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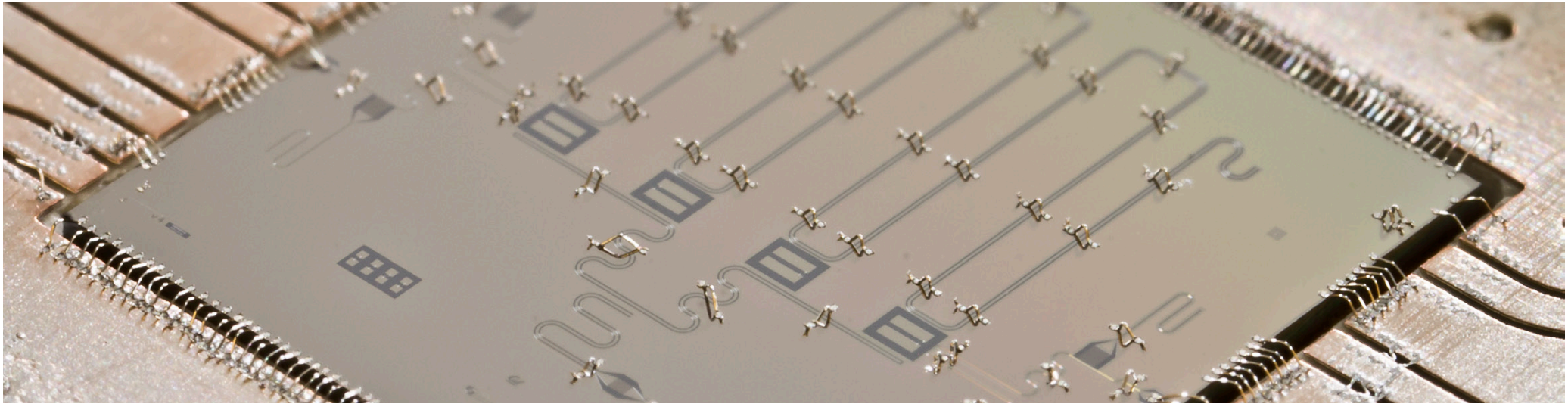
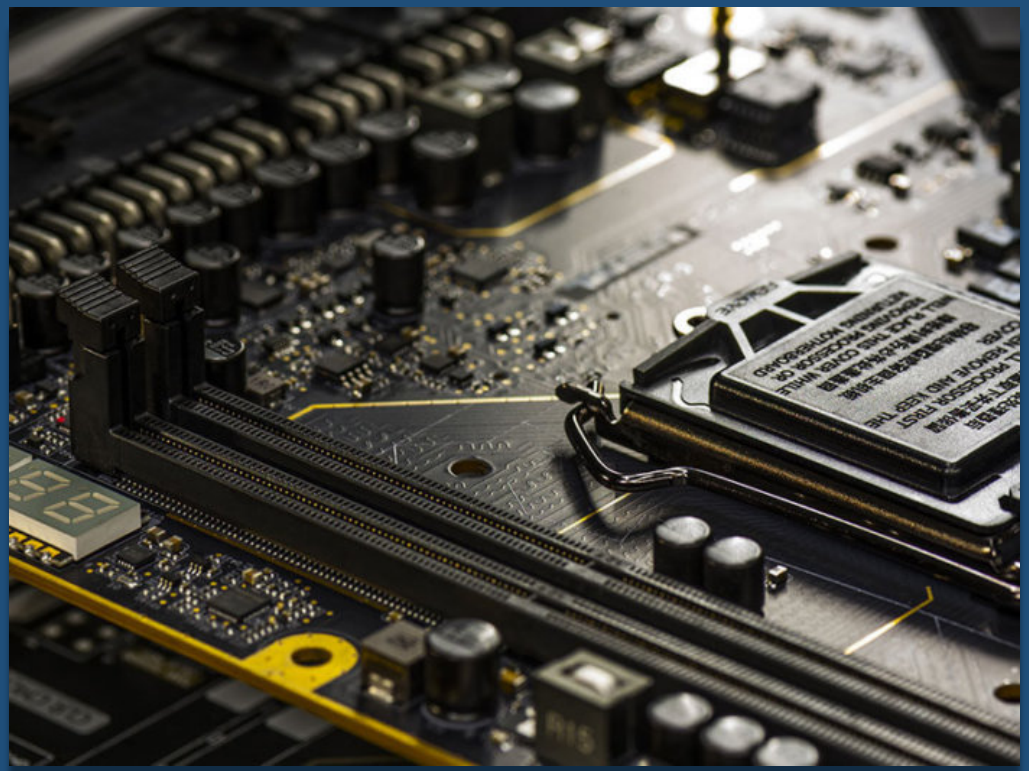
AQT at Berkeley Lab

WIRING UP SUPERCONDUCTING QUBITS

Irfan Siddiqi
Computational Research and Materials Sciences Divisions, Lawrence Berkeley National Laboratory
Department of Physics, University of California, Berkeley



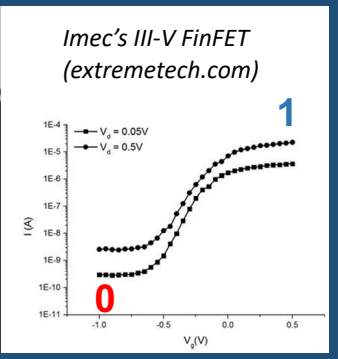
THE QUANTUM INFORMATION PARADIGM SHIFT



(Z370: www.pcworld.com)

- Start with a good switch…

Imec's III-V FinFET (extremetech.com)

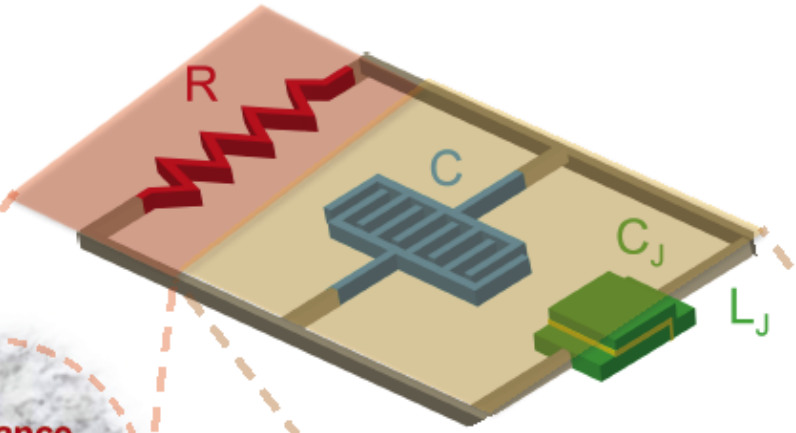


- Advanced materials science, electromagnetism, and thermodynamics at the nm scale
- Different functional units (processor, memory,..)

- Qubits: Write **0** *and* **1** , Read **0** *or* **1**
- N quantum bits *entangle* to form 2^N states !
- **Scaling entanglement (correlation between bits) is hard! → decoherence & "cross-talk"**

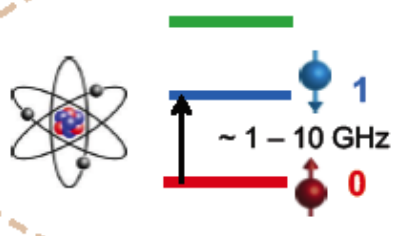
QUANTUM IS FUNDAMENTALLY DIFFERENT AT ALL LEVELS!

A QUBIT IS JUST A NONLINEAR OSCILLATOR

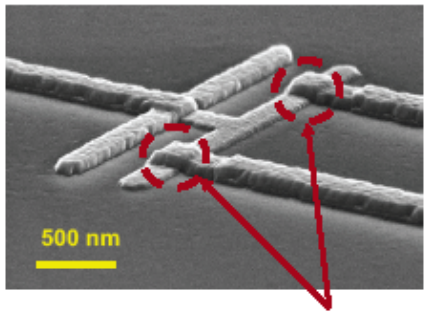


- Quantum harmonic oscillator: only certain energies (currents) are allowed
- Tunnel junction → Nonlinear, isolate **0**, **1**

Resistance (fluctuations) causes decoherence

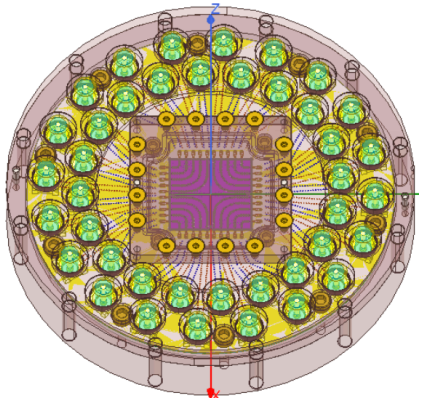


Isolated Qubit: ~ 1 ms
Bulk resonator: ~ 1s
One qubit operations ~ 1-10 ns
Two qubit operations ~ 10-100ns



