WACQT | Wallenberg Centre for Quantum Technology

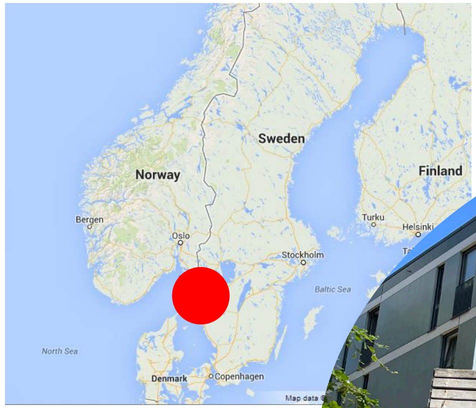
Building a full-stack quantum computer in an academic environment

Lessons from the WACQT center, Sweden

Simone Gasparinetti

Principal Investigator, WACQT
Assistant Professor, Chalmers University of Technology

My research group



202Q·LAB

Superconducting circuits for

- Quantum computing with bosonic modes
- Quantum thermodynamics
- Quantum-enabling technologies

CHALMERS

WACQT

Department MC2 Microtechnology and Nanoscience

Nano-fabrication facility myfab

Knut and Alice Wallenberg Foundation

Swedish Research Council

erc

European Innovation Council

Contact: simoneg@chalmers.se
Visit our website 202q-lab.se

How we work

Superconducting circuit design

Simulations of open quantum systems

Nanofabrication

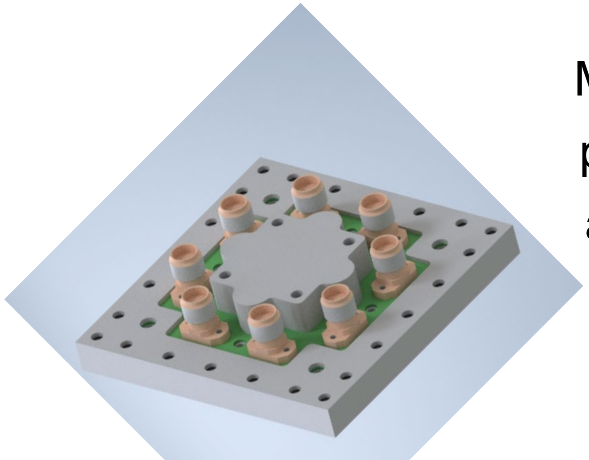
Circuit quantum electrodynamics

Microwave packaging and filters

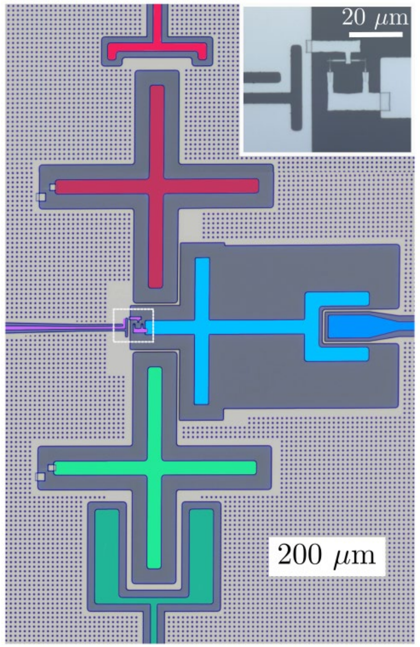
Microwave electronics

Cryogenic techniques

Quantum-limited measurements



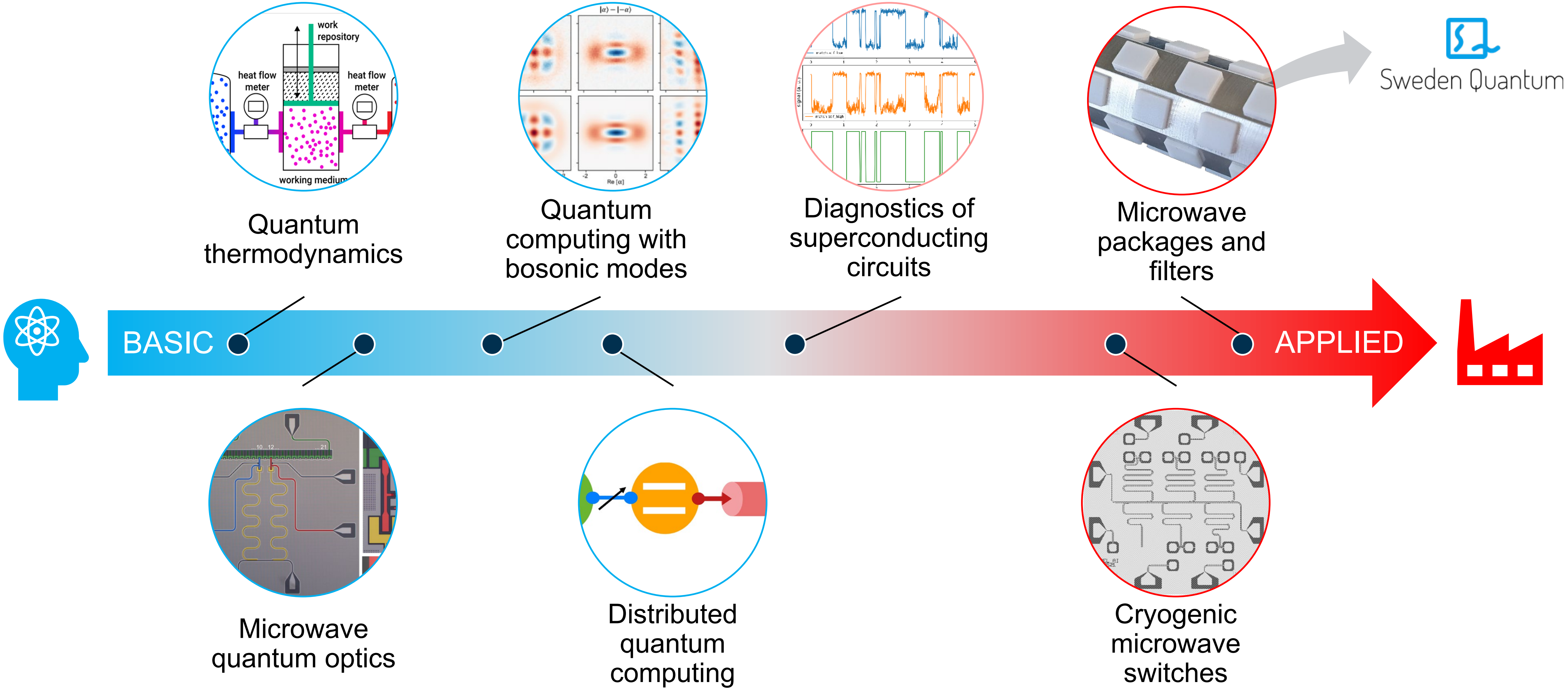
Own microwave package



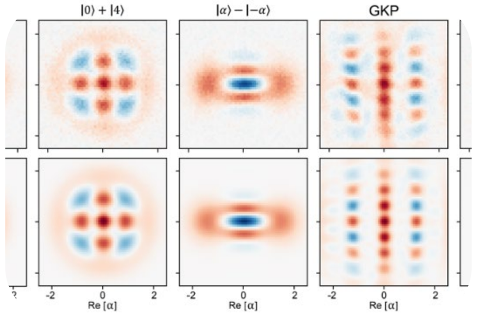
One-of-a-kind quantum circuit

Customized electronics

Our research

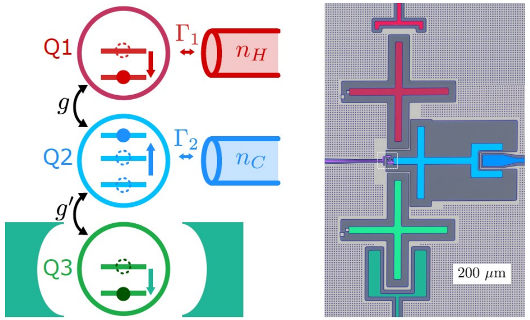


Some research highlights



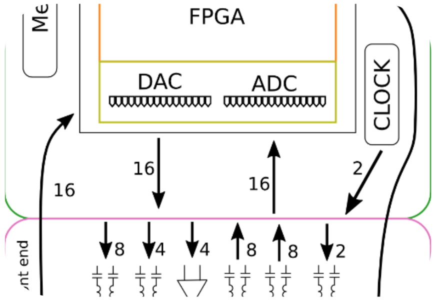
Quantum state preparation in 3D cavities

PRX Quantum **3**, 030301 (2022)



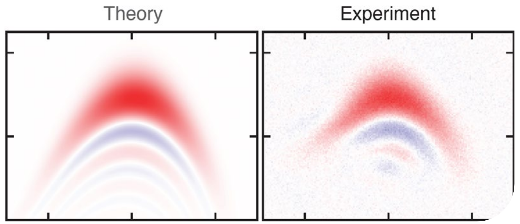
Autonomous qubit reset with quantum absorption refrigerator

arXiv:2305.16710



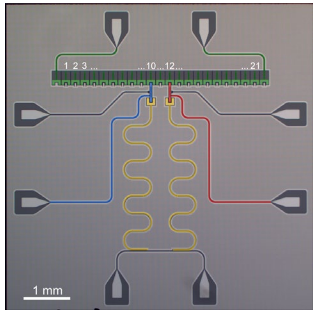
Qubit meas&control with integrated RF-SoC platform

Rev Sci Instr **93**, 104711 (2022)



