Office of the Director of National Intelligence
IARPA
BE THE FUTURE

QUANTUM ENHANCED OPTIMIZATION

Quantum Enhanced Optimization: Experimental Study Overview

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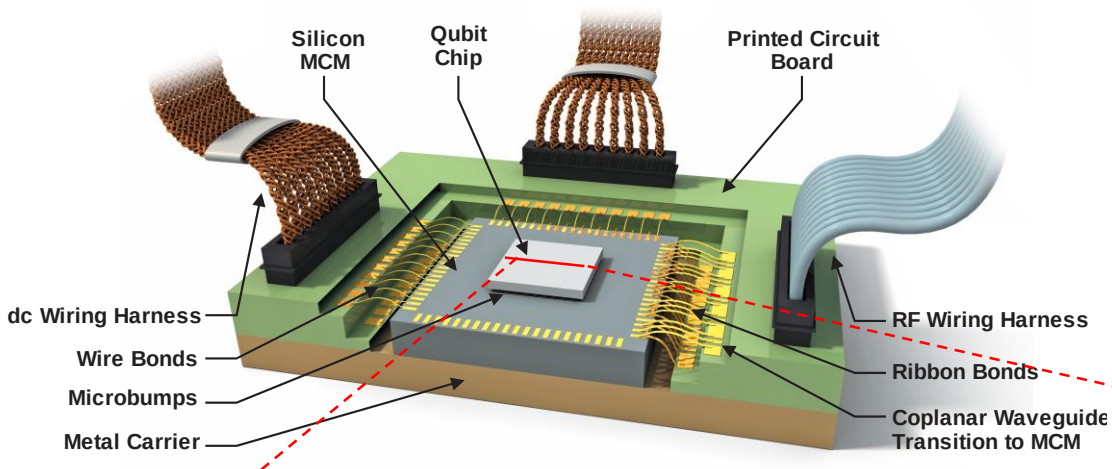
MIT Lincoln Laboratory

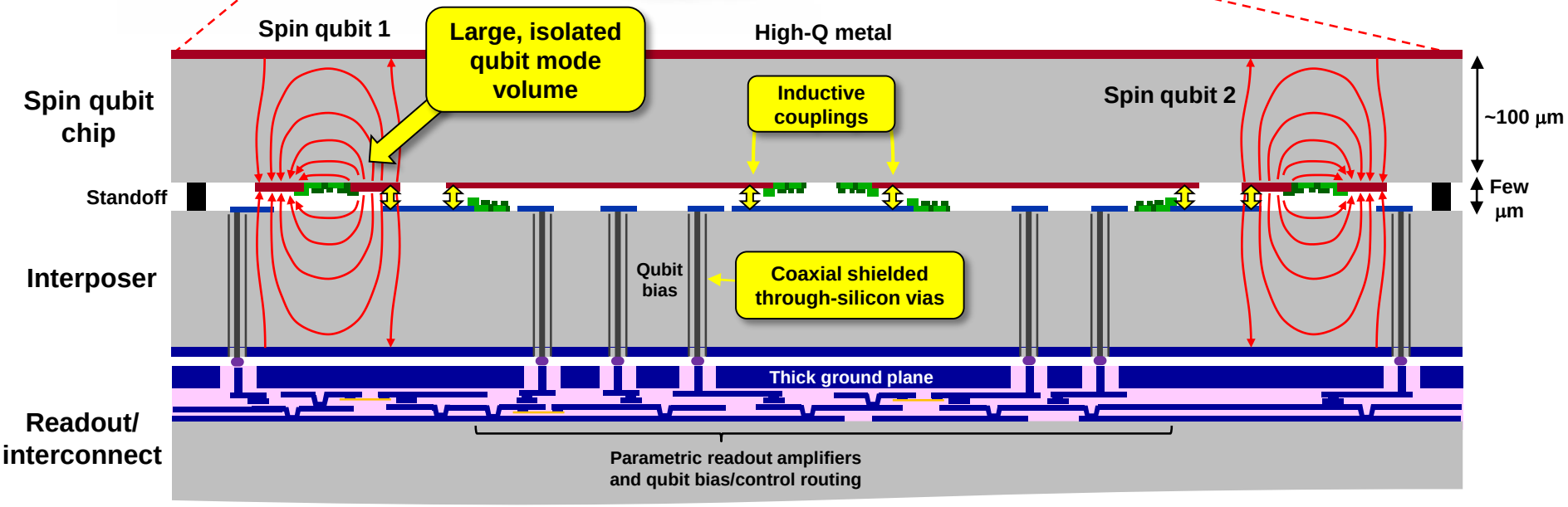
10/26/2015

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Quantum Annealing Testbed Concept

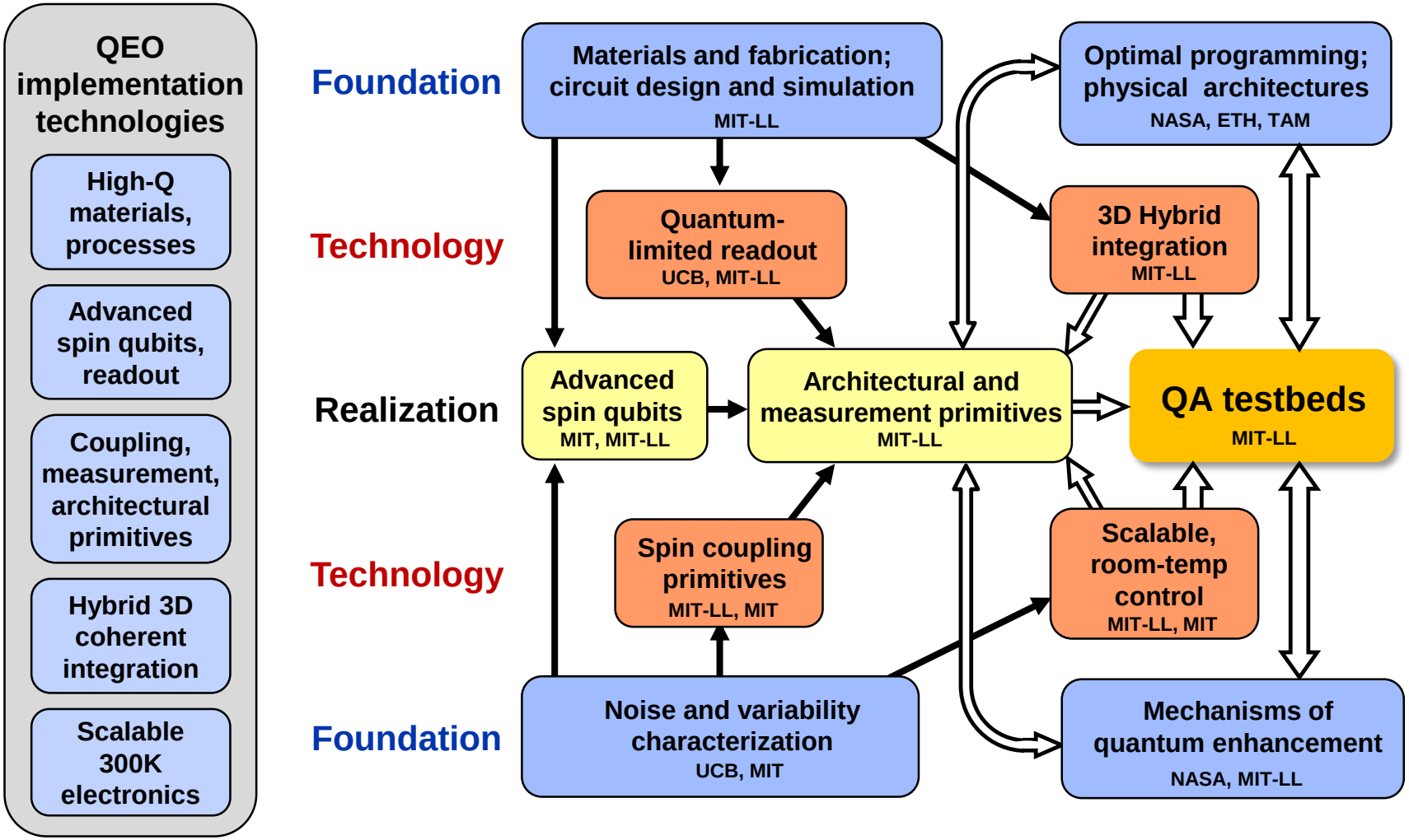


- High interconnect density allows highly-capable, reconfigurable room-temp electronics
- Qubits, interconnects, control are optimized separately, independently
- Maximize isolation of qubits from lossy and uncontrolled surfaces



Develop technologies that enable a validated basis of design for application-scale quantum annealing machines that provide quantum-enhanced performance

QEO Implementation Overview



Many requisite QEO technologies incubated in the IARPA CSQ program
(high-coherence materials & qubits, noise & variability characterization, high-fidelity readout, …)

QEO Implementation Team

QEO implementation technologies

- High-Q materials, processes
- Advanced spin qubits, readout
- Coupling, measurement, architectural primitives
- Hybrid 3D coherent integration
- Scalable 300K electronics

- **Quantum Information and Integrated Nanosystems Group, MIT-LL**
  - Device design,
  - Materials & fabrication
  - 3D integration & control electronics
  - Quantum annealing testbed development
  - Advanced annealing protocol development
- **Orlando group, MIT Campus**
  - Advanced spin qubit development
  - Noise, variability, control characterization
- **Clarke and Siddiqi groups, UC Berkeley**
  - Flux noise characterization with DC SQUIDs
  - Scalable, quantum-limited readout development
- **These teams worked together in the IARPA CSQ program**

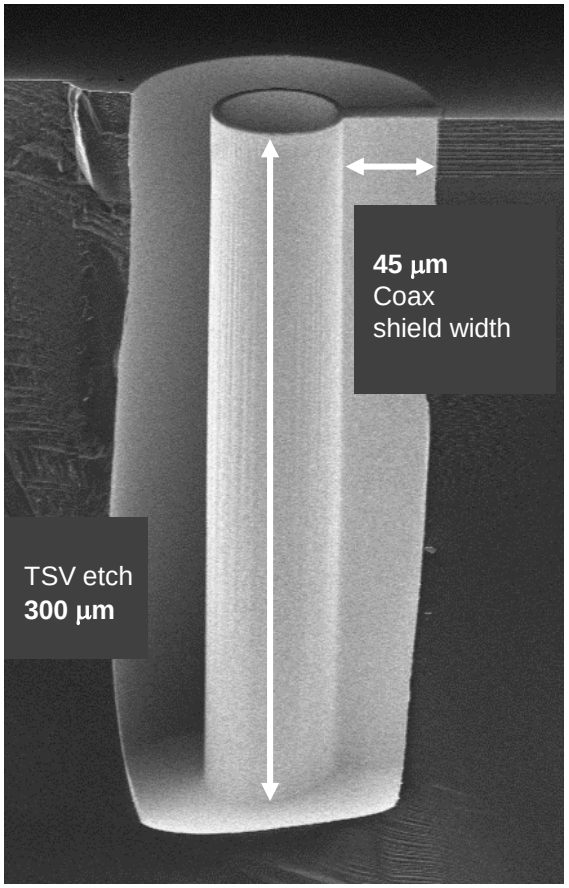
Many requisite QEO technologies incubated in the IARPA CSQ program
(high-coherence materials & qubits, noise & variability characterization, high-fidelity readout, …)

QEO Experimental Overview

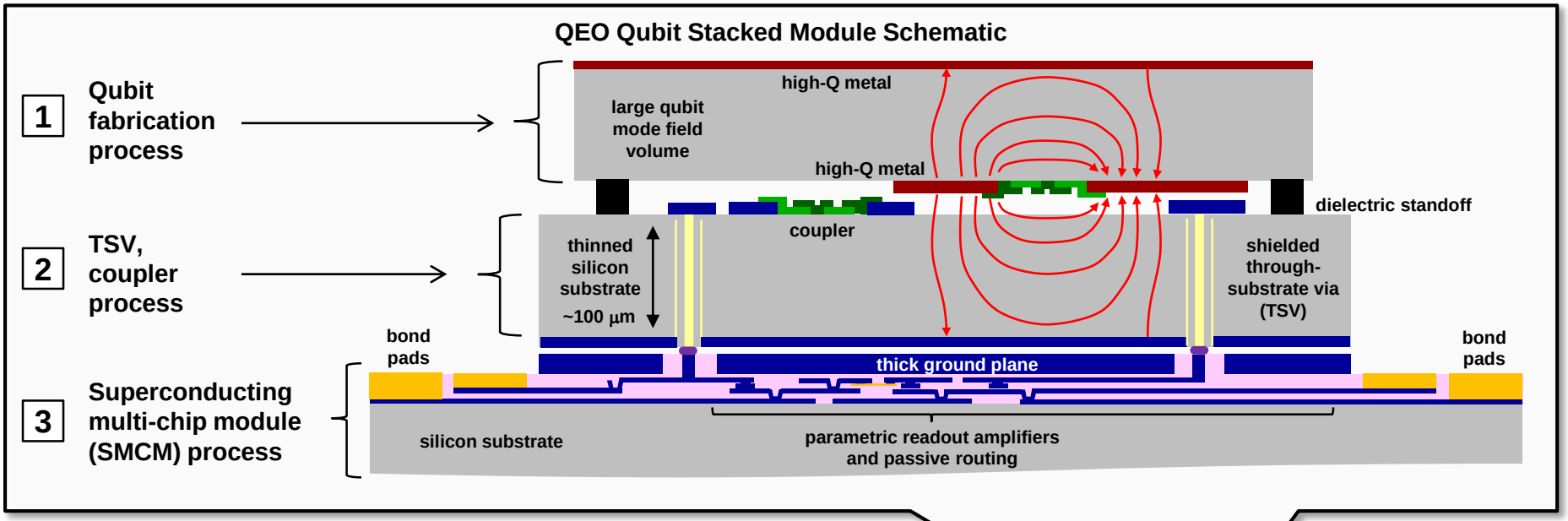
- Introduction
  - Tasks
  - Teams
- Approach & motivation
  - 3D integration
  - Tunable, high-coherence qubits
- Supporting technologies
  - High-Q materials & fab
  - TSVs
  - Flip-chip qubits
  - Electronics
  - J-TWPA

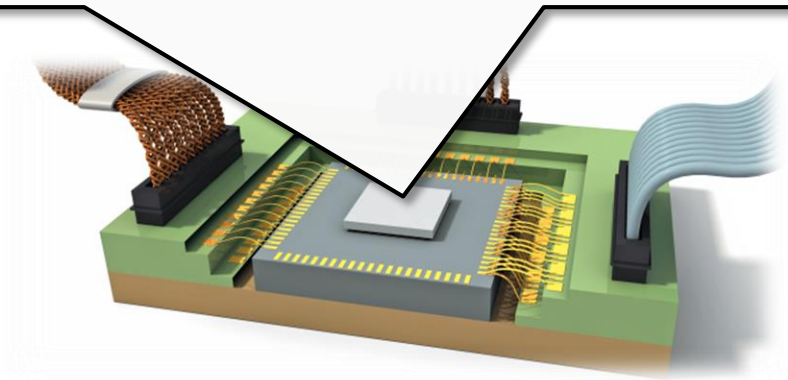
Coaxial TSV

Tilted SEM cross-section



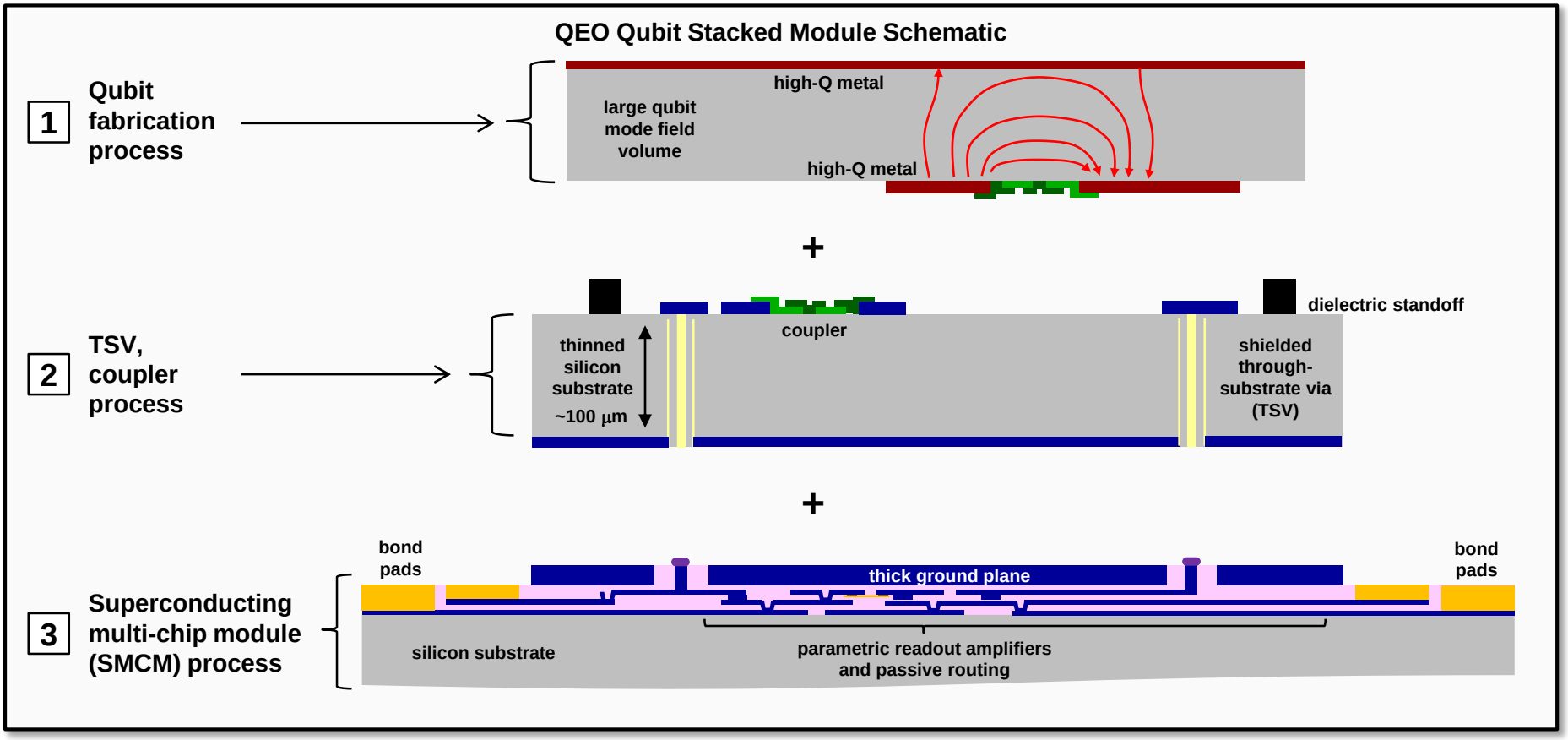
Approach to 3D Integration





Goal: Improve test bed performance by maintaining process independence for each wafer (layer), allowing each to be separately optimized

Approach to 3D Integration



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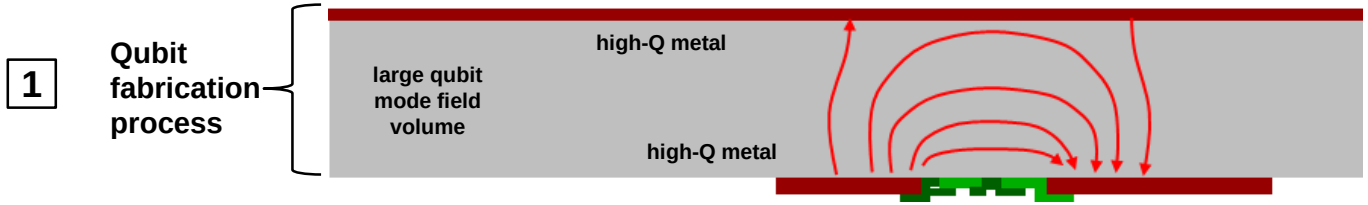
Qubit Plane