Al/AlOx/Al Josephson tunnel junctions

SOURCES OF UNWANTED FLUCTUATIONS



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- CLASSICAL CROSSTALK: E-M DESIGN — CHIP
- QUANTUM CROSSTALK: QUBIT COUPLING — QUBIT
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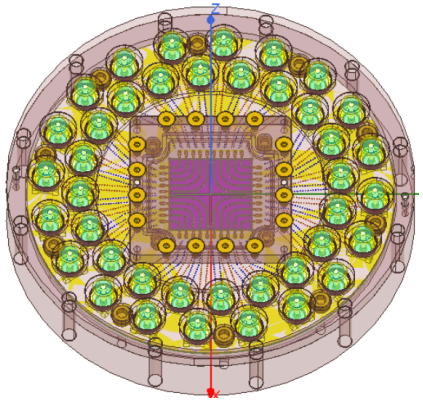

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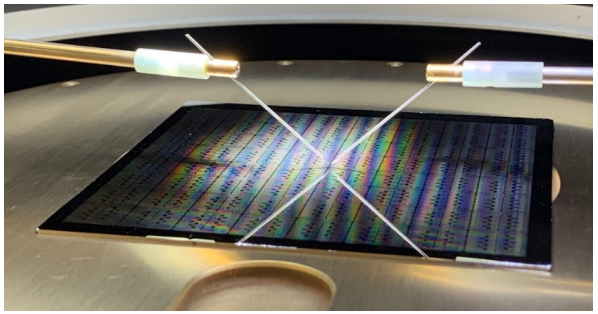
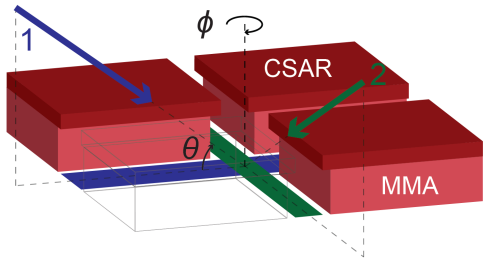
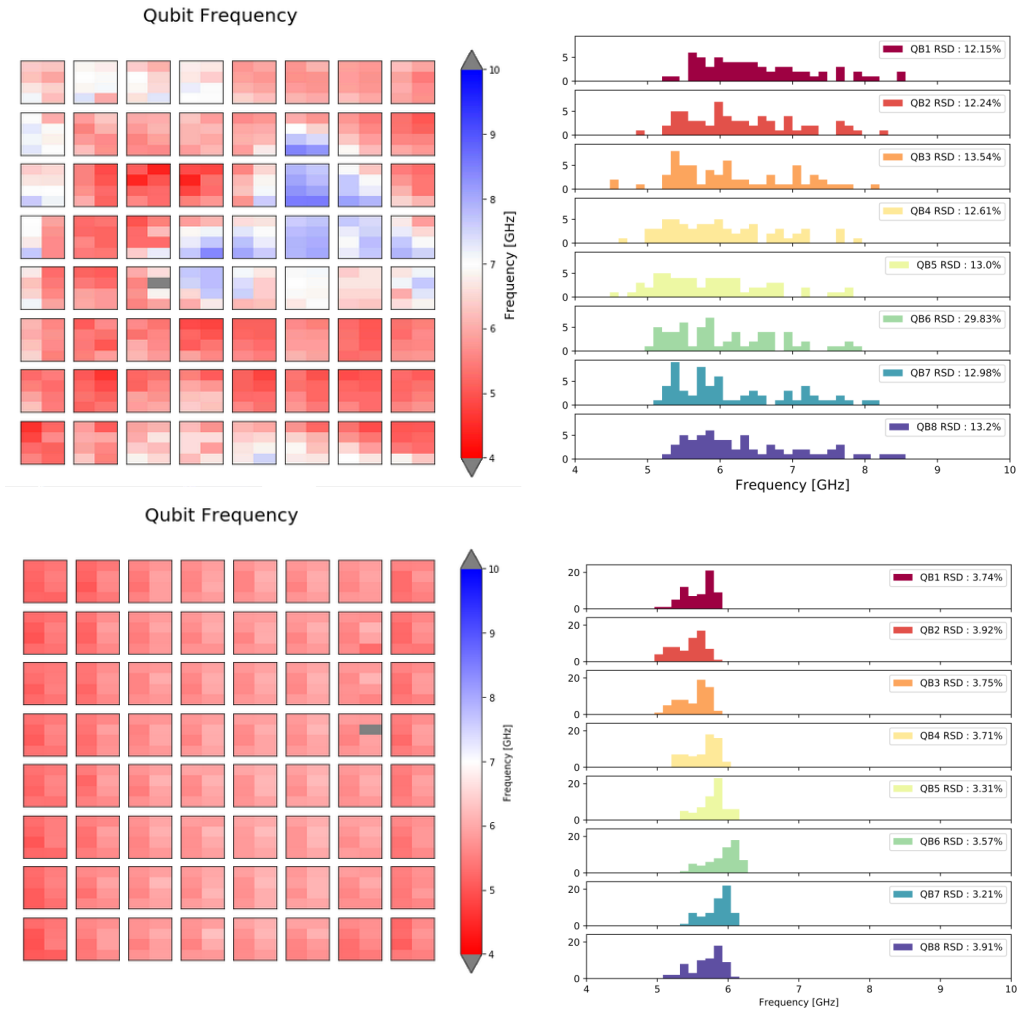
QUBIT UNIFORMITY



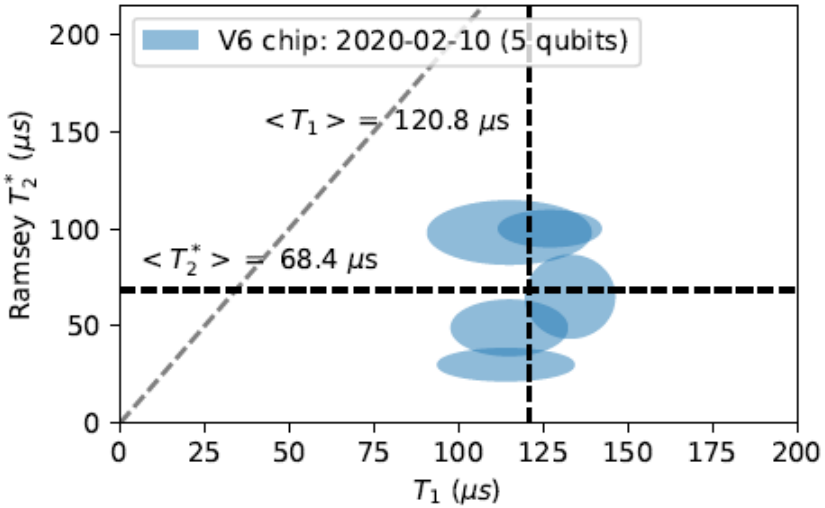


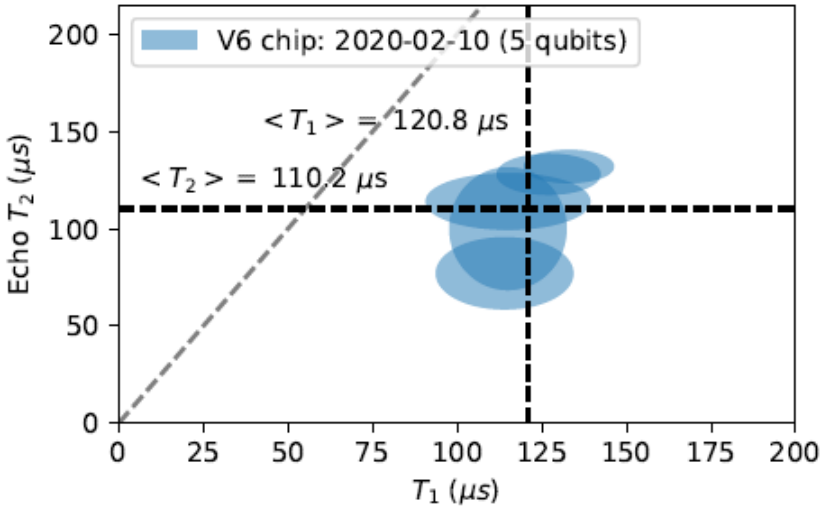
Key improvements:
- ultrasonically assisted development
- O_2 plasma uniformity
- dynamic oxidation
- decreased evaporation rate