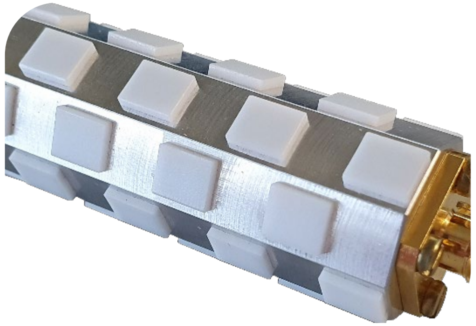
Control of a bosonic mode via native cubic interactions

arXiv:2308.15320



Atom-photon bound states in JJ resonator arrays

PRX **12**, 031036 (2022)



Low-pass filter for quantum computing applications

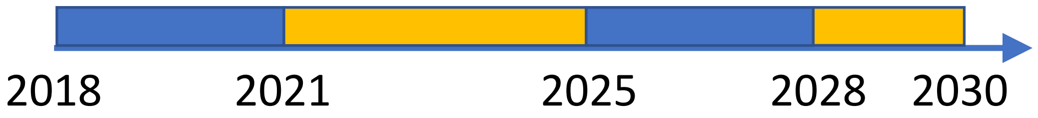
IEEE TMTT 1 (2023), patent pending

Outline

- Overview of WACQT
- Building a full-stack quantum computer at WACQT
- WACQT’s 25-qubit quantum processor
- Personal reflections

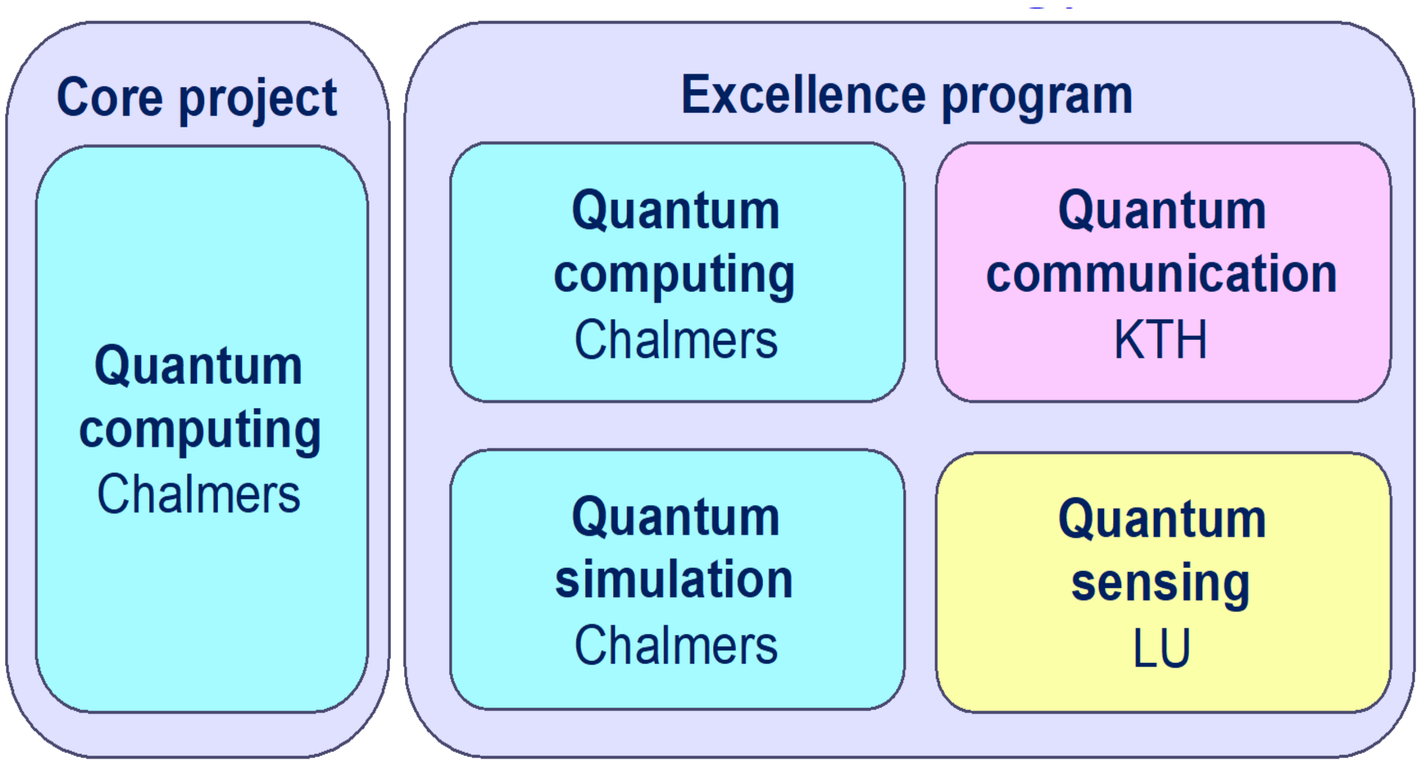
Wallenberg Centre for Quantum Technology

Main goals	i) To build a broad competence base in Sweden for Quantum Technology ii) To build a quantum computer based on superconducting circuits
Two parts	Core project on quantum computing Excellence program including all of Quantum Technology
Universities:	Chalmers, KTH, Lund, SU, LiU, GU 120+ people involved
Duration:	12 years, (3+4+3+2 years) Started Jan 1, 2018
Involving industry	Big industry for applications + SME for enabling technology
Funding:	1400 MSEK (~120 MEUR) from KAW foundation + Universities + Industry partners



Wallenberg Centre for Quantum Technology

Core project and Excellence program



WACQT total ~140 people

Graduate School
Guest researcher program
Industry collaboration

Total over 12 years:
85 PhD students
70 Postdocs
14 Assistant professors

Quantum industry related to WACQT

User companies

Volvo
AstraZeneca
Jeppesen (A Boeing Company)
Hitachi Energy
SAAB
Ericsson

7 industrial PhD students

Technology enablers

Spectracure
Intermodulation Products
Low Noise Factory
ConScience
RISE/SP

3 industrial PhD students

Spin-off companies

Deep Light Vision AB
Atlantic Quantum AB
ScalinQ
Sweden Quantum AB
quCertify
WACQT-IP

All started within the last 2 years

Quantum technology testbed(s)

Quantum algorithm testbed (for researchers and big companies; start in 2025)

- User facility for testing quantum algorithms
- Dedicated cryostat with an operational 25 qubit processor
- Upgrading to 40 qubits later when WACQT-platform after 4 years

Quantum algorithm help desk (start in 2024)

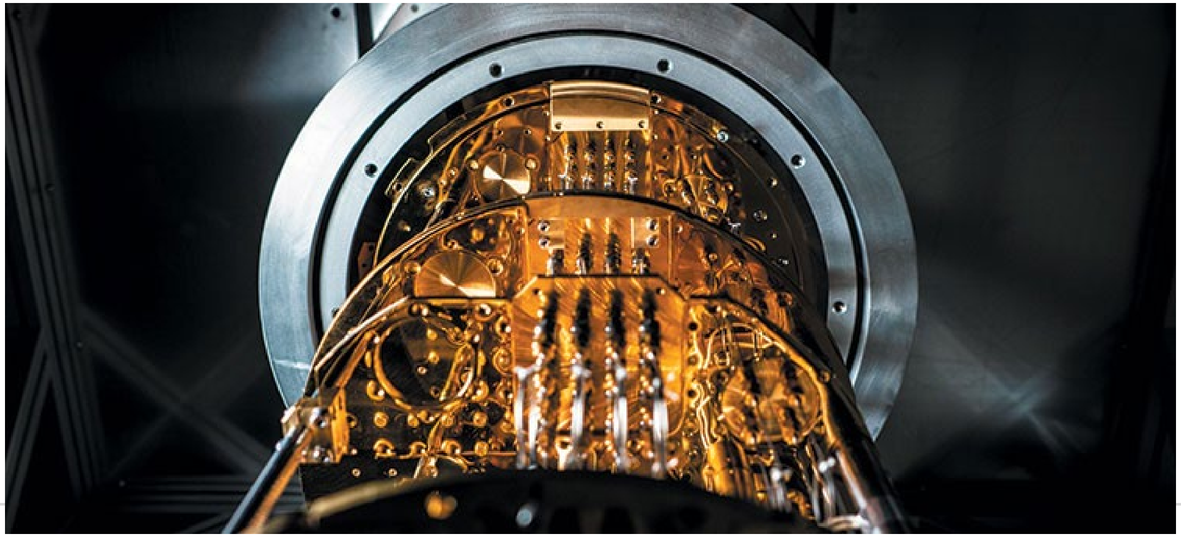
Quantum hardware testbed (for SMEs and spin-offs; start in 2024)

- User facility for testing quantum hardware at cryogenic temperatures
- Dedicated (smaller) cryostat
- Expertise on cryogenics and quantum technology

