INTRODUCTION TO QUANTUM AND TKET

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Quantum Evangelist
Quantinuum

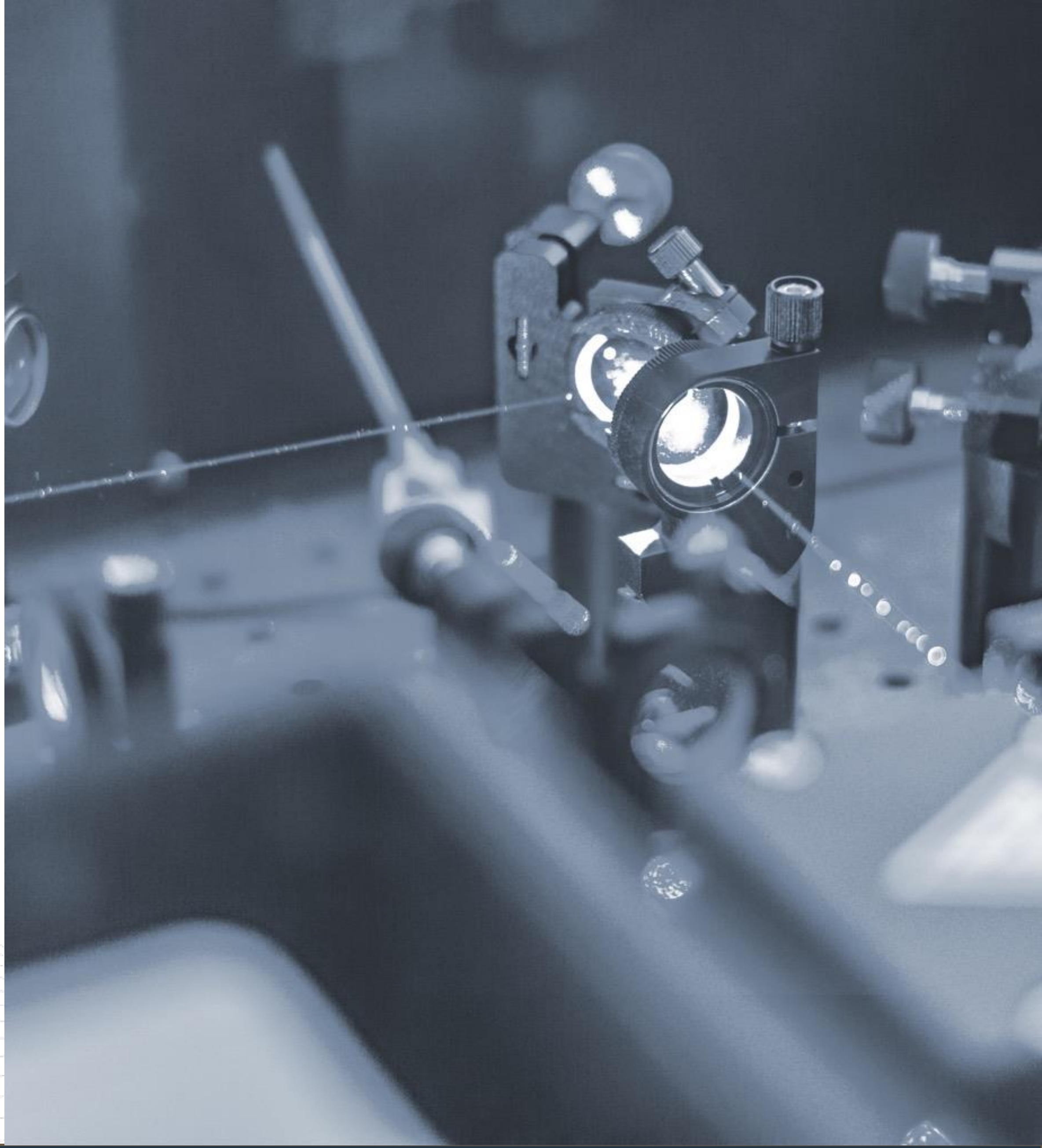
October, 2023

Overview

- Introduction to Quantinuum
- Quantum Computing Hardware
- Quantum Computing Software
- Introduction to TKET
- TKET coding example
- Summary

