IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 2-DI-I-3 given at ISEC, 28 July-1 August 2019, Riverside, USA.

# Digital coherent control of a superconducting qubit

**Abstract:** 1570559977
**Talk:** 2-DI-I-3

Edward Leonard Jr.[1], Matthew Beck[1], JJ Nelson[2], Kenneth Dodge[2], Caleb Howington[2], Jaesung Ku[2], Alex Kirichenko[3], Daniel Yohannes[3], Oleg Mukhanov[3], Britton Plourde[2], Maxim Vavilov[1], Robert McDermott[1]

1 – Dept. of Physics, *University of Wisconsin – Madison, Madison, WI, USA*
2 – Dept. of Physics, *Syracuse University, Syracuse, NY, USA*
3 – *SeeQC, Inc, Elmsford, NY, 10523*

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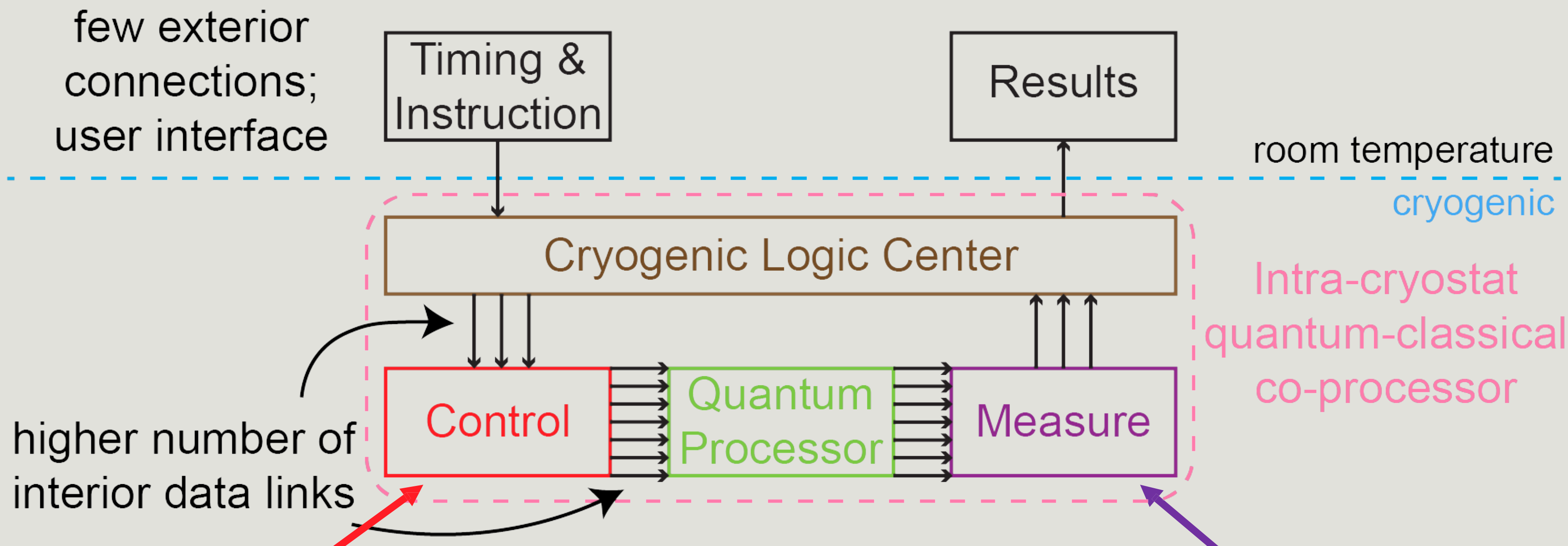
# The Vision




E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

A. Opremcak *et al*., Science **341**: 6408 (2018)

- SFQ a natural candidate
- Control and feedback with lower latency
- Reduced wiring overhead and heat load from 300 K
- Smaller overall system footprint in both size and power

R. McDermott *et al*., *QST* **3**, 2 (2018)

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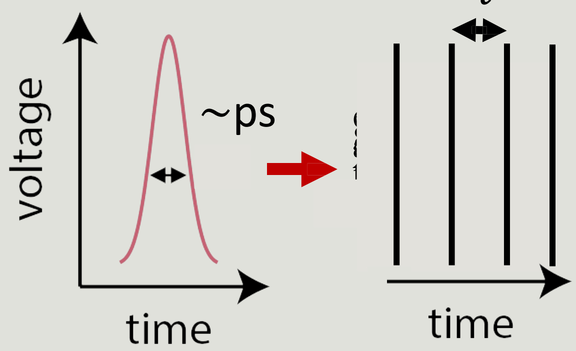
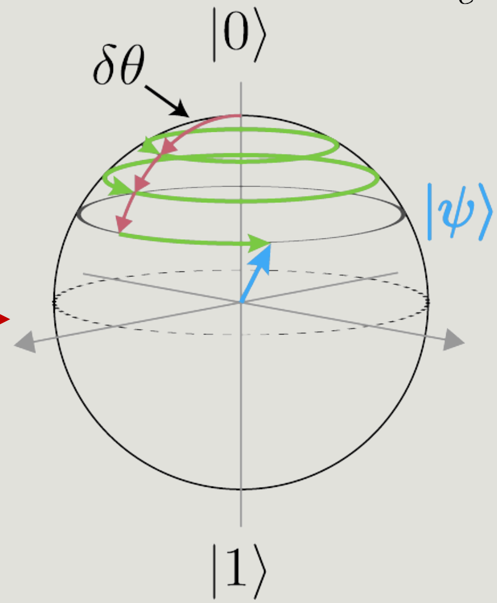
# Resonant SFQ Pulse Trains for Rotations

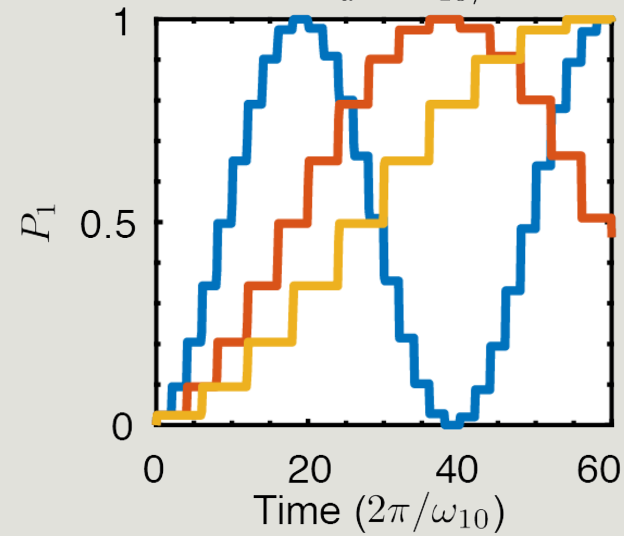
$$\int V(t)dt = \Phi_0$$




$$\tau = n\frac{2\pi}{\omega_{10}}$$

$$\delta\theta = C_c\Phi_0\sqrt{\frac{2\omega_{10}}{\hbar C}}$$



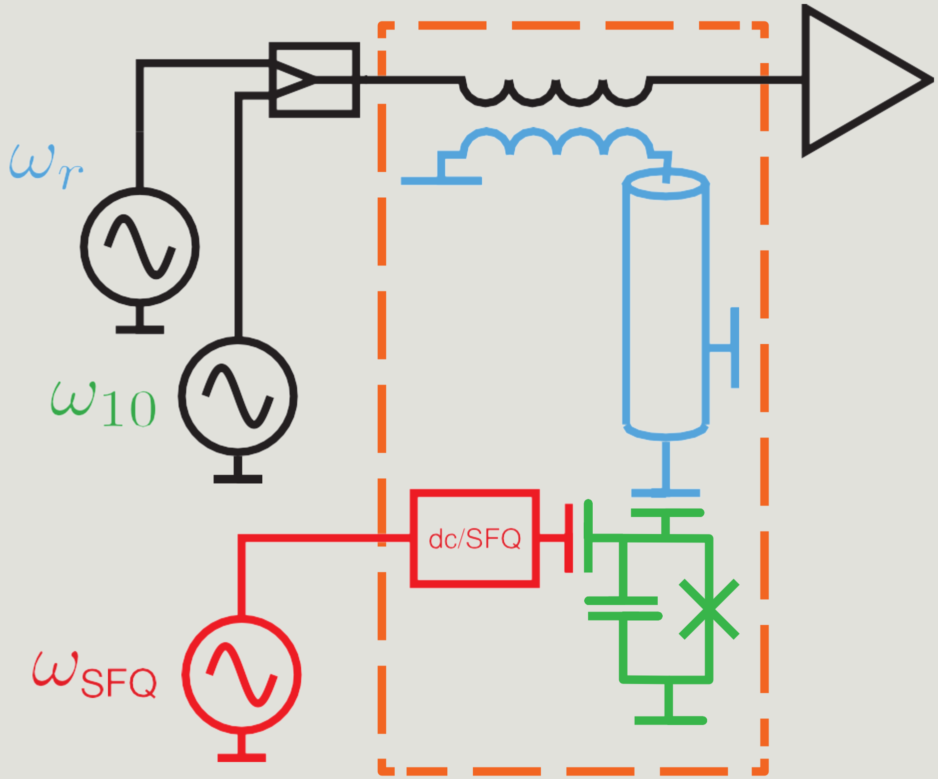

$$H_{\mathsf{SFQ}}(t) = C_c\Phi_0\sqrt{\frac{\hbar\omega_{10}}{2C}}\left(\delta(t)+\delta(t-\tau)+\cdots+\delta(t-n_\pi\tau)\right)\hat{\sigma}_y$$

R. McDermott & M. Vavilov., *Phys. Rev. Appl.* **2**, 014007 (2014)

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

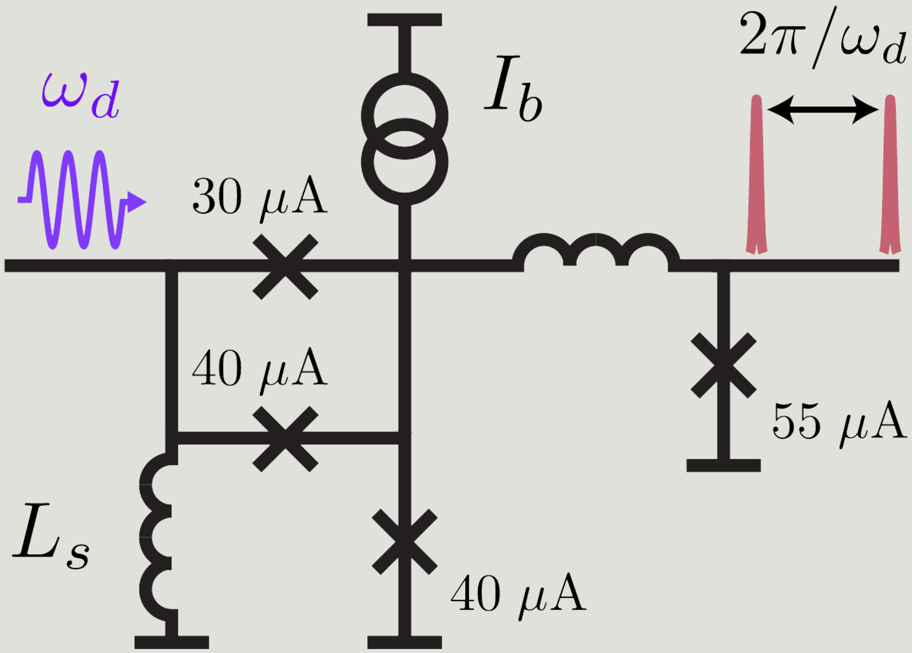
# Approach to SFQ-based control

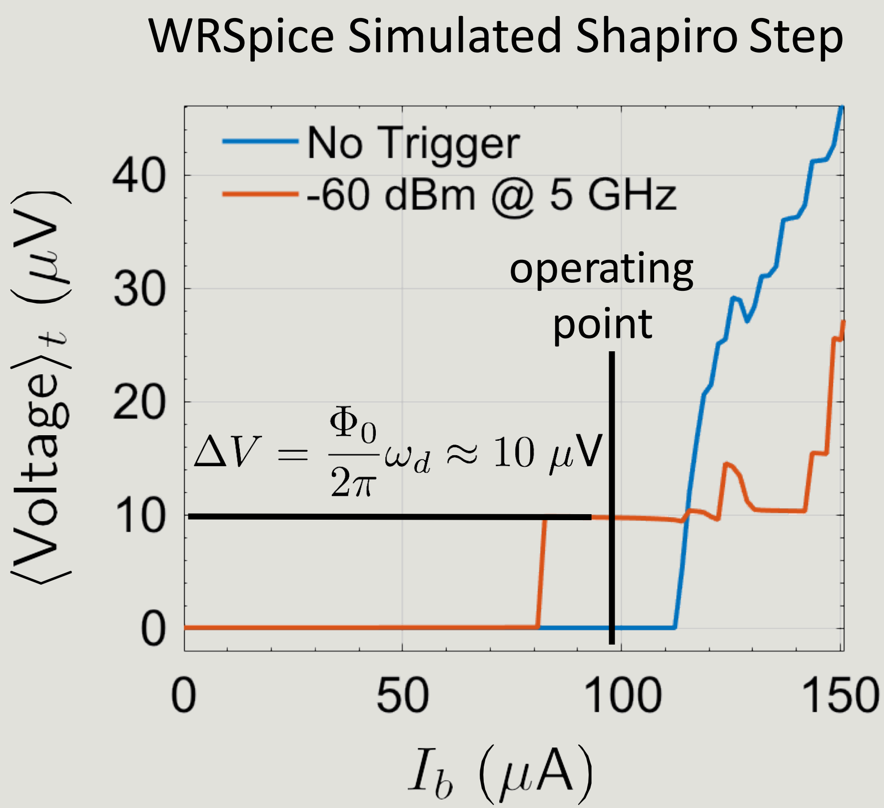
- Ability to independently validate quantum circuit and classical circuit




E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# dc/SFQ converter



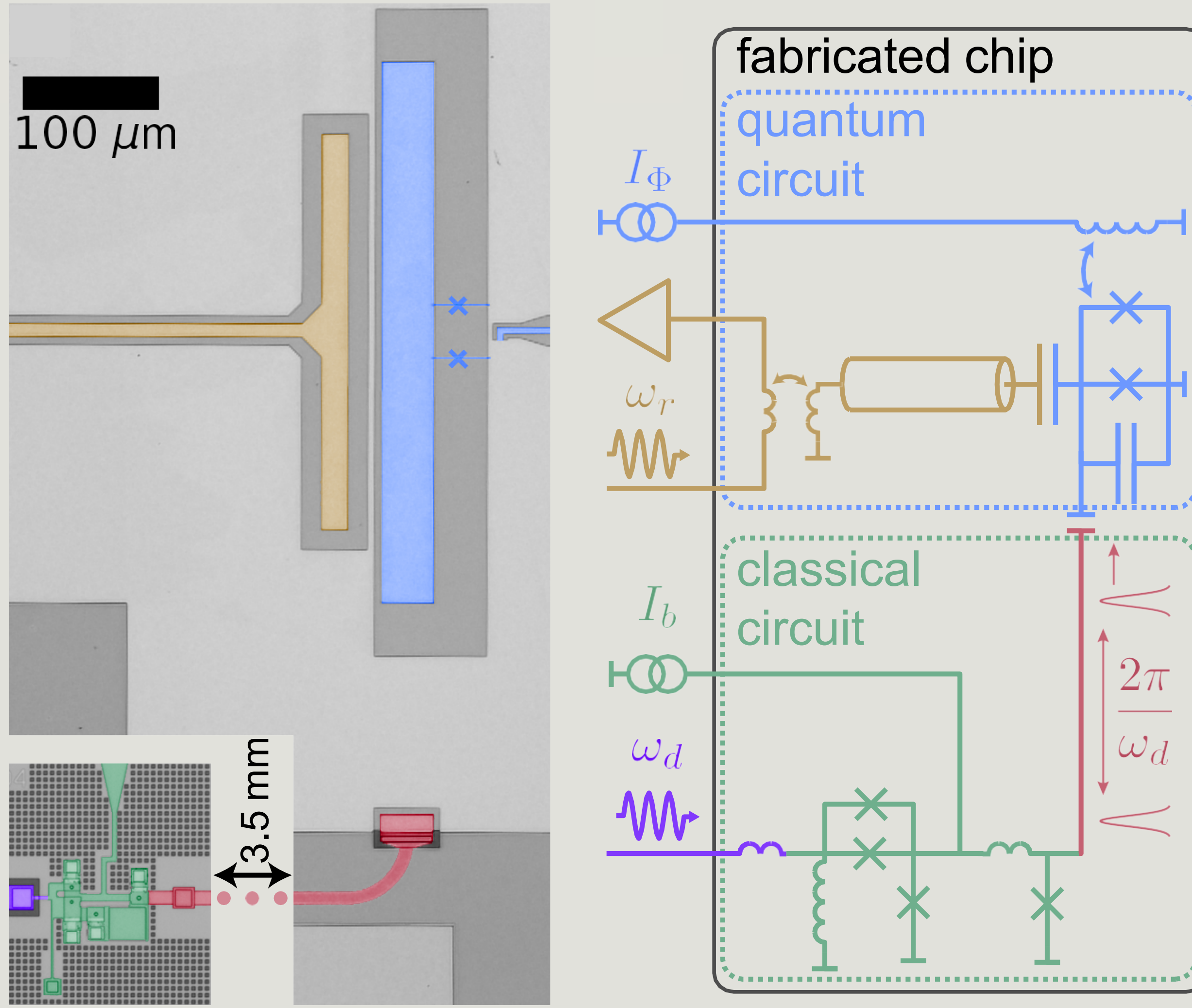




K. K. Likharev and V. K. Semenov, *IEEE Trans. Appl. Supercond.* **1**, 1 (1991)

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Quantum / Classical Integrated Circuit

