

Coherent control of superconducting transmon qubits with an on-chip single flux quantum driver

4EO1-04



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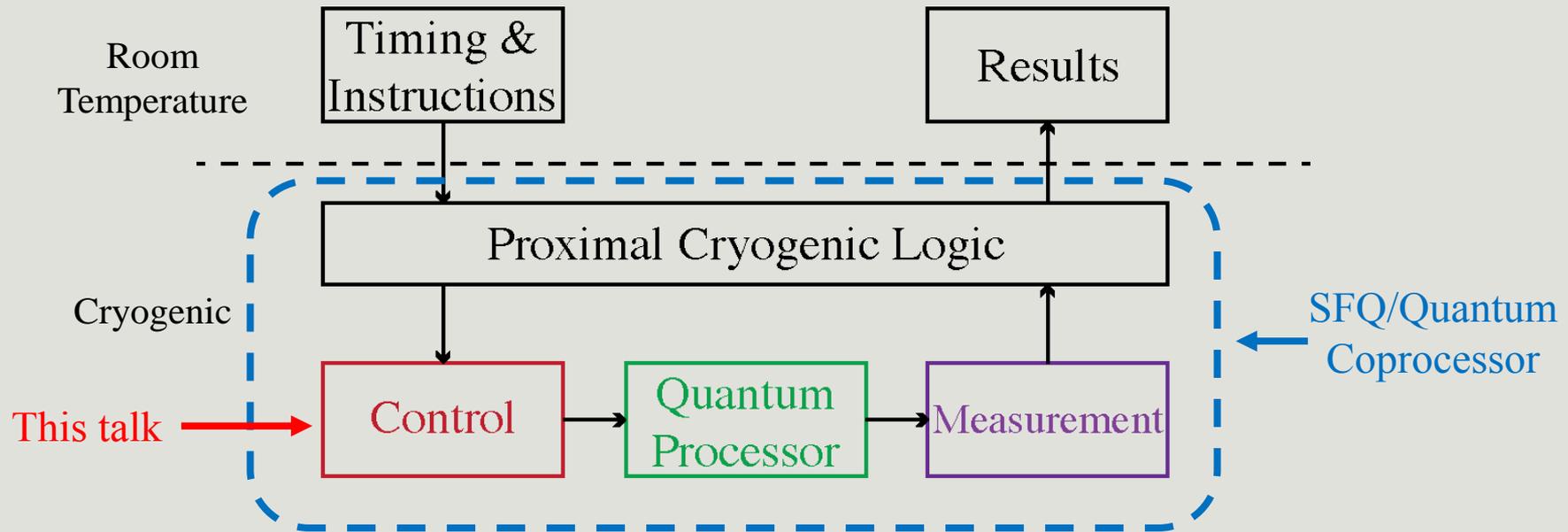
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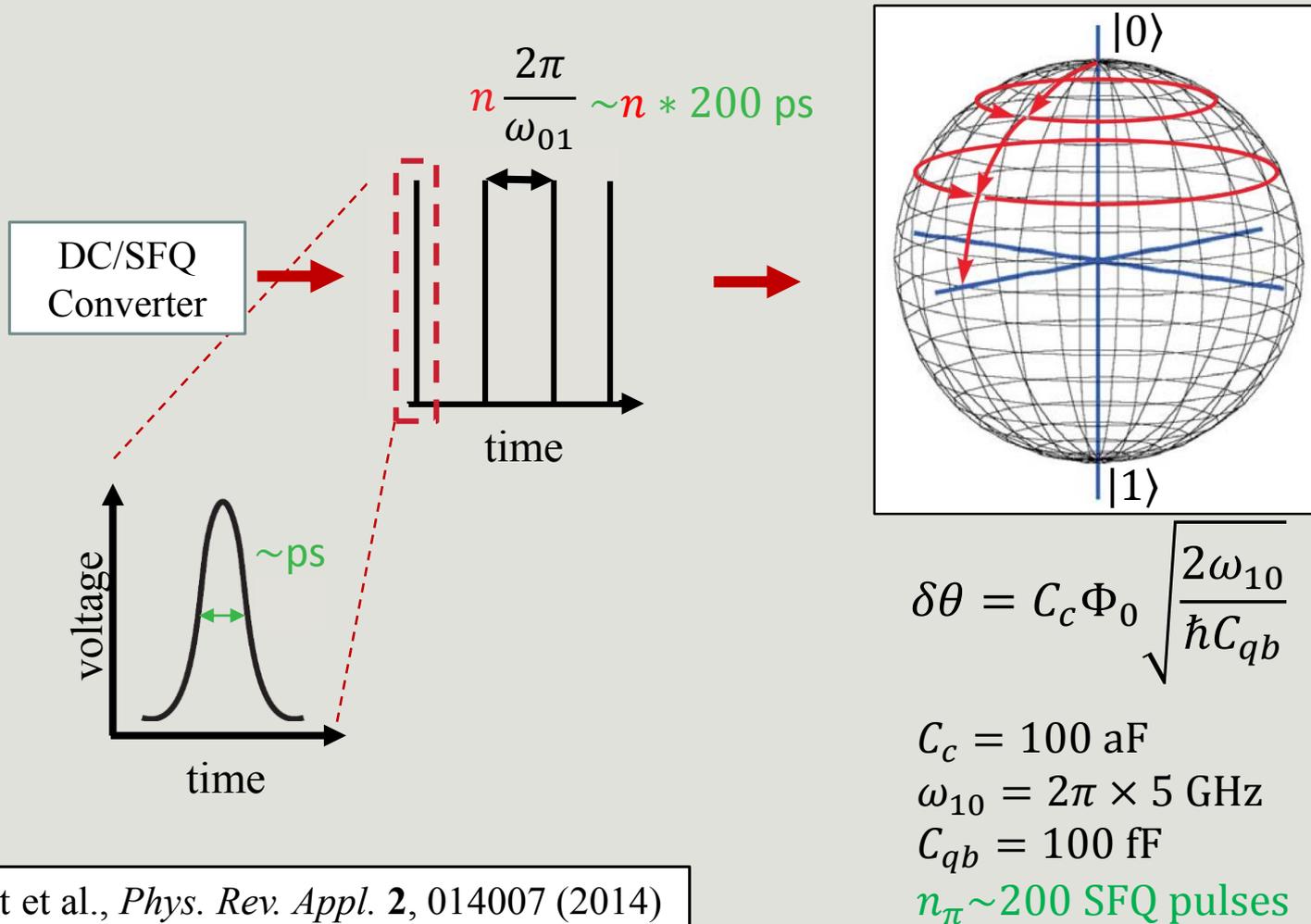


A Scalable Digital/Quantum Architecture



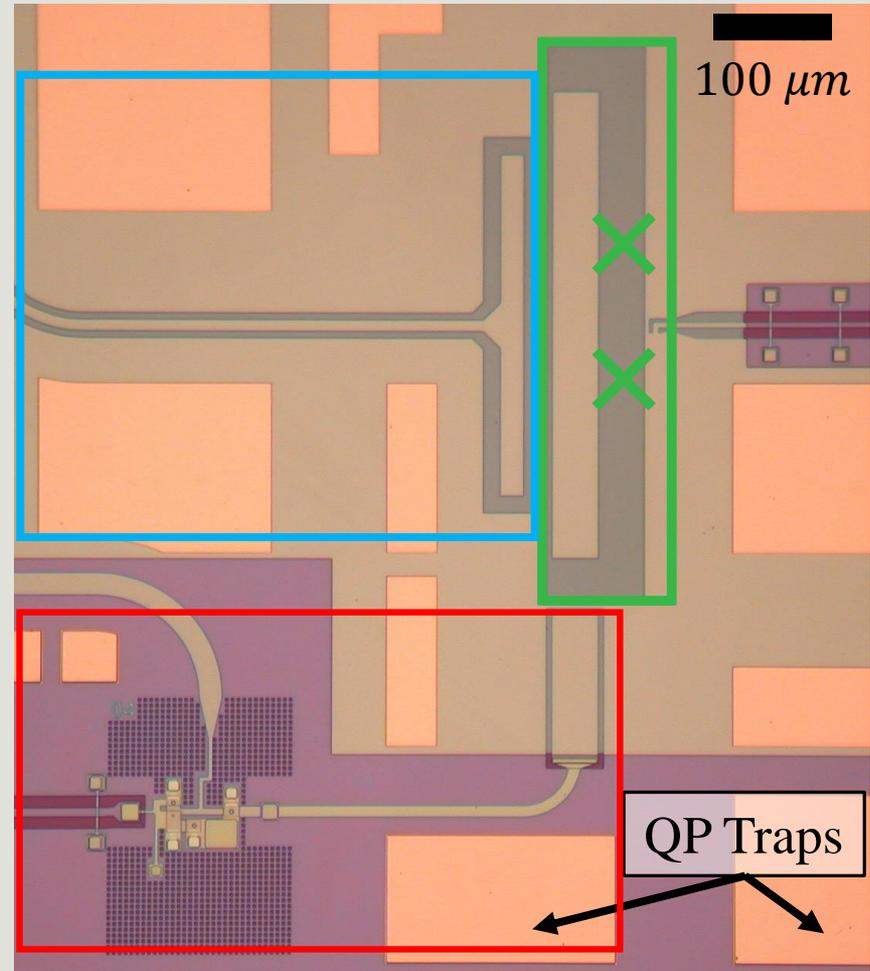
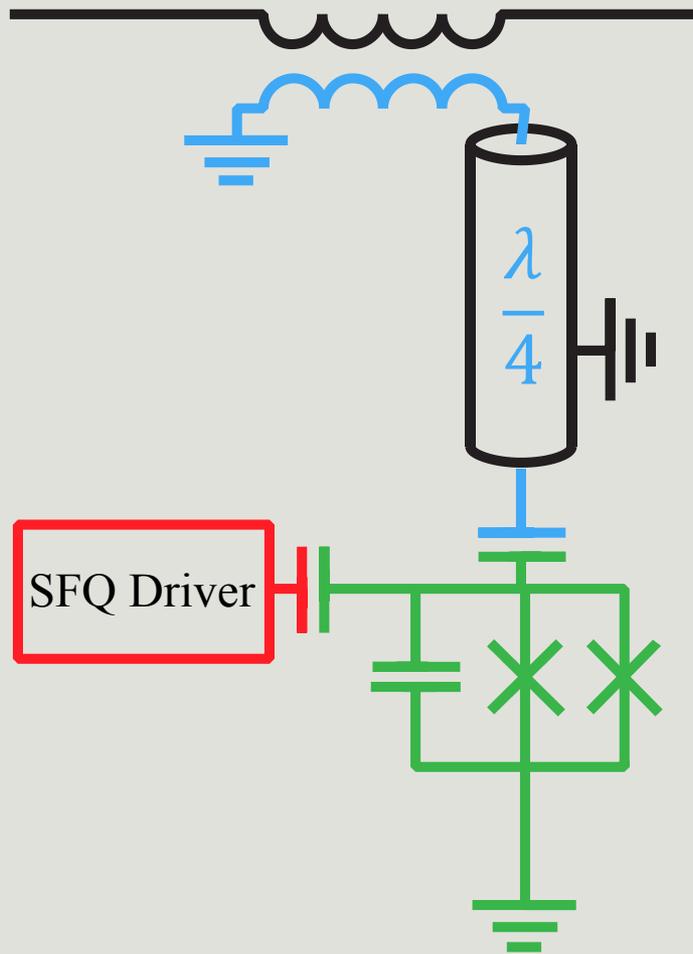
- ❖ Control and feedback with lower latency (installed in the cryostat)
- ❖ Reduced wiring overhead and heat-load from room temperature
- ❖ Smaller overall system footprint in both size and power