QEO Qubit Process Development



Qubit Materials

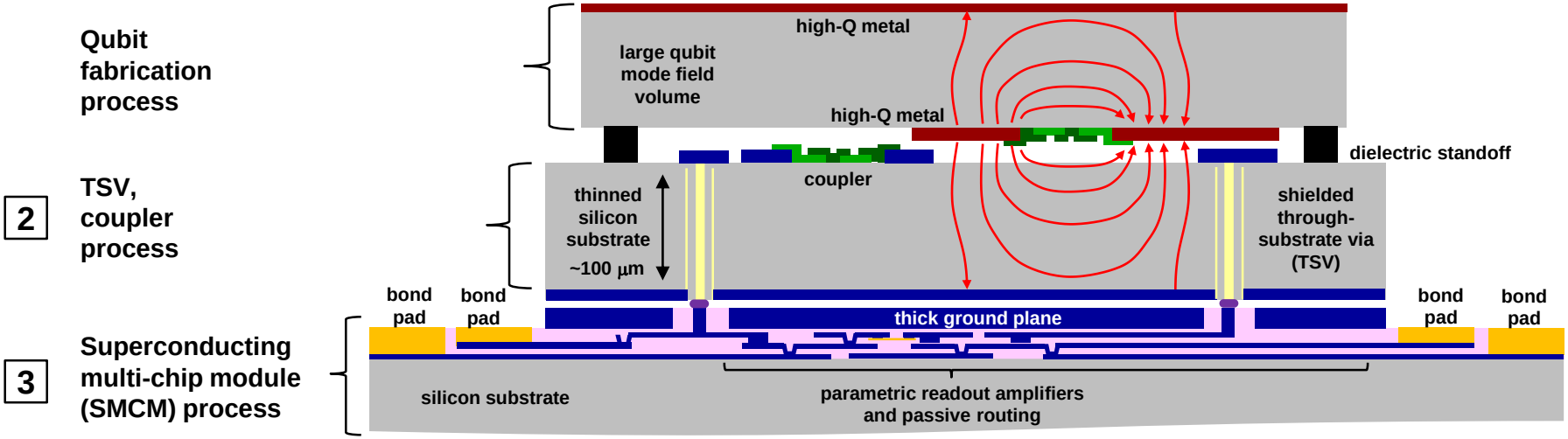
- Substrate preparation
  - Surface reconstruction
  - Si(100) and Si(111)
- High-Q materials
  - TiN and Al growth
  - Surface passivation layers
- Noise characterization
  - Resonators, DC SQUIDs, and qubits
  - Variability and reproducibility

Qubit Fabrication

- Qubit fabrication processes
  - C-shunt flux qubit (baseline)
  - Crossover development
  - Resonators and DC SQUIDs
- High-Q fabrication techniques
  - TiN and Al fabrication
  - Sidewall profiles
  - Trenching
  - Post-process cleaning
  - Passivation layers

TSV and SMCM Planes

TSV and SMCM Processes



TSV Interposer

- Thru-silicon vias (TSVs)
  - Shielded / coaxial TSVs
  - High-density qubit arrays
- Qubit-couplers and readout resonators
  - Reduces crosstalk
  - Higher connectivity
- Isolation of qubit and SMCM planes

SMCM Plane

- Wiring and routing
  - Increased I/O to annealer
  - Room temperature control
- Qubit readout
  - Traveling wave paramps
  - Frequency multiplexing
- Leverages IARPA C3 program

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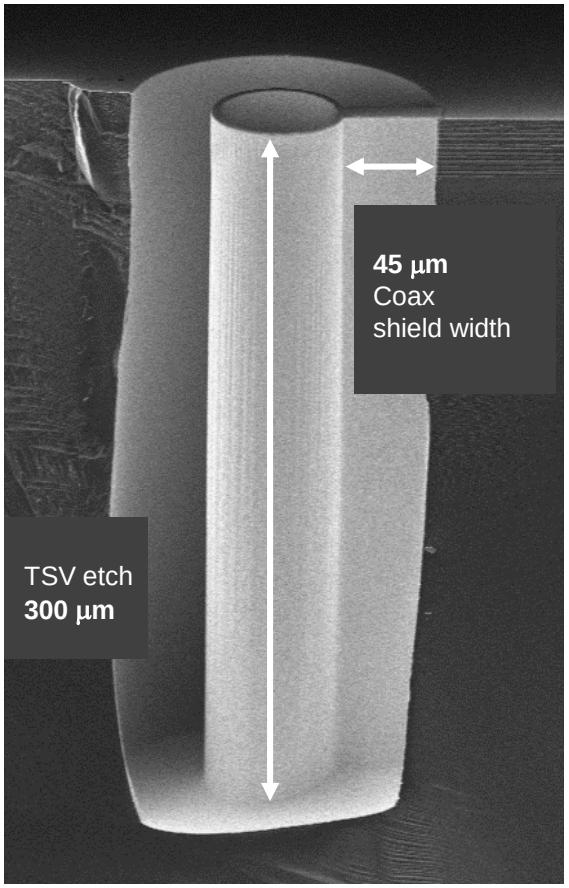
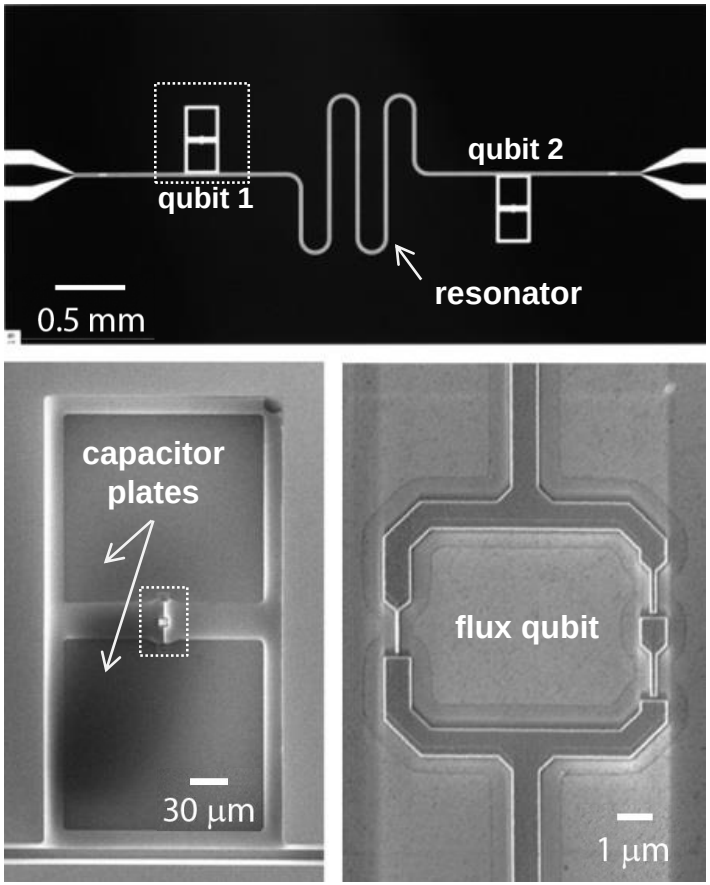
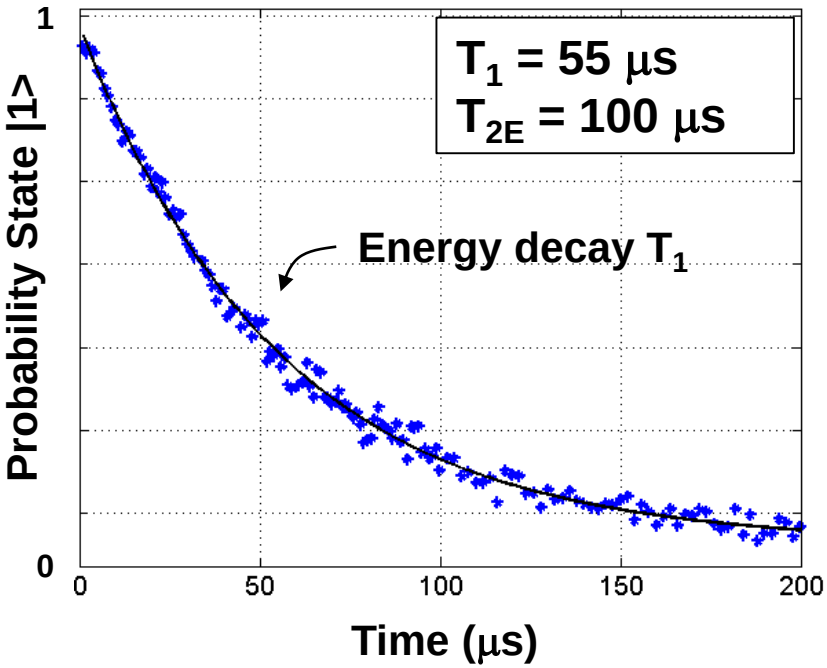


C-Shunt Flux Qubit

C-Shunt Flux Qubit
with 2D Resonator



T_1 Measurement
C-Shunt Flux Qubit with 2D Resonator



Coherence times:

T_1 = 55 μs at degeneracy (CSQ result)

T_{2E} = 40 μs at degeneracy (CSQ result)

→ 100 μs at degeneracy (QEO result)

F. Yan et al., arXiv:1508.06299

C-Shunt Flux Qubit

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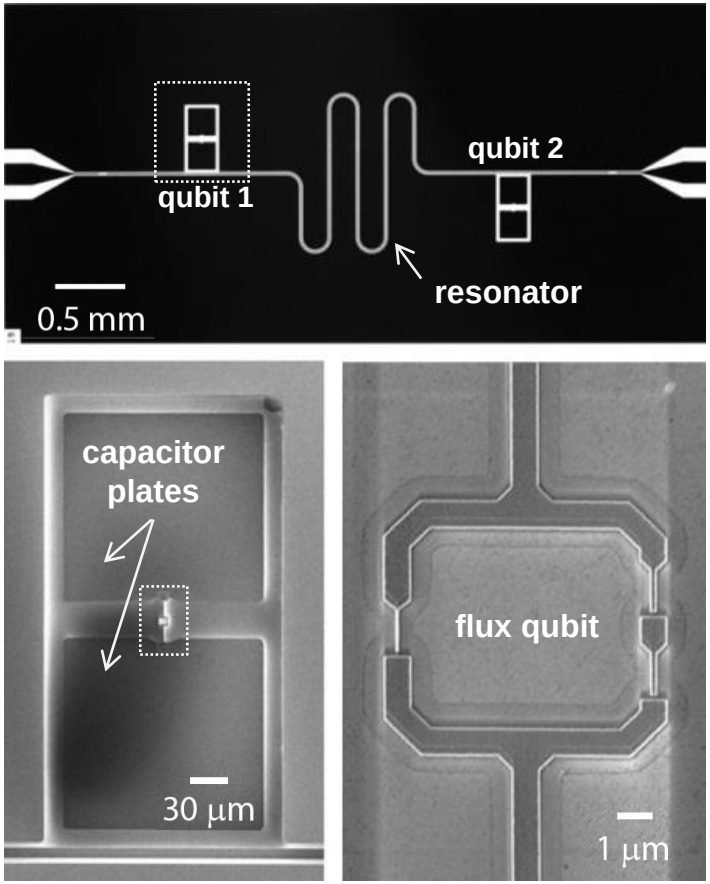
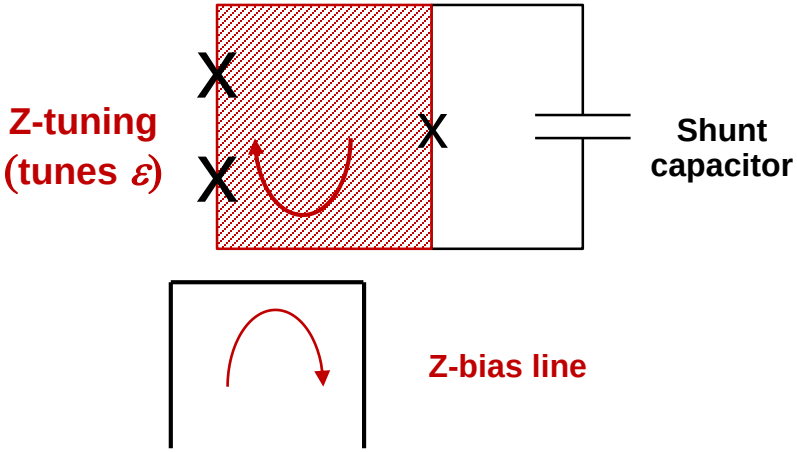
with 2D Resonator



Electrical Schematic
single Z-loop

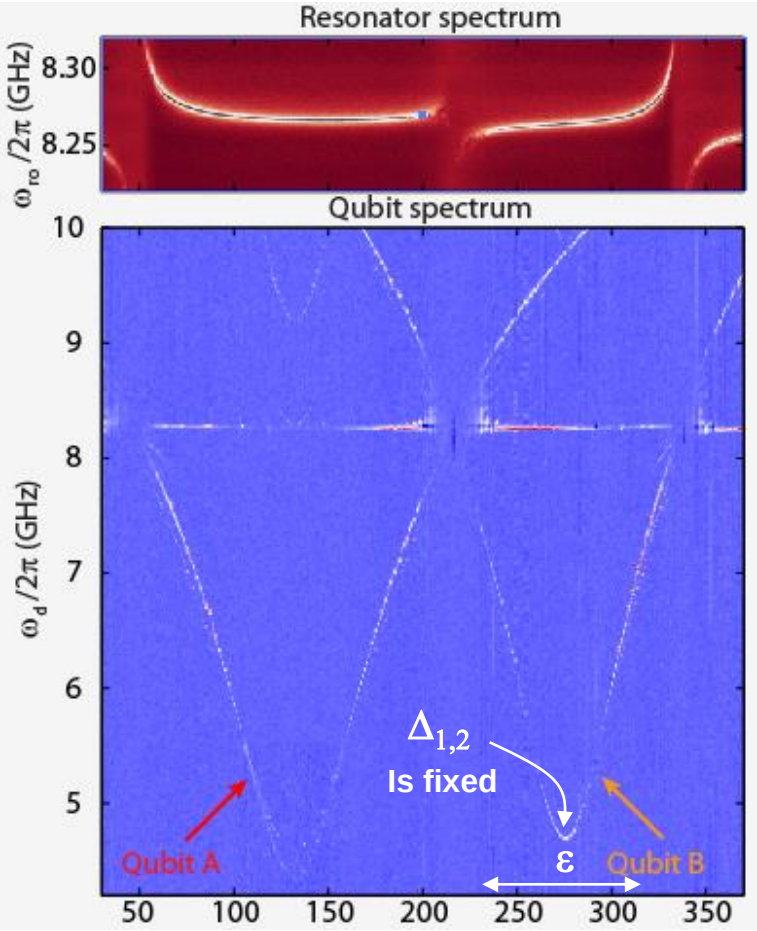


$$H = \varepsilon\hat{\sigma}_Z + \Delta\hat{\sigma}_X$$

F. Yan et al., arXiv:1508.06299

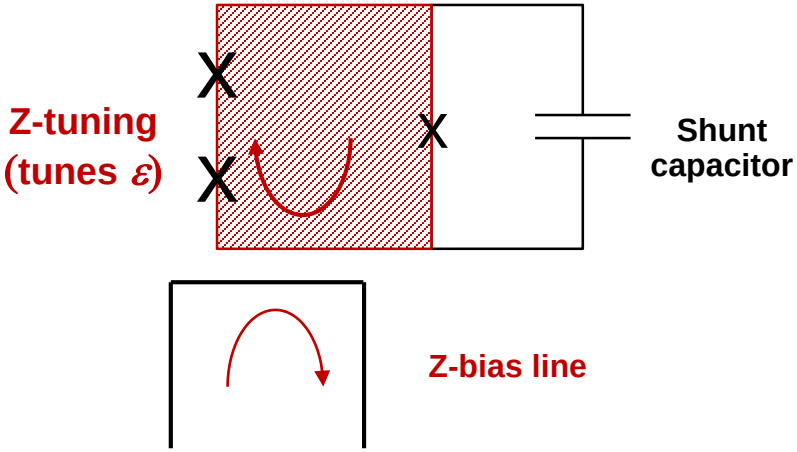
C-Shunt Flux Qubit

C-Shunt Flux Qubit
spectroscopy



Z-bias line (μA)

Electrical Schematic
single Z-loop



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C-Shunt Flux Qubit

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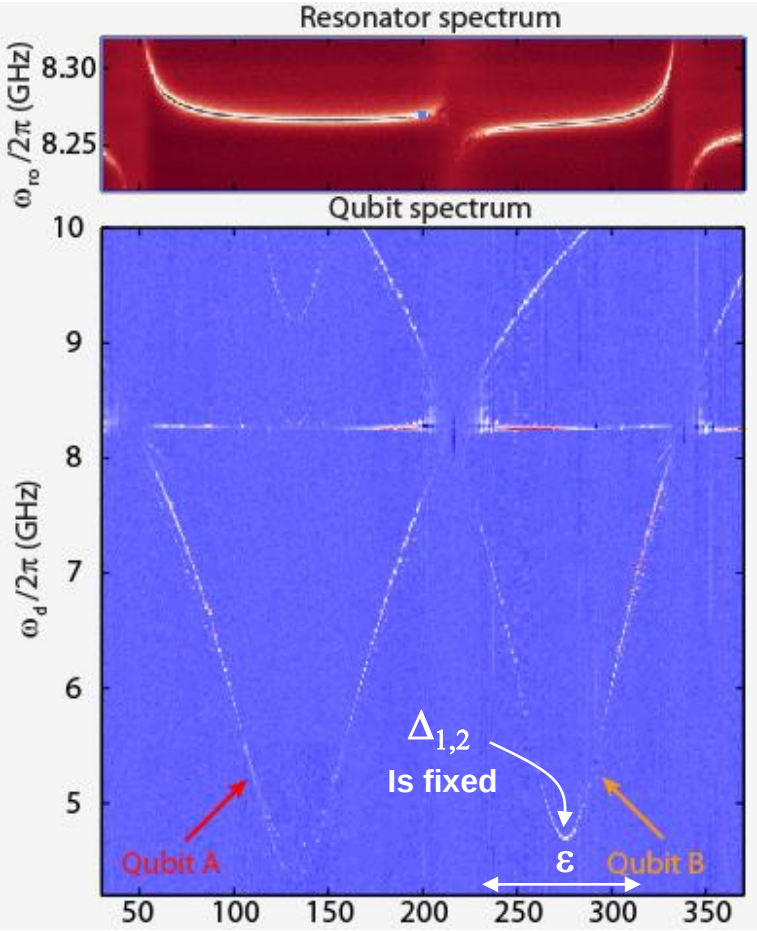

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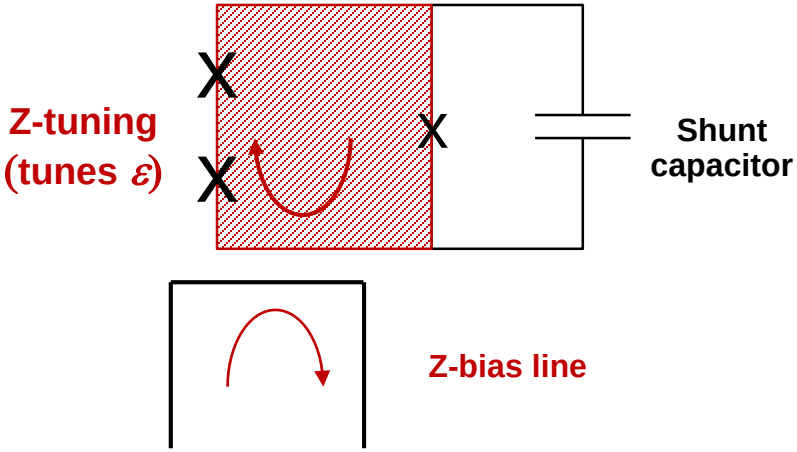


$$H = \varepsilon\hat{\sigma}_Z + \Delta\hat{\sigma}_X$$

Single-loop qubits: tunes Z-field only

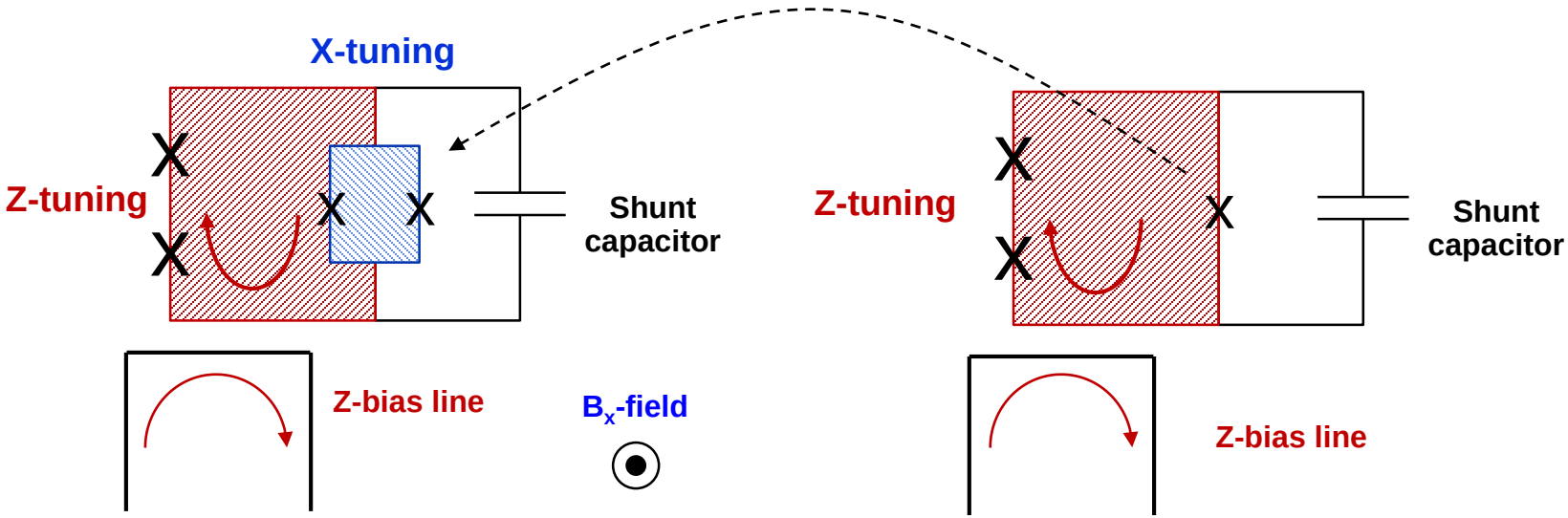
Annealing protocols require both Z- and X-field tunability → two-loop flux qubits