arXiv: 1909.09165

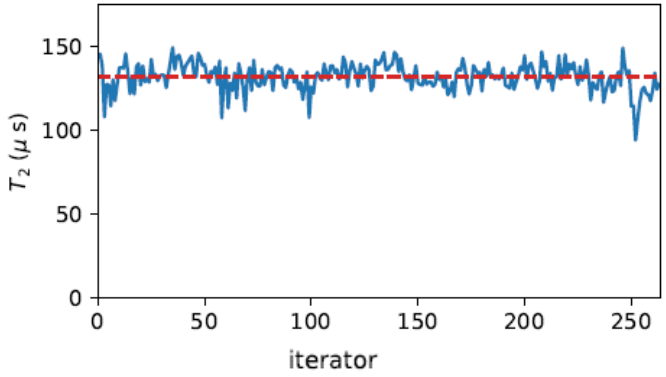


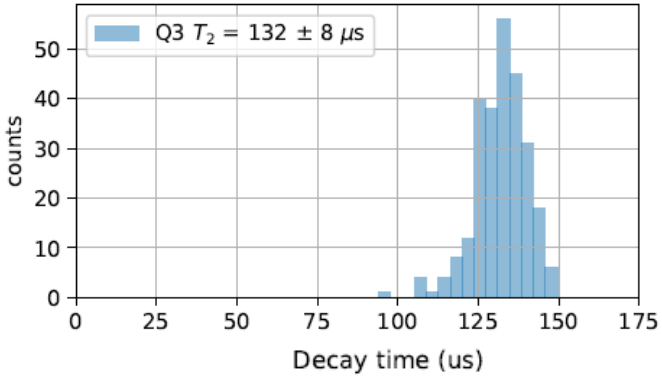
MULTI-QUBIT CHIP LIFETIMES



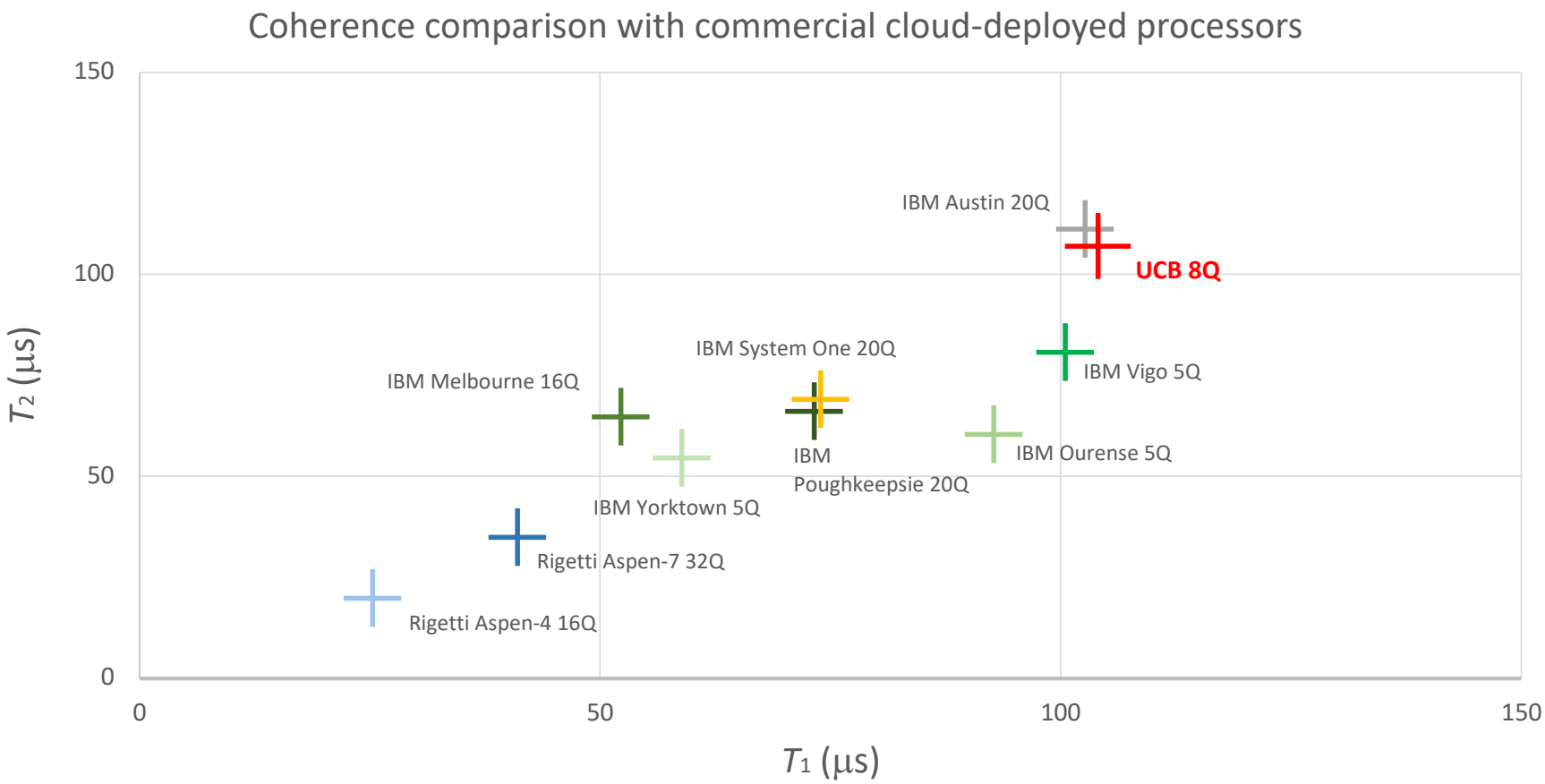


- Data obtained with repeated measurement over 2 hours (264 iterations)
- The size of the ellipse is given by the std of the measured distribution





QUBIT COHERENCE



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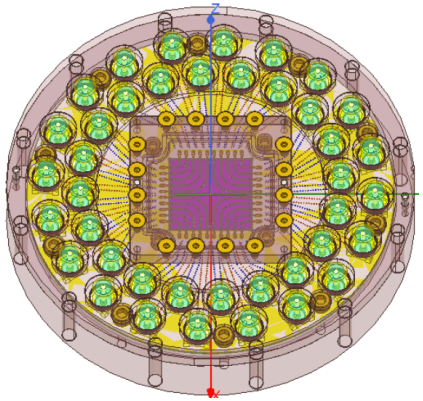

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PICKING A GEOMETRY AND SIZE

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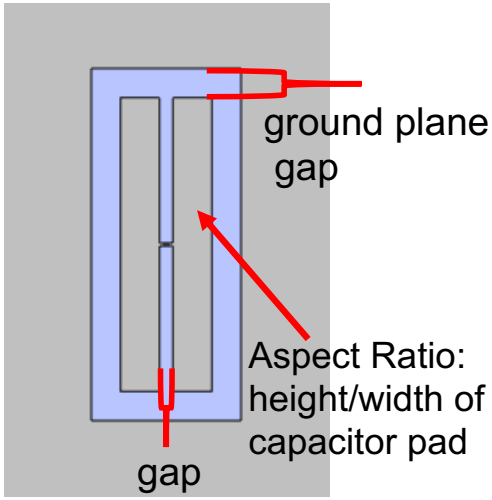
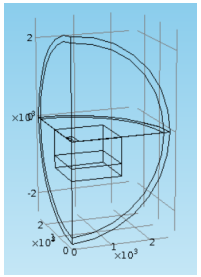
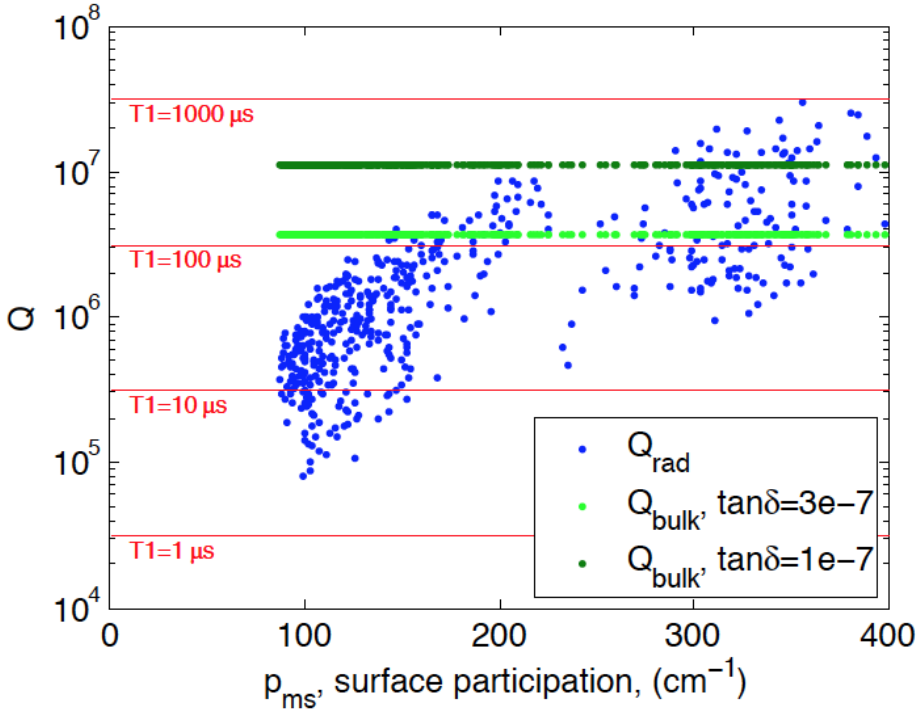