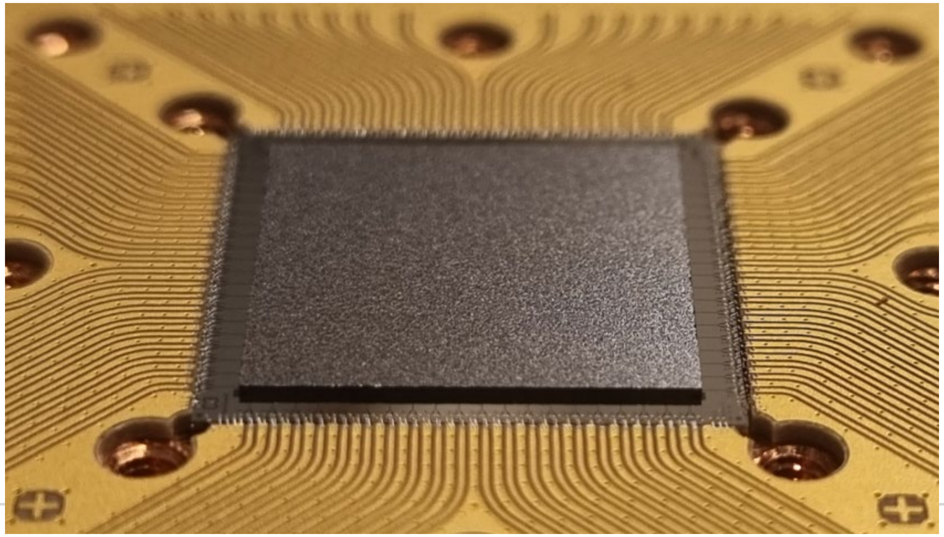
Operated by Next Labs, a company owned by the Chalmers Foundation

The WACQT Quantum Computer

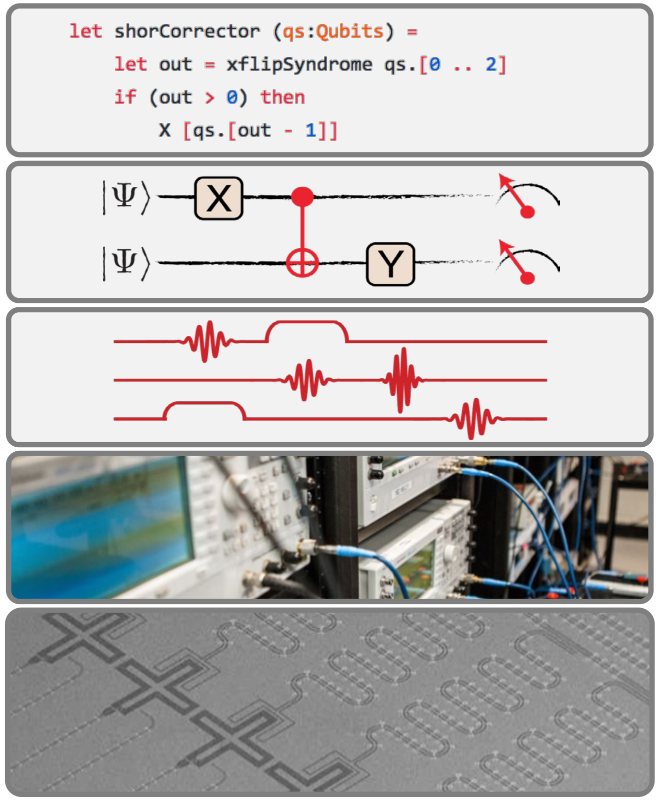
- A Swedish quantum computer based on superconducting circuits
- Application to use cases within optimization and quantum chemistry
- Full stack HW and SW development



The 25-qubit platform



WACQT has a full-stack approach



Quantum algorithms

Quantum compiler

Control system

Classical hardware

Qubit register

Engineering needs + opportunities for science at each layer, and their interface!

- Coherence + reproducibility
- Gates
- Readout
- 3D integration & packaging
- Crosstalk
- Control systems
- Software & automation
- … And many more

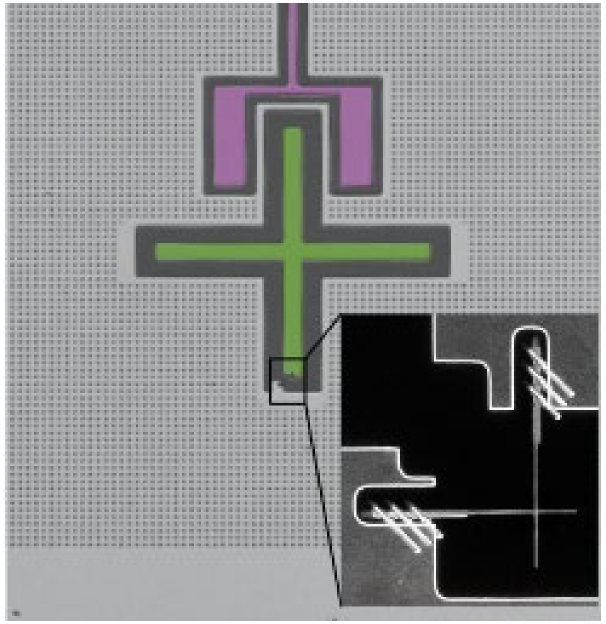
Experimental team working on core project

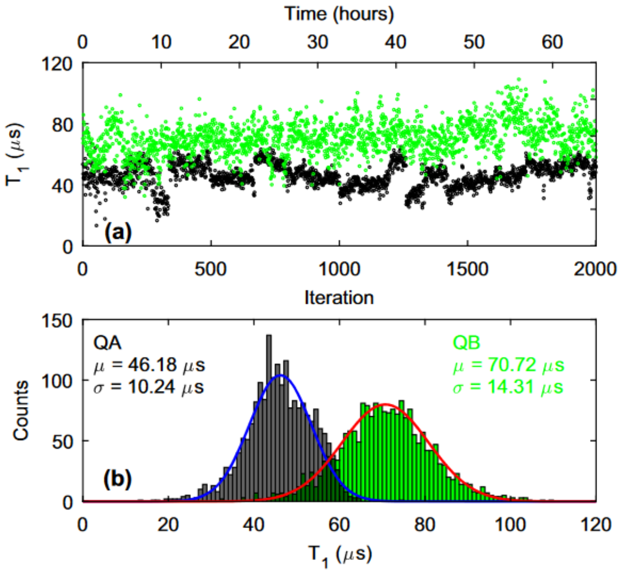
PIs	**Jonas Bylander** **Per Delsing** **Giovanna Tancredi**
Researchers	Anita Fadavi Robert Rehammar Daryoush Shiri
Senior res. engineers	Abdullah-al Amin (SW) Miroslav Dobsicek (SW) Marcus Rommel (Fab)
Research engineers	Martin Ahindura (SW) Nicklas Botö (SW) Stefan Hill (SW) Andreas Nylander (Fab) Krishnasamy Subramaniam
Lab Manager	Olga Yuzefovych

Postdocs	Sahara Hejazi Tangyou Huang Anna Kepiklova Sumit Kumar Eleftherios Moschandreou Tom Vethaak
PhD students	Anuj Aggarwal Janka Biznárová Liangyu Chen Christian Krizan Hang-Xi Li Amr Osman Hampus Rehnberg Nilsson Emil Rehnman Christopher Warren
MS	Maurizio Toselli Halldór Jakobsson

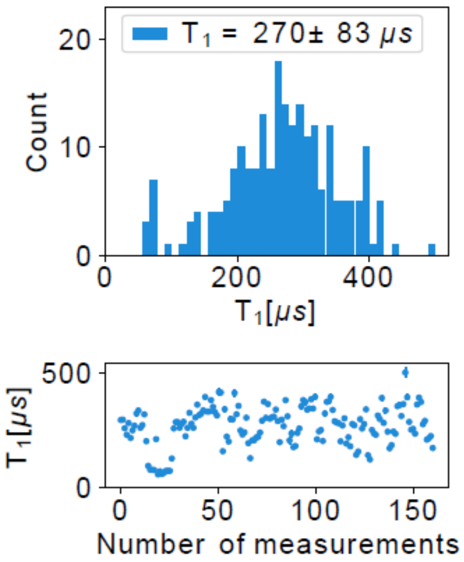
One qubit

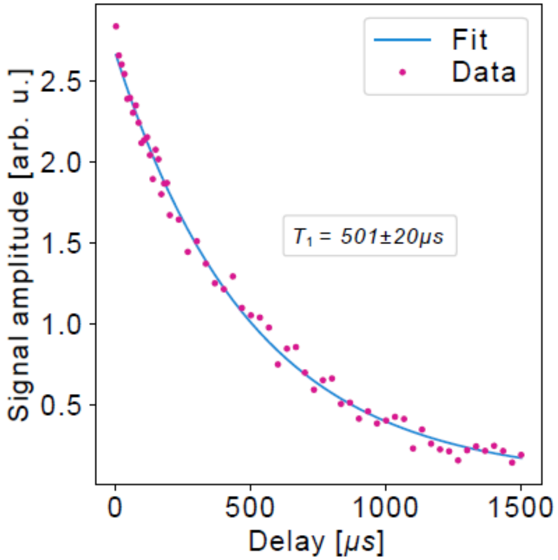
- Conventional transmon qubits, Al on Si
- Constantly improved thanks to material science + process development