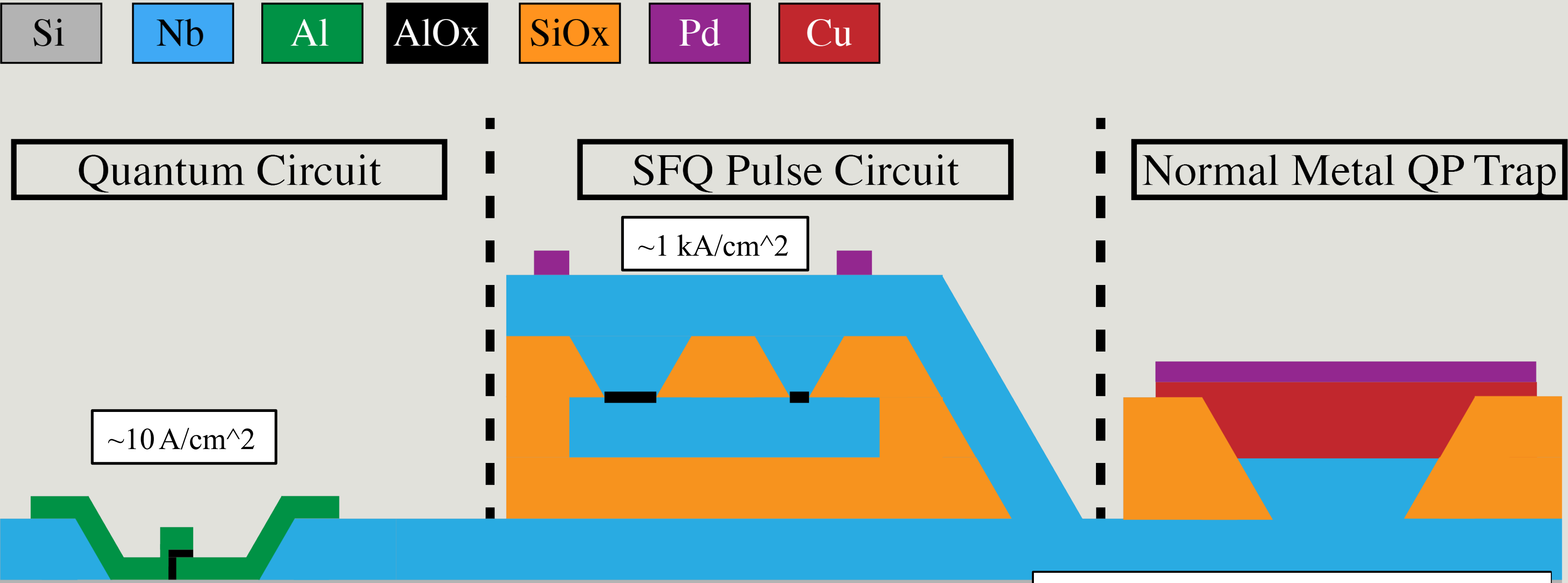
- Simultaneous realization of high-Q CPW resonators / qubits with wiring stack and high-$J_+$ JJs for classical SFQ circuit




E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Integrated Fabrication

- six metallization steps
  - 4 superconducting (3 Nb + 1 Al)
  - 2 normal (Pd + Cu / Pd)
- two PECVD SiOx insulating layers
- need high-Q quantum circuit




U. Patel et al., *PRB* **96**, 220501(R) (2017)

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

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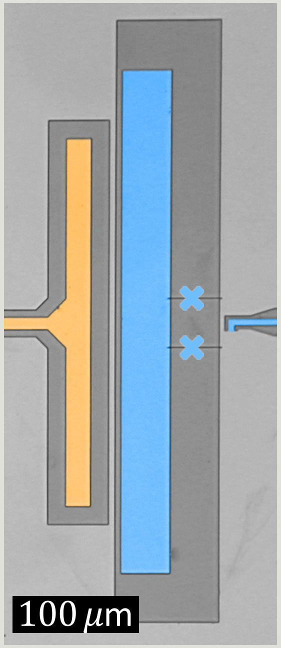
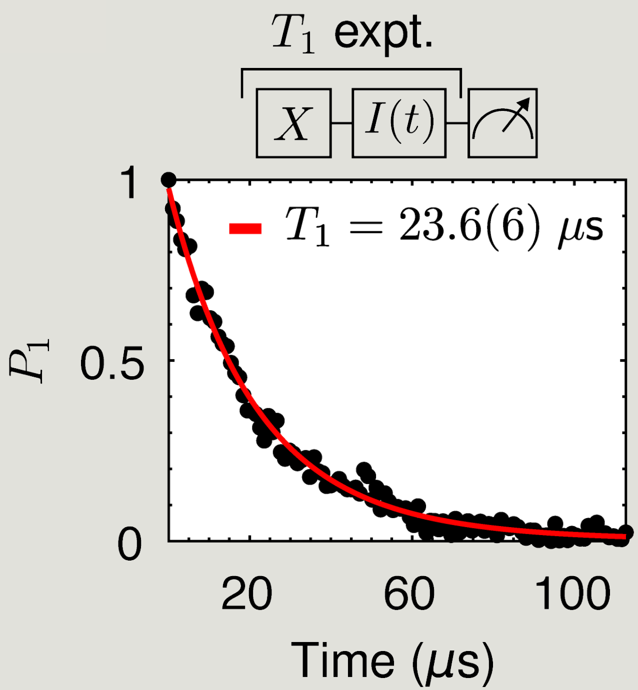
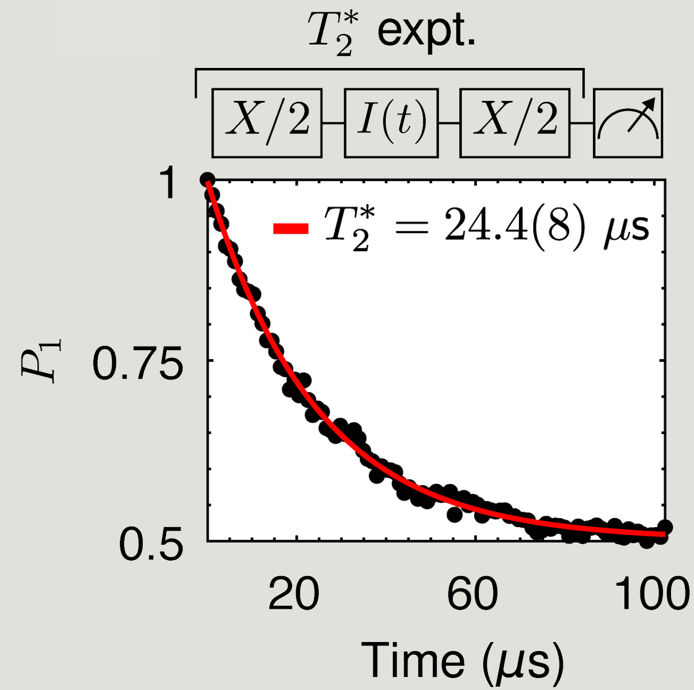
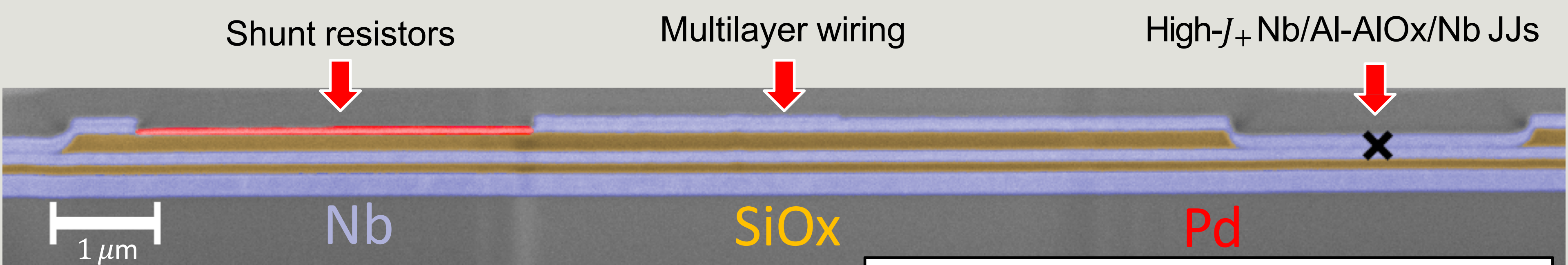
# Qubit Performance after IC fabrication