Google Colab

https://tinyurl.com/dtdrhvab



Quantinuum at-a-glance

WHO WE ARE

350+

scientists and engineers
(of which > 200PhDs)

LARGEST PLAYER

in integrated quantum hardware and software

Global teams in largest quantum markets
(USA, UK, Europe, Japan)

WHAT WE OFFER

H-SERIES

World class QCCD, ion trap hardware

FULL STACK

InQuanto™ Quantum chemistry software.
TKET™ open-source developer tool kit.
LAMBEQ™ open-source natural language processing

Collaborations and partnership with leading commercial and academic organization

USER COMMUNITY

>80

Scientific publications using H-Series hardware

> 400

Global users of H-Series hardware

>1,000,000

Downloads of TKET™ open-source tool kit

Led by industry pioneers

Rajeeb Hazra
President & CEO

Tony Uttley
Founder & Chief Operating Officer

Ilyas Khan
Founder &
Chief Product Officer

Platform Inclusive

INQUANTO™
Quantum Chemistry

Applied Quantum Algorithms (AQUA)
Machine Learning, Financial Modeling, Simulation, and Optimization

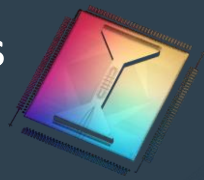
Quantum NLP

TKET

QUANTUM ORIGIN
Verifiably the world's strongest encryption key generation

Microsoft Google OQC IONQ
aws IBM IQM ... and many more

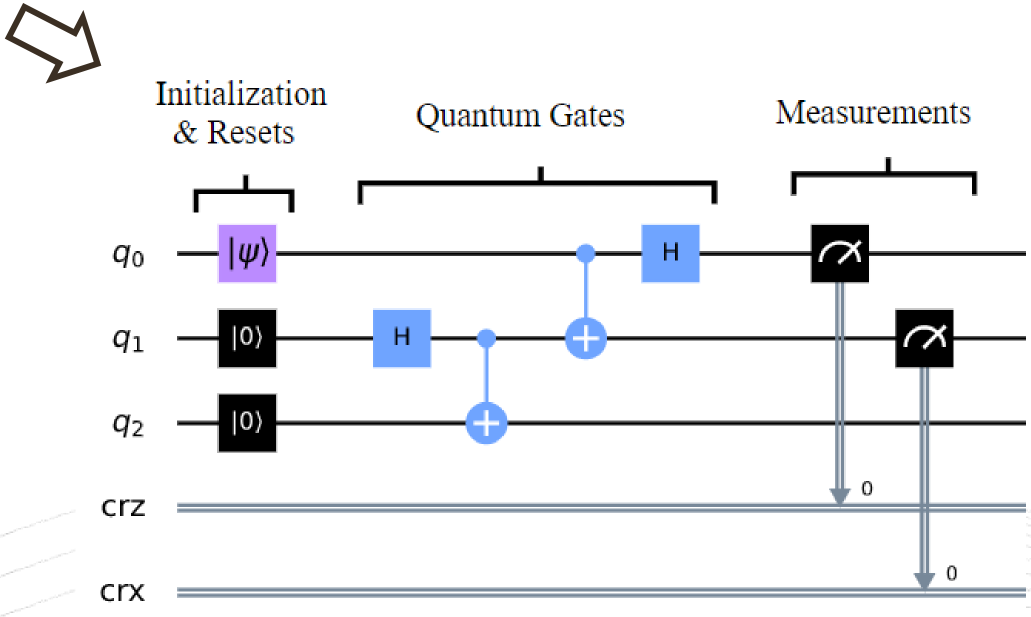
H – Series Quantum Computers
Powered by Honeywell

