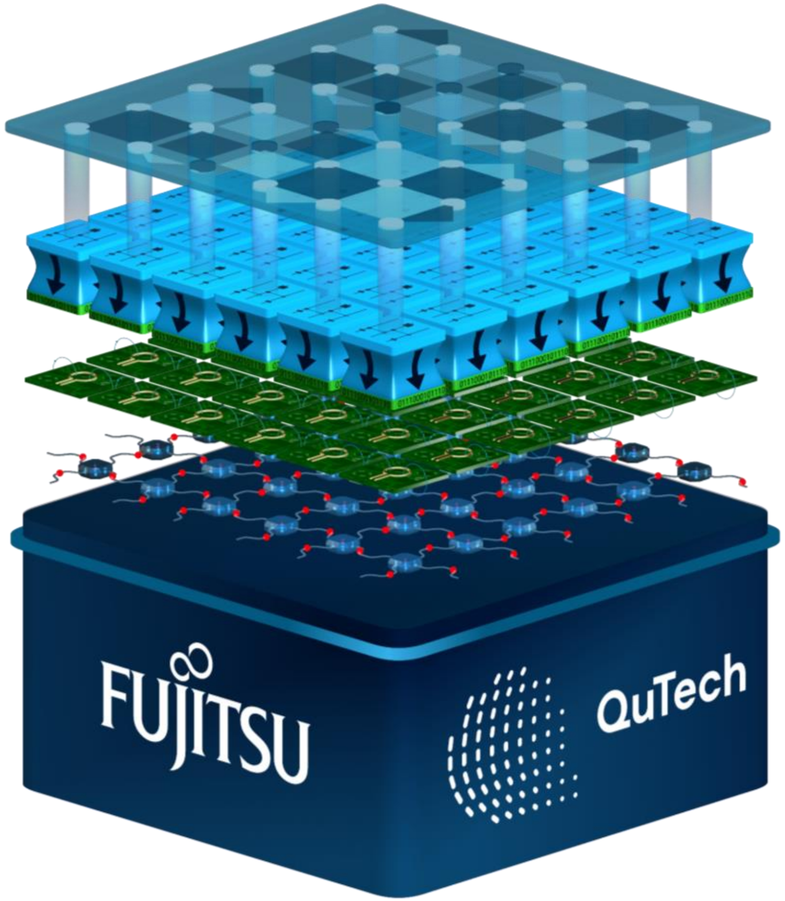
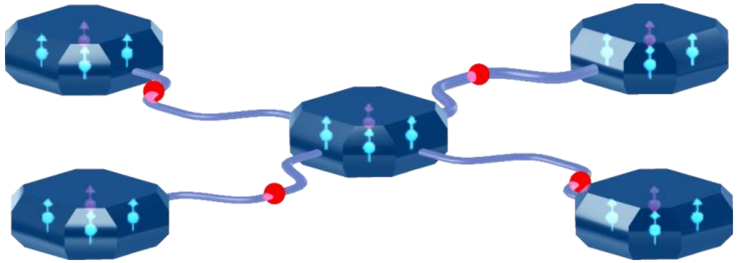
Towards modular quantum computation with spin qubits in diamond

Tim Hugo Taminiau and Ryoichi Ishihara, QuTech, Delft University of Technology





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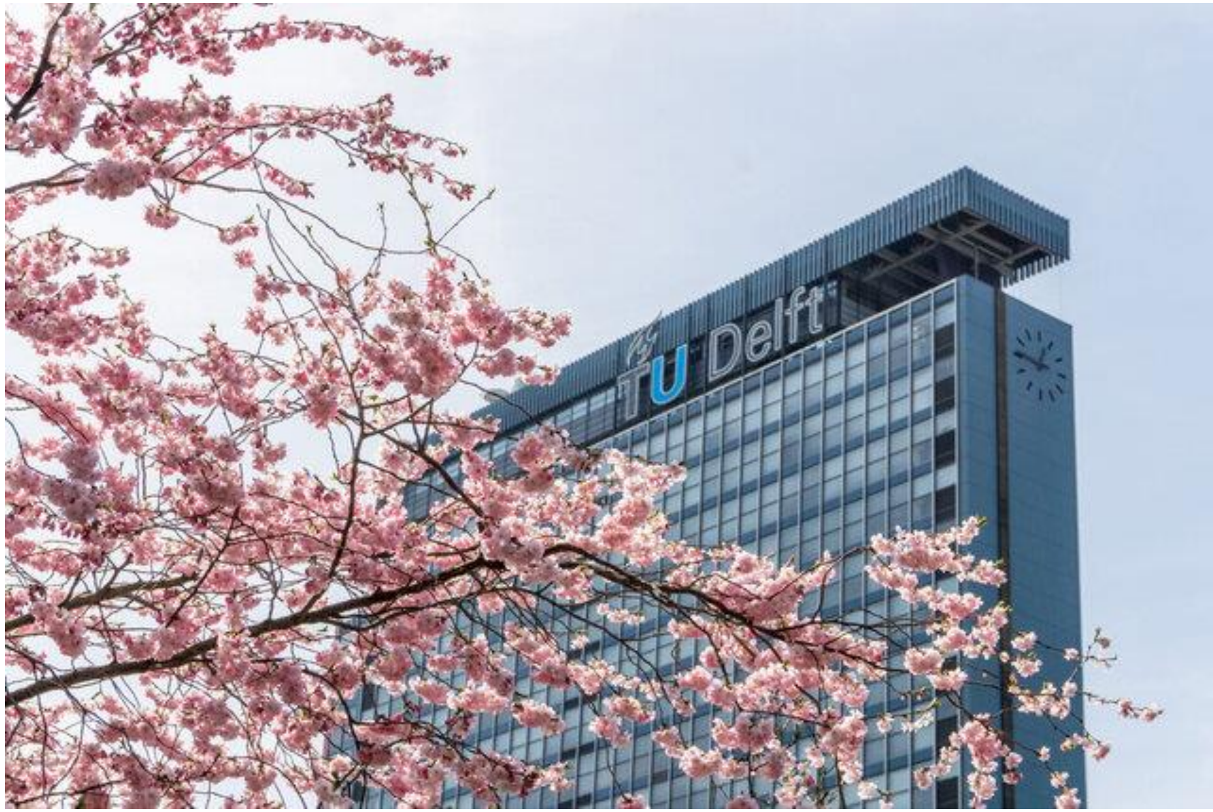
Spring at the TU Delft



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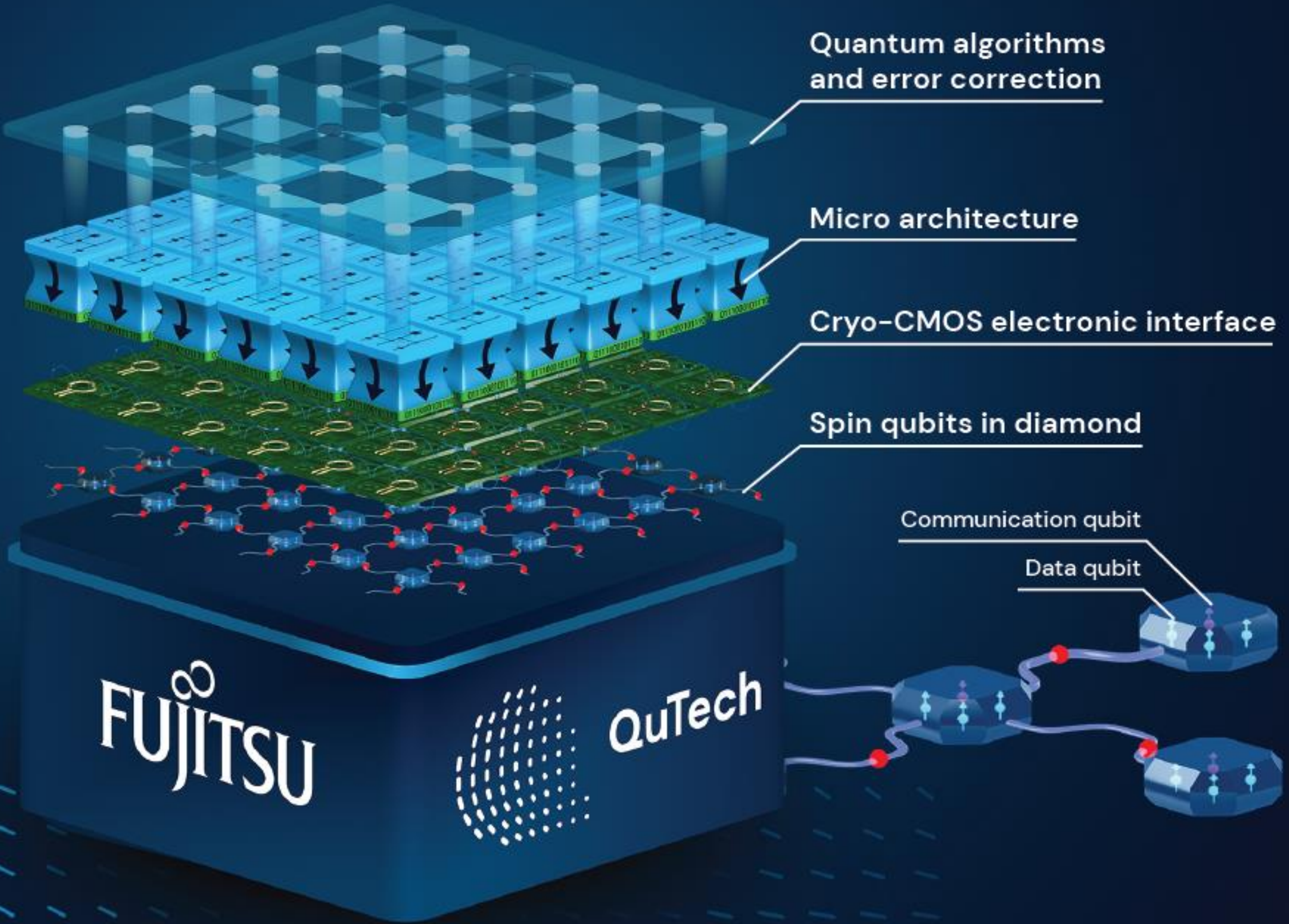
A blueprint for a scalable quantum computer

A full-stack approach

Fujitsu and QuTech are working together to realize a complete blueprint for a scalable quantum computer based on optically linked spin qubits in diamond. This includes proof of principle demonstrations of the key building blocks.

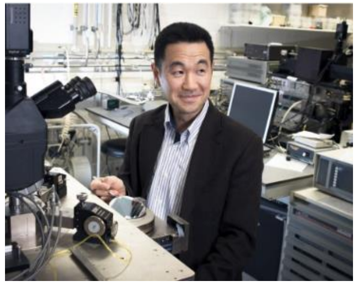


Team at QuTech, TU Delft


Fabio Sebastiano


Masoud Babaie


Stephan Wong

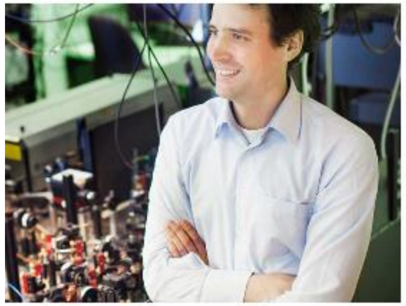

Ryoichi Ishihara


Carlos Errando-Herranz


Salahudin Nur


Ronald Hanson


Slava Dobrovitski


Tim Taminiau


David Elkouss


Erwin van Zwet


Karindra Perrier

TNO

+ approximately 35 students, postdocs and engineers

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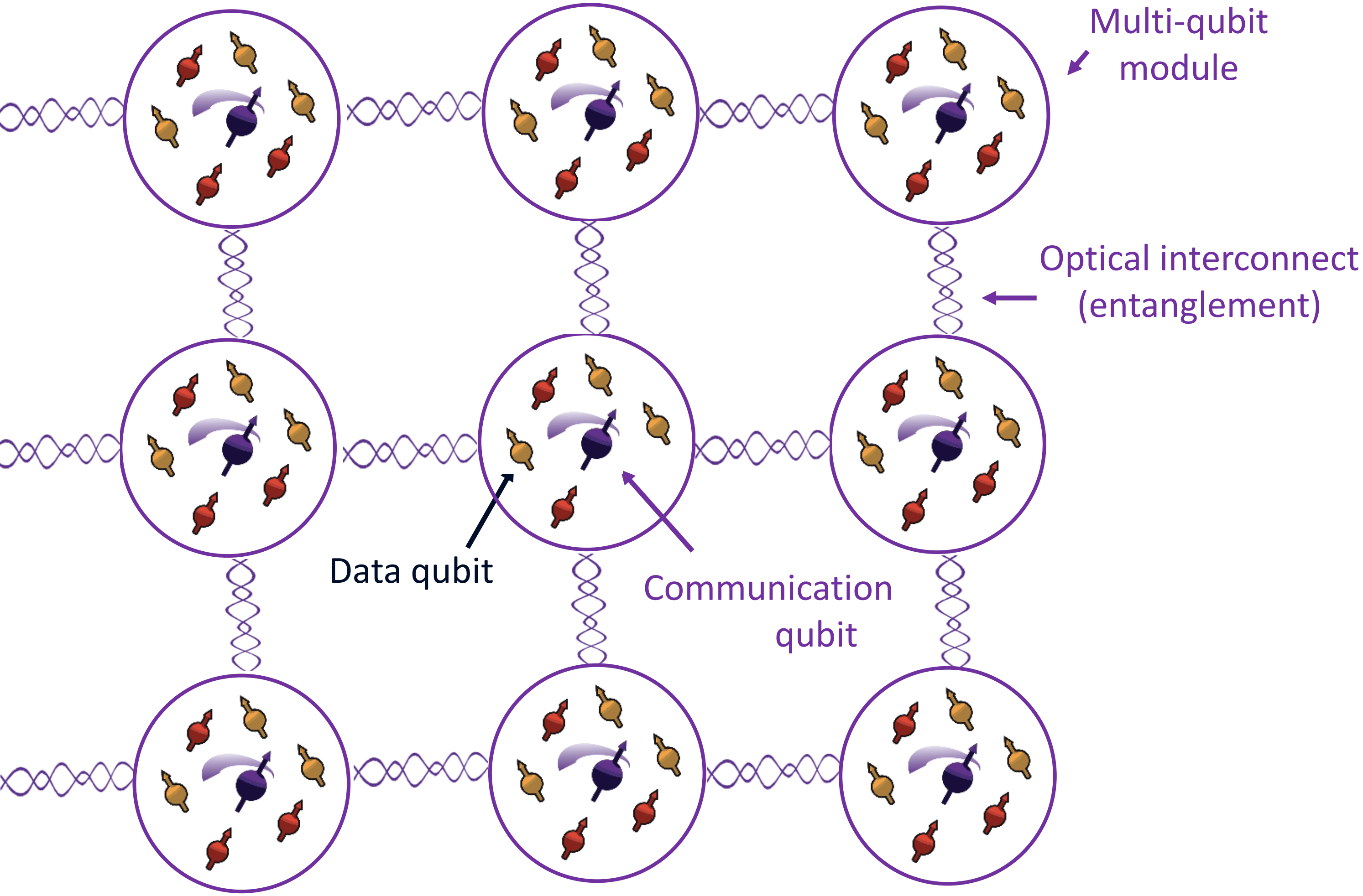
TUDelft

