Title: Advances in controlling superconducting qubits for quantum computing

Speakers: Stefan Filipp

Collection/Series: Waterloo-Munich Joint Workshop

Subject: Quantum Information

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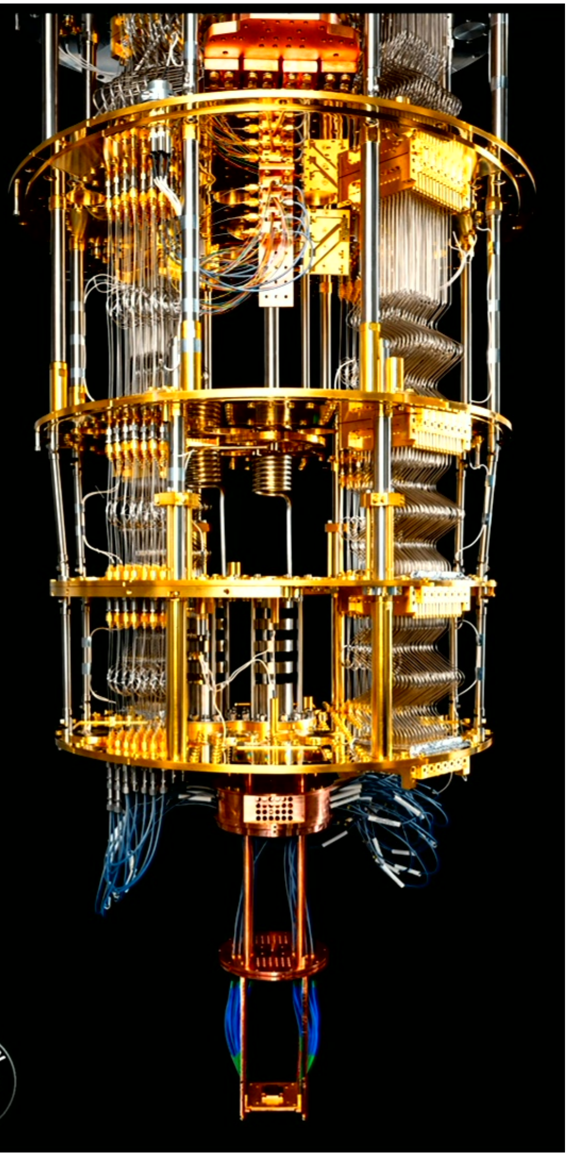
Walther-Meißner-Institut
DER BAYERISCHEN AKADEMIE DER WISSENSCHAFTEN

Advances in controlling superconducting qubits for quantum computing

Stefan Filipp
Walther-Meißner-Institute
Technical University of Munich

Munich-Waterloo Joint Workshop , Waterloo – Sept 30, 2024



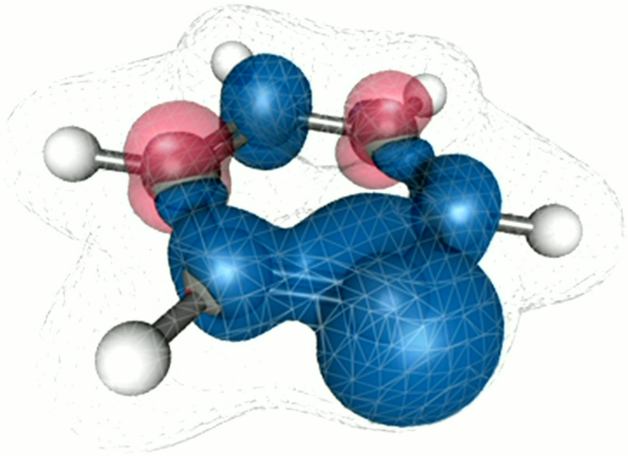
OpenSuperQPlus MCQST MOQS Molecular Quantum Simulations QUSTEC

DFG GeQCoS MUNIQC-SC Munich Quantum Valley

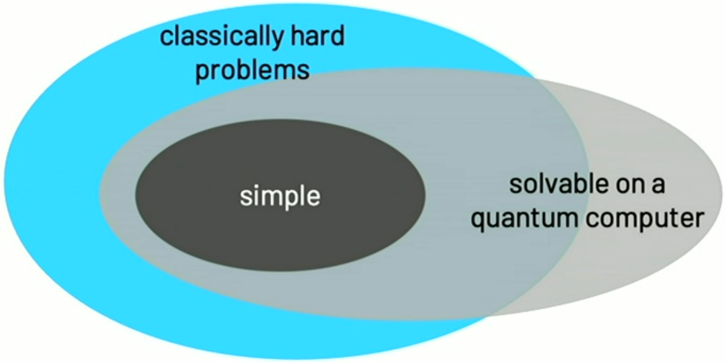
Quantum Computing to solve intractable problems

Many problems in science and business are too complex for classical computing systems!

Simulation of quantum-mechanical systems:
Chemistry, material science,...



Algebraic algorithms:
Machine learning, cryptography, ...



classically hard problems

simple

solvable on a quantum computer

Optimization problems:
Travelling salesman, logistics, portfolio optimization

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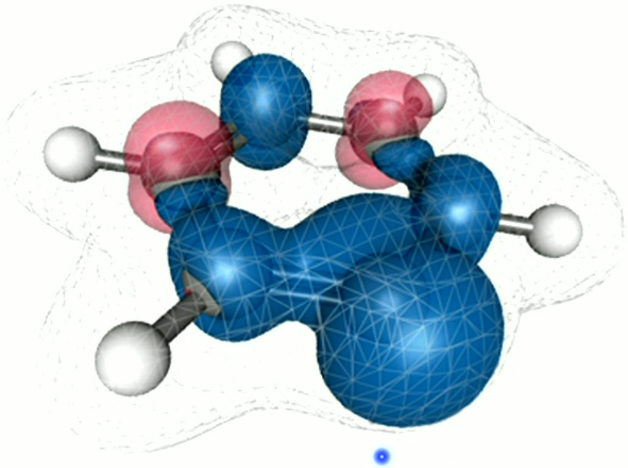
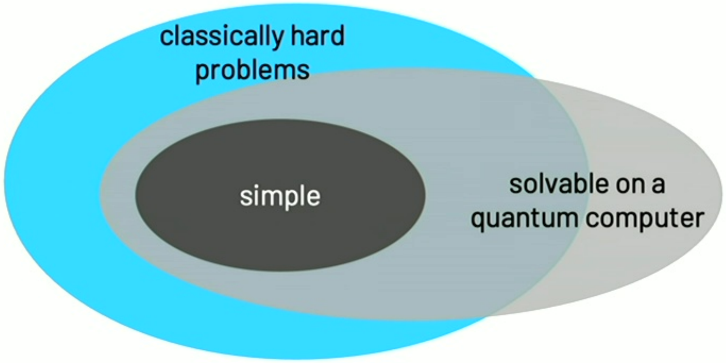




Challenge:

Realization of a quantum computer with many (1.000.000+) **good qubits** and **high-fidelity gate operations**

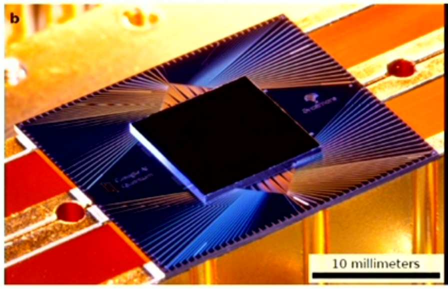
WMI

State of the art Quantum Computation

TUM

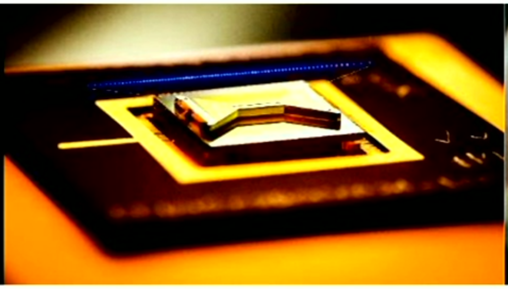
1st quantum computer prototypes are 'on the market' (>100 qubits)