F. Yan et al., arXiv:1508.06299

QEO Tunable C-Shunt Flux Qubits

Non-Gradiometric Two-Loop Qubit

Single-Loop Qubit



● Splitting small junction into a loop with two junctions allows for X-field tunability

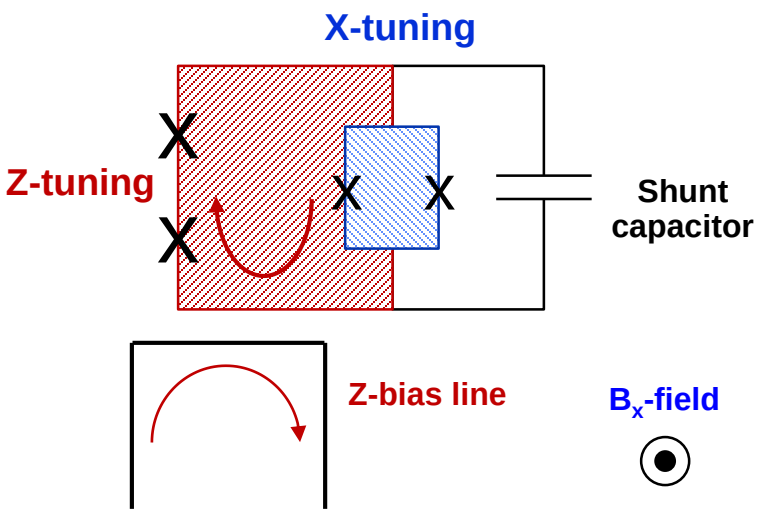
X Crosstalk between X-loop and Z-loop is undesirable

S. Gustavsson et al., PRB 84, 014525 (2011)

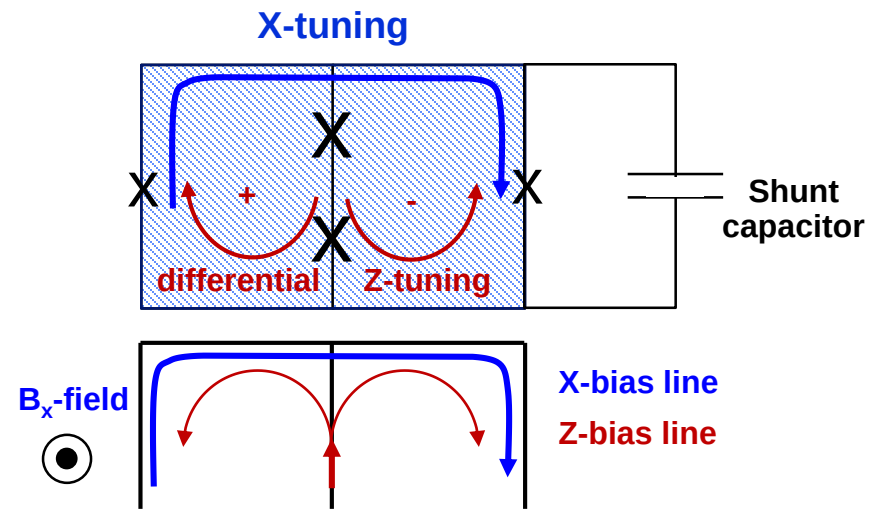
QEO Tunable C-Shunt Flux Qubits:

Non-Gradiometric and Gradiometric Configurations

Non-Gradiometric Two-Loop Qubit



Gradiometric Two-Loop Qubit



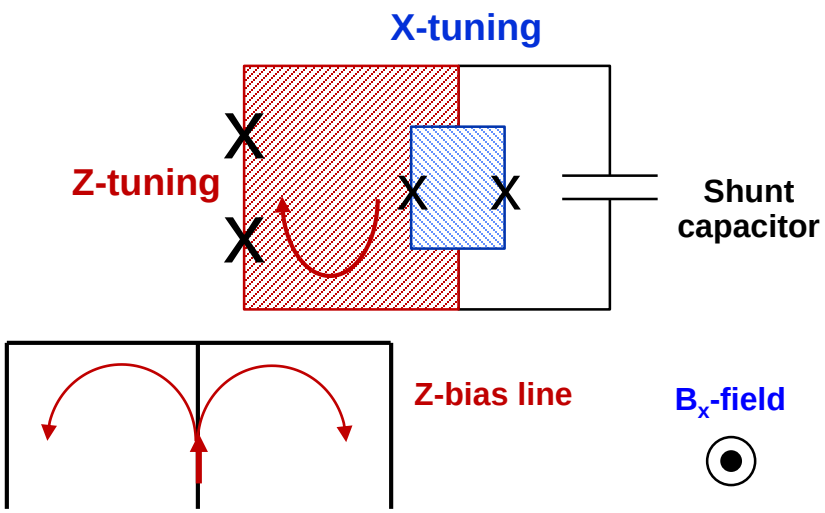
- Splitting small junction into a loop with two junctions allows for X-field tunability
- Gradiometric two-loop design minimizes crosstalk between X and Z loops

Tunable C-shunt is the baseline qubit for QEO Study

QEO Tunable C-Shunt Flux Qubits:

Non-Gradiometric and Gradiometric Configurations

Non-Gradiometric Two-Loop Qubit



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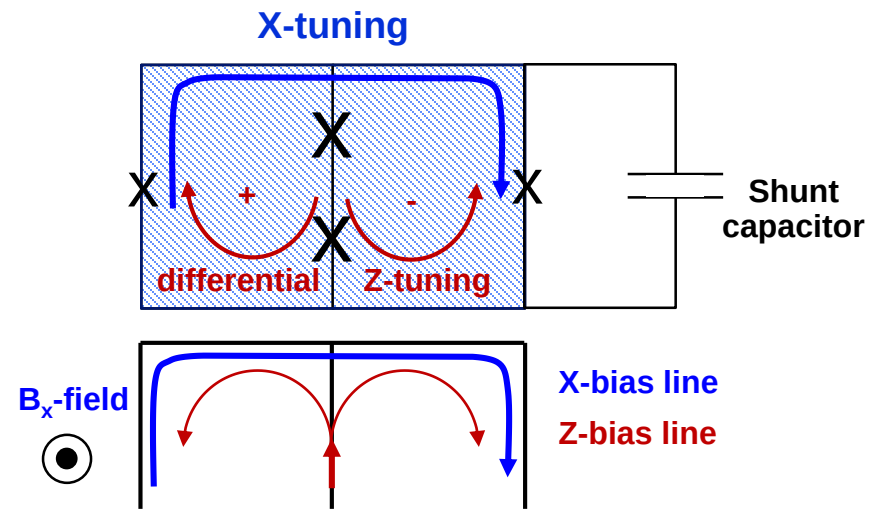
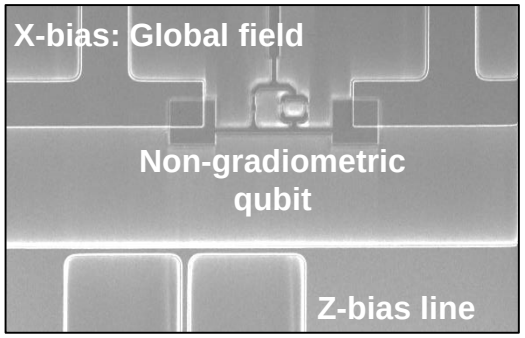
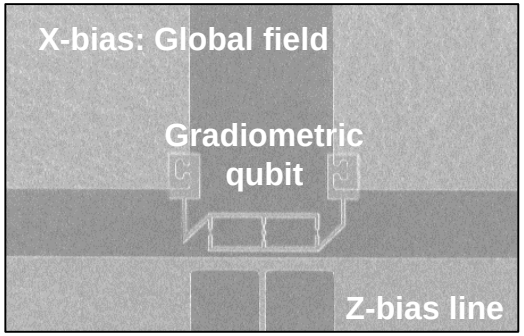


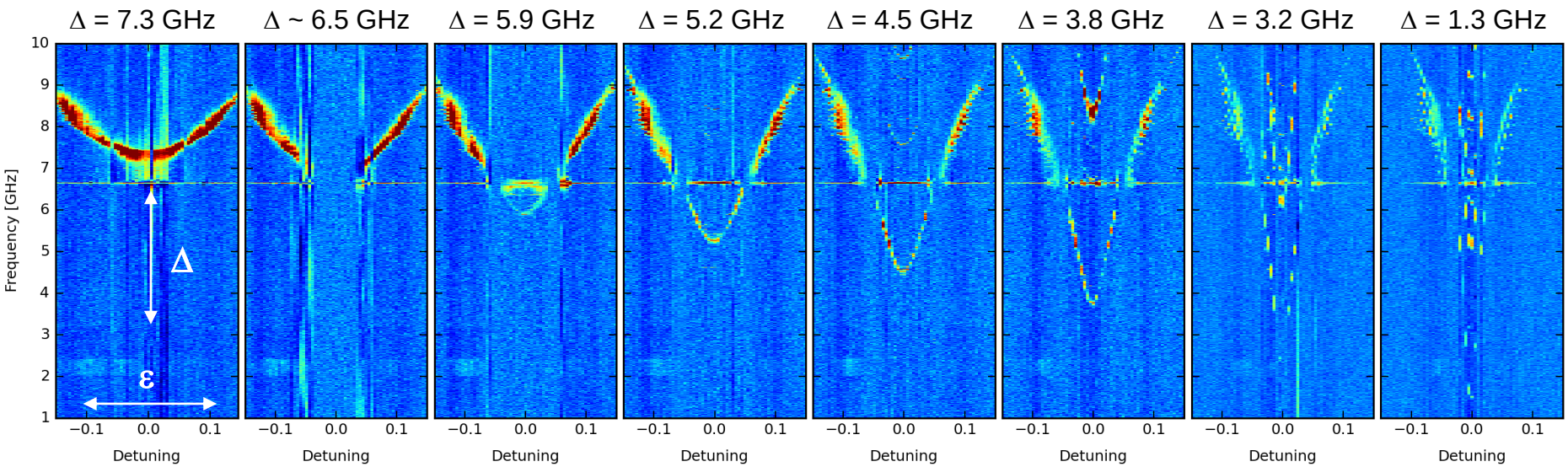
Non-Gradiometric Flux Qubit SEM Image



Gradiometric Flux Qubit SEM Image



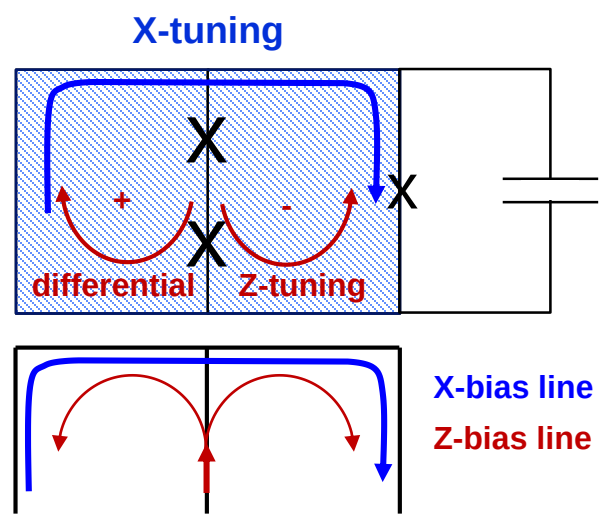
Qubit Spectra: Z and X Tuning



$$H = \varepsilon\hat{\sigma}_Z + \Delta\hat{\sigma}_X$$

Annealing Cheat Sheet

Direction	Z	X
Field	Longitudinal	Transverse
Pauli operator	$\hat{\sigma}_Z$	$\hat{\sigma}_X$
Annealing notation	$2h$	2Δ
Qubit notation	ε	Δ



S. Gustavsson et al., unpublished (2015)

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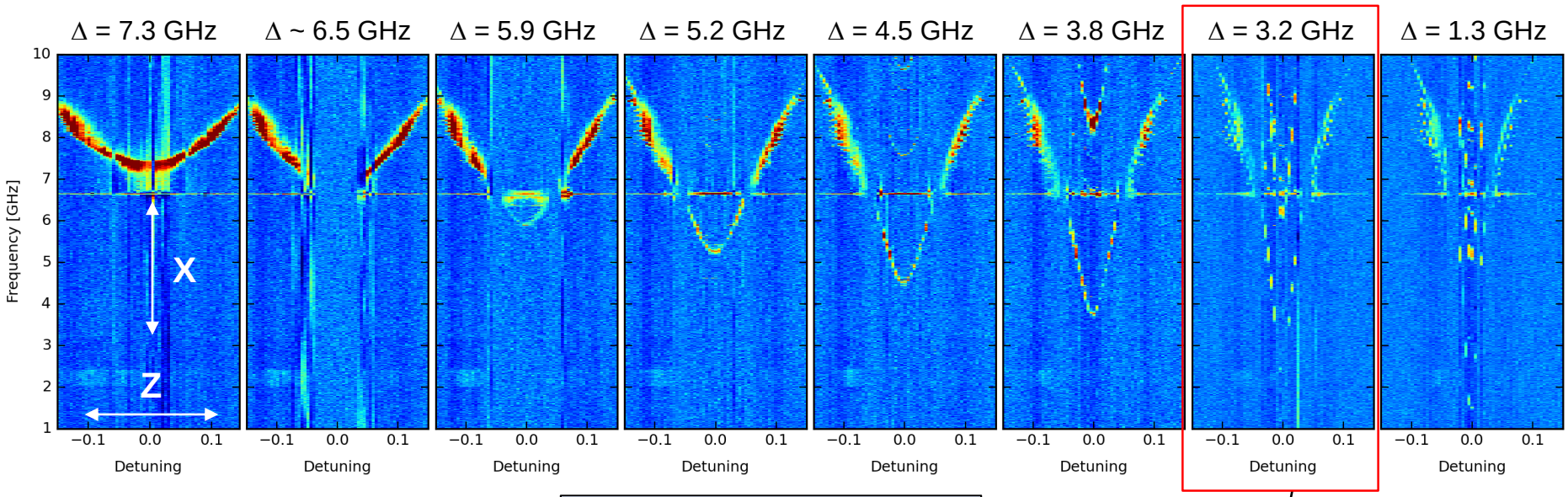
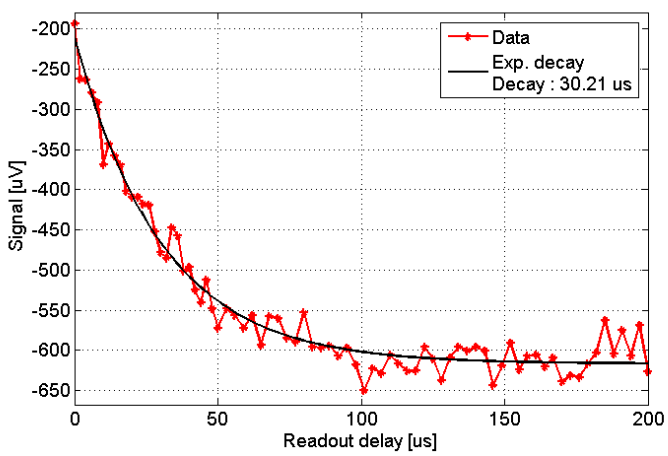
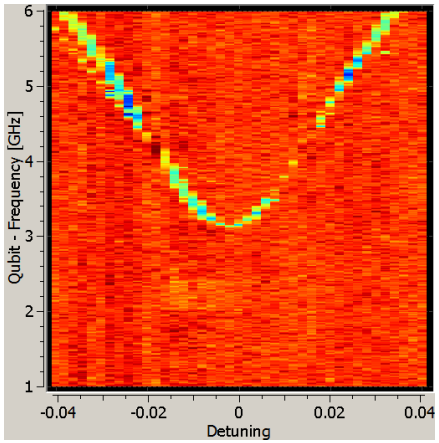


Δ = 3.2 GHz: T_1 = 30 μs





S. Gustavsson et al., unpublished (2015)

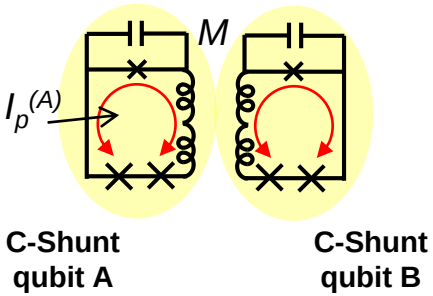
Qubit Coupling

- **Annealing requires tunable couplers**
  - **Direct coupling: "always on"**
    - **Capacitively coupled transmons**
    - **Inductively coupled flux qubits**
  - **Coupler-mediated coupling: tunable**

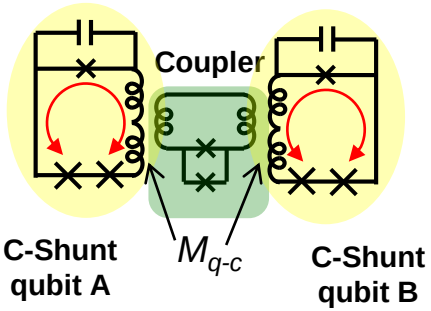
- **Desire a "generalized coupling scheme"**
  - **Independently tunable XX and ZZ**
  - **Ability to tune sign of coupling**
  - **Stoquasitic and non-stoquastic**

- **Ideally uses same coupler for all actions**

Direct coupling ("always on")

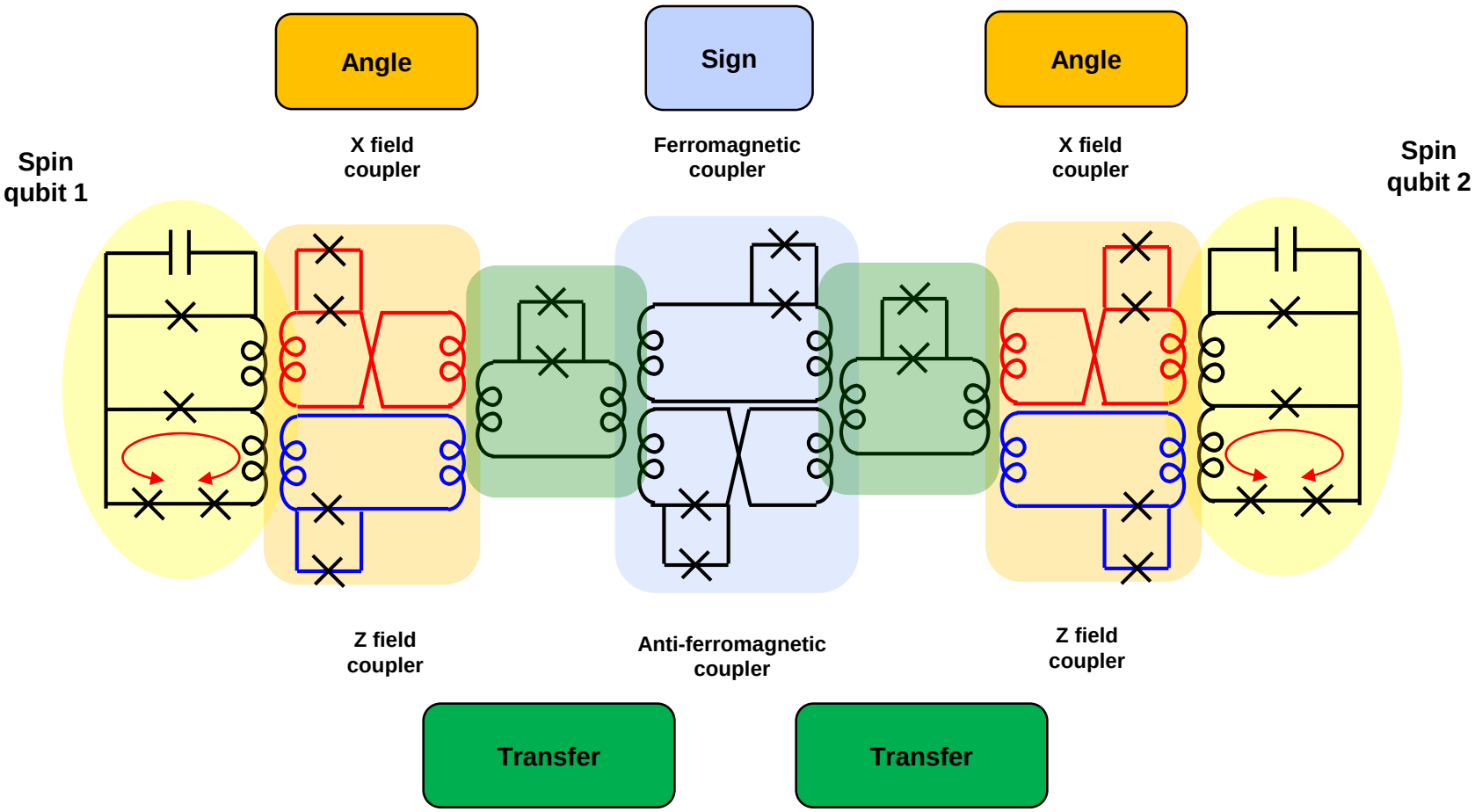


Tunable coupling



A.J. Kerman and W.D. Oliver, PRL 101, 070501 (2008)