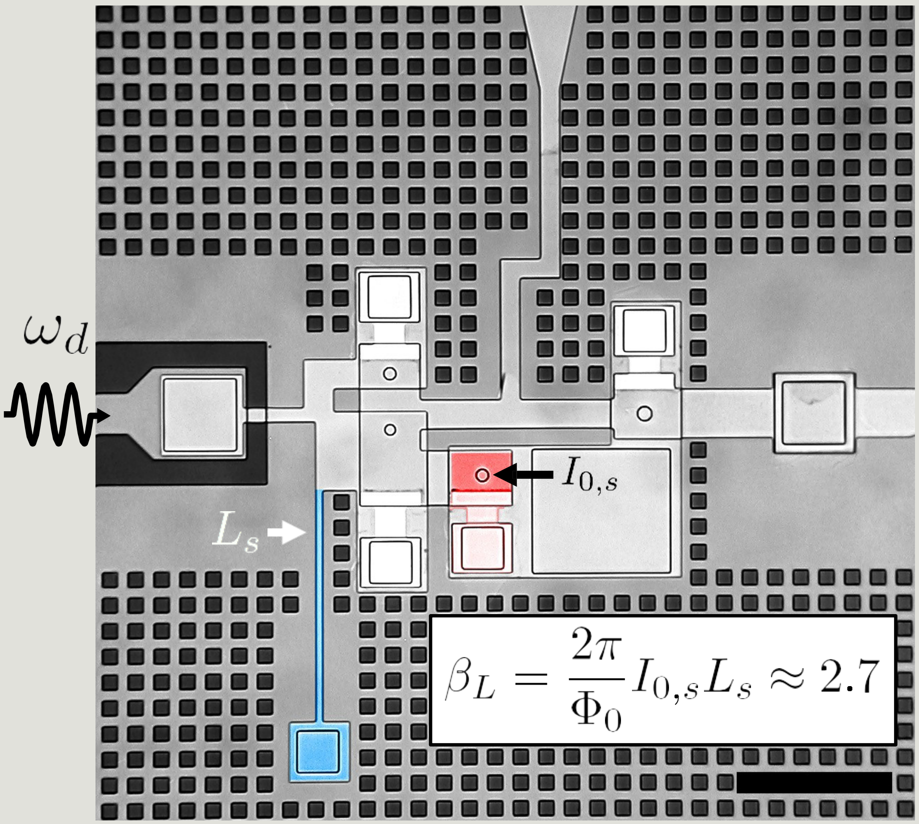



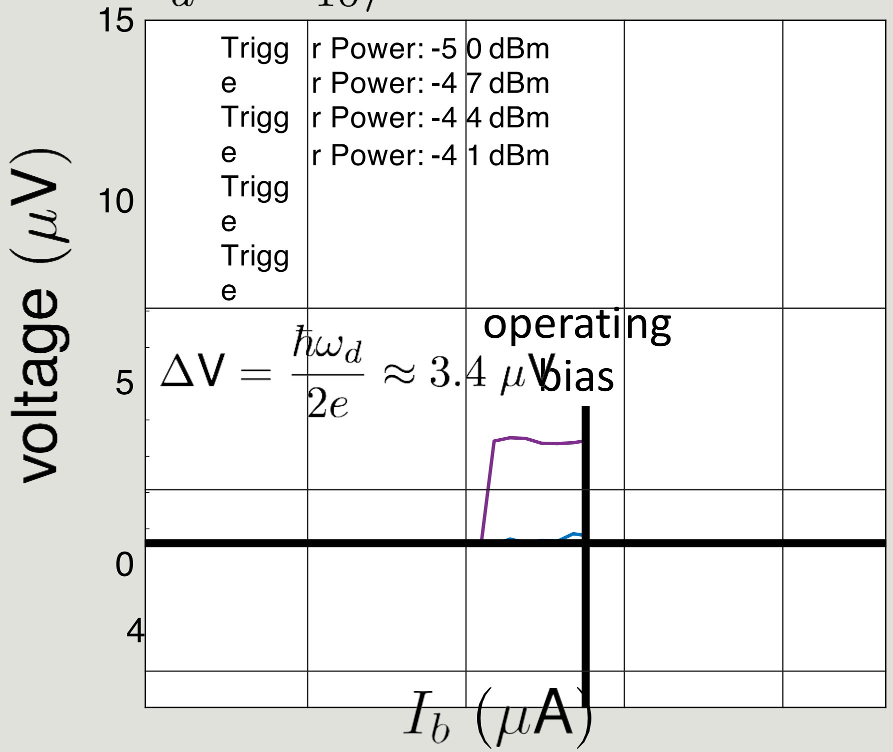




E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# dc/SFQ converter

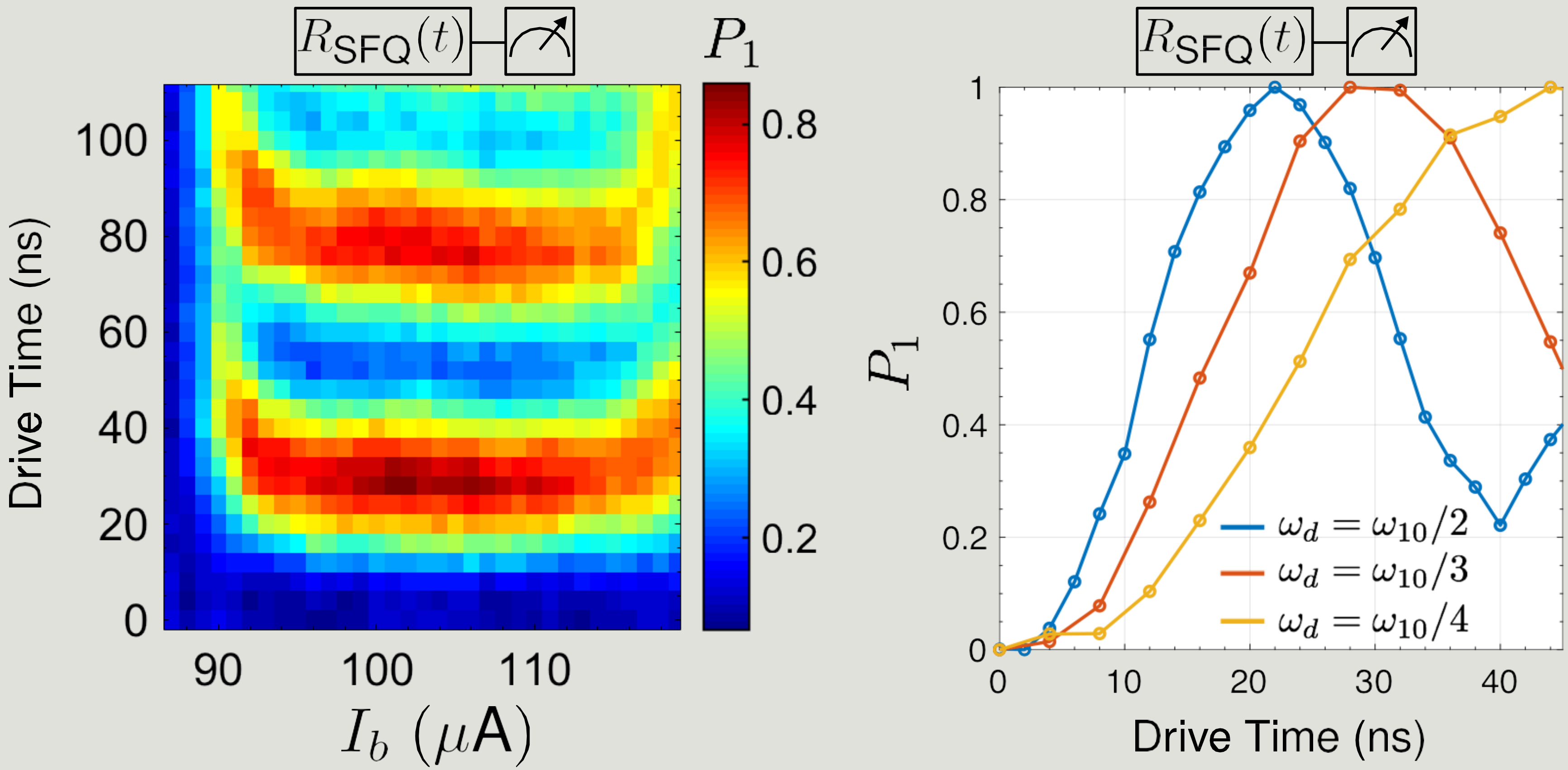



$\omega_d = \omega_{10}/3 = 2\pi \times 1.65$ GHz



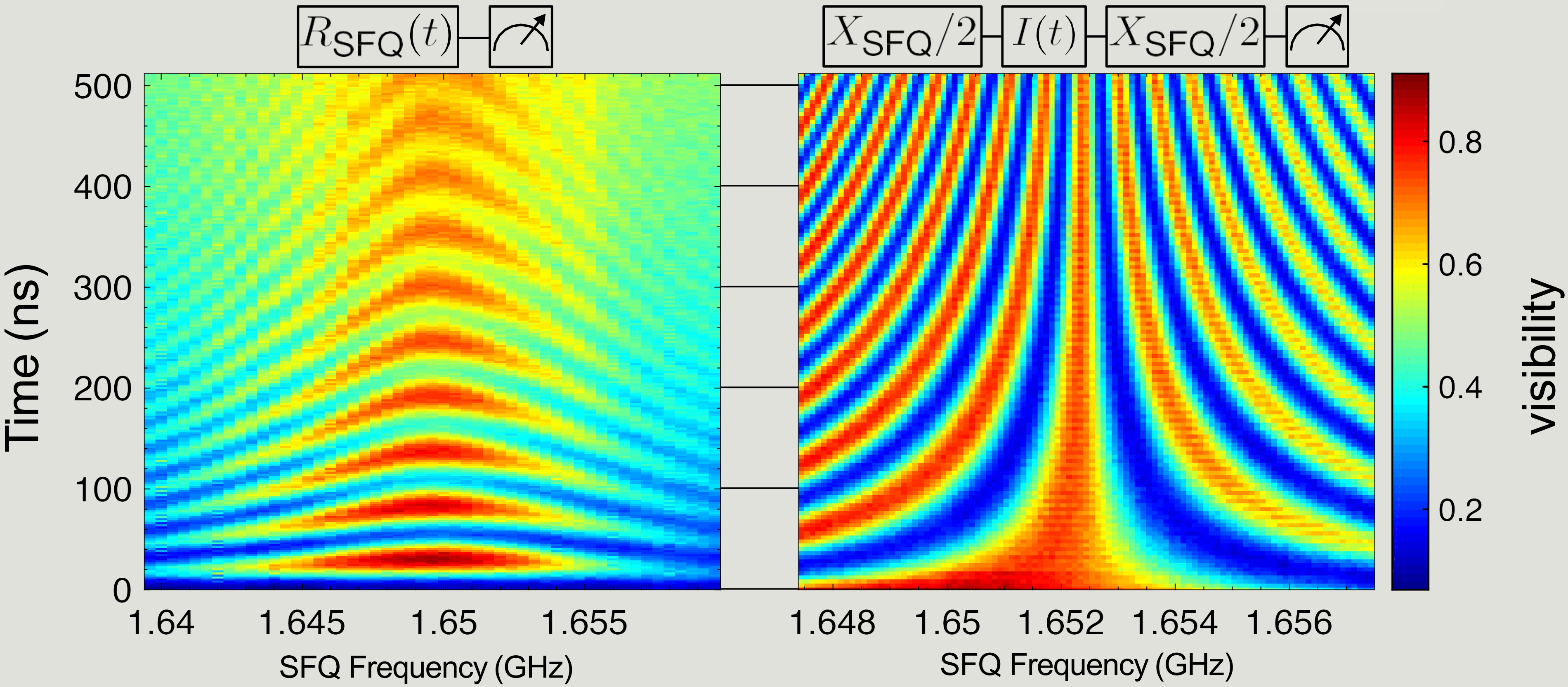

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Rabi Oscillations: using the qubit to measure the dc/SFQ converter output



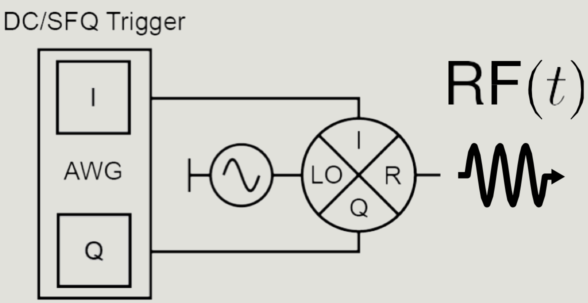

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Qubit Experiments at $\omega_q/3$

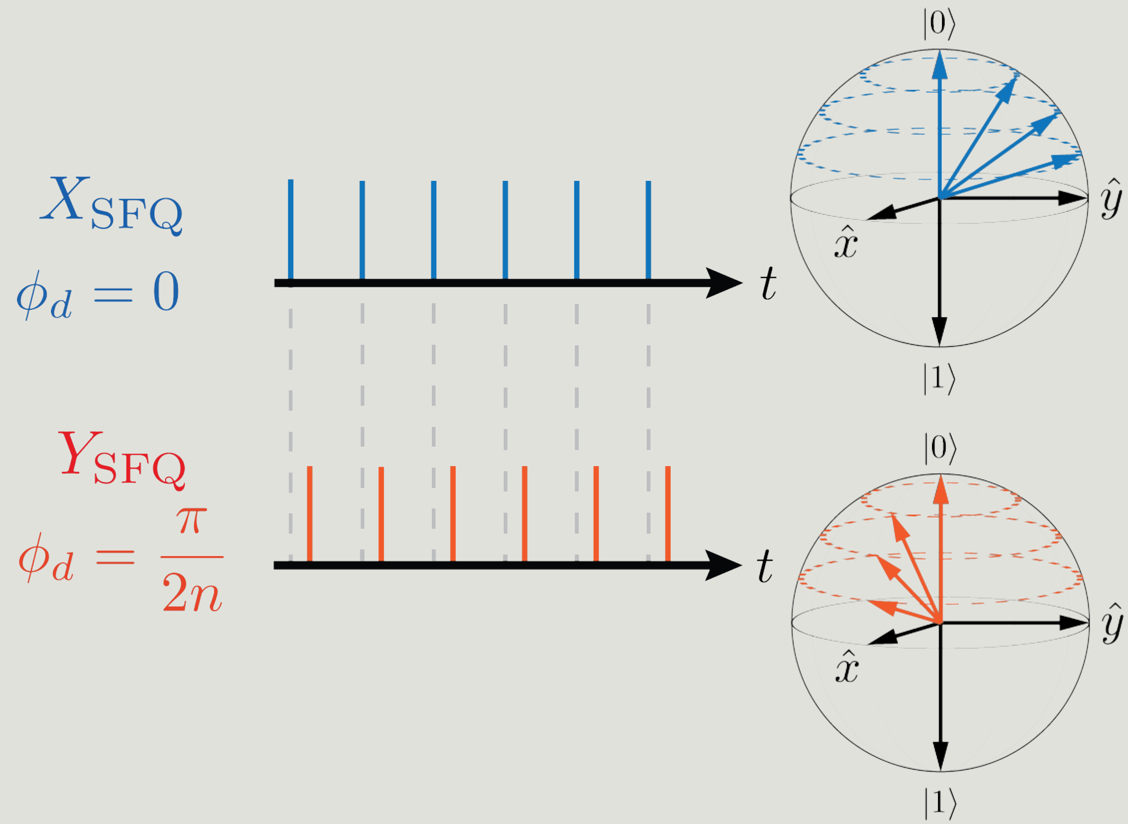



E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

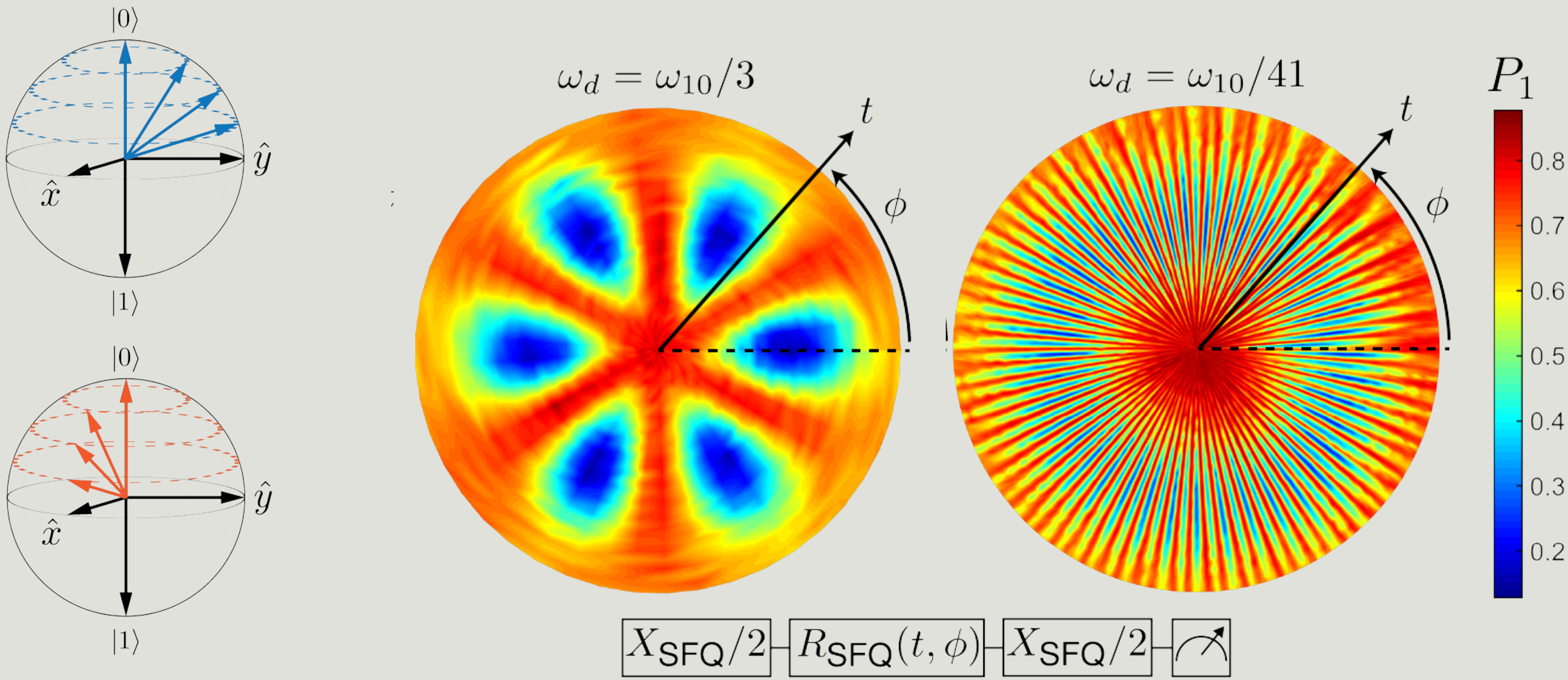
# Orthogonal SFQ-based gates




$$\text{RF}(t) = \cos[\underbrace{(\omega_{\text{LO}} - \omega_{\text{IF}})}_{\omega_d} t + \phi_d]$$

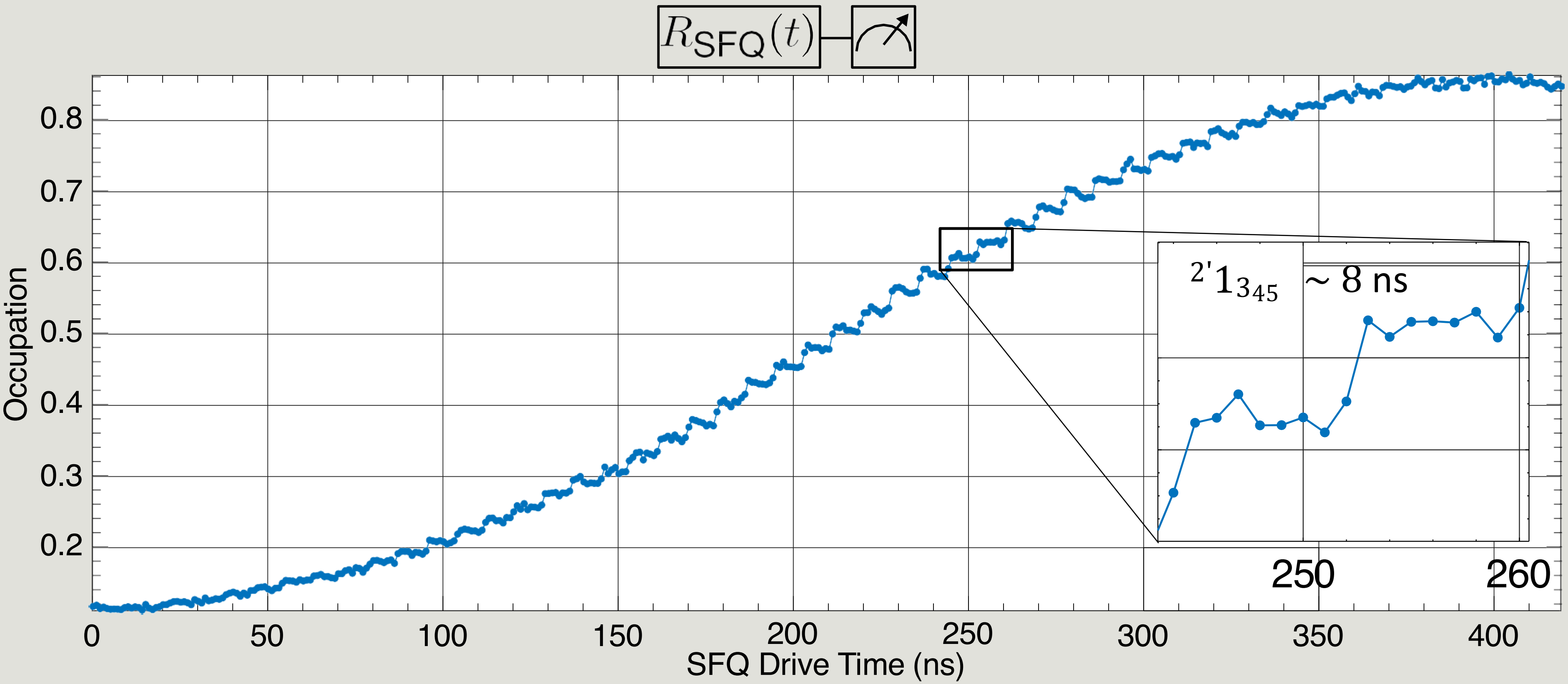


# Orthogonal SFQ-based gates



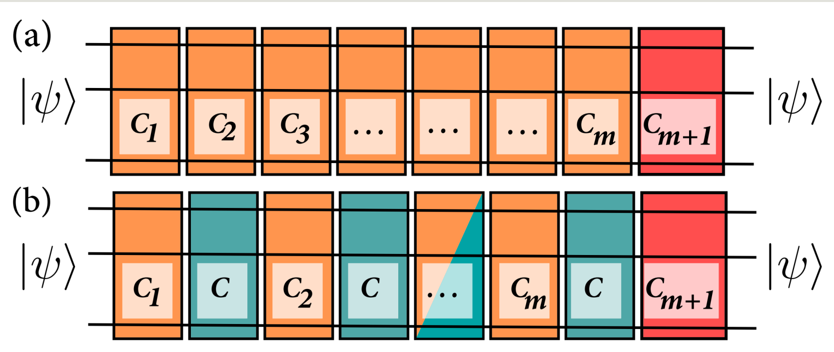

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Stair-Step Rabi Flop at ω'(/41

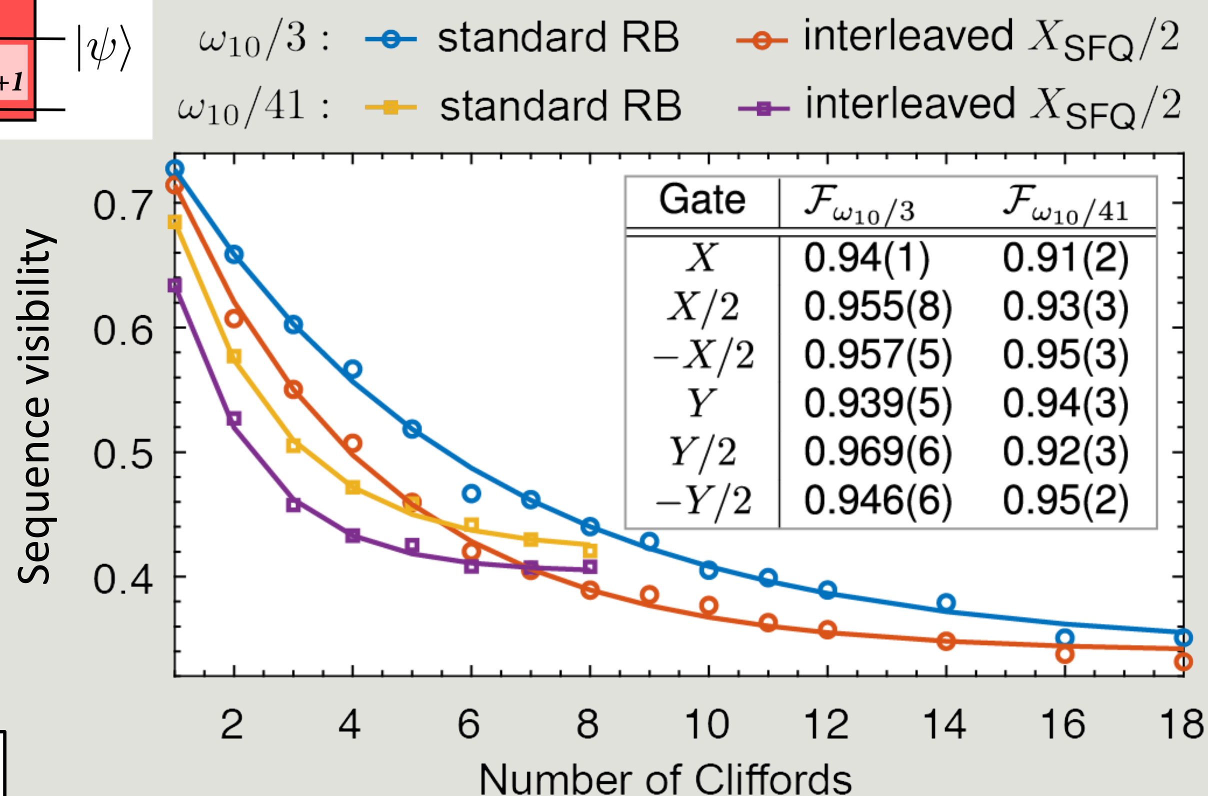



E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Randomized Benchmarking Results




E. Magesan et al, *PRL* **109**, 080505 (2012)




| Gate | $\mathcal{F}_{\omega_{10}/3}$ | $\mathcal{F}_{\omega_{10}/41}$ |
|---|---|---|
| $X$ | 0.94(1) | 0.91(2) |
| $X/2$ | 0.955(8) | 0.93(3) |
| $-X/2$ | 0.957(5) | 0.95(3) |
| $Y$ | 0.939(5) | 0.94(3) |
| $Y/2$ | 0.969(6) | 0.92(3) |
| $-Y/2$ | 0.946(6) | 0.95(2) |

Gate fidelities limited by on-chip quasiparticle generation!