Google AI



IBM

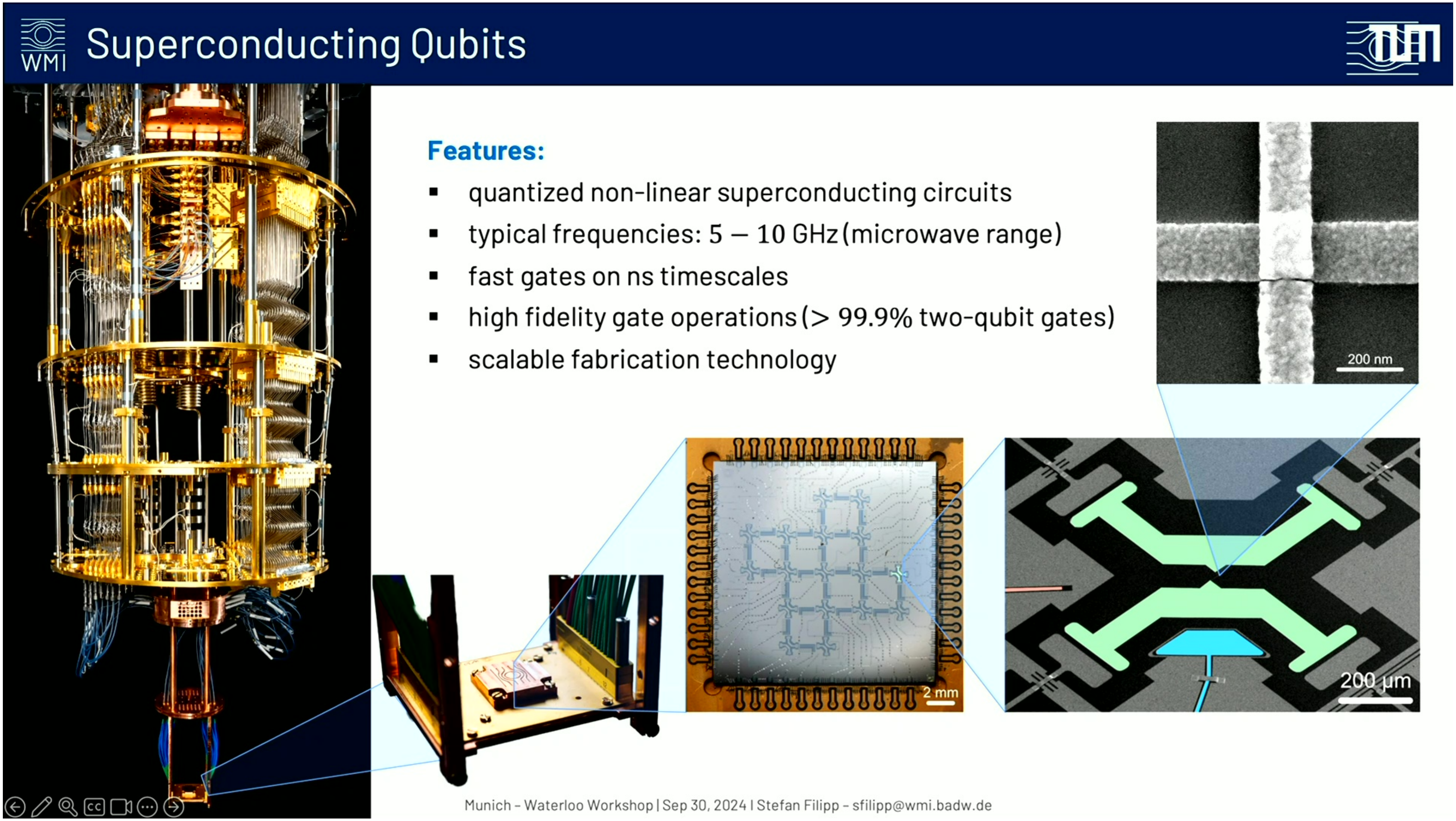
IonQ



AQT

or in development (OpenSuperQ GeQCoS MUNIQC-SC SOLID ...)
on different platforms (solid state systems, atomic systems, photons, ...)

→ next milestones: practical quantum algorithm, logical qubits
→ many challenges ahead (scaling, coherence, control & readout, system integration)



Superconducting Qubits

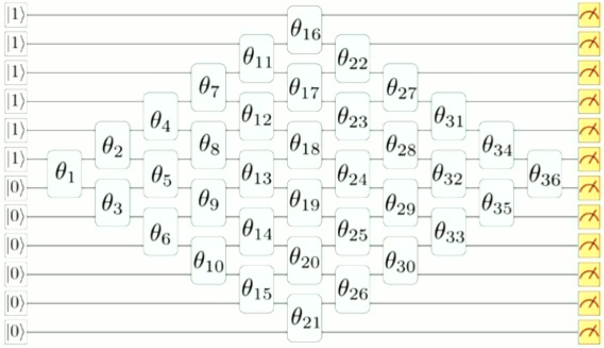
Features:

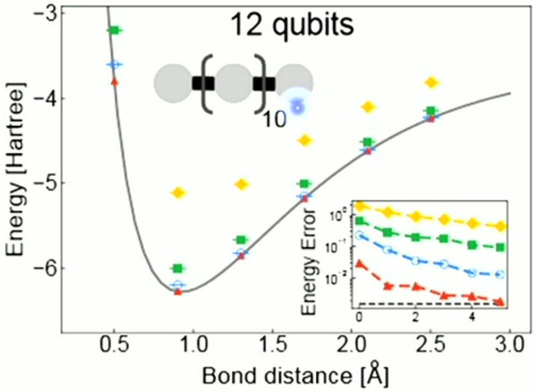
- quantized non-linear superconducting circuits
- typical frequencies: 5 – 10 GHz (microwave range)
- fast gates on ns timescales
- high fidelity gate operations (> 99.9% two-qubit gates)
- scalable fabrication technology

Munich – Waterloo Workshop | Sep 30, 2024 I Stefan Filipp – sfilipp@wmi.badw.de

NISQ applications

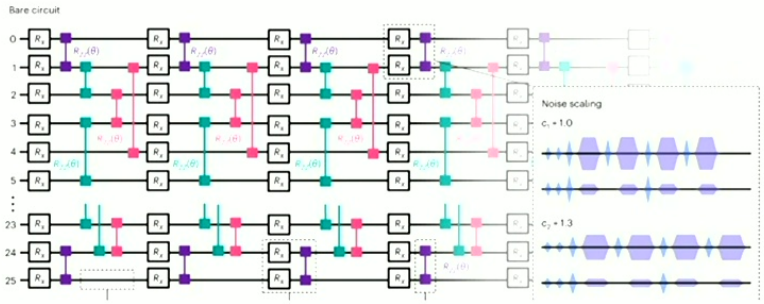
Quantum chemistry: calculate ground state of simple molecules (hydrogen chain)

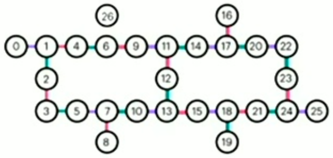


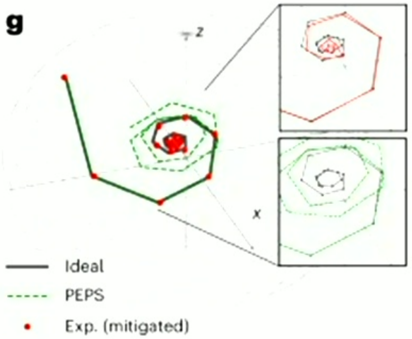


F. Arute, Science 369, 2020;
A. Kandala, Nature 549 (2017); Nature 567 (2019)]

Material science: dynamics of spin systems (with up to 127 qubits)







Y. Kim et al. (IBM), Nat. Phys 1 (2023); Nature (2023)

The Universal Quantum Computing System

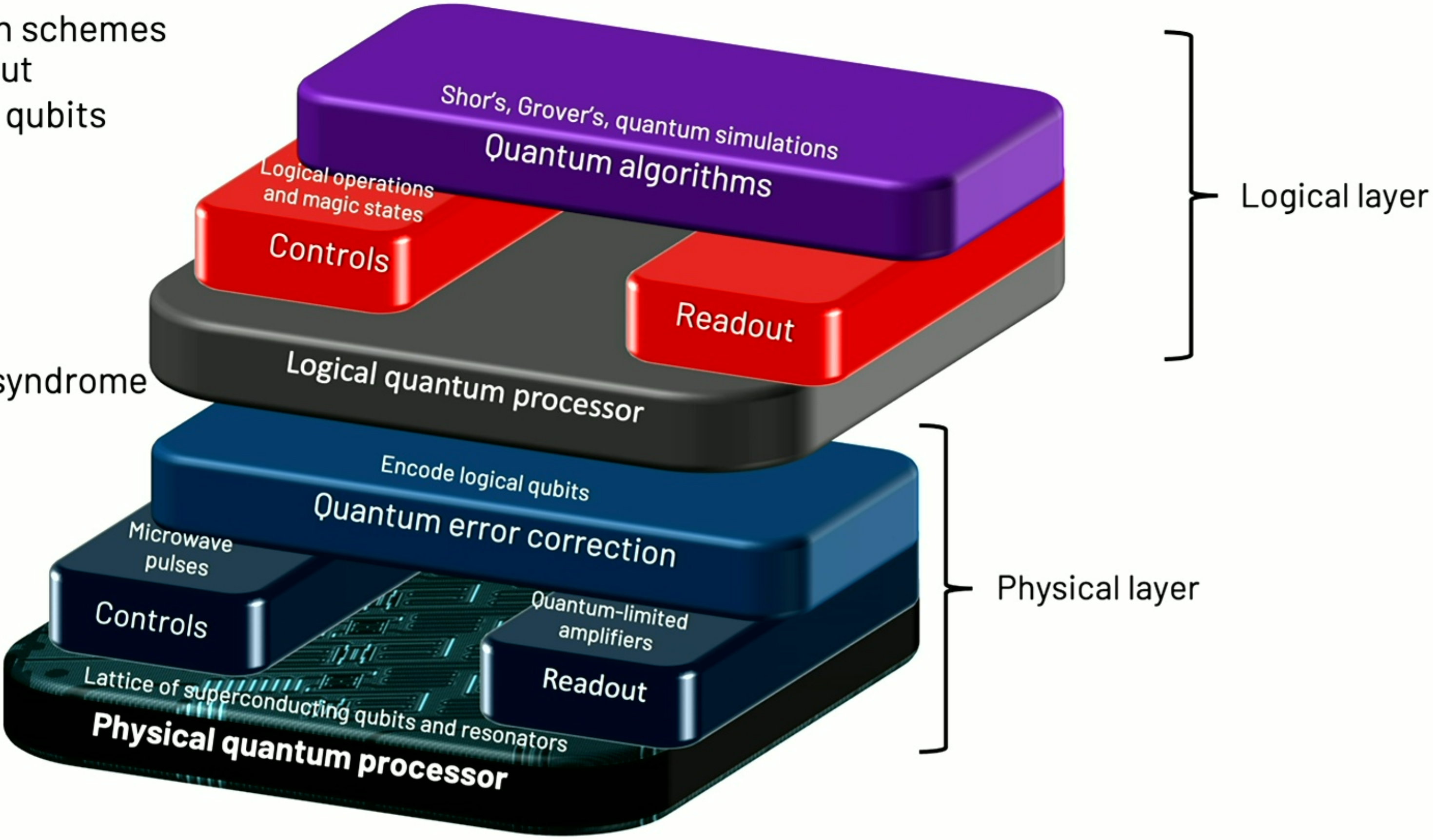
Idea: use error correction schemes to make a 'logical' qubit out of several 'good' physical qubits

