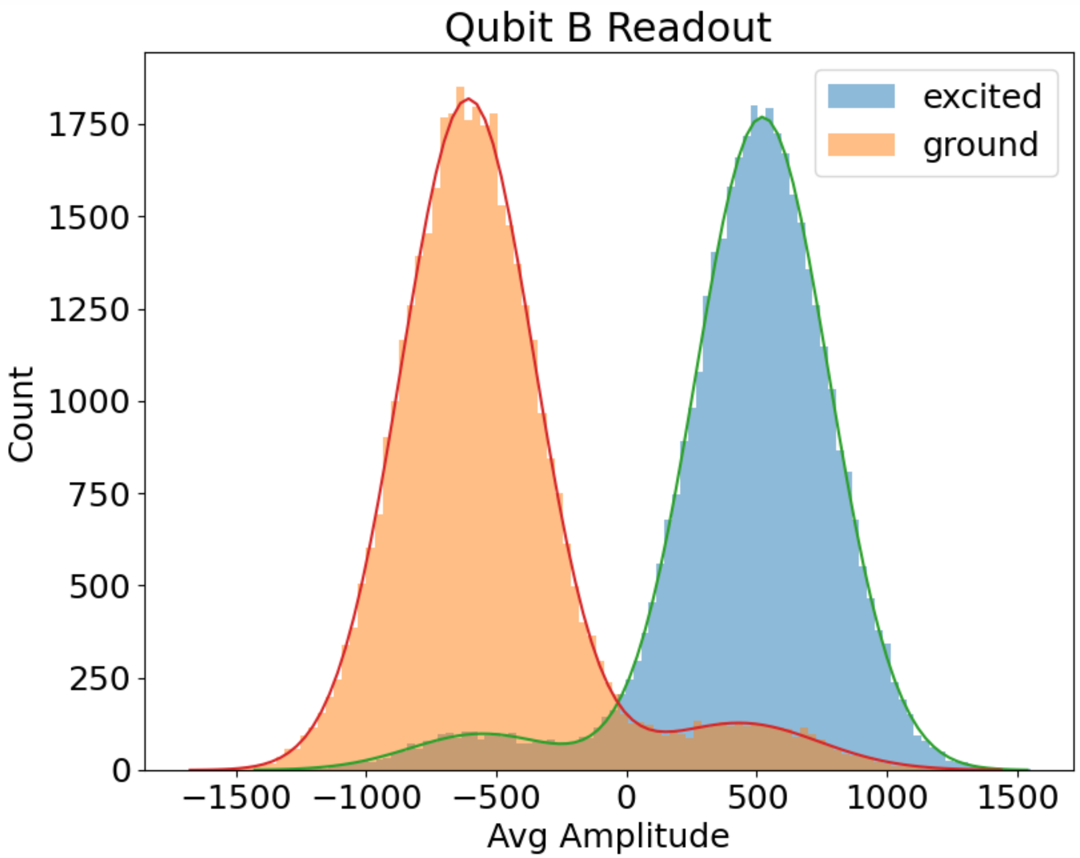


SQBSWAP XEB



Real time dispersive readout

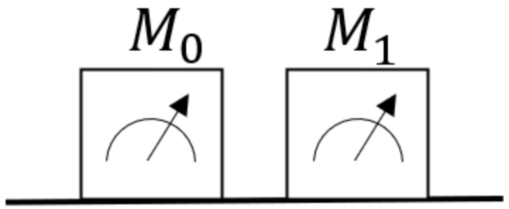


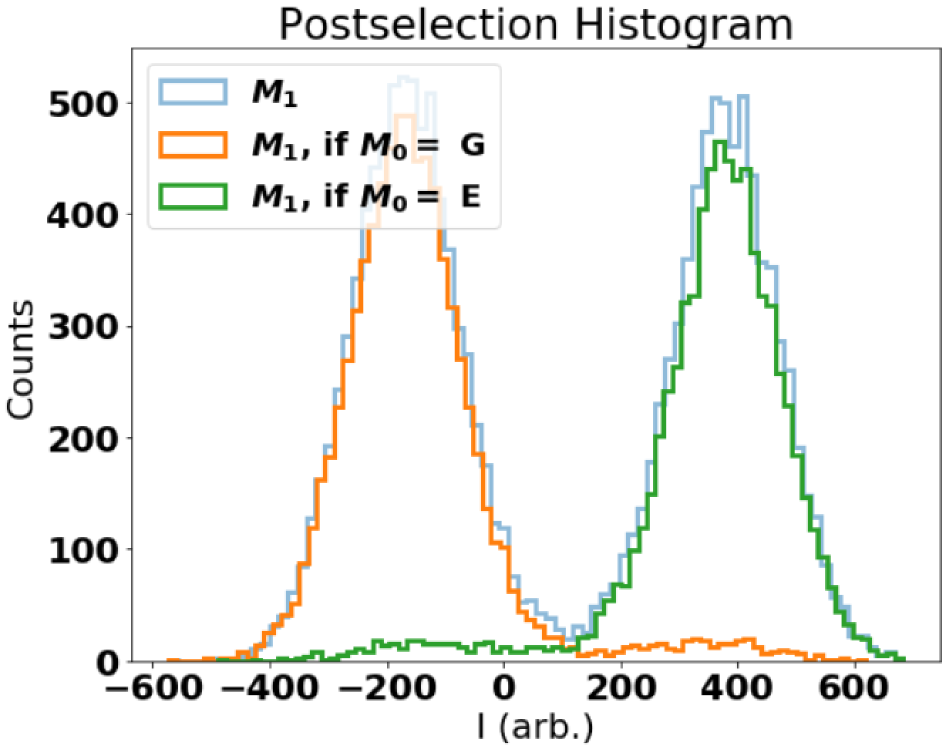


- Better readout design results in high fidelity readout
- Paramp would still speed up (and improve) measurement, state preparation

- Qubit prepared by measurement w/ feedback
- Statistical infidelity ~ 2%
- Infidelity of prepared states ~18% (~.98mK)

Demonstration of post-selection protocol





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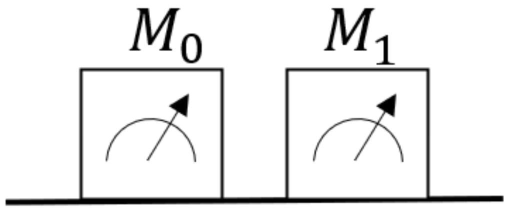

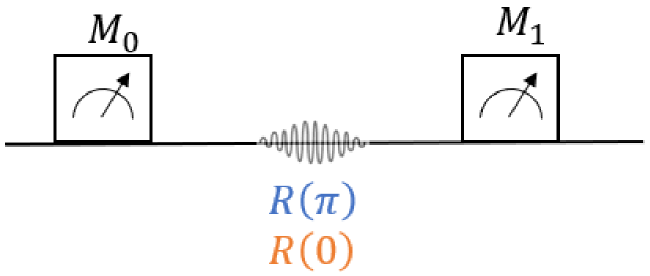

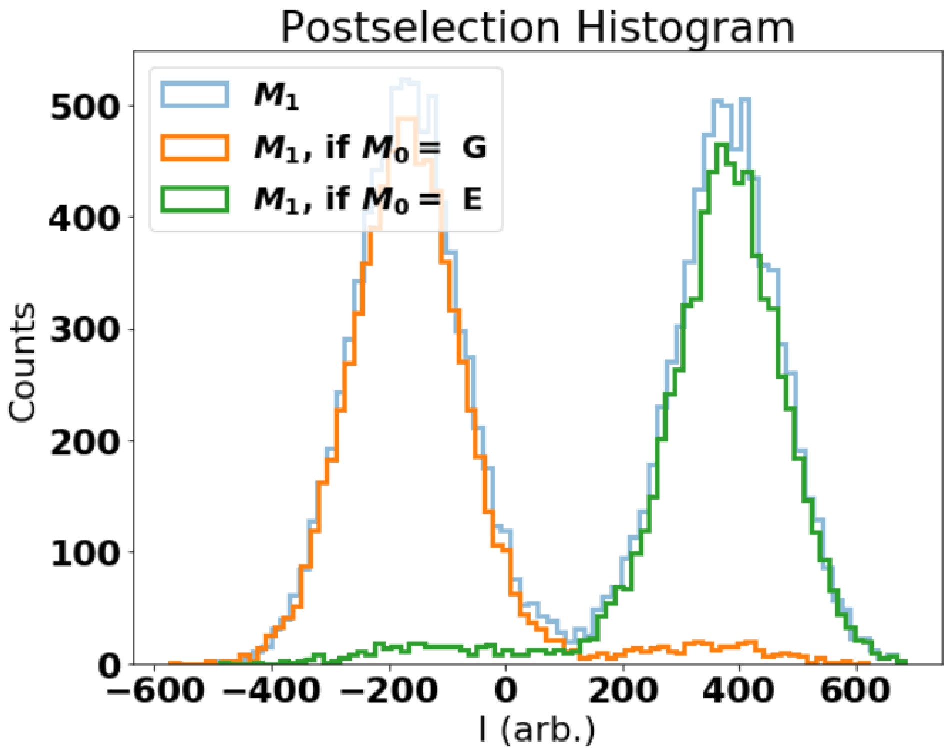

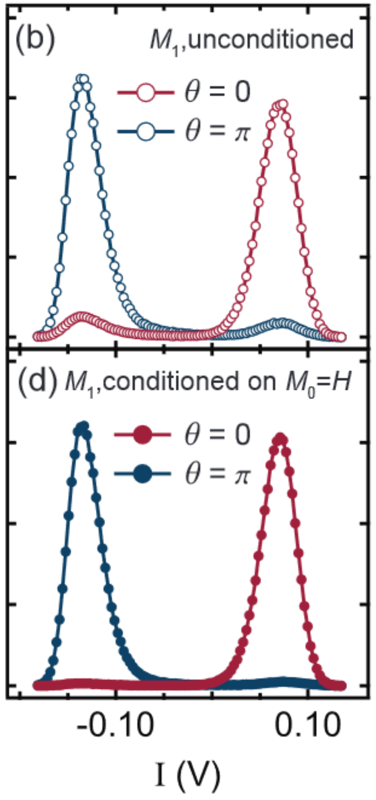

Riste 2012 *Phys. Rev. Lett.* **109** 050507

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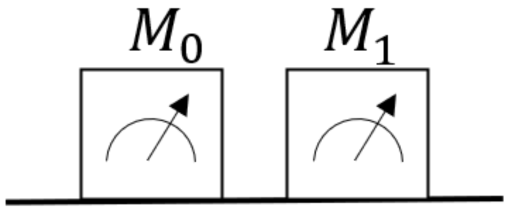