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

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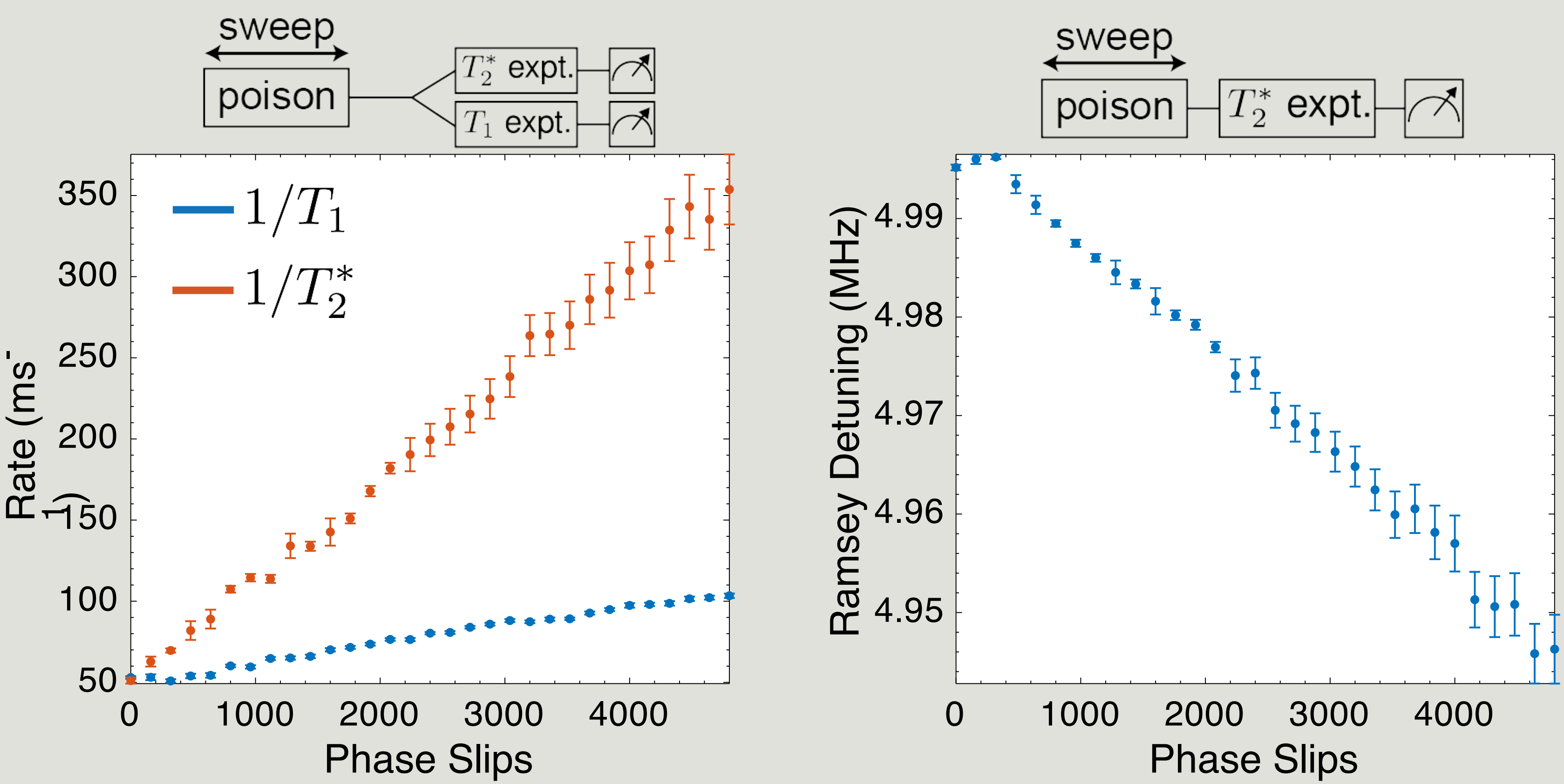
# Quasiparticle poisoning: decoherence




E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

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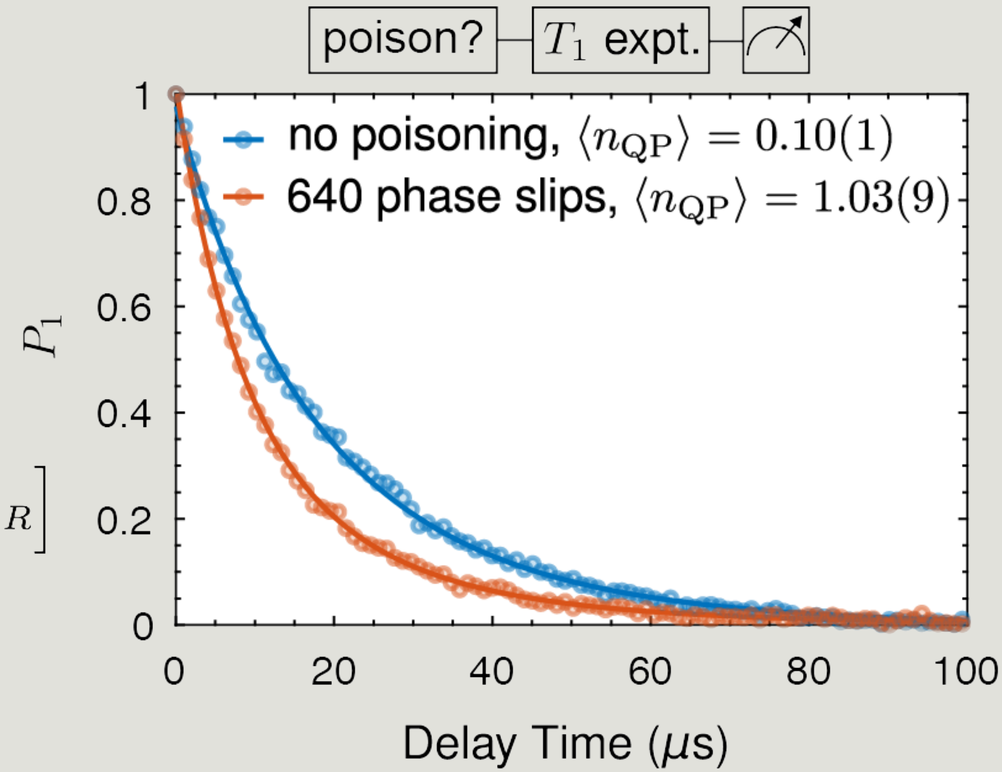
# Quasiparticle dynamics: coupling QPs to the qubit

Assume a Poisson distribution in number of quasiparticles coupled to the qubit with mean $\langle n_{9:} \rangle$:

$$P_1(t) = \exp\left[\langle n_{qp}\rangle \left(e^{-t/T_{1,qp}} - 1\right) - t/T_{1,R}\right]$$

I. M. Pop et al., *Nature* **508**, 369 (2014)




E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

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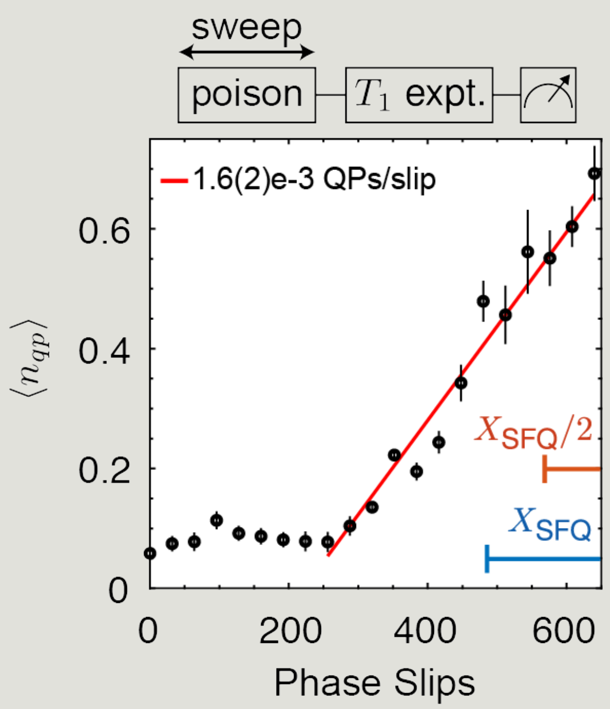
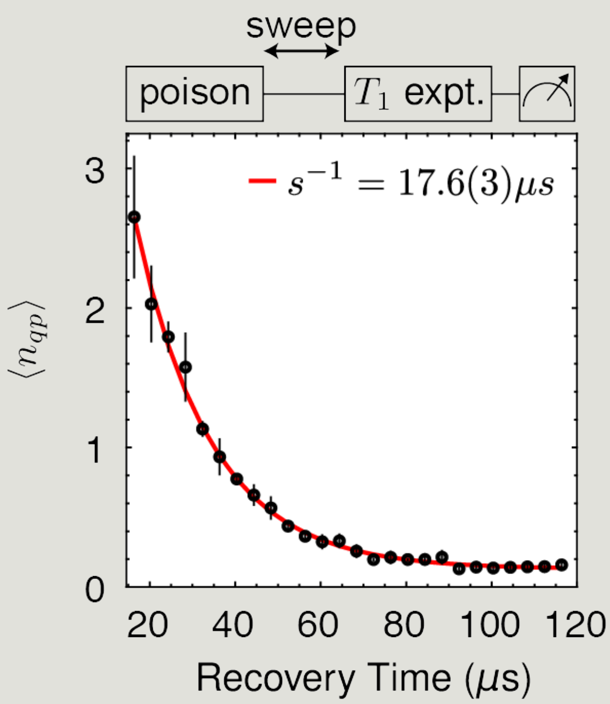
# Quasiparticle dynamics: accrual and retrapping experiments

$$\frac{dx_{qp}}{dt} = -rx_{qp}^2 - sx_{qp} + g$$

QP recovery in this system on similar timescale to another experiment in planar Al resonators on Si

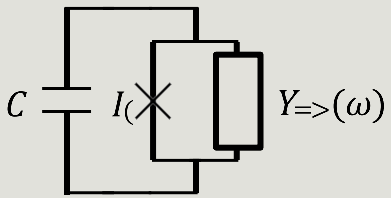



U. Patel et al., *PRB* **96**, 220501(R) (2017)




E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

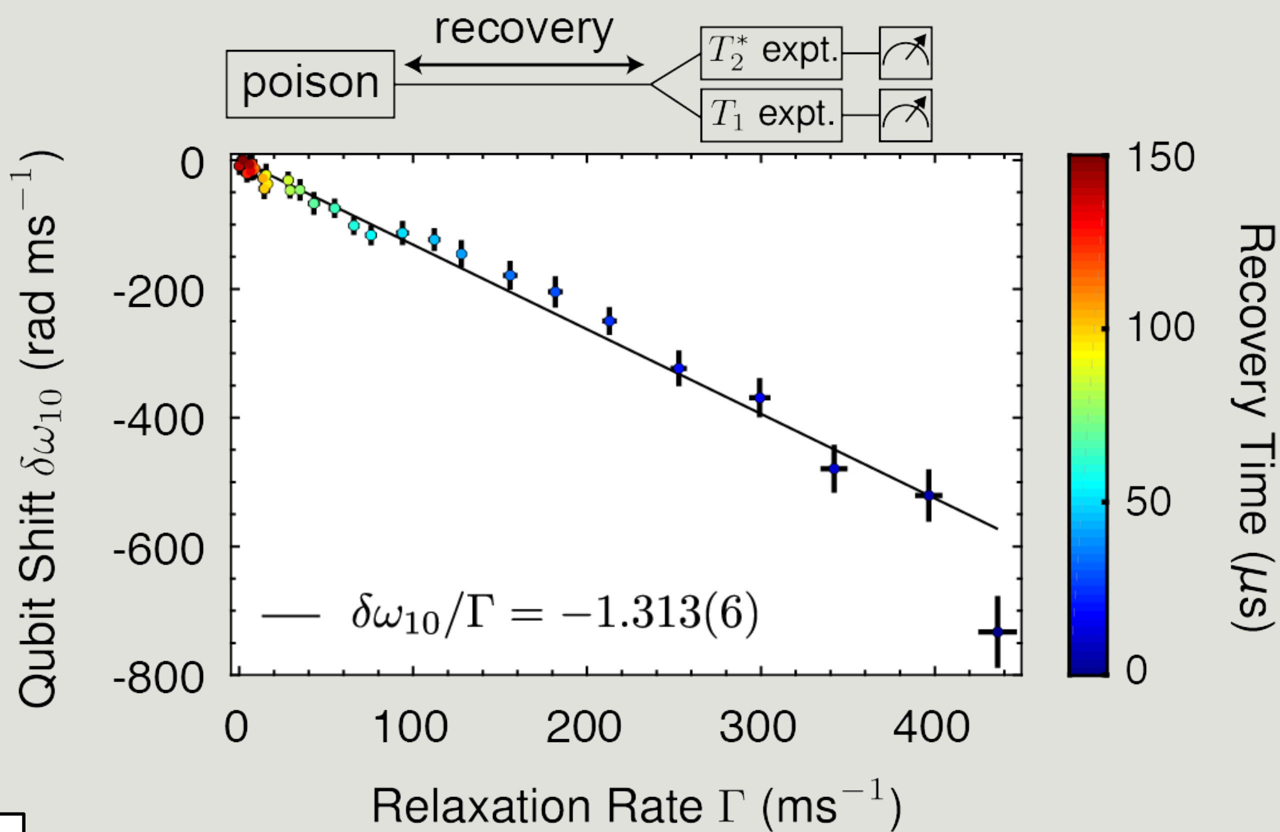
# Quasiparticle dynamics: relationship between decoherence and frequency shift




$$\delta\omega_{10} \simeq -\frac{\mathrm{Im}\{Y_{QP}(\omega_{10})\}}{2C}$$

$$\Gamma_{QP} \simeq \frac{\mathrm{Re}\{Y_{QP}(\omega_{10})\}}{C}$$

$$\frac{\delta\omega_{10}}{\Gamma} = -\frac{1}{2}\left[1 - \pi\sqrt{\frac{\hbar\omega_{10}}{2\Delta}}\right]$$