Tunable Qubits and Couplers



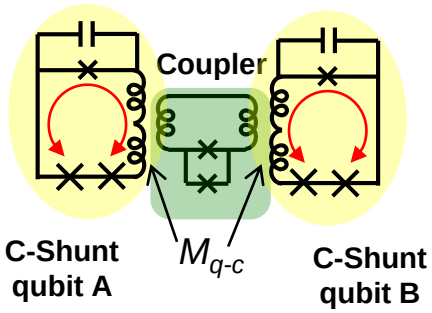
Generalized +/- XX and +/- ZZ coupling achievable using a *single* type of tunable coupling element (with crossover)

A.J. Kerman, unpublished (2015)

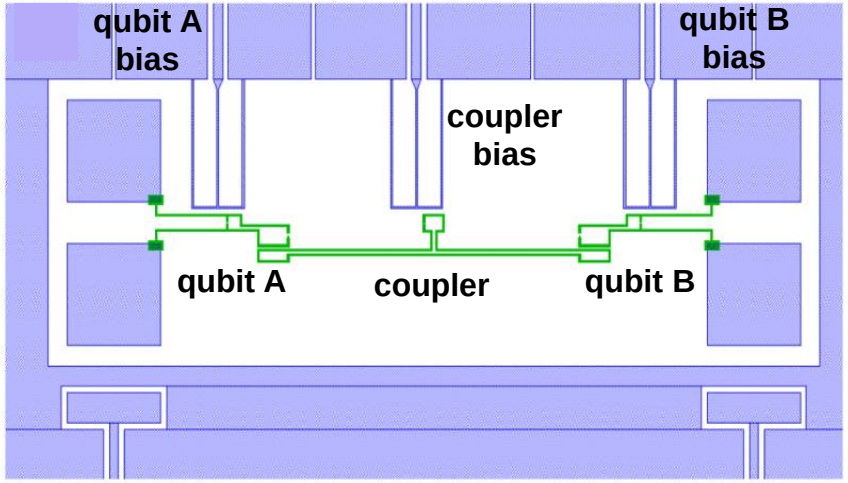
Qubit Coupler Demonstration

- **Characterizing the coupler**
  - **Demonstrated it with Z-Z coupling**
  - **Same coupler for X-X coupling**

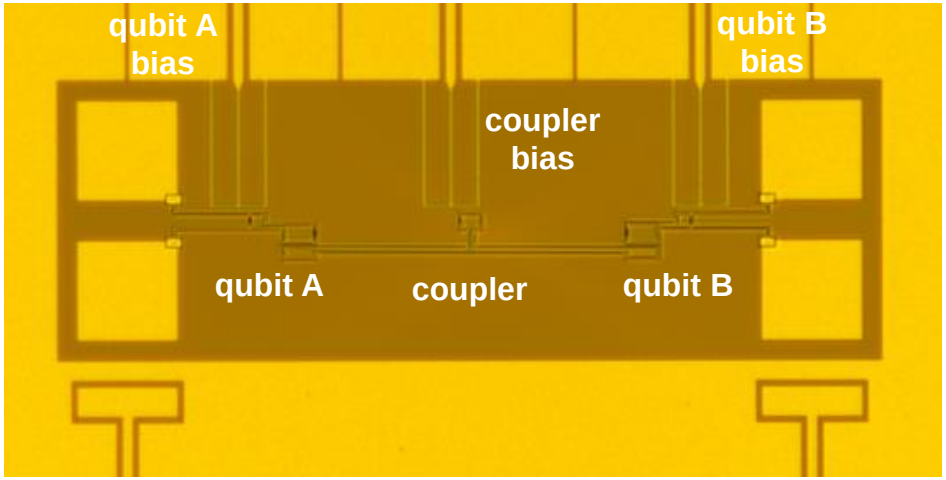
Tunable coupling



Z-Z coupling: GDS file



Z-Z coupling: optical image

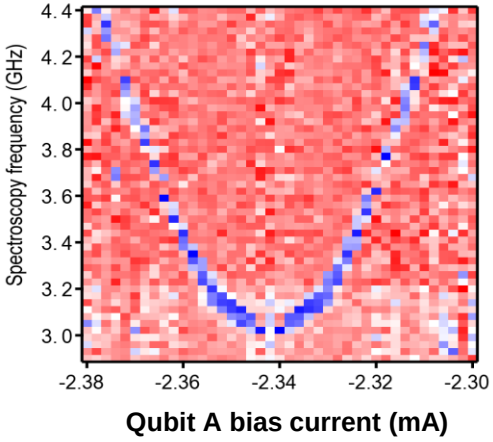


S. Weber et al., unpublished (2015)

Qubit Coupler Demonstration

Qubit A Spectroscopy

vs. qubit A flux bias



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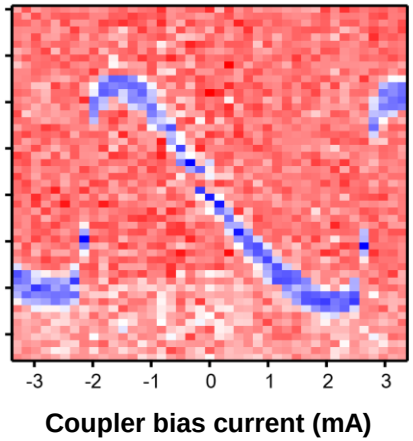
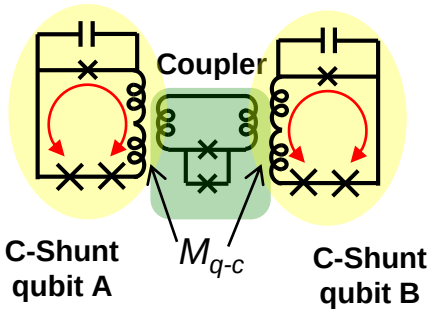


Tunable coupling



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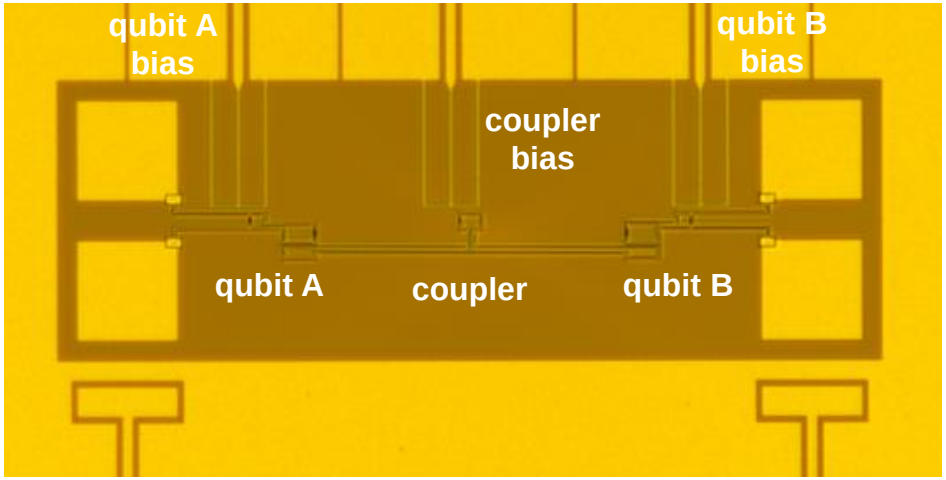

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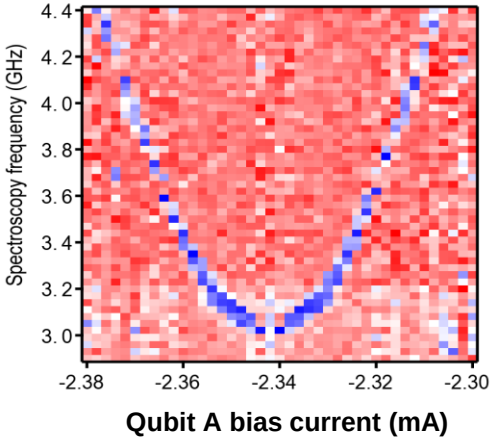

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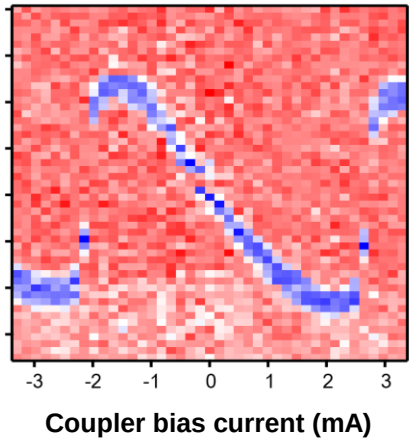

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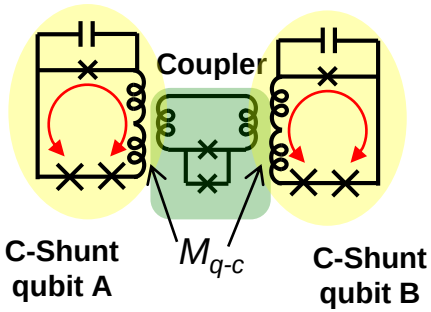
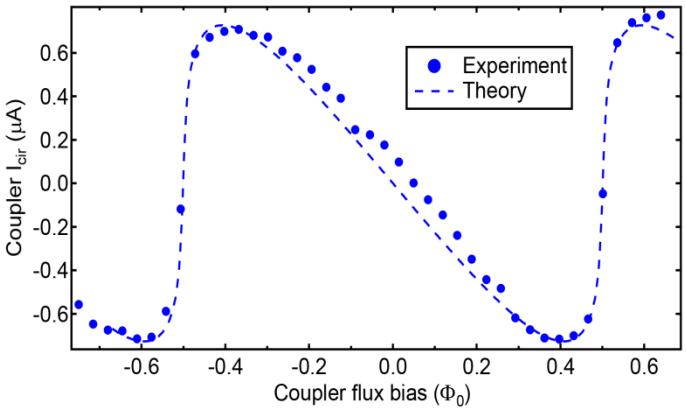


Coupler Circulating Current



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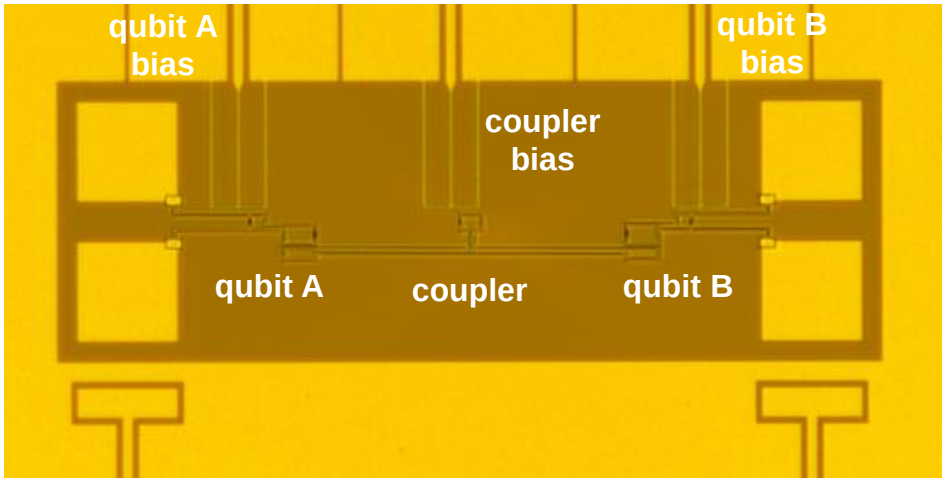
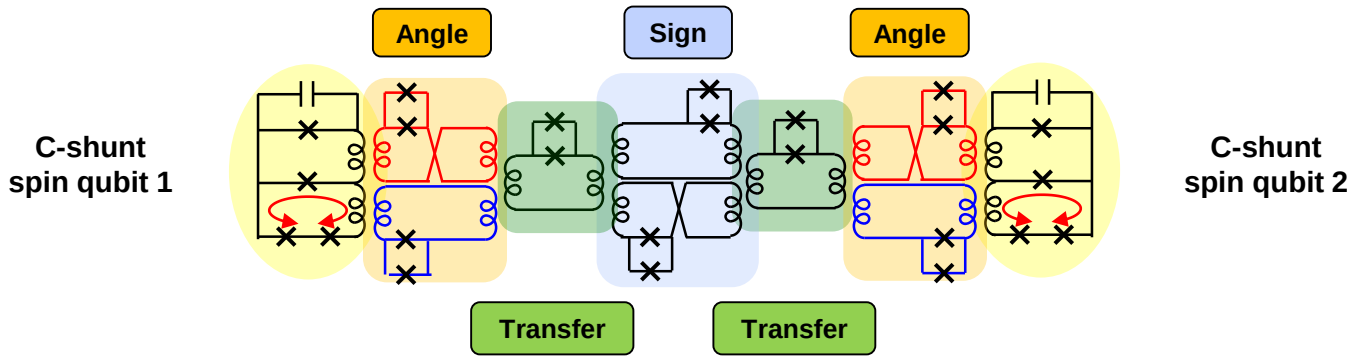
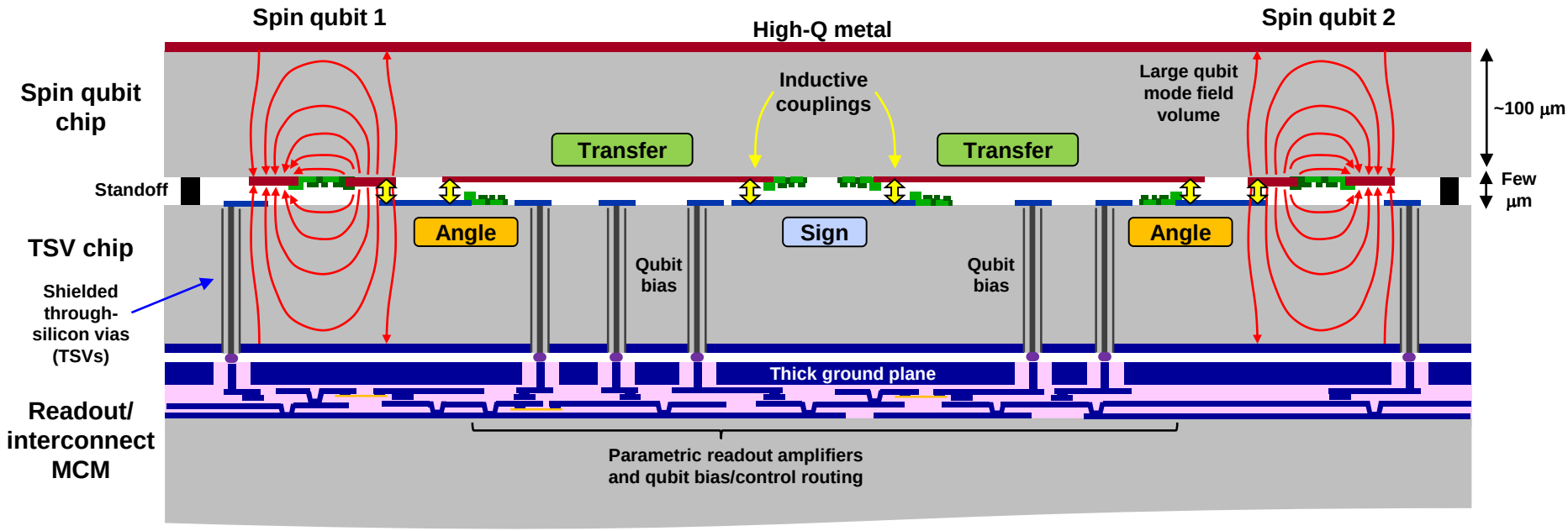


Coupler current changes qubit frequency as expected

3D Integrated Tunable Qubits & Couplers





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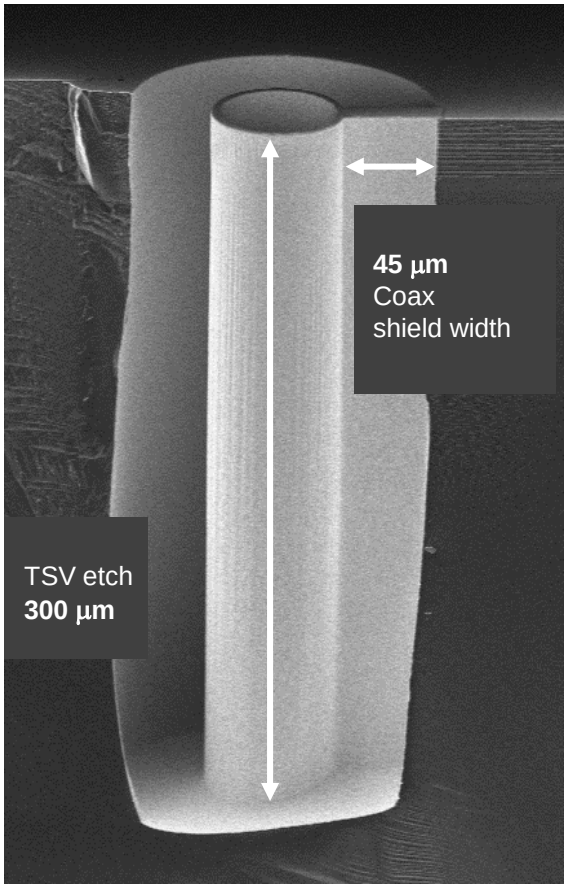
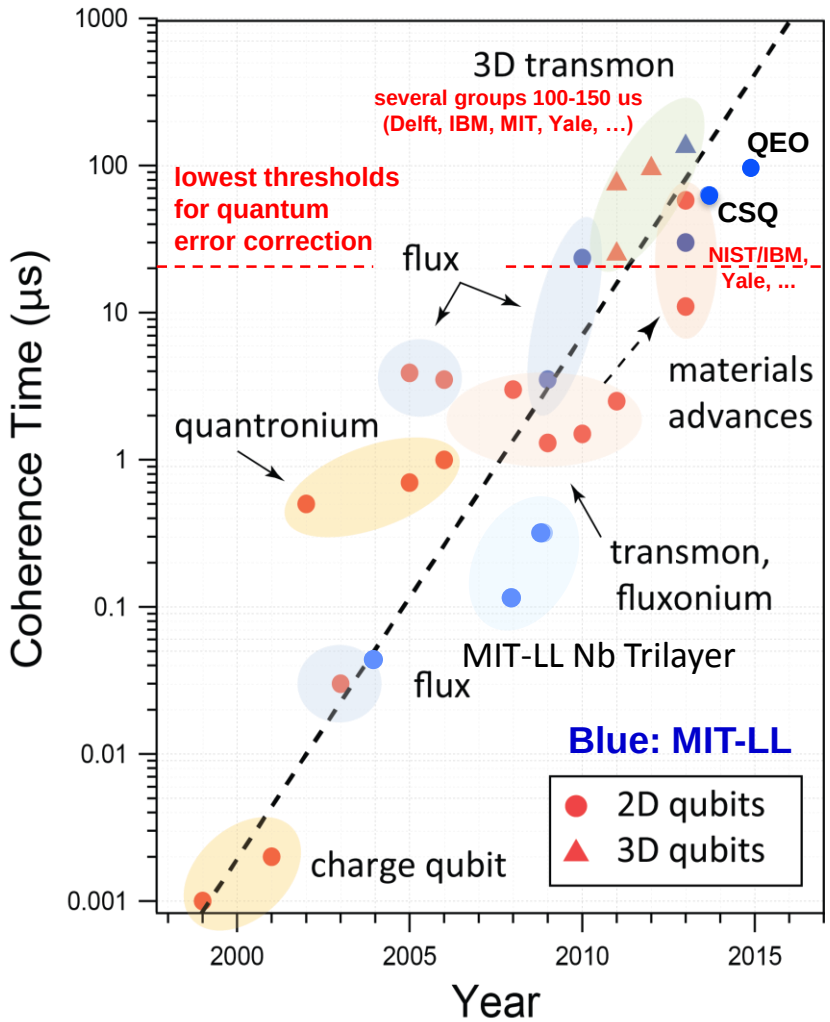
Tilted SEM cross-section



Qubit Coherence

- **Remarkable improvement in $T_{1,2}$ by groups worldwide**
- **All major qubit types at MIT/LL**
  - **Flux qubit: T_2 = 23 us**
  - **2D transmon: T_2 = 35 us**
  - **3D transmon: T_2 = 150 us**
  - **C-shunt flux qubit: T_2 = 100 us**
- **Resonators at MIT/LL**
  - **Q = 1 – 2M for TiN / Si**
  - **Q = 0.5 – 1.0M for Al / Si**
  - **Q ~ 0.5M for Al / Al_2O_3**
- **Applications**
  - **Gate-based quantum computing**
  - **Quantum annealing**
- **Results based on improvements in:**
  - **Design**
  - **Materials**
  - **Fabrication**