SFQ Pulse Control of Qubits



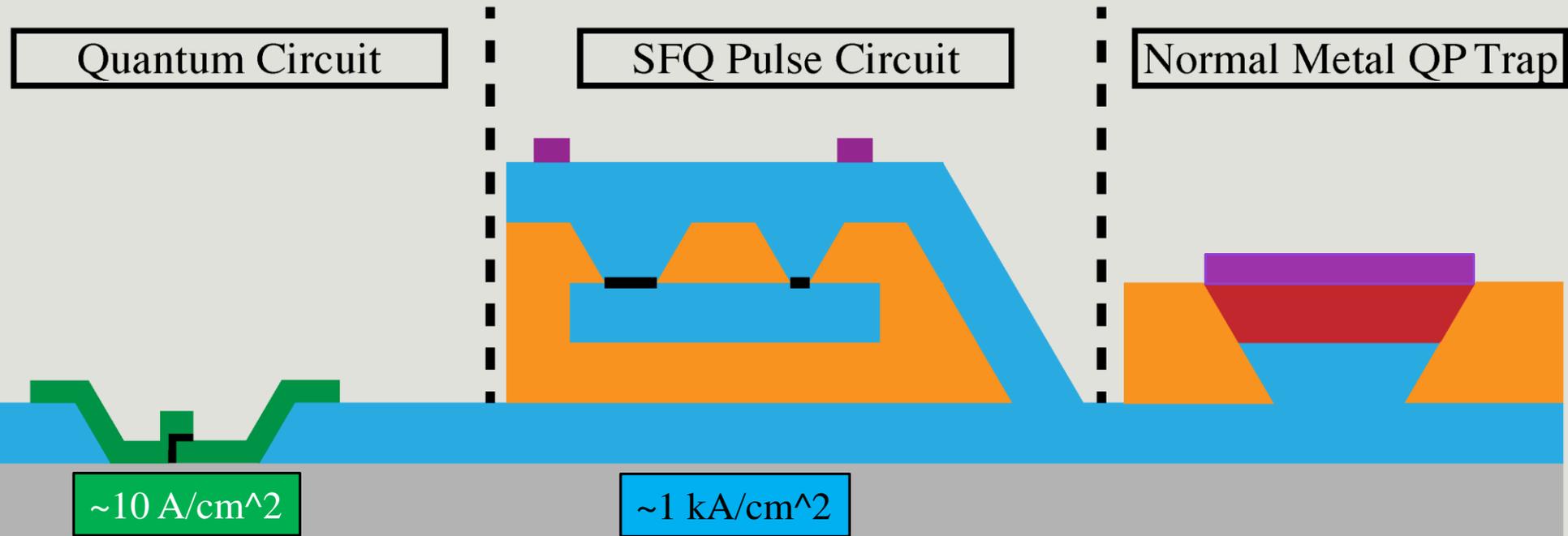
R. McDermott et al., *Phys. Rev. Appl.* **2**, 014007 (2014)

SFQ Driven Qubit Circuit

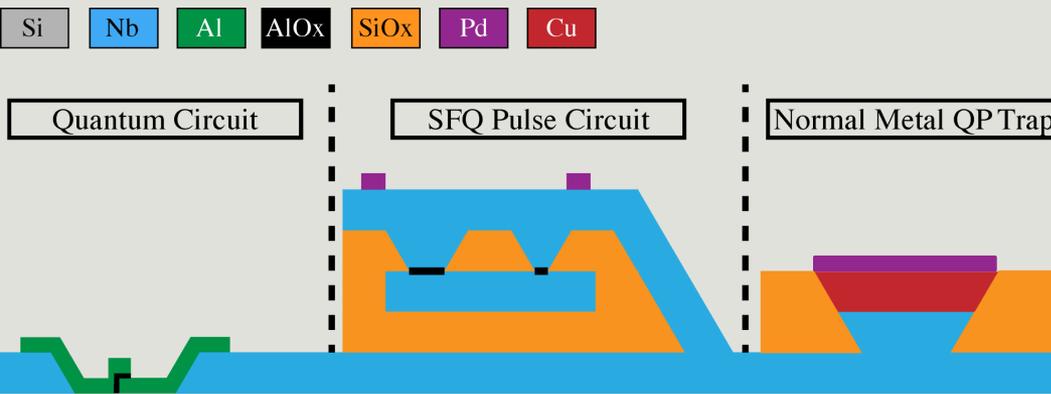
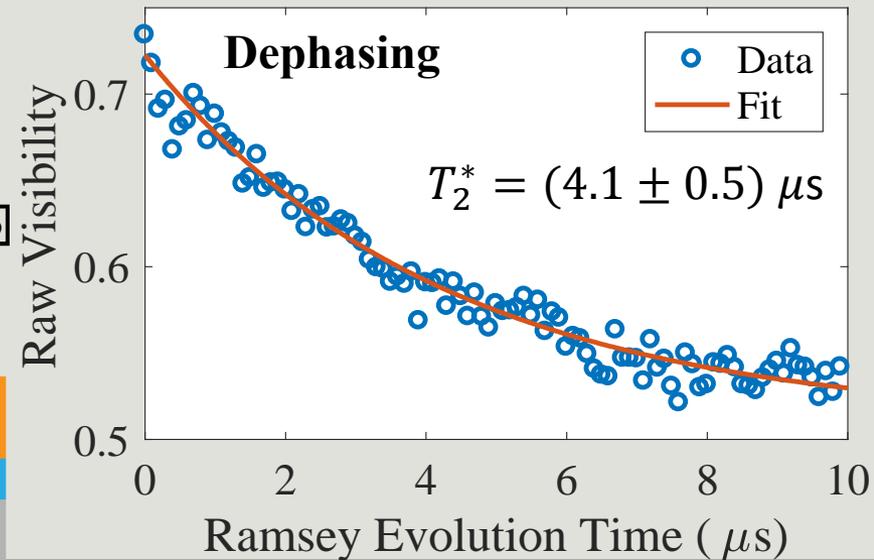
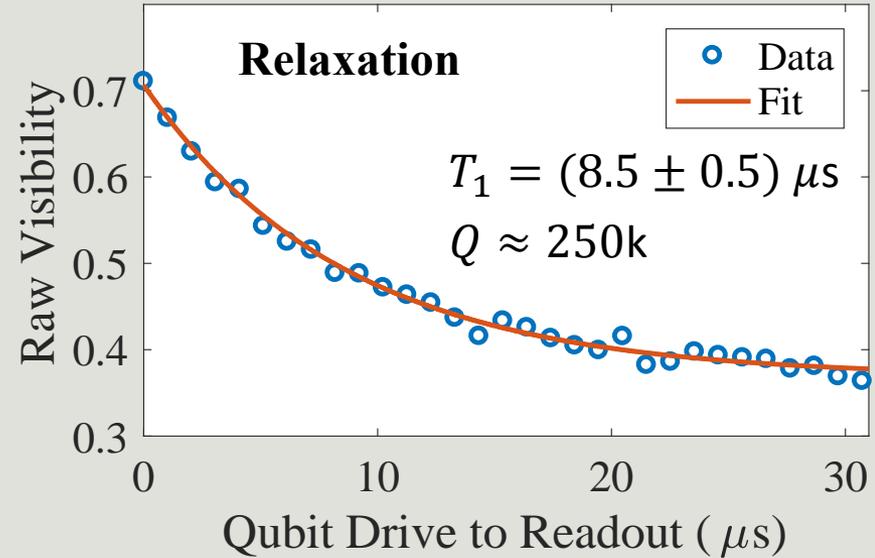
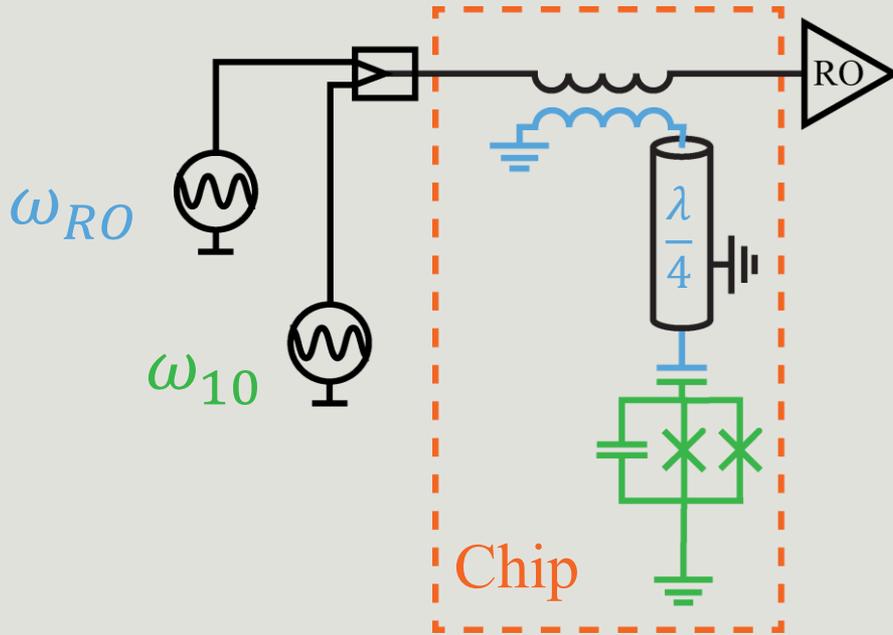