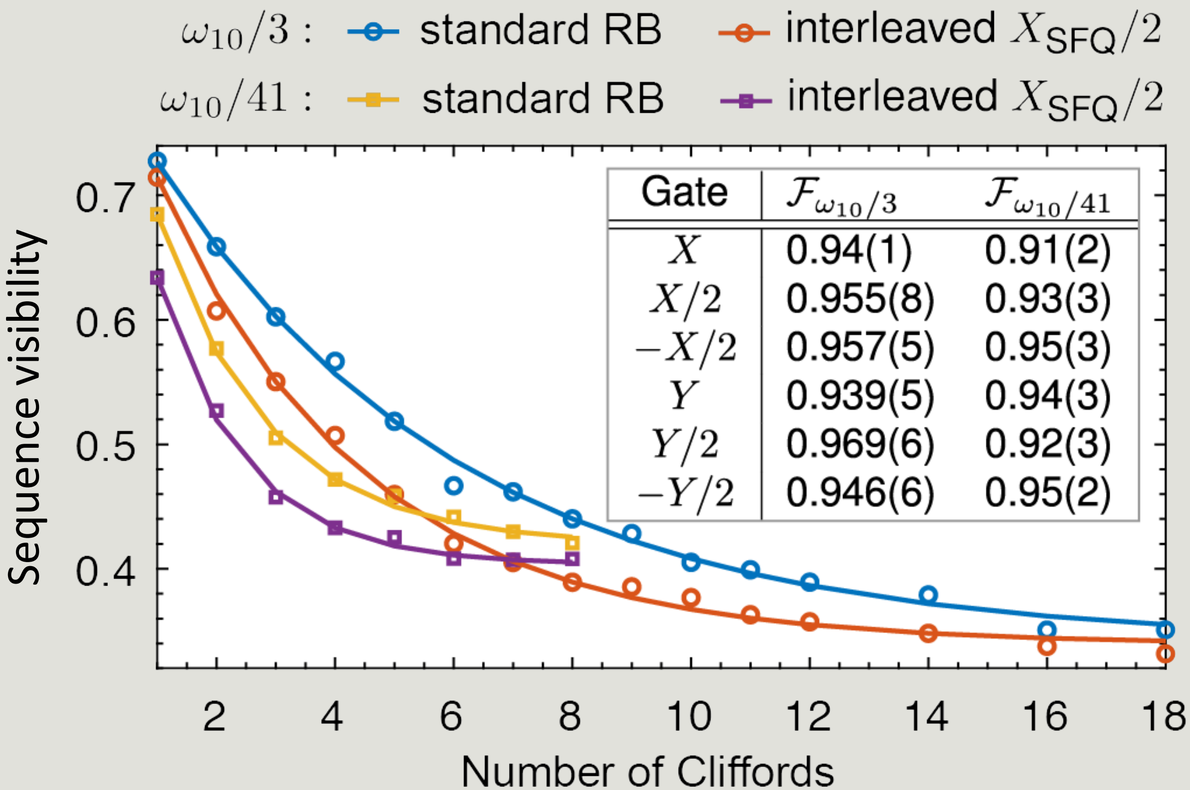

G. Catelani et al., *PRB* **84**, 064517 (2011)

M. Lenander et al., *PRB* **84**, 024501 (2011)

C. Wang et al., *Nat. Comm.* **5**, 5836 (2014)

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Benchmarking Revisited

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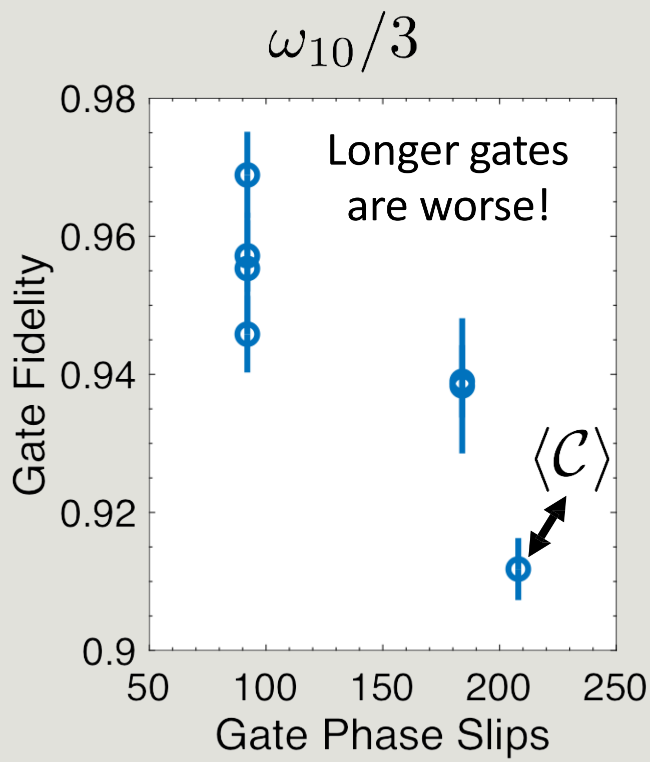
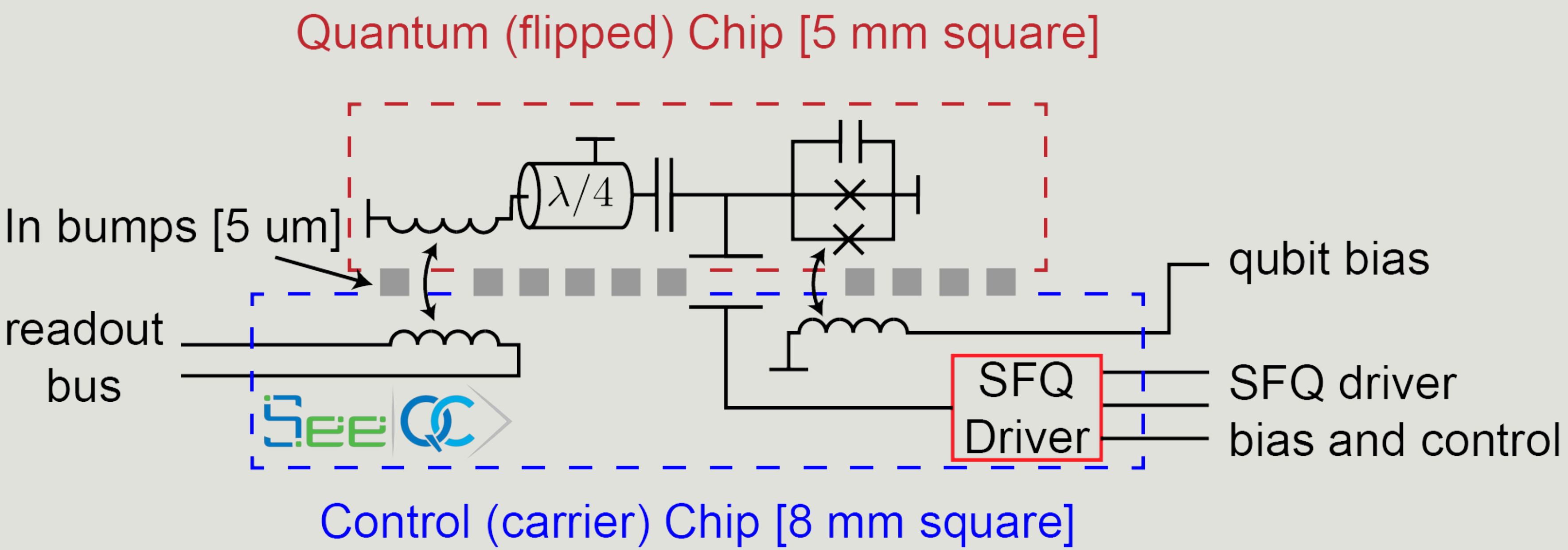



E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Multi-chip module circuit design



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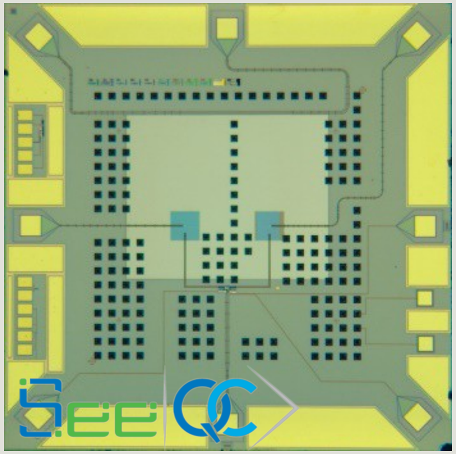
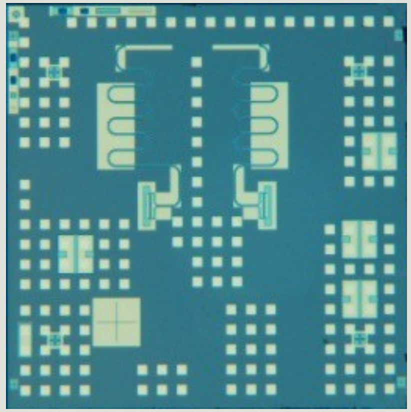
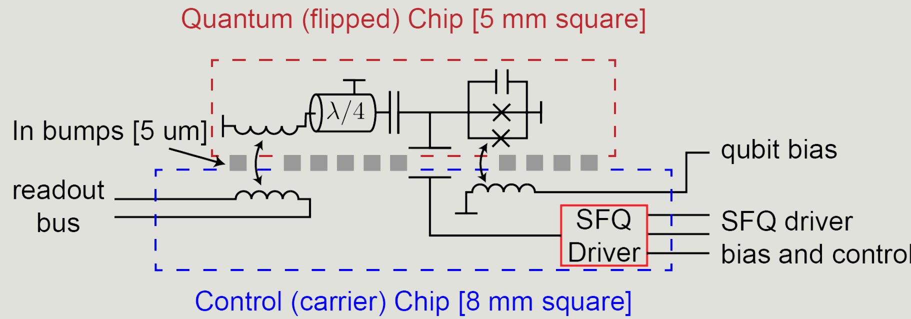
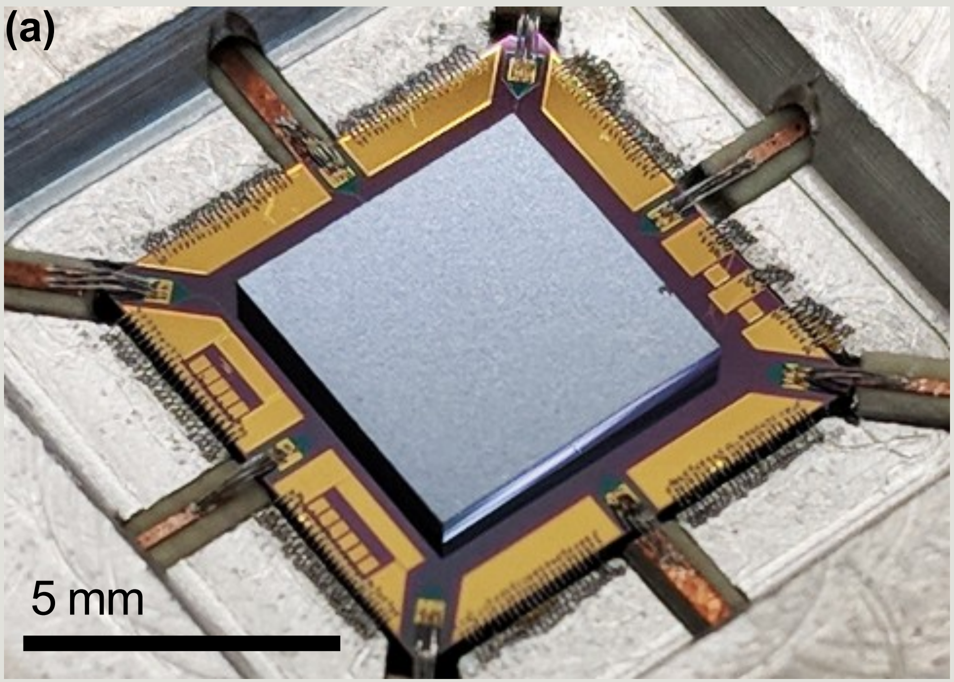
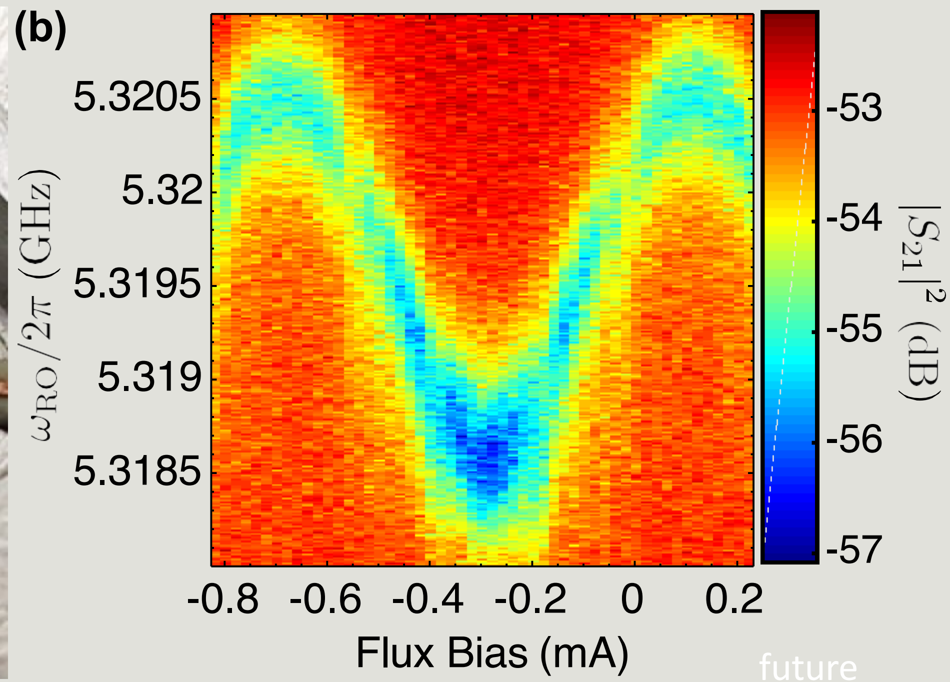
# Multi-chip module in test now; qubits live








future

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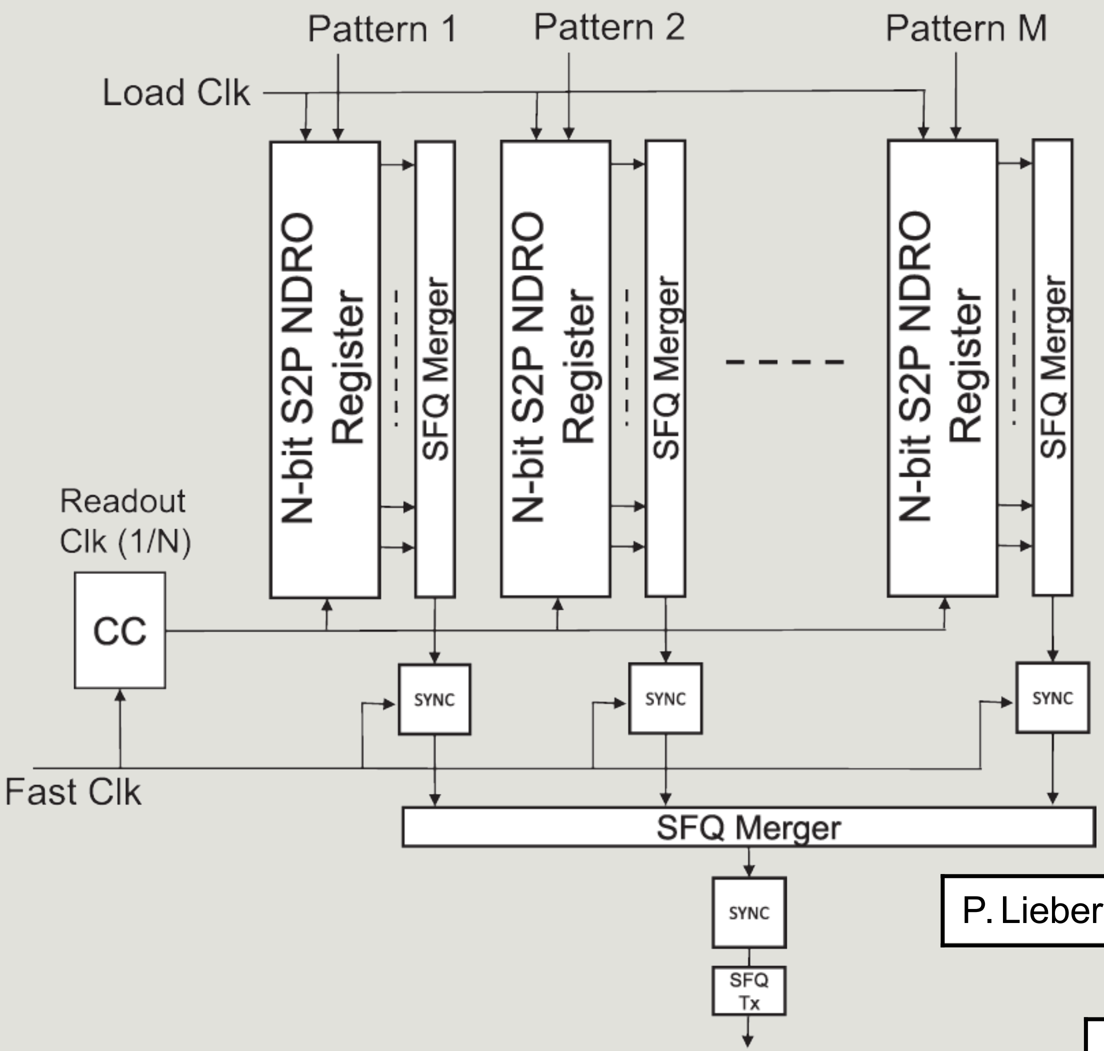
# Future concept: SFQ Pulse Pattern Generator




- Single global clock (e.g. $6f$ (~30 GHz)
- Banks of shift registers to store/stream sequence (e.g., 100 bits / qubit operation)
- Ability to program more complex sequences to minimize excitations out of the computational manifold
  - P. Liebermann (2016), R. McDermott (2018), K. Li (2019)

P. Liebermann *et al.*, *Phys. Rev. Appl.* **6**, 024022 (2016)

R. McDermott *et al.*, *QST* **3**, 2 (2018)

K. Li *et al.*, *Phys. Rev. Appl.* **12**, 014044 (2019)

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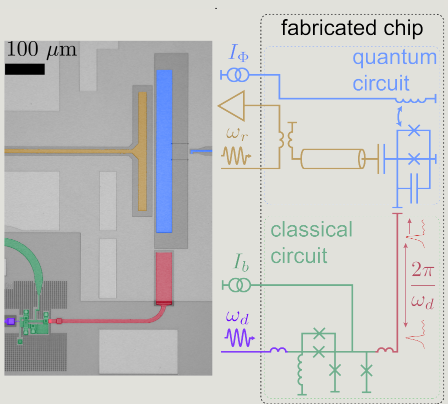
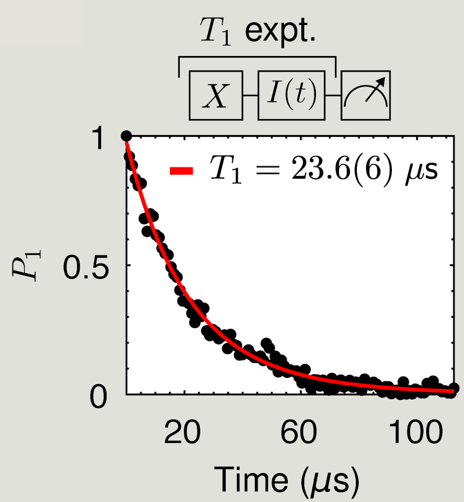
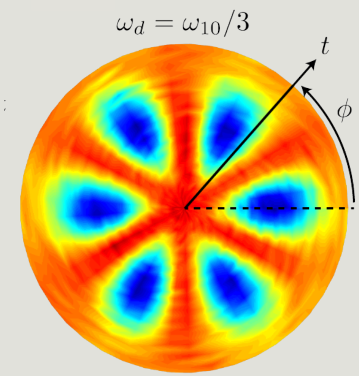
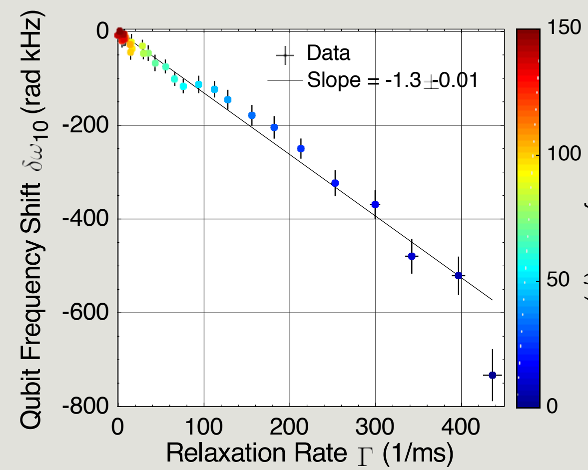
# Summary