Resonance freq. 5-6 GHz



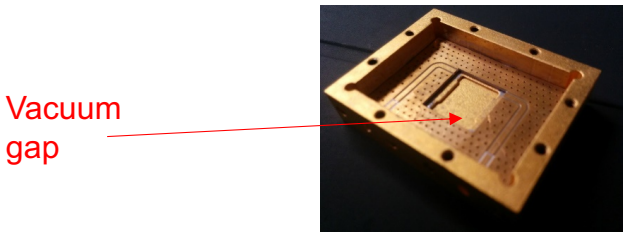


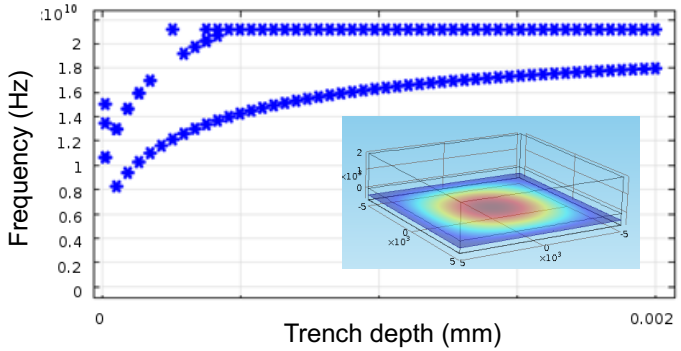
Geometry dependence of radiation Q and surface participation

Conservative bound for radiation loss:
Qubit surrounded by a perfect absorber (PML)

MODE ENGINEERING

Suppressing package + chip modes





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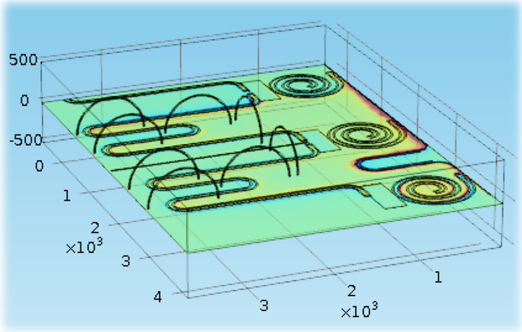
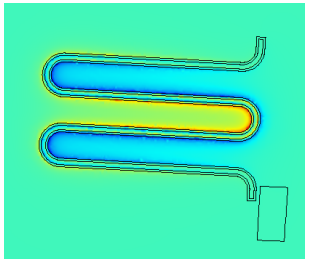
Spurious mode identification and mitigation

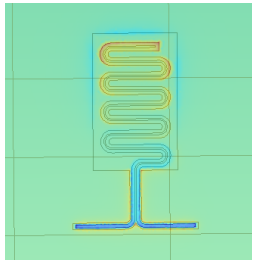


Hybrid CPW-CPS resonators with higher spurious mode frequencies

10 GHz slotline mode



17 GHz slotline mode



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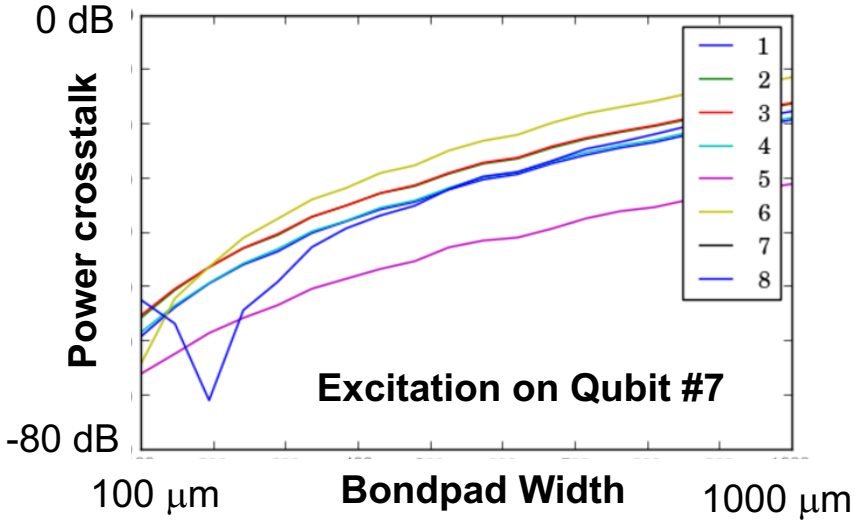
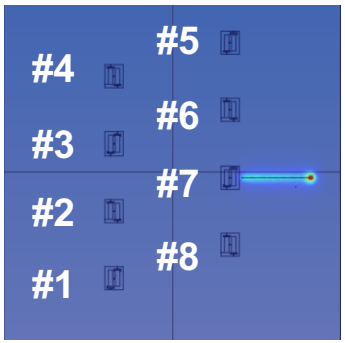
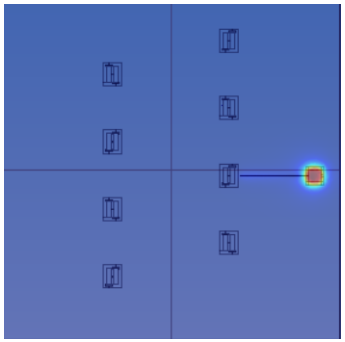
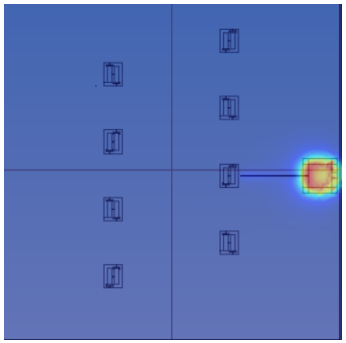




100x100 um^2 bondpad



500x500 um^2 bondpad



1000x1000 um^2 bondpad

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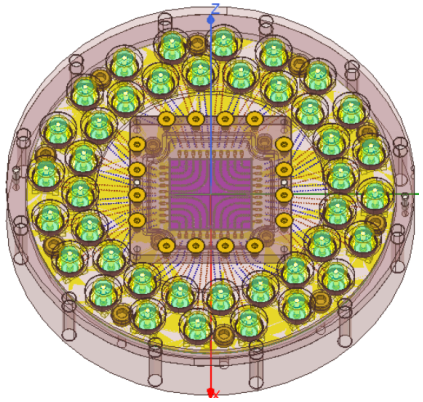

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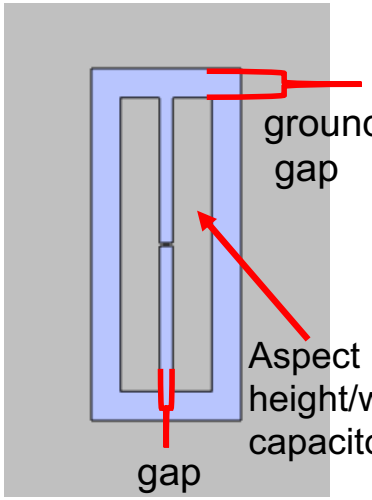

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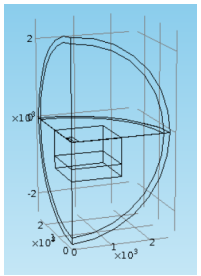