Layer Stack

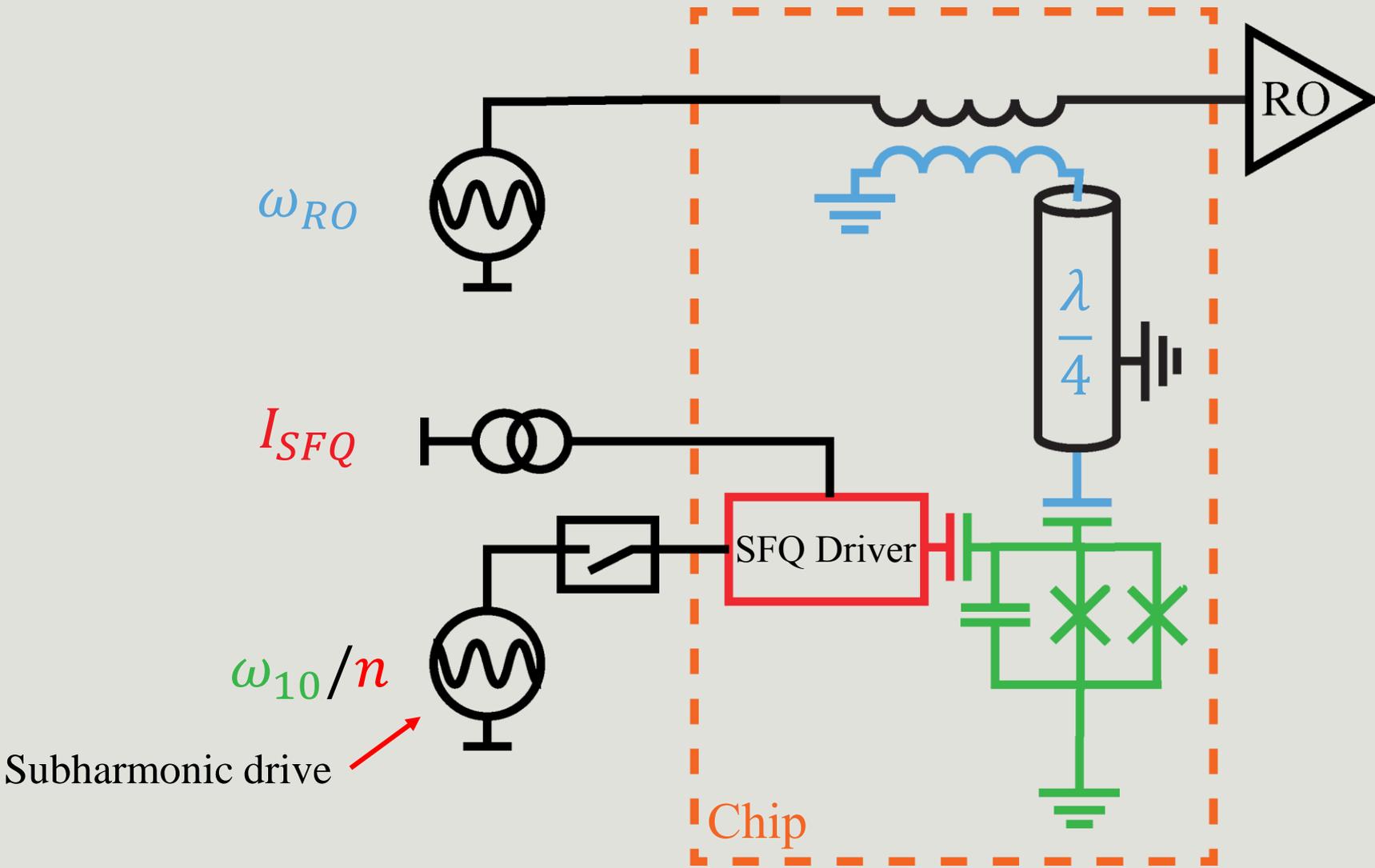
- Six metallization layers
 - 4 Superconducting (3 Nb + 1 Al)
 - 2 Normal Metal (Pd + Cu / Pd)
- Two PECVD SiOx insulating layers
 - Also used to protect Q. Circuit



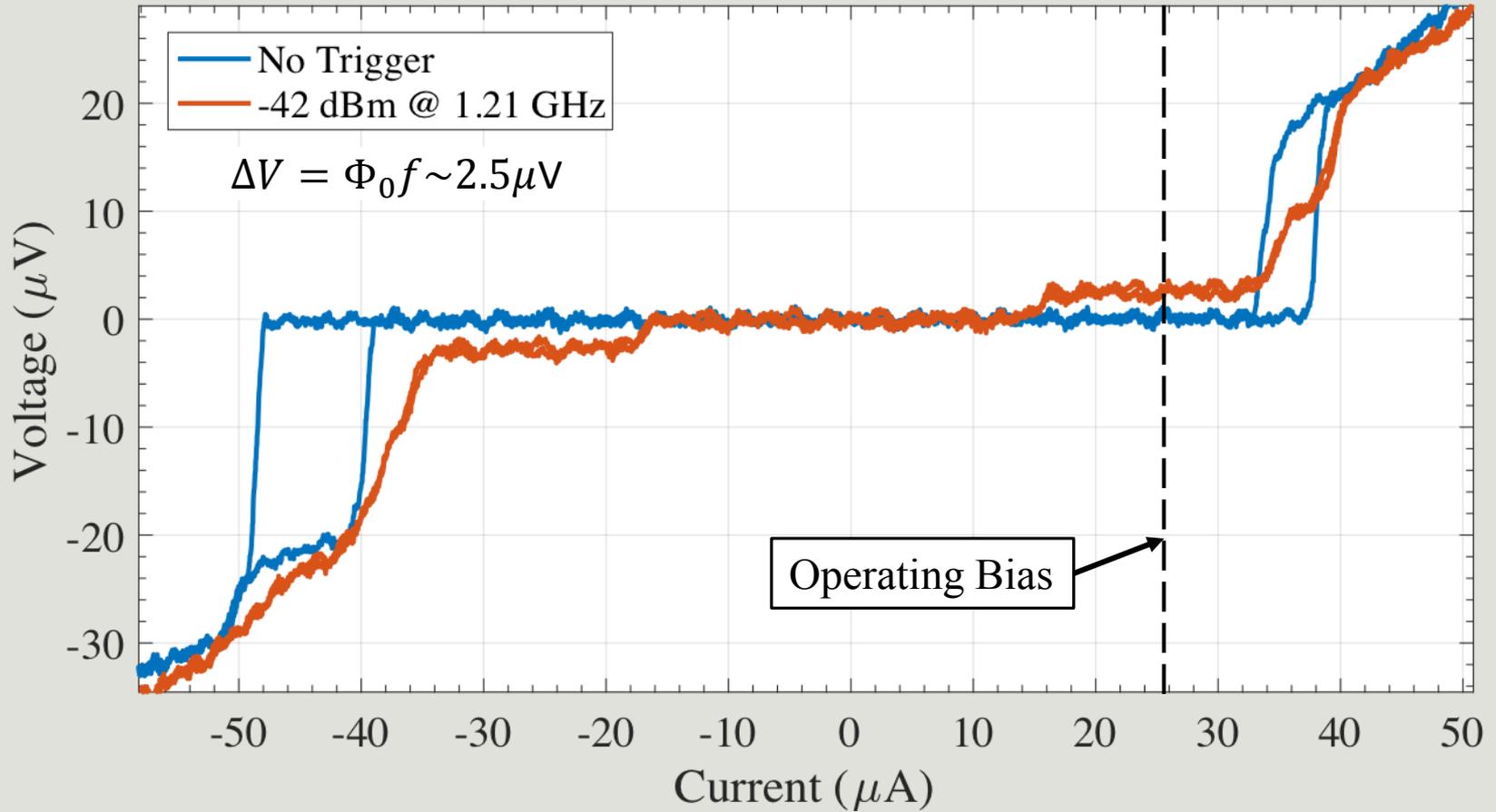
Qubit Coherence



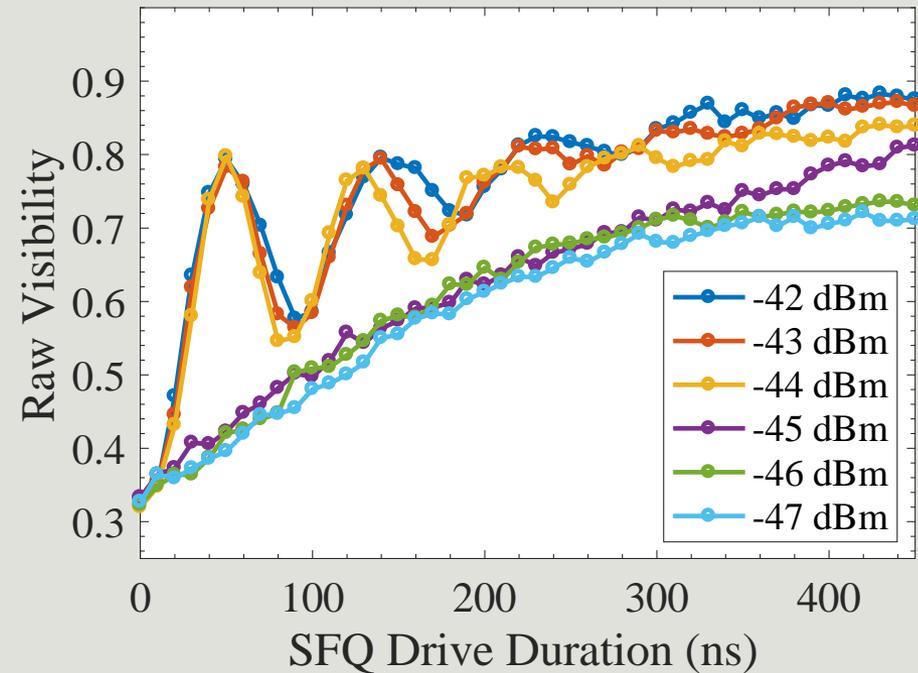
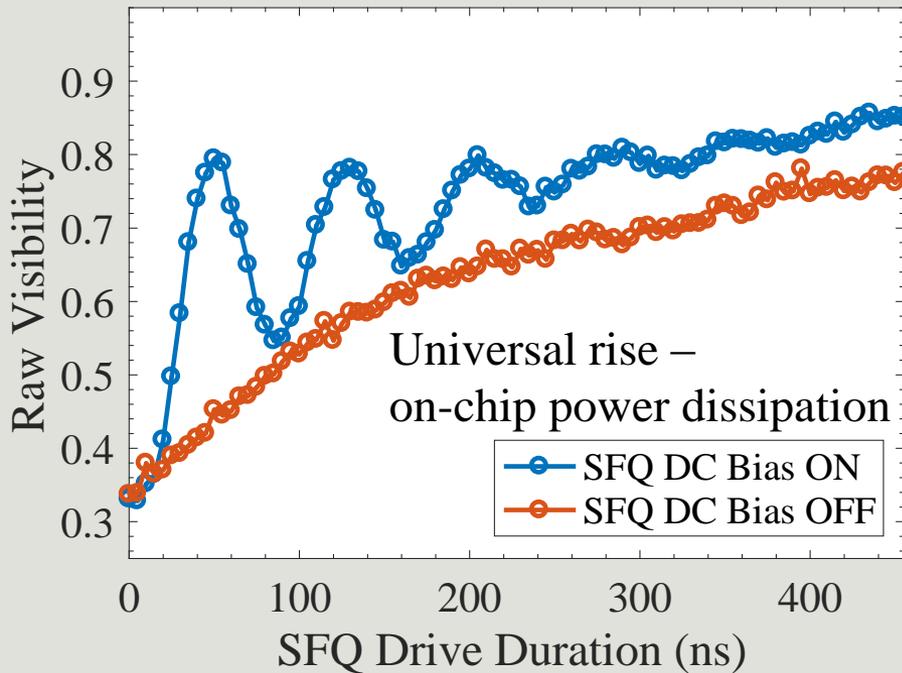
Signal Setup