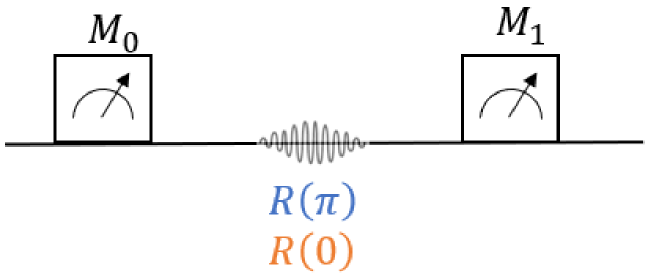

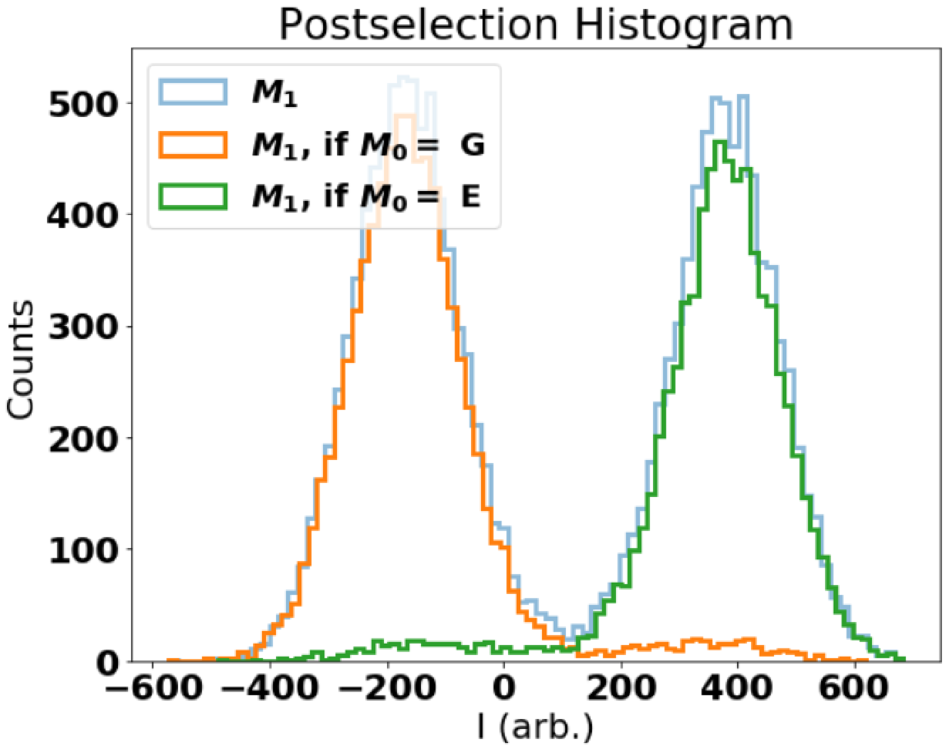

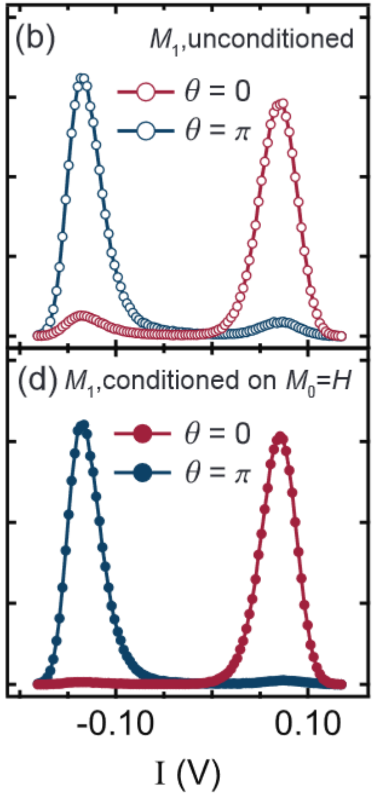

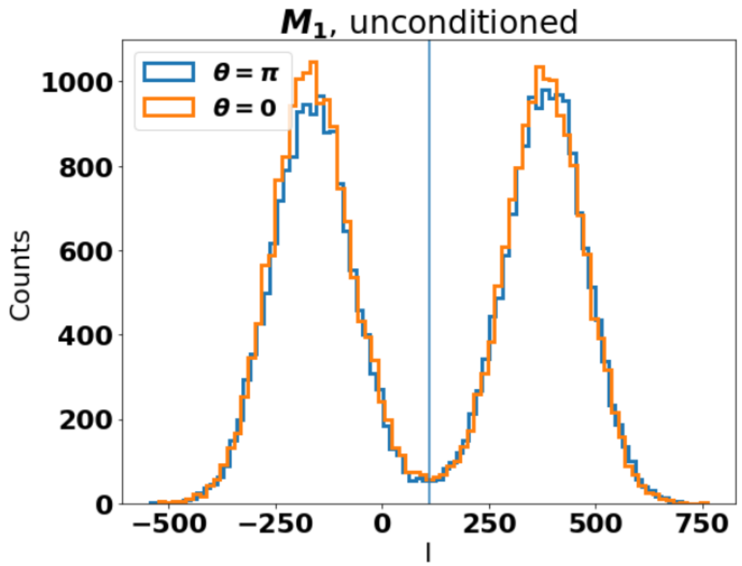

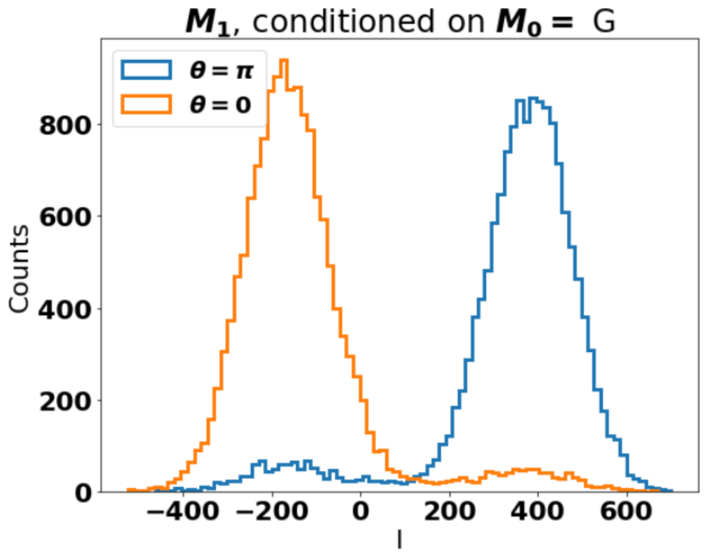

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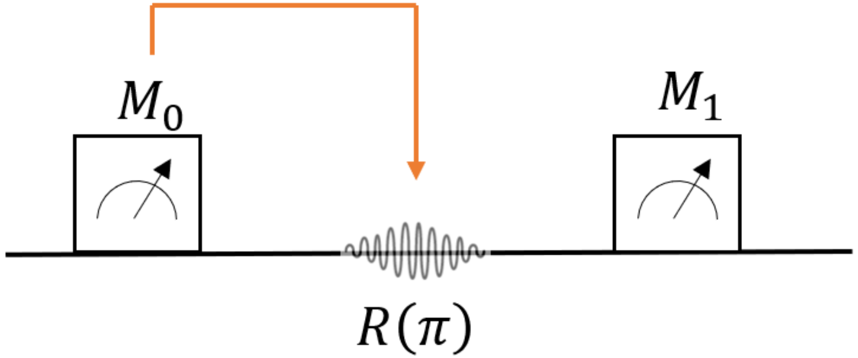
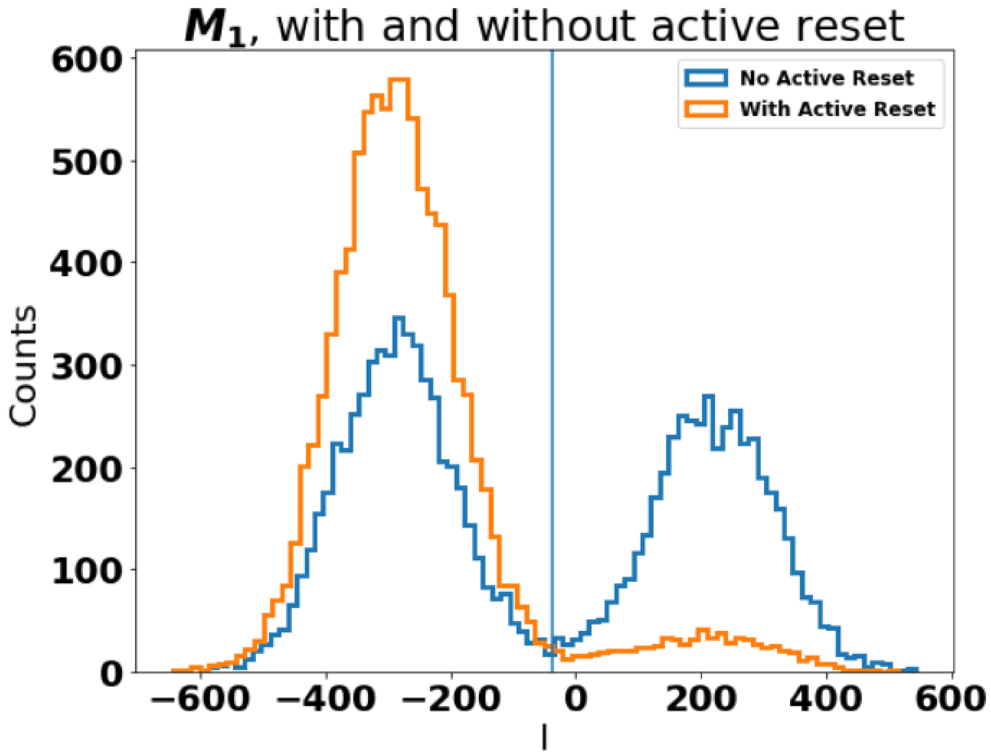
Executing the active reset protocol with the QICK

Stefanazzi 2021 arXiv: 2110.00557





Firmware and software is published and **open-source**
https://github.com/openquantumhardware/qick

Developed with team at Fermi National Lab
Review of Scientific Instruments **93**, 044709 (2022)

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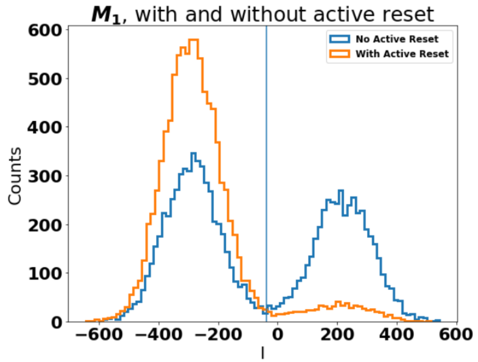
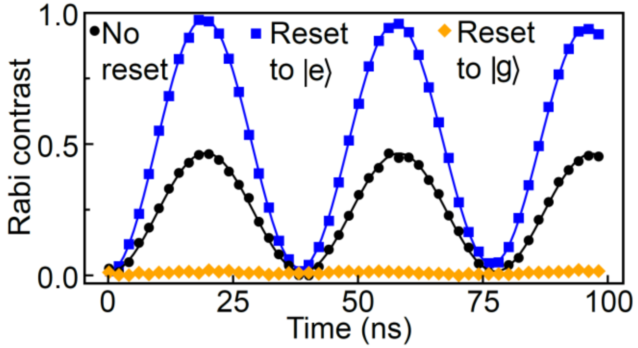
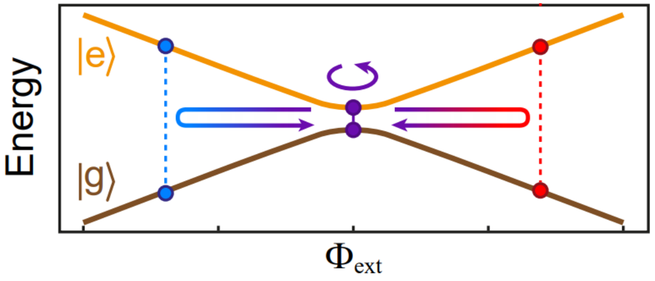
- Initialization via active reset
- **Ultrafast single qubit gates**
- High fidelity galvanically-coupled two qubit gates







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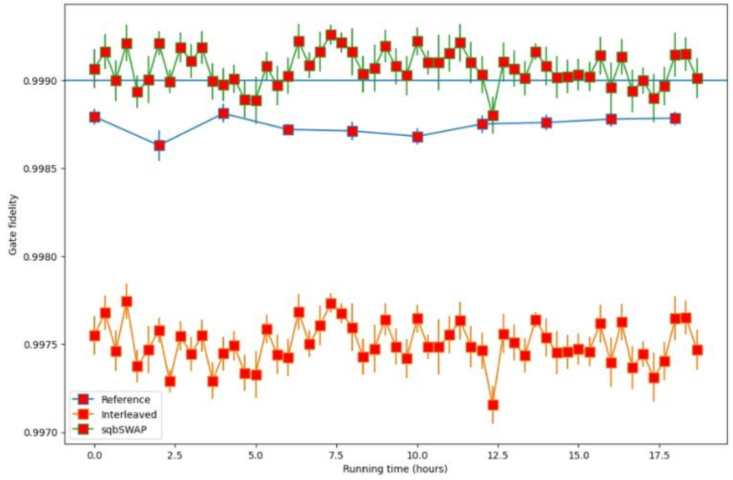
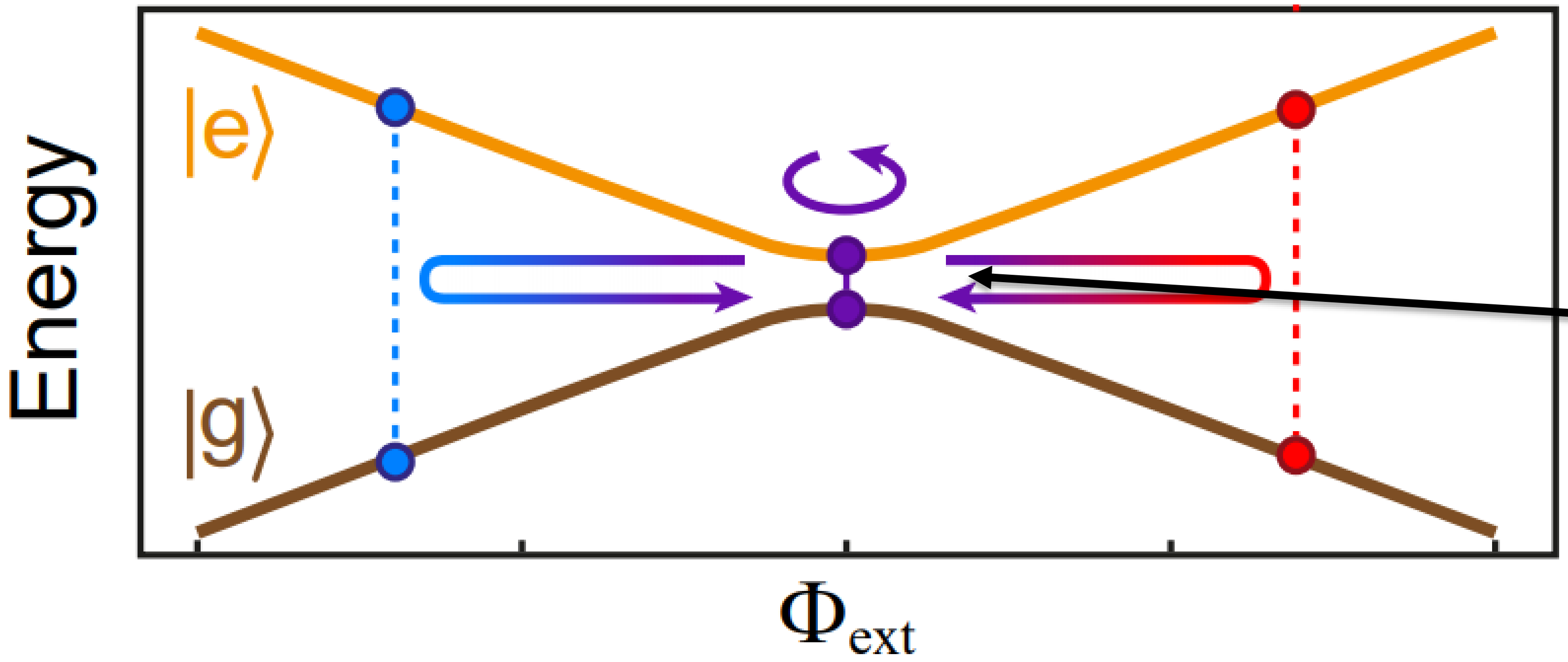


Fast single-cycle flux gates

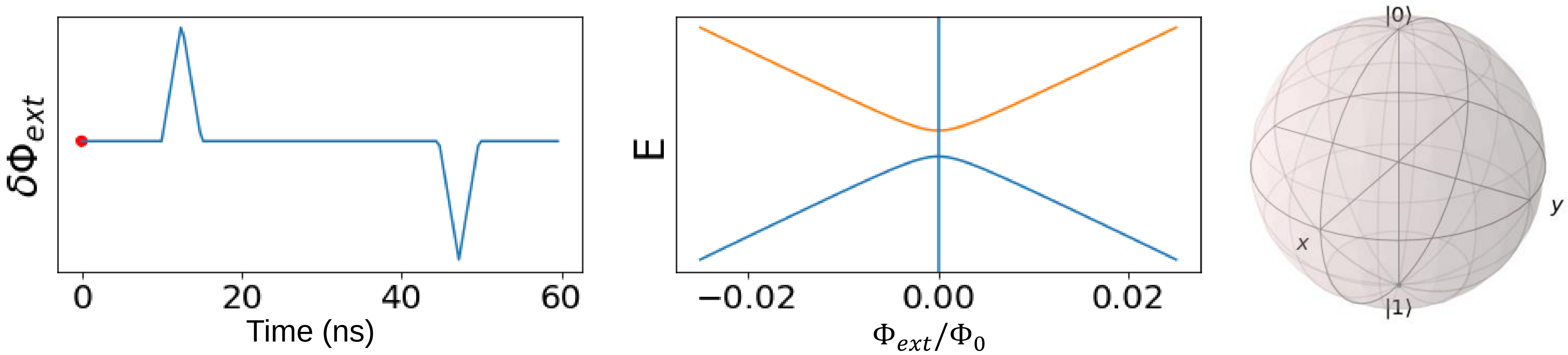


14-61 MHz

$$H/h = A\delta\Phi_{ext}\sigma_x + \frac{\omega_q}{2}\sigma_z$$

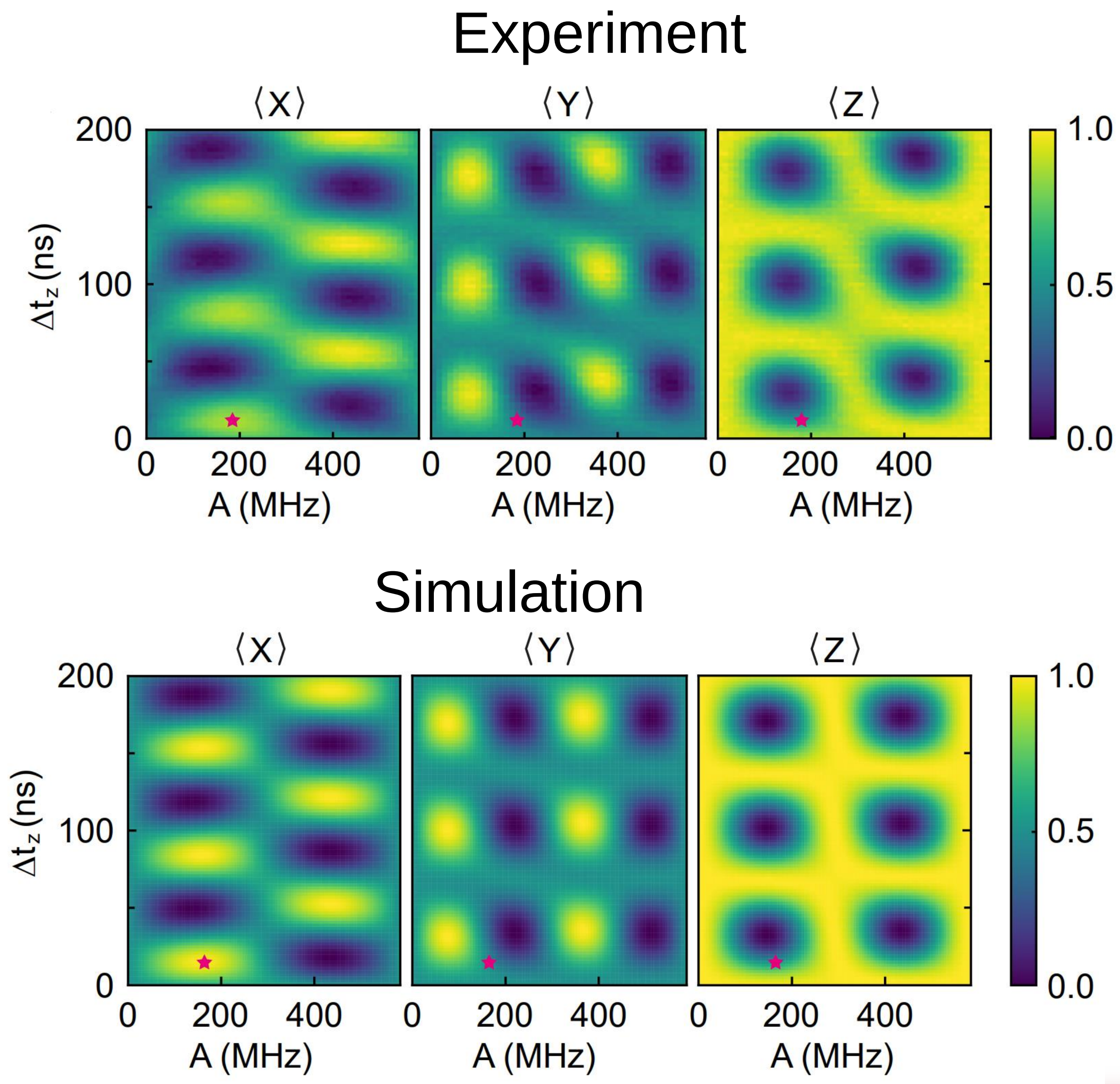
It's easy to have $A\delta\Phi_{ext} \gg \frac{\omega_q}{2}$

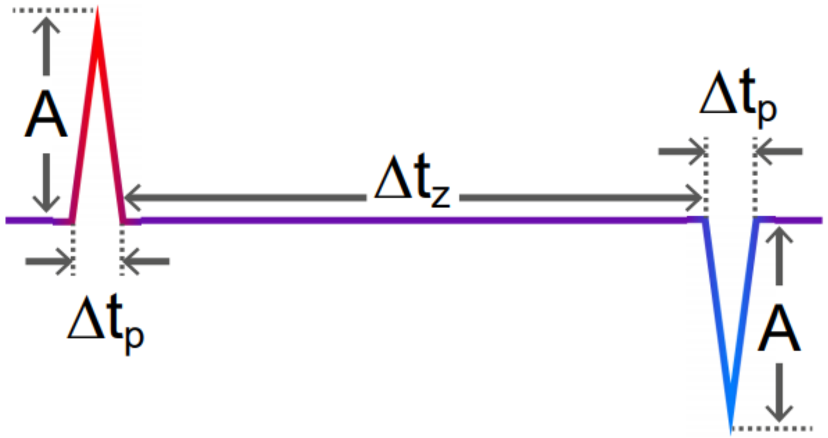
Fast single-cycle flux gates



- Lab frame
- Finished within a qubit cycle
- zero total net flux, effective echo for low frequency noise

Fast single-cycle flux gates





Duration (about 4x faster than previous gen)
Y/2: 5.5 ns Z/2: 6ns Y: 8ns (total pulse)

Qubit frequency **100x slower** than transmon,
gate speed **2x faster**!