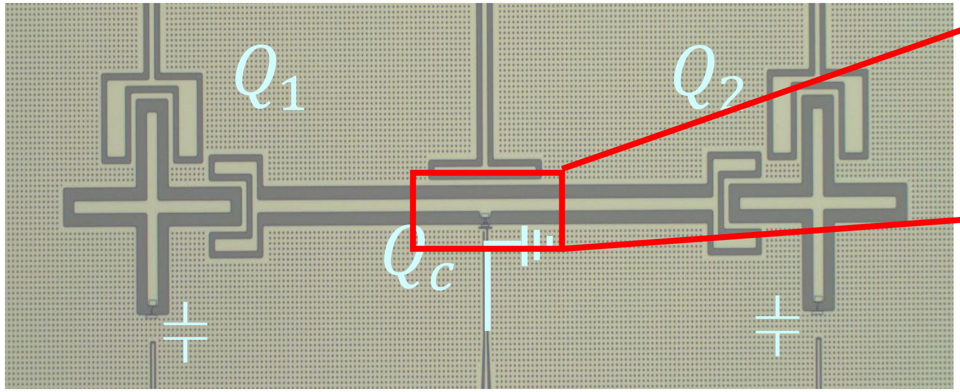
Burnett 2019, T_1 ~ 70 us

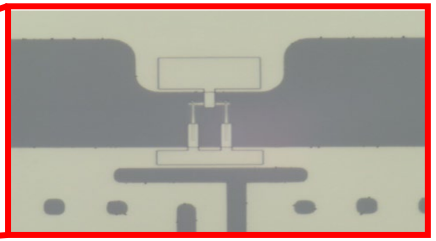




Biznarova 2023, T_1 ~ 270 us

Two qubits





Coupler SQUID

Single-qubit gates in 10-20 ns

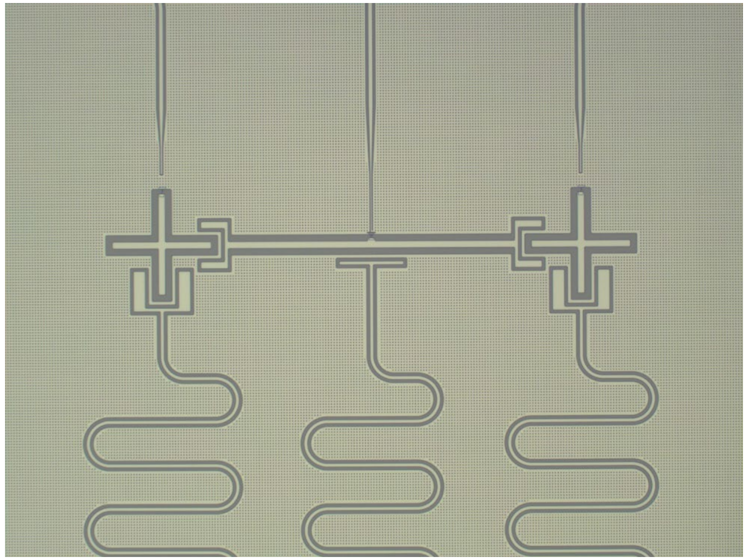
Two-qubit gate in ~ 300 ns

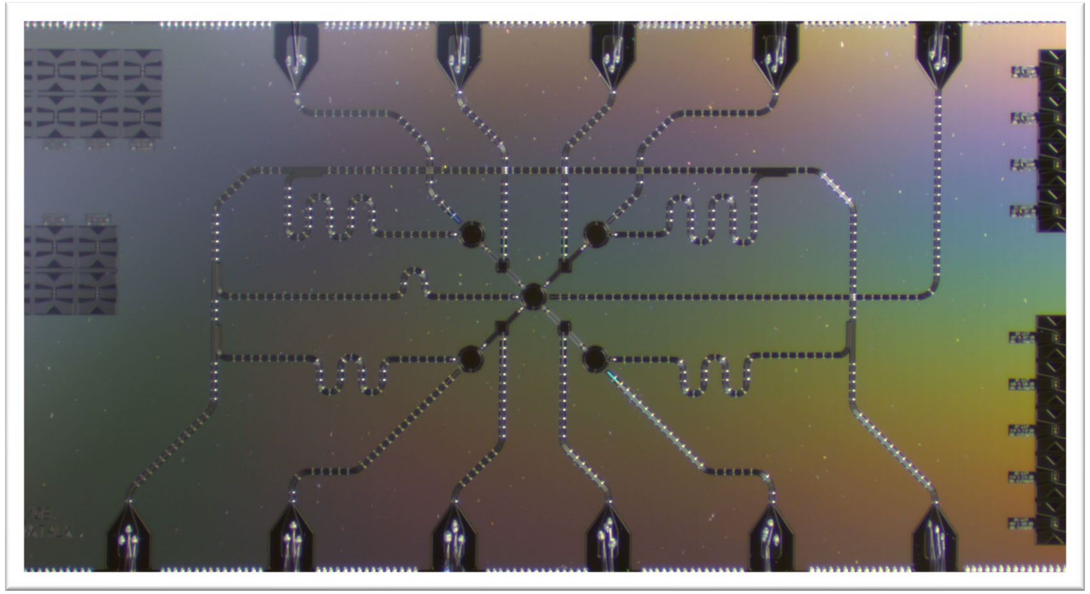
Readout 1-2 us (now 180 ns)

- Frequency-fixed qubits, frequency-tunable coupler
- Two-qubit gate (CZ) by parametric drive on coupler
- QAOA algorithm implemented on this device

McKay, PRAppl. 6, 064007 (2016)
Bengtsson, PRAppl. 14, 034010 (2020)

From 2 to 5 qubits





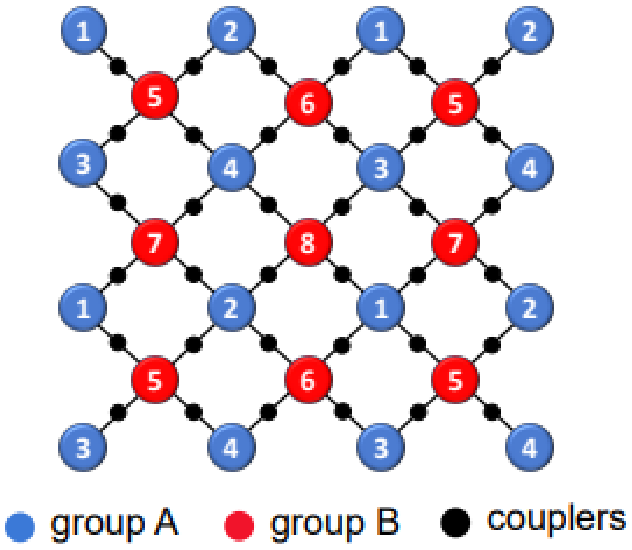
As we scale up, there is many more things to take care of!

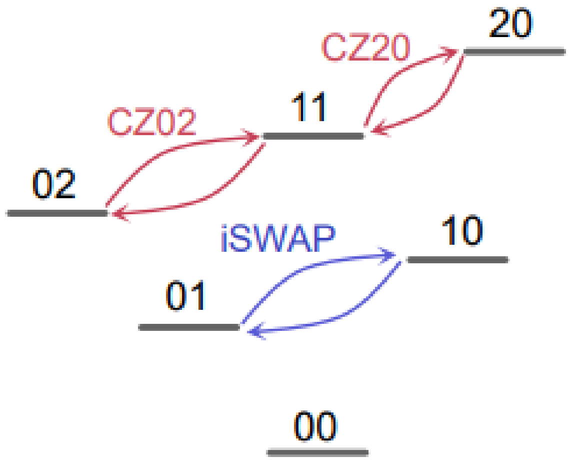
Connectivity Frequency collisions Crosstalk Reproducibility …