DC/SFQ Converter Operating Point



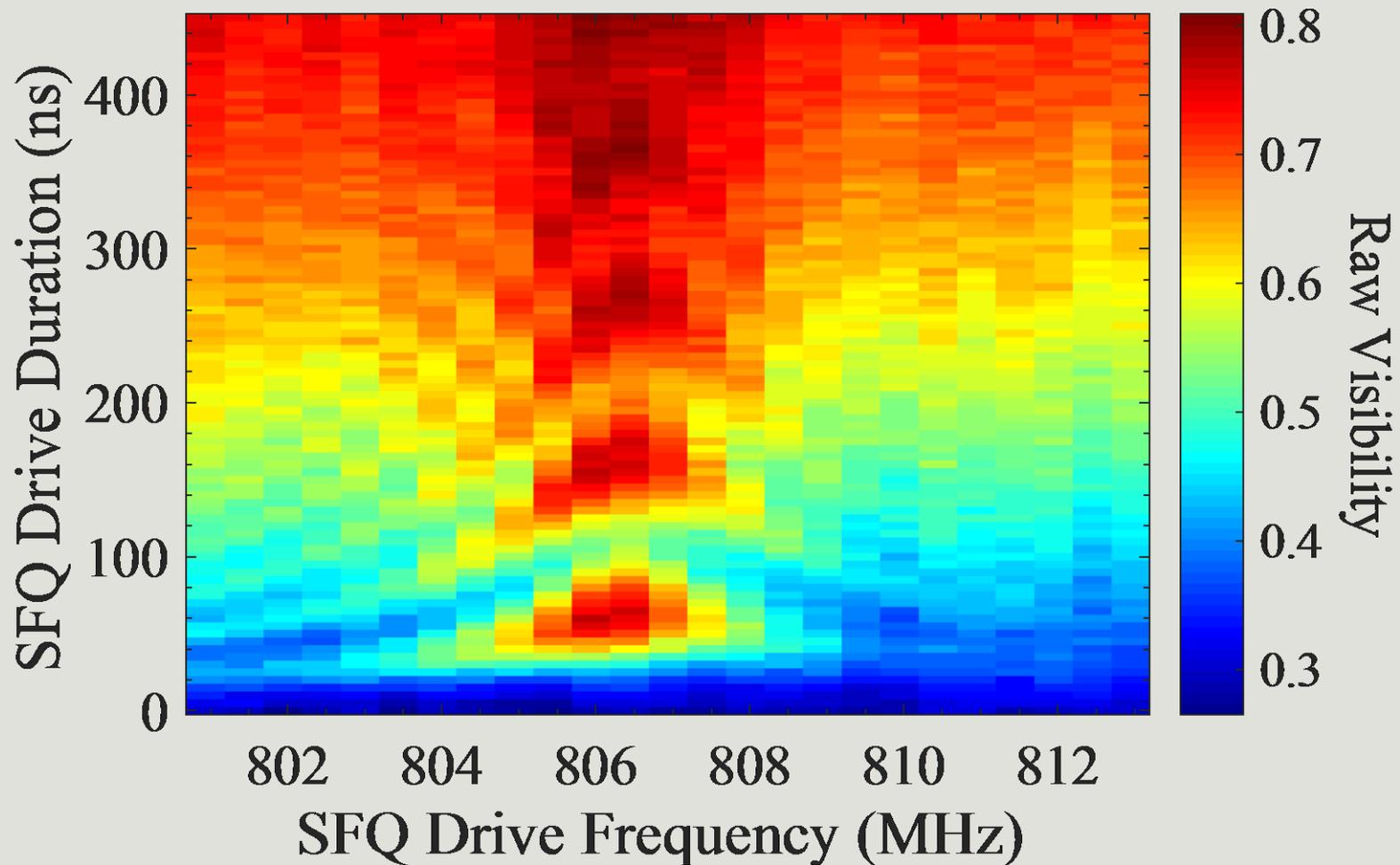
SFQ-driven Rabi @ $\omega_{01}/4$



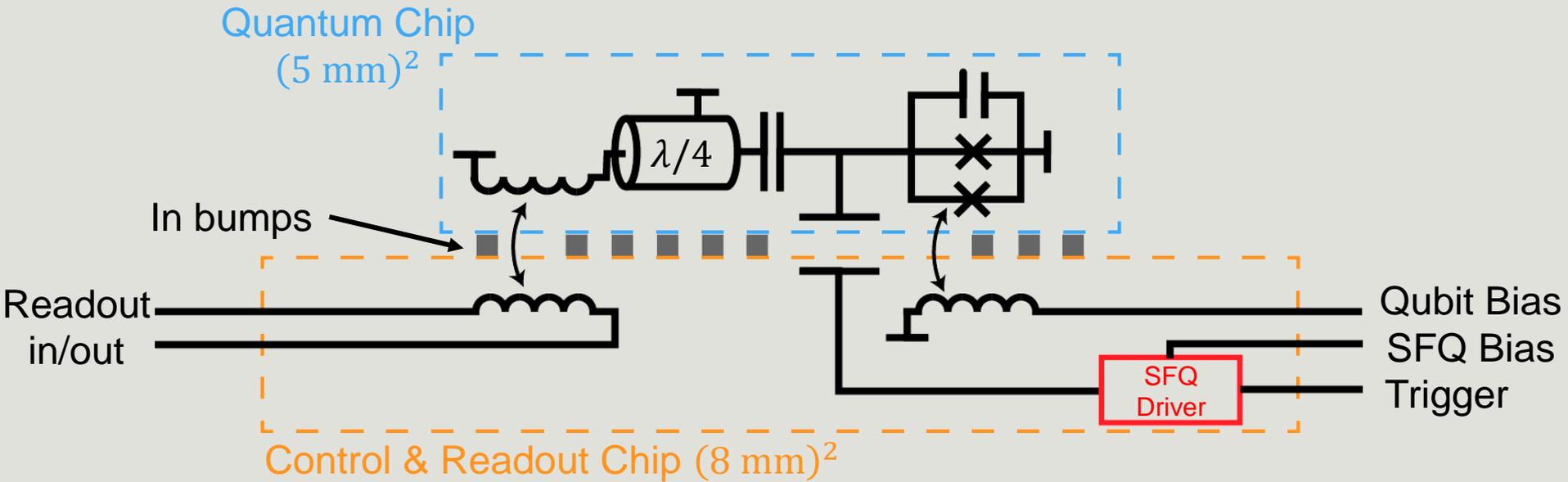
$$\delta\theta = C_c \Phi_0 \sqrt{\frac{2\omega_{10}}{\hbar C}} \approx 0.062 \text{ rad/pulse}$$