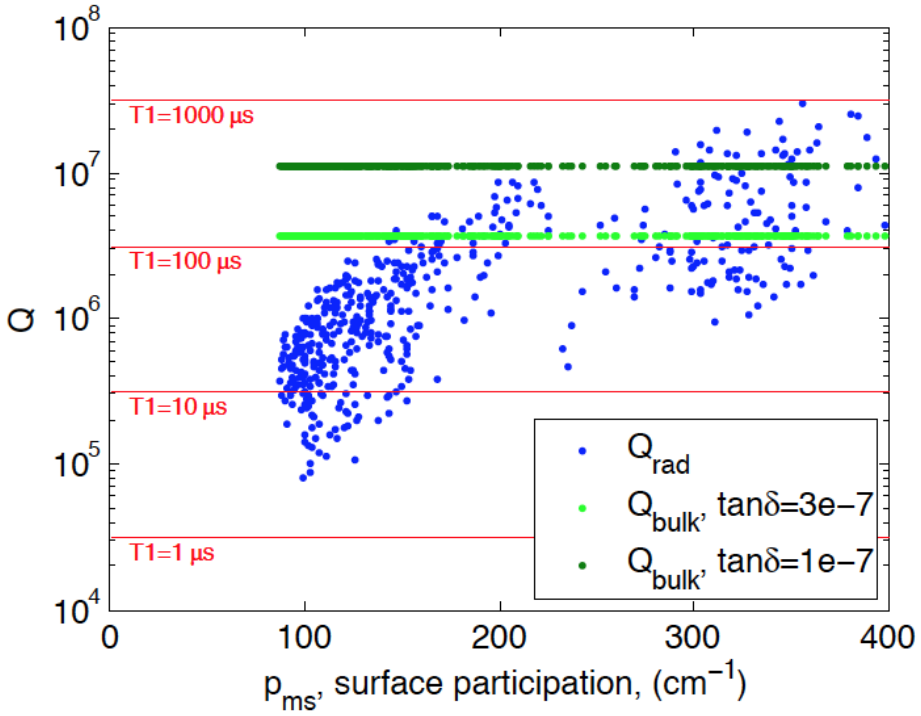

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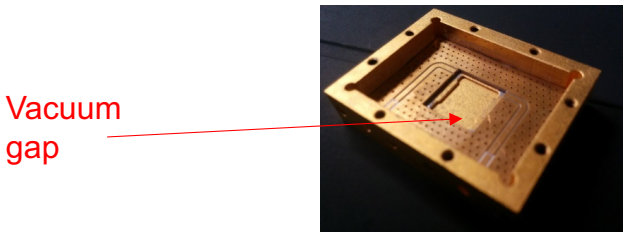

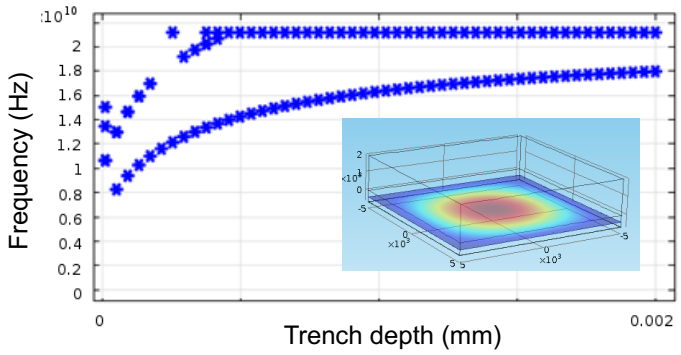

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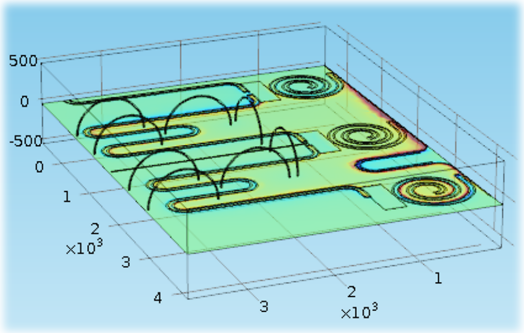

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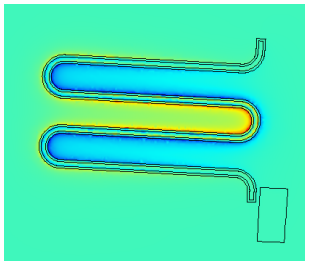

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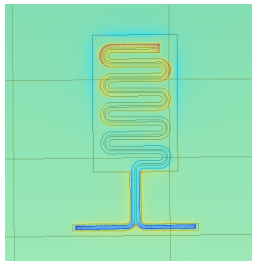

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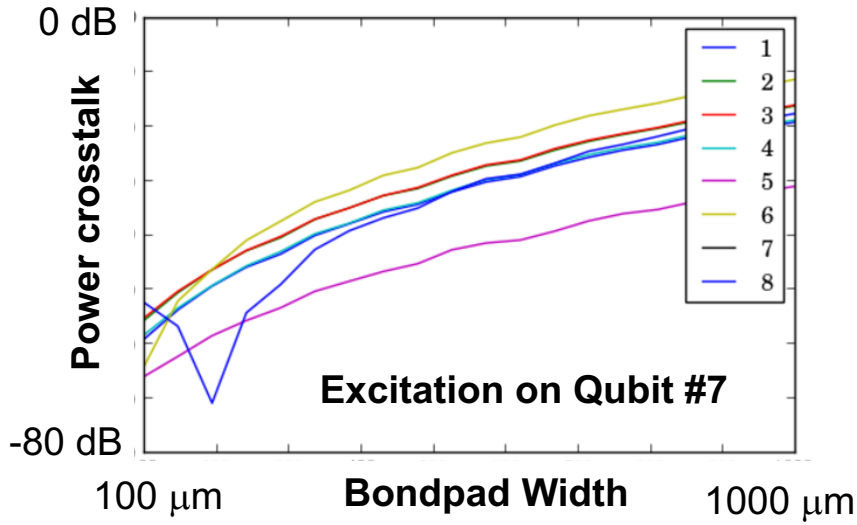
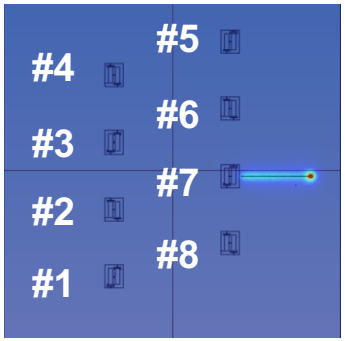
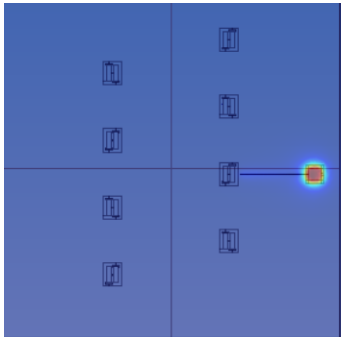




100x100 um^2 bondpad



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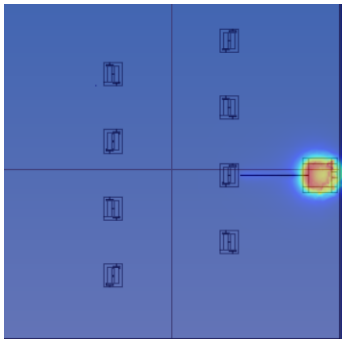

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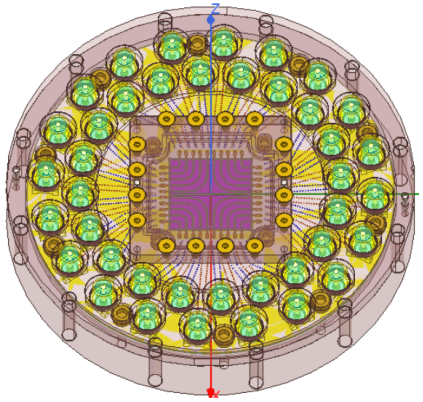

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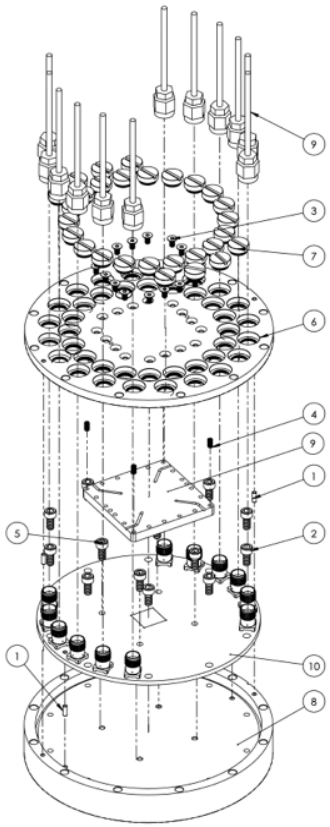
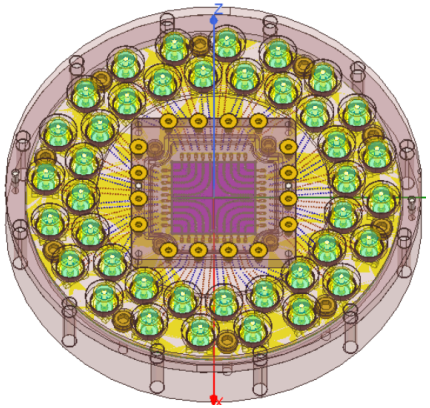
CRYOPACKAGE