$$|0\rangle \rightarrow |00\ldots0\rangle$$

$$|1\rangle \rightarrow |11\ldots1\rangle$$

100-1000 x

measure parity as error syndrome

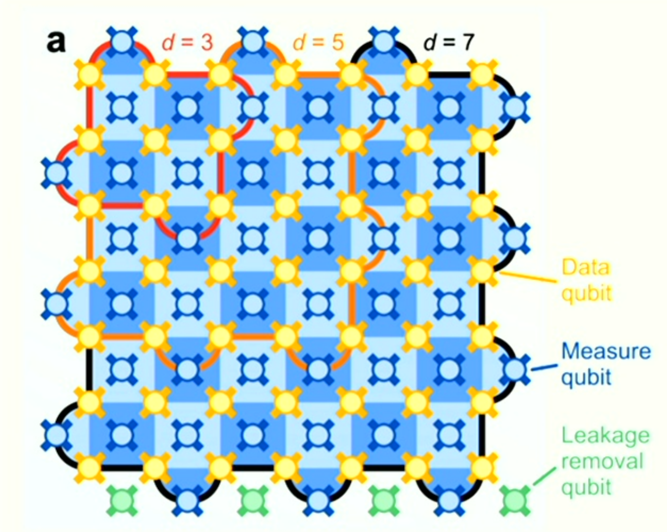


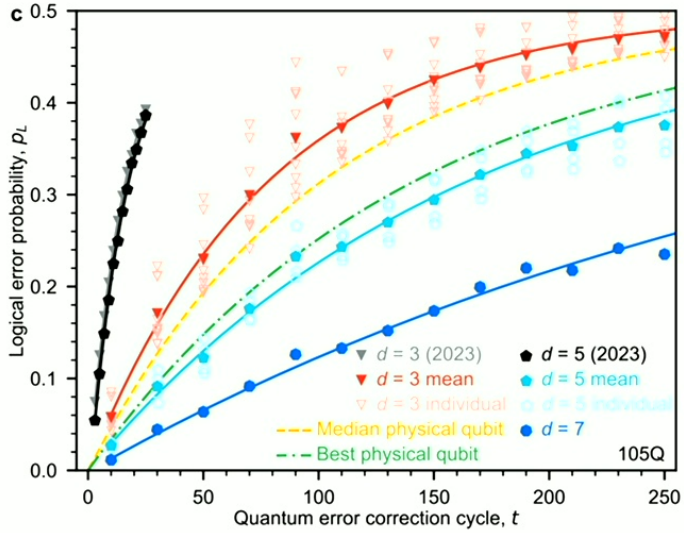
[Gambetta, Chow, Steffen, npj Quantum Information 3, 2 (2017)]

QEC – lowering logical error rates

Surface Code error threshold:

Logical error should decrease for increasing number of physical qubits per logical qubit





[R. Acharya et al., Nature (2023); Google AI, Nature (2024)]

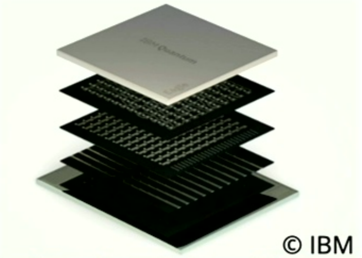
Challenges ahead (hardware centric)

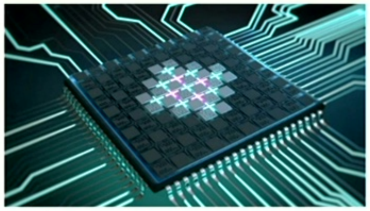
Scaling: *guarantee performance at scale*
cross-coupling and cross-talk, uniformity & reproducibility, scalable control, I/O, size of qubits, thermal budget

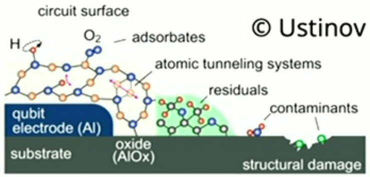
System: *guarantee stable operation conditions*
automated calibration & bring-up, run-time environment, characterization & verification, quantum/classical integration, (cryogenic) electronics,...

Coherence: maximize lifetime of quantum states
identification of loss channels and noise sources (two-level fluctuators, quasi-particles, B-field fluctuations), mitigation (by design, by choice of materials, by fabrication)

Control & readout: coherence-limited high-fidelity gates
pulse optimization, benchmarking sequences, multi-qubit operations & extended gate sets,...


© IBM





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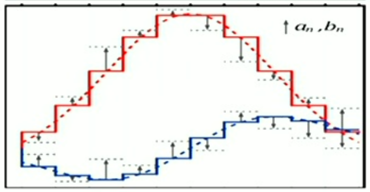
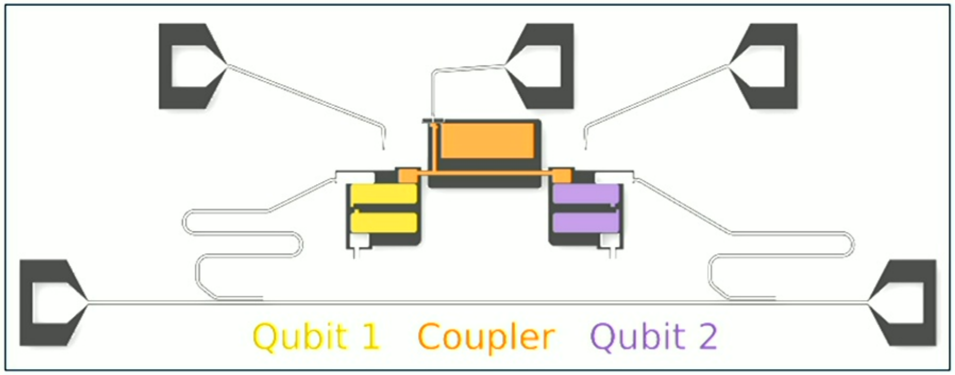


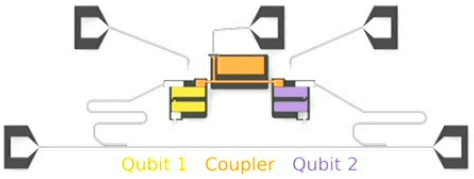
Two-qubit architecture

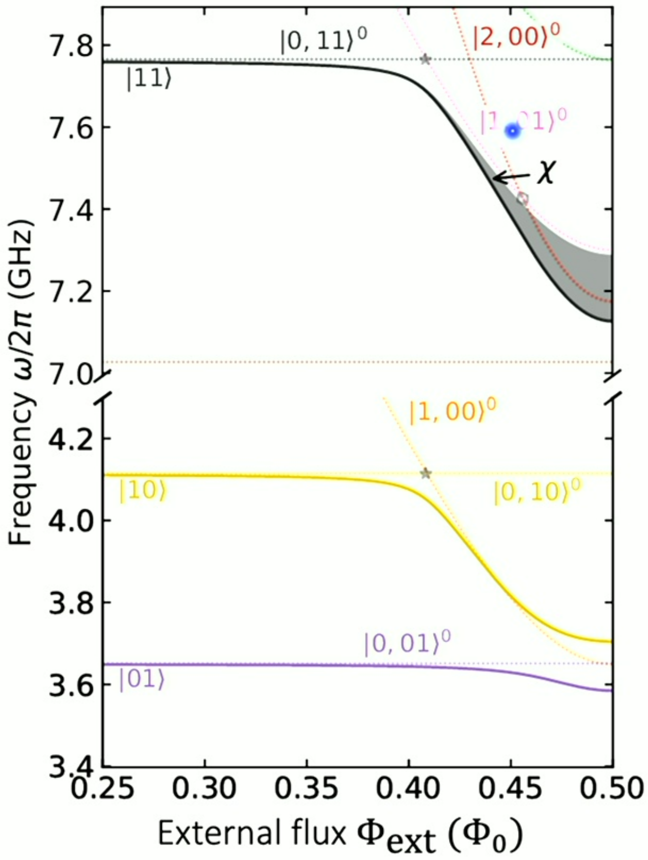


- **Fixed frequency** qubits with control via dedicated **drive lines**
- Two-qubit **CPHASE** gate by adiabatic flux control of **tunable coupler**

	Frequency ω	Anharmonicity α	T_1	T_2^{Echo}	T_2^*
Qubit 1	4.115 GHz	-261(1) MHz	52(4) μs	111(41) μs	23(4) μs
Qubit 2	3.651 GHz	-275(1) MHz	103(20) μs	54(11) μs	5.6(5) μs
Coupler	3.7 - 6.3 GHz	-124 (1) MHz	16(5) μs	–	–