"Moore's Law" for T_2

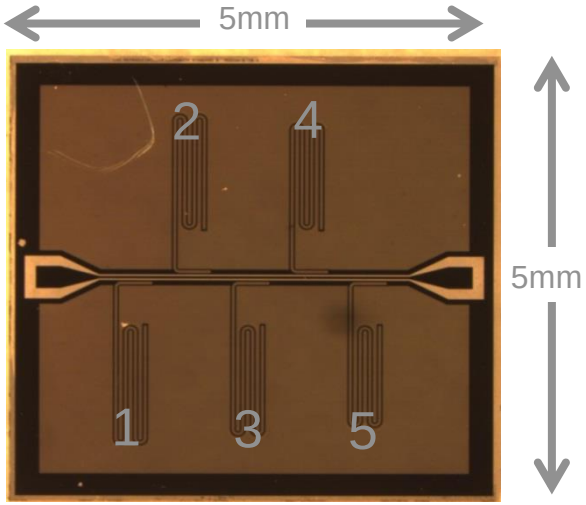


Oliver & Welander, MRS Bulletin (2013)

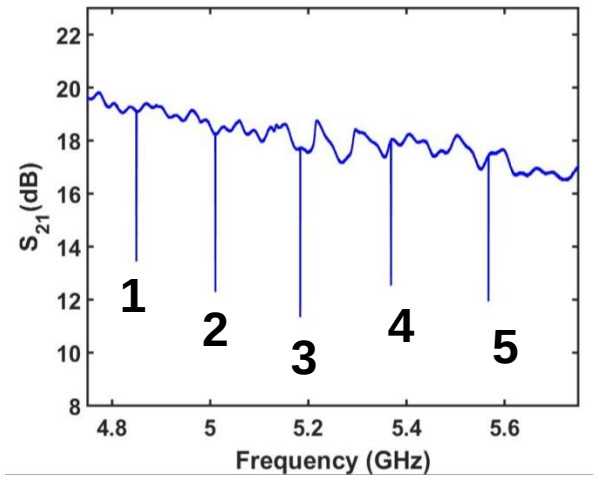
Materials & Fabrication Characterization

Multiplexed Resonator Standard

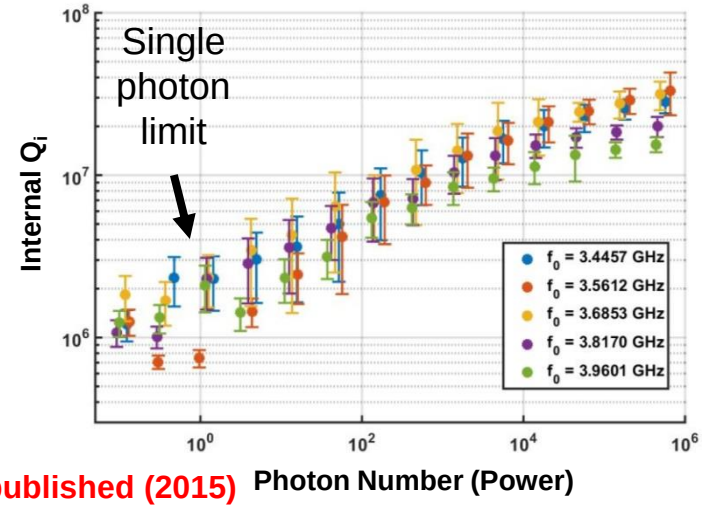
Frequency-multiplexed λ/4 resonators



Resonator Transmission Spectrum



Resonator Internal Q_i vs. Power

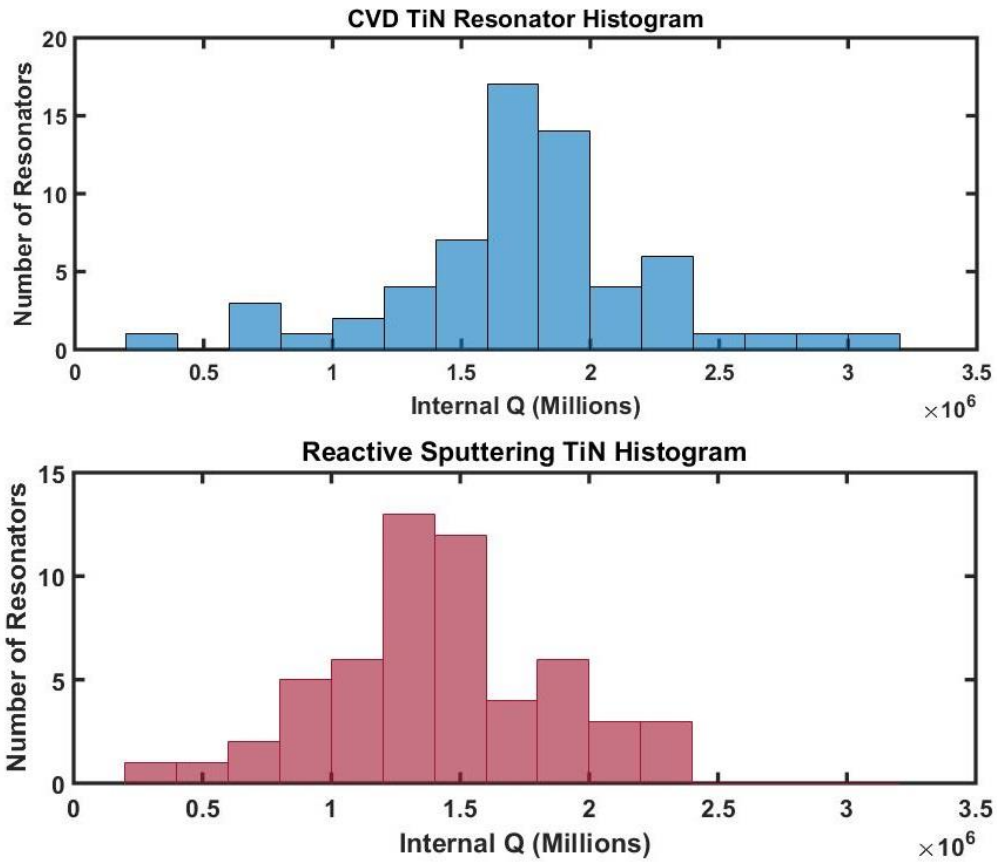


- **Community-standard design (CSQ)**
  - **5 resonators per chip**
- **Two parallel measurement chains**
  - **2 x 6 coaxial positions = 12 chips**
- **Total of 60 resonators per cooldown**
- **Automated measurement and analysis**
- **Internal Q at single-photon limit is key metric**

D. Rosenberg, G. Calusine, et al., unpublished (2015)

Reproducibility of TiN Films on Si

High-Q results for TiN using two deposition systems



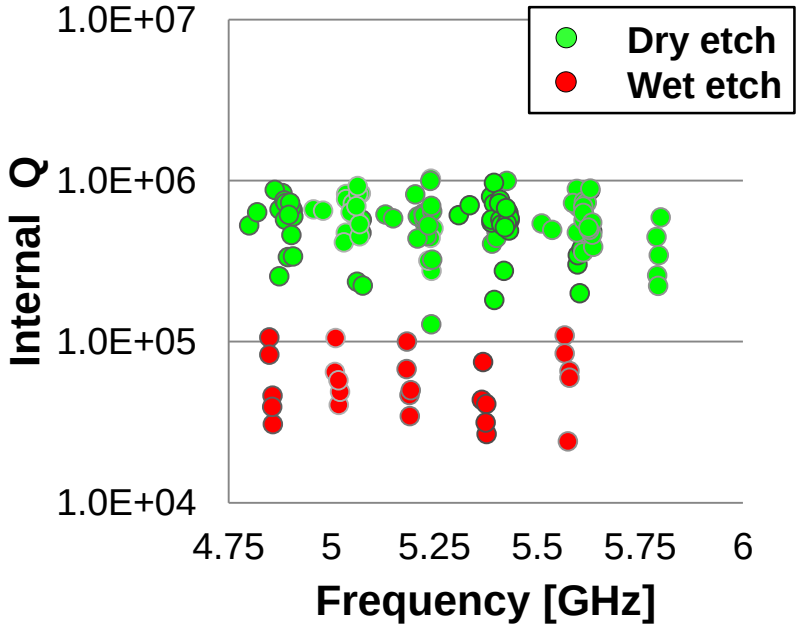
- ~100 total resonators measured
- Low-power Q_i exceeded 1M for 90% of resonators
- Best device Q_i ~4M
- High cross-wafer uniformity (stress control over 200 mm)

D. Rosenberg, G. Calusine, et al., unpublished (2015)

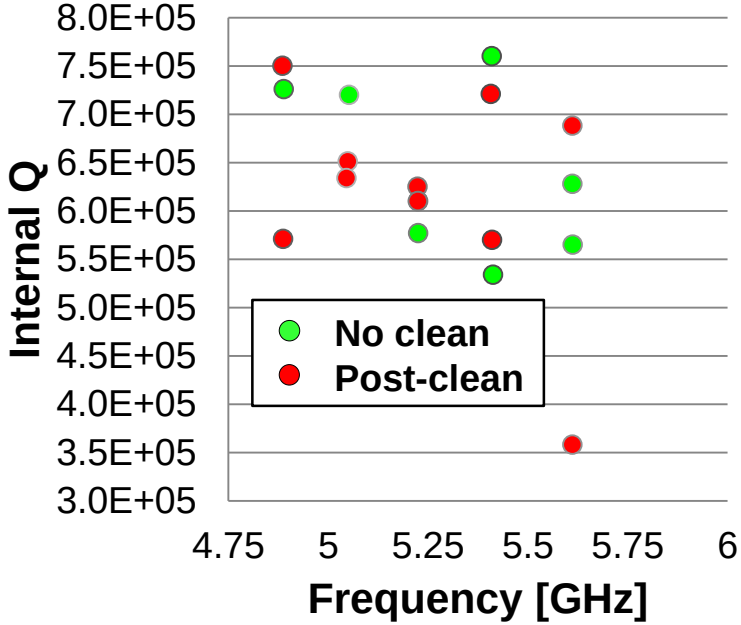
Assessing Fabrication Processes

Dry vs Wet Etch & Clean vs No-clean

Etch dependence for MBE Al on Si



Post-process clean dependence



Dry etch order of magnitude better than wet etch for MBE Al on Si

No obvious impact from "short" post-process cleaning

J. Yoder, et al., unpublished (2015)

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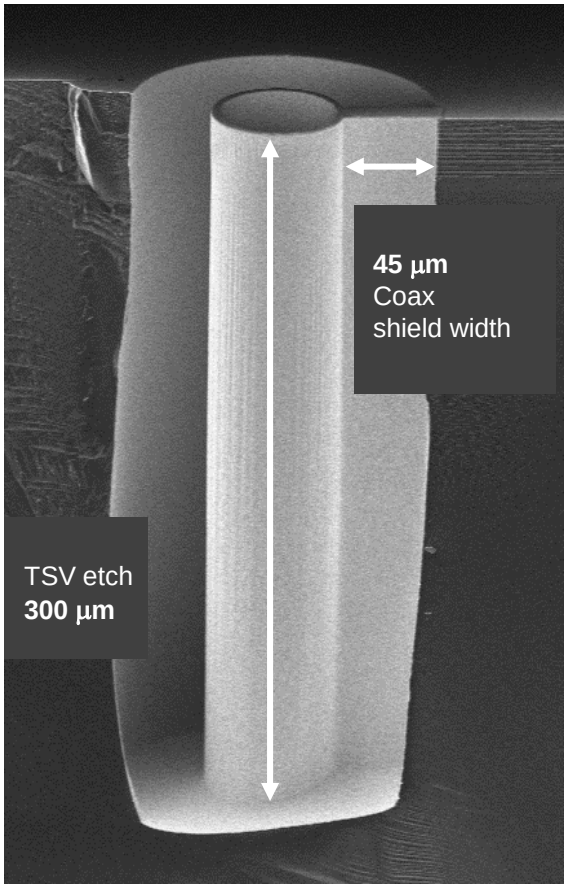
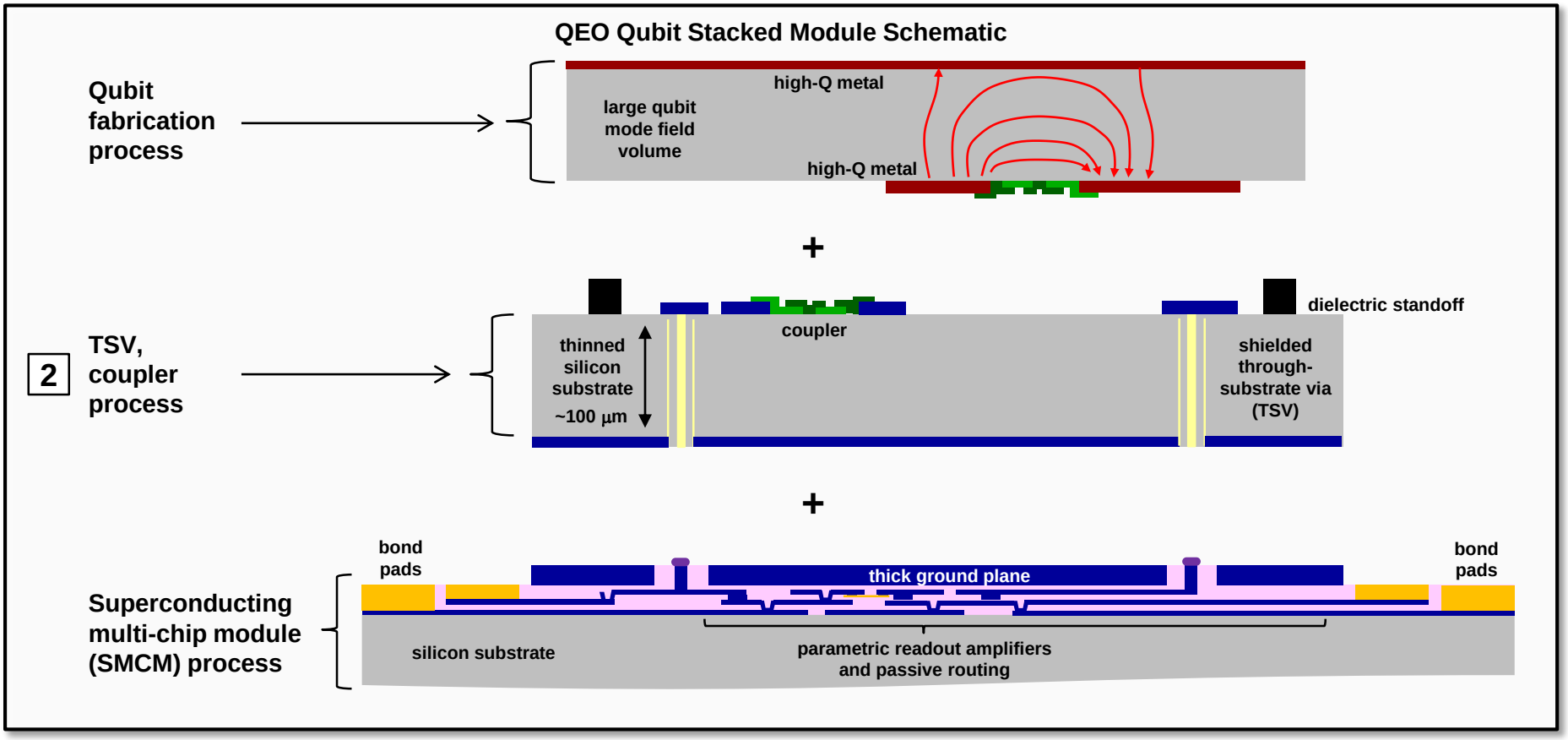


Approach to 3D Integration

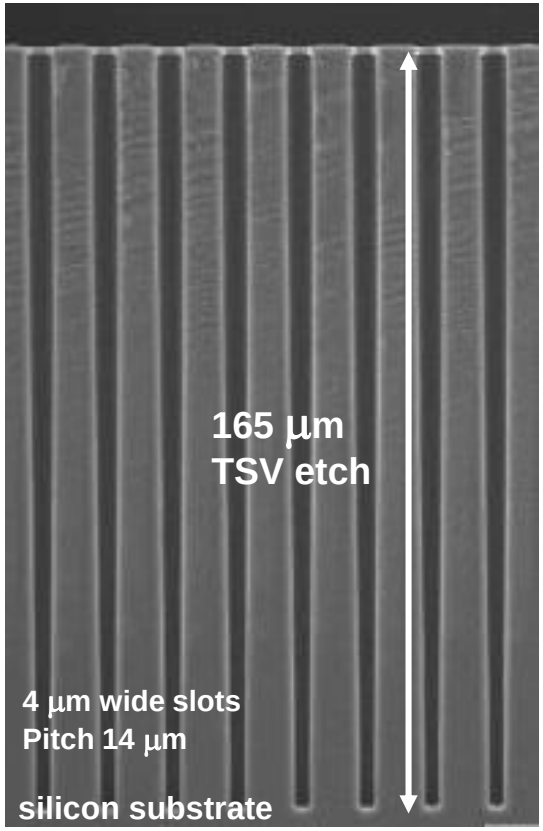


TSV layer enables isolation and increased wiring complexity while allowing for fabrication independence between the qubit and SMCM layers

TSVs for 3D Integration

- **High-aspect-ratio deep-silicon TSV etch demonstrated**
  - **Etched TSVs (see SEM cross-sections)**
- **Deposited continuous Ti/TiN liner in TSVs**
- **Deposited Tungsten with CVD over liner**

SEM cross section of LAM TSV

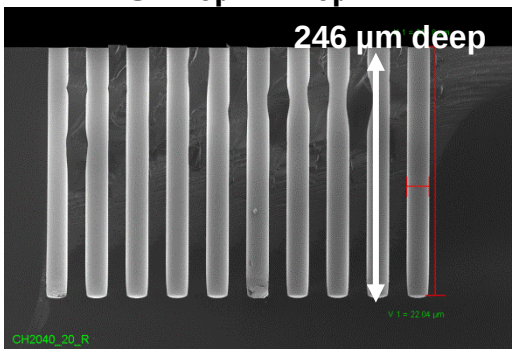


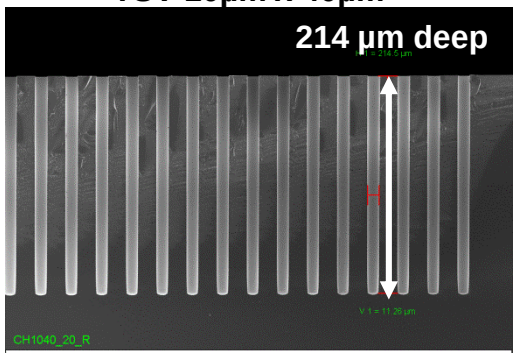
D. Yost, et al., unpublished (2015)