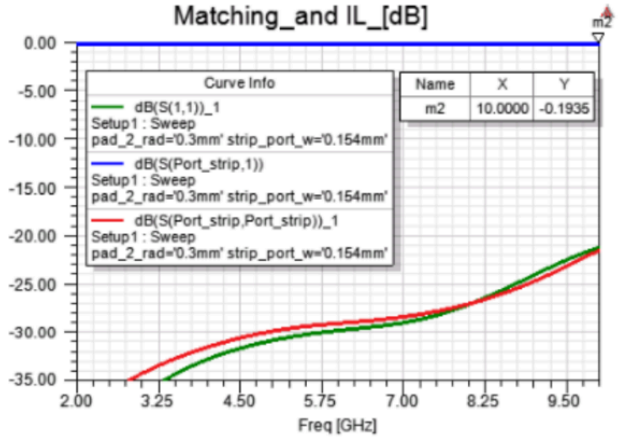
12-line version for Trailblazer chip

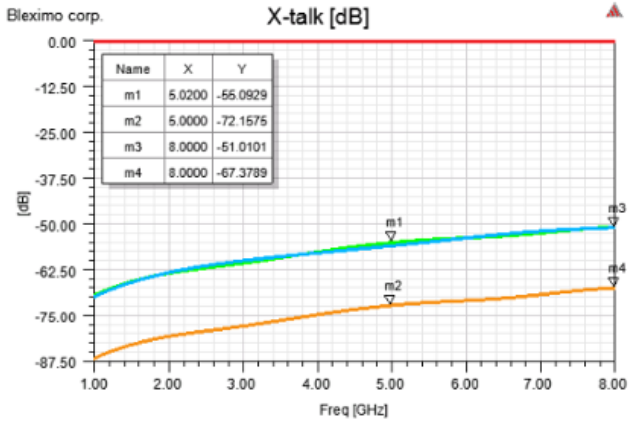
GEN2 PACKAGING WAS DESIGNED TO ACCOMMODATE UP TO 20 X 20 mm^2 CHIPS WITH UP TO 40 RF LINES AND STRIPLINE PRINTED CIRCUIT BOARDS TO MININIMIZE CROSS-TALK



SIMULATIONS

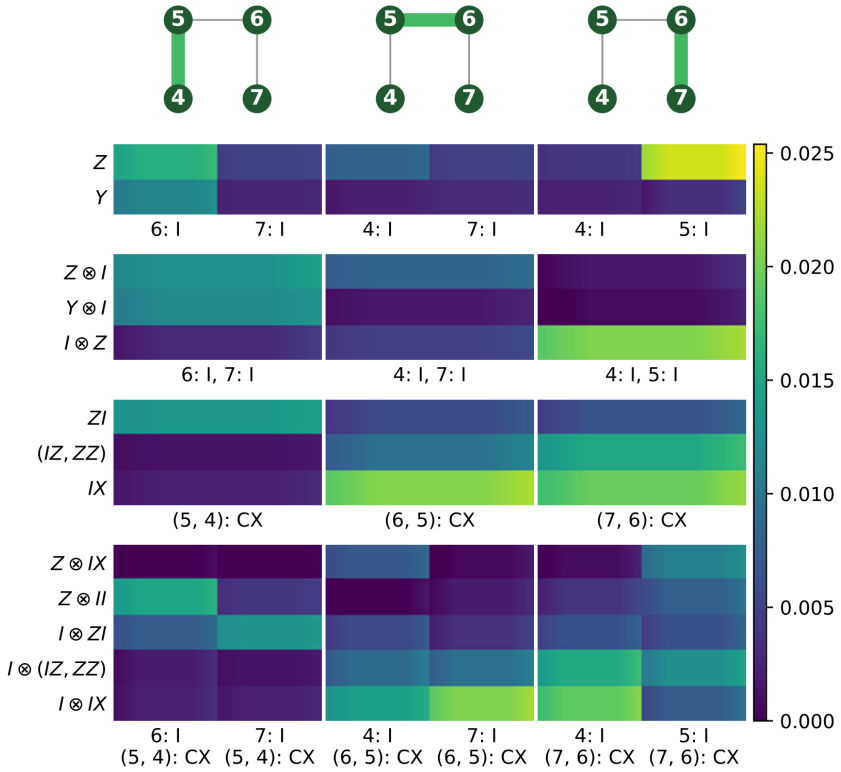
- Input port matching < -25dB over 2-8 GHz band (-30dB at 5 GHz)
- Next-neighbor cross-talk levels is below -55dB over 2-8 GHz band for the closest pair of lines on the Trailblazer chip and below -72dB for other pairs of lines





MULTI-QUBIT CONTEXT FOR BENCHMARKING GATES

- Reconstructing specific error syndromes using cycle benchmarking
- Able to monitor and correct errors on spectator qubits
- Realistic assessment of algorithmic performance under randomized compiling



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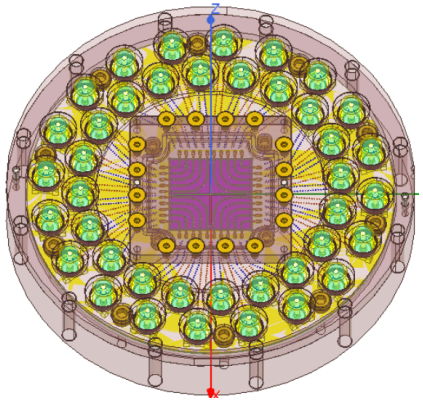

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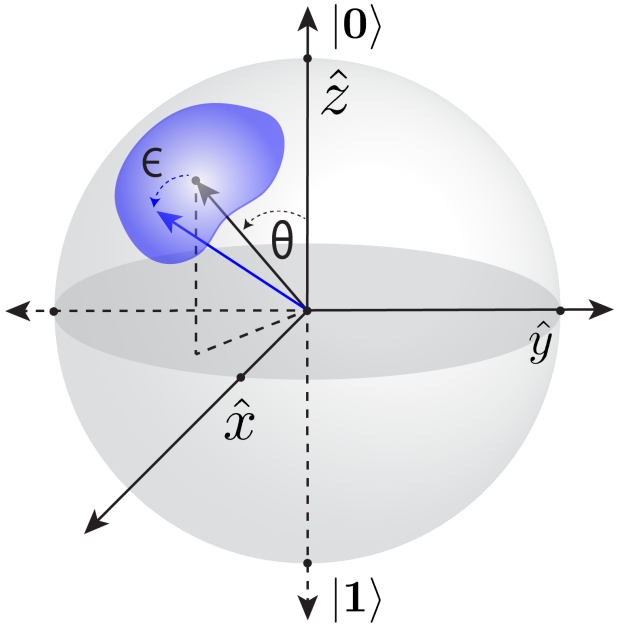
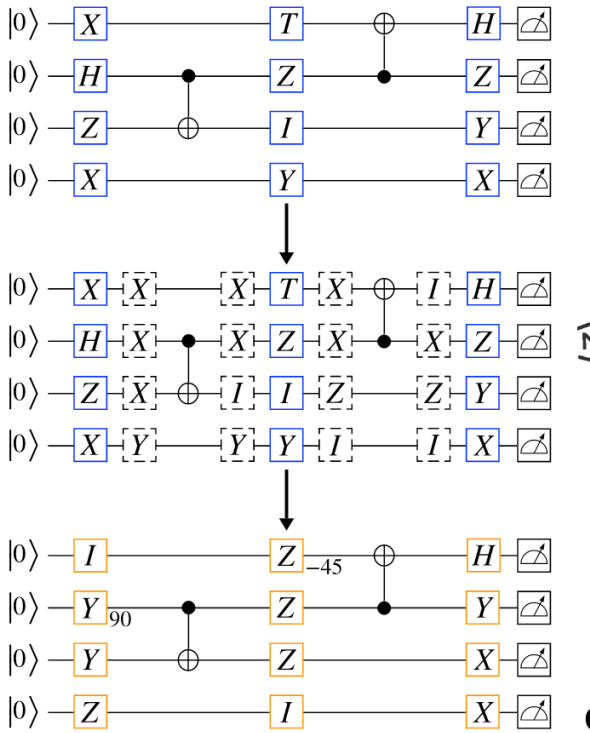
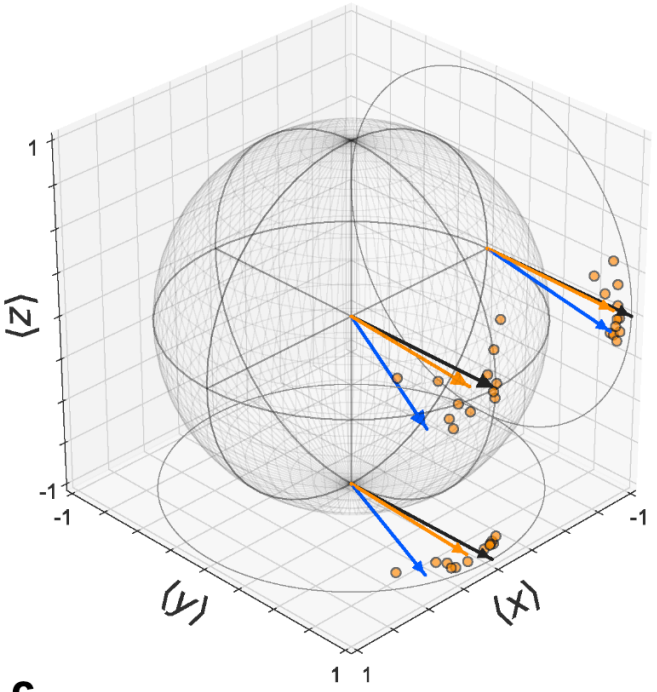
- ERROR MITIGATION: FLOQUET STYLE GATES — ALGORITHM