Zhang, H. *et al* Phys. Rev. X 11, 011010 (2021)

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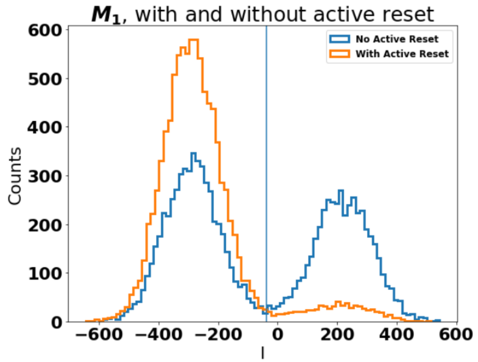

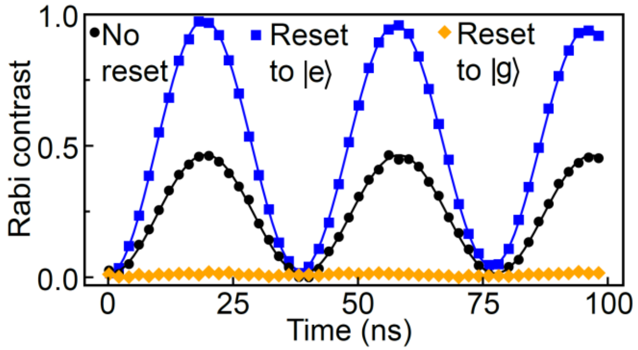

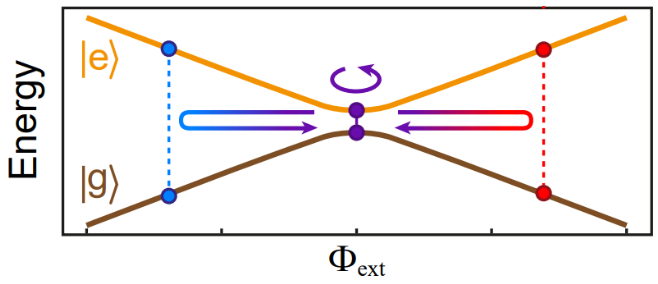

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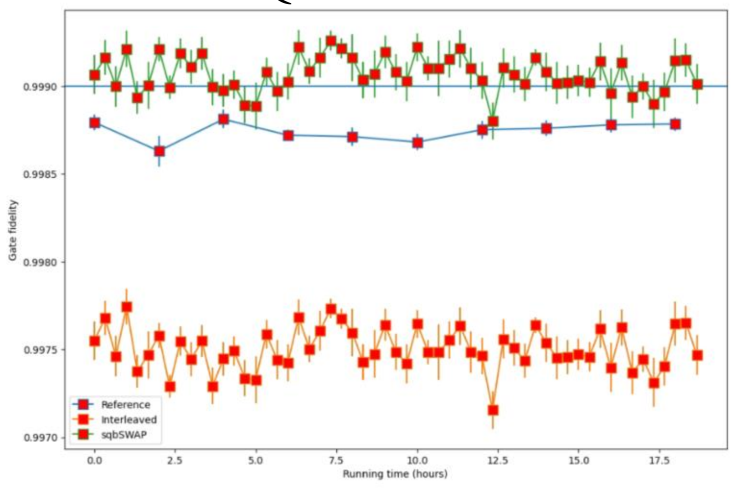
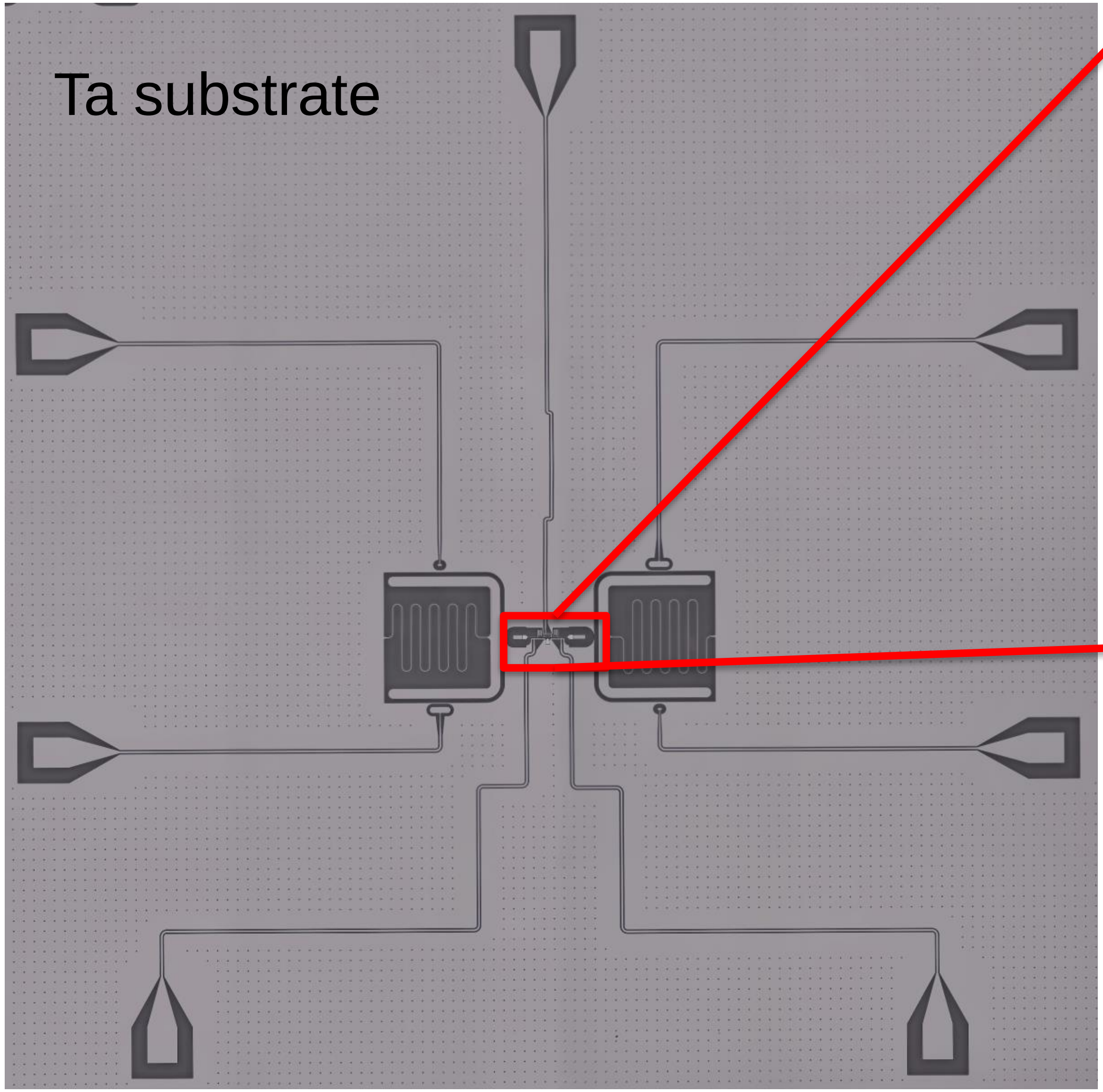
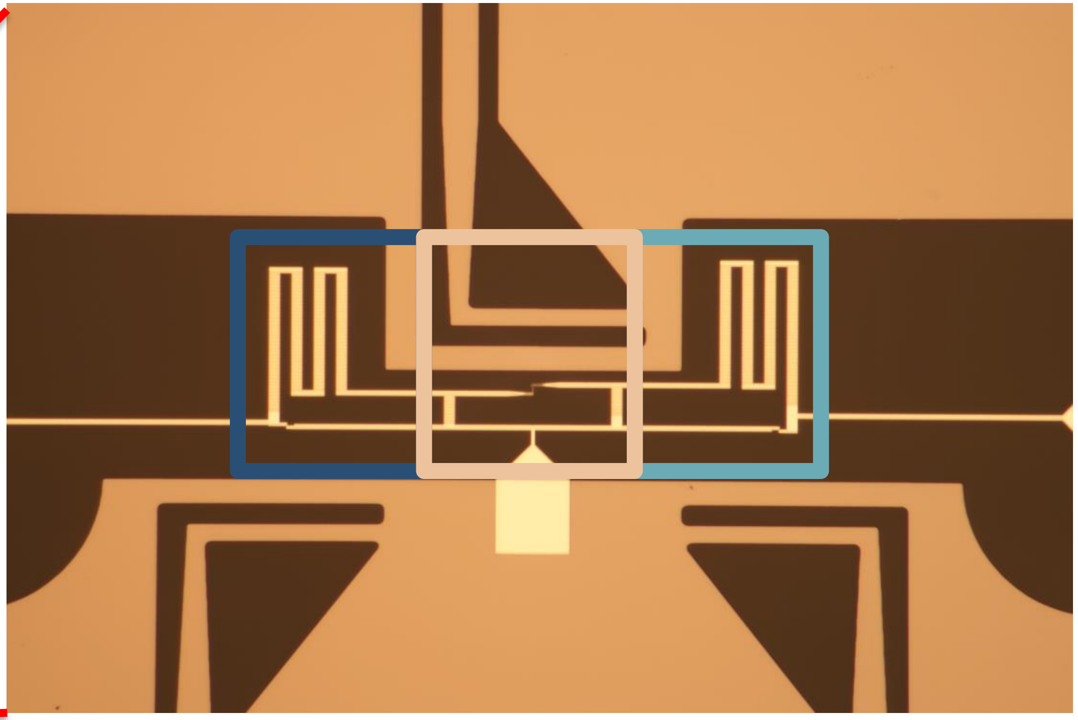
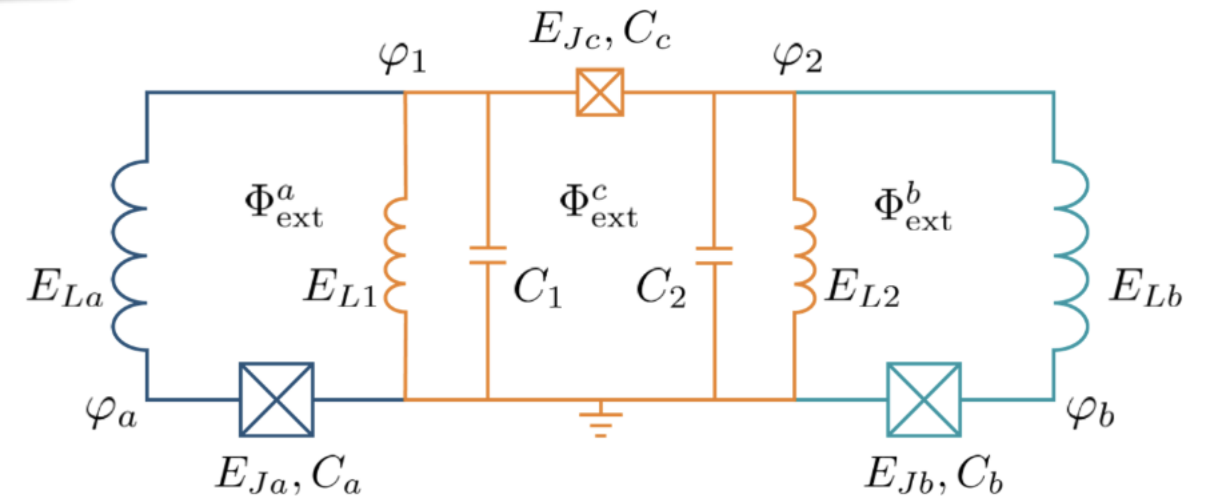