Towards modular quantum computation



1. Scalability through modularity
2. Optimisation on the level of modules. Control over crosstalk and crowding.
3. High-connectivity enables many quantum error correction codes (e.g. qLDPC codes)

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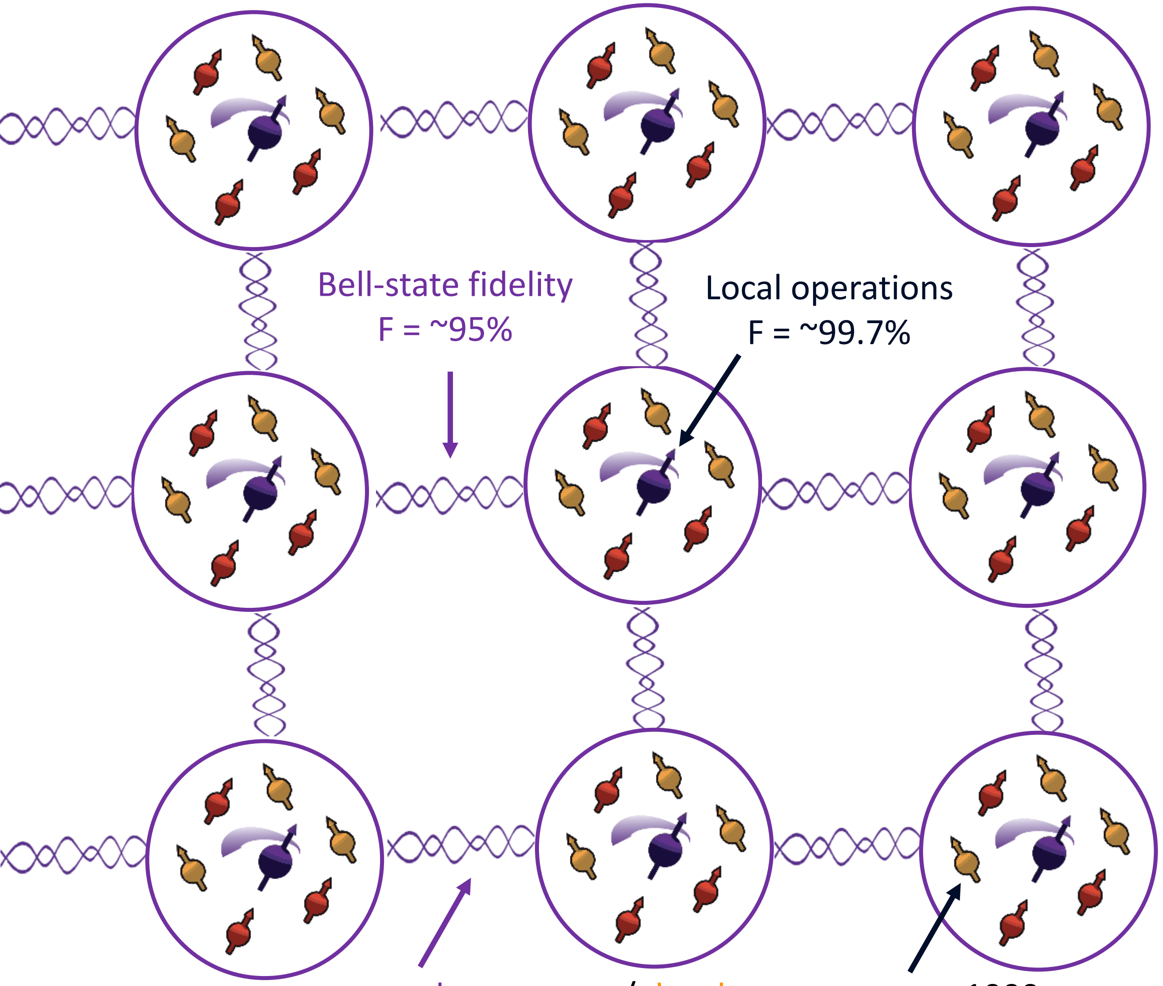
Fault-tolerant thresholds



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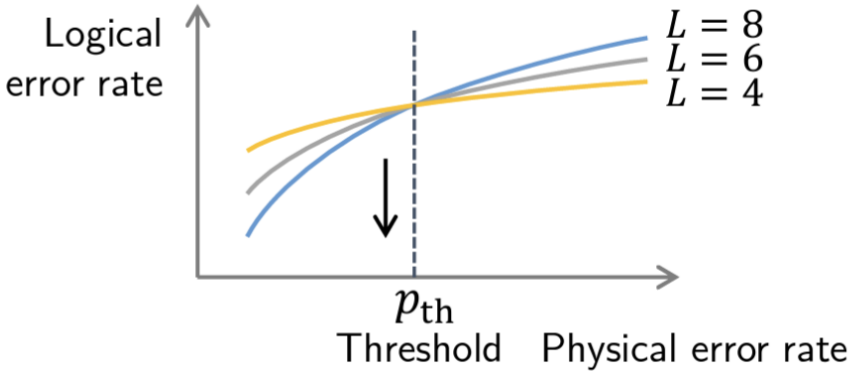
Thresholds for the distributed surface code in the presence of memory decoherence

Sébastian de Bone,[1,2] Paul Möller,[1] Conor E. Bradley,[1,3] Tim H. Taminiau,[1] and David Elkouss[1,4]



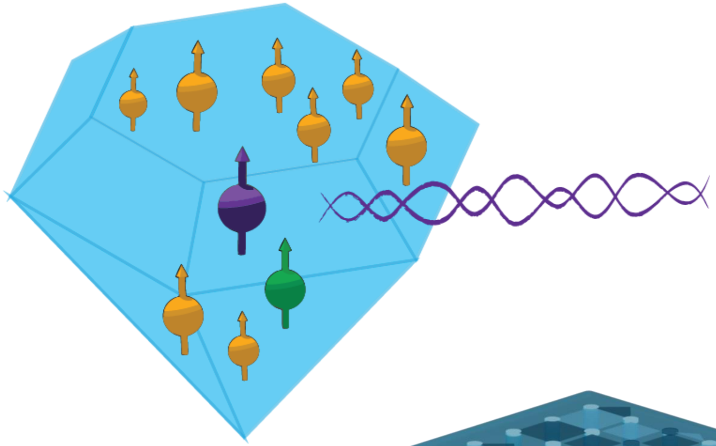
Beyond the surface code

Quantum Low-Density Parity-Check (q-LDPC) codes and other high-connectivity codes

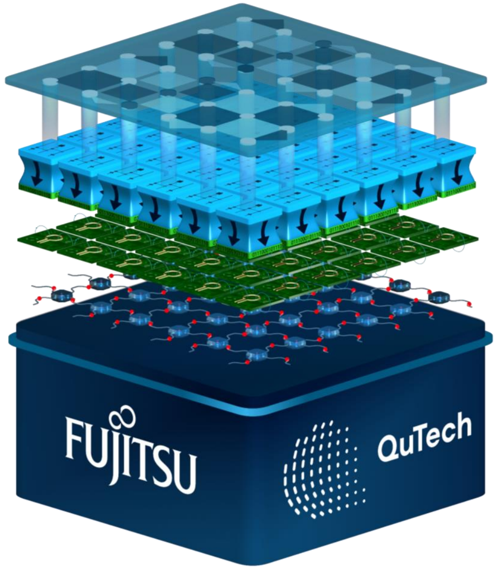
AVS Quantum Sci. 6, 033801 (2024)
Singh arXiv 2408.02837 (2025)

Three challenges for scalability

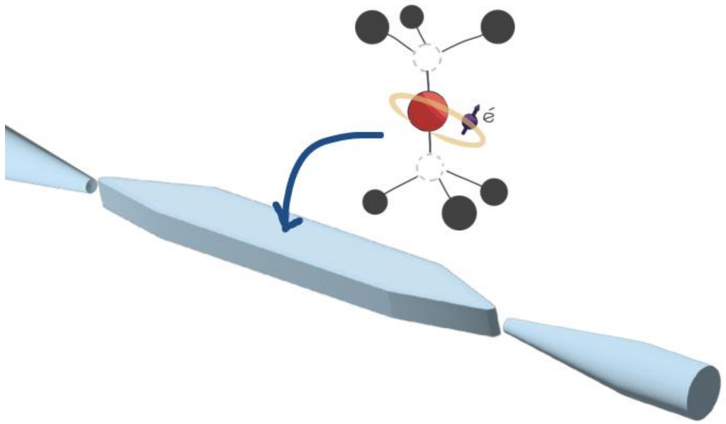
1. High-fidelity qubits



3. Integration and scalability:
Fabrication,
Optics,
Electronics,
Microarchitecture.



2. Efficient optical interconnects



Challenge: current
entanglement rate/decoherence rate < 1

Some example demonstrations @ QuTech:
Delle Donne et al., Nature 2025
Hermans et al., Nature 2022
Pompili et al., Science, 2021

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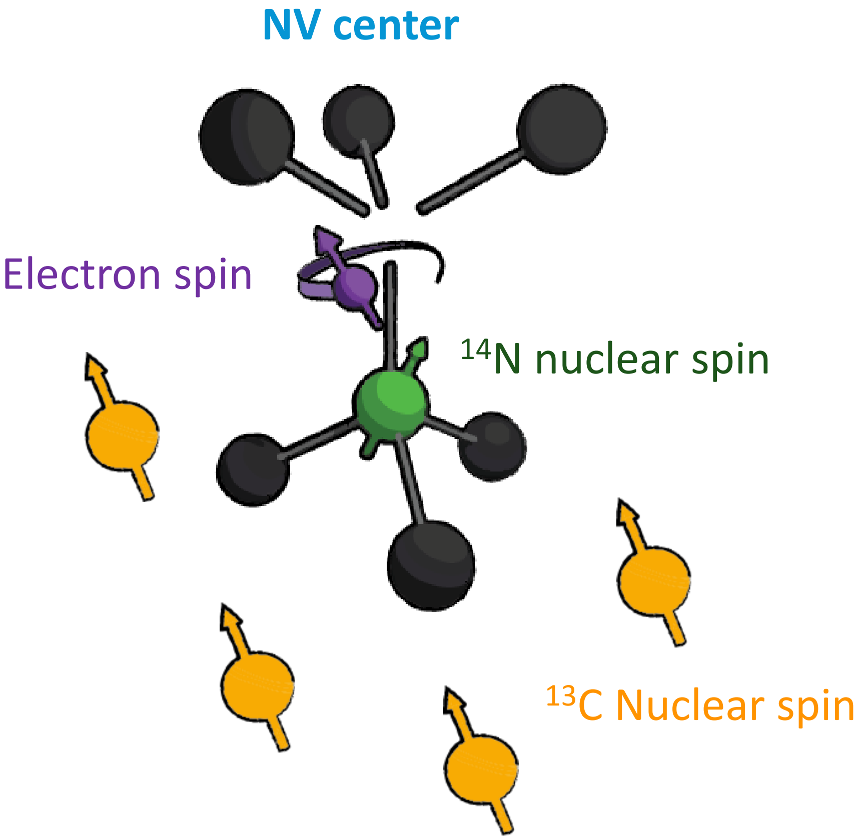
The qubits: spins in diamond

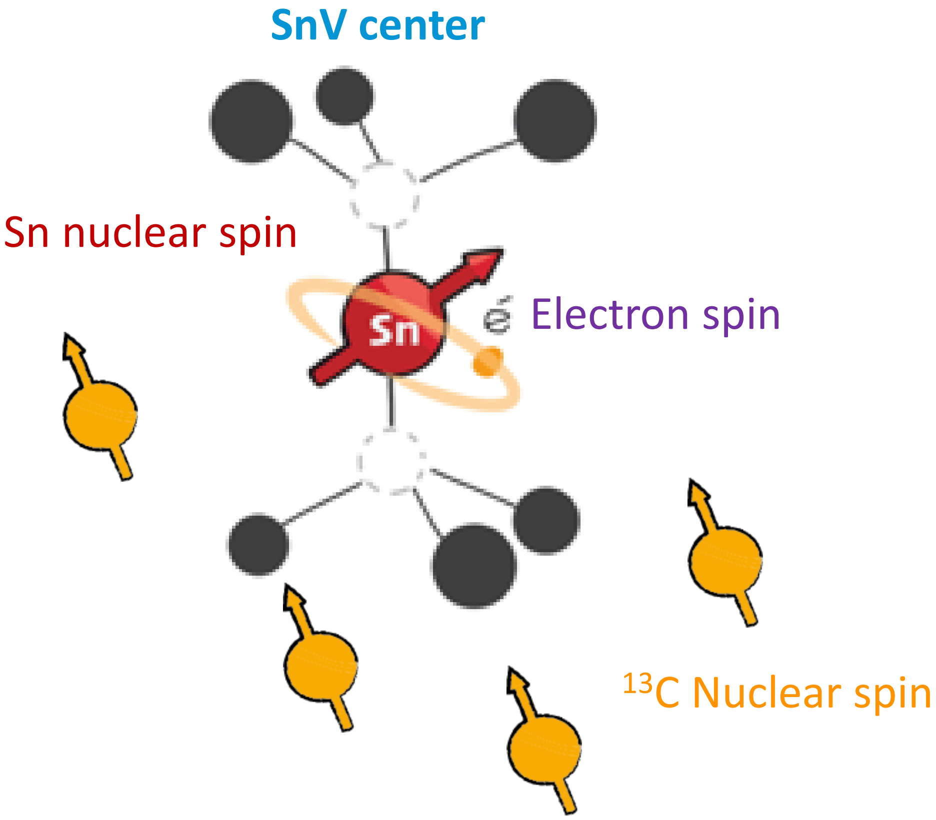
Coherences (NV, 4 Kelvin):