RANDOMIZED COMPILING

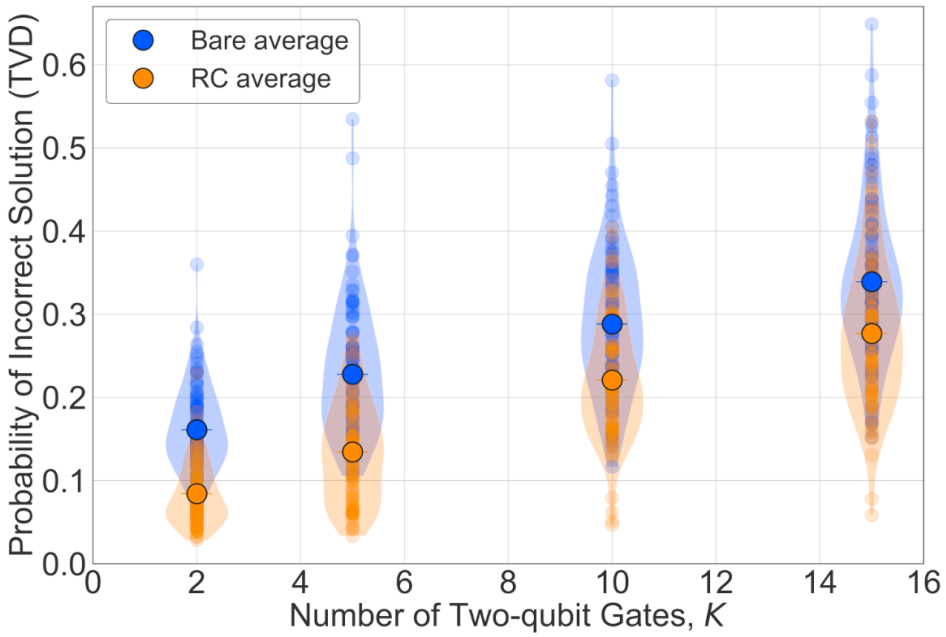


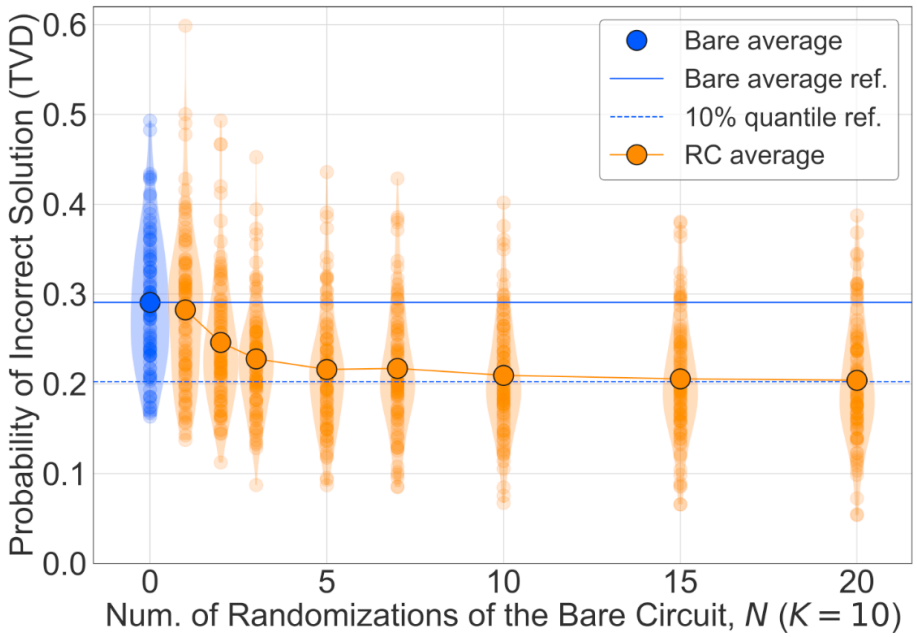




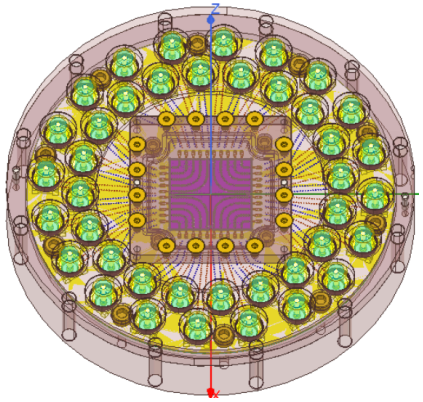
c

INCREASING CIRCUIT DEPTH

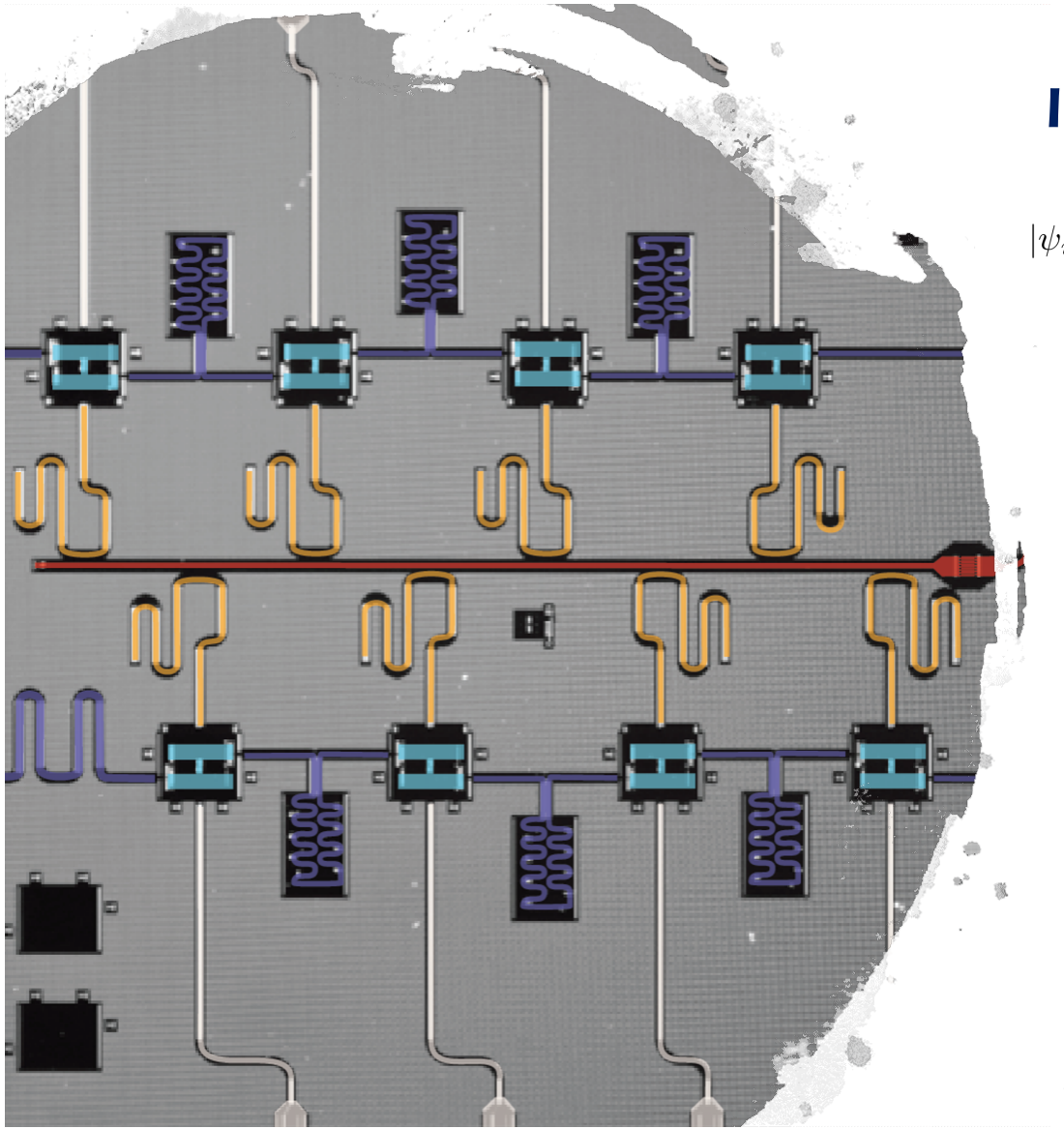




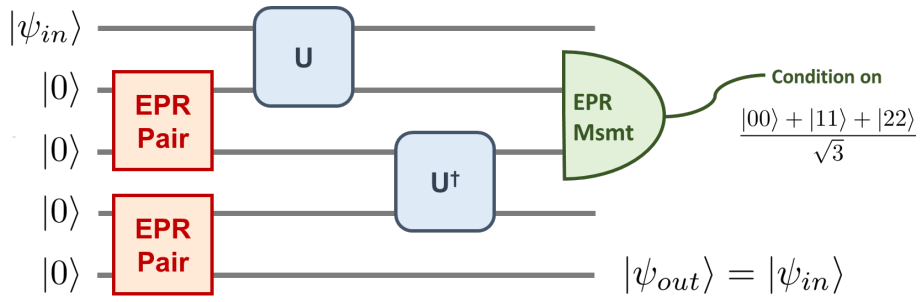
SOURCES OF UNWANTED FLUCTUATIONS



- CHIP SCALE COHERENCE — CYROPACKAGE
- CLASSICAL CROSSTALK: E-M DESIGN — CHIP
- QUANTUM CROSSTALK: QUBIT COUPLING — QUBIT
- ERROR MITIGATION: RANDOMIZED COMPILING — COMPILATION
- ERROR MITIGATION: FLOQUET STYLE GATES — ALGORITHM



INFORMATION SCRAMBLING



Qutrit EPR pair:
$\mathcal{N}(|00\rangle + |11\rangle + |22\rangle)$

Scrambling unitary:
U |i , j⟩ = |2i + j , i + j⟩

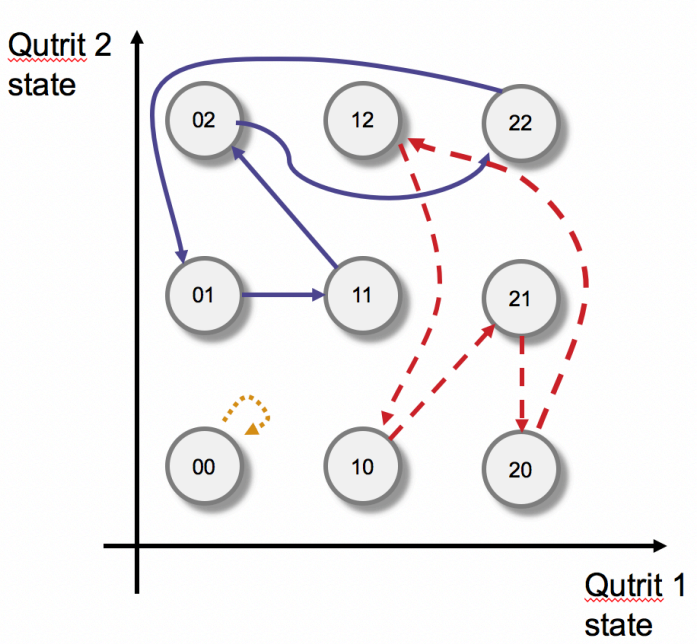
Goals:

- Realize quantum ternary logic
- Realize scrambling operator (U)
- Demonstrate teleportation is a probe

DECOMPOSING A SCRAMBLER: PERMUTING QUANTUM INFO

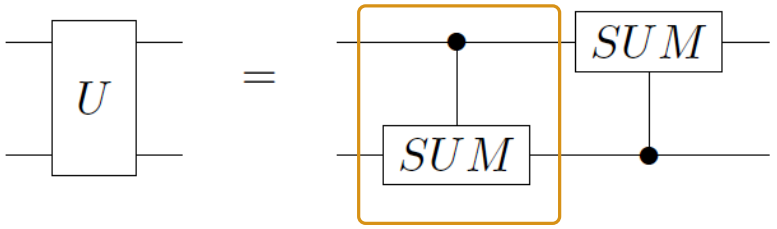
Scrambling Unitary U

$$U_{scrambler}\,|i,j\rangle \;=\; |2i+j,\,i+j\rangle$$



Decomposition of U:

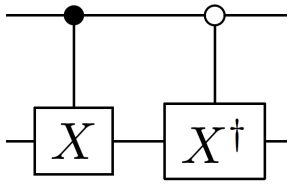