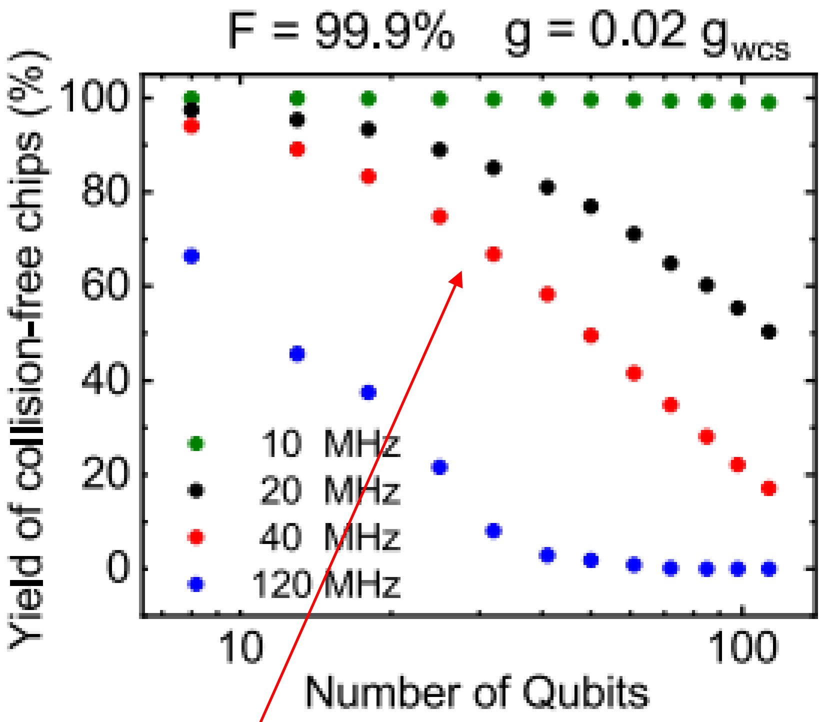
25-qubit processor: avoiding collisions

Tileable 4 x 4 pattern

Two groups of qubits with different anharmonicities





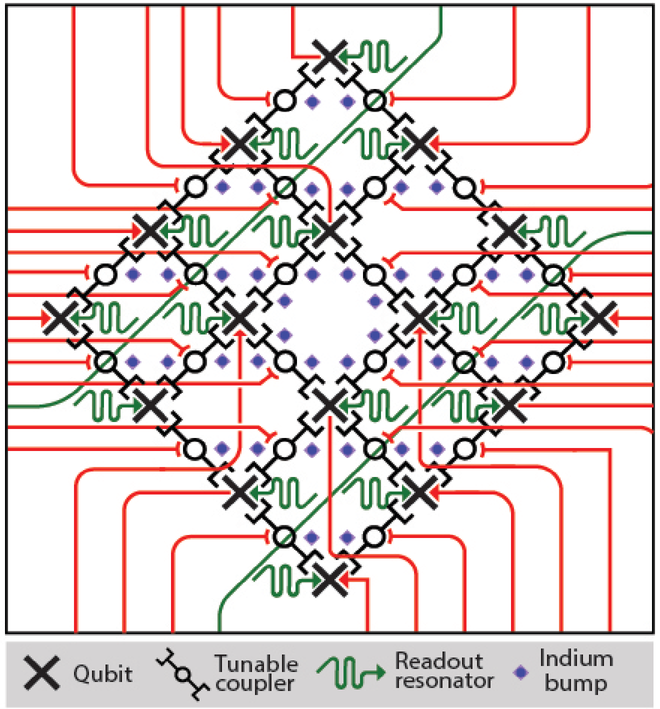


Our standard deviation of qubit frequencies is 40 MHz

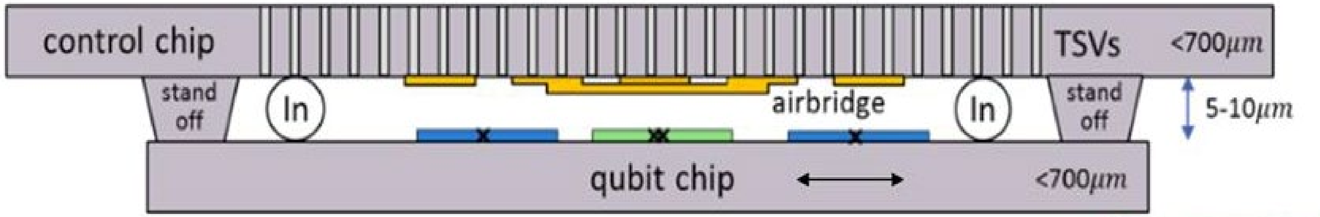
Osman, PRR 5, 043001 (2023)

25-qubit processor: 3D integration

Conceptual architecture



Flip-chip module



Flip-chip module

- **Quantum chip**: qubit array and couplers
- **Control chip**: measurement & control lines
- **Bump-bonded module**

Features

- Scalable
- Highly connected
- Addressable
- Crosstalk-mitigated
- Packaged
- Standardized

Kosen *et al.*, Quant Sci Tech 7, 035018 (2022)

25-qubit processor: physical design

Device layout (qubits, control lines, read-out)

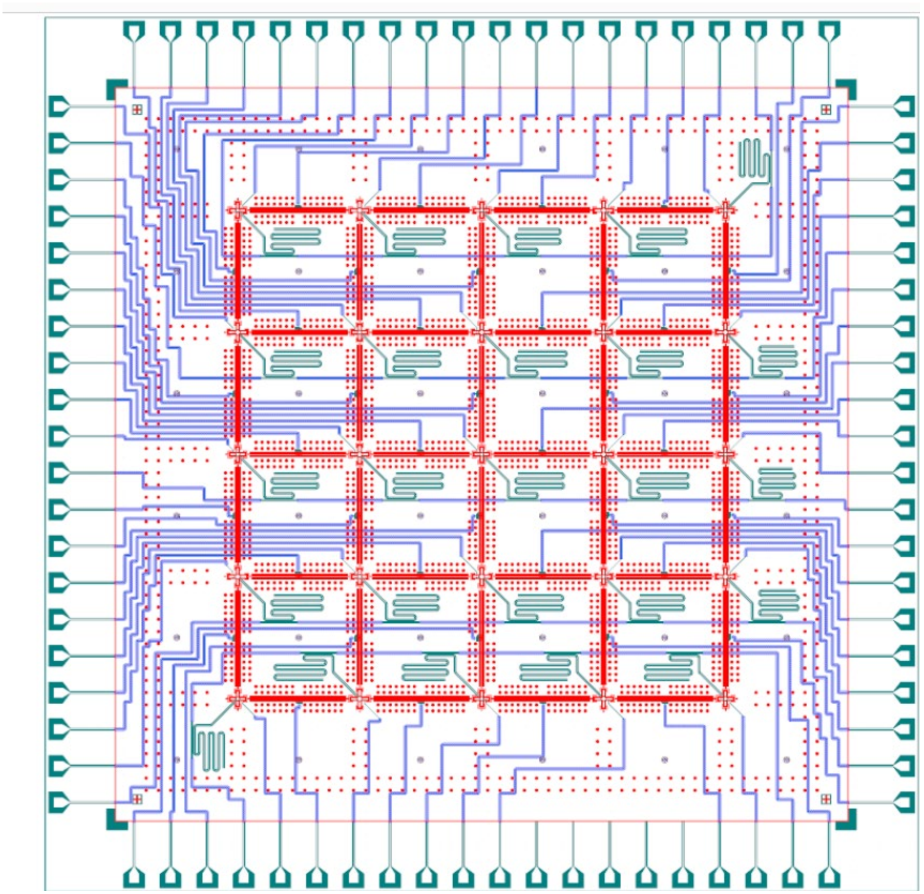
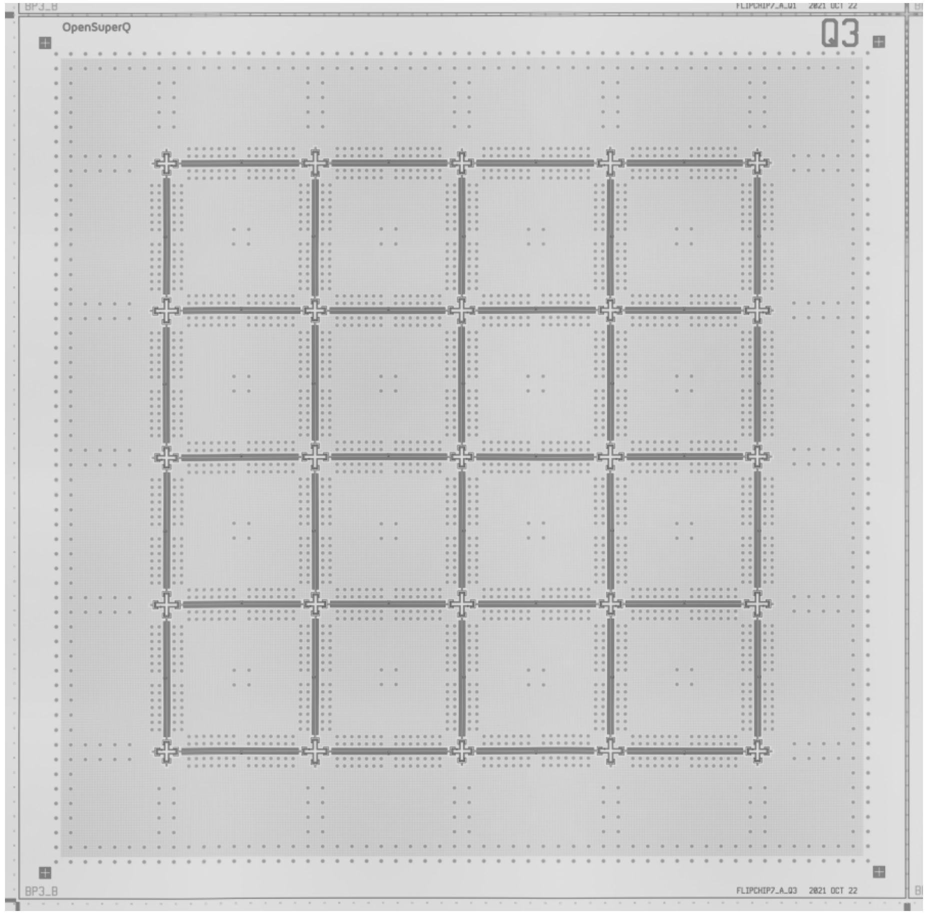
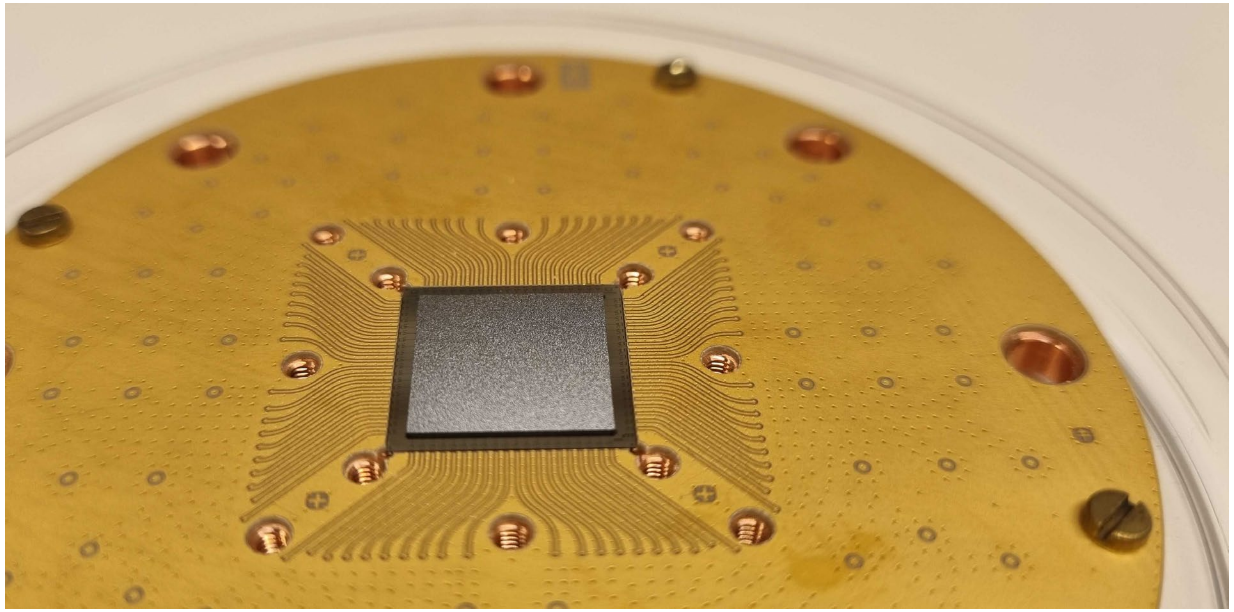