T1	> 1 hour
T2 (DD) Electron	> 5 seconds
T2 (DD) Nuclear	> 2 minutes

Abobeih Nat. Commun. 2018
Bradley PRX 2019



Established and well understood testbed



Next generation for optical integration and high entanglement rates

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Up to 50 nuclear spin qubits

Abobeih Nat. Commun. 2018
Bradley PRX 2019
Abobeih Nature 2019
van de Stolpe Nature Comm. 2024

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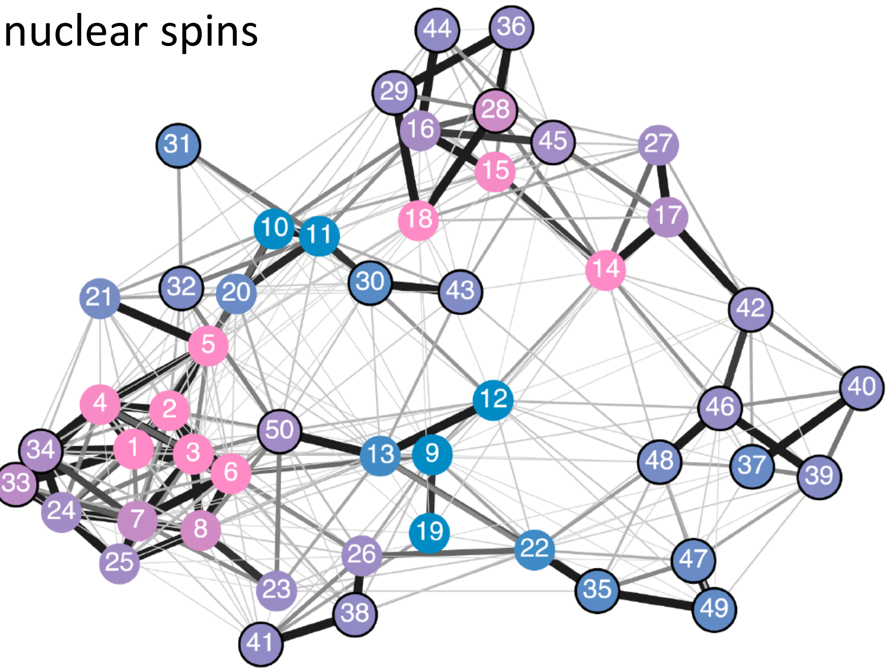
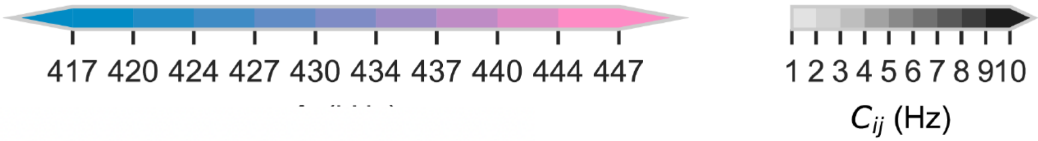
Up to 50 nuclear spin qubits

Abobeih Nature 2019
van de Stolpe Nature Comm. 2024

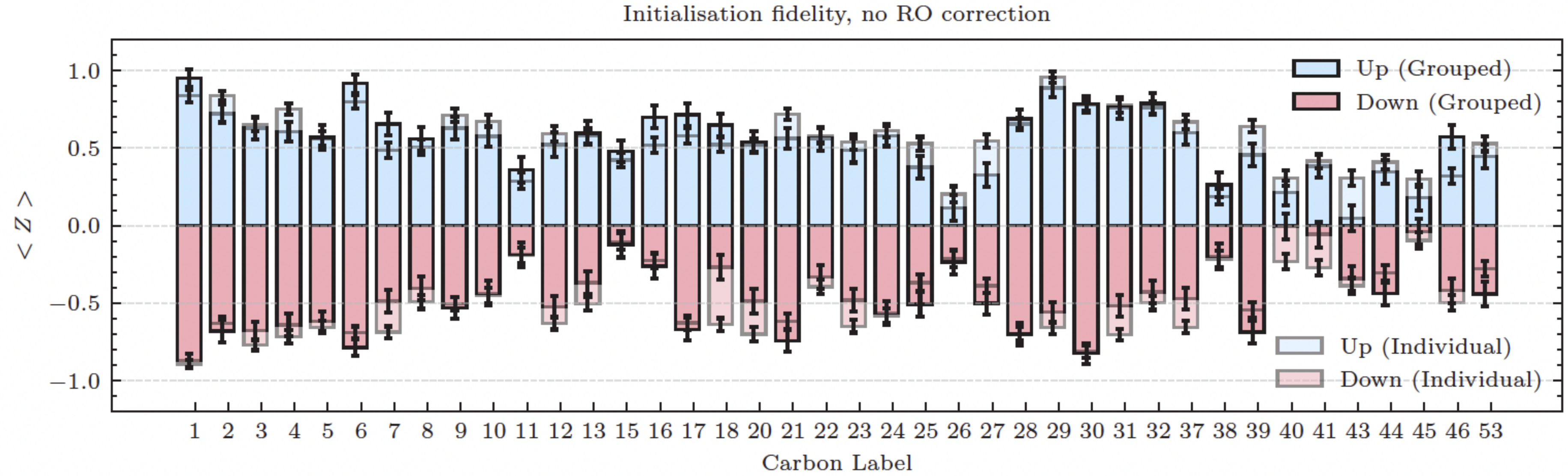
50 nuclear spins

All 1225 two-qubit interactions are known





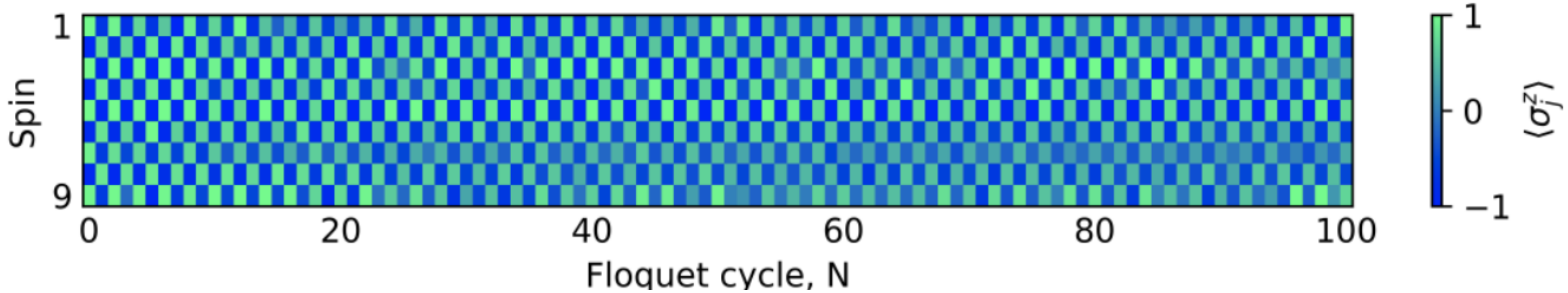
Initialization, individual readout and control



Potential for quantum simulations

Early "applications" : many-body physics and error correction

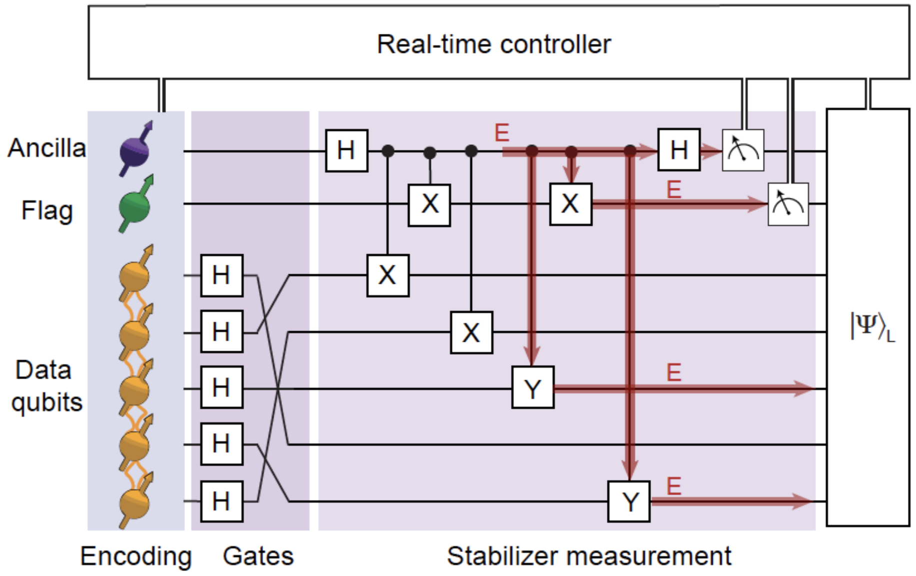
Realization of a discrete time crystal



J. Randall et al., **Science 2021**

See also superconducting processors:
Google – Mi et., Nature 2022
IBM – Frey et., Science Adv 2022

Fault-tolerant operation of a logical qubit (5-qubit code with a flag qubit)



Previous demonstrations with ion traps:

Monroe/IonQ – Egan et al., Nature 2021
Quantinuum – Ryan-Anderson et al., PRX 2021

Abobeih et al., **Nature 2022** ; QuTech – Fujitsu

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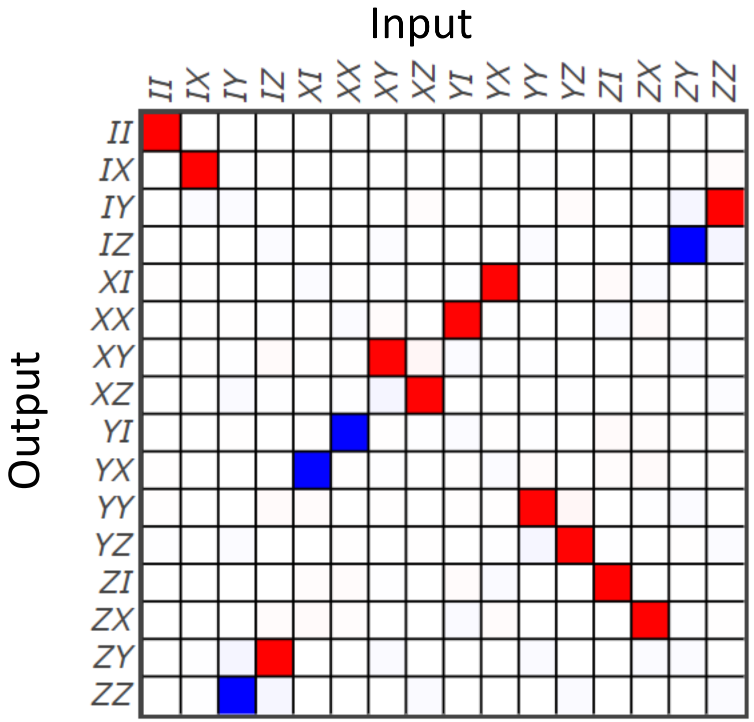
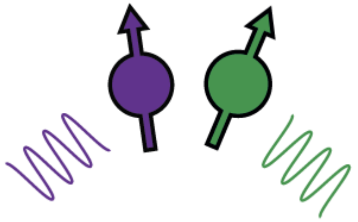
High-fidelity gates



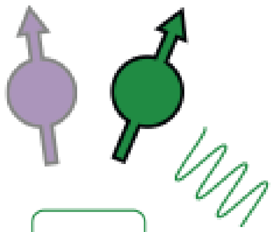
Experimental process matrix
(two-qubit gate)
Gate Set Tomography

Two-qubit subspace



$I_e \otimes I_n$	XY8 (τ)	99.98(5) %	Identity
$R_x(\frac{\pi}{2})_e \otimes I_n$	$R_x(\frac{\pi}{2})_{XY8}$	99.93(3) %	Electron qubit
$R_y(\frac{\pi}{2})_e \otimes I_n$	$R_y(\frac{\pi}{2})_{XY8}$	99.94(5) %	Electron qubit
$I_e \otimes R_x(\frac{\pi}{2})_n$	$R_x(\frac{\pi}{2})_{ddrf}$	99.94(2) %	Nitrogen qubit
$I_e \otimes R_y(\frac{\pi}{2})_n$	$R_y(\frac{\pi}{2})_{ddrf}$	99.94(2) %	Nitrogen qubit
controlled-$R_x(\mp\frac{\pi}{2})_n$	$R_x(\mp\frac{\pi}{2})_{ddrf}$	99.93(5) %	Two-qubit gate