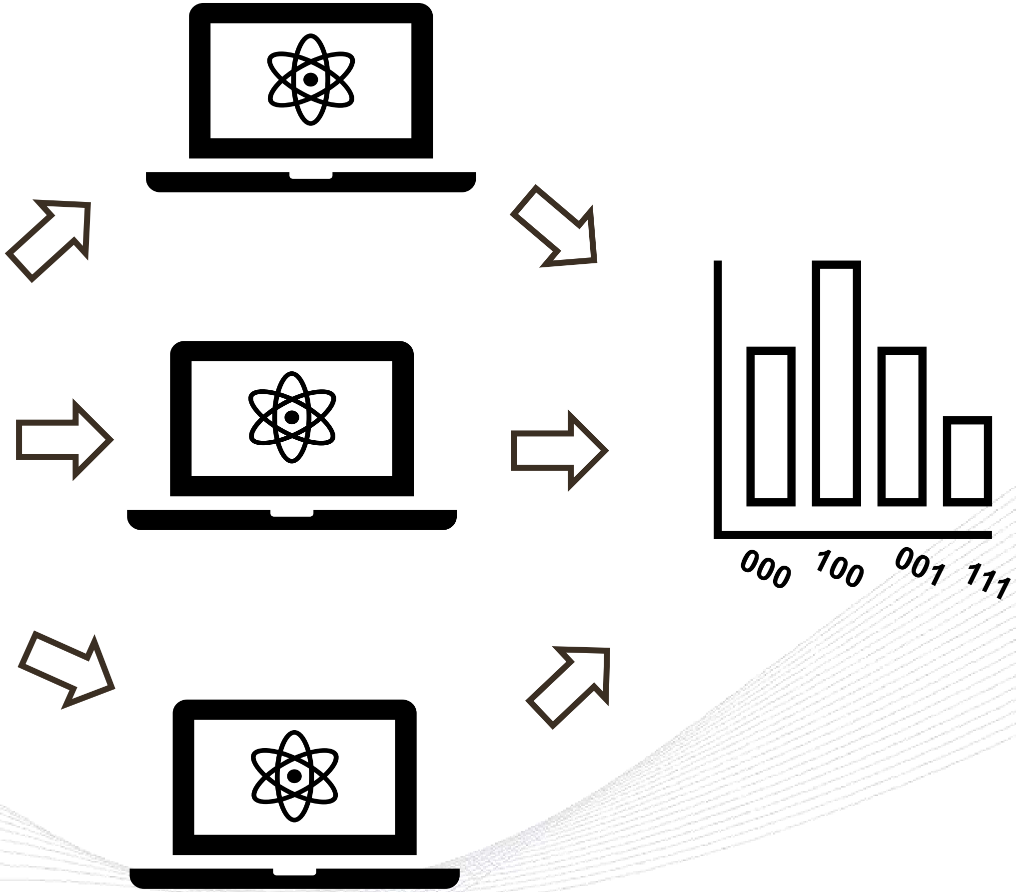


QUANTUM COMPUTING HARDWARE

GENERAL COMPUTATION ON A GATE-BASED QUANTUM COMPUTER