Photo of 25 qubit chip



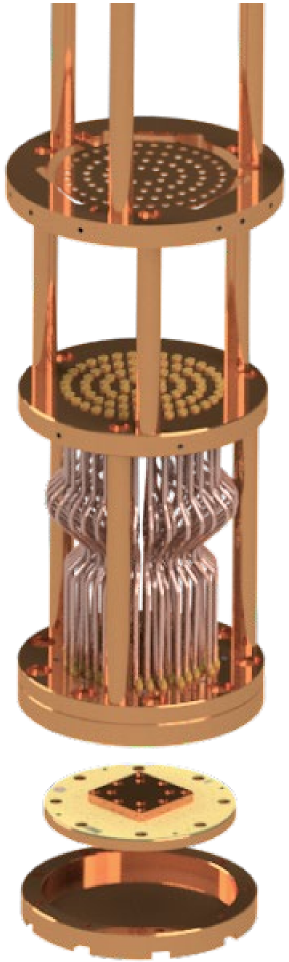
25-qubit processor

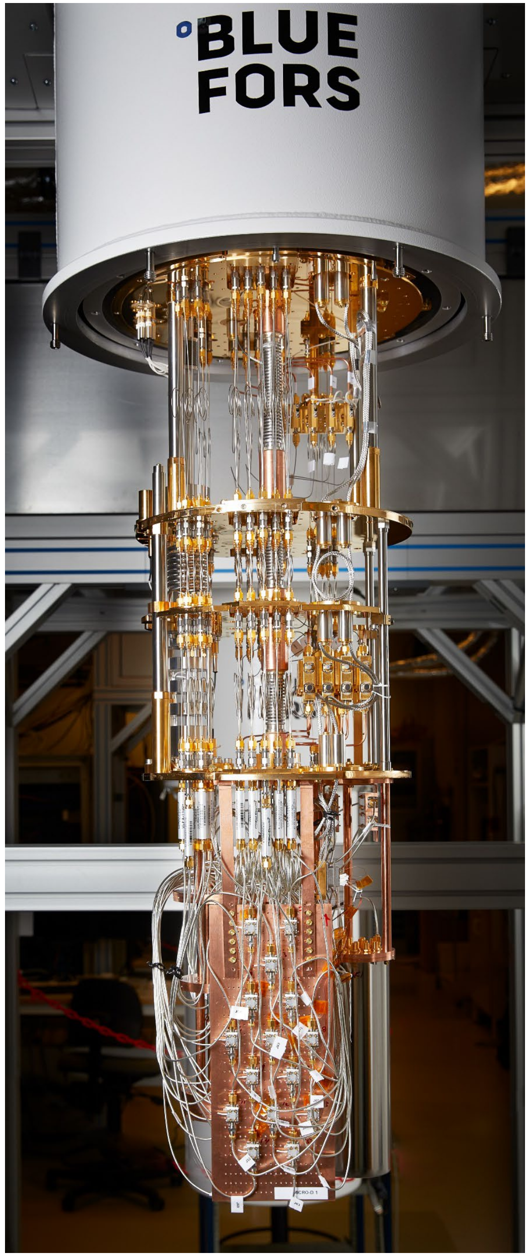
Made at Chalmers, bonded at VTT, measured at Chalmers



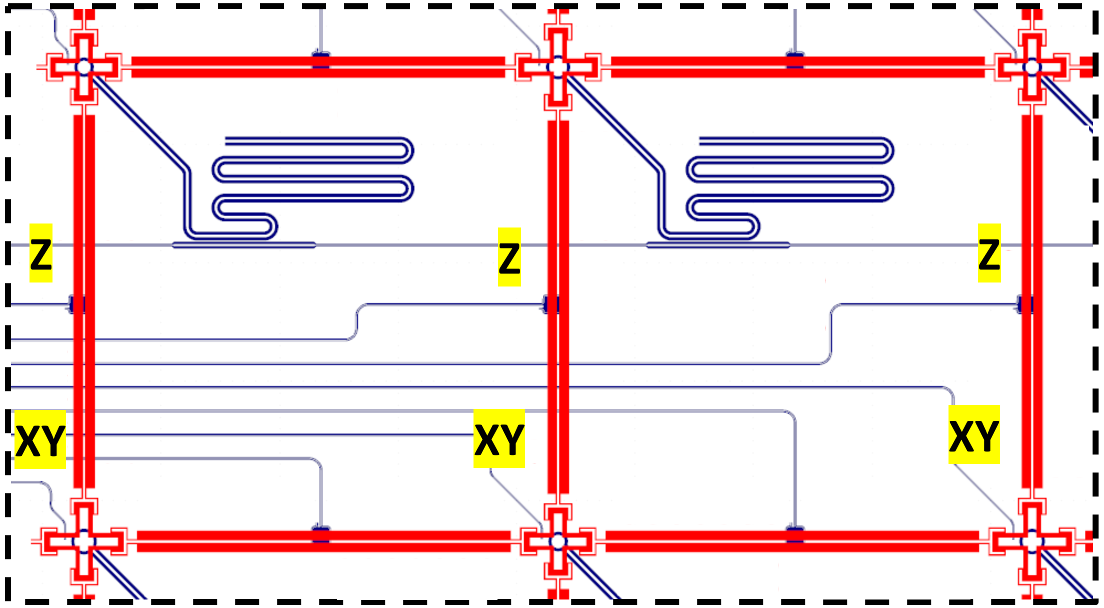
- 25 qubits in a 5 x 5 grid
- Pairwise coupled
- CZ parametric gates

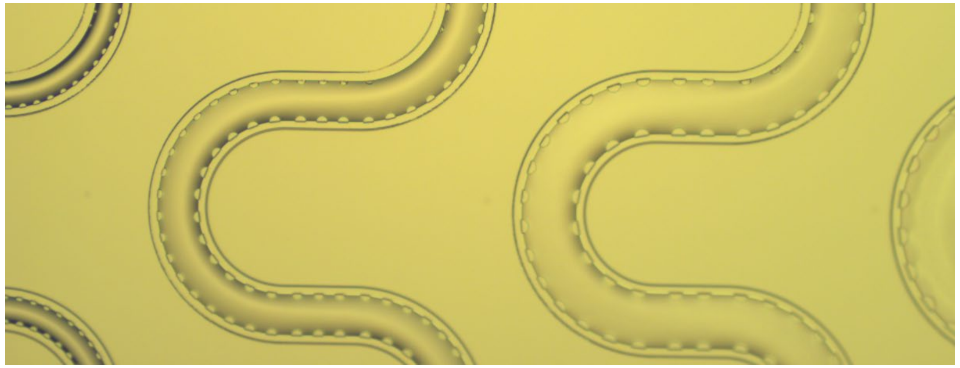
- $T_1 > 90\ \mu s$
- F(1Q) > 99.9%
- F(CZ) > 98.6%