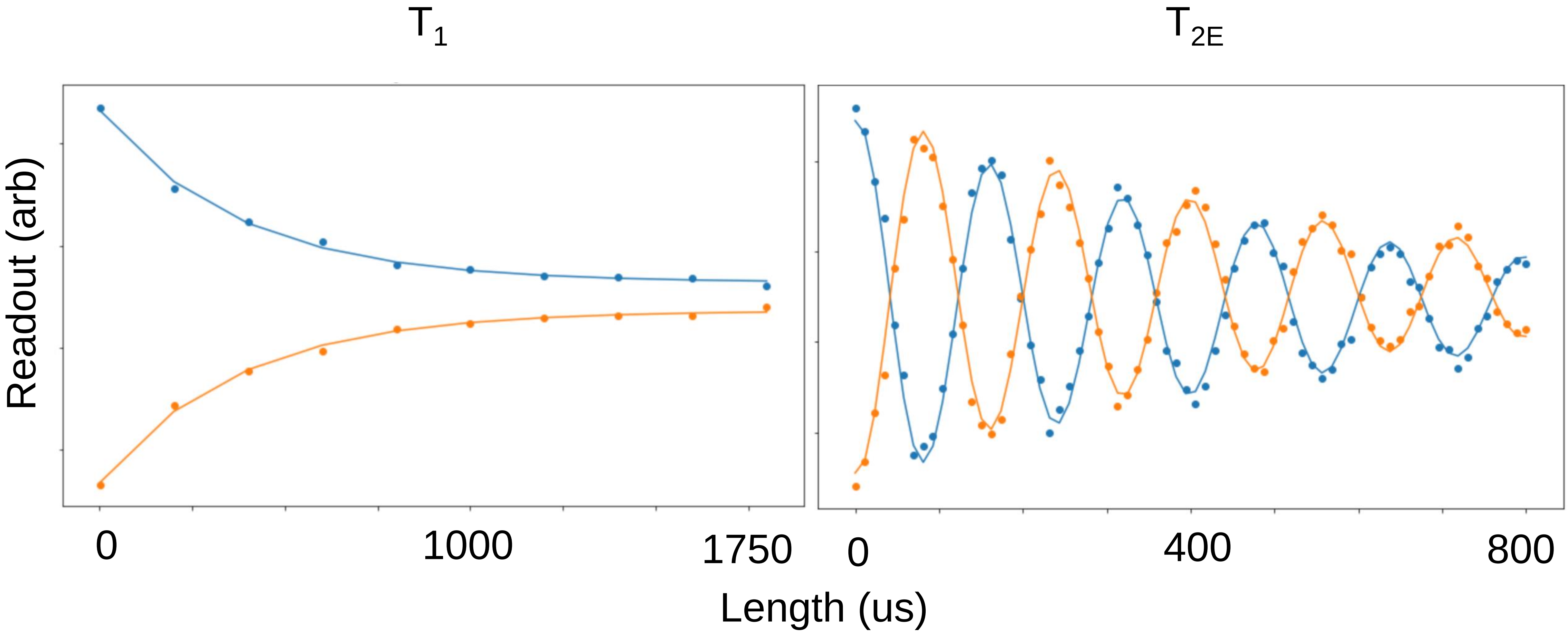
Optical Image of the device





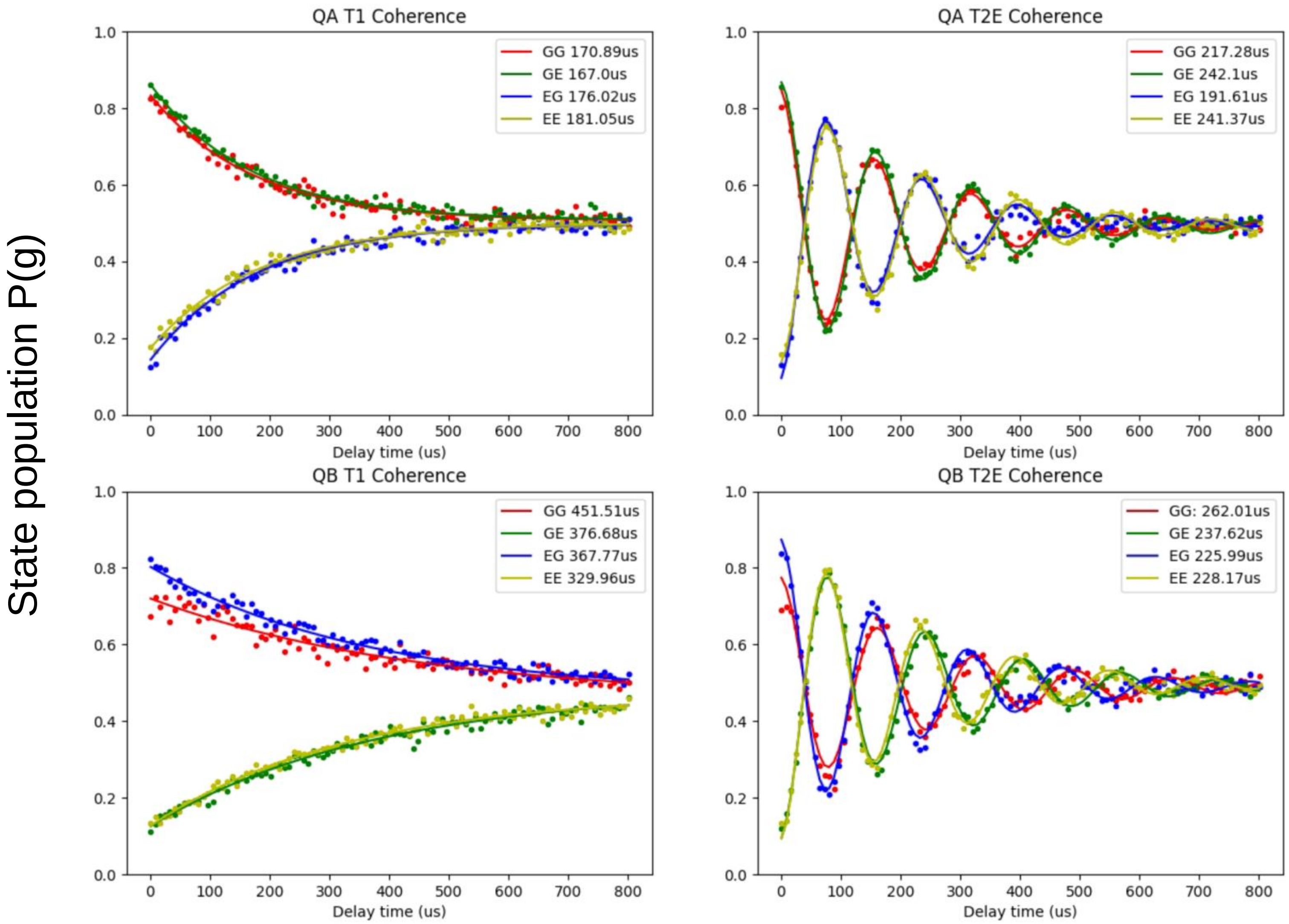


Coherences – best case (qB)



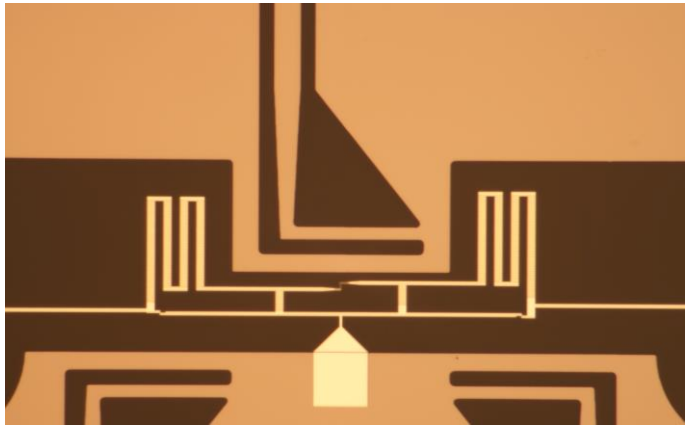
$T_1 \sim 370\ \mu s, T_{2E} \sim 580 us$

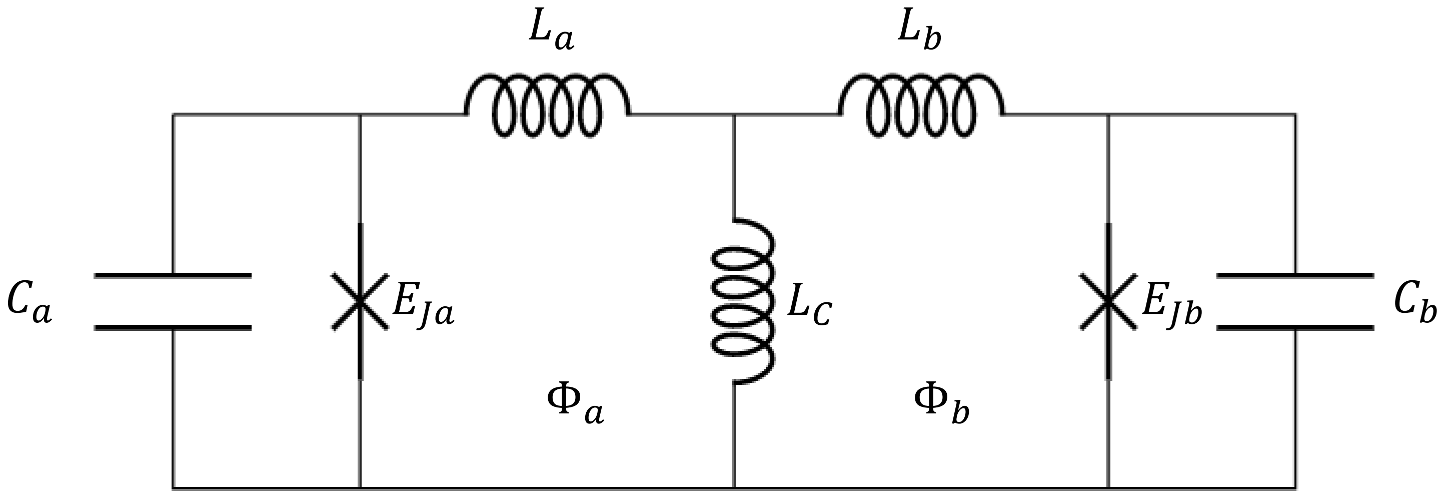
Coherences – working point



	Freq (MHz)	$T_1(us)$	$T_{2E}(us)$
qA	48.45	173.74	223.09
qB	61.76	381.48	238.45

Two inductively coupled fluxoniums





Two qubits are coupled via a shared inductor

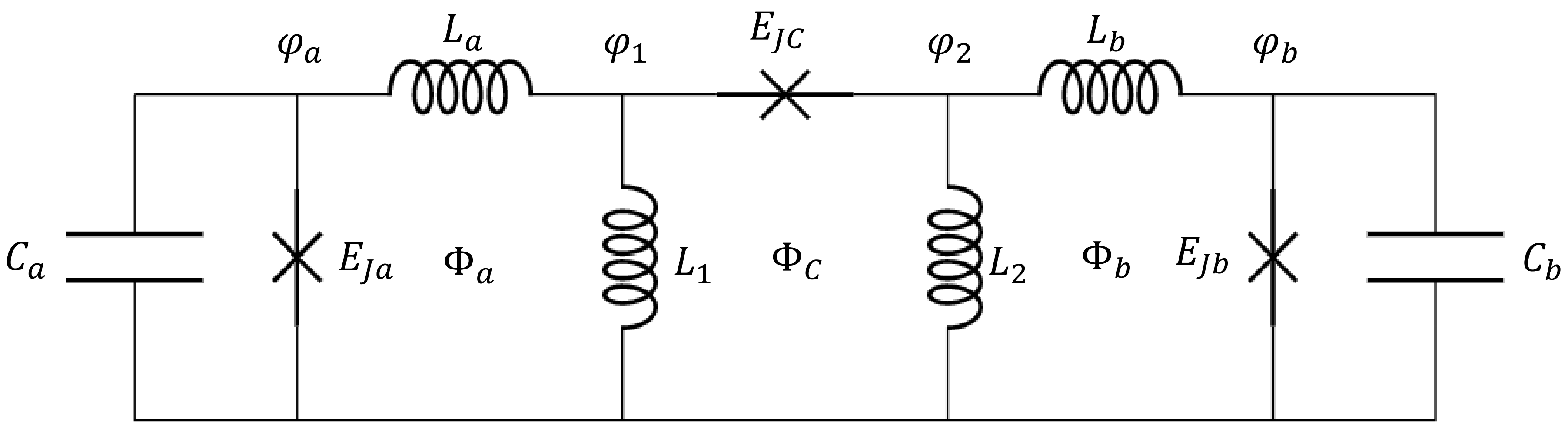
$$H \approx H_a + H_b + \frac{L_c}{L_a} E_L \varphi_a \varphi_b$$

In computational basis looks like

$$H_c \approx 4\pi^2 \frac{L_c}{L_a} E_L \sigma_x \sigma_x$$

Problem: It's always on!

Tunable Coupler – Circuit Analysis

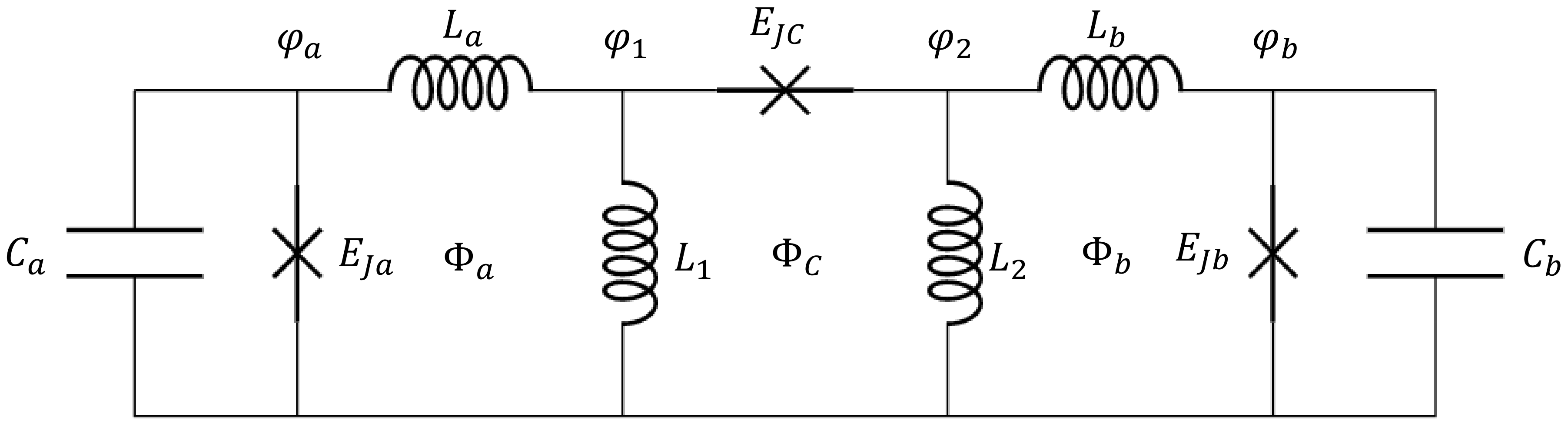


Now the shared inductance is tunable with coupler flux Φ_C

To the second order, it gives a tunable coupling term from 0 to

$$\sim E_{JC}\frac{E_{La}E_{Lb}}{E_{L1}E_{L2}}\varphi_a\varphi_b$$

Tunable Coupler – Circuit Analysis

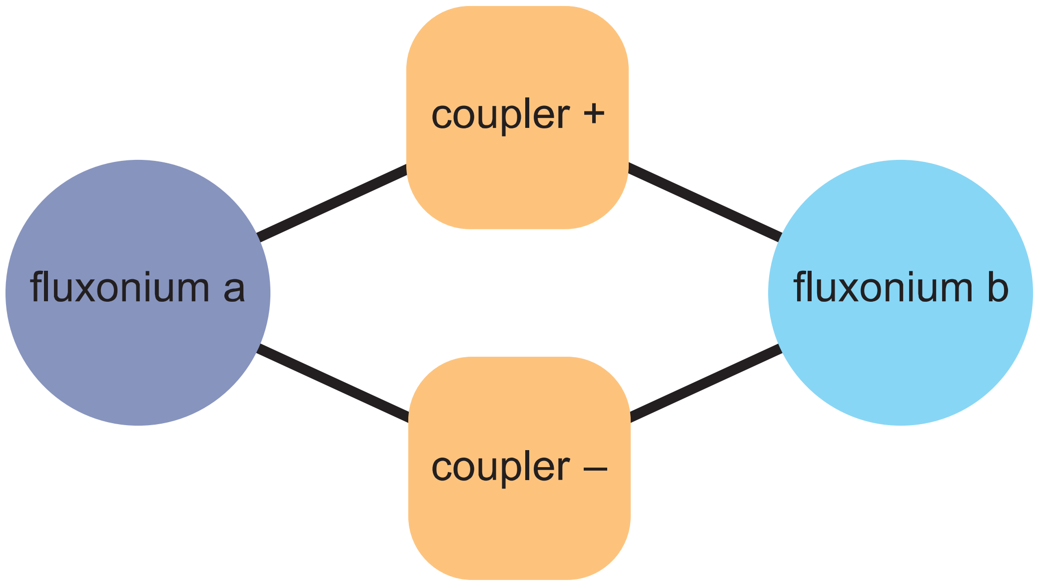


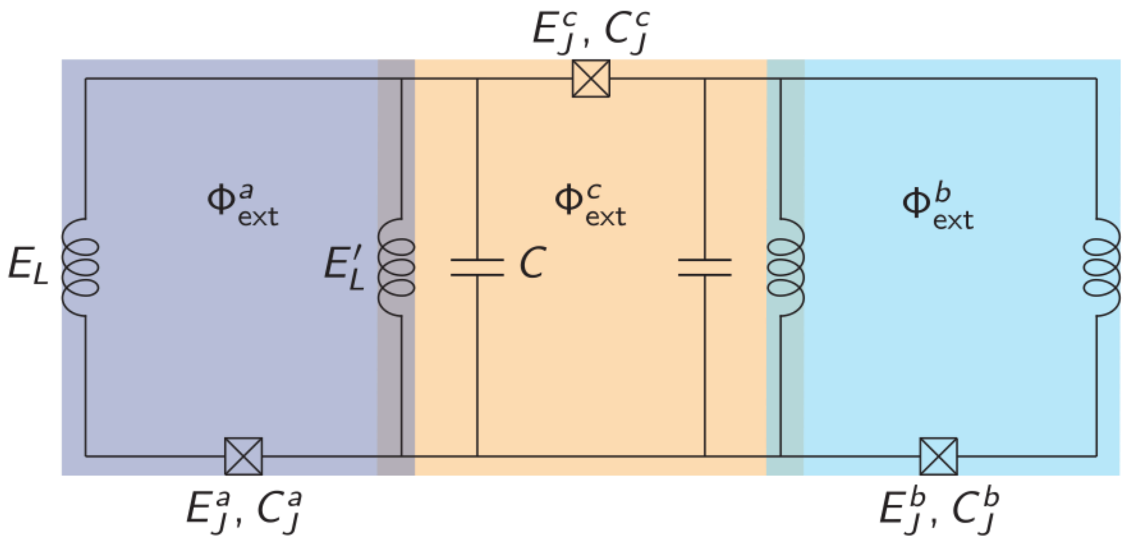
Decomposing the two qubit Hamiltonian into single qubit bases:

$$H = \omega_1\sigma_{z1} + \omega_2\sigma_{z2} + A_1(\Phi_\mathrm{a}, \Phi_C)\sigma_{x1} + A_2(\Phi_b, \Phi_C)\sigma_{x2} + J(\Phi_C, \Phi_a, \Phi_b)\sigma_{x1}\sigma_{x2}$$

Tunable-coupled fluxonium

- Couple two fluxonium qubits galvanically/inductively:
  - Tunable coupling
  - Exactly cancel coupling
  - Coupling strength can rival single qubit energy