Number of SFQ pulses per π – rotation $\rightarrow 51$

SFQ-driven Rabi @ $\omega_{01}/6$

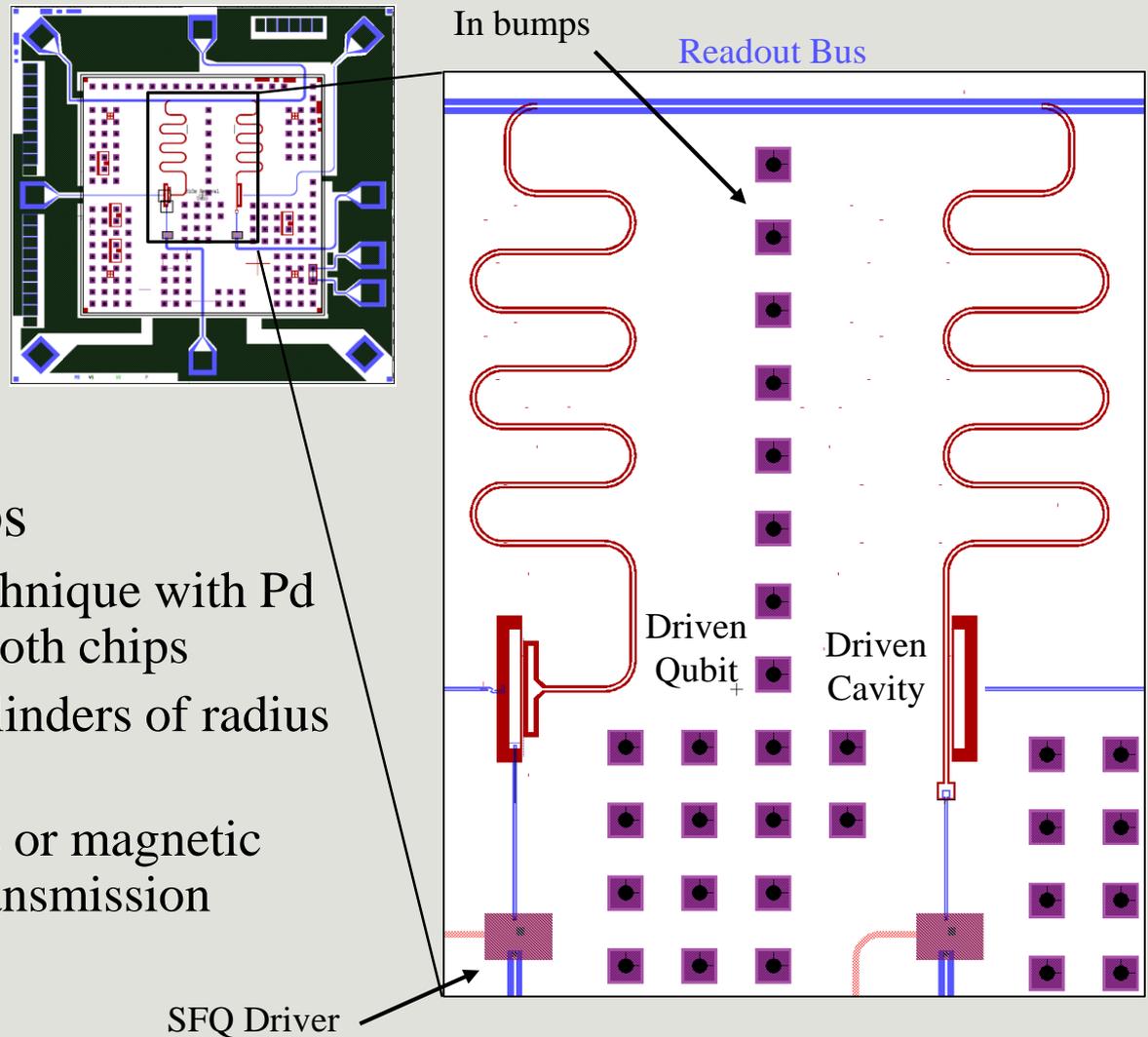


MCM Circuit Layout

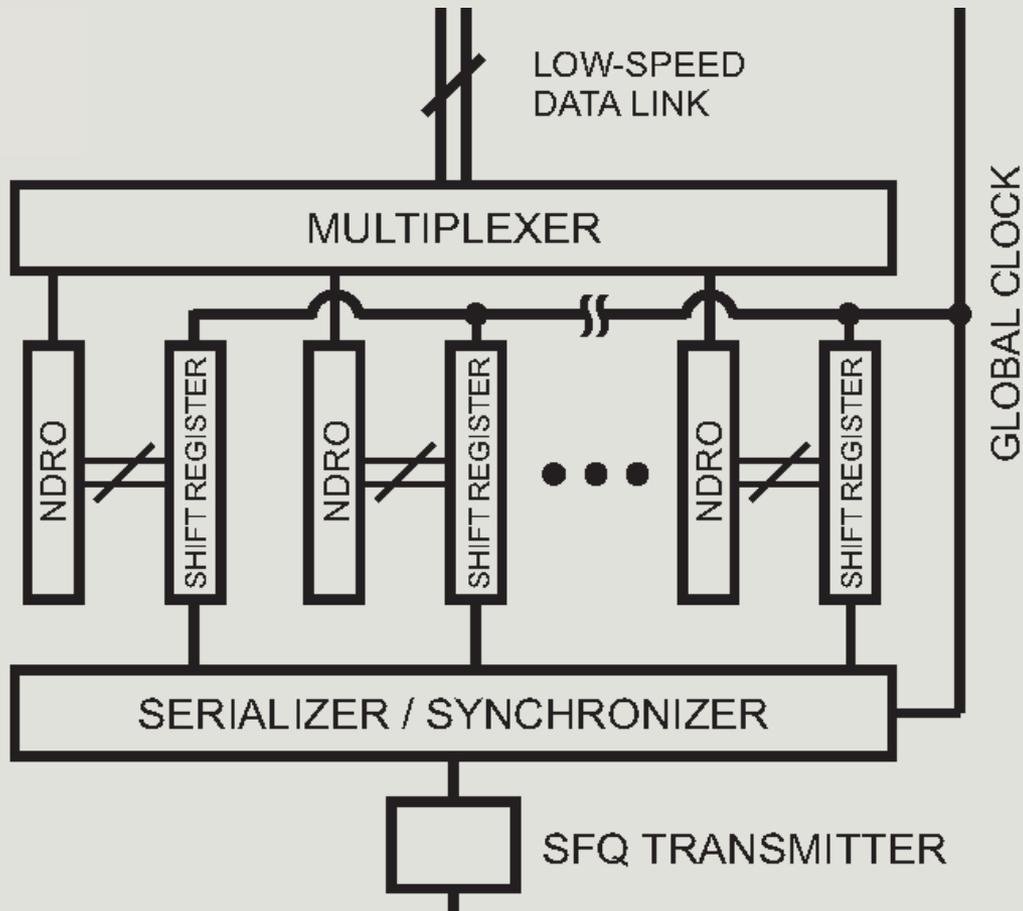


MCM Circuit Design

- Two chips flip-chip bonded together using superconducting In bumps
 - Employs bump-to-pad technique with Pd under-bump material on both chips
 - Bumps are $\sim 5 \mu\text{m}$ tall cylinders of radius $25 \mu\text{m}$
 - All signals are via electric or magnetic coupling – no galvanic transmission



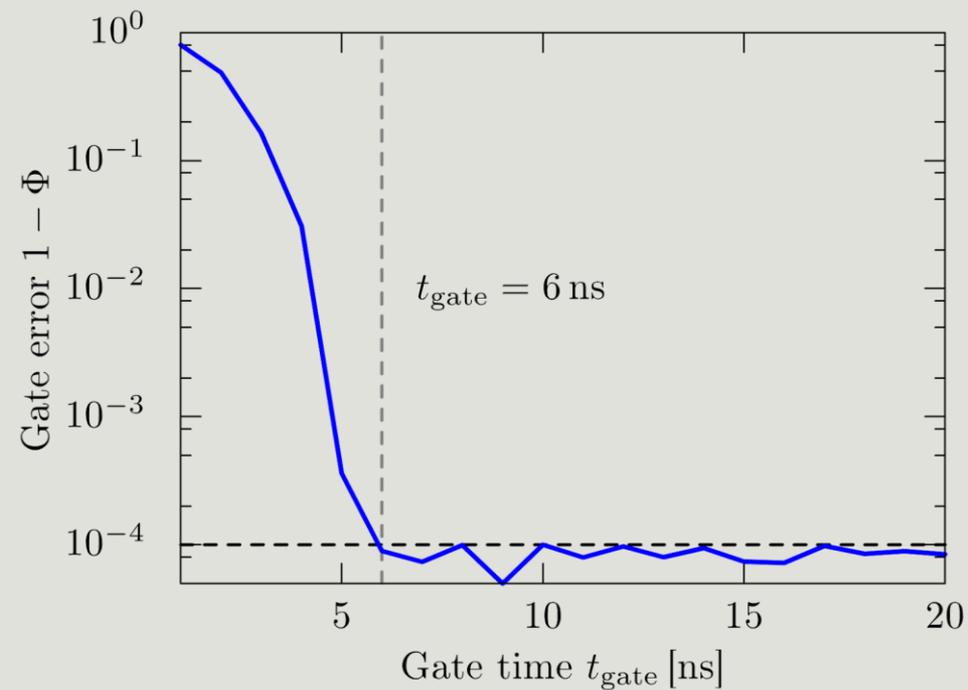
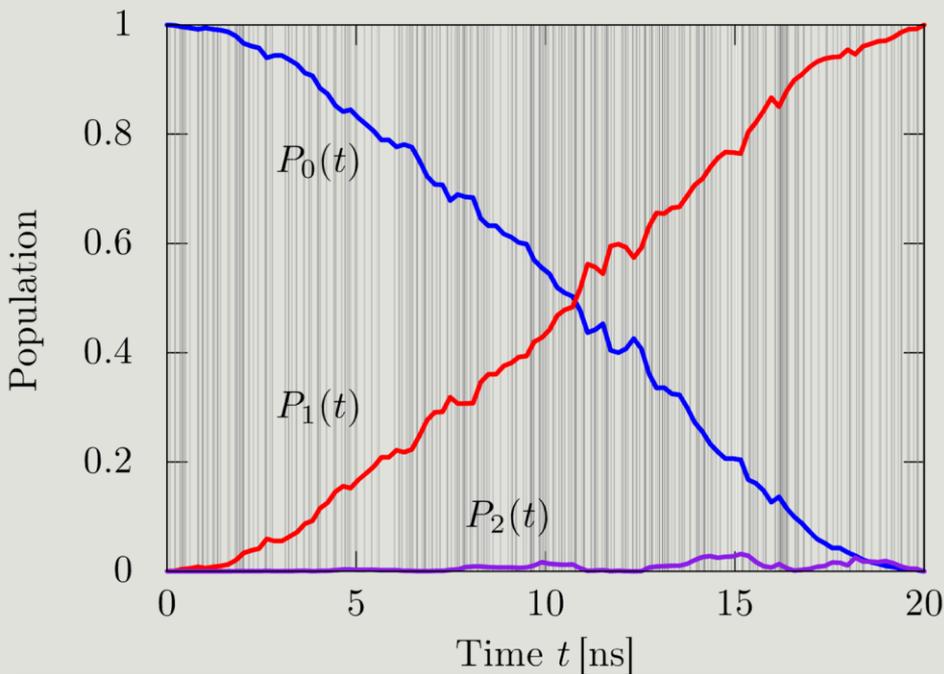
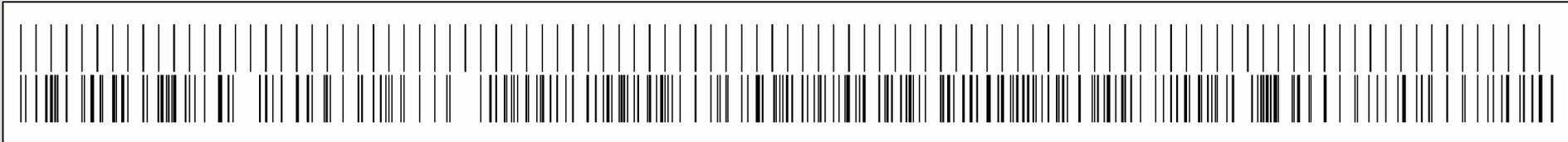
Classical SFQ Pulse Pattern Generator



- Single global clock (e.g. 30 GHz)
- Banks of shift registers to store/stream sequence (e.g., 10x200 bits)