- Designed/fabricated/characterized quantum-classical integrated circuit
- Qubit performance not significantly degraded by extensive fabrication
- Orthogonal SFQ pulse-based gate set characterized with IRB
- Quasiparticle poisoning is a limiting factor in same-chip operation
- 3D integration currently in test

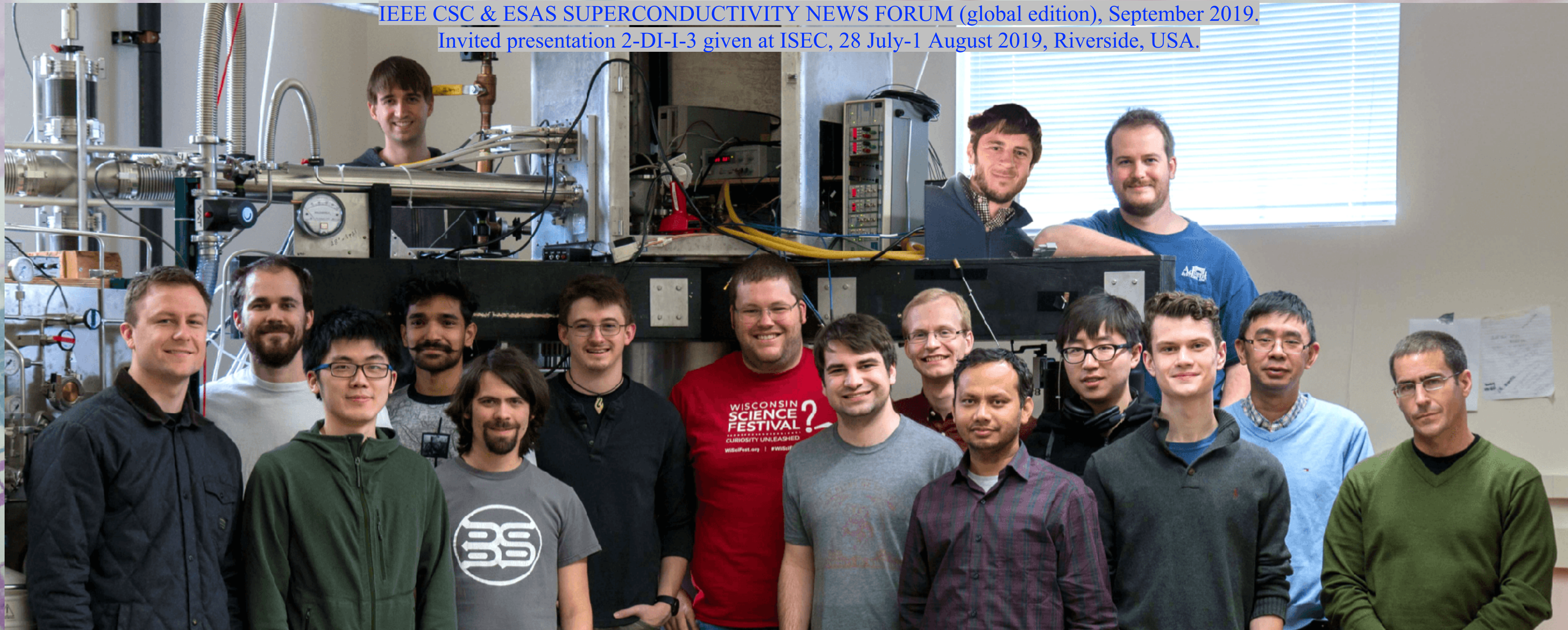



E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)




PHYSICAL REVIEW APPLIED

# Digital Coherent Control of a Superconducting Qubit

E. Leonard, Jr., M. A. Beck, J. Nelson, B.G. Christensen, T. Thorbeck, C. Howington, A. Opremcak, I.V. Pechenezhskiy, K. Dodge, N.P. Dupuis, M.D. Hutchings, J. Ku, F. Schlenker, J. Suttle, C. Wilen, S. Zhu, M.G. Vavilov, B.L.T. Plourde, and R. McDermott

Phys. Rev. Applied **11**, 014009 – Published 7 January 2019

SYRACUSE UNIVERSITY

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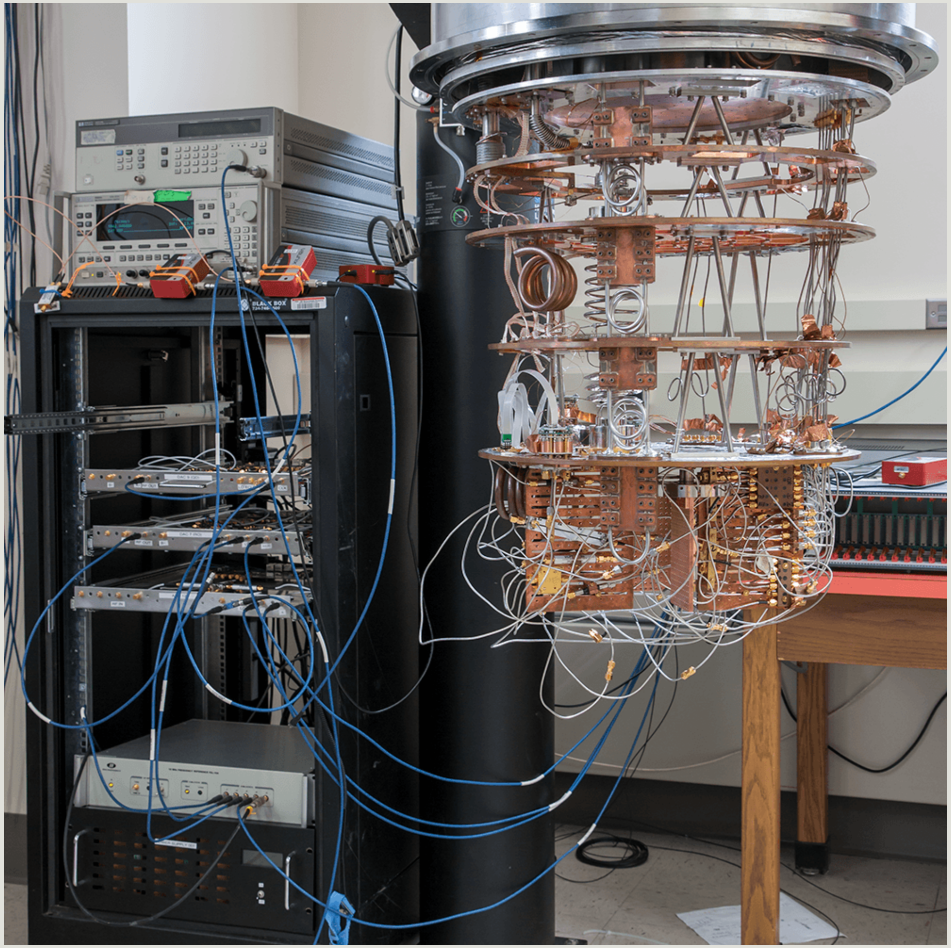
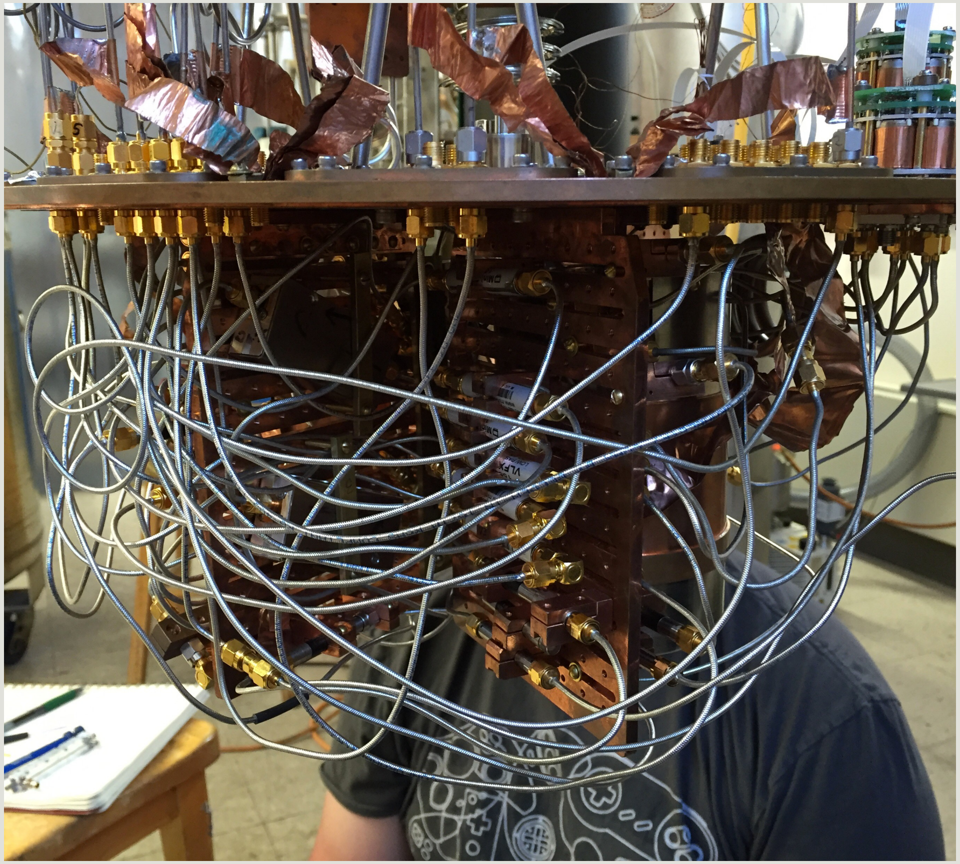
# Backup

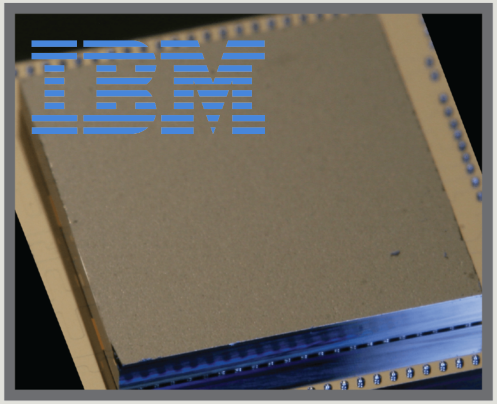
future

# Qubit Control and Measurement

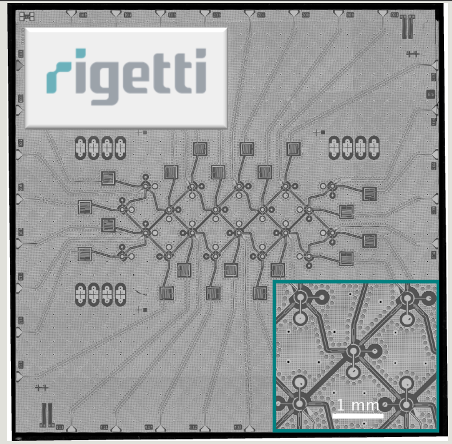




# Processor I/O: Interconnects




| | |
|---|---|
| # of qubits | 50 |
| # control wires | ~50 |
| devices per wire | ~1 |




| | |
|---|---|
| # of qubits | 19 |
| # control wires | 28 |
| devices per wire | 0.7 |

intel inside pentium® 4

| | |
|---|---|
| # of transistors | 100M |
| # control wires | 775 |
| devices per wire | 150k |

How to wire-up 100M qubits is unknown.

IBM Blog: "The Future is Quantum" (November, 2017)

J. S. Otterbach, arXiv:1712.05771 (2017)

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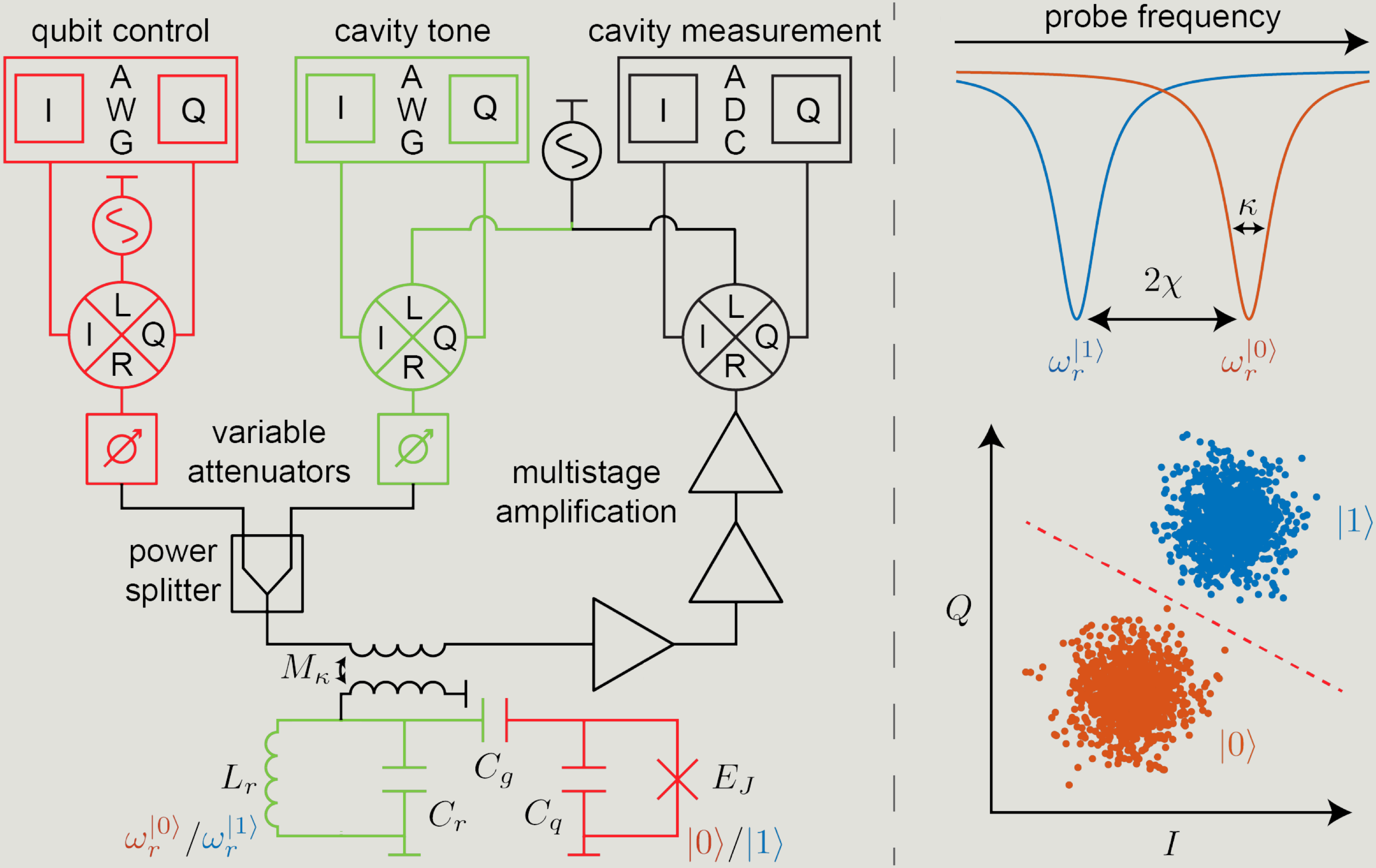
Invited presentation 2-DI-I-3 given at ISEC, 28 July-1 August 2019, Riverside, USA.