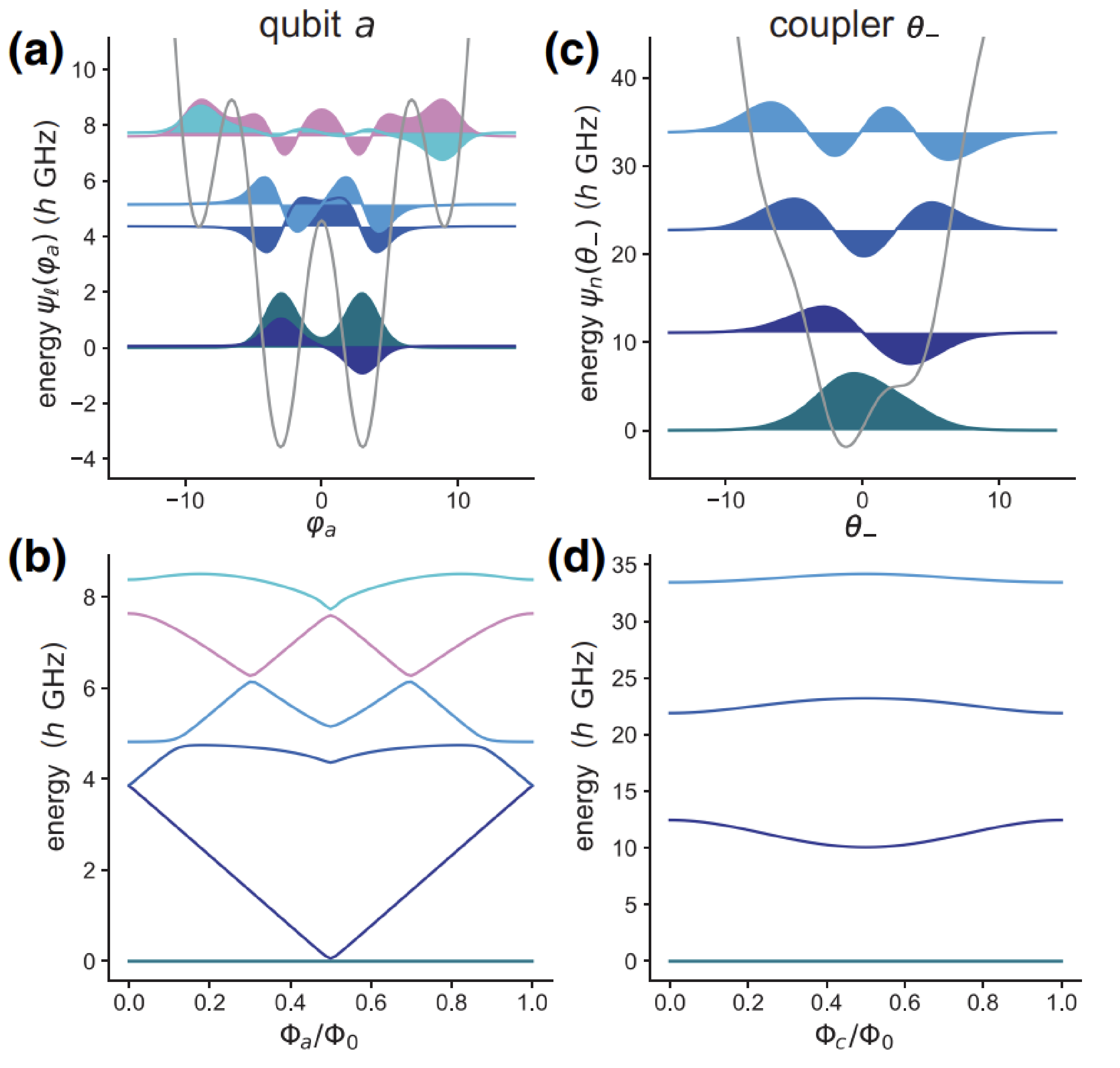
experiment: capacitive coupling

F. Bao *et al.* arXiv:2111.13504 (2021)
Q. Ficheux *et al.* PRX **11**, 21026 (2021)
H. Xiong *et al.* arXiv:2103.04491 (2021)
L. Ding *et al.* arXiv: 2304.06087 (2023)

theory: capacitive coupling

Y. Chen *et al.* arXiv:2110.00632 (2021)
K. N. Nesterov *et al.* PRX Quantum **2**, 020345 (2021)
I. N. Moskalenko *et al.* arXiv:2107.11550 (2021)

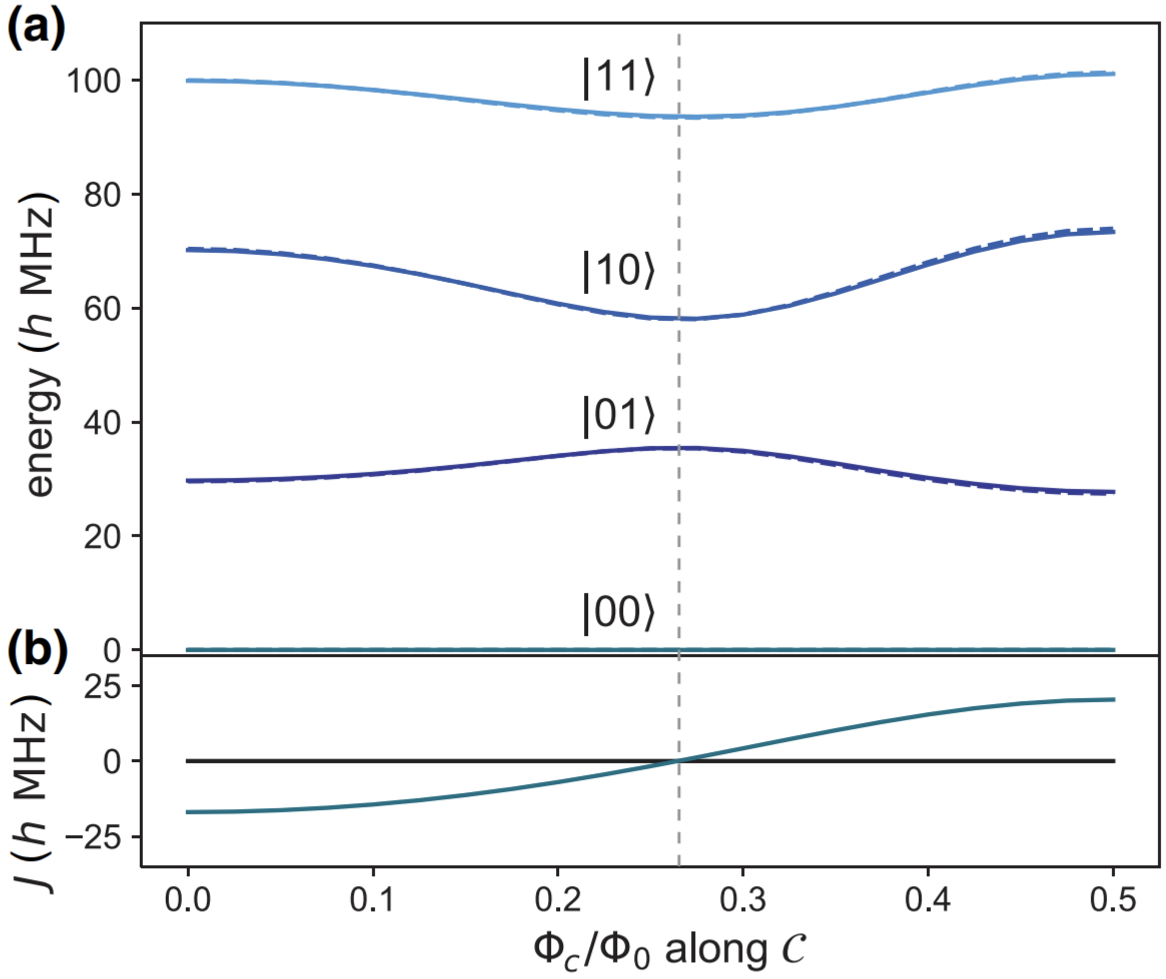
Tunable Coupler – Circuit Analysis



- Coupler E_L>>Qubit E_L
- Lowest coupler mode frequency ~ 10 GHz
- $J = J_+ + J_-$, thus when $J_+ = -J_-$, we turn off all coupling

DK. Weiss, PRX Quantum 3 (4), 040336

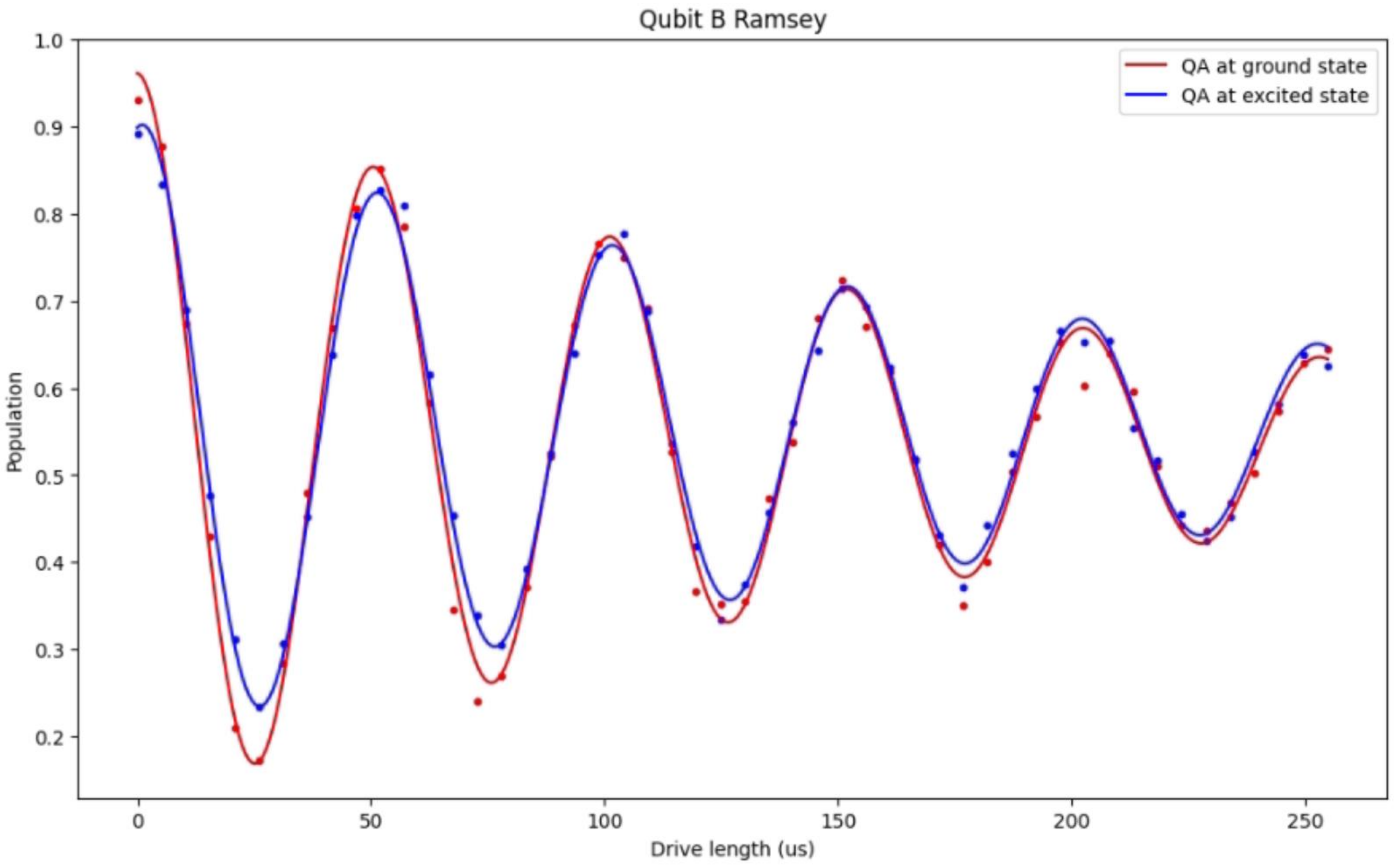
Tunable Coupler – Couplings vs coupler flux



Effective Hamiltonian

$$H = \omega_1\sigma_{z1} + \omega_2\sigma_{z2} + A_1(\Phi_a, \Phi_C)\sigma_{x1} + A_2(\Phi_b, \Phi_C)\sigma_{x2} + J(\Phi_C, \Phi_a, \Phi_b)\sigma_{x1}\sigma_{x2}$$

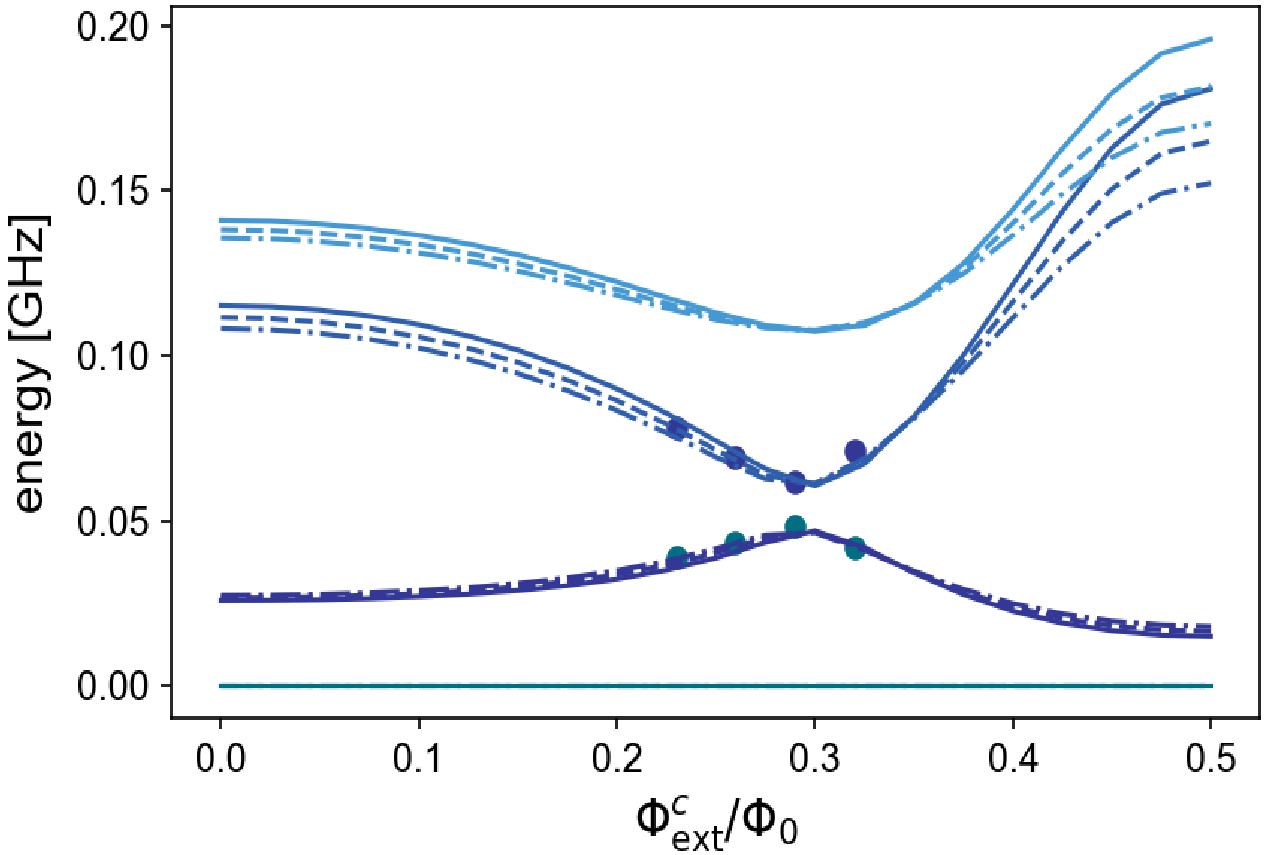
ZZ coupling measurement by Qubit B Ramsey