With O. Mukhanov, *HYPRES Inc.*

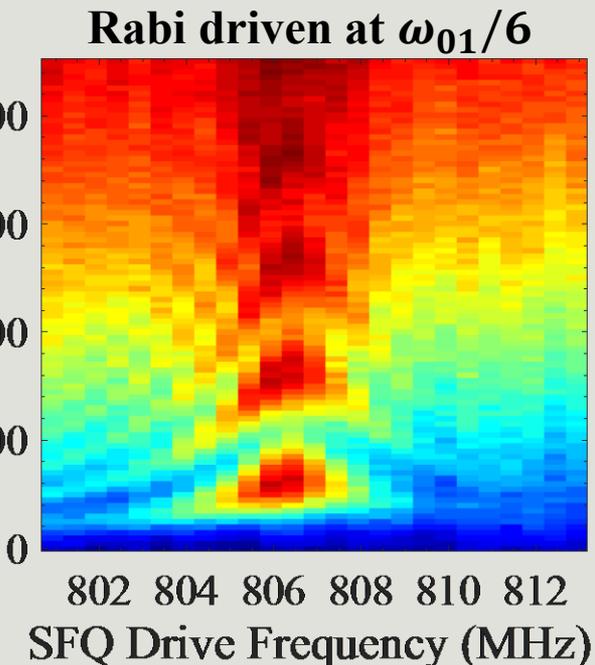
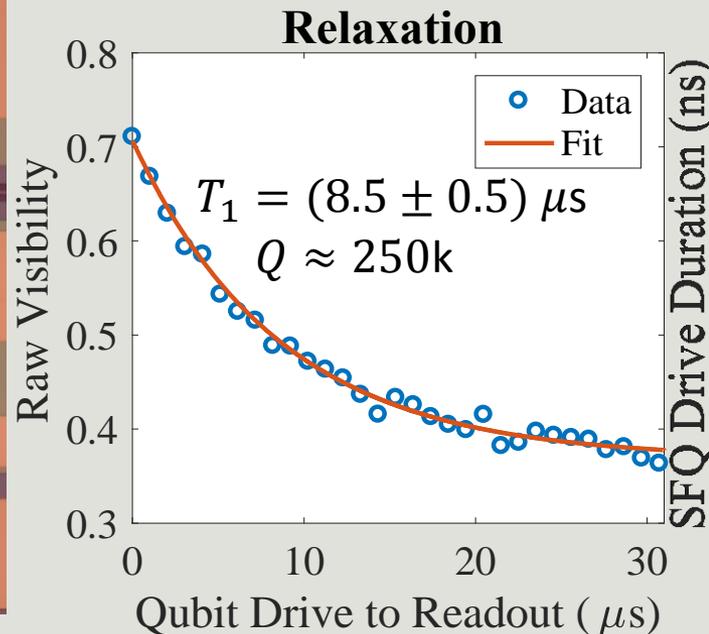
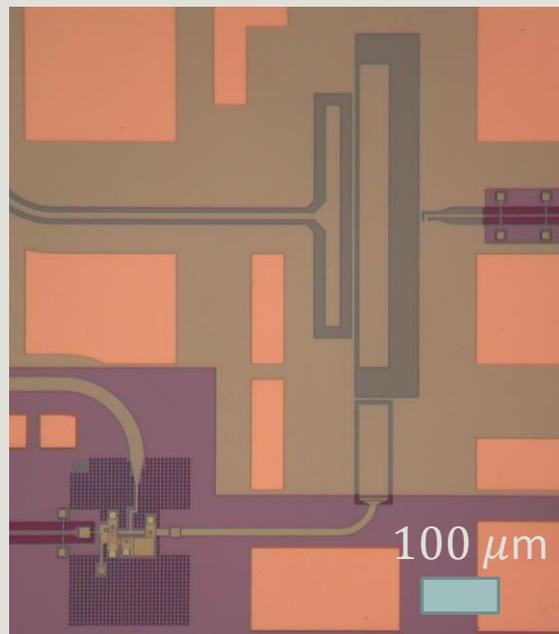
Optimal Control

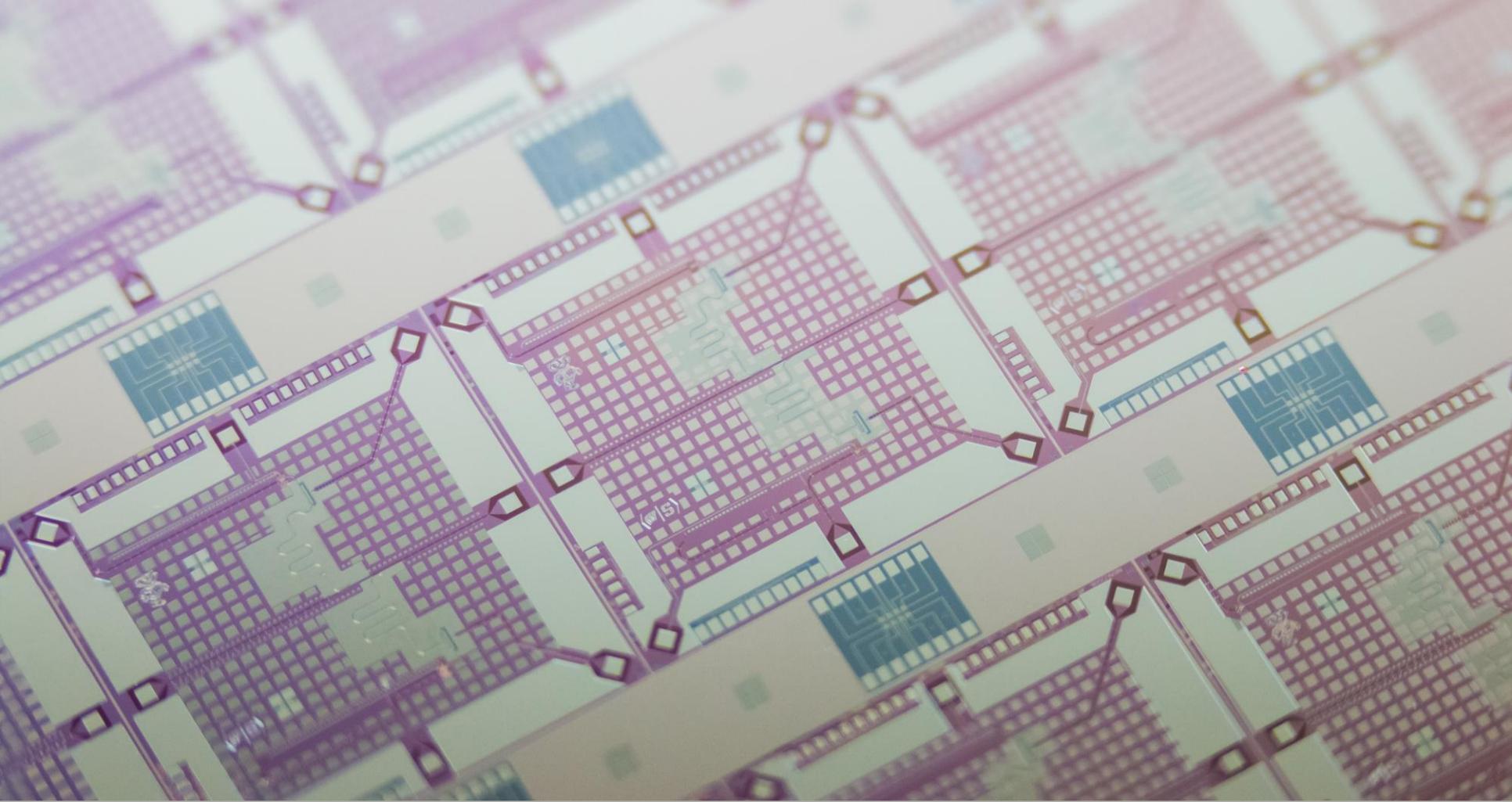


P. Liebermann *et al.*, *Phys. Rev. Appl.* **6**, 024022 (2016)

Summary

- ❖ Designed/fabricated eight layer SFQ/qubit integrated circuit
- ❖ Qubit performance not significantly degraded by enhanced fabrication
- ❖ SFQ driven Rabi oscillations
- ❖ 3D integration next logical step – soon to come!





Thank you



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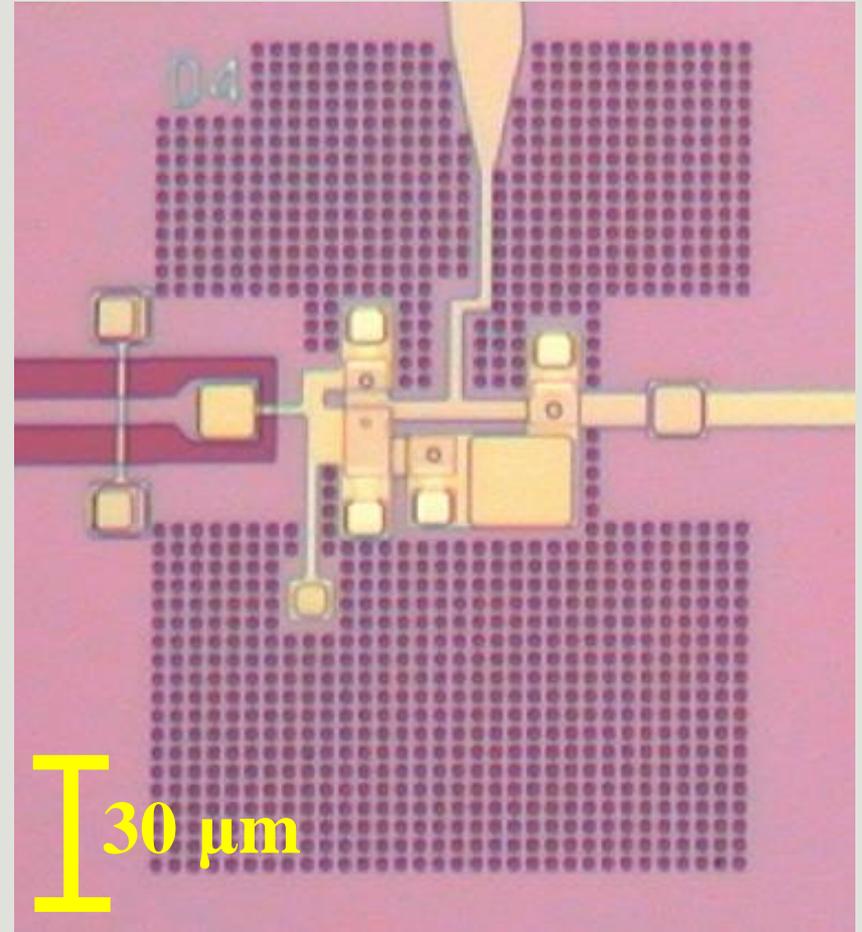
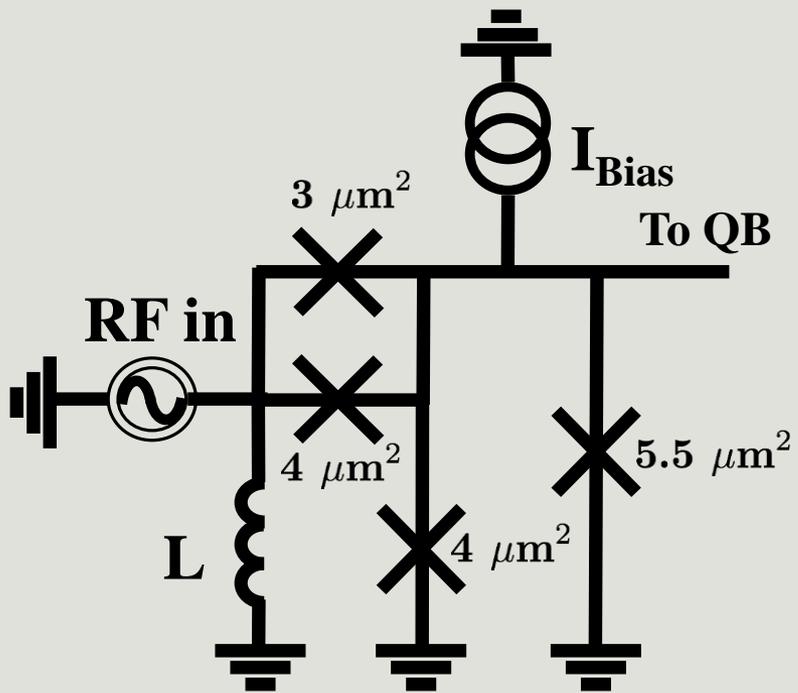
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Backup