Single-qubit gates



$R_x(\frac{\pi}{2})_{rf}$	99.999(1) %
$R_y(\frac{\pi}{2})_{rf}$	99.999(1) %

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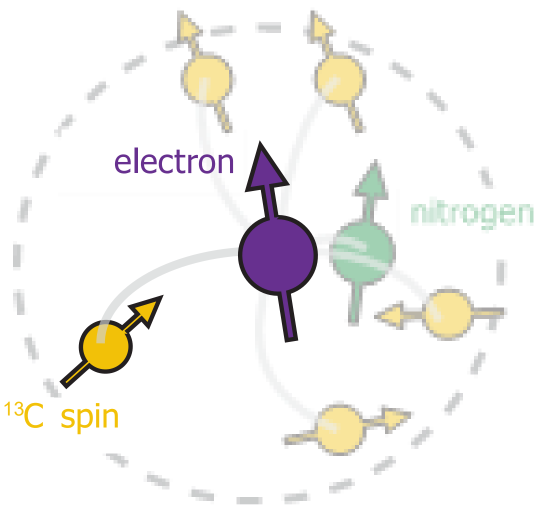
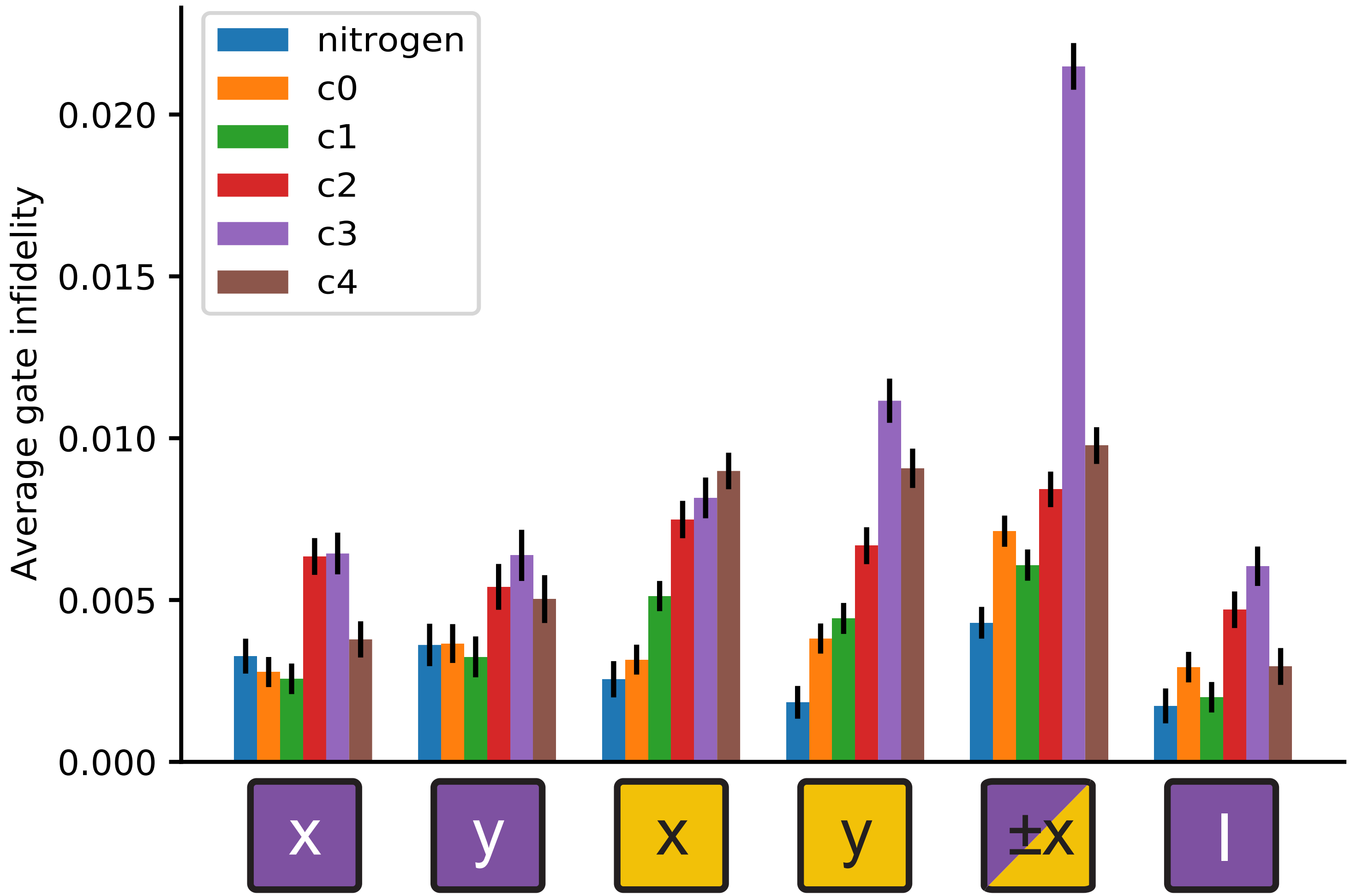
H.P. Bartling et al.
Phys. Rev. Applied 23, 034052 (2025)

High-fidelity gates

7-qubit device:
Pairwise gate set tomography





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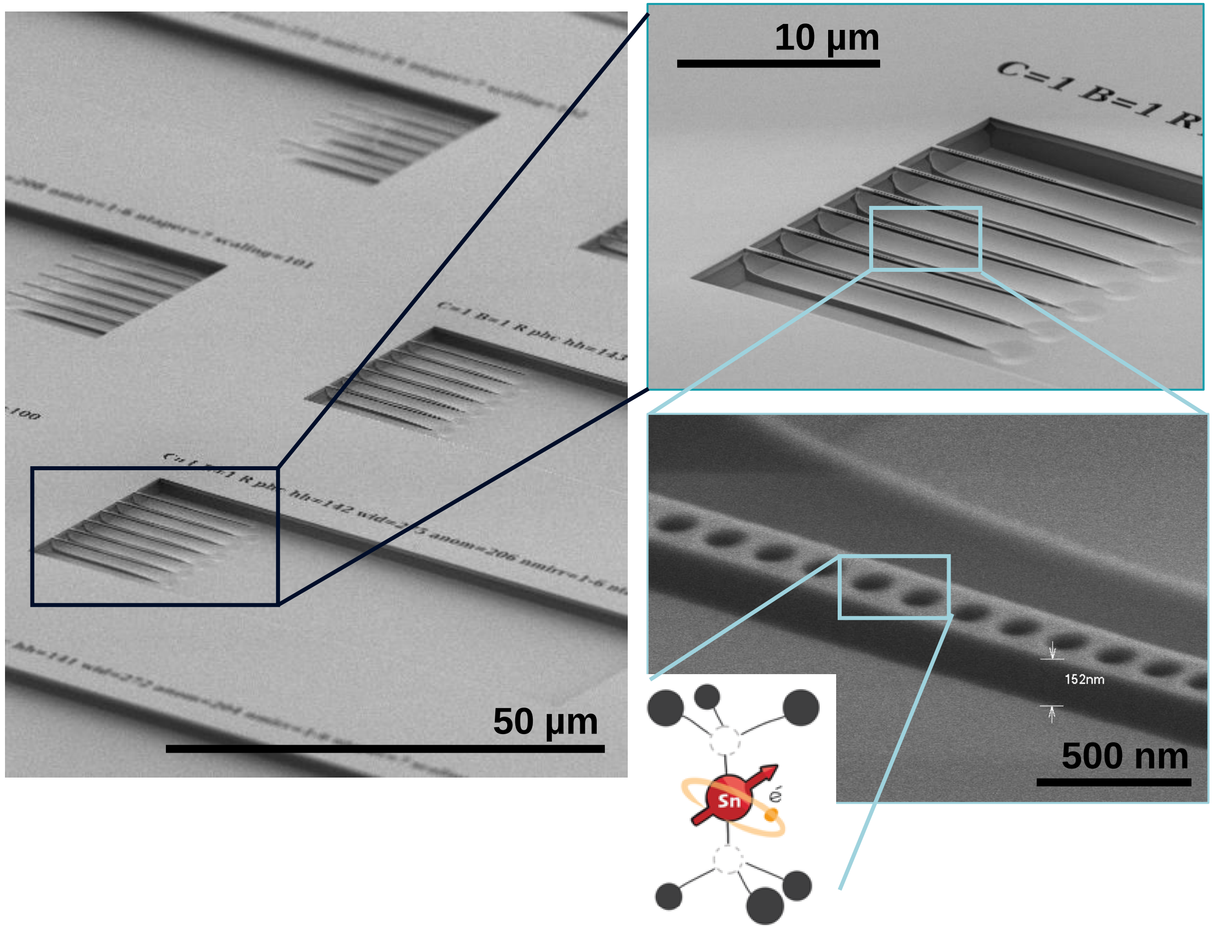
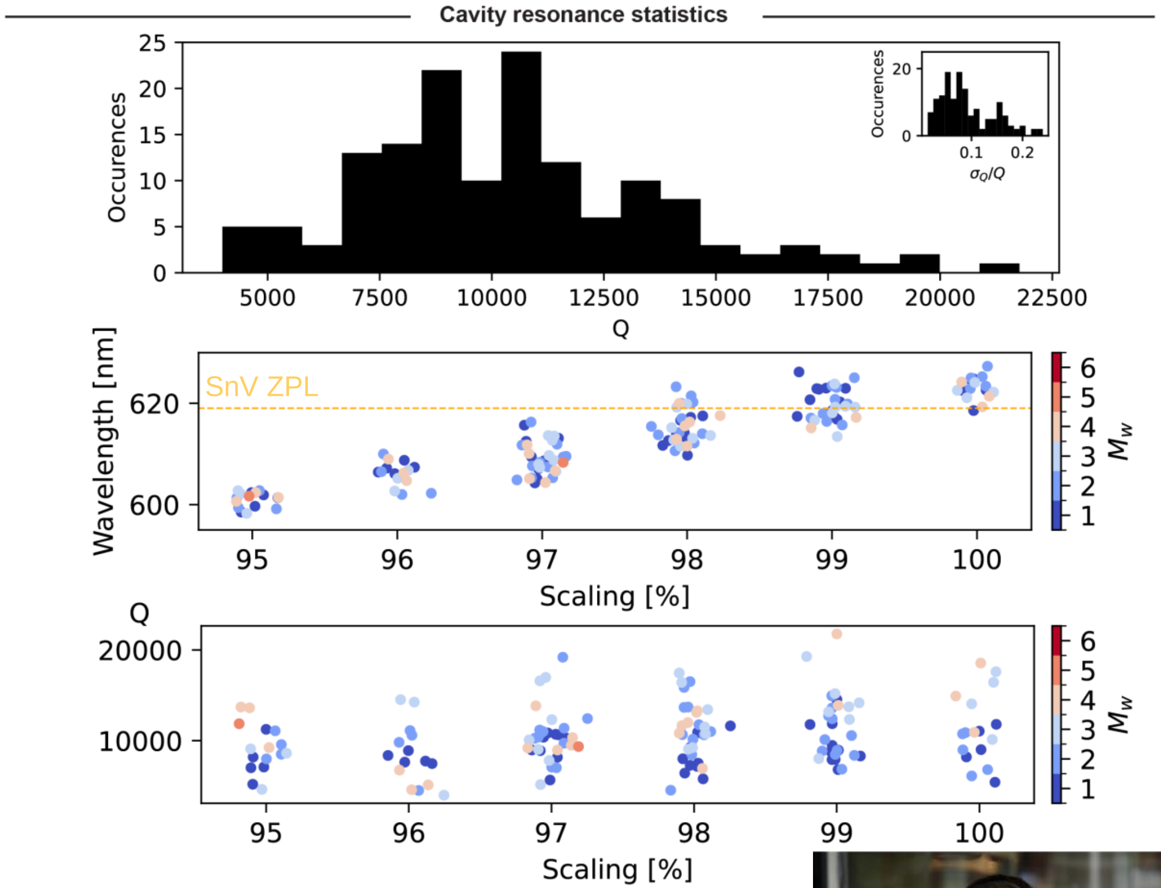
Work in progress

The SnV center: next generation qubit





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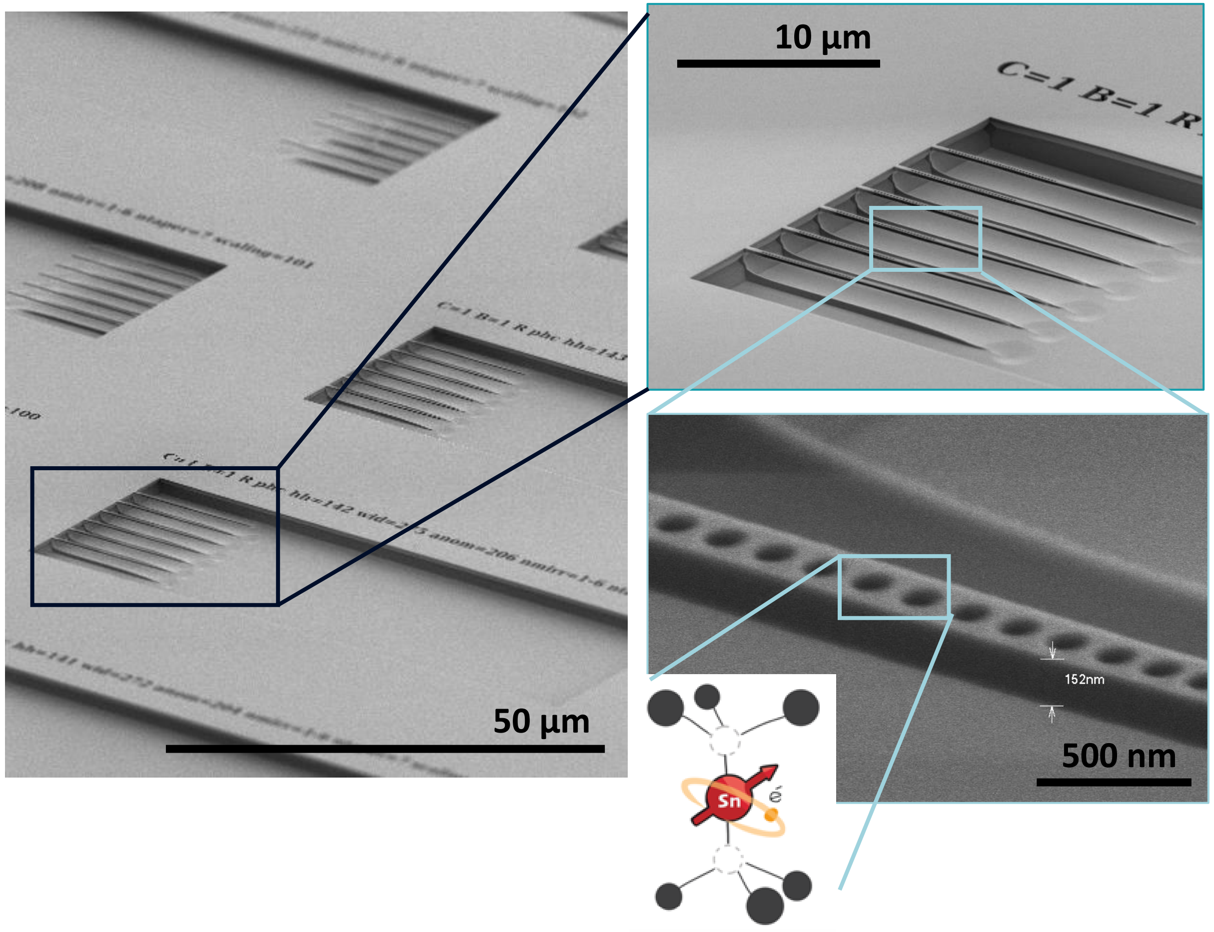
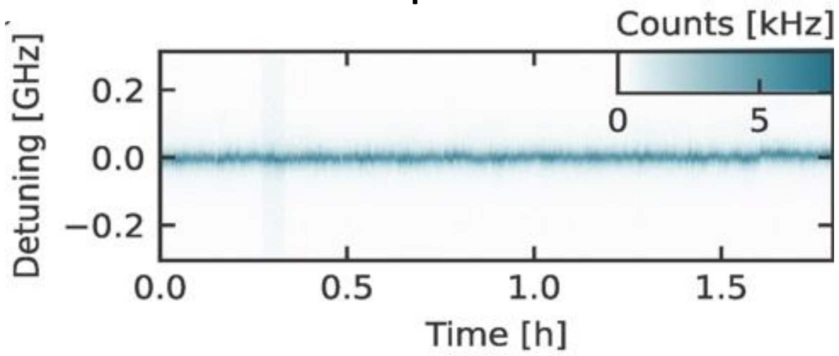
Ronald Hanson