$$|\psi\rangle = c_1 \, |0 \dots 0\rangle + \cdots + c[2^N]|1 \dots 1\rangle$$



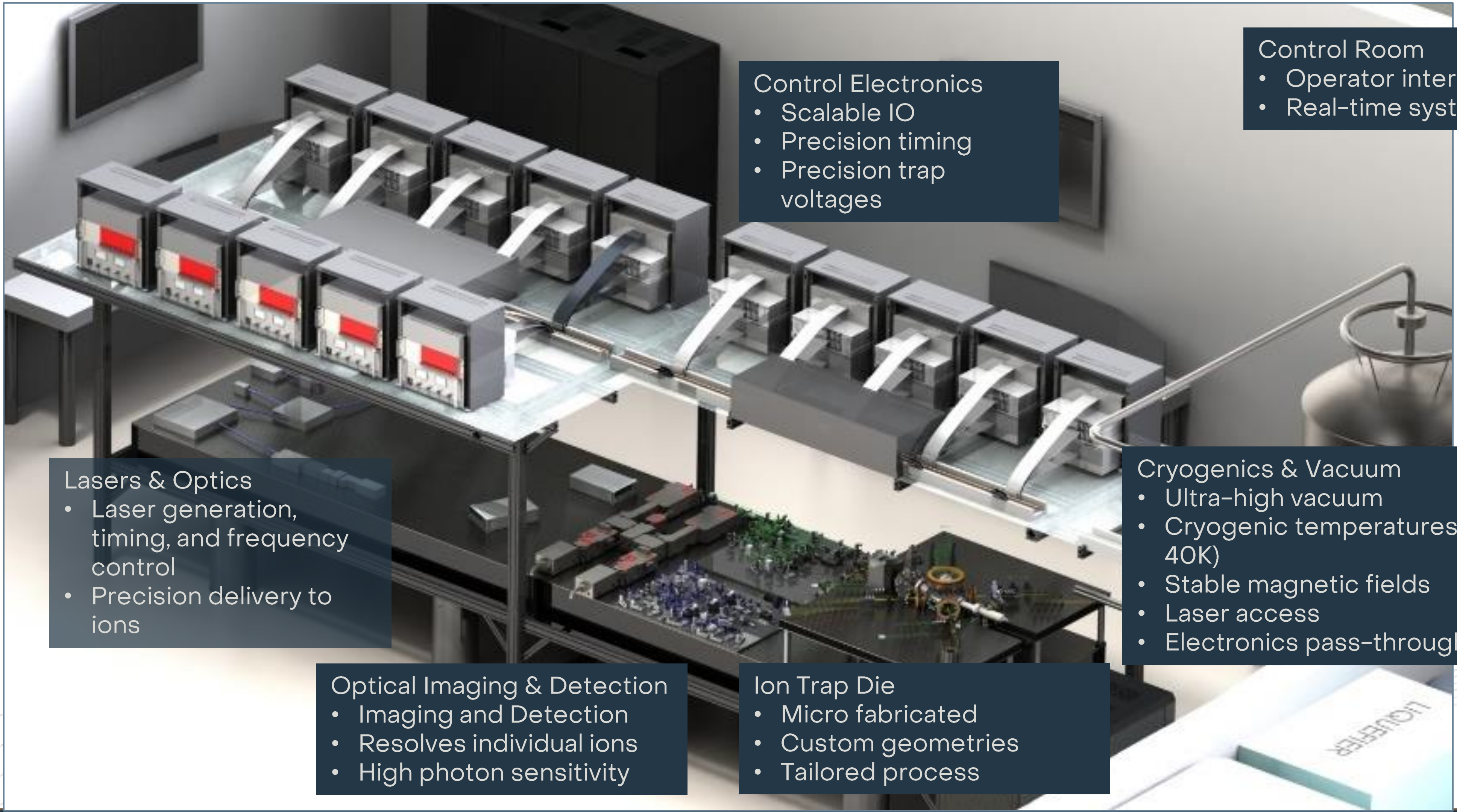


What Does a Quantum Computer Look Like?