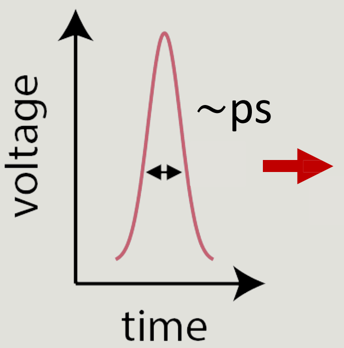
# Qubit Control and Measurement

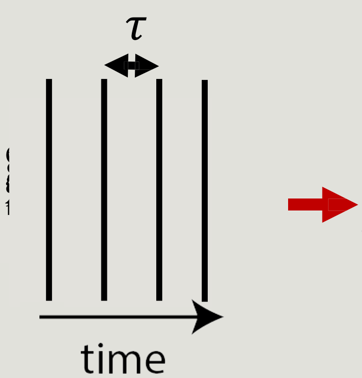



future

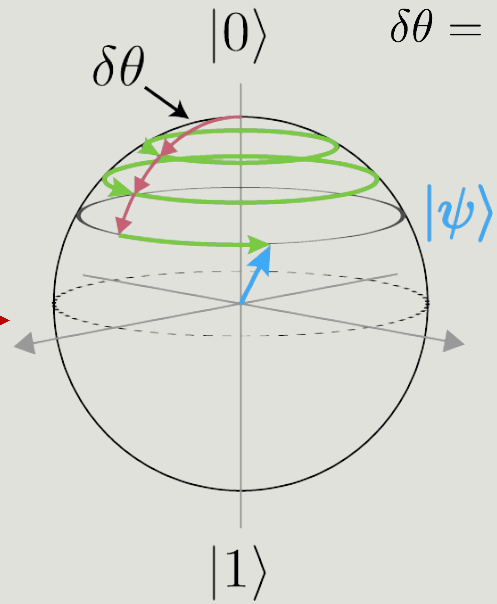
# Resonant SFQ Pulse Trains

$$\int V(t)dt = \Phi_0$$




$$\tau = n\frac{2\pi}{\omega_{('}}$$




$$\delta\theta = C_c\Phi_0\sqrt{\frac{2\omega_{10}}{\hbar C}}$$

$C_+ = 100$ aF
$\omega_{'(} = 2\pi\times 5$ GHz
$C = 100$ fF
$n_M \sim 200$ SFQ pulses
$t_M = 40$ ns

$$H_{\mathsf{SFQ}}(t) = C_c\Phi_0\sqrt{\frac{\hbar\omega_{10}}{2C}}\left(\delta(t)+\delta(t-\tau)+\cdots+\delta(t-n_\pi\tau)\right)\hat{\sigma}_y$$

R. McDermott & M. Vavilov., *Phys. Rev. Appl.* **2**, 014007 (2014)

E. Leonard Jr. et al., *Phys. Rev. Appl.* **11**, 014009 (2019)

# Resonant SFQ Pulse Trains

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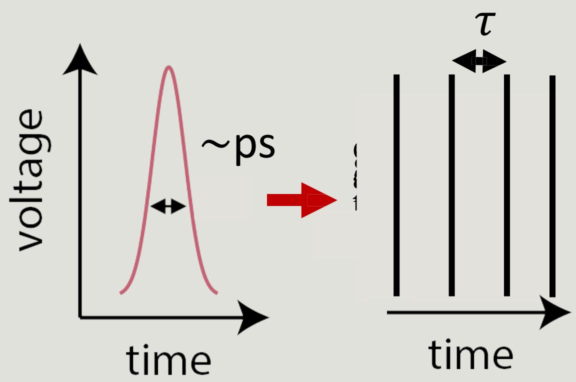
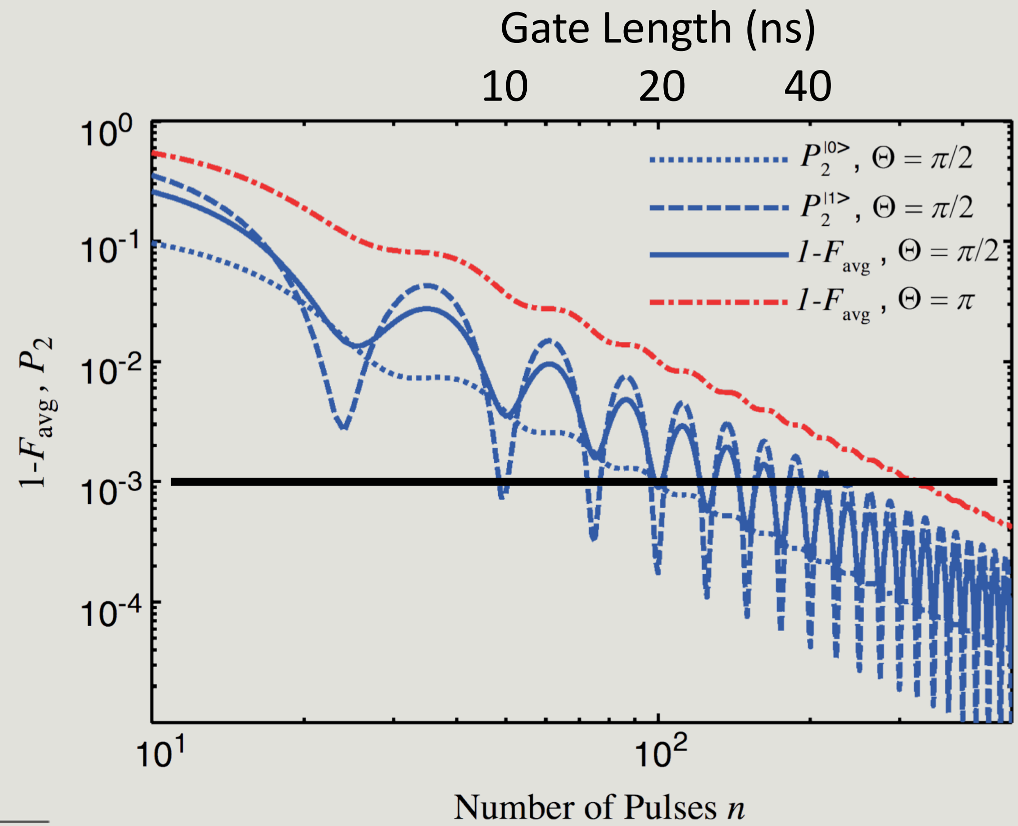



$$\tau = n \frac{2\pi}{\omega' \,(}$$

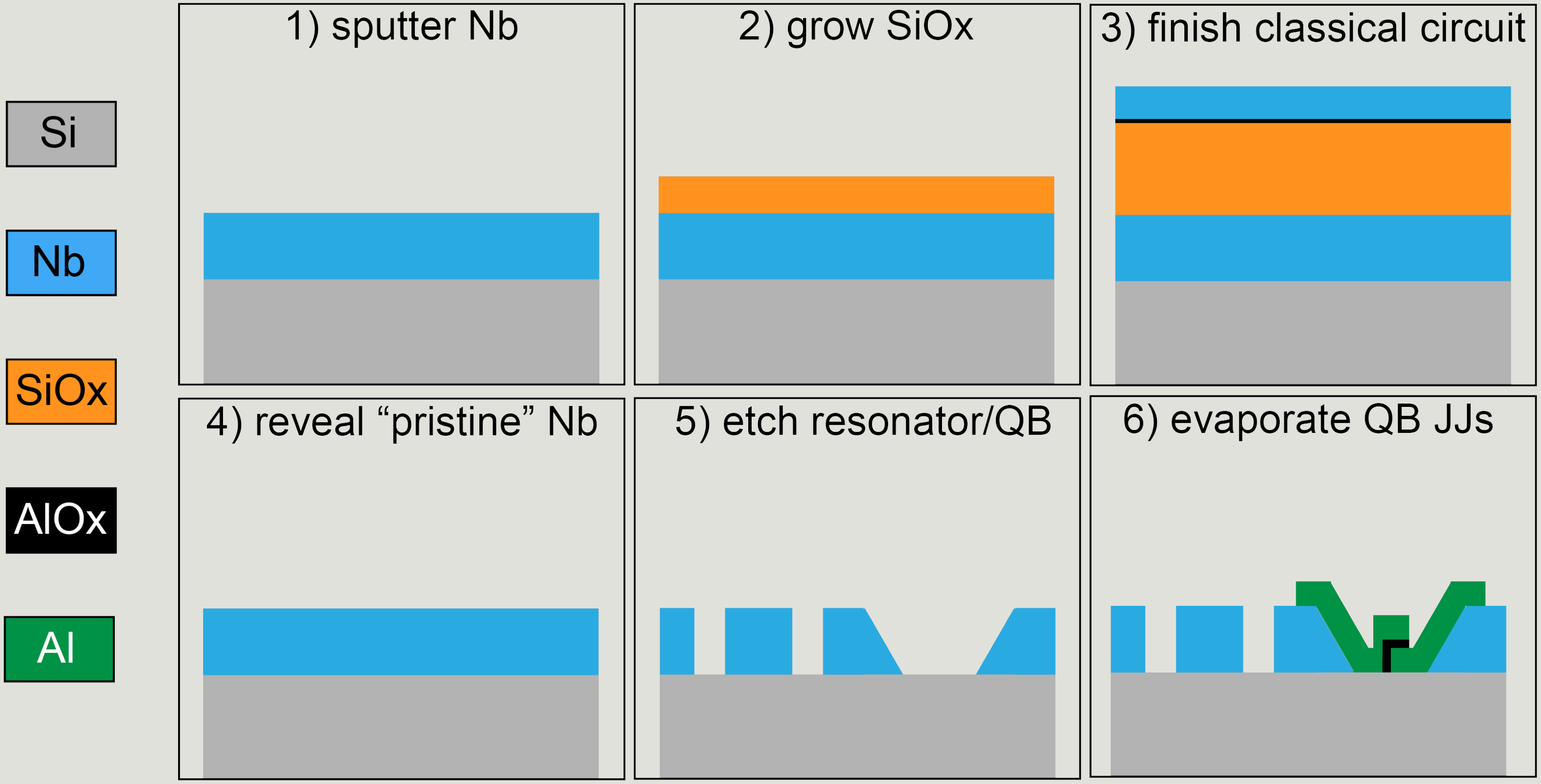



$$H_{\mathsf{SFQ}}(t) = C_c\Phi_0\sqrt{\frac{\hbar\omega_{10}}{2C}}\left(\delta(t) + \delta(t-\tau) + \cdots + \delta(t - n_\pi\tau)\right)\hat{\sigma}_y$$

R. McDermott & M. Vavilov., *Phys. Rev. Appl.* **2**, 014007 (2014)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 2-DI-I-3 given at ISEC, 28 July-1 August 2019, Riverside, USA.

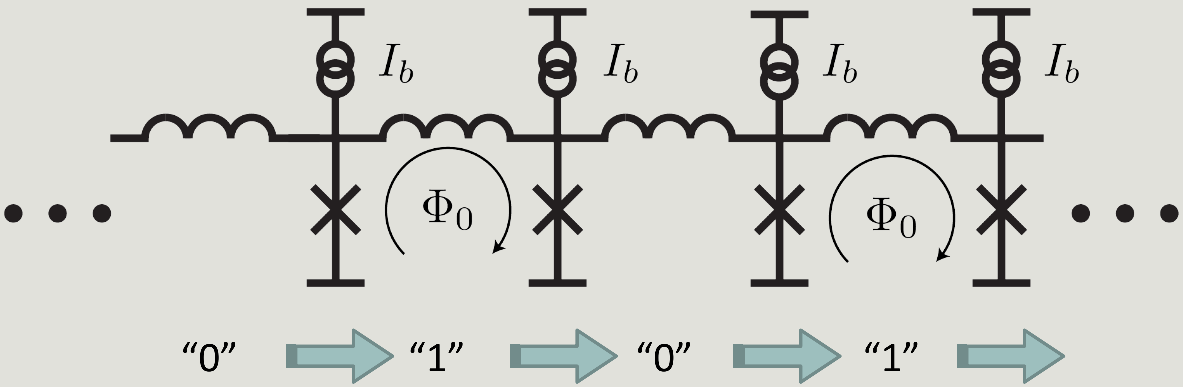
# Using SiOx to protect quantum circuit

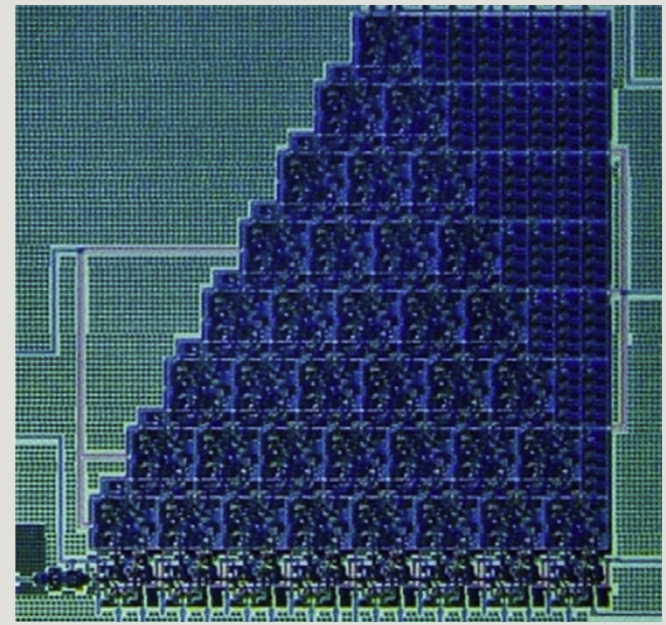


IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 2-DI-I-3 given at ISEC, 28 July-1 August 2019, Riverside, USA.

# Single Flux Quantum Tech

- **S**ingle **F**lux **Q**uantum (SFQ) logic family composed of basic classical gates; implemented in superconducting circuits
  - Logical data encoded in the presence (1) or absence (0) of JJ phase slips
  - Low-energy variants with reduced power draw
  - Enormous modern advances (see IARPA C3)



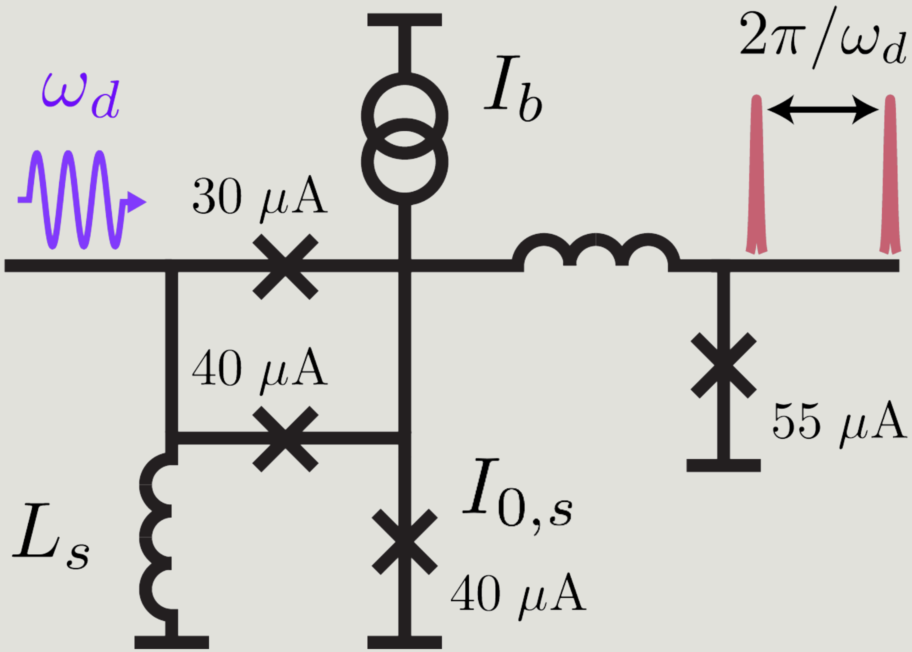



$$V(t) = \frac{\Phi_0}{2\pi}\frac{\partial \delta}{\partial t} \qquad \Phi_0 \approx 2\ \text{mV} \times \text{ps}$$

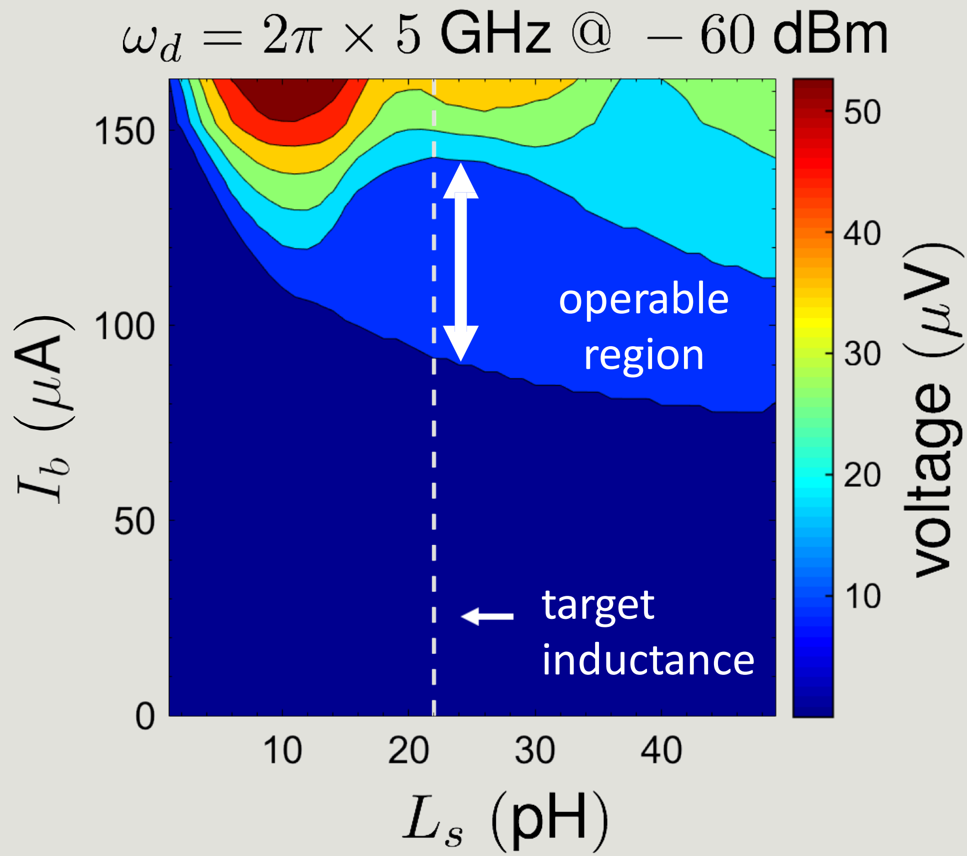
K. K. Likharev, *Physica C* **482**, 6 (2012)