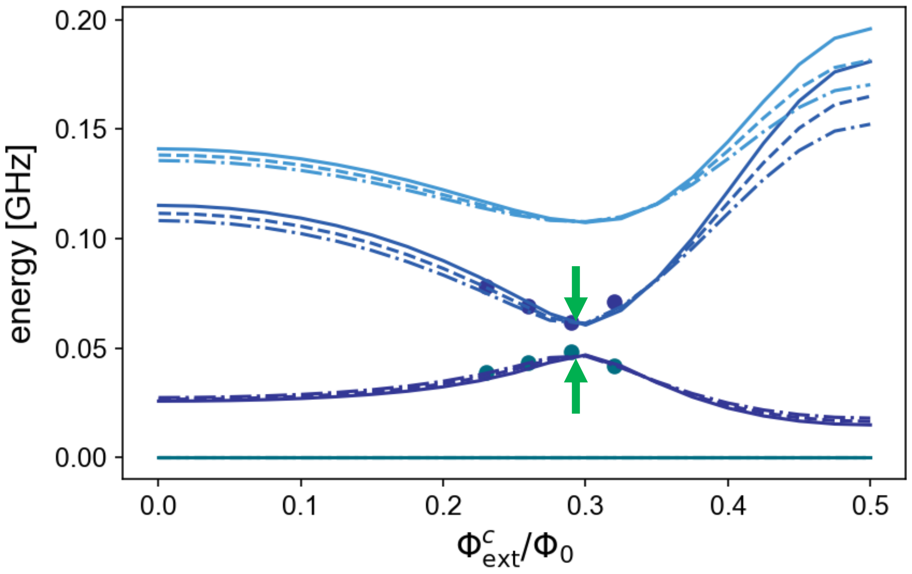
$T_2^* \approx 180\ \mu s \qquad ZZ \approx 0.2\ kHz$

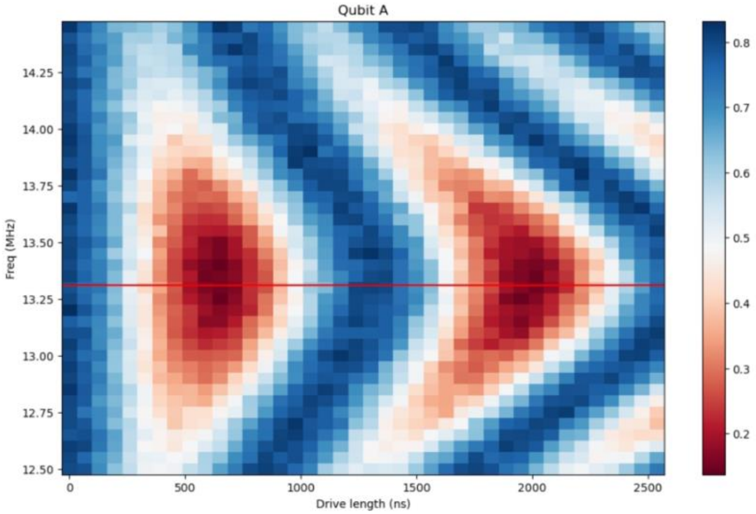
Coupler parameters

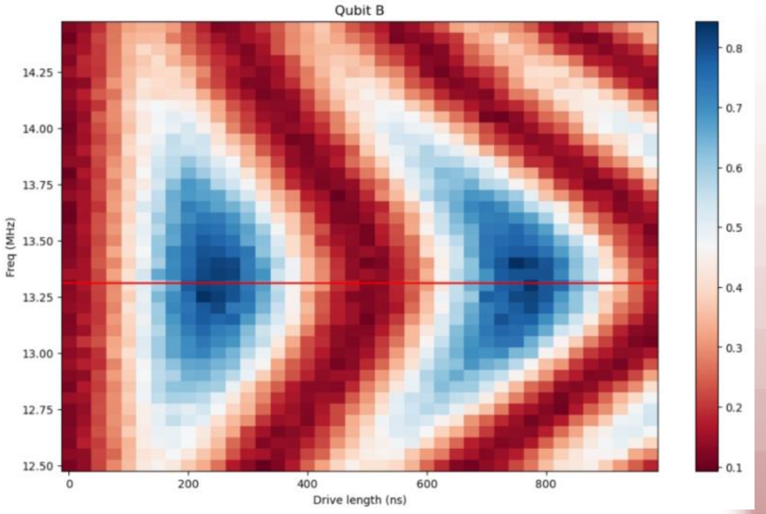
Checking coupler parameters by varying coupler Ec from -5% to 5%