2 Conditional SUM (CSUM) gates



Conditional SUM (CSUM) Gate

Add state of qubit 1 to qubit 2

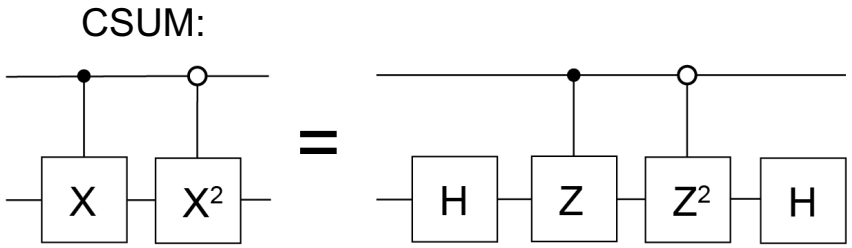
$$CSUM\,|i,j\rangle \;=\; |i,\,i+j\rangle$$



Decomposed into 3 Qutrit CNOT!

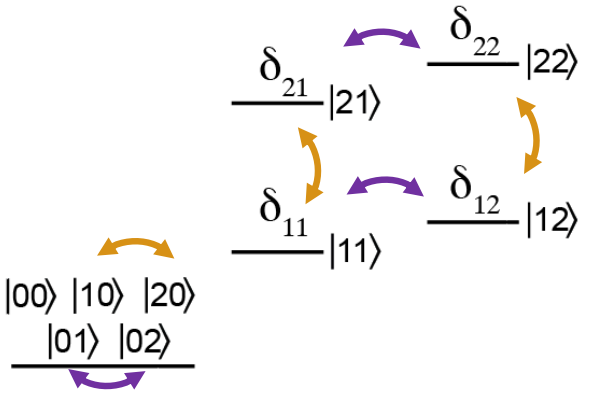
USING THE STATIC ZZ INTERACTION FOR SCRAMBLING

Insight 1:
CSUM is locally equivalent to a diagonal (ZZ) gate



If we can imprint correct phases -> CSUM !
(remember $U_{scrambler}$) takes 2 CSUM gates

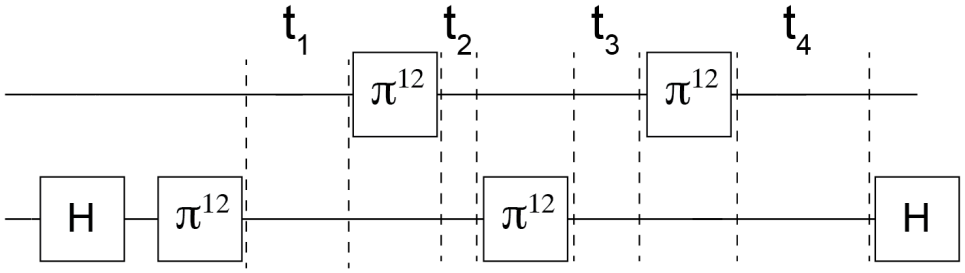
Insight 2:
Local gates 'permute' phase acquired by eigenstates



Wait times + permutations -> arbitrary phases

CSUM
by pi pulses and wait

Parameters by solving
linear set of equations



Total time:

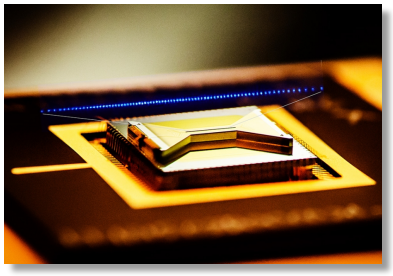
CSUM = 0.8 μs
Scrambler = 1.6 μs

QUANTUM SYSTEMS ACCELERATOR

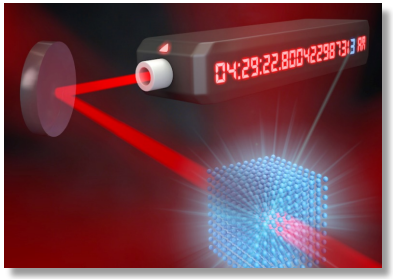
Catalyzing the Quantum Ecosystem

Completing the Quantum Co-Design Cycle

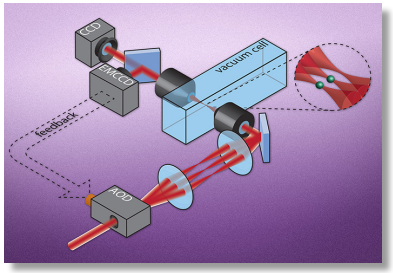
Trapped Ions



Atomic Tweezers



Rydberg Simulators



Superconducting Circuits