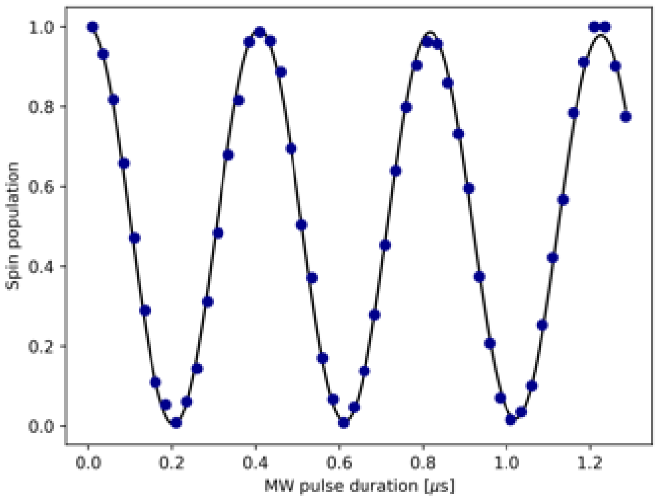
The SnV center: next generation qubit



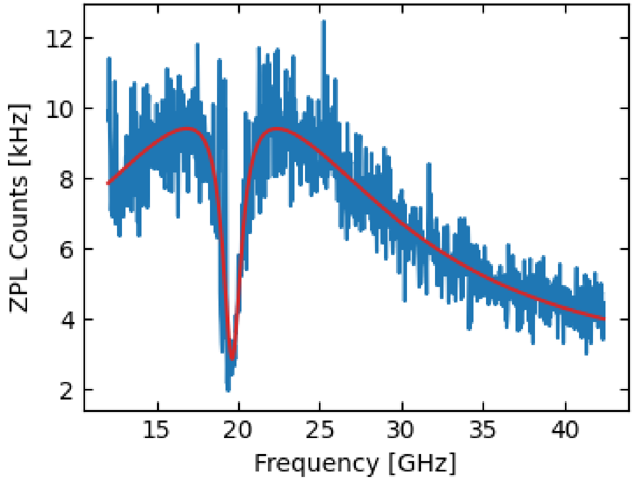
Stable optical transitions



Electron and nuclear spin control



Strong cavity-emitter interaction



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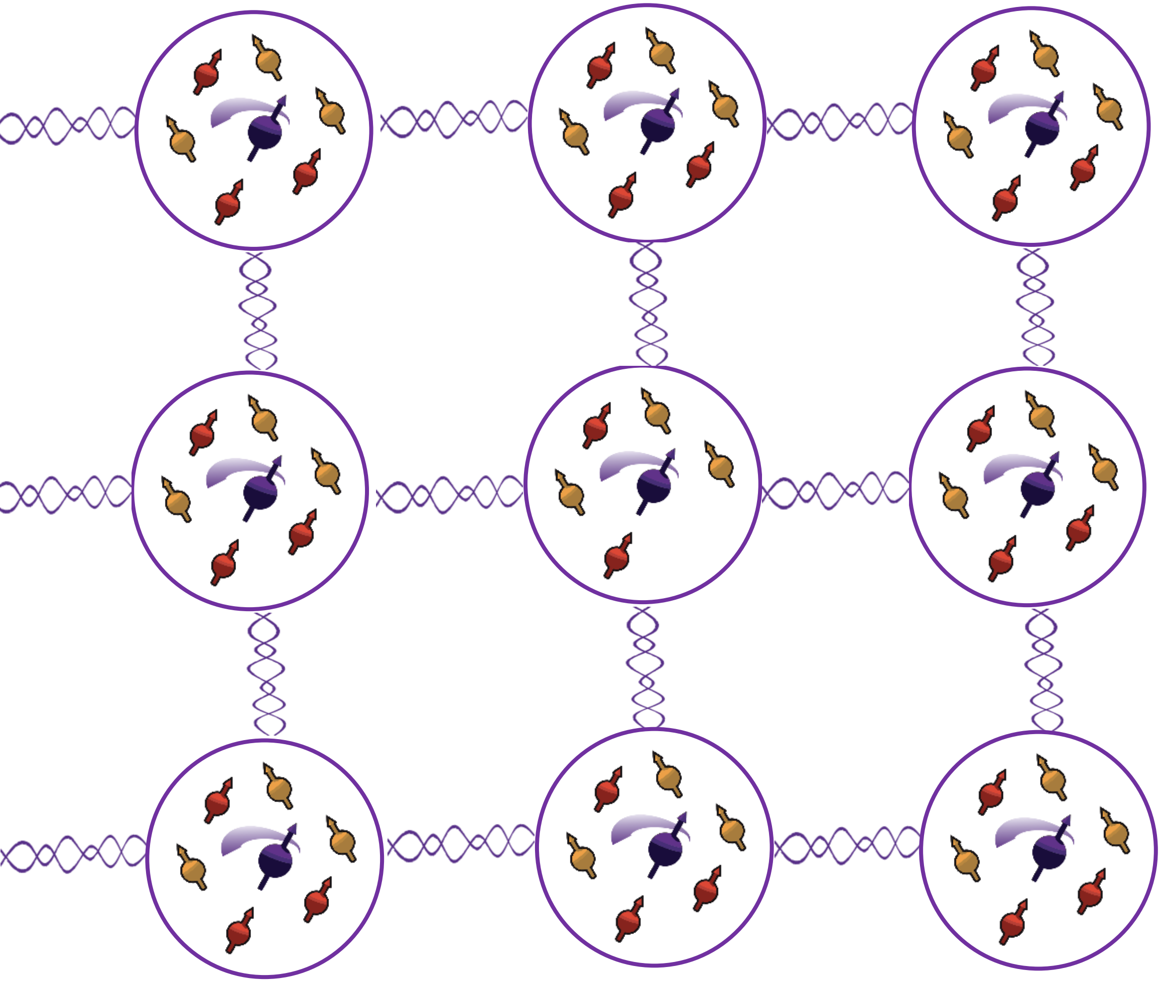
Control of nuclear spins: Beukers, et al. arXiv:2409.08977

Towards modular quantum computation



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Next big step

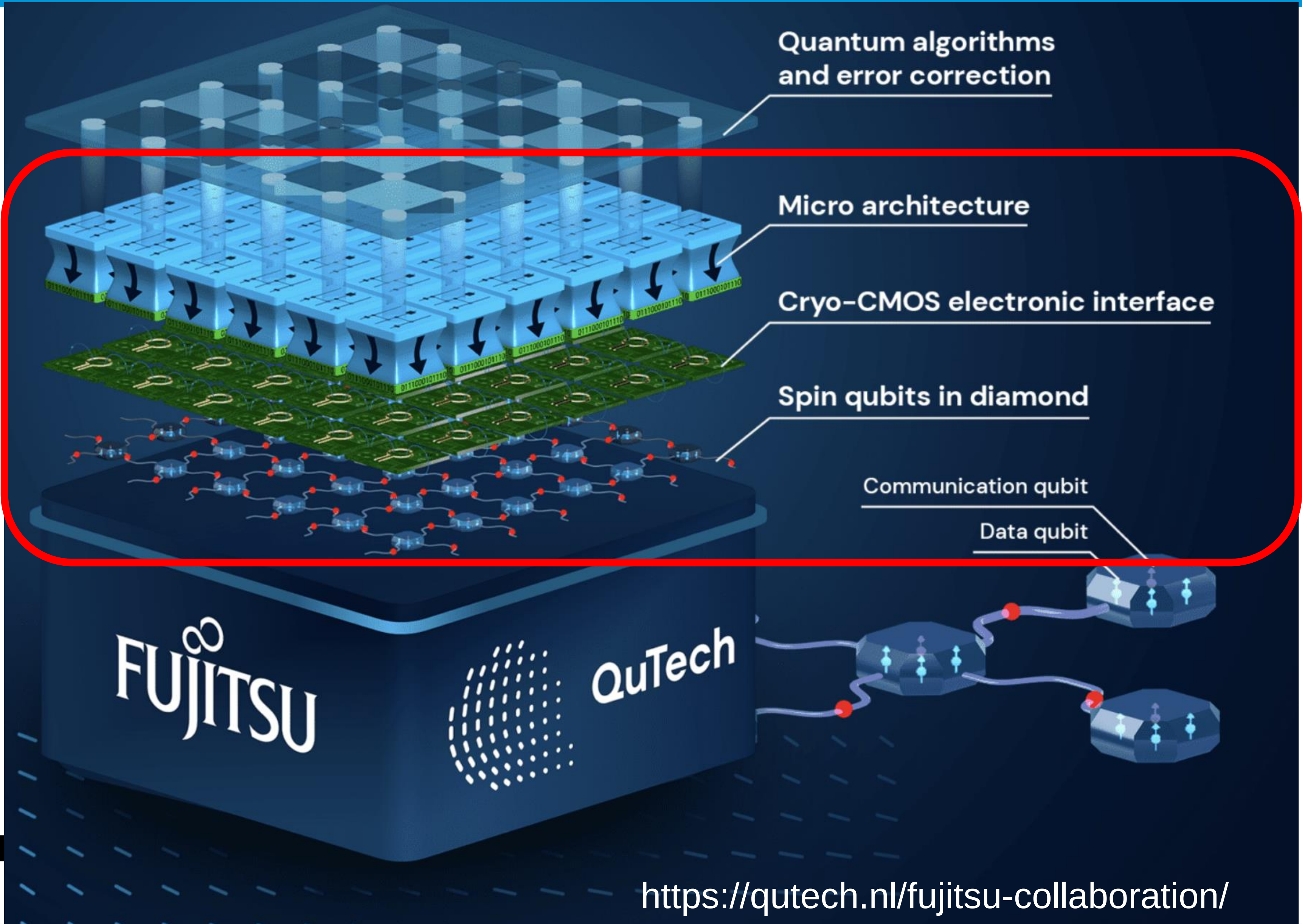
Fast optical interconnects with SnV
(expected soon!)

Outlook

Create first functional small/medium-sized
error-corrected systems.

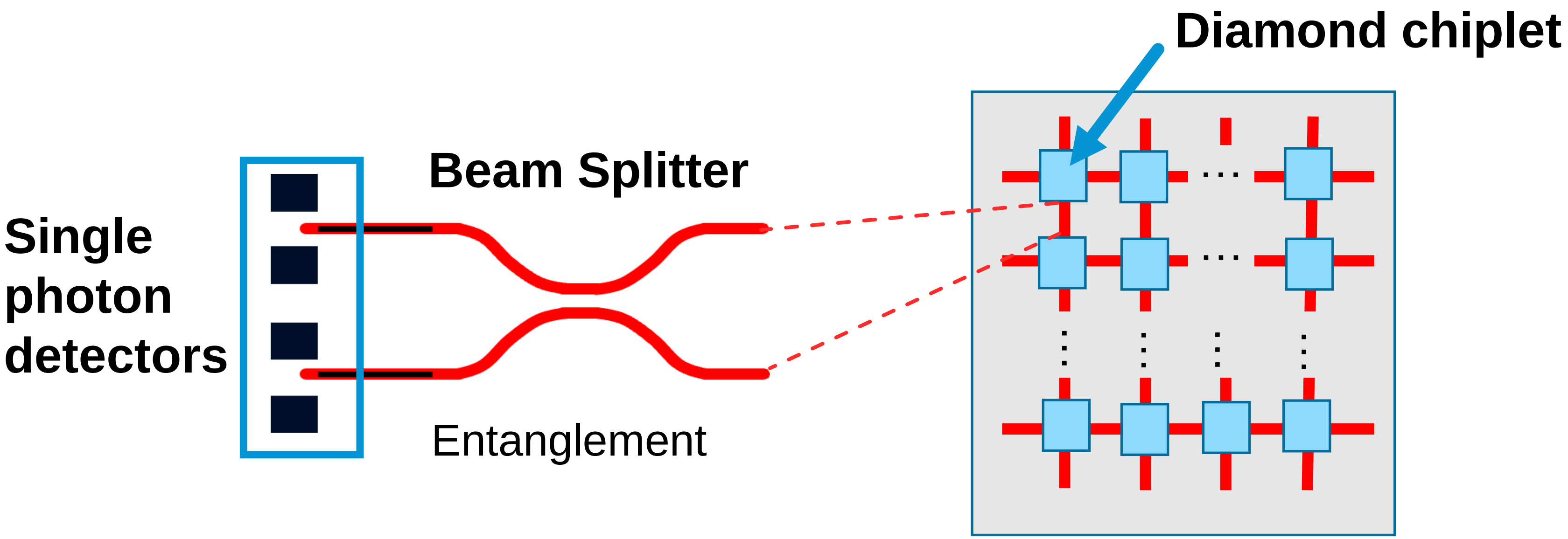
For *examples:*
9 modules (surface code)
72 modules (qLDPC code with 12 logical qubits)