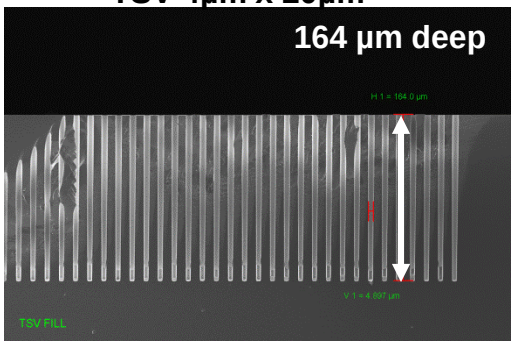
High Aspect Ratio TSVs: TiN and W

TSV 20µm x 40µm | **TSV 10µm x 40µm** | **TSV 4µm x 20µm**

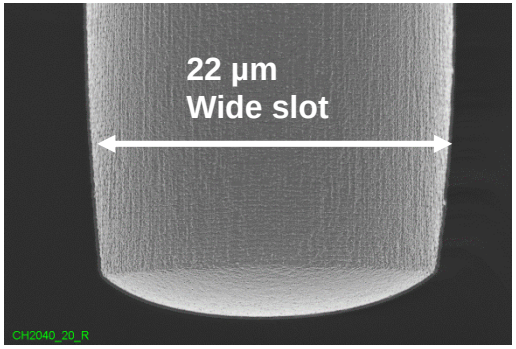
SEM cross section chain array

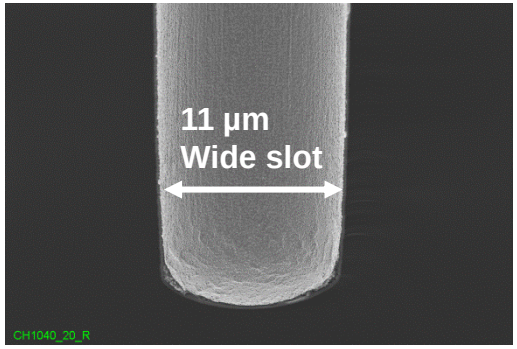


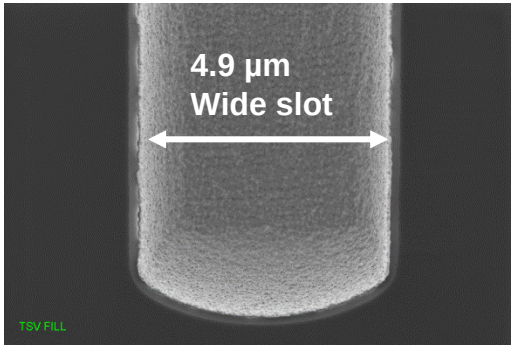




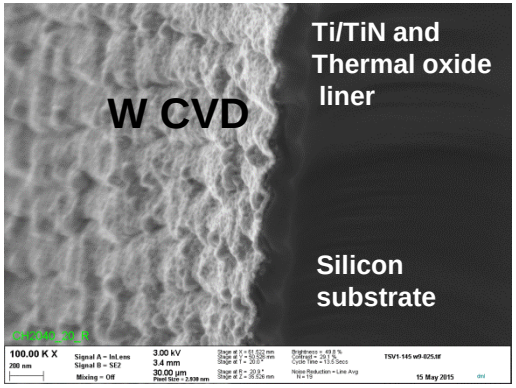
Via fill at base

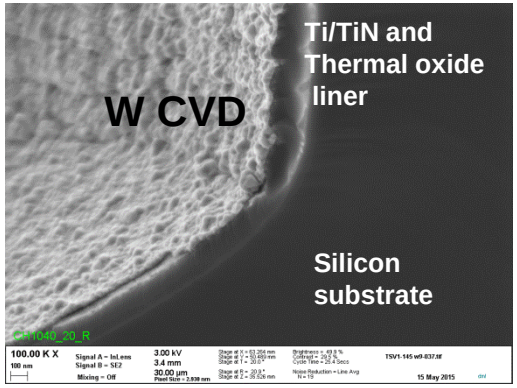


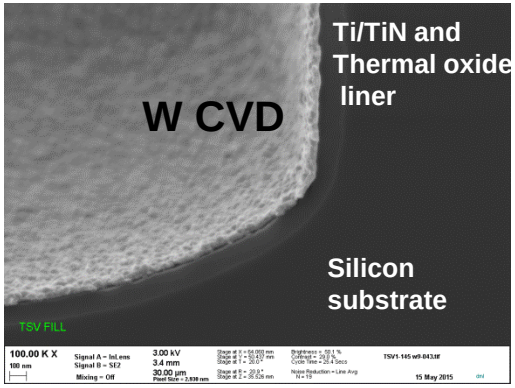




100 kX CVD W over IMP PVD + CVD + ALD Ti/TiN and Thermal Ox







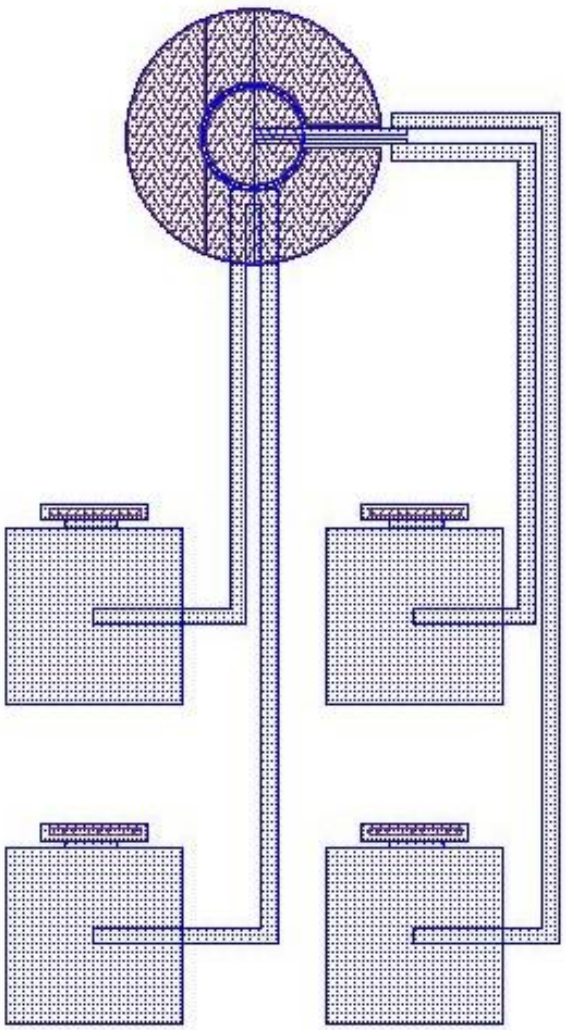
11:1 aspect ratio in X
6:1 aspect ratio in Y

19:1 aspect ratio in X
5:1 aspect ratio in Y

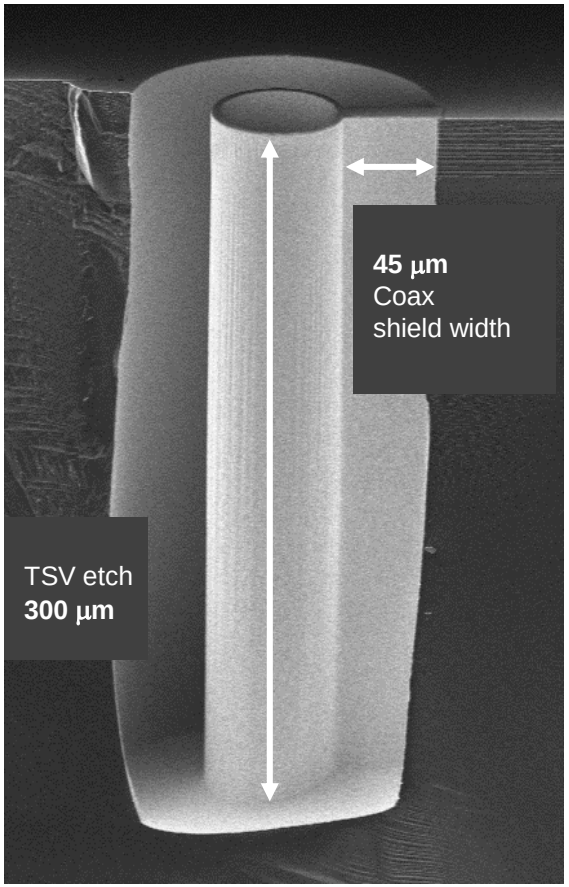
33:1 aspect ratio in X
8:1 aspect ratio in Y

Large Co-Axial Vias Successfully Etched and lined with Ti/TiN and W

GDS of Co-Ax TSV
Top View



Coaxial TSV
Tilted SEM cross-section

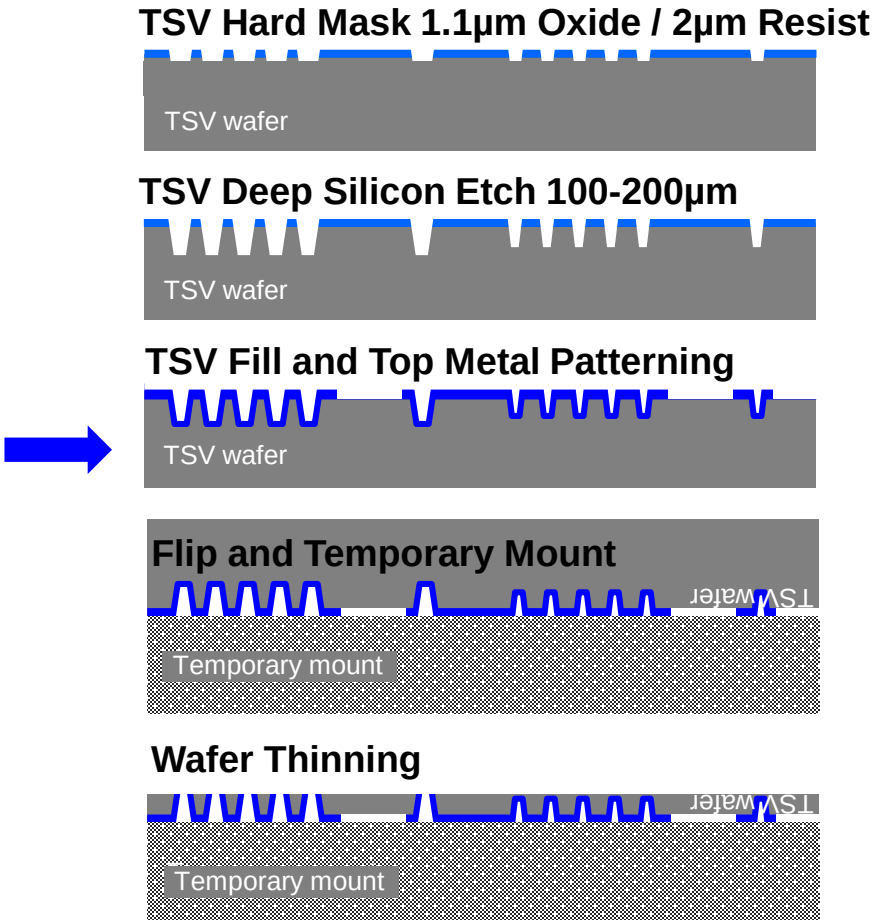


Will enable electrically testable co-ax TSVs

TSVs for 3D Integration

Next Steps

- Continue to improve filling of high aspect ratio TSVs
- Top metal patterning over planarized TSV's
- TSV interposer wafer flipping, mounting and thinning from the backside



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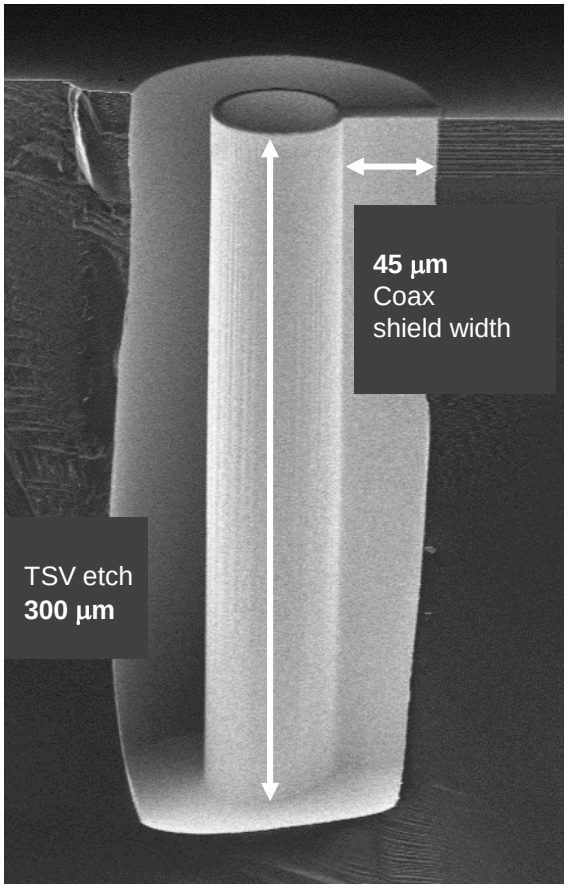
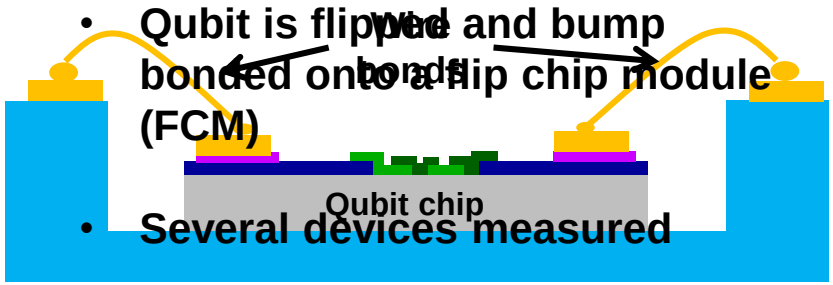


Flip Chip Motivation

Standard Qubit Packaging

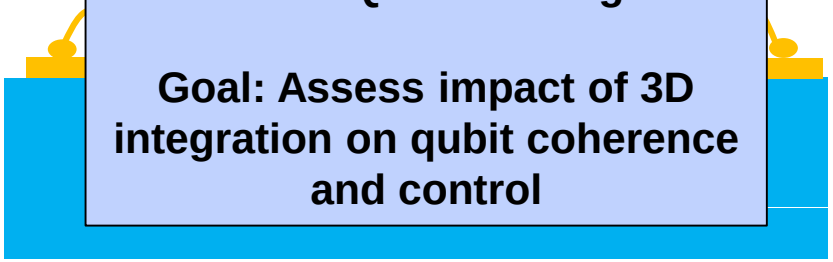
- Qubit is flipped and bump bonded onto a flip chip module (FCM)
- Several devices measured



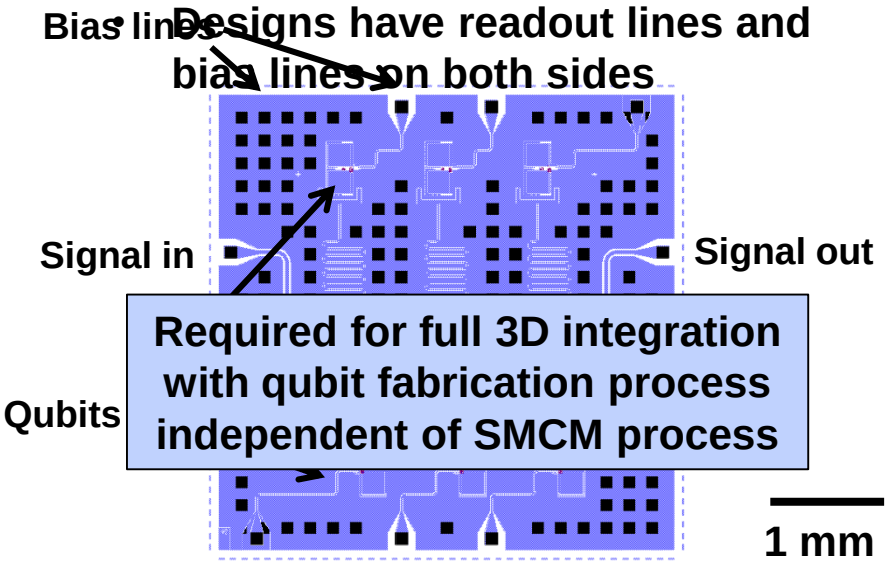
Flip Chip Qubit Packaging

Motivation: QEO 3D integration

Goal: Assess impact of 3D integration on qubit coherence and control

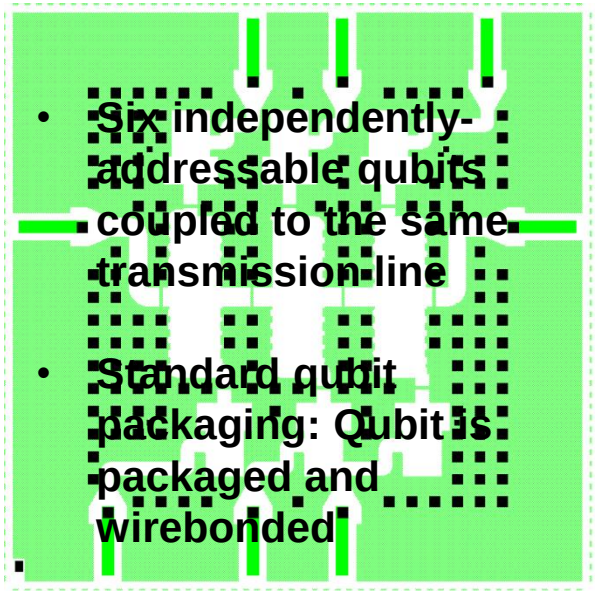


- Designs have readout lines and bias lines on both sides



Required for full 3D integration with qubit fabrication process independent of SMCM process

6-qubit chip with independent bias lines

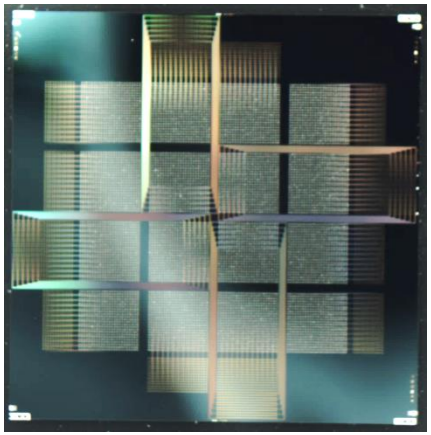


- Six independently-addressable qubits coupled to the same transmission line
- Standard qubit packaging: Qubit is packaged and wirebonded

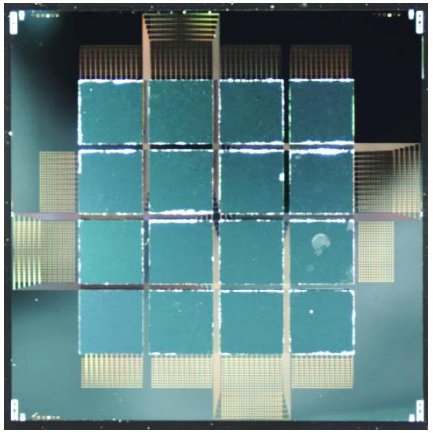
D. Rosenberg, D. Yost, et al., unpublished (2015)

Junction Rn Before / After Bump Bonding

S-MCM for 16-Chip Packaging

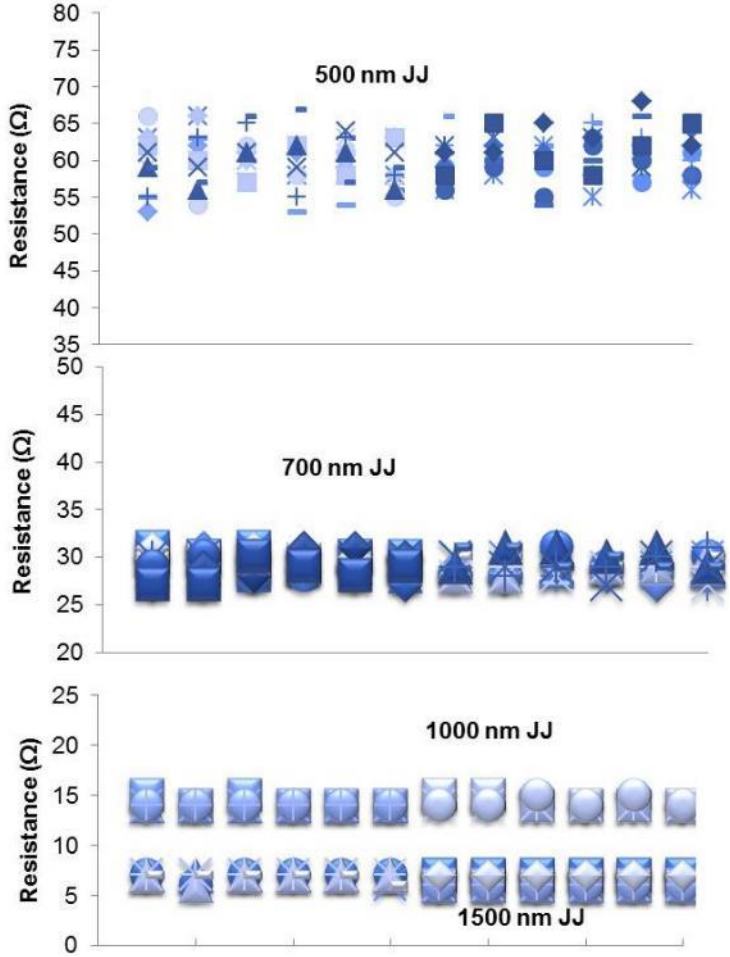


Bumped S-MCM before bonding



S-MCM after bonding

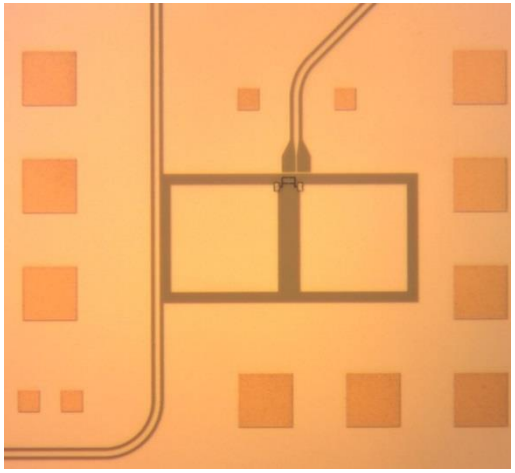
- JJs on all 16 chips electrically connected after bonding (at RT).