Two-qubit controlled phase gate





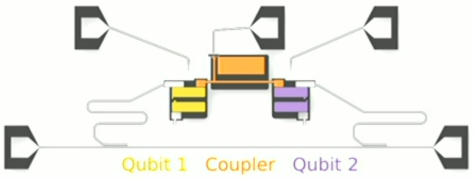
$$\chi = \omega_{11} - (\omega_{01} + \omega_{10})$$

adiabatic states: $|n_1 n_2\rangle$

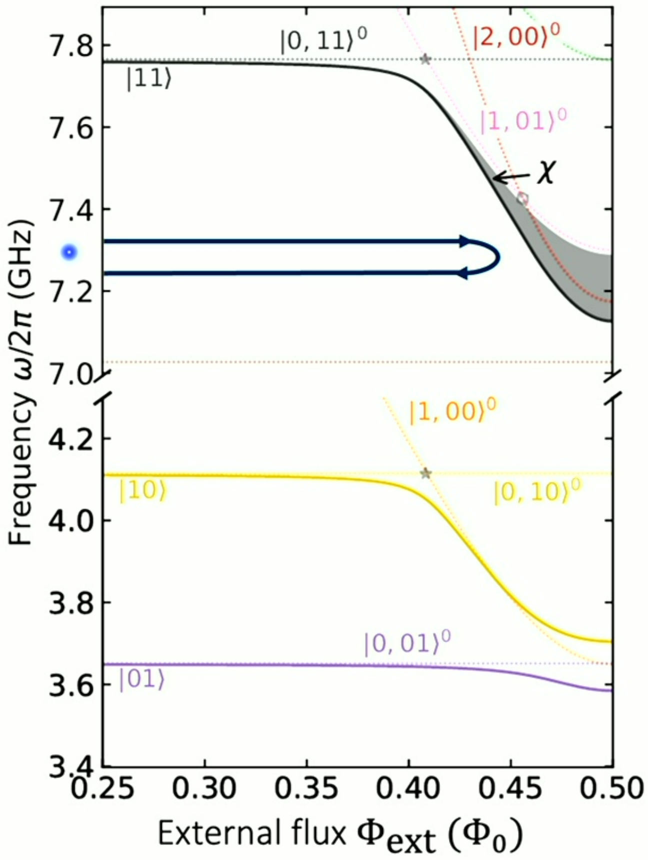
bare states: $|n_c, n_1 n_2\rangle^0$

[M. C. Collodo et al., Phys. Rev. Lett. 125, 240502 (2020)
Y. Xu et al., Phys. Rev. Lett. 125, 240503 (2020)
J. Chu & F. Yan, *Physical Review Applied*, *16*(5), 054020 (2021).
Stehlik, J. et al., Physical Review Letters, 127(8), 080505 (2021)]

Two-qubit controlled phase gate



$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\alpha} & 0 & 0 \\ 0 & 0 & e^{i\beta} & 0 \\ 0 & 0 & 0 & e^{i(\varphi+\alpha+\beta)} \end{pmatrix}$$



$$\chi = \omega_{11} - (\omega_{01} + \omega_{10})$$

$$\varphi = \int_0^{t_p} \chi\left(\Phi_{\text{ext}}(\tau)\right) \mathrm{d}\tau$$

adiabatic states: $|n_1 n_2\rangle$
bare states: $|n_c, n_1 n_2\rangle^0$

[M. C. Collodo et al., Phys. Rev. Lett. 125, 240502 (2020)
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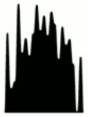
J. Chu & F. Yan, *Physical Review Applied*, *16*(5), 054020 (2021).
Stehlik, J. et al., Physical Review Letters, 127(8), 080505 (2021)]

Pulse parametrizations

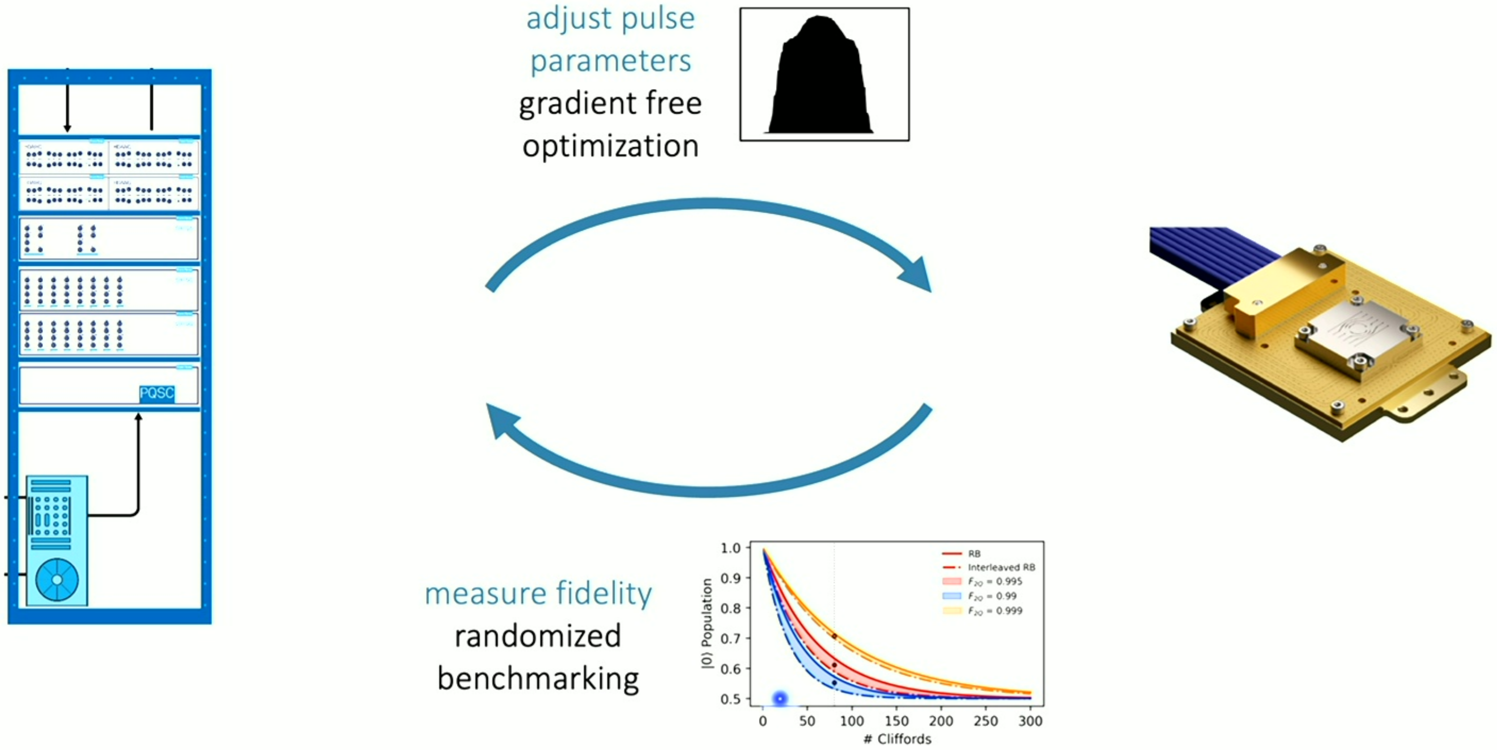
Different pulse shapes: optimize parameters for highest fidelity (numerical simulation)

	#Parameters	**Pulse shape**	t_p ($\mathcal{F} > 99.9\,\%$)
Gaussian-square	3		51 ns
Fourier Series	5		15 ns
Piecewise-constant Using AWG limitations	22		9 ns

Trade-off between parameter count and gate time / fidelity

C^3-toolset: N. Wittler, *et al.*, *Phys. Rev. Applied* **15**, 034080 (2021)

Optimal Control for high-fidelity pulses



adjust pulse parameters
gradient free optimization

measure fidelity
randomized benchmarking

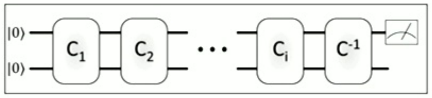
18.01.2024 Niklas.Glaser@wmi.badw.de

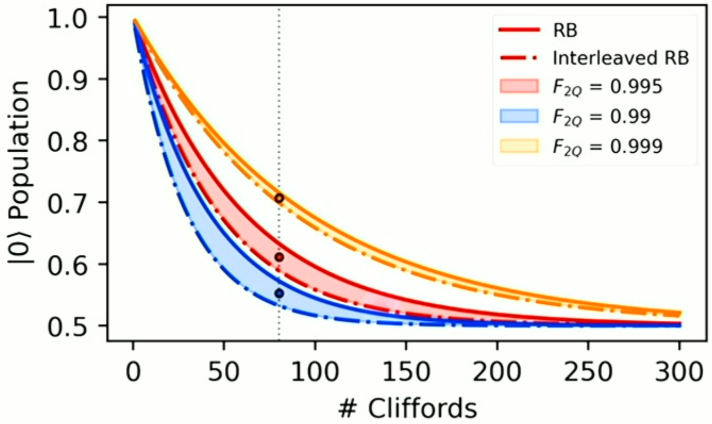
Experimental Optimization

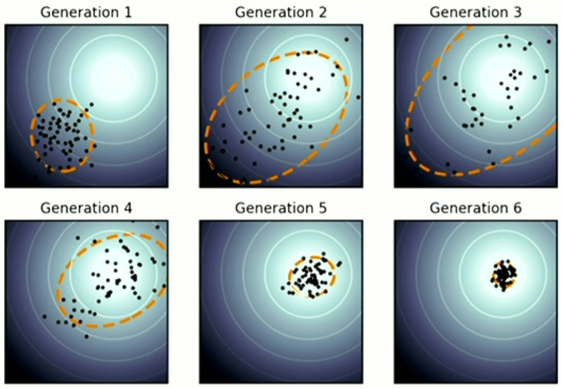
Cost function:
N random pseudo-identity clifford sequences of length M

Optimization:
CMA-ES Algorithm (Noise resilient, point-cloud-based evolutionary algorithm)