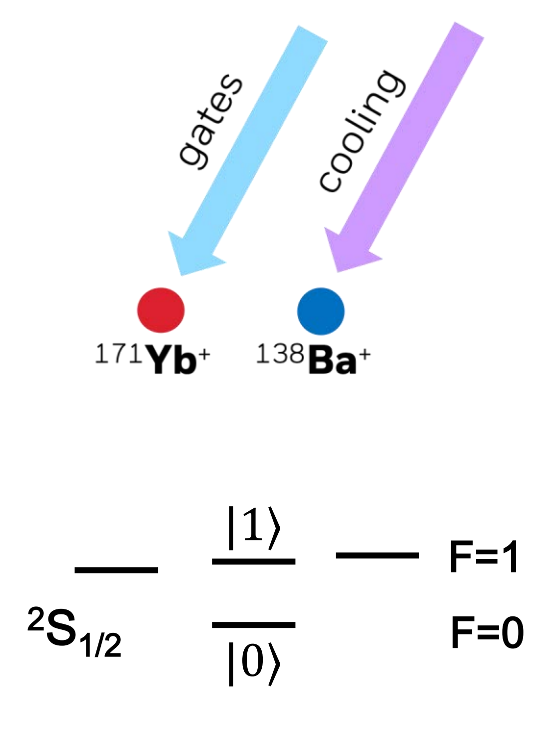
IBM

Quantinuum

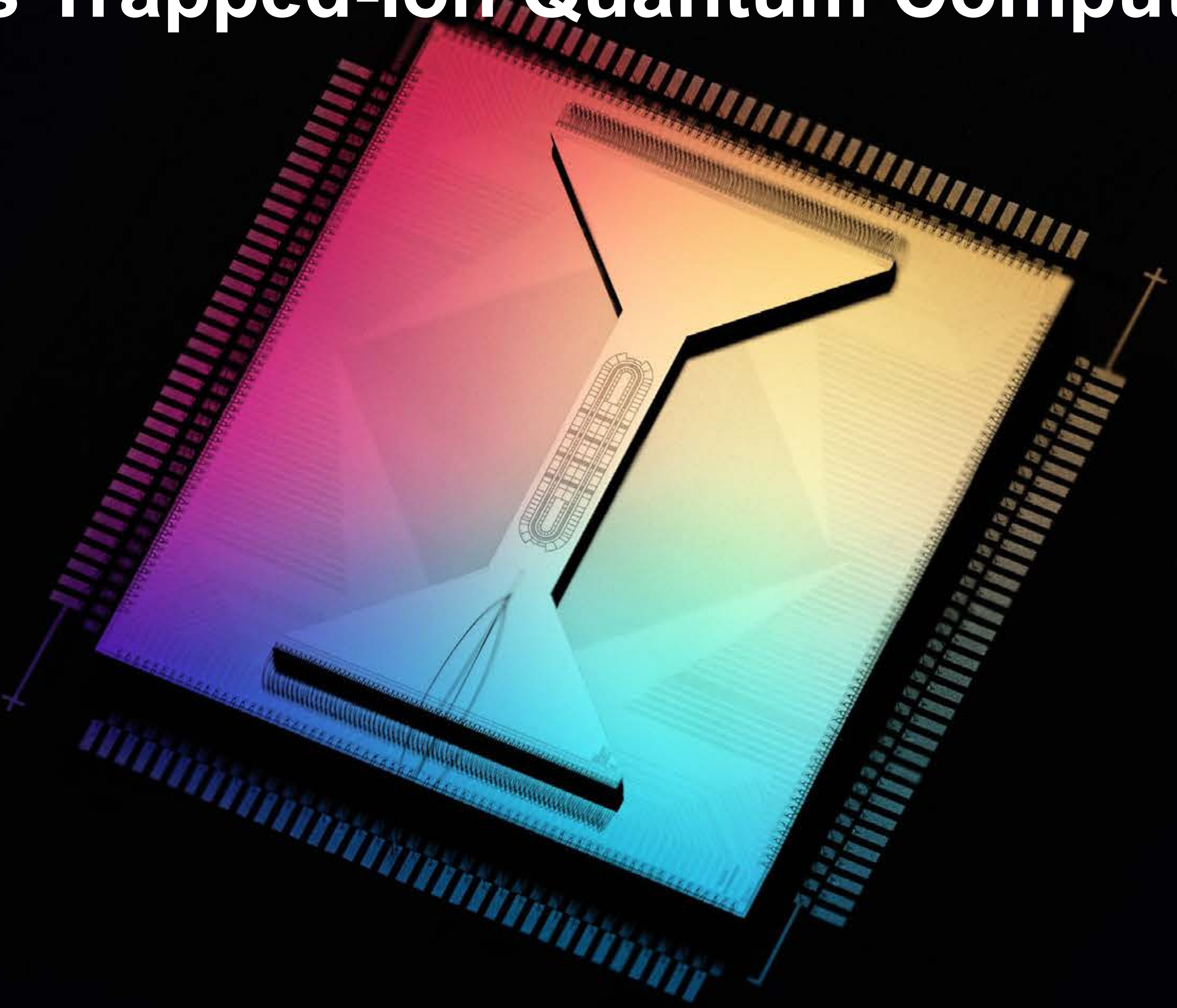
Key Subsystems for H-Series Quantum Computers