Large-scale integration



https://qutech.nl/fujitsu-collaboration/

Photonic integrated circuit



R. Ishihara *et al.*, *IEDM* 2021, pp. 14.5.1-14.5.4

Challenges

- Visible wavelength (532 nm to 638 nm)
- Heterogeneous integration

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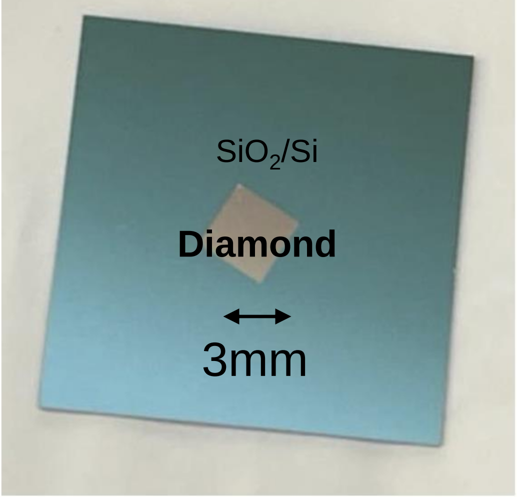
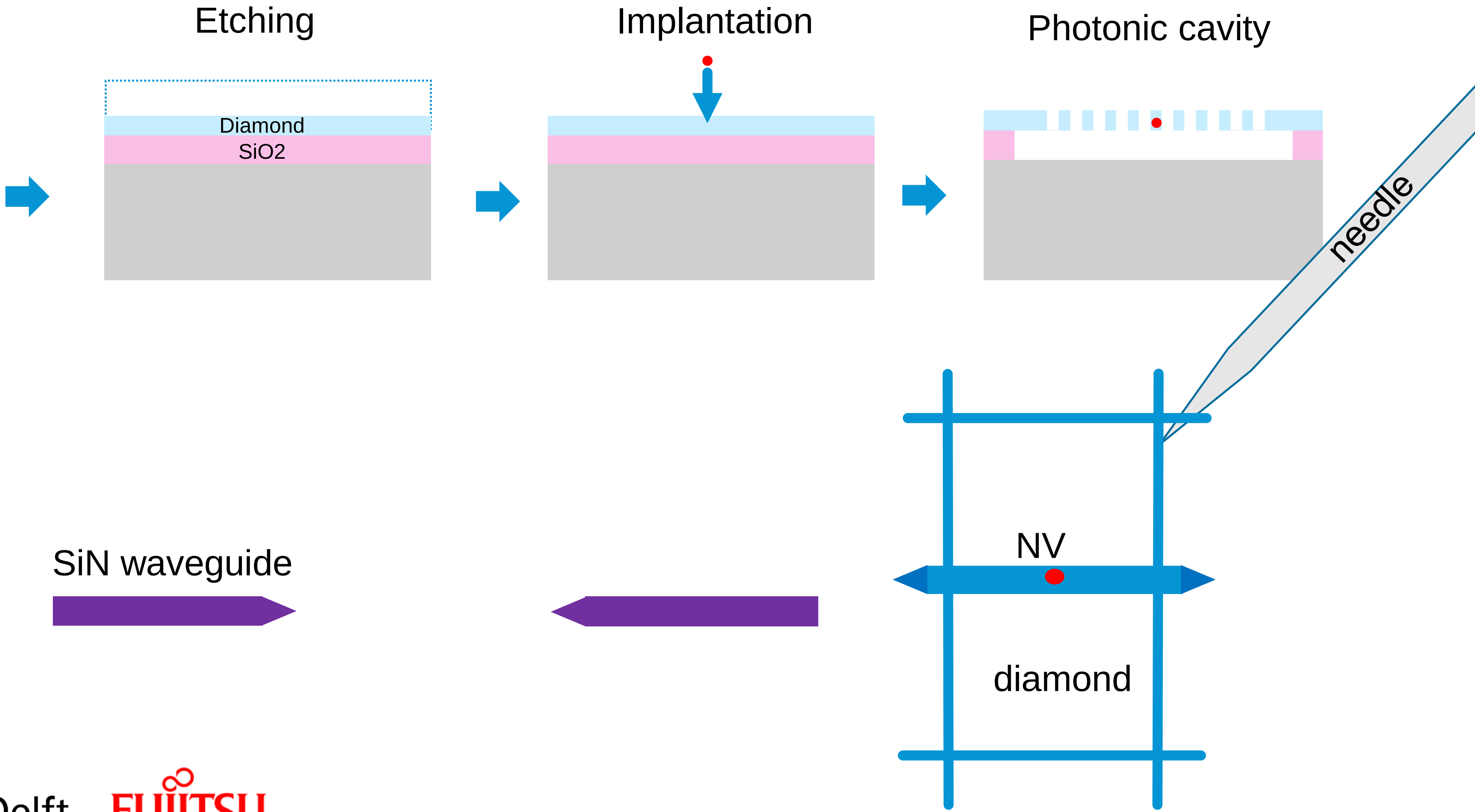
Diamond-on-insulator and chiplet

DOI substrate



T. Chen, et al., arxiv:2501.12831



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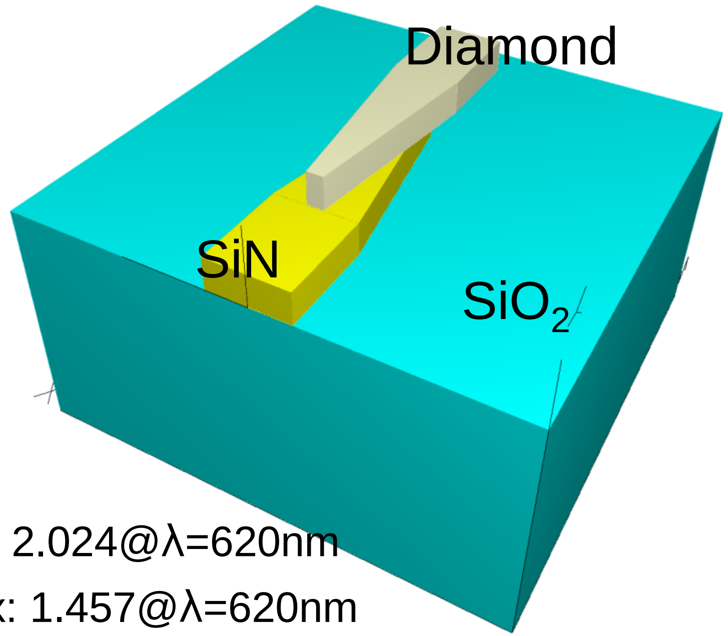
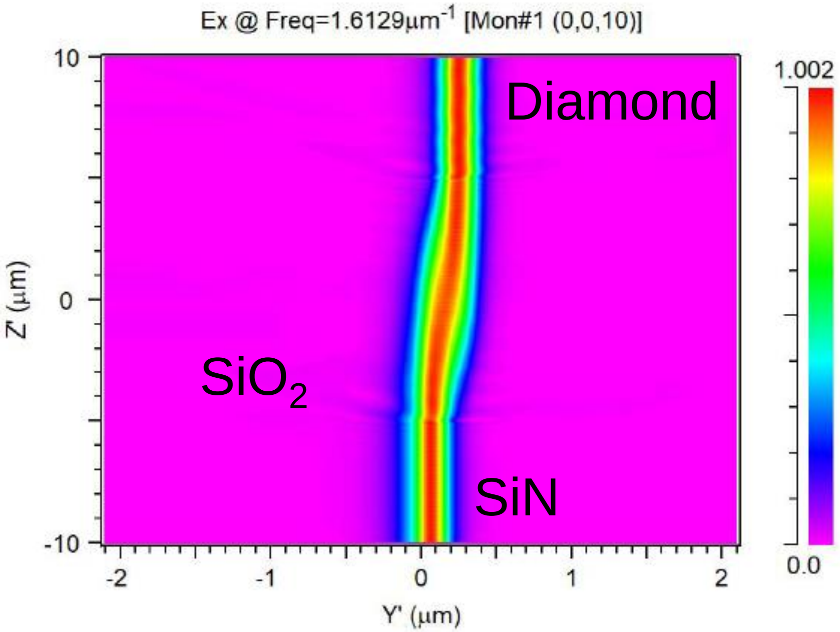
Diamond/SiN waveguide coupling

FDTD simulation by T. Miyatake and S. Miyahara, Fujitsu



SiN Index: 2.024@λ=620nm

SiO_2 Index: 1.457@λ=620nm



Coupling efficiency >99%

60nm misalignment: 3dB loss

SiN waveguide

- Low transmission loss for visible light
- Si photonics foundry compatible

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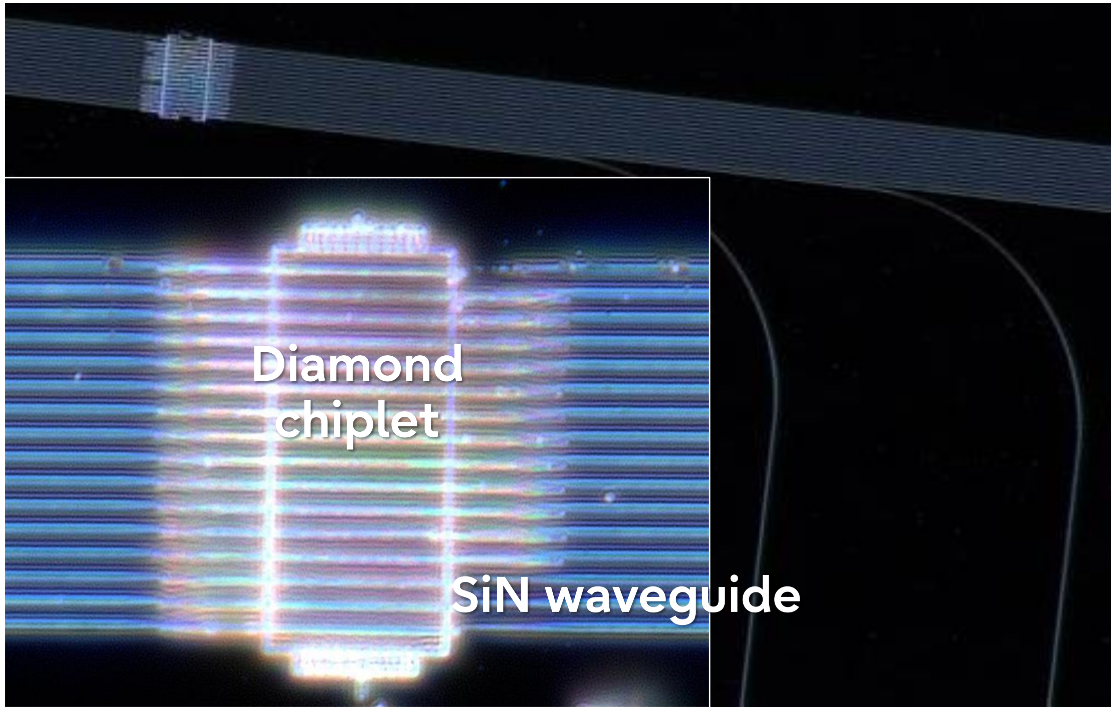
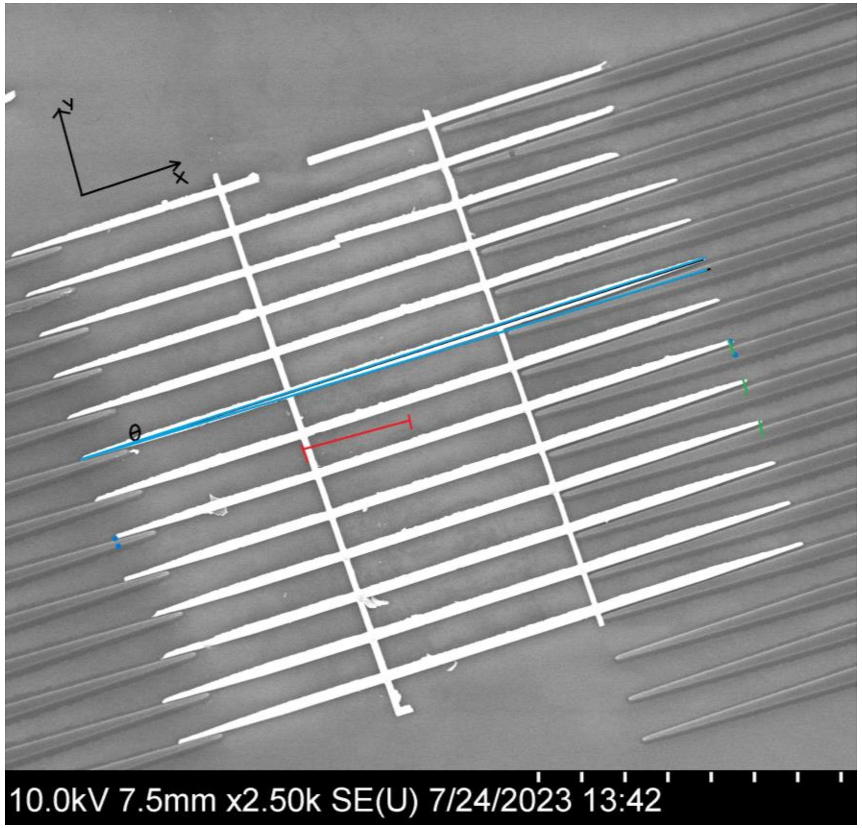
Pick-and-place assembly