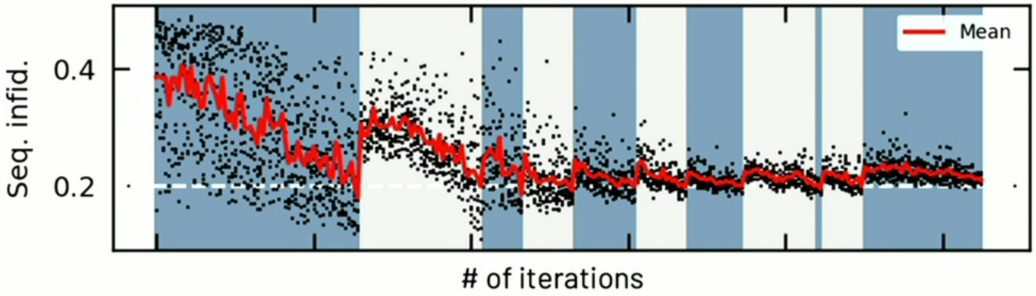
Sensitivity:
Gradually increment sequence length M for sensitivity improvement







Wikipedia: CMA-ES



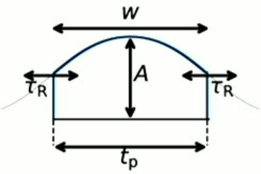
[Hansen N., arXiv:1604.00772 (2016); J. Kelly et al., Phys. Rev. Lett. 112, 240504 (2014); N. Glaser et al. In preparation (2024)]

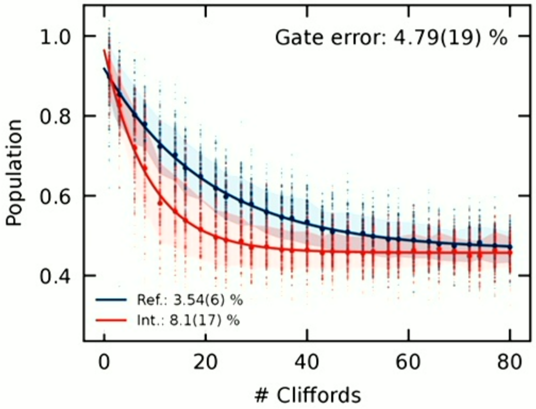
C-Phase gate pulse shapes

Gaussian Square

- 3x Shape parameters
- 2x Z-Rotation

Convergence:
40 evolutions (40 min)

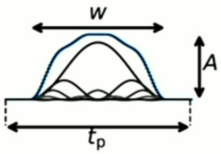


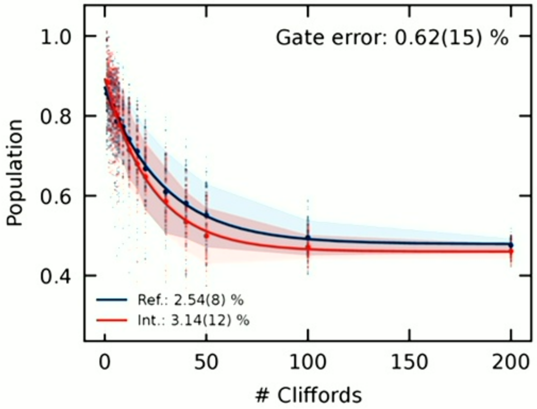


Fourier Series

- 5x Fourier parameter
- 1x Width
- 2x Z-Rotation

Convergence:
80 evolutions (80 min)

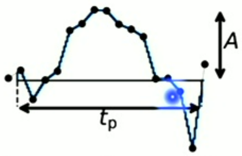


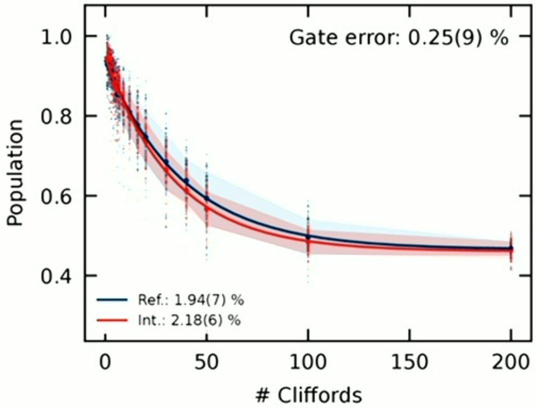


Linear Interpolation

- 17x Nodes
- 1x Amplitude, 1x Width
- 2x Z-Rotation

Convergence:
260 evolutions (250 min)





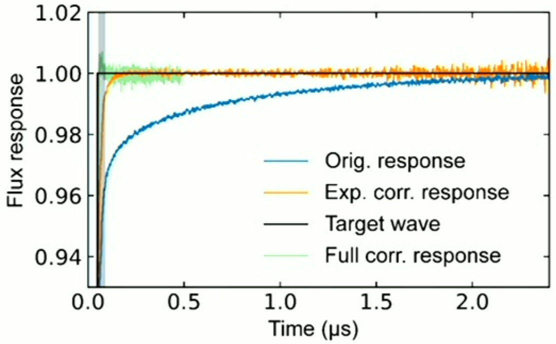
C-Phase gate correction for long-term drifts

Correct effect of long term flux distortions

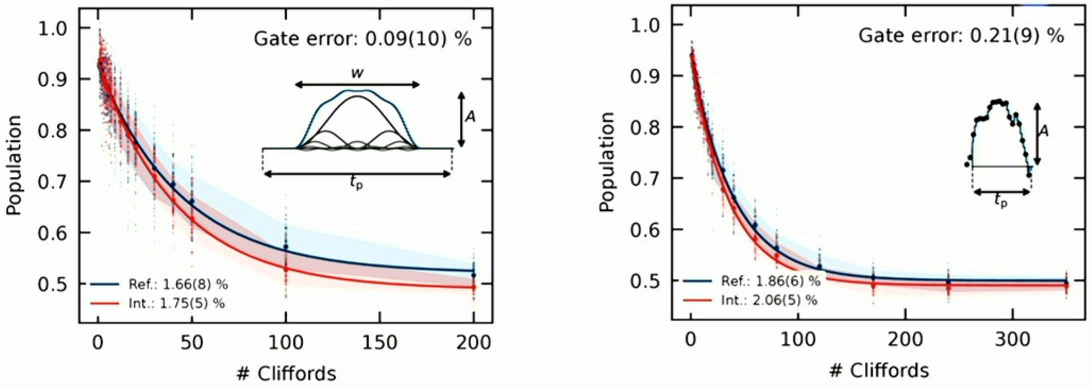
- cryoscope measurement
- correction with HDAWG real-time exponential filters + FIR filter

→ error for 60ns Fourier series reduced by a factor of six: $\epsilon = 0.09 \pm 0.1\%$

→ fast 20 ns gate with linear interpolation: $\epsilon = 0.21 \pm 0.09\%$



M. Rol et al., *Applied Physics Letters* 116.5 (2020).

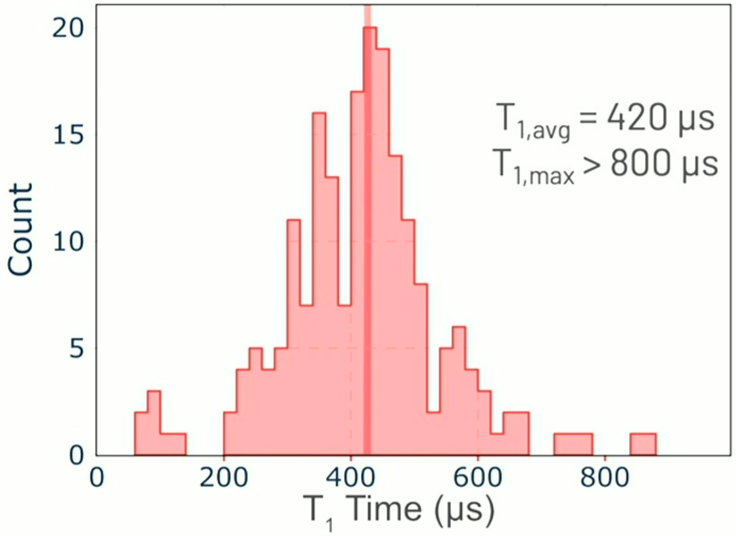


[N. Glaser et al., in preparation (2024)]

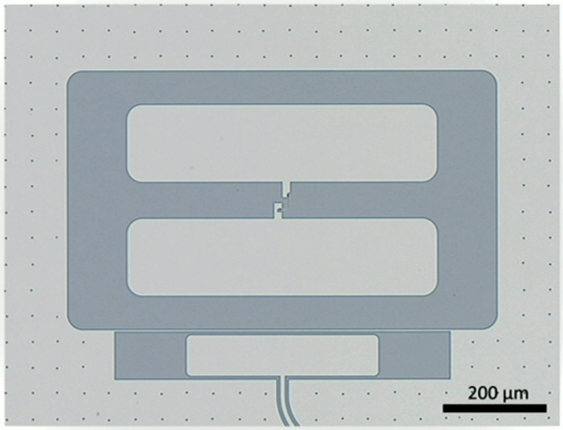
Qubit coherence

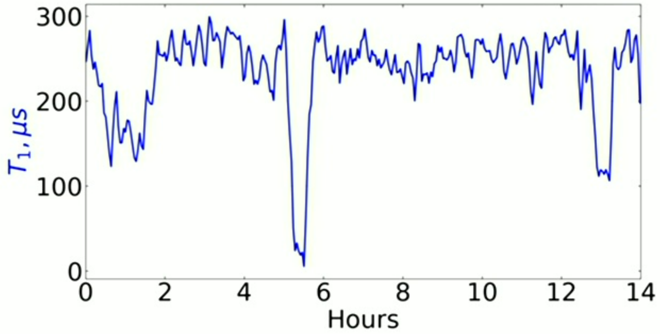
- Fixed-frequency single transmon qubits (frequency around 4.4 GHz
- Al/AlO$_x$/Al Josephson junctions with Niobium ground plane