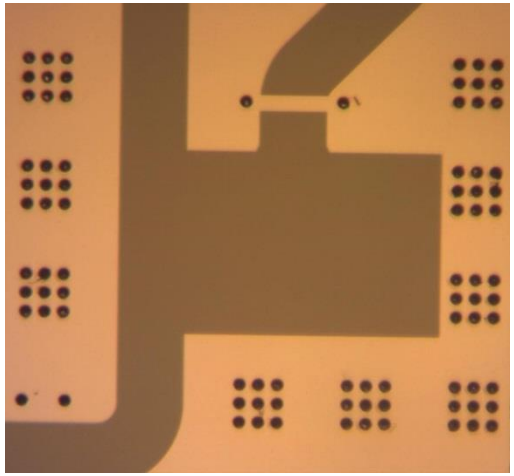
R. Das, et al., unpublished (2015)

Flip Chip Fabrication: Two Components

1 **C-shunt Flux Qubit Chip with underbump pads**



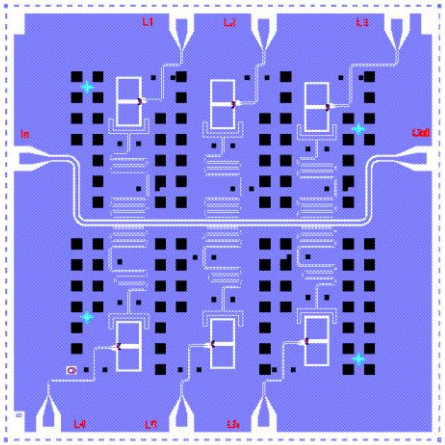
2 **Flip Chip with Indium Bumps**
(inverted for comparison)



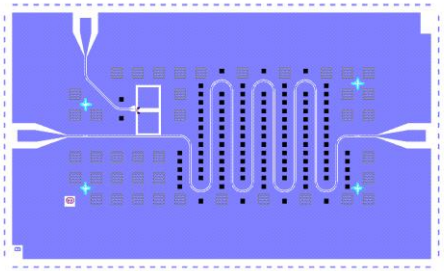
D. Rosenberg, D. Yost, et al., unpublished (2015)

Bump-bonded Flip Chip

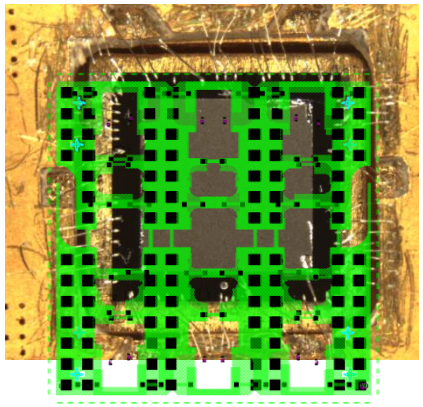
6 identical qubits coupled to quarter wave resonators



Single qubit coupled to half wave resonator



Packaged qubit with flip chip bonded on top



Packaged qubit with flip chip bonded on top

- **Coherence times**
  - **T_1 = 10-20 μs**
  - **T_2 = 15-25 μs**
- **Passed control and readout signals between chips**
- **Demonstrated flux biasing the qubit (flip chip) from the MCM module**

D. Rosenberg, D. Yost, et al., unpublished (2015)

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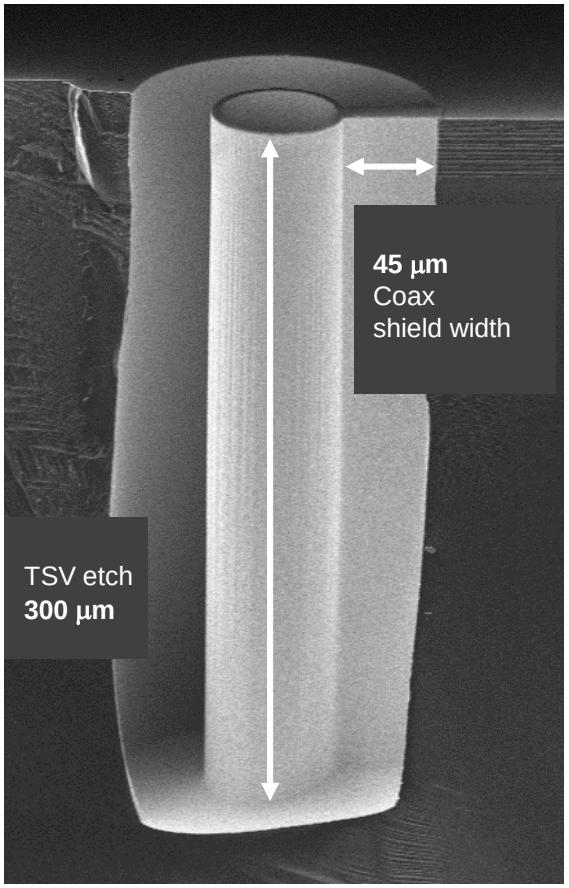
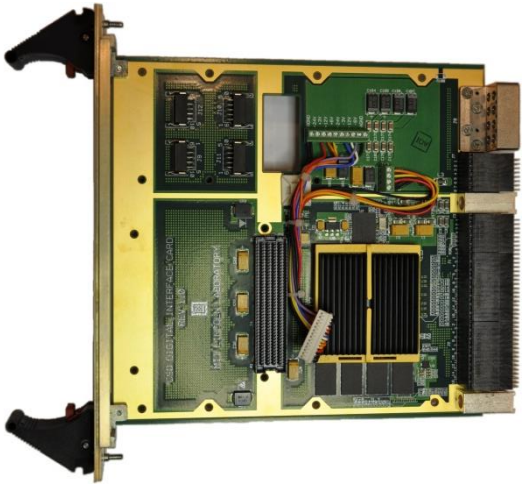


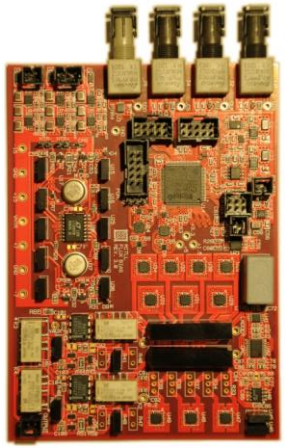
Room Temperature Control Electronics

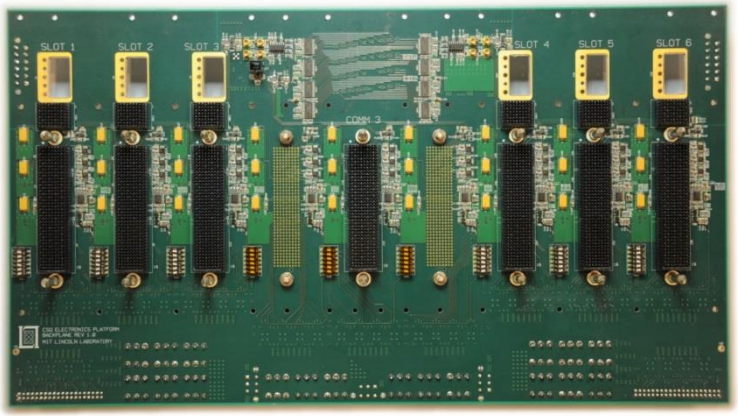
Rack-Mount Chassis

FPGA Card



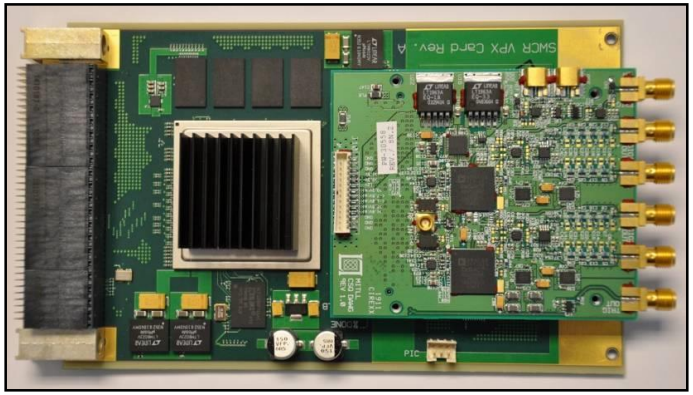
Low-noise DC bias



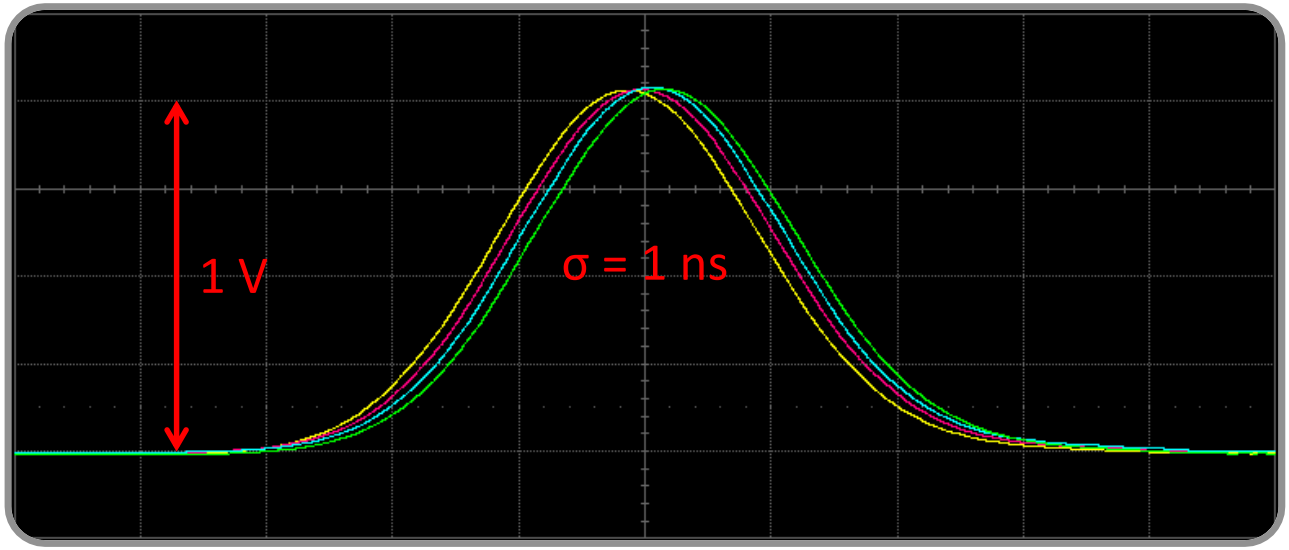


Backplane

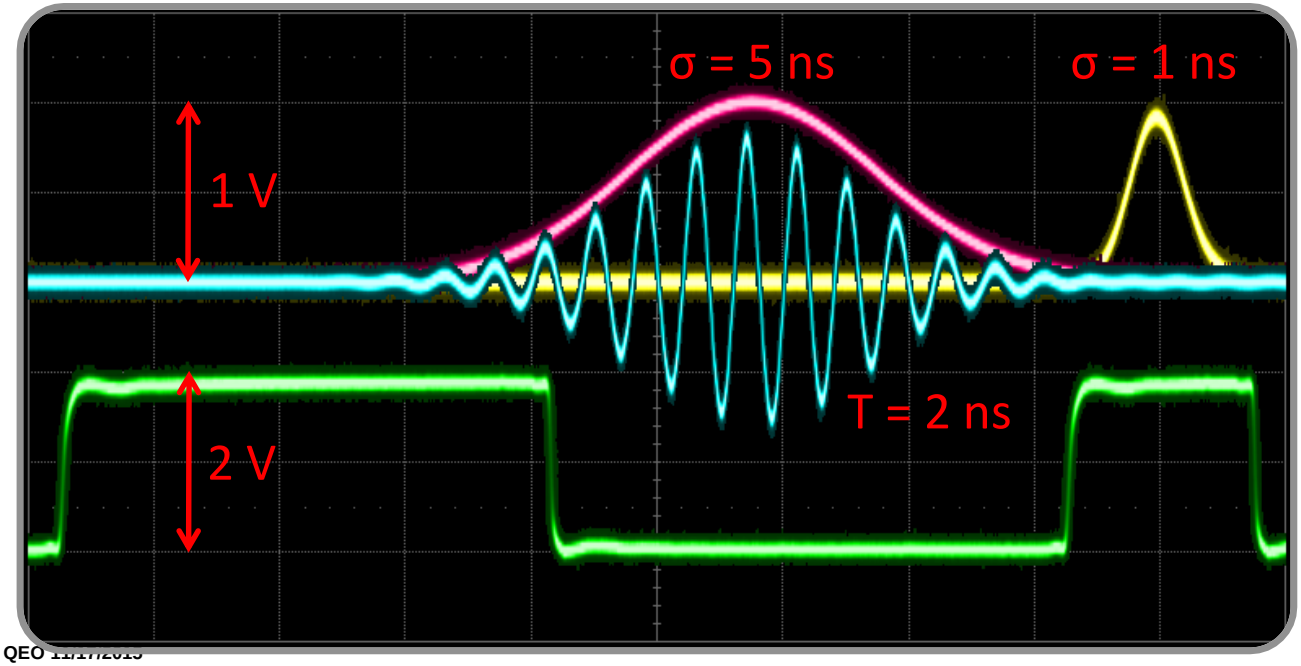
Dual-Channel, 2GS/s, 14-bit AWG



DAWG: Waveform Generation



- 2 DIUs
- 4 DAWG channels
- Predistortion applied
- 100 ps spacing between waveforms
- 1 ns/div, 10 ns record
- Externally Triggered



- 3 DIUs
- 3 DAWG channels
- 1 marker bit
- Persistence enabled
- 5 ns/div, 50 ns record
- Externally Triggered

Fast Upload Application:

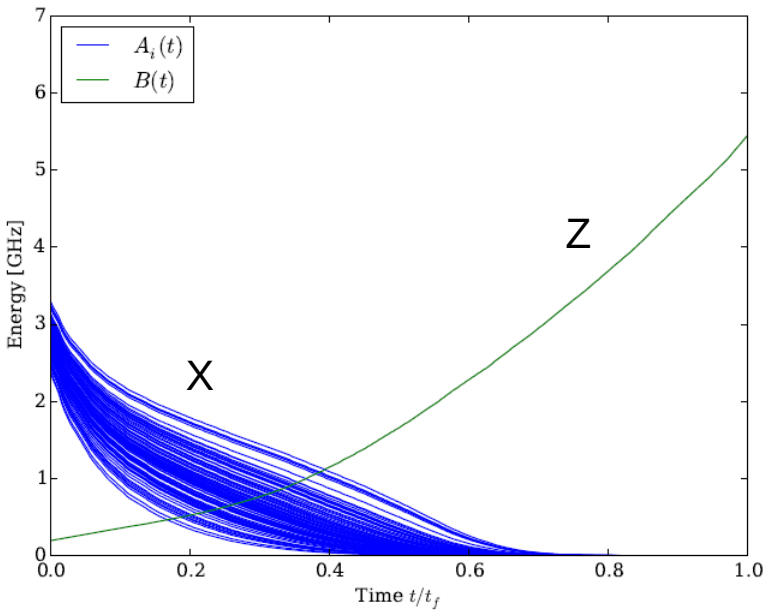
Quantum Annealing

- **Fast waveform upload is a resource**
  - **Gate based QC**
  - **Quantum annealing QC**

- **Quantum annealing requirements**
  - **Sweep X and Z fields of each qubit and coupler**
  - **Long timescales**
  - **Deep AWG memory**
  - **Means to quickly change waveforms**
  - **DAWGs provide this capability**

Annealing Schedule for Spins

example testing different X-field schedules



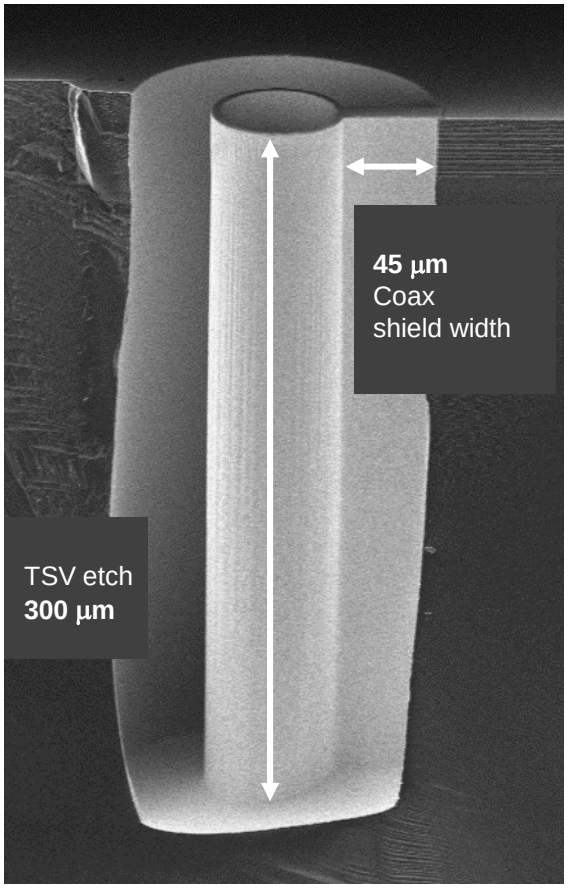
$$H(t) = -\sum_i A_i(t)\sigma_i^x + B(t)H_{\text{Ising}}$$

QEO Experimental Overview

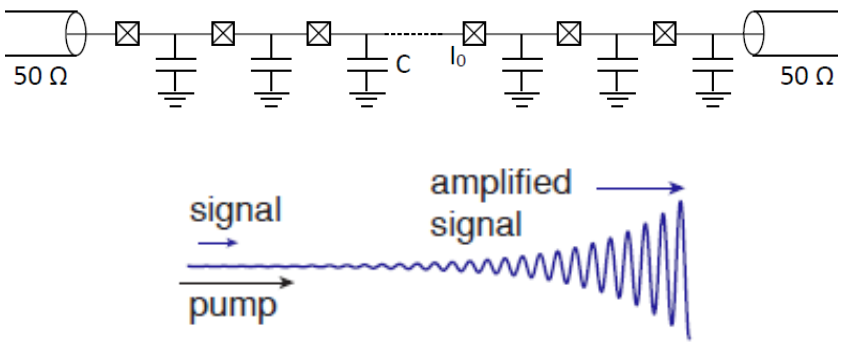
- Introduction
  - Tasks
  - Teams
- Approach & motivation
  - 3D integration
  - Tunable, high-coherence qubits
- Supporting technologies
  - High-Q materials & fab
  - TSVs
  - Flip-chip qubits
  - Electronics
  - J-TWPA

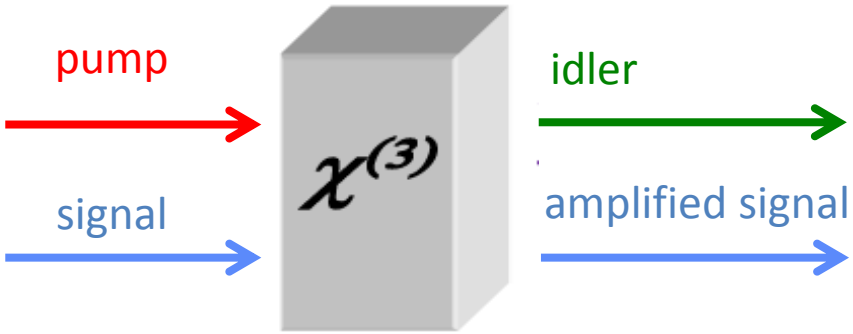
Coaxial TSV

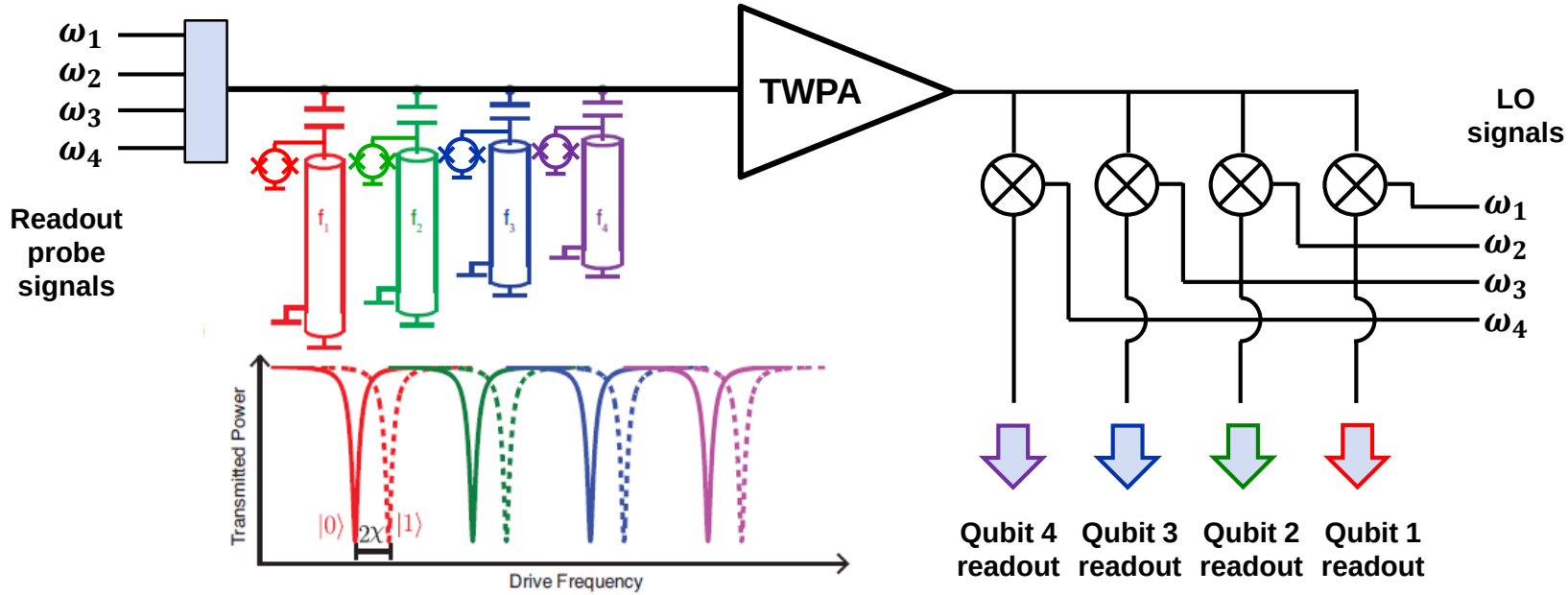
Tilted SEM cross-section



Josephson Traveling-Wave Parametric Amplifier (J-TWPA)