Investigating cross-talk





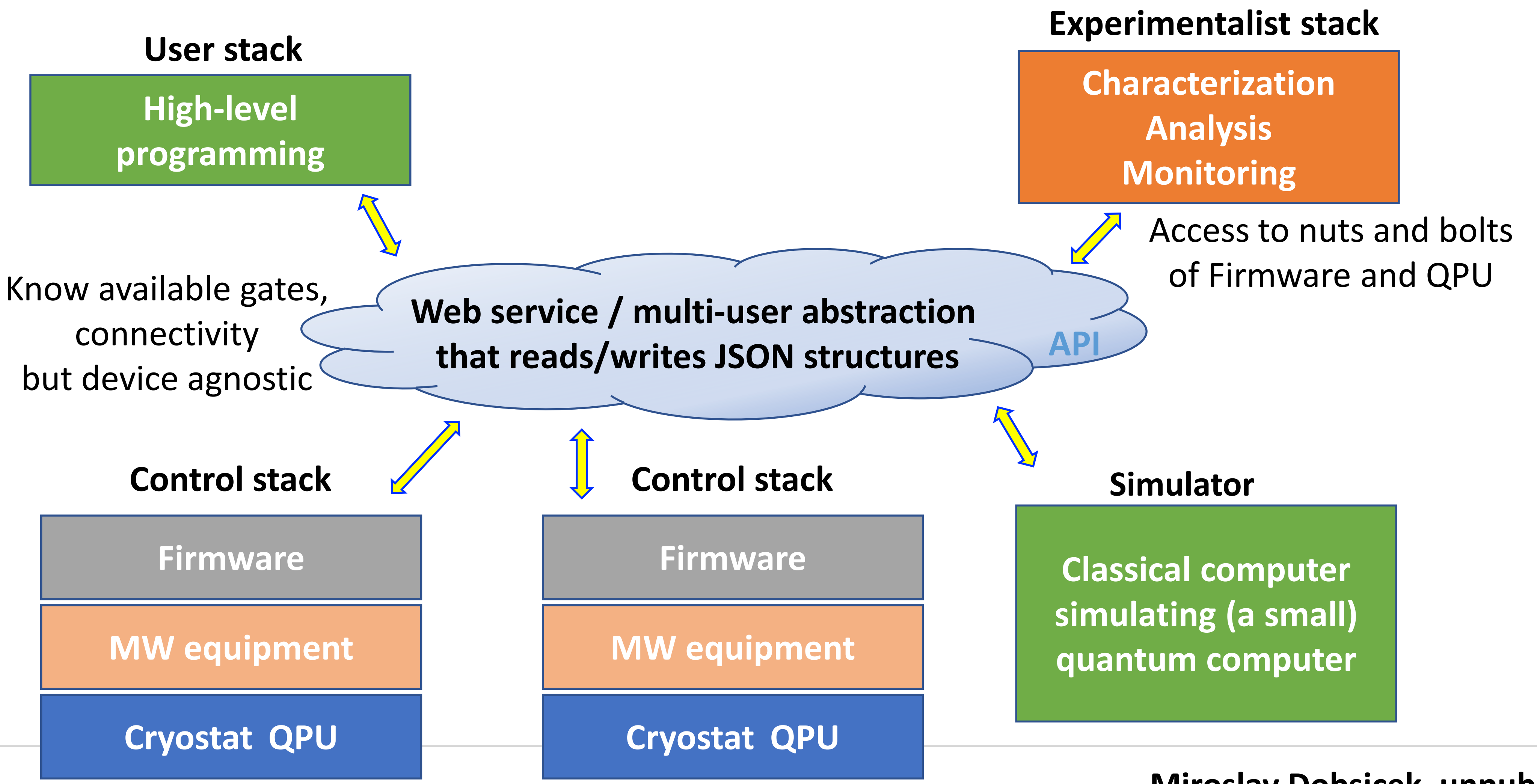
Superconducting tunnels to shield all the control lines on the C-chip

- XY on-resonant crosstalk ~ -40 dB
- DC flux crosstalk below ~ 0.1%

This is really good!
Thanks to flip-chip environment, return current engineering, magnetic field shielding via airtunnels

Kosen *et al.*, in prep.

Software stack



<u>**Miroslav Dobsicek, unpublished**</u>

Software stack – automated tune-up

Single-qubit simultaneous calibration

15 qubits

11 routines
- Resonator spectroscopy
- Qubit spectroscopy
- Rabi (f01)
- Ramsey (01)
- DRAG optimization (amplitude and derivative)
- Resonator spectroscopy (with qubit in|0>, |1>)
- Qubit Spectroscopy (f12)
- Rabi (f12)
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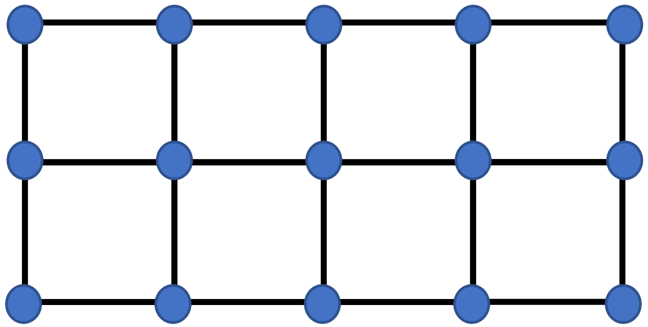
- Resonator spectroscopy (with qubit in|0>, |1>, |2>)



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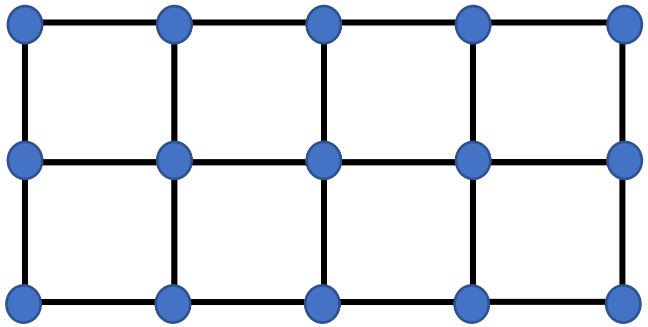

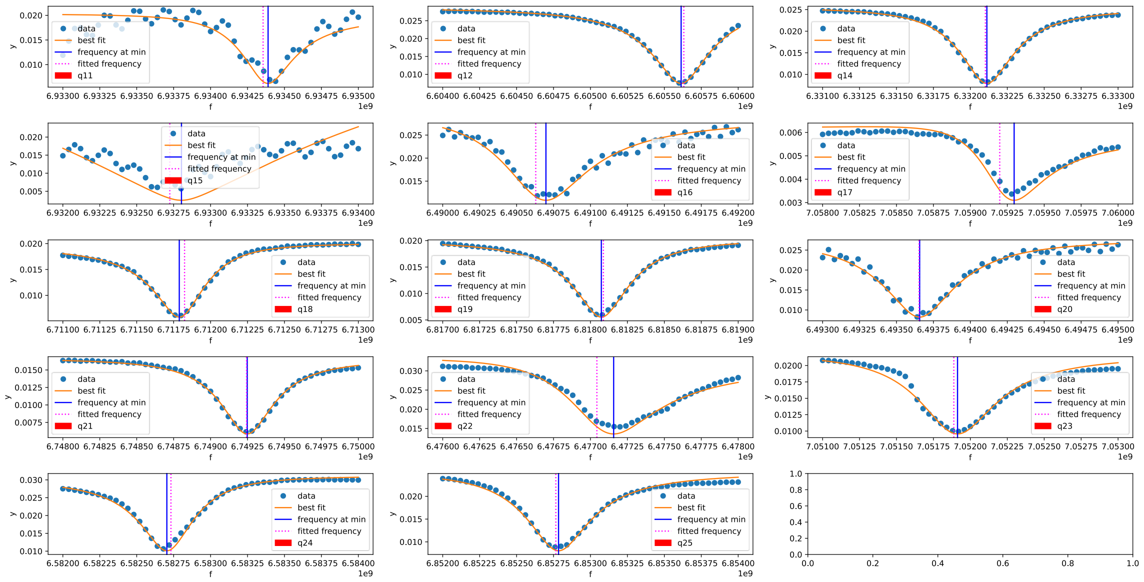

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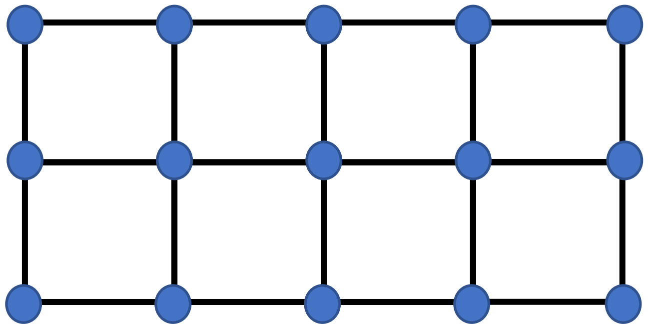

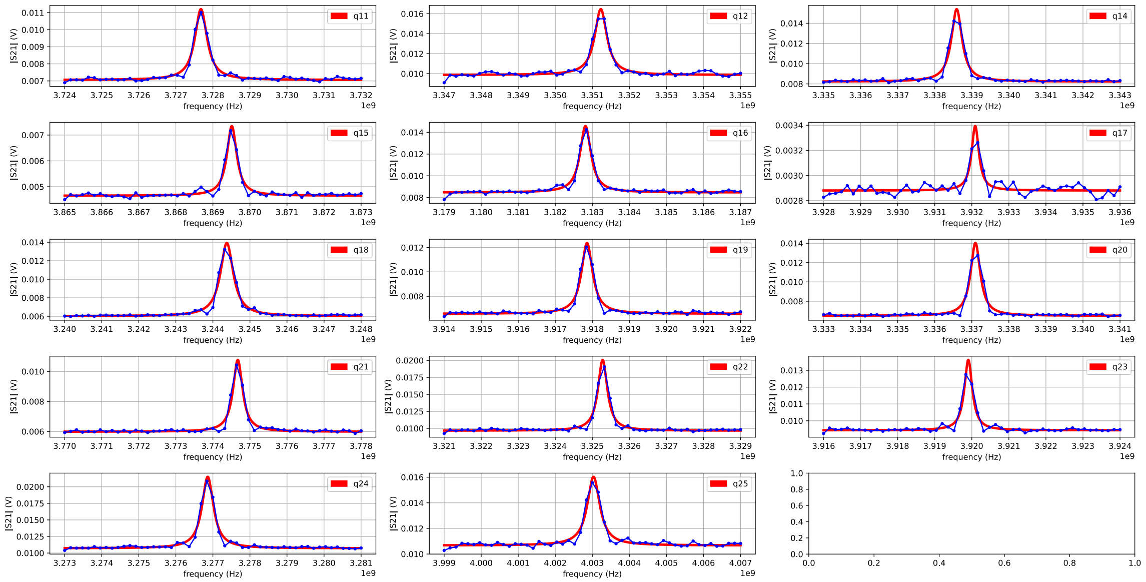

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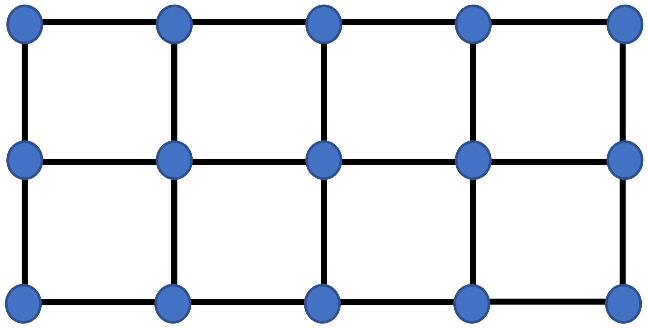