[L. Koch, N. Bruckmoser, in preparation (2024)]



$\rightarrow T_{1,2}/T_{gate} > 10000$





→ fluctuating environment (TLSs)

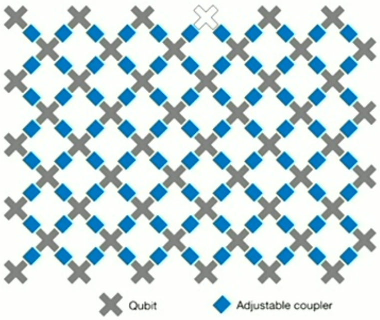
Simultaneous multi-qubit operations

Quantum processors increase in size

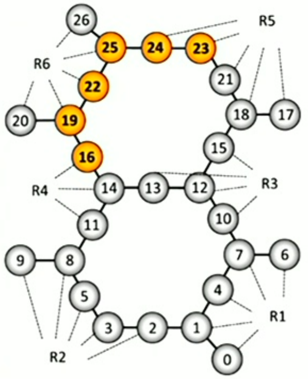
low connectivity and local operations lead to large gate overhead

control multiple local interactions simultaneously

Arute et al., Nature 574 (2019)



Petar et al., QS&T 6 (2021)



multi-qubit and non-local operations

Gu et al., PRX Quantum 2 (2021)
Burkhart et al., PRX Quantum 2 (2021)
Zhang et al., PRL 128 (2022)
Warren et al., arXiv 2207.02938 (2022)

Glaser et al., PR Applied 19 (2023)
Kim et al., Nature Physics 1 (2022)
Baker et al., Appl PL 120 (2022)
Lu et al., PRX Quantum 3 (2022)

efficient state transfer along chains

Christandl et al., PRL 92 (2004)
Li et al., PRApplied 10 (2018)
Genest et al., Annals of Physics 371 (2016)
Lemay et al., JPA 49 (2016)
Nägele et al., PR Research 4 (2022)

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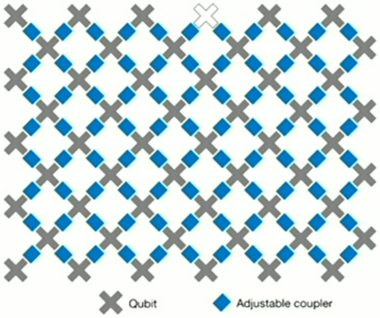

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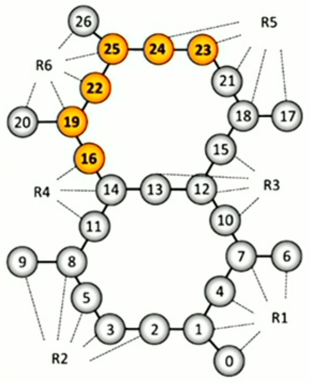

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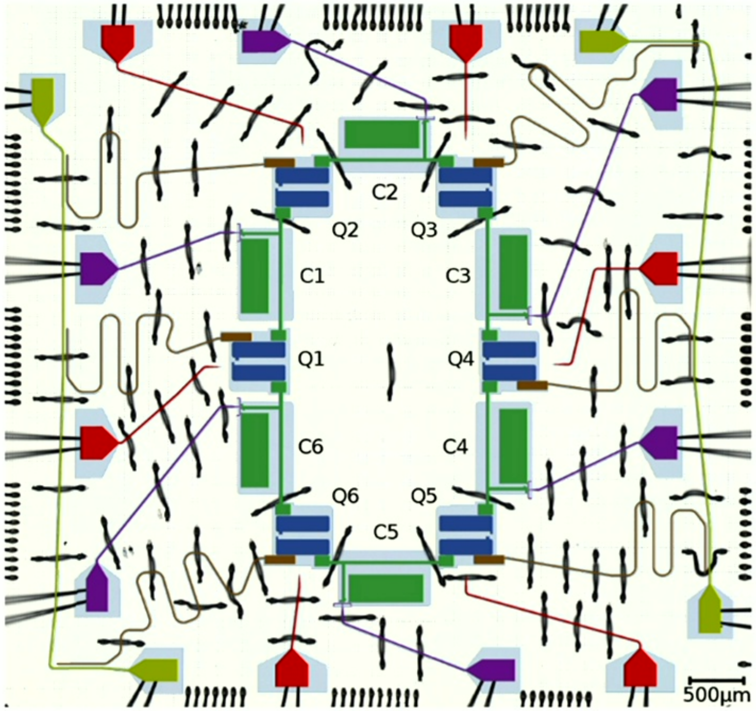
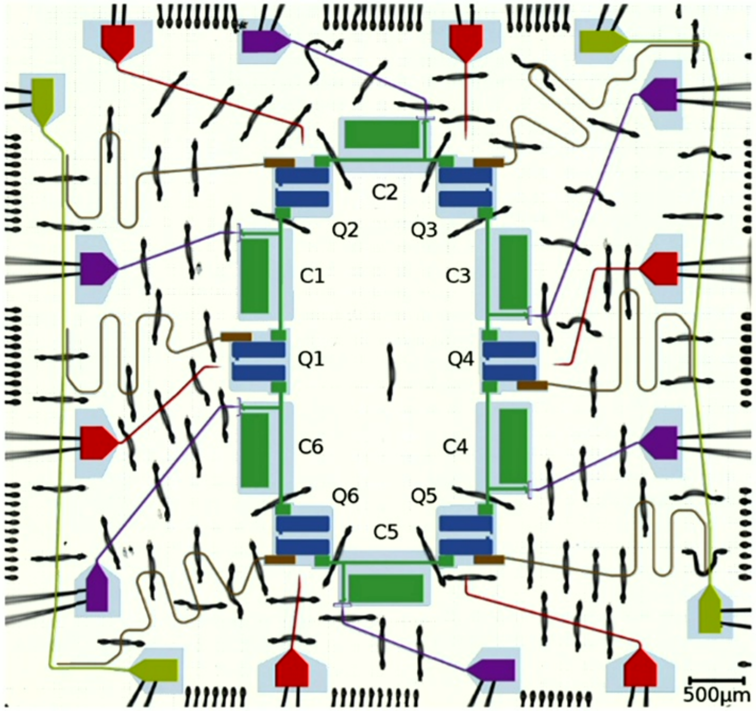
Nägele et al., PR Research 4 (2022)

6-qubit ring



- 6 fixed-frequency **transmons**, individual **drive lines**.
- 6 **resonators**, 2 **feedlines**.
- 6 **tunable-couplers**, individual **flux lines**.

6-qubit ring



- 6 fixed-frequency **transmons**, individual **drive lines**.
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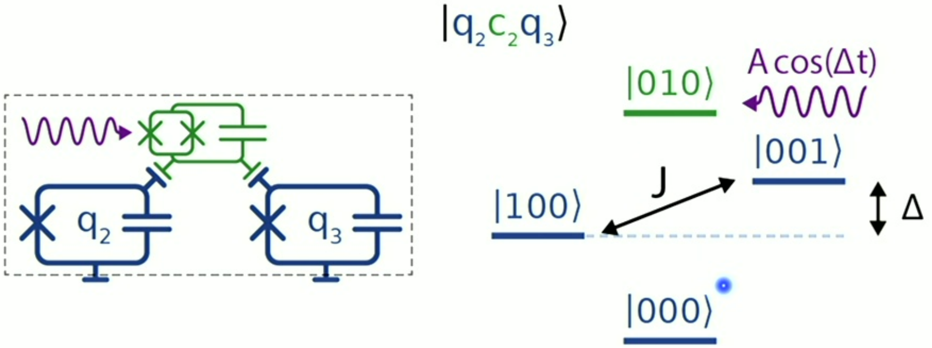
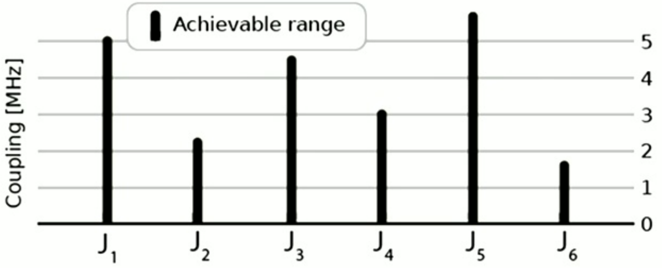
Two-qubit interactions by **parametric drive** of the coupler.



coupling strength **J** is controllable via amplitude **A**.