Surface energy optimization
Highly accurate (misalignment ~50nm)

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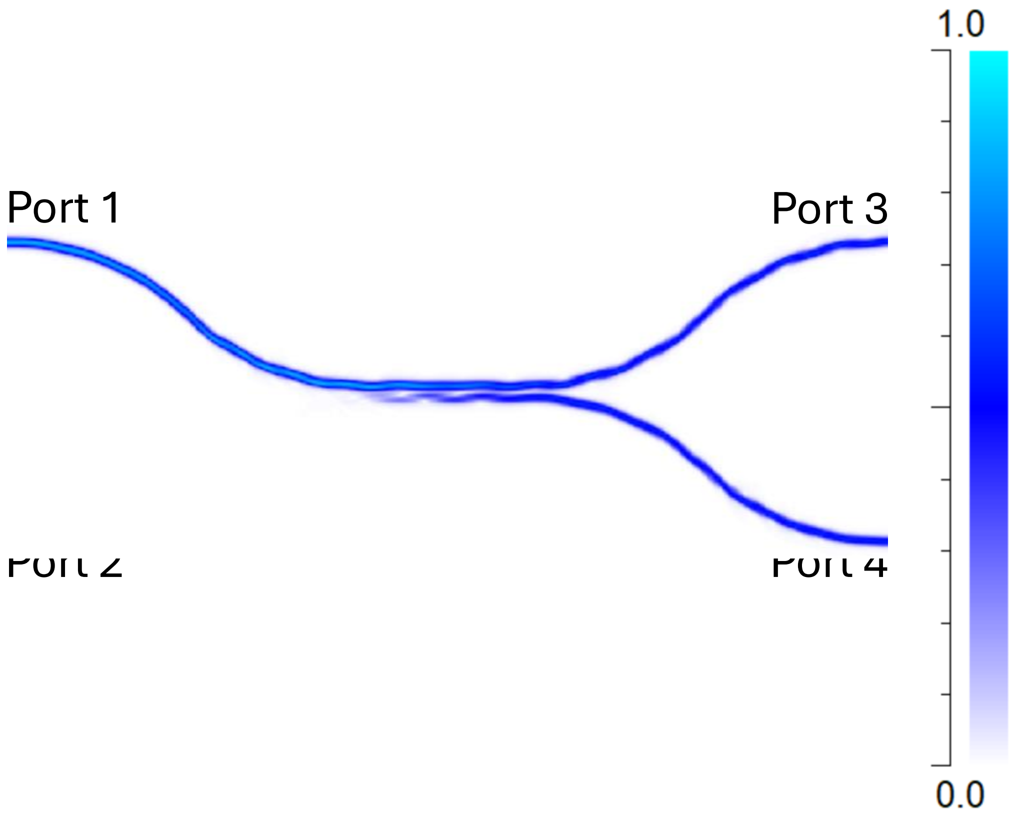
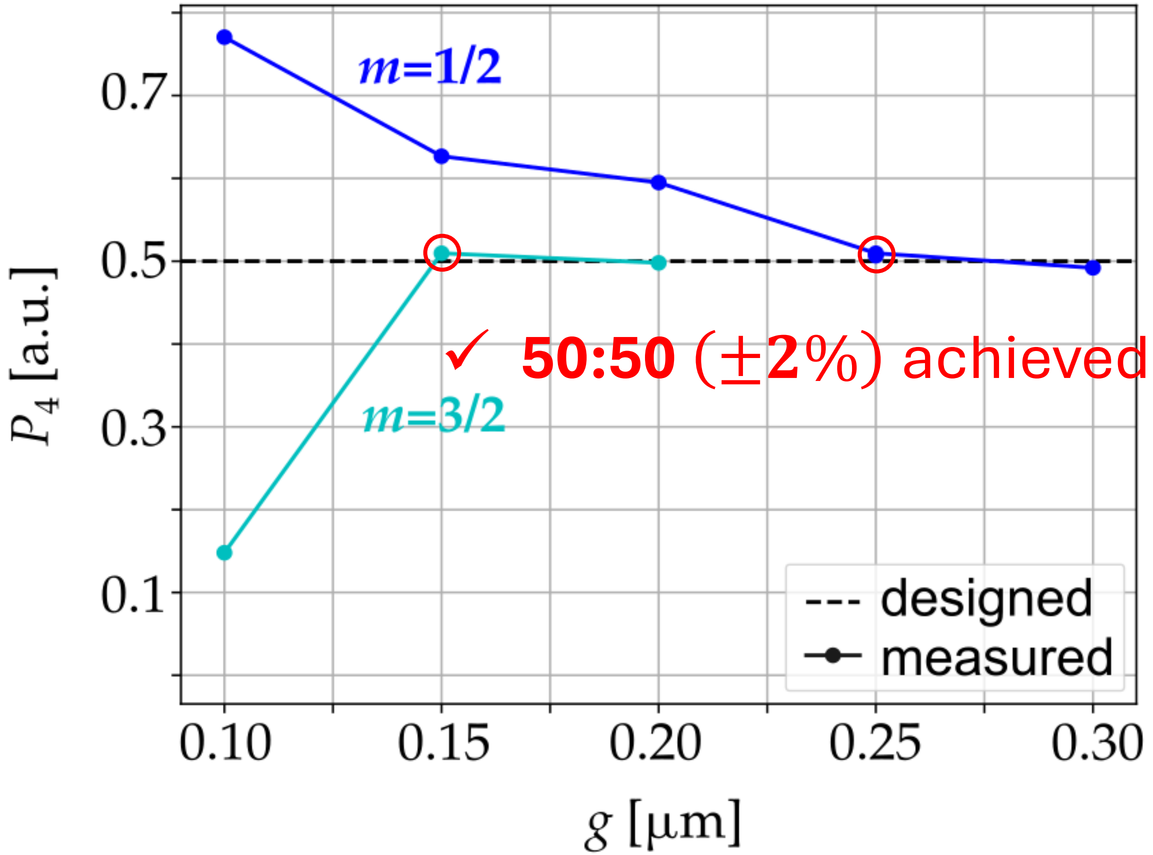
L. Rami, et al., in preparation

Beam splitter with SiN waveguide

FDTD Simulation



Experiment with SiN waveguide



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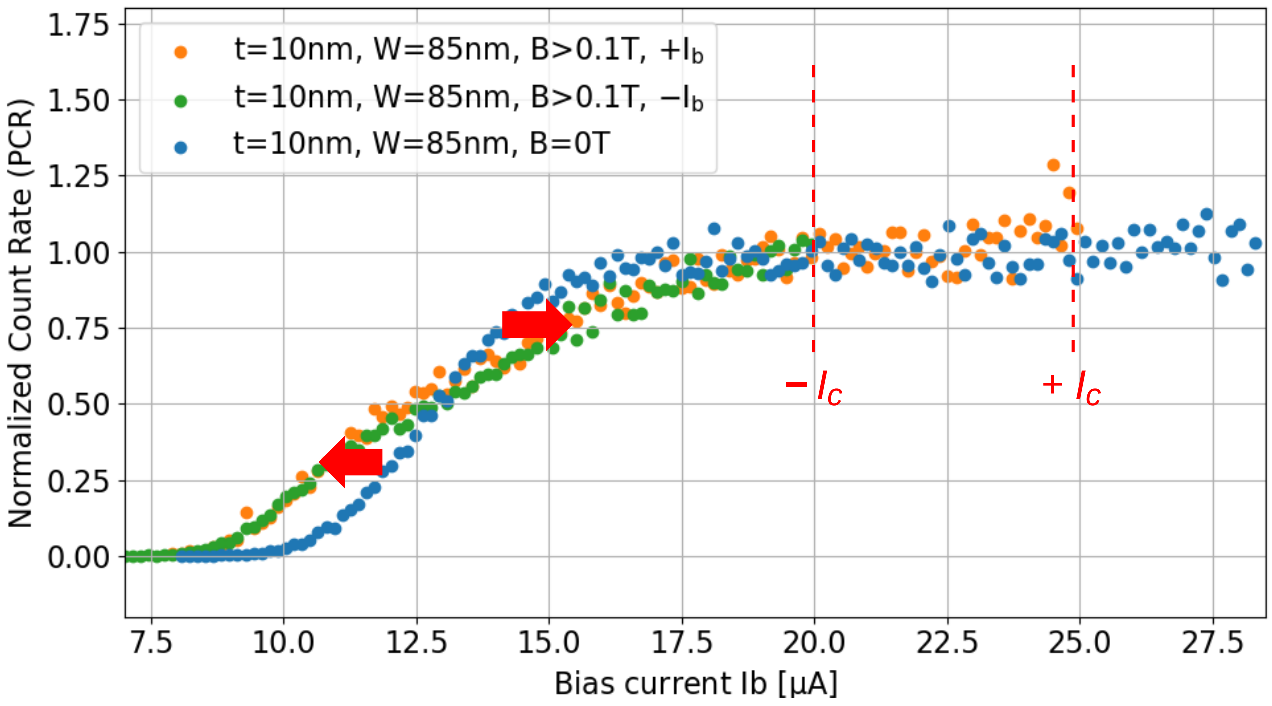
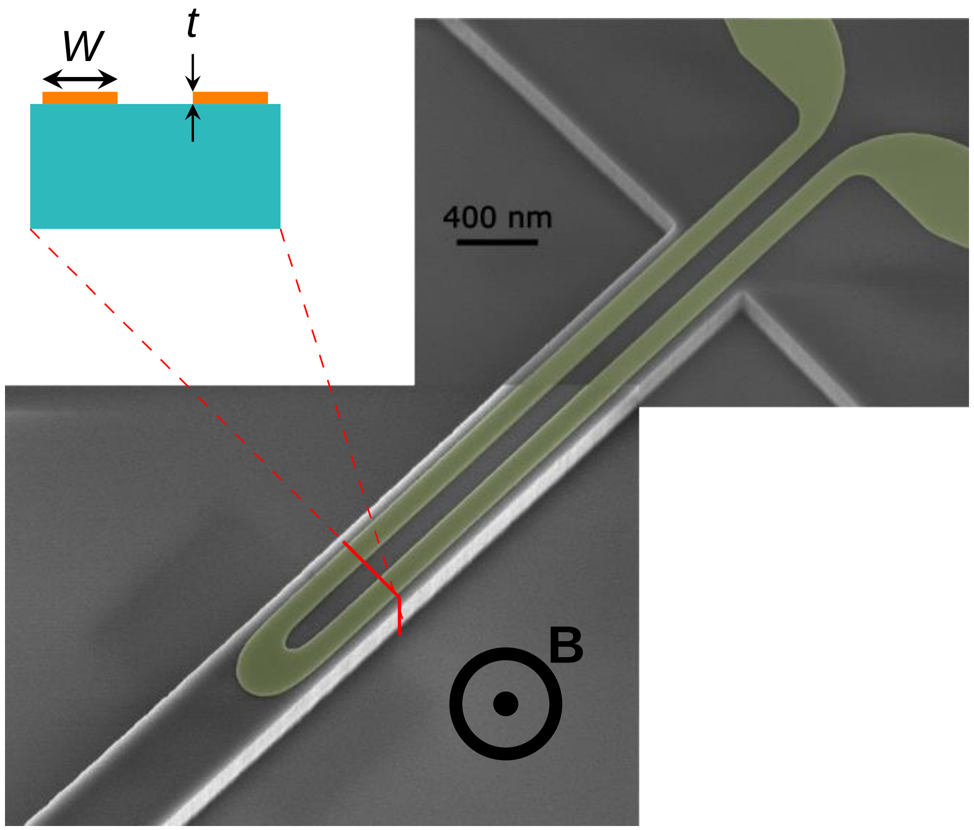
SNSPD Superconducting nanowire single photon detector

- 10nm NbTiN in SiN waveguide
- Magnetic field = 130mT
- Intrinsic quantum efficiency = 100%





M. van der Maas, et. al,

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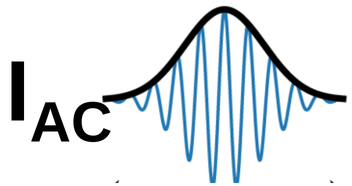
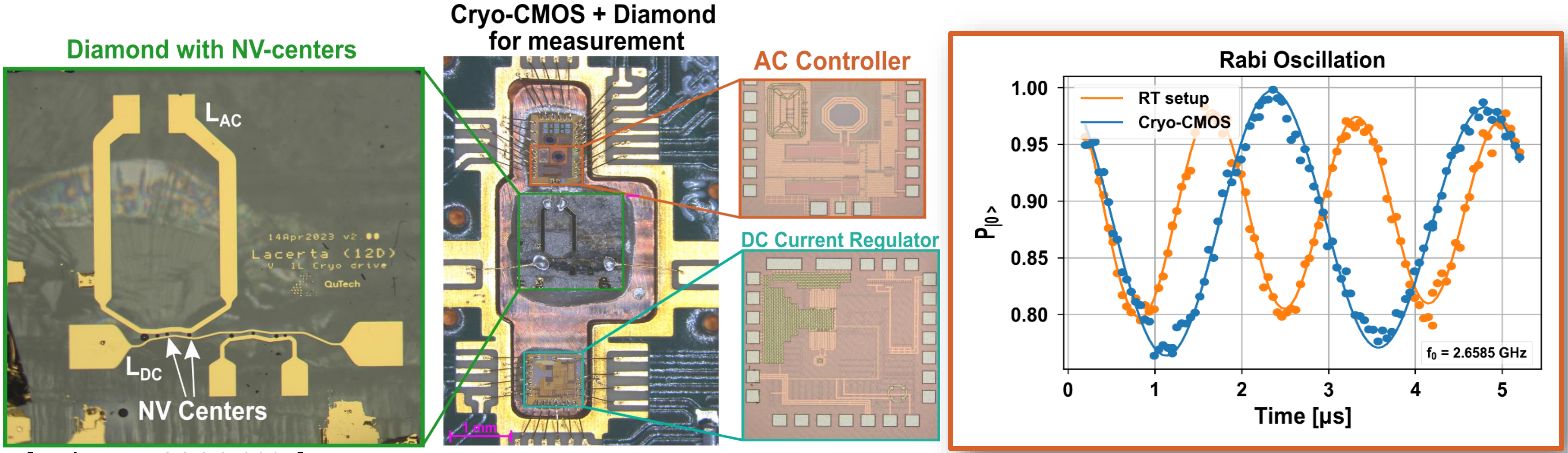
APS JOINT MARCH MEETING AND APRIL MEETING Global Physics Summit
March 16–21, 2025, Anaheim, CA and virtual