Inducing a parametric interaction – iSwap



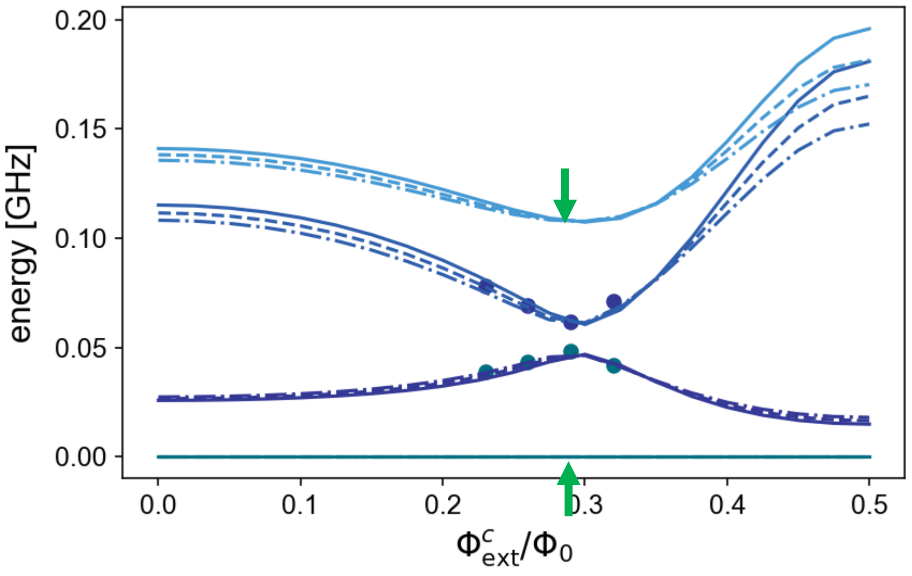


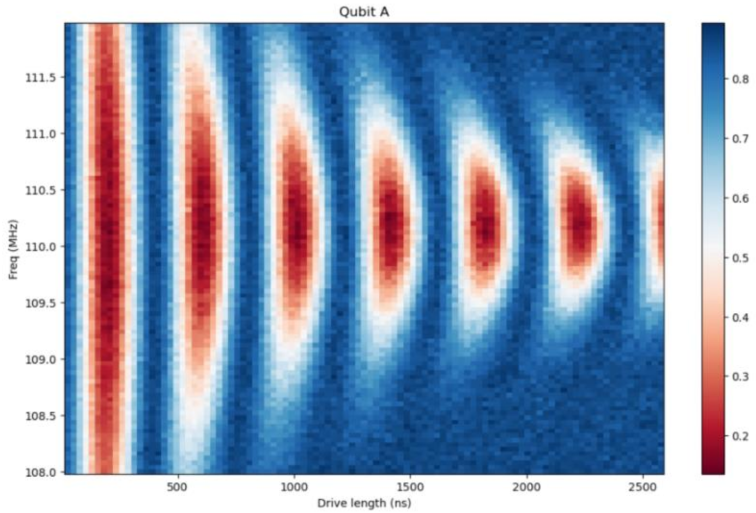


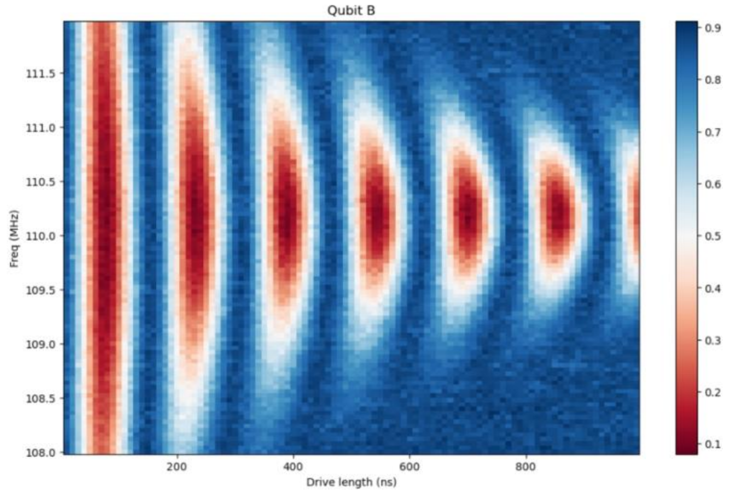
$$\omega_d = \omega_B - \omega_A$$

$\sqrt{iSWAP}$ gate length = 170ns

Inducing a parametric interaction - bSwap



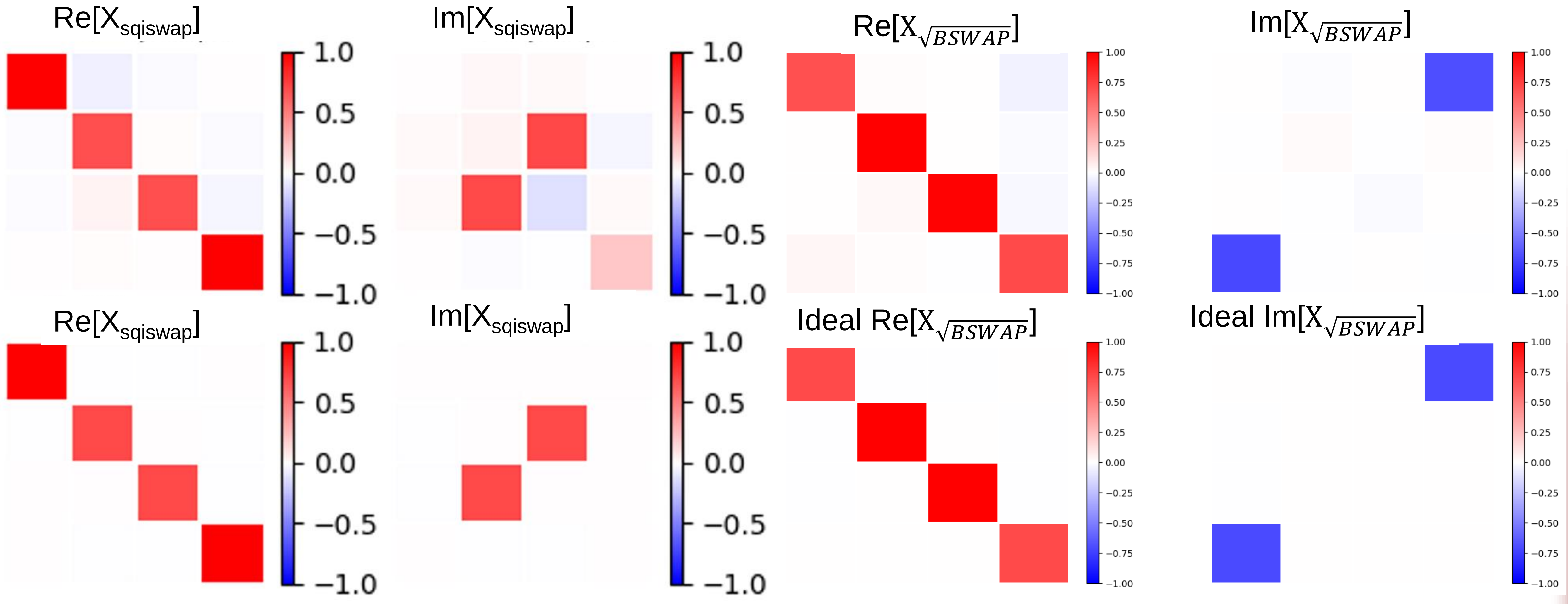




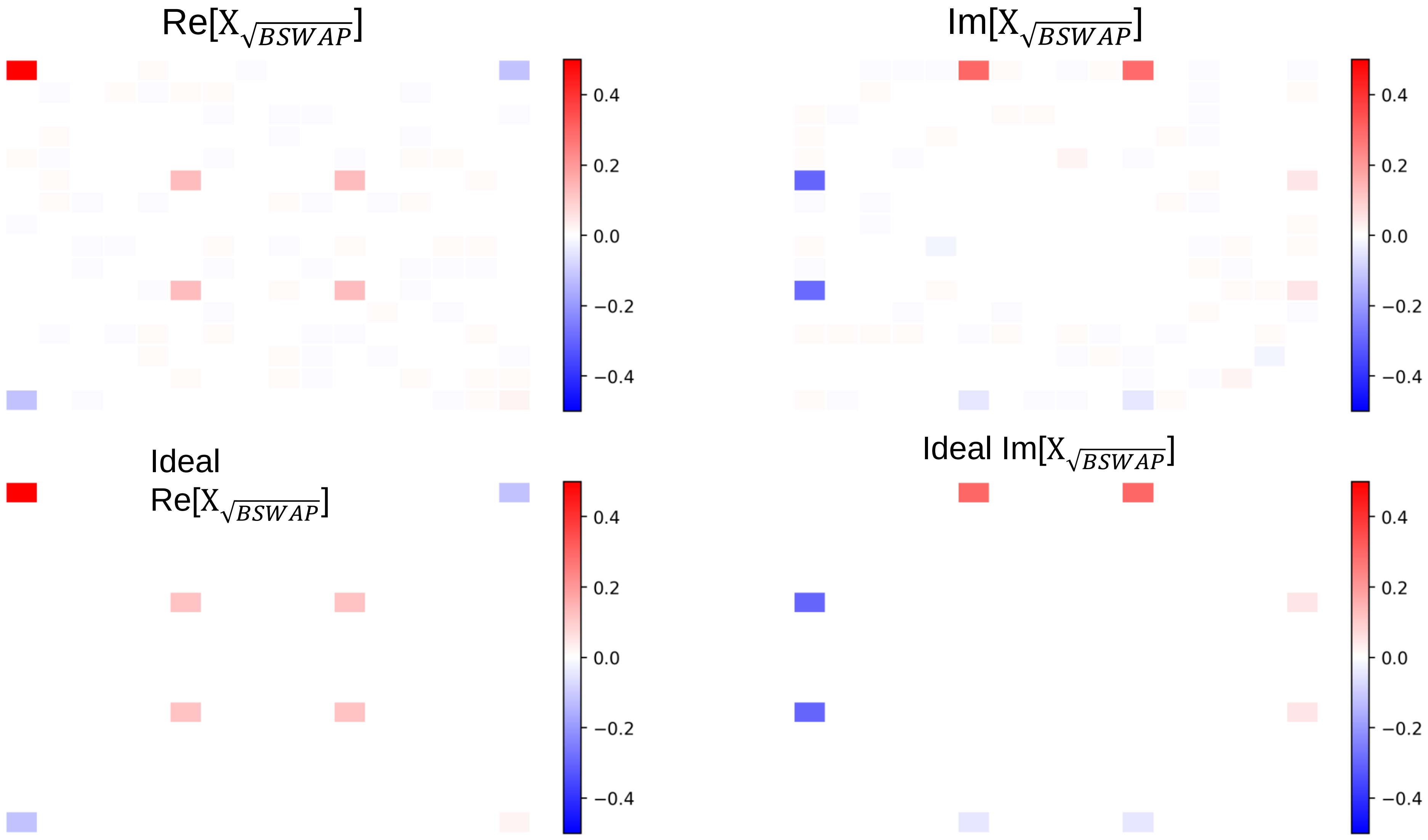
$$\omega_d = \omega_B + \omega_A$$

$\sqrt{bSWAP}$ gate length = 101ns

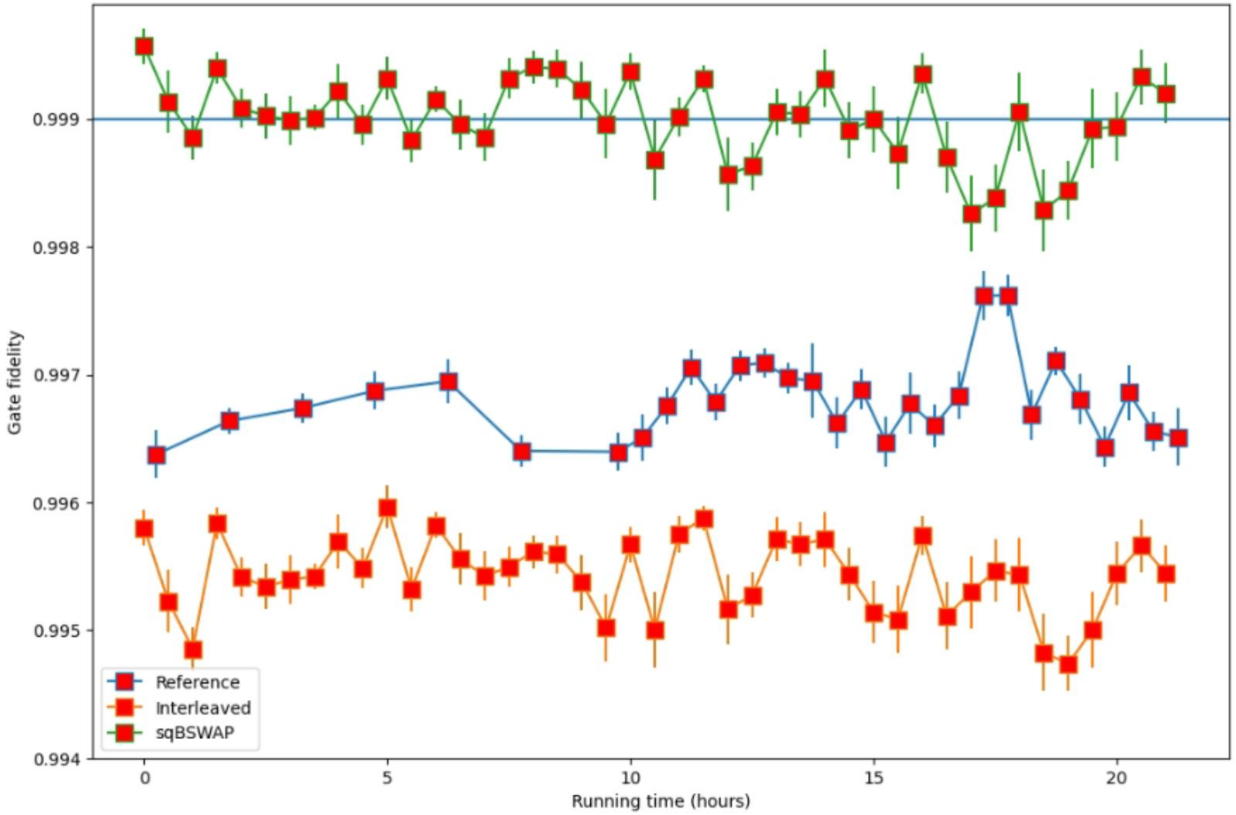
sqiSWAP and sqbSWAP Kraus matrix

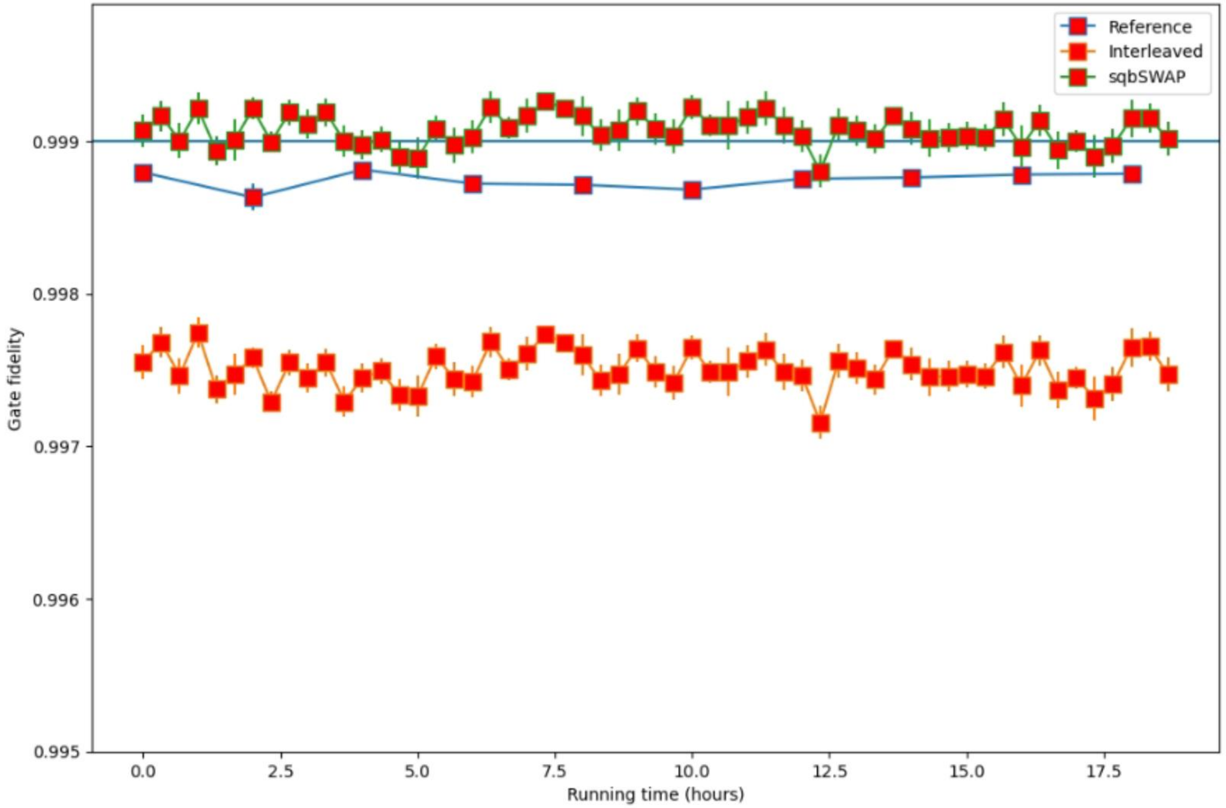


SQBSWAP Process Matrix



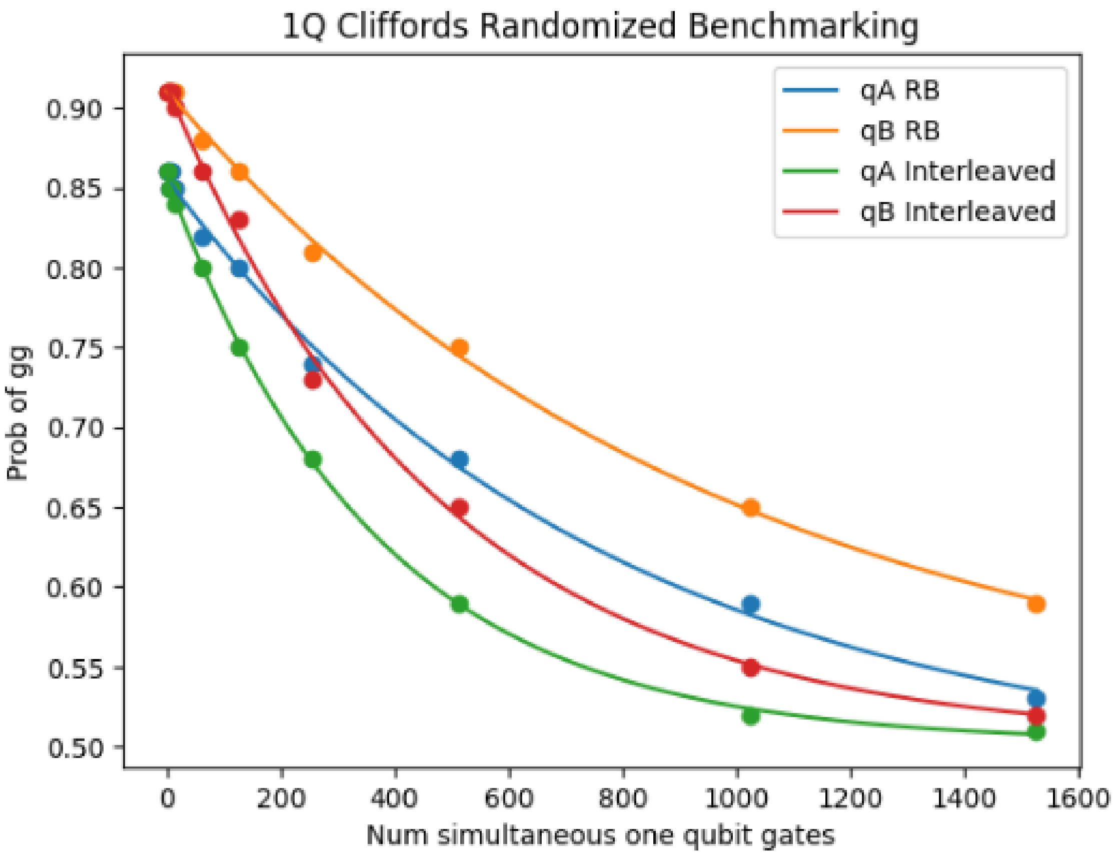
XEB results - sqbswap



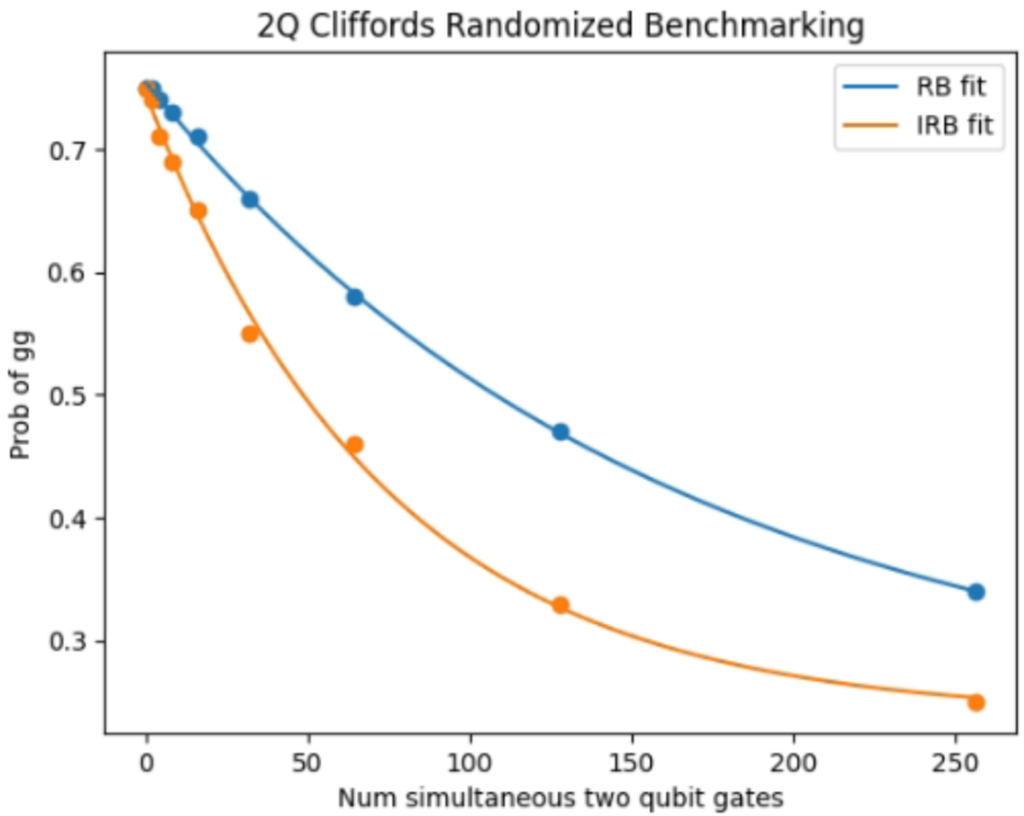


Interleaved Randomized Benchmarking

```
0.065% +/- 0.006% error per qA 1Q Clifford
0.052% +/- 0.004% error per qB 1Q Clifford
0.137% +/- 0.003% error per 1Q Clifford (Interleaved qA X/2)
0.104% +/- 0.006% error per 1Q Clifford (Interleaved qB X/2)
0.072% error per qA X2 gate (IRB extracted)
0.052% error per qB X2 gate (IRB extracted)
```

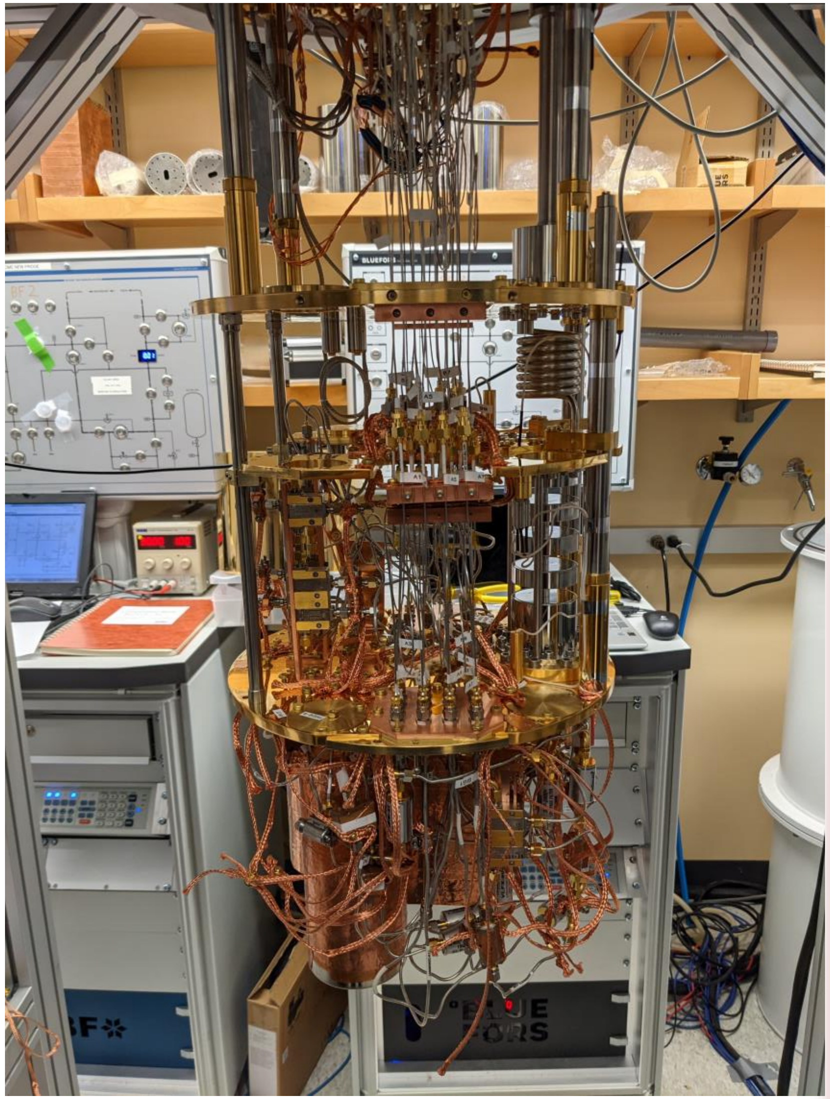



```
99.533 +/- 0.02% fidelity per average 2Q Clifford
98.986 +/- 0.064% fidelity per 2Q Clifford (Interleaved CNOT)
99.45% fidelity per CNOT gate (IRB)
```

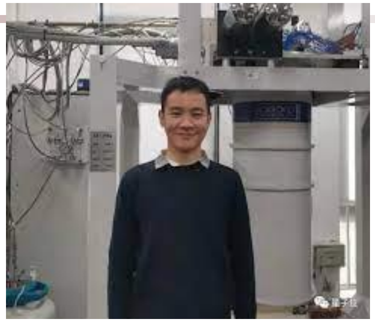


Major challenges?

- Very sensitive to flux bias noise (sweet spot <1e-4 Φ_0), and thus requires a very clean fridge ground
- Crosstalk between gates is very significant, requires the use of cancellation pulses, careful tuning procedures, and prevents gates from being played in parallel
- Scaling the galvanically coupled design might be difficult for large 2D array of qubits

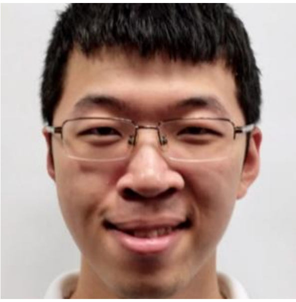


Thank you!