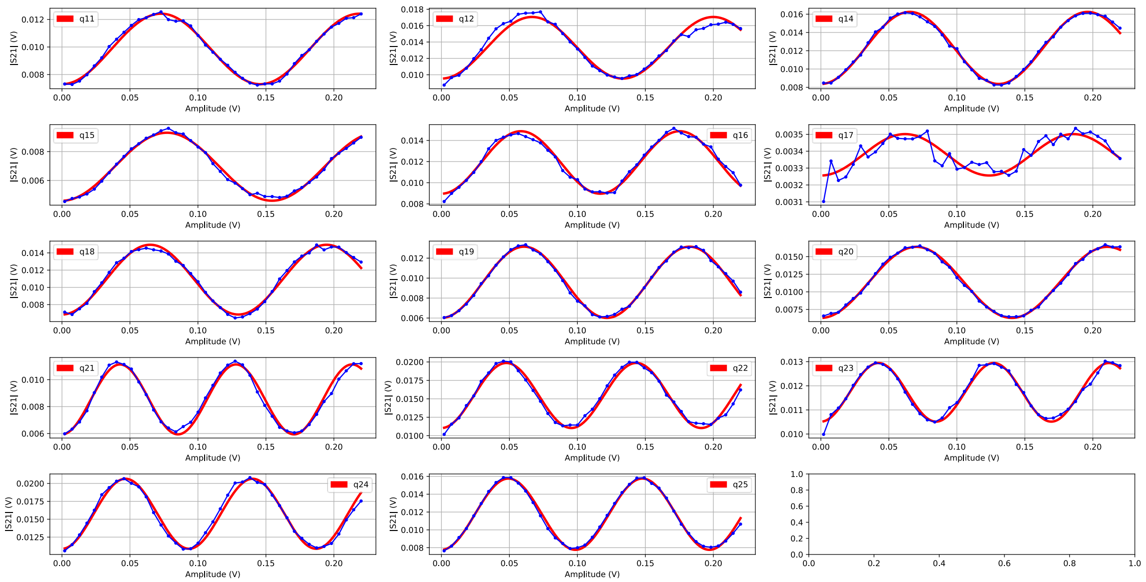

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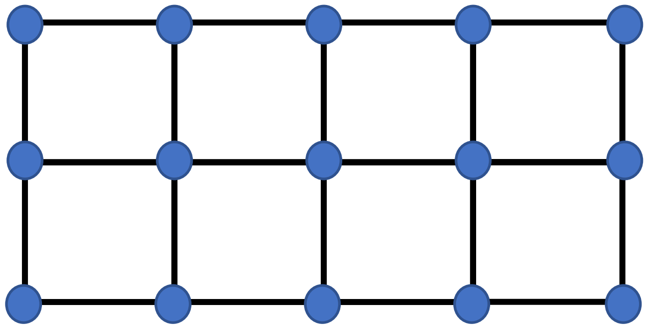
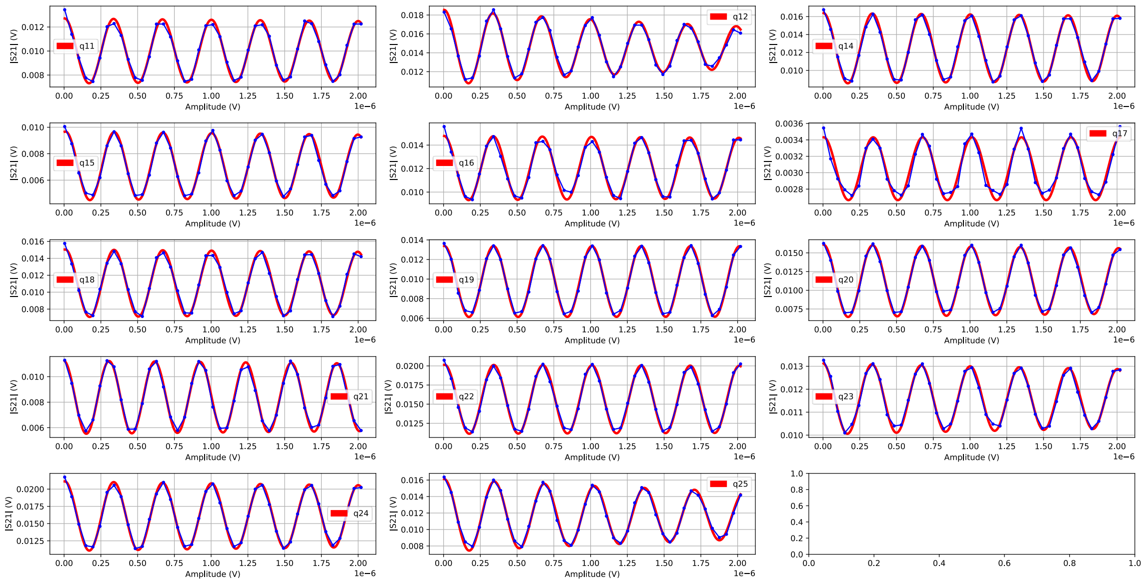
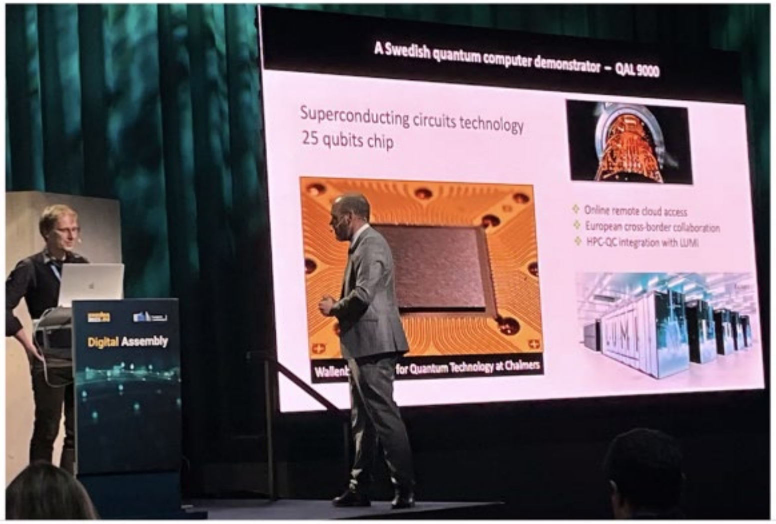


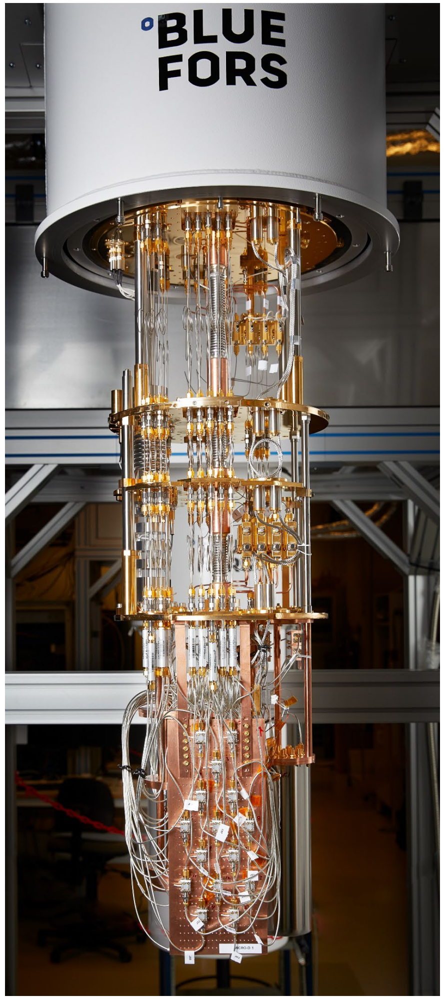


Software stack: connecting to HPC



Live demonstration at the EU Digital Assembly 2023
https://www.youtube.com/watch?v=52vOdakwT1Q
(WACQT Demo: 5h 9min)

Miroslav Dobsicek



- Online remote cloud access
- HPC-QC integration with Lumi
- HPC pre- and post-processing capabilities for quantum jobs
- Simple demonstration of QML

Still so much to do…

Improving qubits

Understand Two-level Fluctuators (TLFs)
Optimize substrate materials
Improve reproducibility
Thermalize qubits (and TLFs)

Develop new types of qubits
Implement error correction

System integration

Packaging at mK temperatures, 3D integration
Microwave solutions for operating a large-scale quantum computer

Software for quantum computers

Quantum computer operation
Quantum algorithms for real world use cases

What have we learned?

Can one build a quantum computer in academia? Yes, but beware:

- High employee turnover! Work on shared documentation and onboarding.
- Hire permanent researchers if you can. Better if they have industry experience.
- Science or engineering? Do it together. Look for inventive tweaks as you catch up.
- Get the theorists on board. Develop a deep mutual understanding.
- Software is very important! Easy to underestimate for (some) physicists
- Enabling companies greatly help. However, promiscuity can cause problems. Set clear boundaries.
- Working with user companies requires patience but is worth it. In Sweden, moderate interest.

Quantum computing still needs major breakthroughs – likely from academia

Thank you!

More questions? simoneg@chalmers.se