Cryo-CMOS for diamond qubits

- Chip fabricated in commercial 40-nm CMOS
- Operating at 4 K next to qubits
- Designed not to limit qubit performance





[Enthoven ISSCC 2024]
[Fakkel JSSC 2024]

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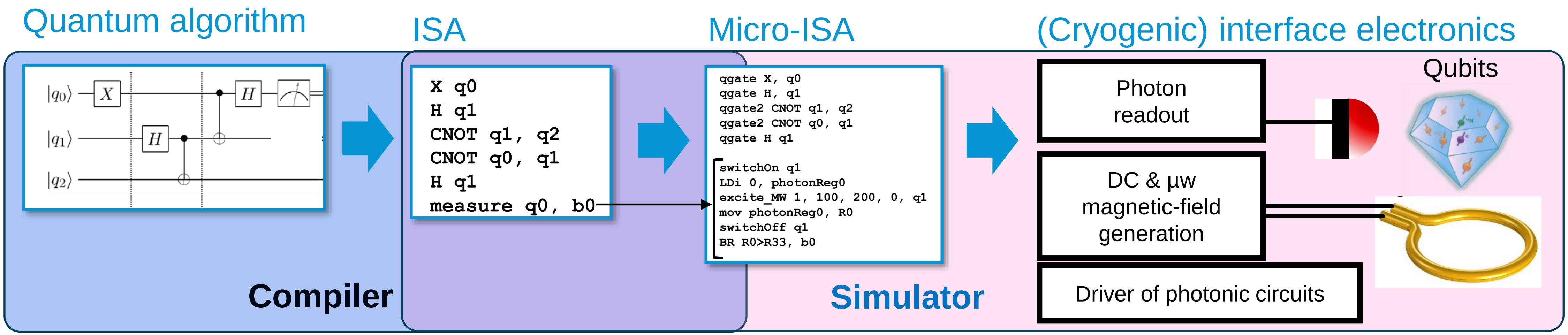
Microarchitecture for diamond qubits

- Digital control (micro-ISA) of MW and RF generators (controlling qubits) and photonics (@cryo temperature)
- Digital (parallel) control of color centers (ISA) (@room temperature)
- Simulation framework (both ISA and micro-ISA level) with noise models
- Compiler framework (using Qiskit)



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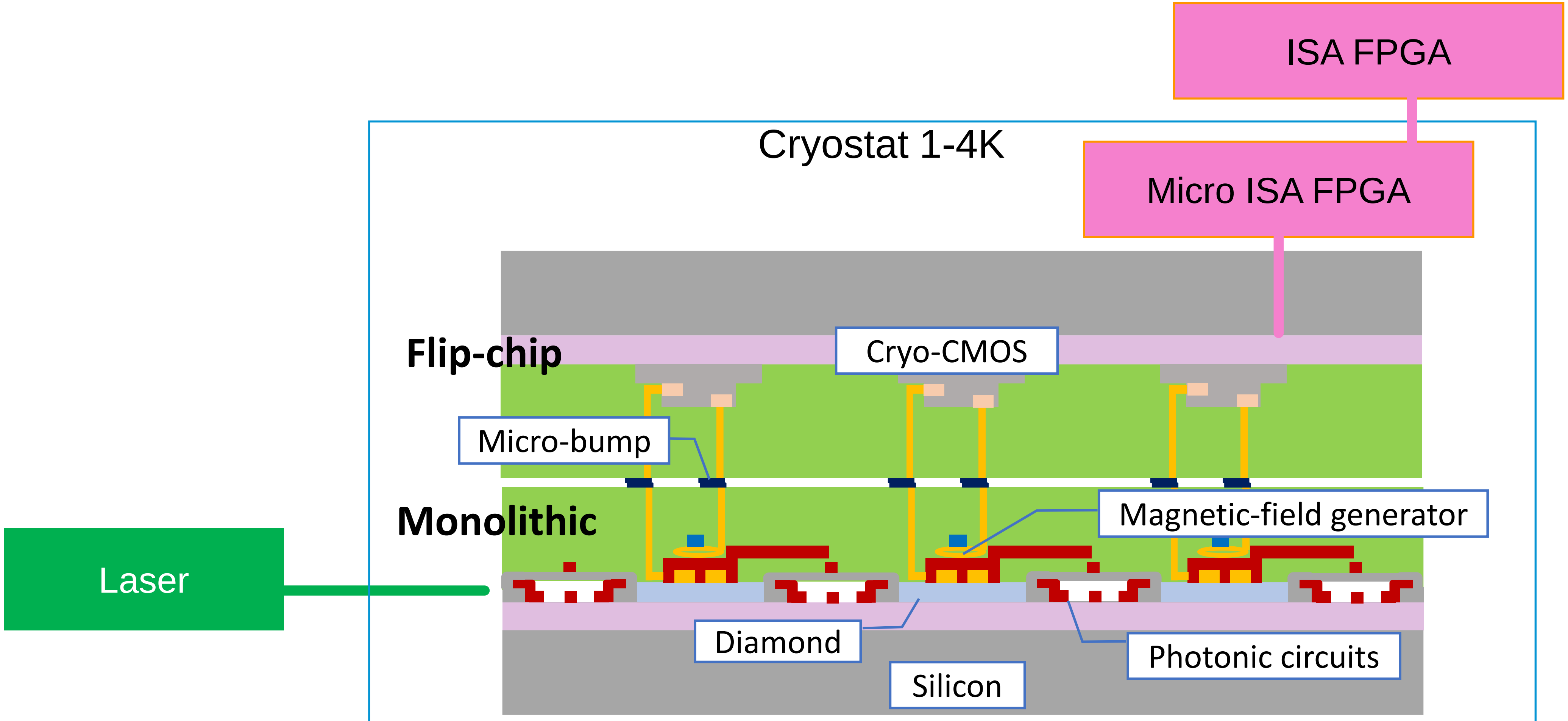
3D integrated system



R. Ishihara *et al.*, *IEDM* 2021, pp. 14.5.1-14.5.4

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A blueprint for a scalable quantum computer

A full-stack approach

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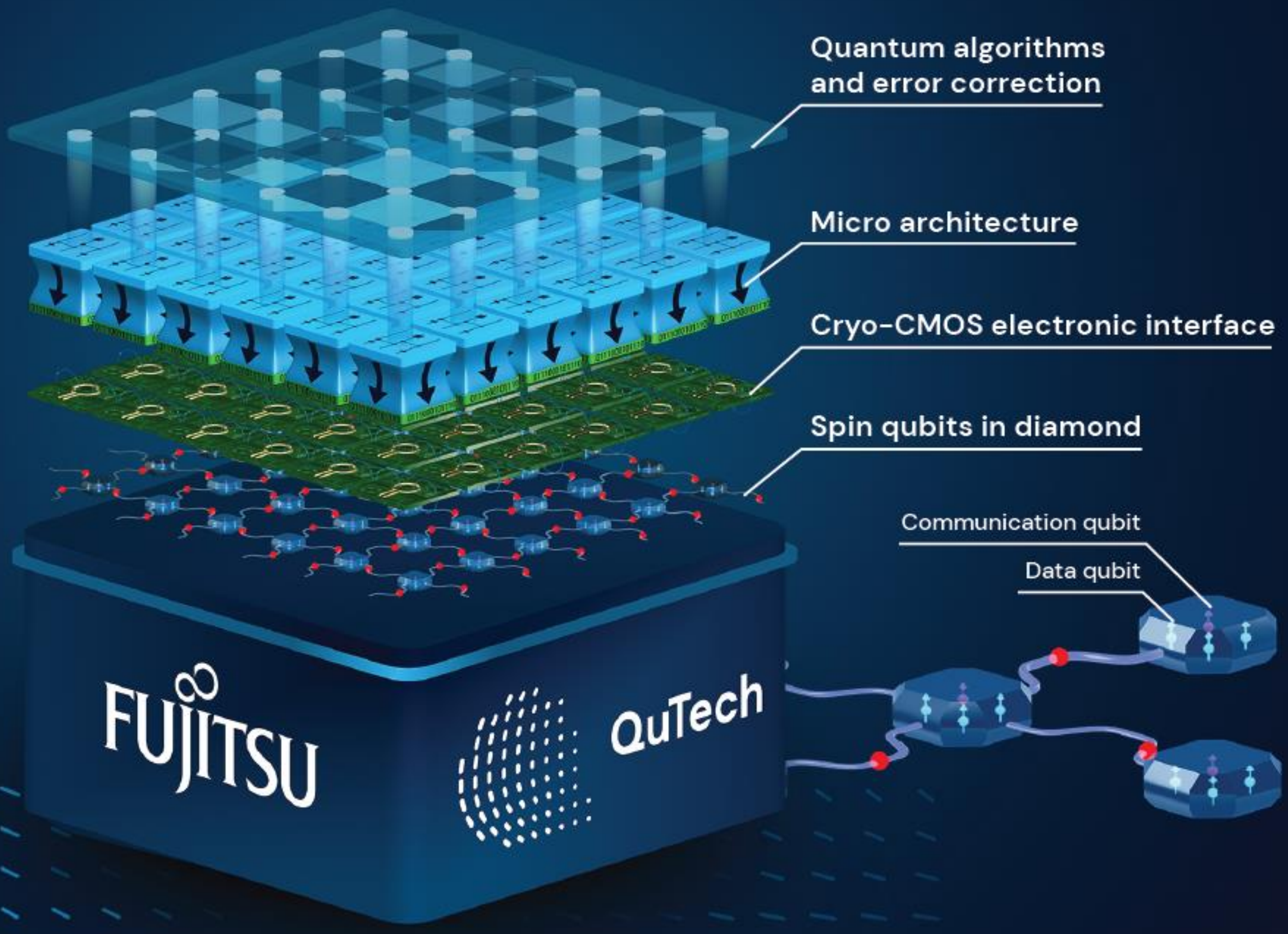
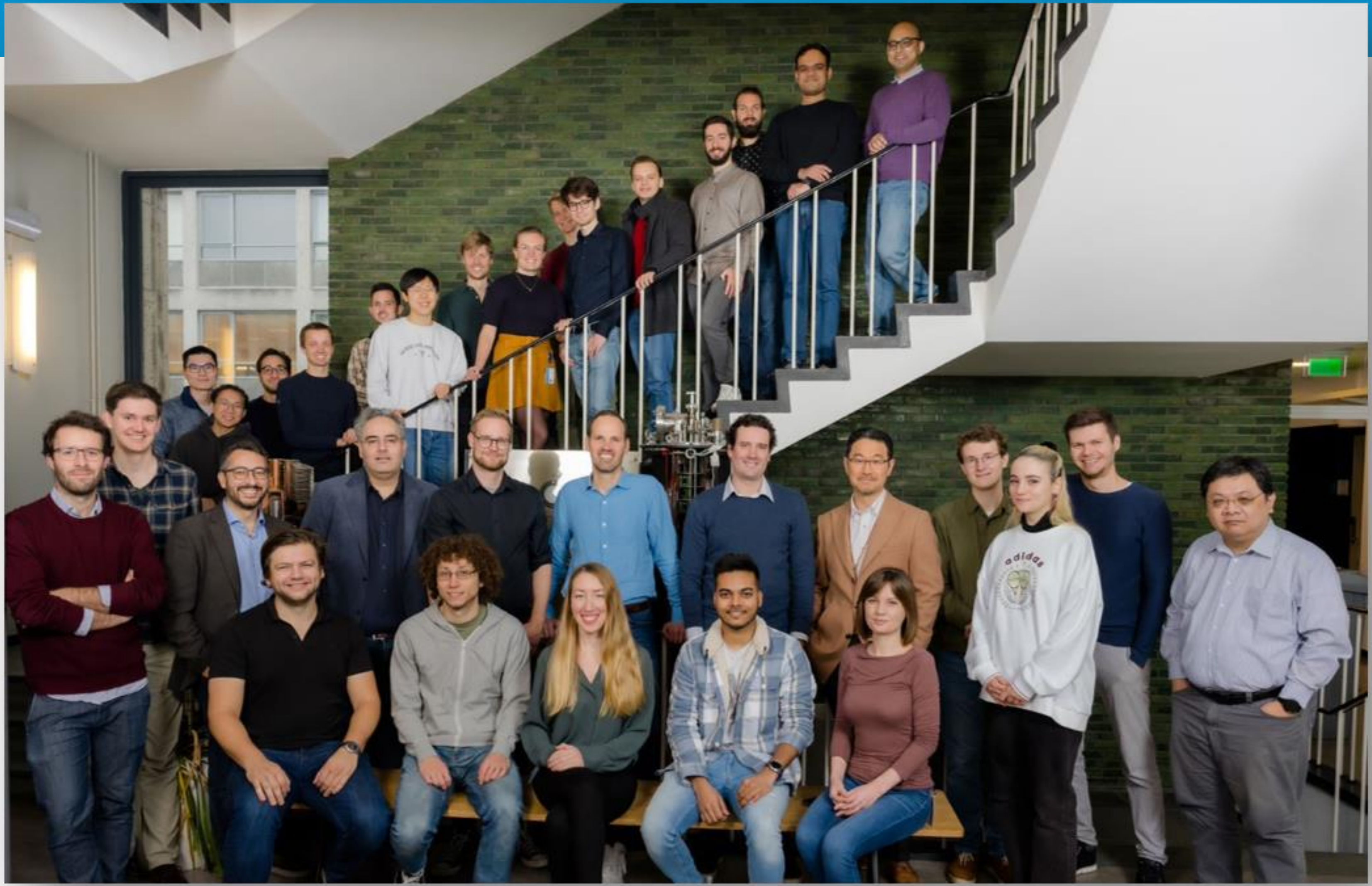


Thank you!



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