ABSTRACT

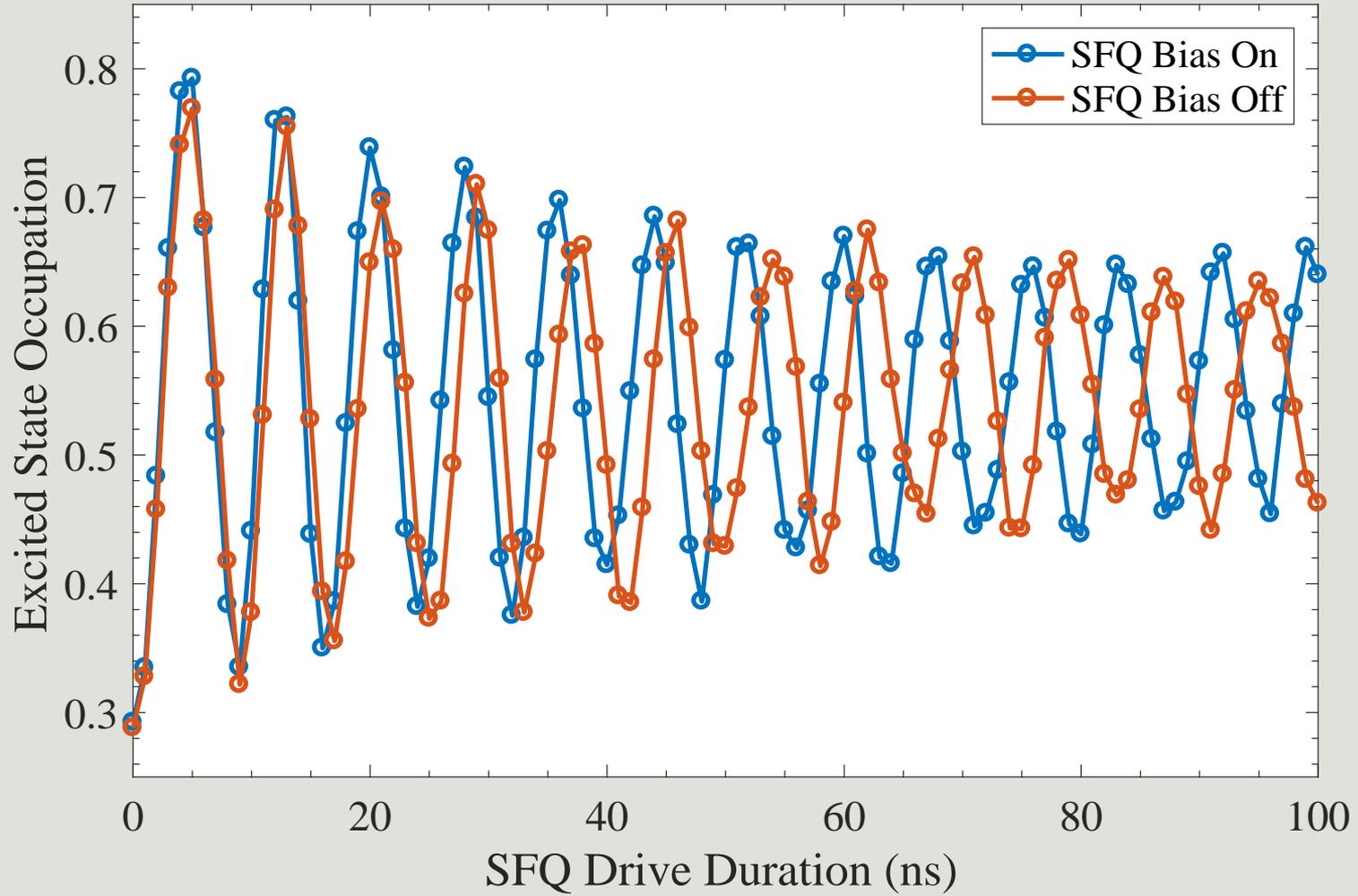
A large-scale superconducting quantum computer will require significant classical resources for operation, including elements for control, measurement, and feedback. A promising candidate technology to reduce both the wiring heat-load and overall system footprint of a future control system is the Single Flux Quantum (SFQ) digital logic family. Here we describe the integration of a single flux quantum driver with a superconducting transmon qubit on a single chip. The SFQ circuit is fabricated in a high- J_c Nb/Al-AlO_x/Nb junction process while the transmon qubit is subsequently formed using submicron Al-AlO_x-Al junctions grown by double-angle evaporation. We show results highlighting the resultant high quality ($T_1=(8.5\pm 0.5)\ \mu\text{s}$) qubit as well as Rabi oscillations driven by resonant SFQ pulse trains.