Perfect state transfer (PST) of single excitations

Spin chain Hamiltonian

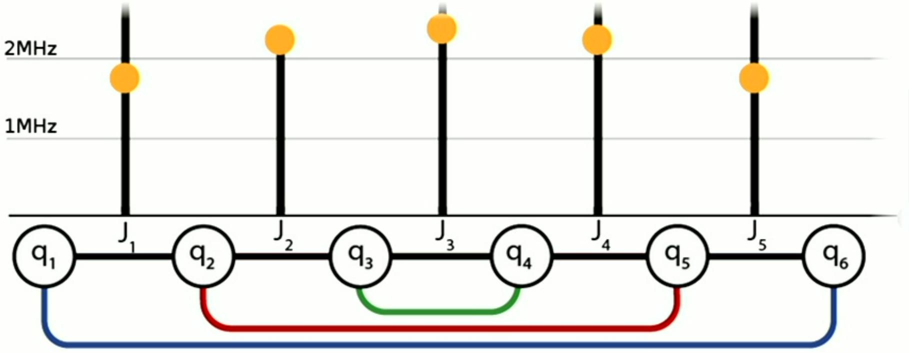
$$H_{\text{chain}} = \sum_{n=1}^{N-1} J_n(\hat{\sigma}_n^- \hat{\sigma}_{n+1}^+ + \hat{\sigma}_n^+ \hat{\sigma}_{n+1}^-)$$

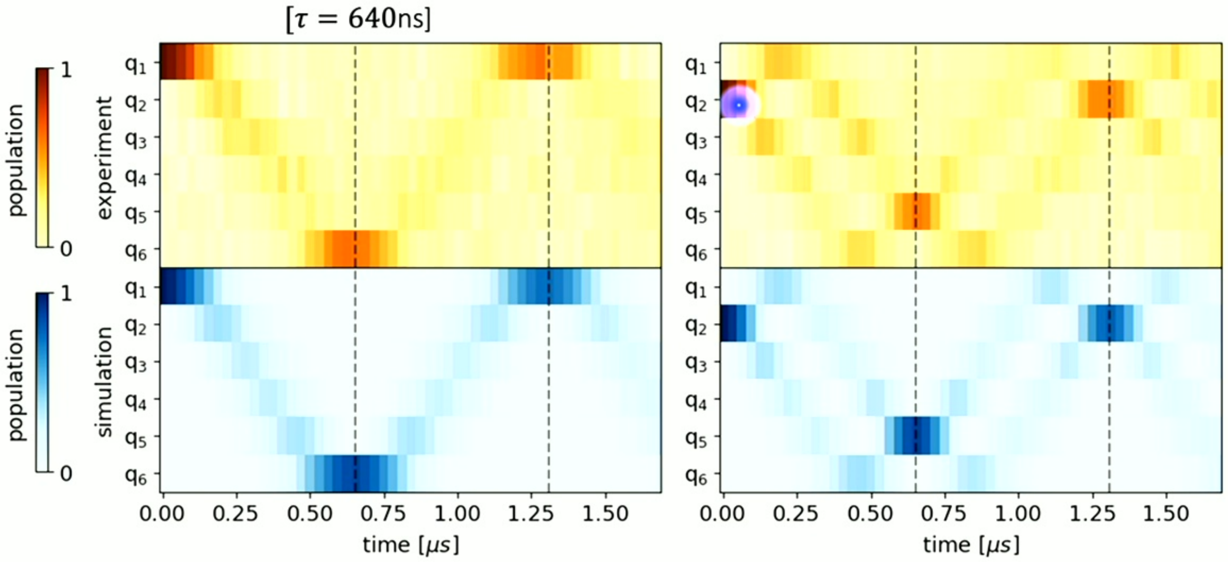
Given $J_n = \pi\sqrt{n(N-n)}/2\tau$

For a **transfer time** $\boldsymbol{\tau}$

$$H_{PST} = \sum_{n=1}^{\lfloor N/2 \rfloor} \frac{\pi}{2\tau}(\hat{\sigma}_n^- \hat{\sigma}_{N+1-n}^+ + \hat{\sigma}_n^+ \hat{\sigma}_{N+1-n}^-)$$

Effective PST Hamiltonian (single excitation)





Multiple excitations: parity-dependence

In the presence of multiple excitations:

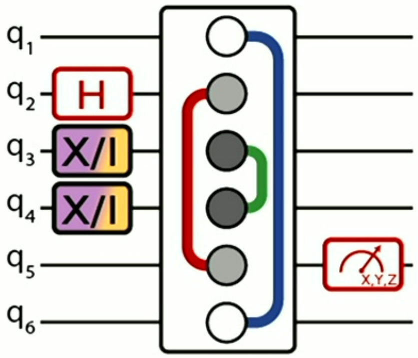
Effective PST Hamiltonian

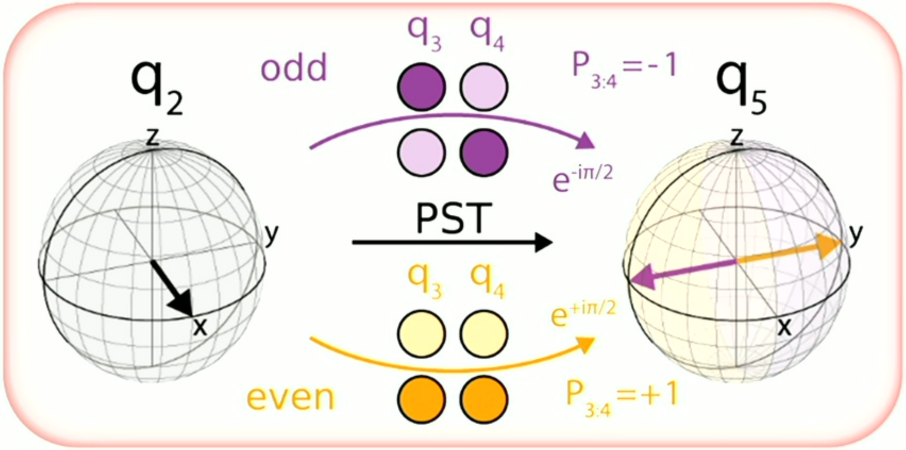
$$H_{PST} = \sum_{n=1}^{\lfloor N/2 \rfloor} \underbrace{\left(\prod_{k=n+1}^{N-n} \hat{\sigma}_k^z \right)}_{\hat{P}_{n+1;N-n}} \frac{\pi}{2\tau} \left(\hat{\sigma}_n^- \hat{\sigma}_{N+1-n}^+ + \hat{\sigma}_n^+ \hat{\sigma}_{N+1-n}^- \right)$$

Nägele et al., PRR 4 (2022)

Parity controls phase of transfer

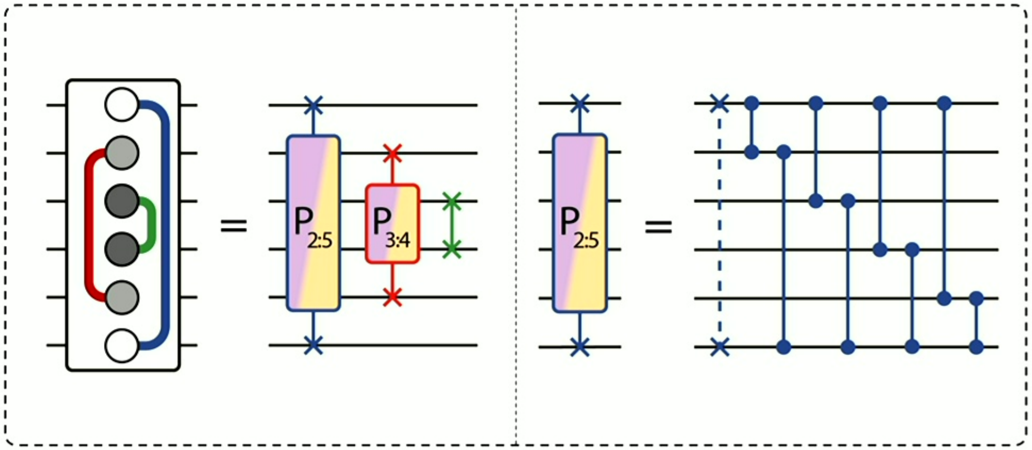
$$iSWAP_{\hat{P}_{3:4}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & \pm i & 0 \\ 0 & \pm i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



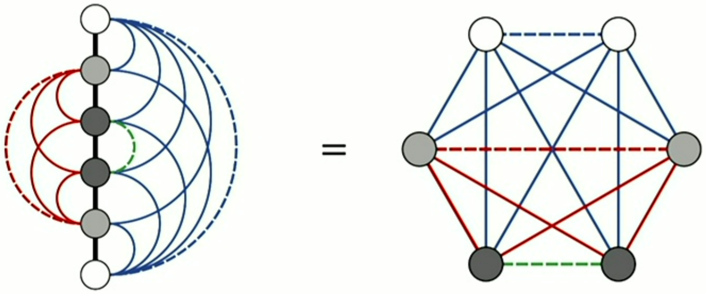


GHZ state preparation

PST's decomposition into 2-qubit gates:



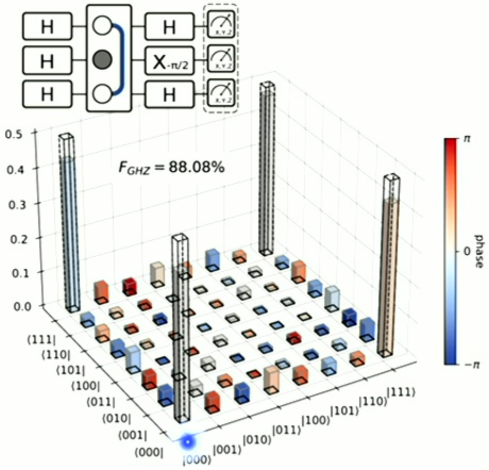
Graph states representation:



Qubits → nodes
Ising interactions → edges

GHZ-state preparation: based on single multi-qubit unitary transformation

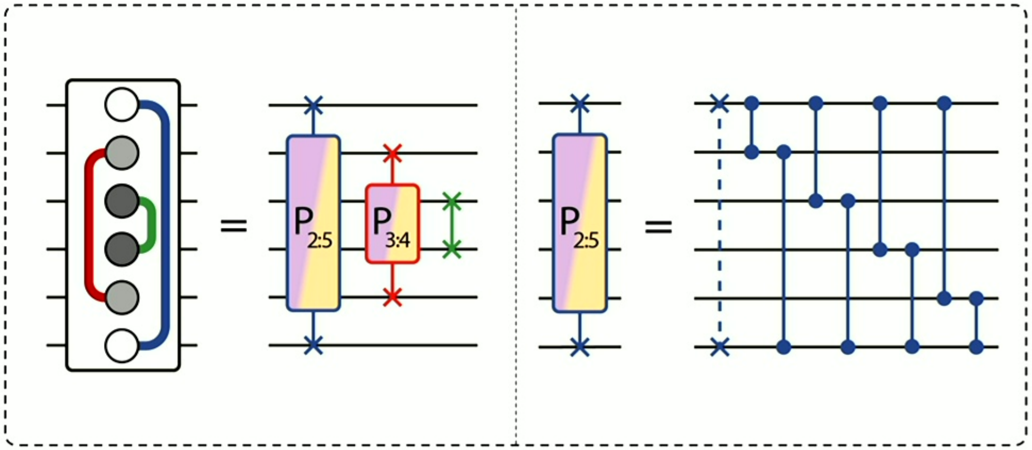
$$|GHZ\rangle = \frac{|0\rangle^{\otimes N} + |1\rangle^{\otimes N}}{\sqrt{2}}$$



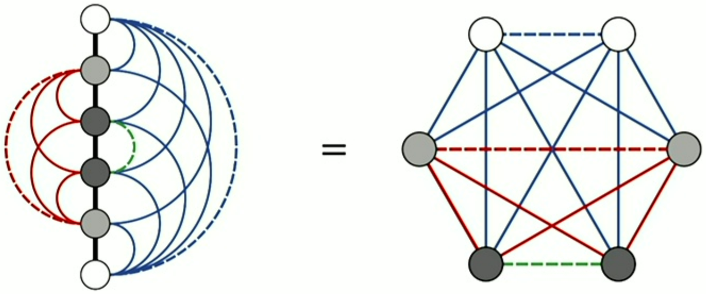
[F. Roy, J. Romeiro et al. arXiv:2405.19408 (2024)]

GHZ state preparation

PST's decomposition into 2-qubit gates:



Graph states representation:



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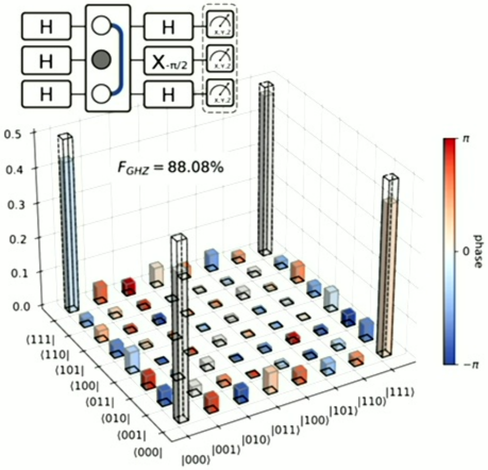


→ reduction of gate overhead, parity-check codes, quantum simulation of fermionic many-body systems, generation of different classes of graph states

[F. Roy, J. Romeiro et al. arXiv:2405.19408 (2024)]

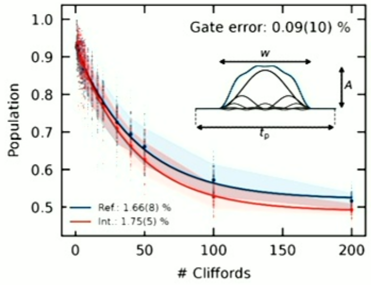
Summary & Outlook

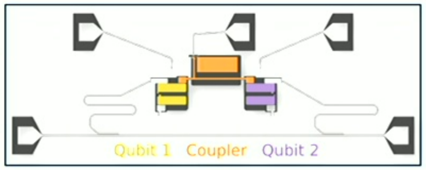
Entangling operations based on tunable couplers

High-fidelity two-qubit gates >99.9%

→ extension to full architecture

[N. Glaser et al. , in preparation (2024)]



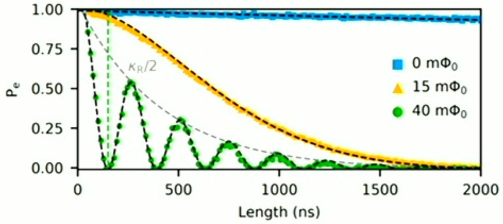


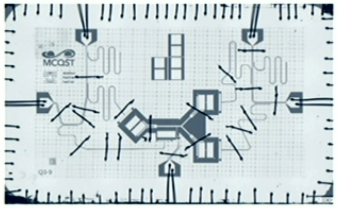
Architecture for reset, leakage reduction and tunable readout

→ multi-qubit couplers

→ extension to full architecture

[G. Huber et al, arXiv:2403.02203 (2023)]





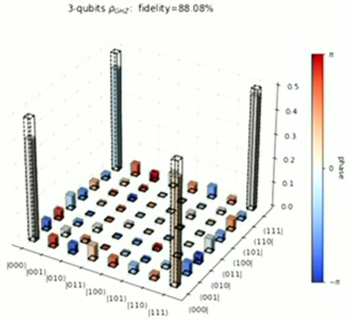
State transfer and multi-qubit entanglement generation

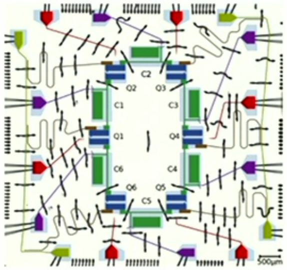
fractional state transfer and entanglement generation demonstrated

→ extended gate set, multi-qubit gates

→ simulation of fermionic systems, parity measurements

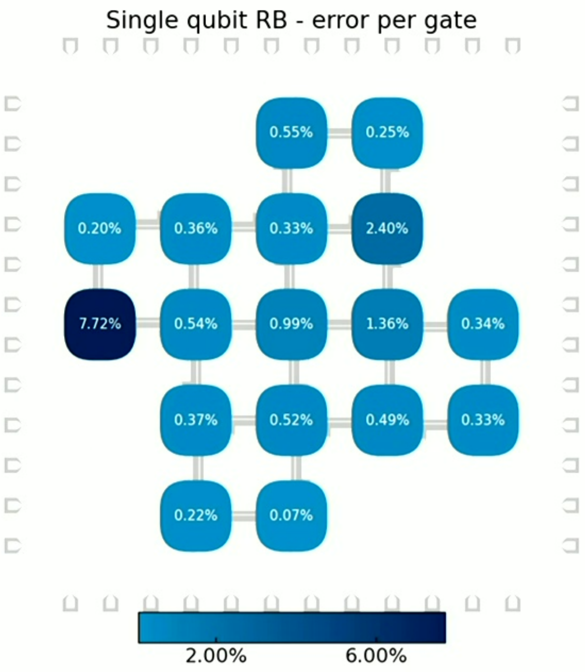
[M. Nägele et al., PRR (2022) F. Roy, J. Romeiro et al., arXiv:2405.19408 (2024)]

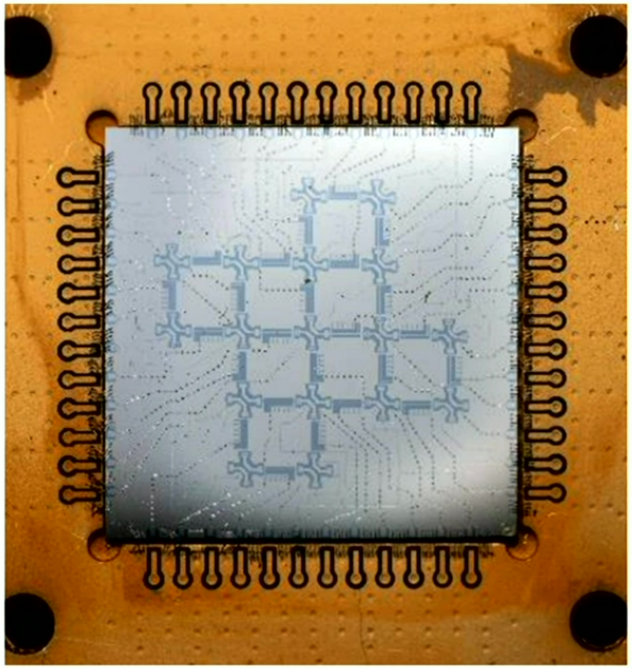


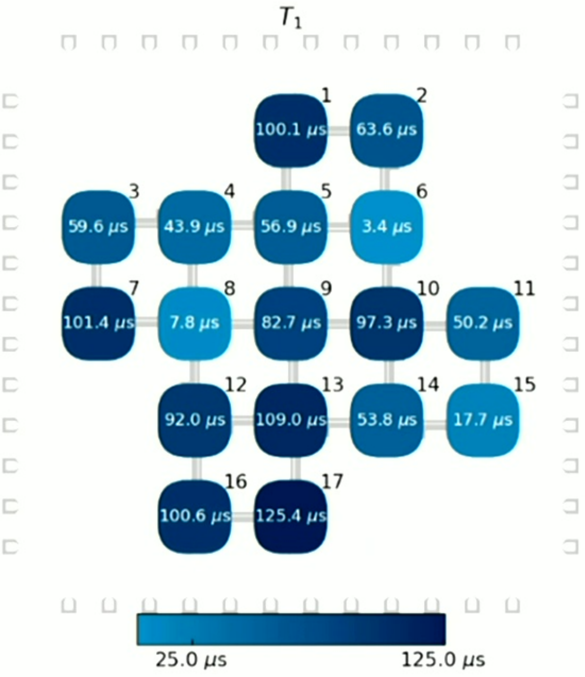


Outlook: a new playground with 17 qubits

Operation of a 17 qubit processor (transmon-based)


Single qubit RB - error per gate

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Munich Quantum Valley

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BAYERN

MCQST

QUSTEC

MOQS Molecular Quantum Simulations

BMW

DFG Deutsche Forschungsgemeinschaft

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