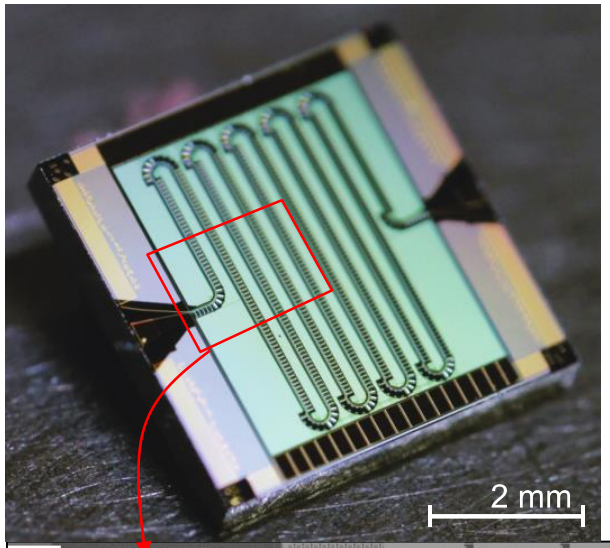


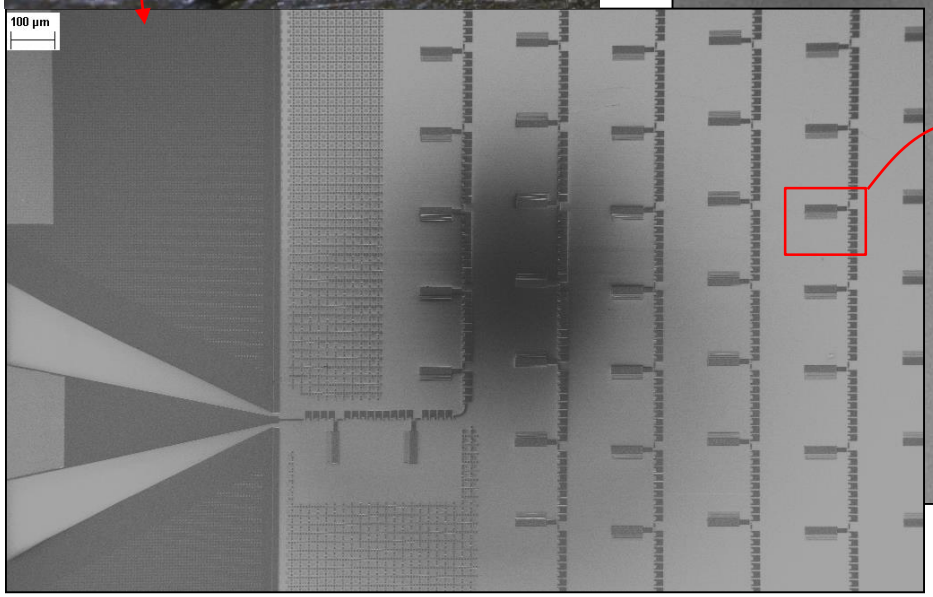


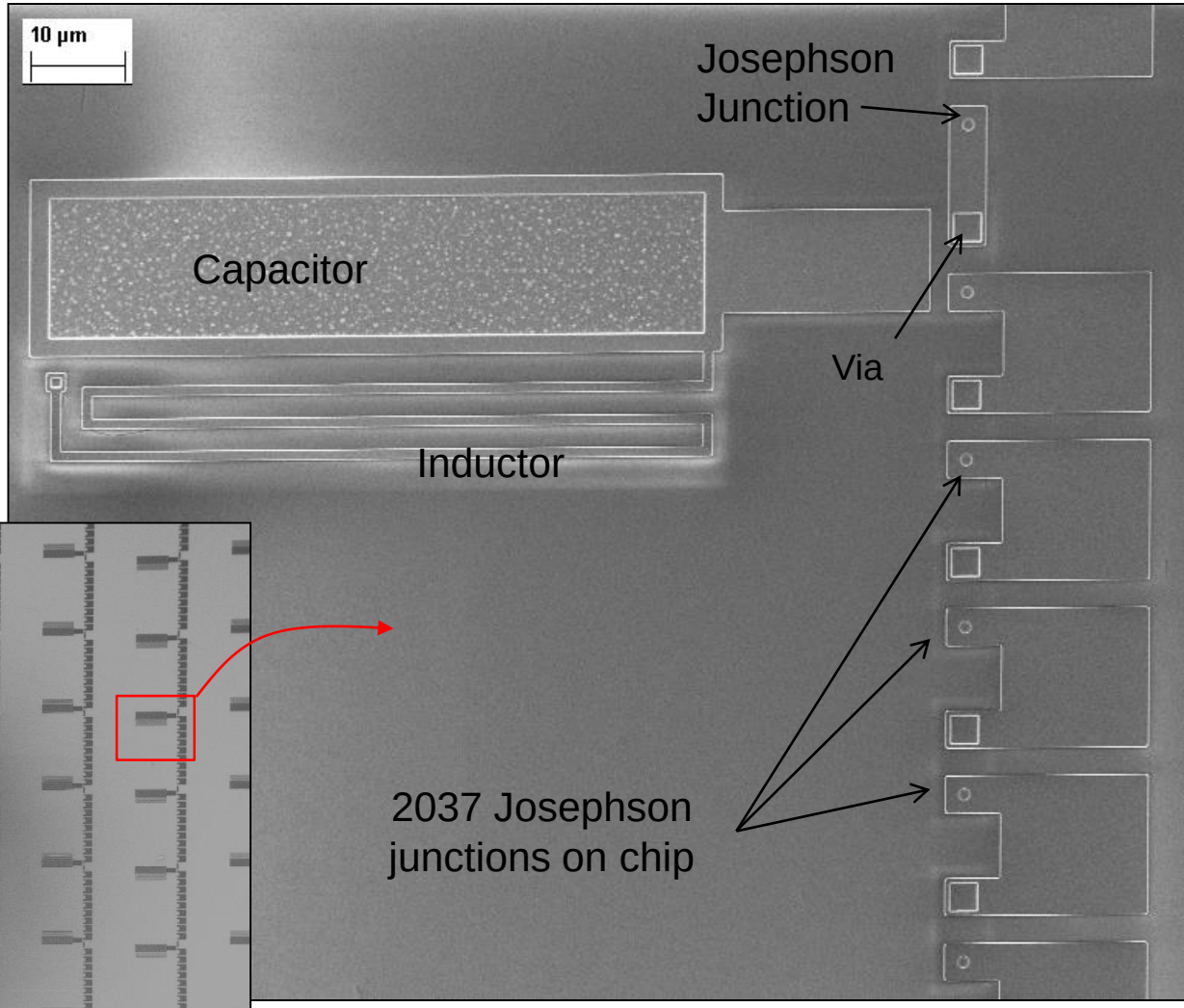


K. O'Brien et al., PRL 113, 157001 (2014), C. Macklin et al., Science 350, 307 (2015)

TWPA: Optical and SEM Images



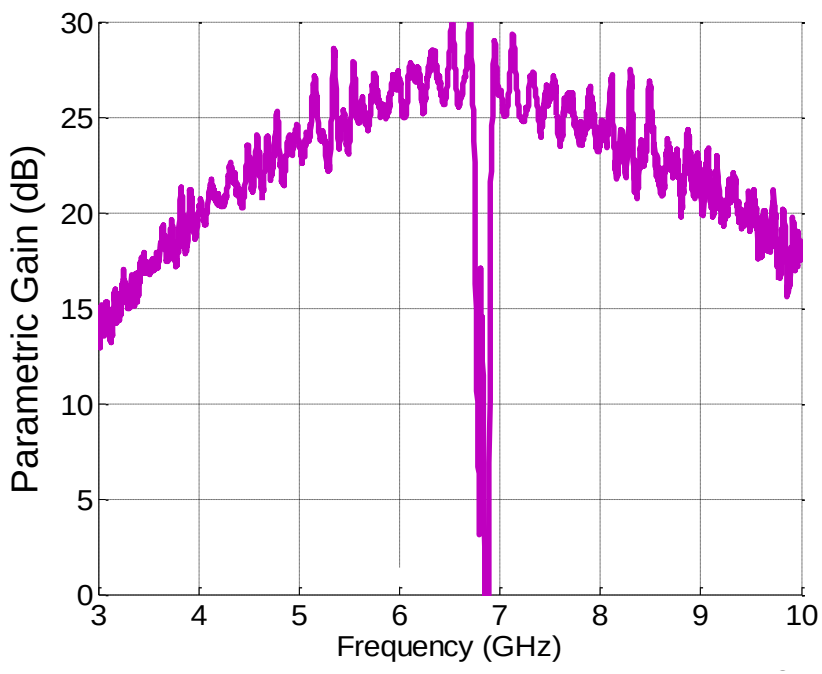




K. O'Brien et al., PRL 113, 157001 (2014), C. Macklin et al., Science 350, 307 (2015)

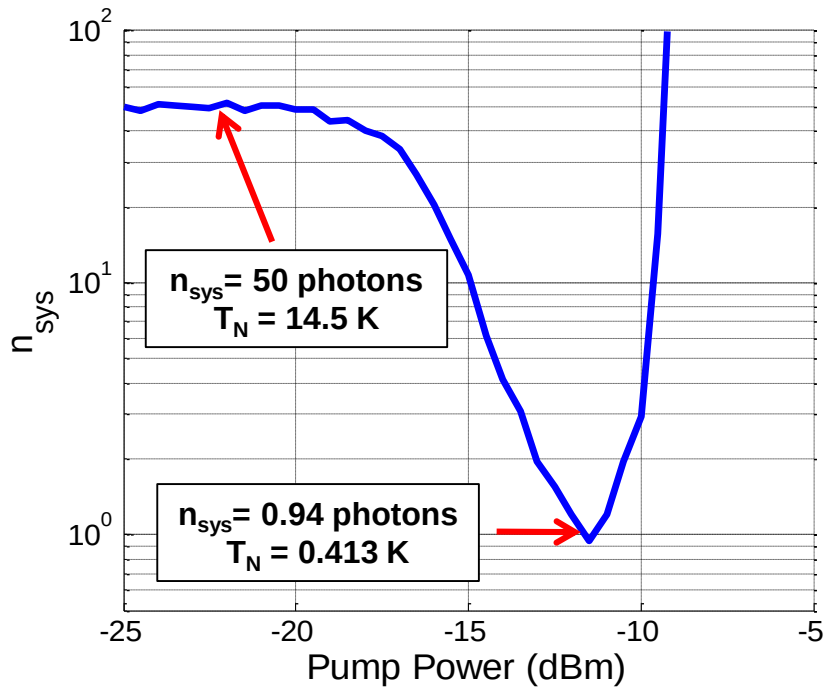
TWPA: Near-Quantum Limited and Broadband Amplifier

TWPA Gain vs. Frequency



> 20 dB gain over 4.25-8.75 GHz band

System Noise vs. Pump Power



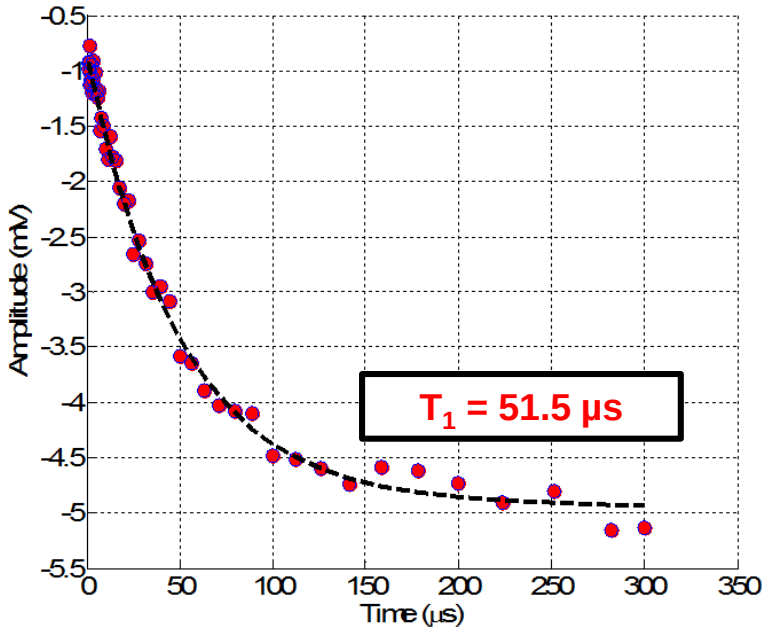
$T_{N,sys}$ = 0.4 K (TWPA quantum efficiency ~ 0.8)

C. Macklin et al., Science 350, 307 (2015); D. Hover et al., unpublished (2015)

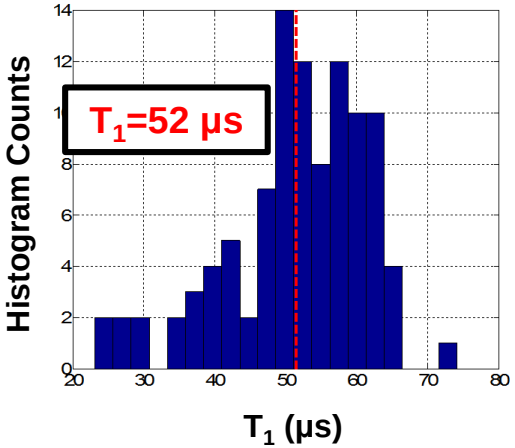
C-shunt Flux Qubit + TWPA

T_1 Measurements: Without Isolator

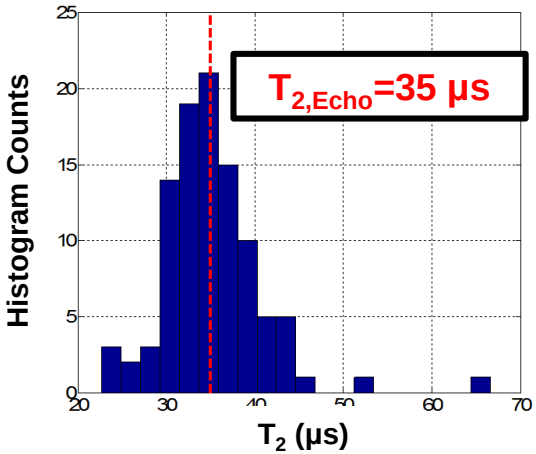
Averaged and Fit



T_1 at Degeneracy



T_{2E} at Degeneracy



- Repeated measurements of T_2 at degeneracy
- Without isolator: T_1 = 51.5 us
- Without isolator: T_{2R} = 17 us
- Without isolator: T_{2E} = 35 us
- Consistent with F. Yan et al.

D. Hover et al., unpublished (2015)

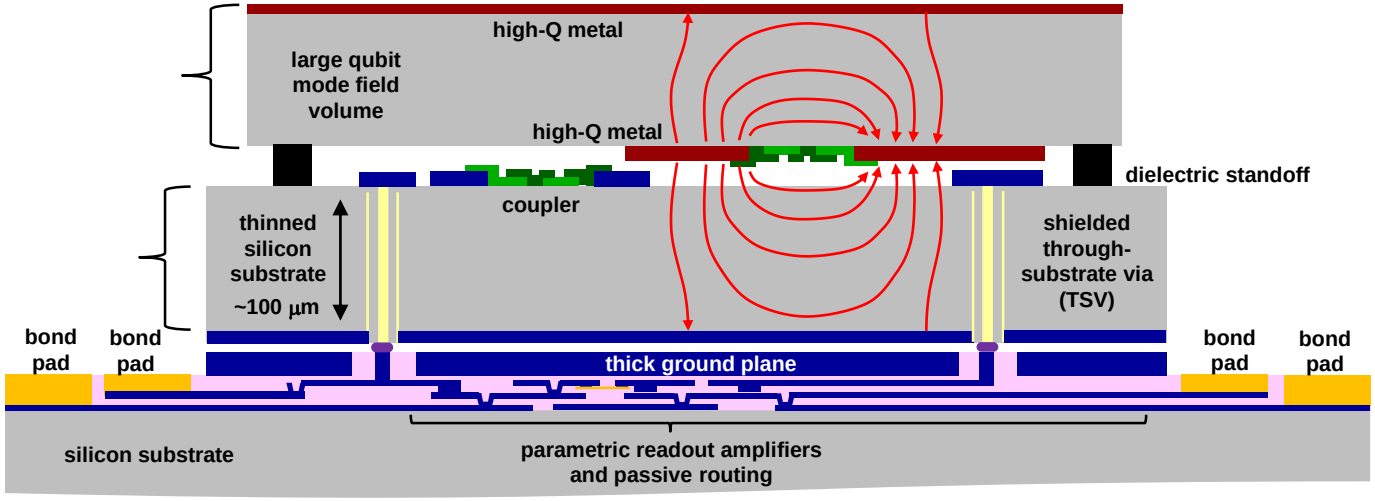
Integration Concept: SMCM Layer

TSV and SMCM Processes

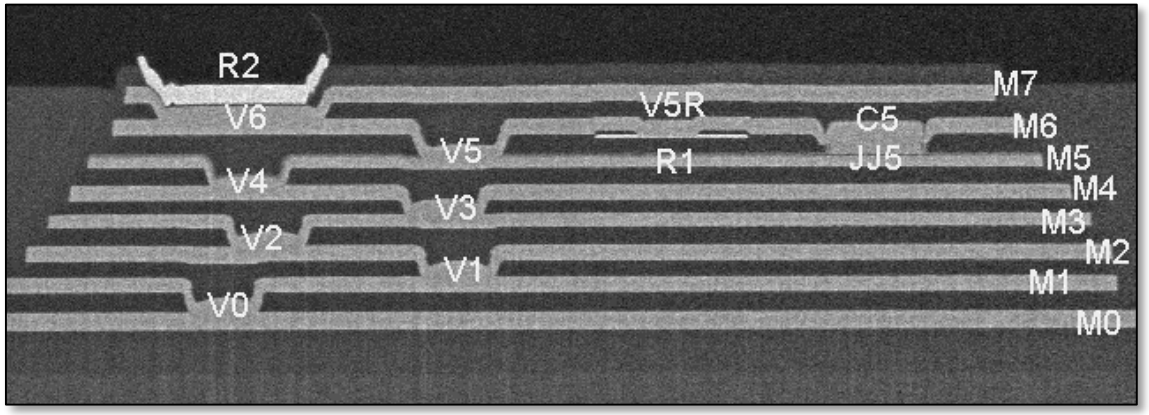
Qubit fabrication process

TSV, coupler process

3 Superconducting multi-chip module (SMCM) process



Niobium S-MCM (Superconducting Multi-chip module – IARPA C3 program)



TWPA and I/O routing in SMCM layer leverages IARPA C3 program (SFQ multi-layer fabrication)

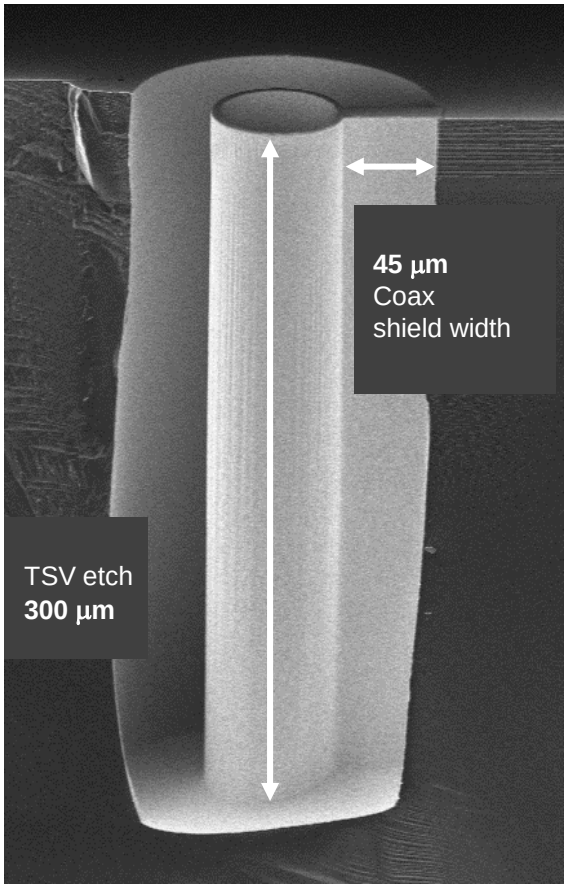
S. Tolpygo et al., IEEE Trans. Supercond. 25, 1101312 (2015)

Summary: QEO Experimental Overview

- **Developed an approach to achieve 3D integration of high coherence qubits for quantum annealing applications**

- **Demonstrated several foundational concepts**
  - **C-shunt flux qubits with state-of-art coherence**
  - **Fully tunable C-shunt flux qubit**
  - **Tunable coupler shifting qubit frequencies in controllable manner**

- **Demonstrated / developed several supporting technologies**
  - **High-Q materials & fabrication**
  - **Crossovers**
  - **TSVs**
  - **Flip-chip qubits (little T1 degradation)**
  - **Qubit ensembles & multiqubit measurements**
  - **Room temperature electronics**
  - **Advanced readout with TWPAs**

Coaxial TSV

Tilted SEM cross-section