K. K. Likharev and V. K. Semenov, *IEEE Trans. Appl. Supercond.* **1**, 1 (1991)

# dc/SFQ converter

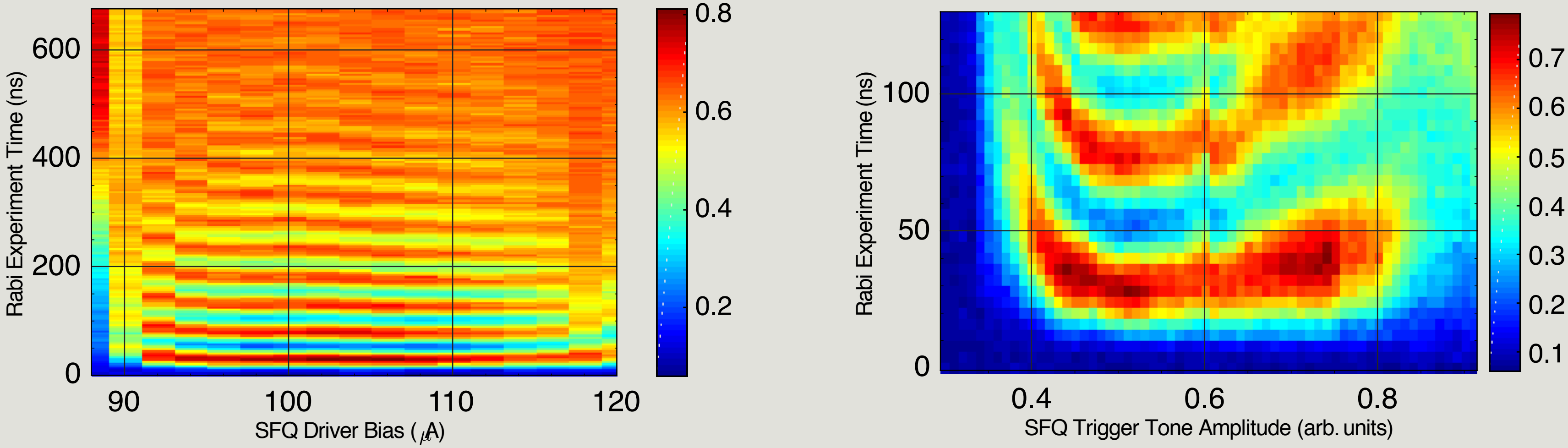



$$\beta_L = \frac{2\pi}{\Phi_0} I_{0,s} L_s \approx 2.7$$




K. K. Likharev and V. K. Semenov, *IEEE Trans. Appl. Supercond.* **1**, 1 (1991)

# Converter Bias Stability

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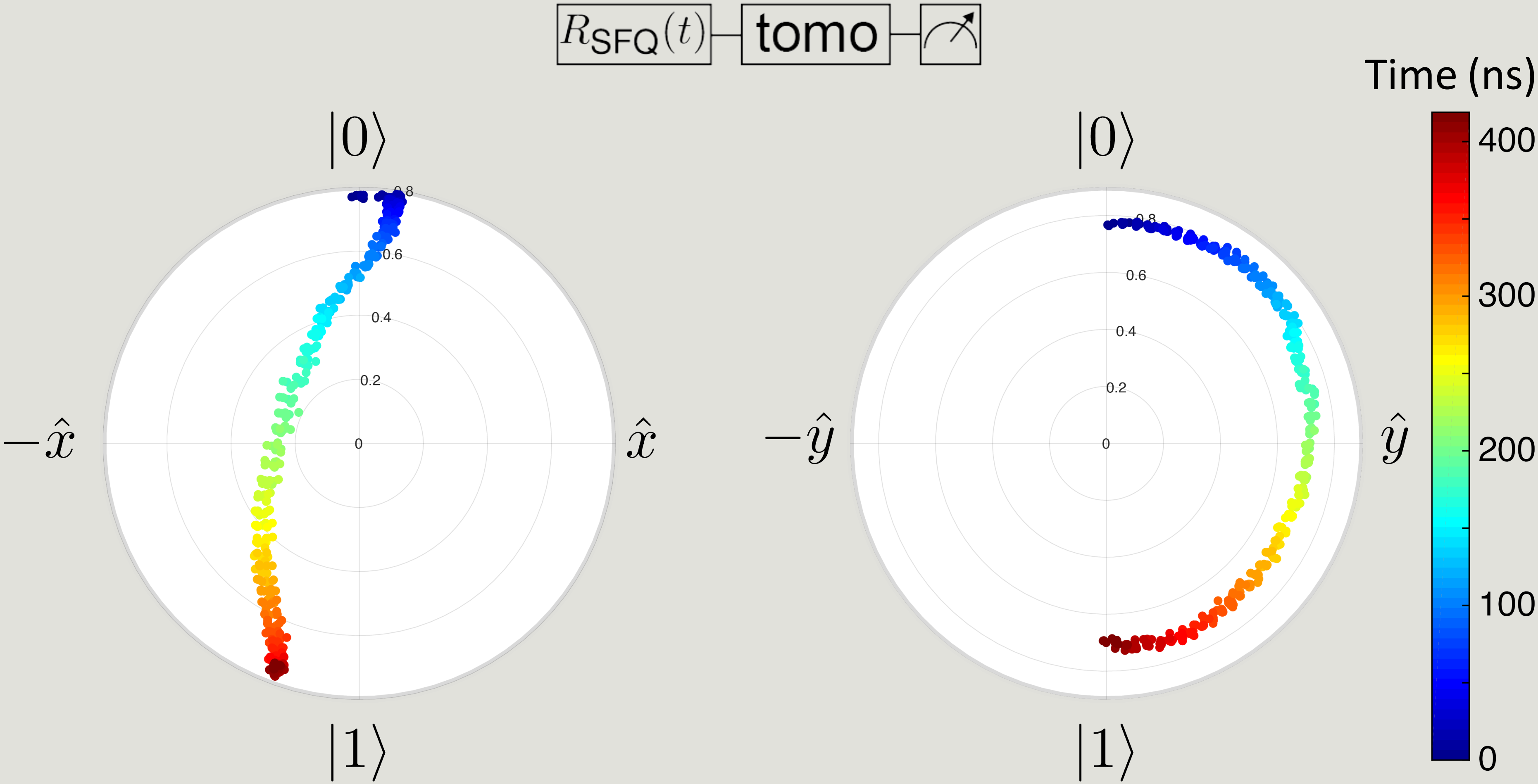
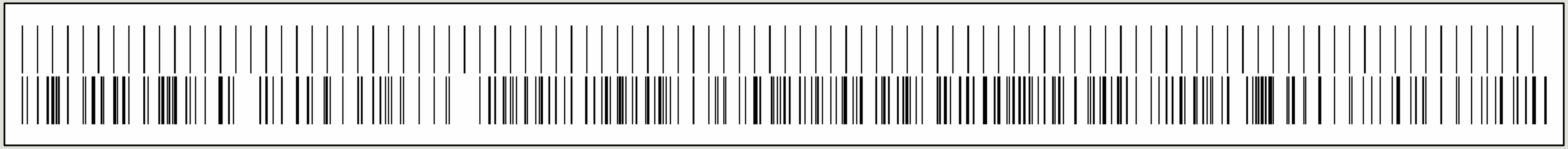
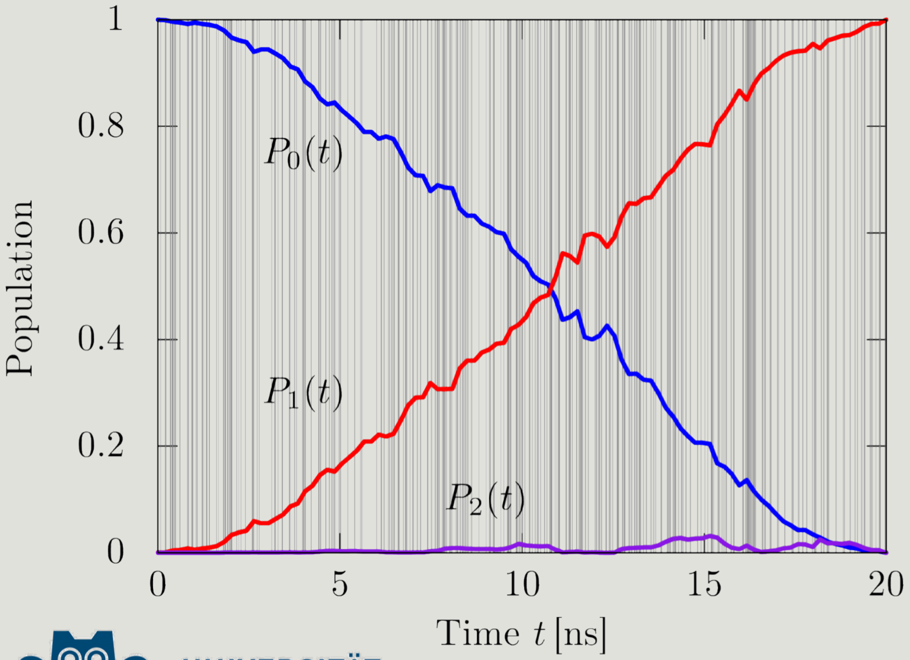
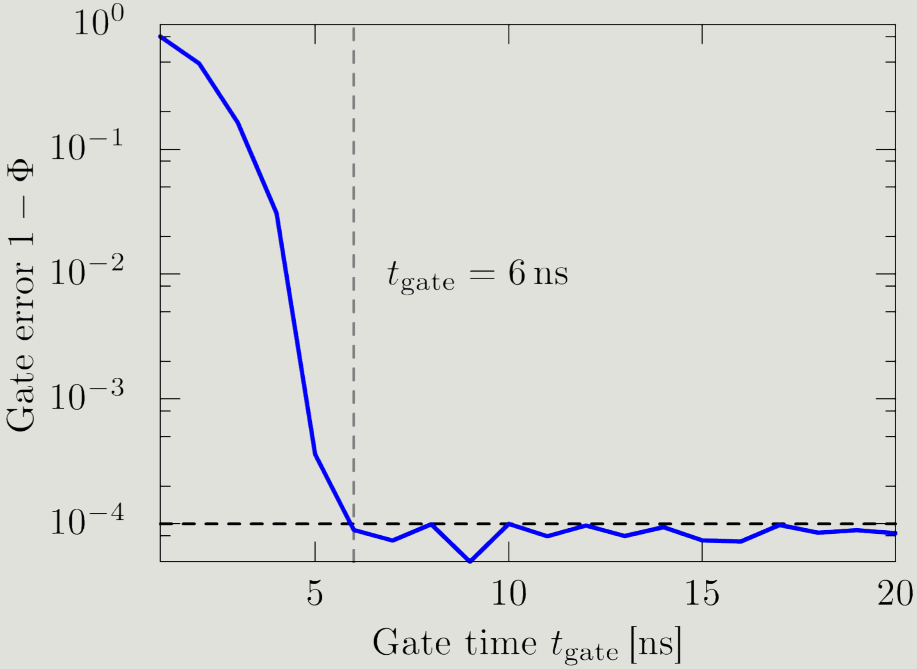
# SFQ Rotation Trajectory



# Optimal Control Prevents Leakage



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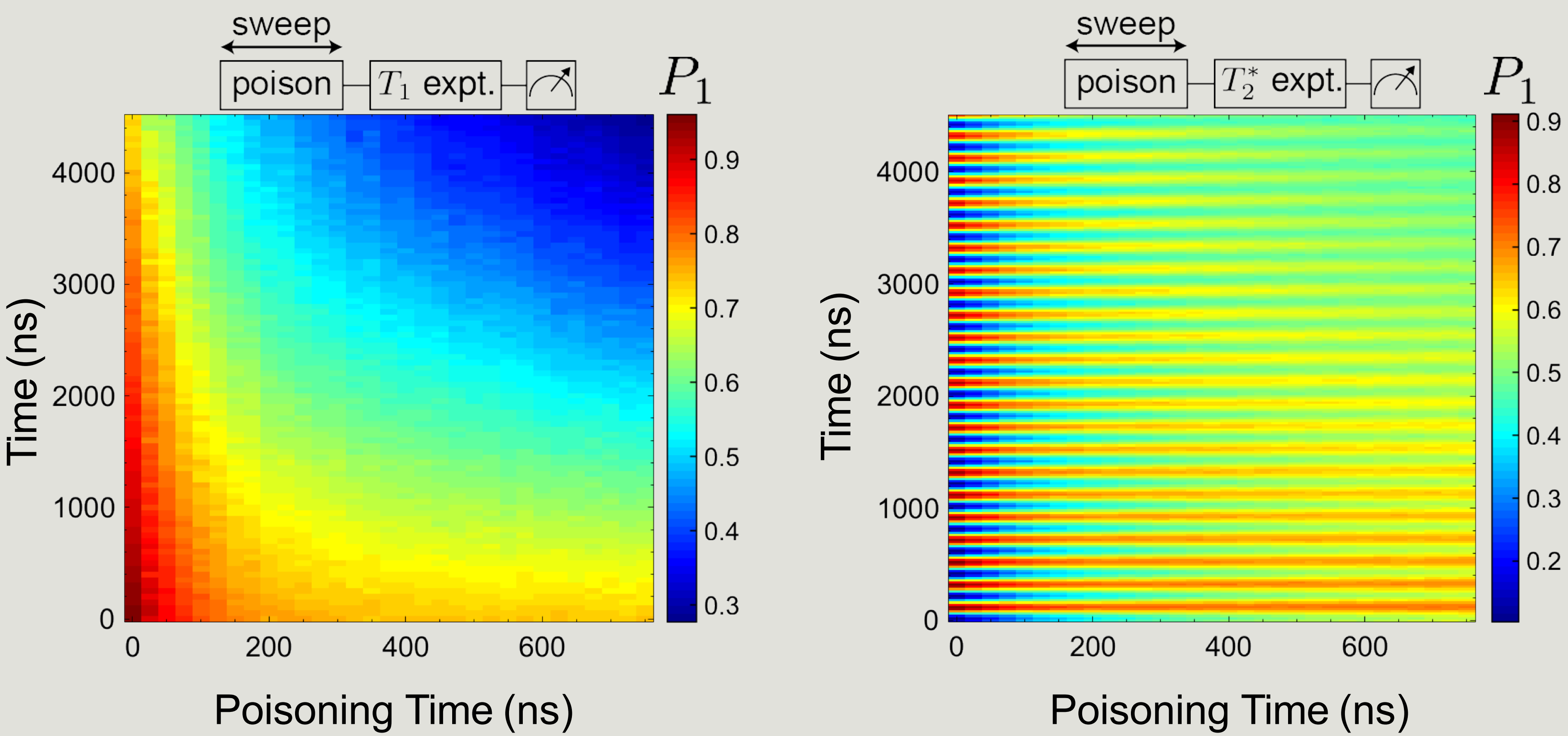
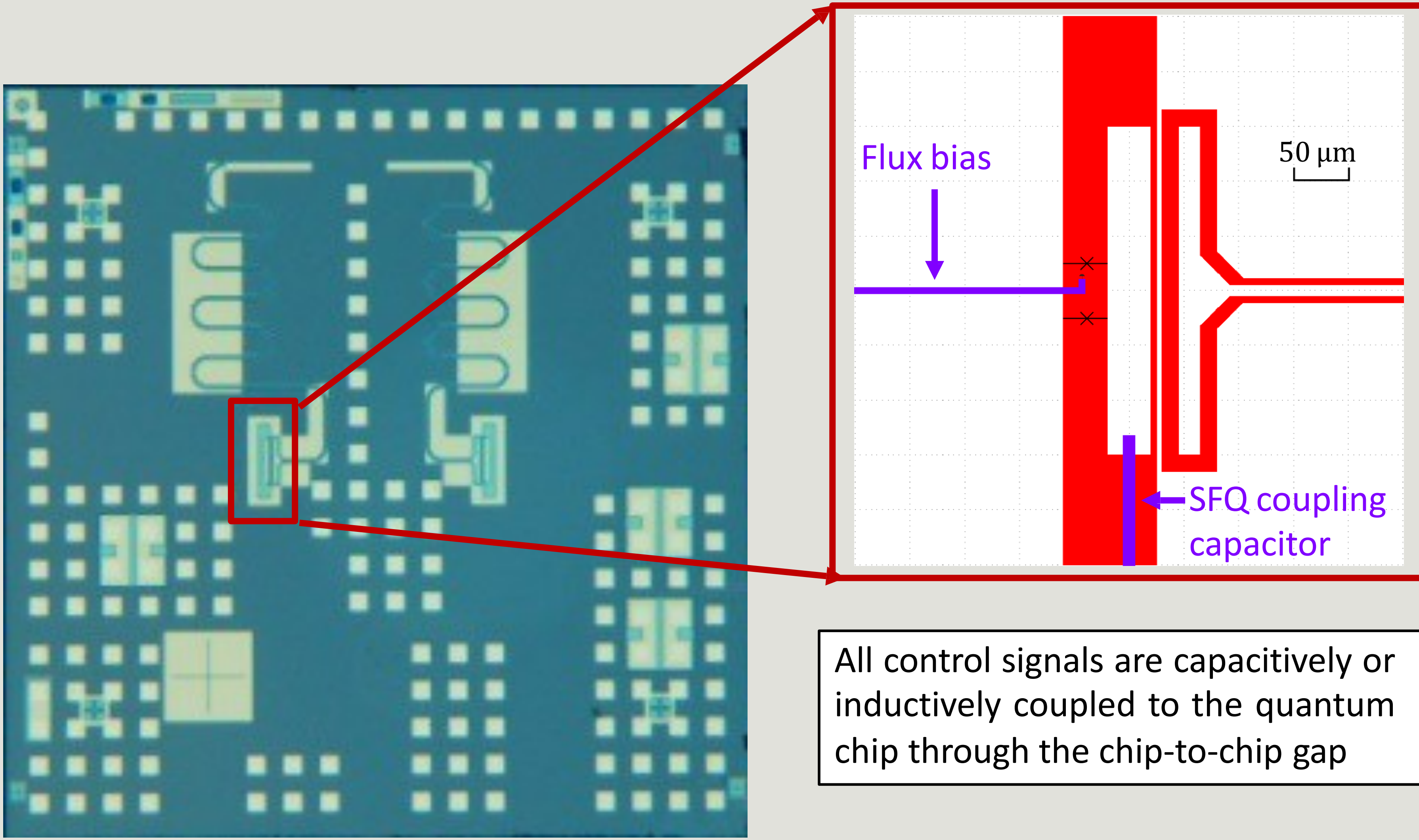
P. Liebermann *et al.*, *Phys. Rev. Appl.* **6**, 024022 (2016)

# Quasiparticle Poisoning



# Multi-chip module circuit design: quantum




All control signals are capacitively or inductively coupled to the quantum chip through the chip-to-chip gap