Yuwei Ma

Daniel Weiss



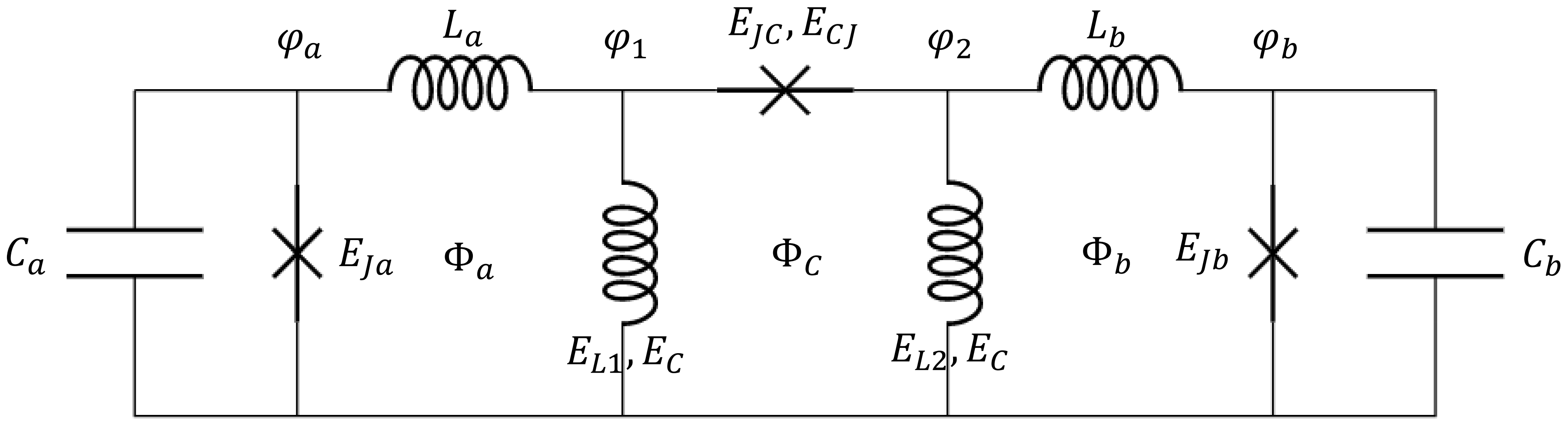
Helin Zhang

Sai Paivan Chitta

PI: David Schuster

PI: Jens Koch

Current sample parameters



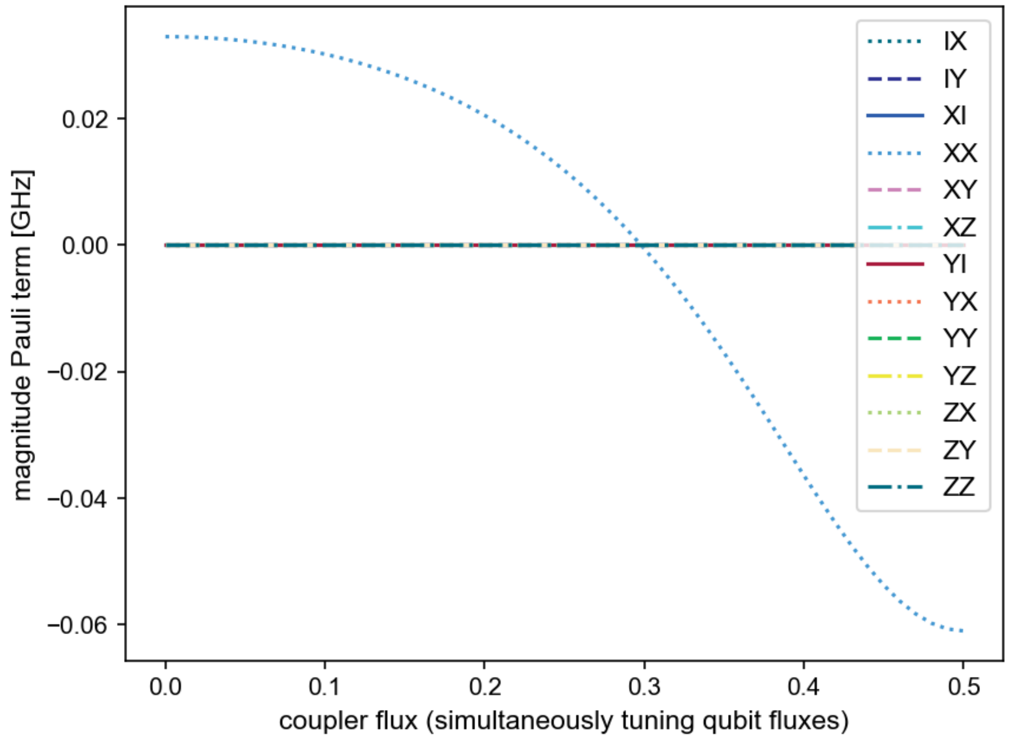
QubitA	Coupler	QubitB
$E_J \approx 5.837$ GHz	$E_J \sim 4.246$ GHz	$E_J \approx 4.930$ GHz
$E_C \approx 0.892$ GHz	$E_C \sim 11$ GHz	$E_C \approx 0.8655$ GHz
$E_L \approx 0.271$ GHz	$E_L \sim 3.52$ GHz	$E_L \approx 0.266$ GHz
$E_r \approx 7.241$ GHz		$E_r \approx 6.9857$ GHz

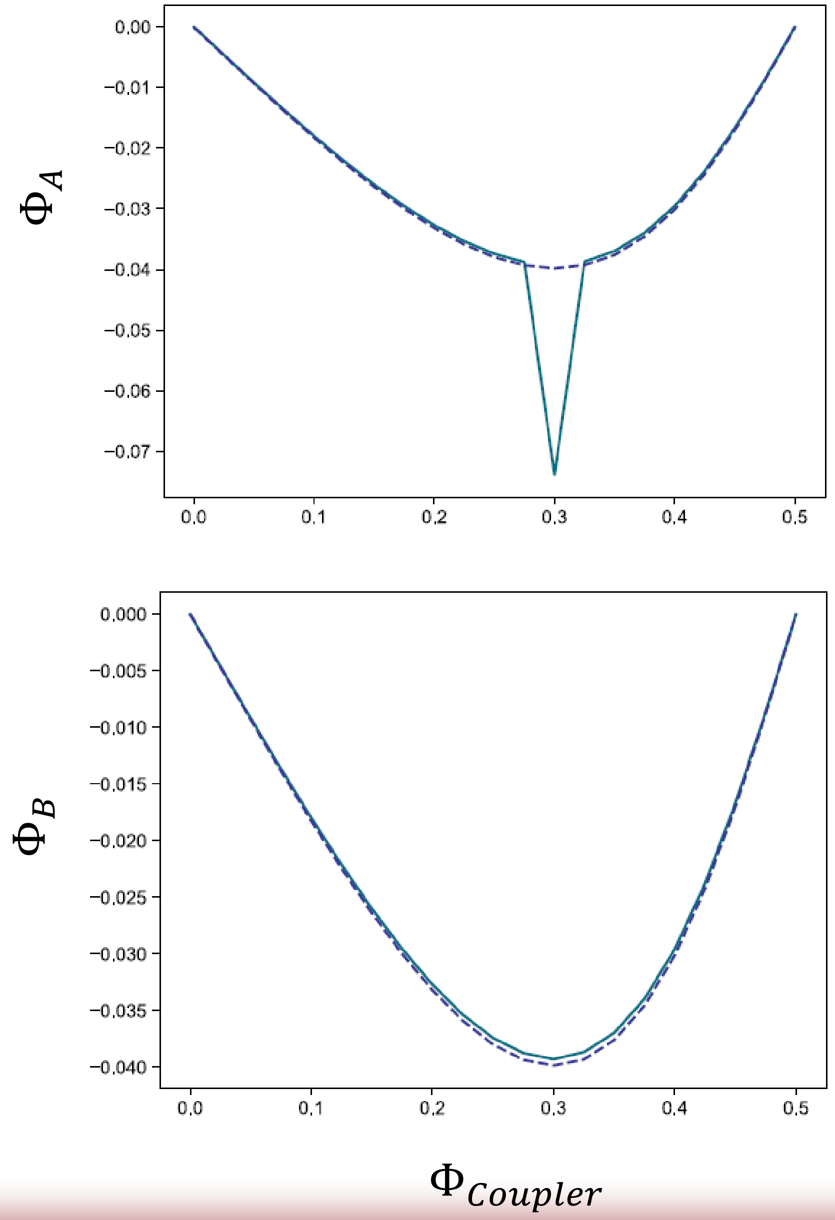
$\omega_{qa} \approx 48$ MHz

$\omega_{qb} \approx 61$ MHz

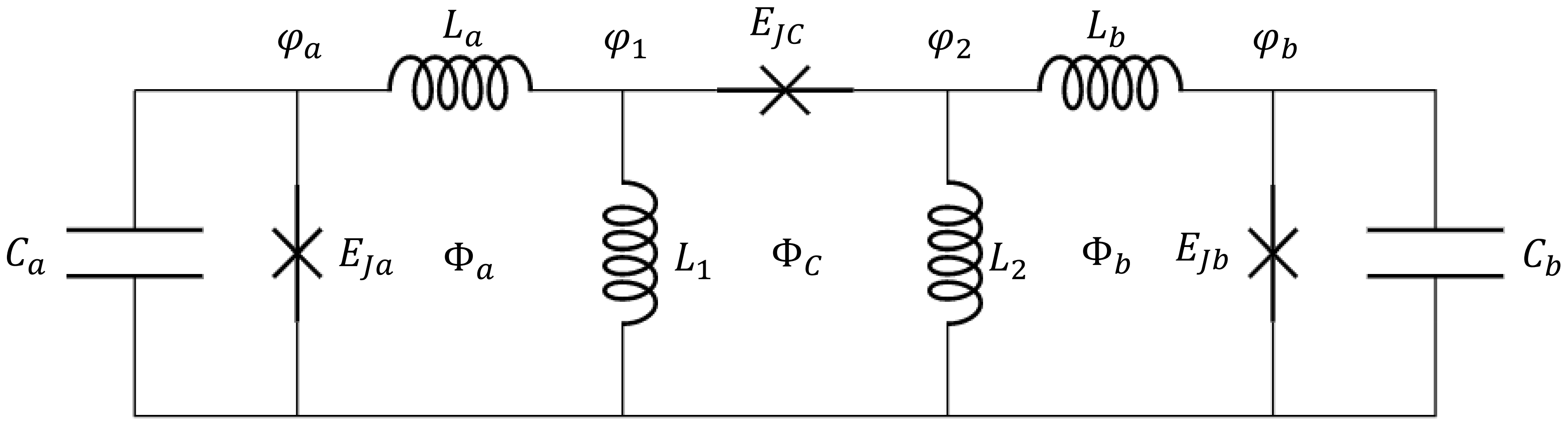
Tunable coupler performance

- Tunable from 0 – 60MHz using coupler flux, results in gate speeds of 20ns
- Requires adjustments to single qubit flux to remain on sweet spot





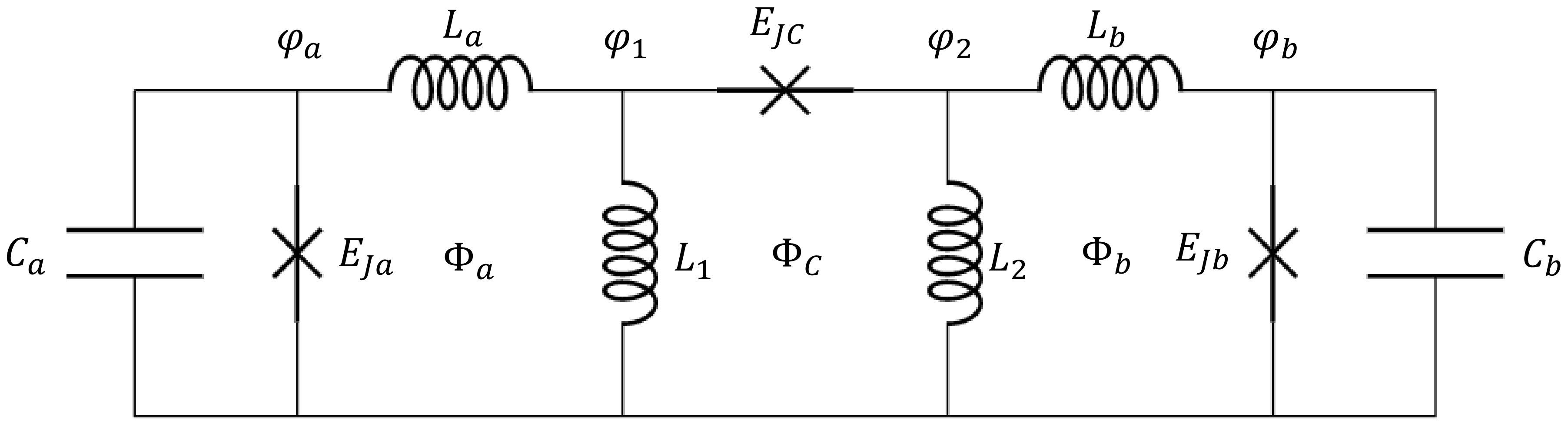
Tunable Coupler – Circuit Analysis



$$\varphi_+ = (\varphi_1 + \varphi_2)/2$$

$$\varphi_- = \varphi_1 - \varphi_2$$

Tunable Coupler – Circuit Analysis



$$H = 4E_{C_a} n_a^2 + 4E_{C_b} n_b^2 + \frac{E_{L_a}}{2}\varphi_a^2 + \frac{E_{L_b}}{2}\varphi_b^2 - E_{J_a}\cos(\varphi_a + \varphi_{e,a}) - E_{J_b}\cos(\varphi_b + \varphi_{e,b})$$

$H_a + H_b$

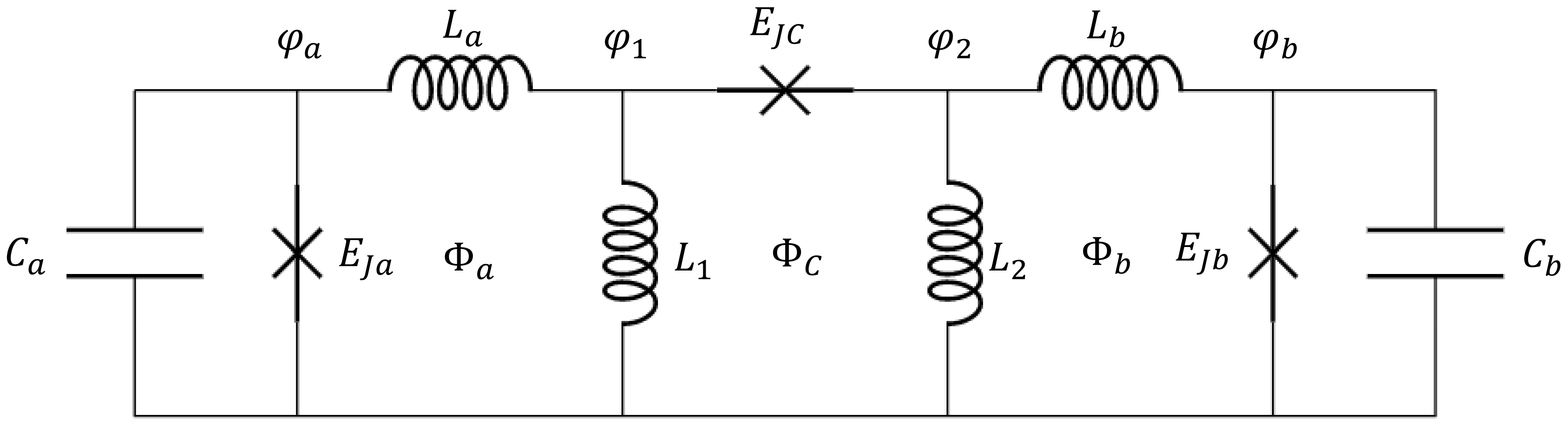
$H_+ + H_-$

$$2E_C n_+^2 + \frac{E_{\widetilde{C}} n_-^2}{2} + \frac{\widetilde{E}_{L_1} + \widetilde{E}_{L_2}}{2}\left(\varphi_+^2 + \frac{\varphi_-^2}{4}\right) - E_J\cos(\varphi_- + \varphi_e)$$ ~~$+ (\widetilde{E}_{L_1} - \widetilde{E}_{L_2})\varphi_+\varphi_-/2$~~

$$- E_{L_a}\varphi_a(\varphi_+ + \varphi_-/2) - E_{L_b}\varphi_b(\varphi_+ - \varphi_-/2).$$

H'

Tunable Coupler – Circuit Analysis



Calculate H' with perturbation theory

First order: $\varphi_a \rightarrow \varphi_a + \frac{\langle \psi_0^{(0)} | \varphi_- | \psi_0^{(0)} \rangle}{2}$, $\varphi_b \rightarrow \varphi_b - \frac{\langle \psi_0^{(0)} | \varphi_- | \psi_0^{(0)} \rangle}{2}$

Second order gives us a coupling term: $E_{La} E_{Lb} (\chi^- / 2 - 2\chi^+) \varphi_a \varphi_b$

where $\chi^- \equiv \sum_{m \neq 0} \frac{|\langle \psi_0^- | \varphi_- | \psi_m^- \rangle|^2}{e_m^- - e_0^-}$ $\chi^+ \equiv \frac{|\langle \psi_0^+ | \varphi_- | \psi_1^+ \rangle|^2}{\omega_+}$

XEB results - sqiswap