DC/SFQ Converter

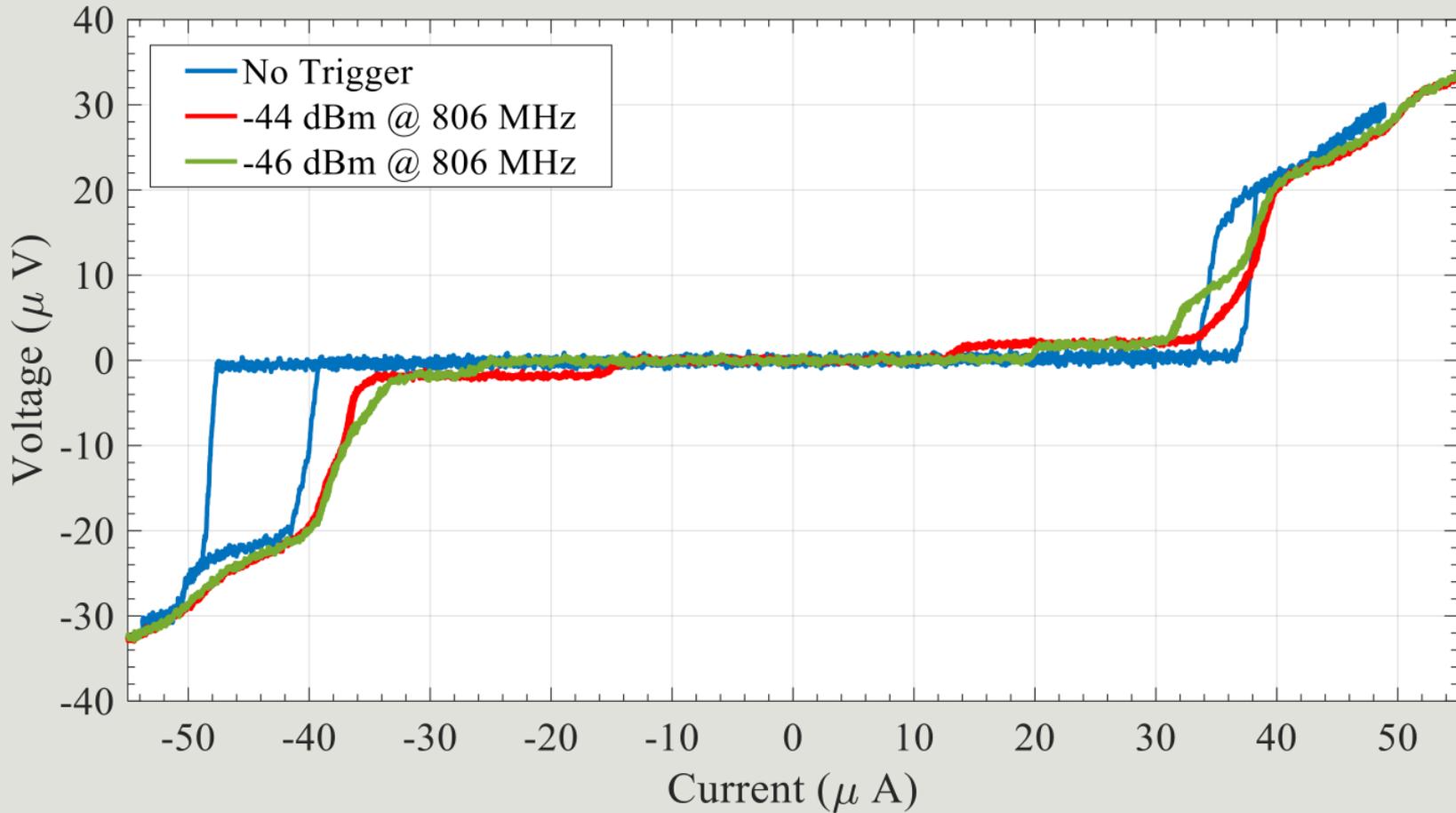


Rabi at ω_{01}

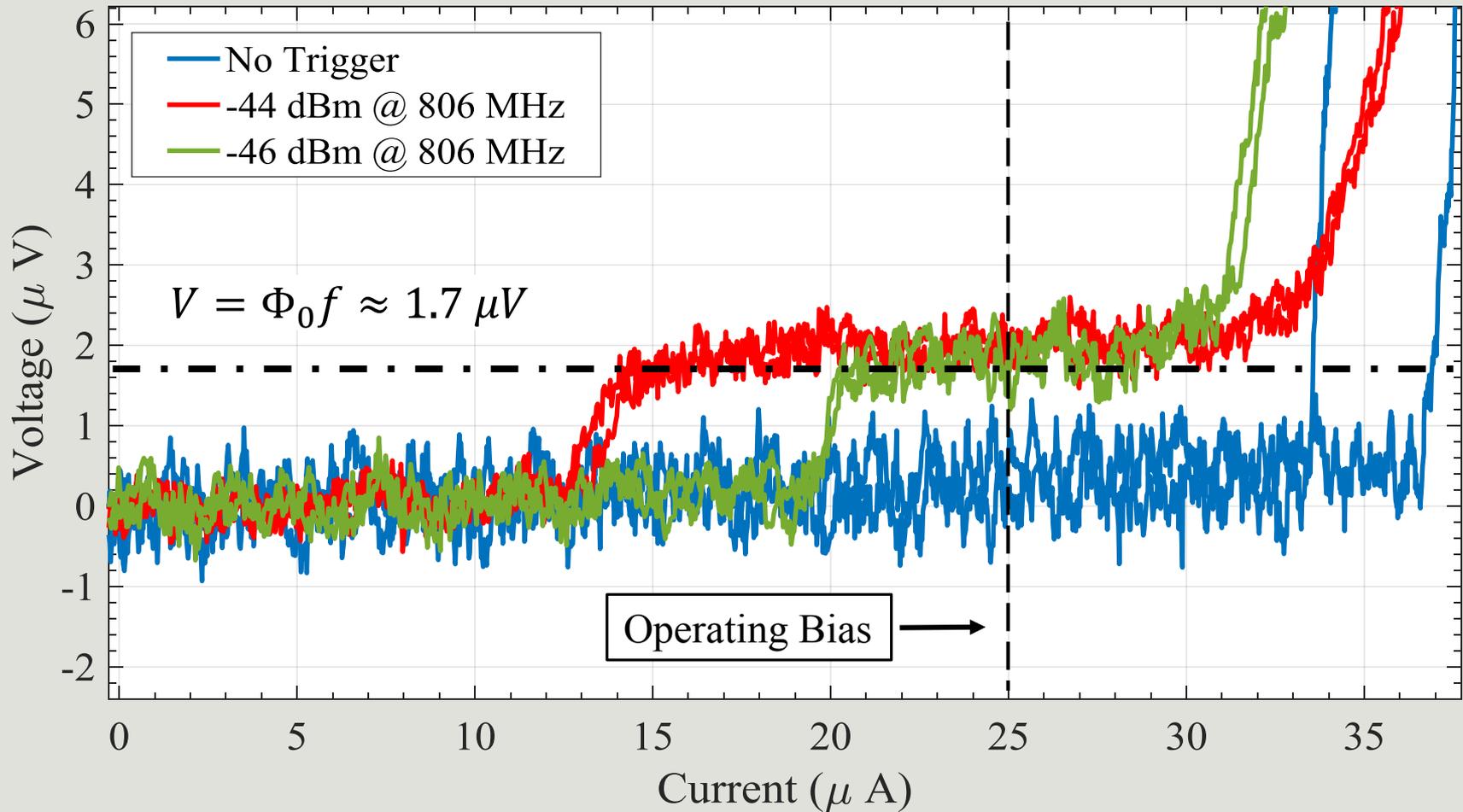
Rabi oscillations driven through the SFQ circuit



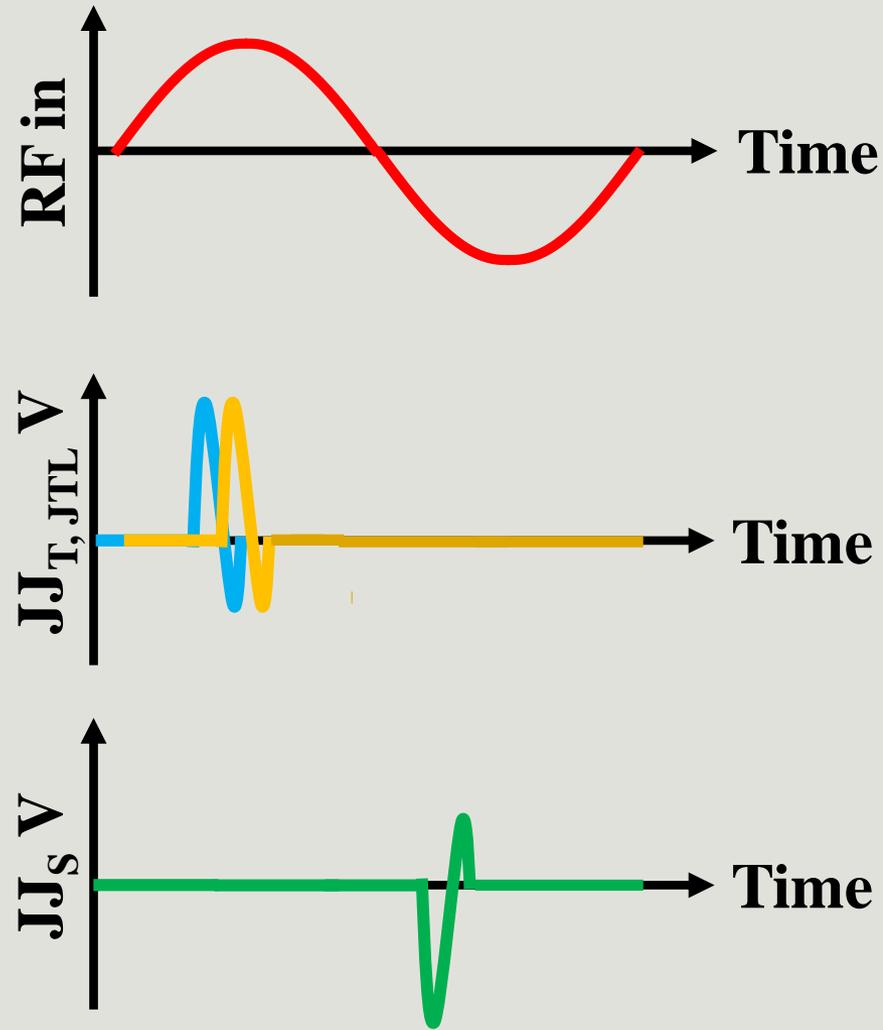
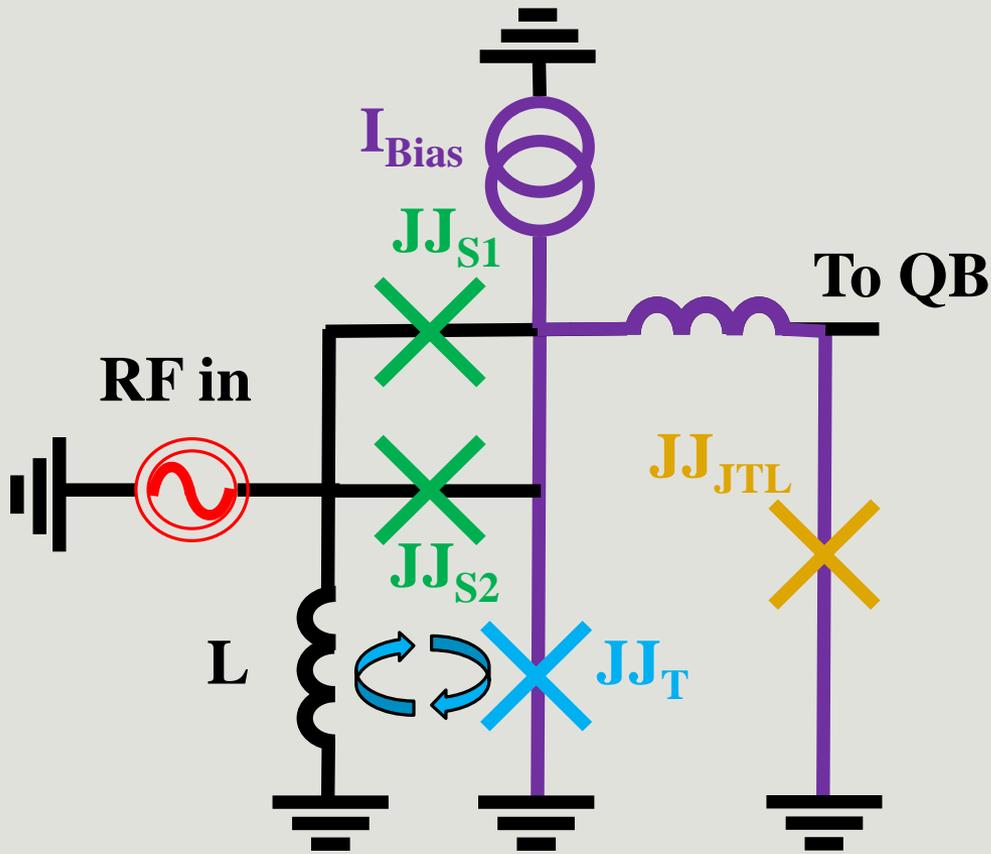
Shapiro Steps for $\omega_{01}/6$



Shapiro Steps for $\omega_{01}/6$

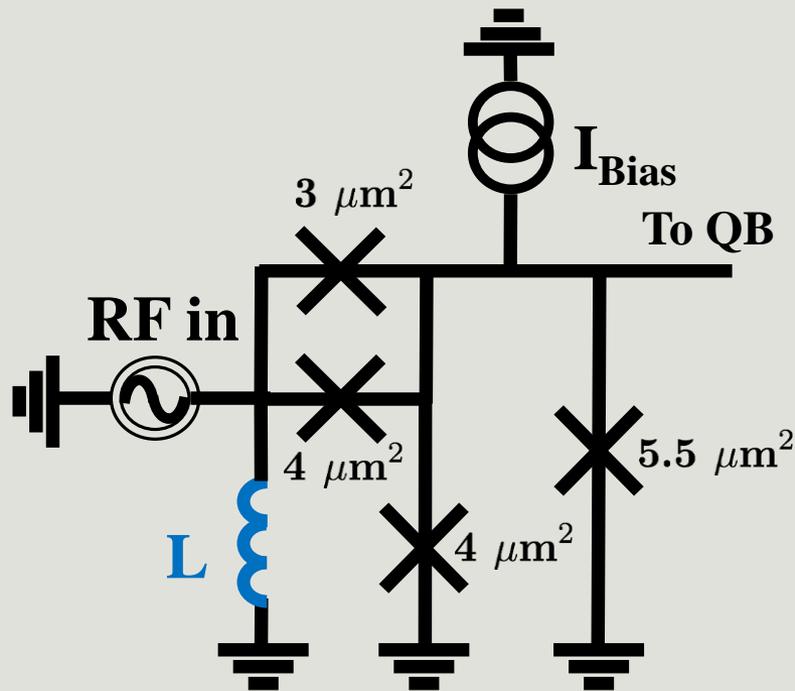


SFQ Driver Operation



SFQ Driver Optimization

Goal: Trigger SFQ Pulses with minimal microwave input power



$$2 \leq \beta_L \leq 6$$

$F = 5 \text{ GHz}$, $P_{\text{RF}} = -60 \text{ dBm}$, $J_c = 1 \text{ kA} / \text{cm}^2$