Quantinuum's Trapped-Ion Quantum Computer



Hyperfine qubit



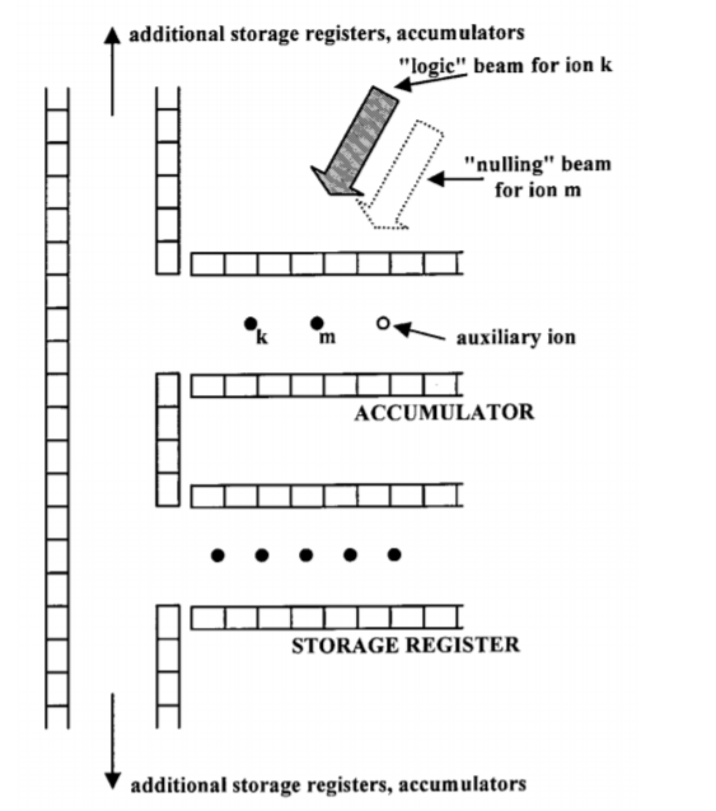
QCCD ARCHITECTURE – PROPOSED IN 1998

Quantum Charge-Coupled Device proposal by NIST Ion Storage Group (1998)

Volume 103, Number 3, May–June 1998
Journal of Research of the National Institute of Standards and Technology

[J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998)]

Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions



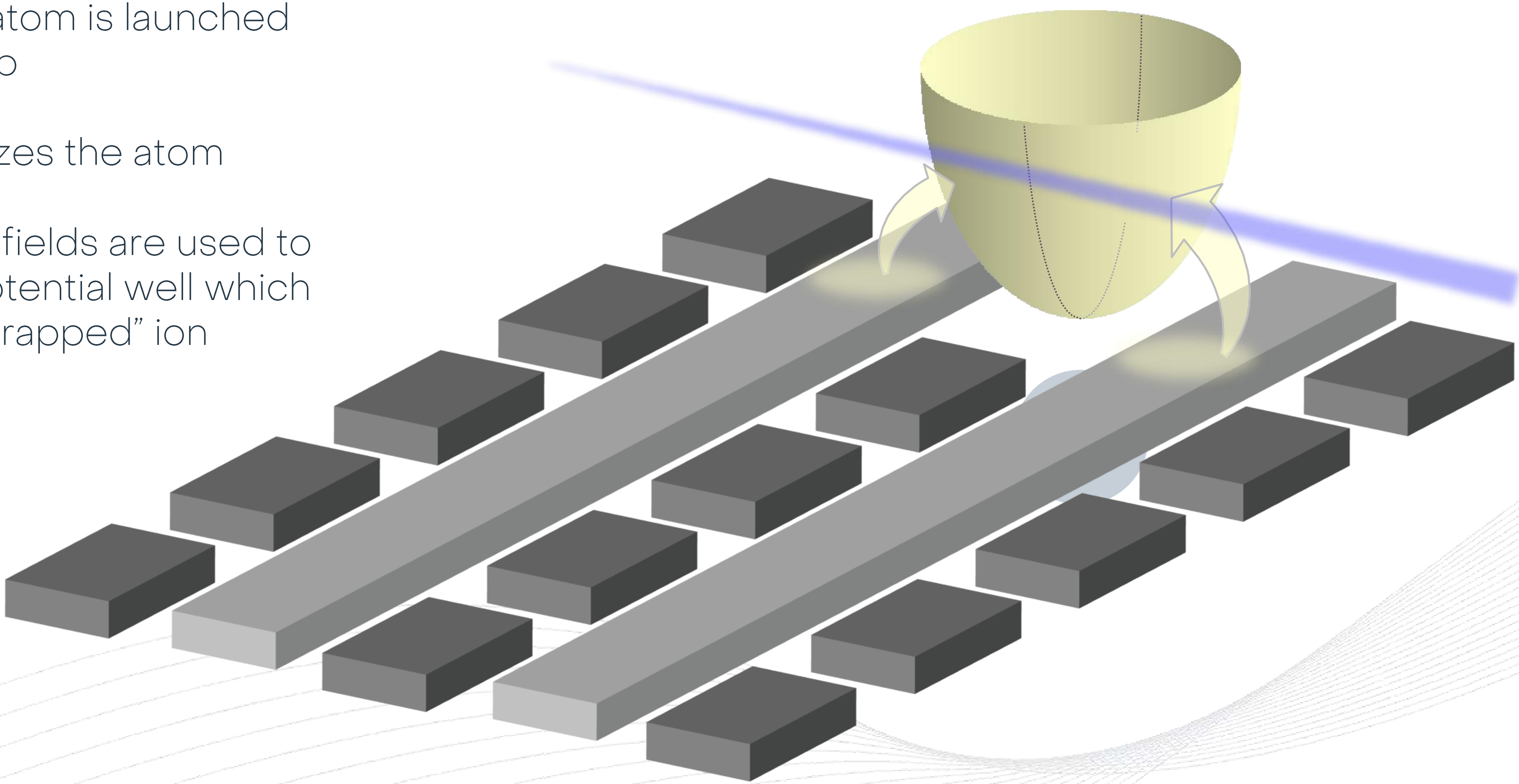
Key technologies needed:

- **Segmented trap** supports multiple zones
- **Transport** of ions with low loss and low heating
- **Beam delivery** to multiple regions
- **Loading** large number of ions fast
- **Scalability** enabled by microfabricated traps

Additional reference:
Kielpinski, D., Monroe, C. & Wineland, D. Architecture for a large-scale ion-trap quantum computer. *Nature* **417,** 709–711 (2002).

Loading Ions

- Ytterbium atom is launched into the trap
- A laser ionizes the atom
- RF electric fields are used to create a potential well which holds the "trapped" ion

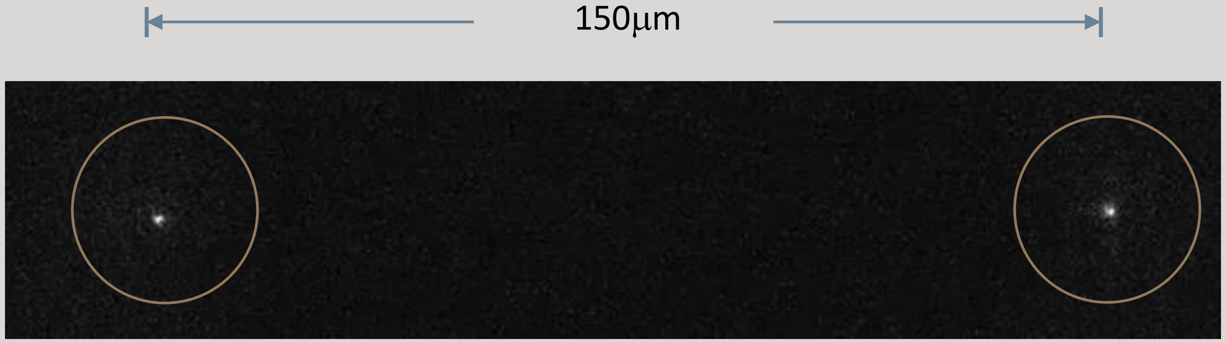


TRANSPORT PRIMITIVES

Split and Combine

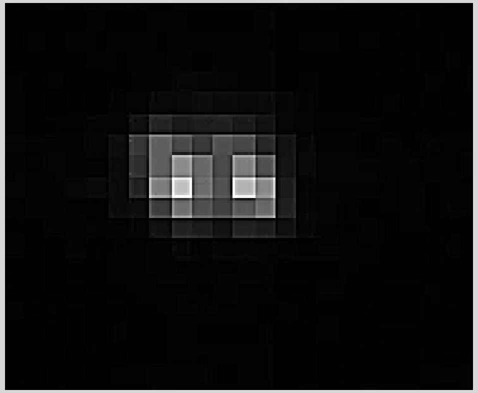
Ion is transported into the same zone

Ions are combined into a single potential well and then re-separated

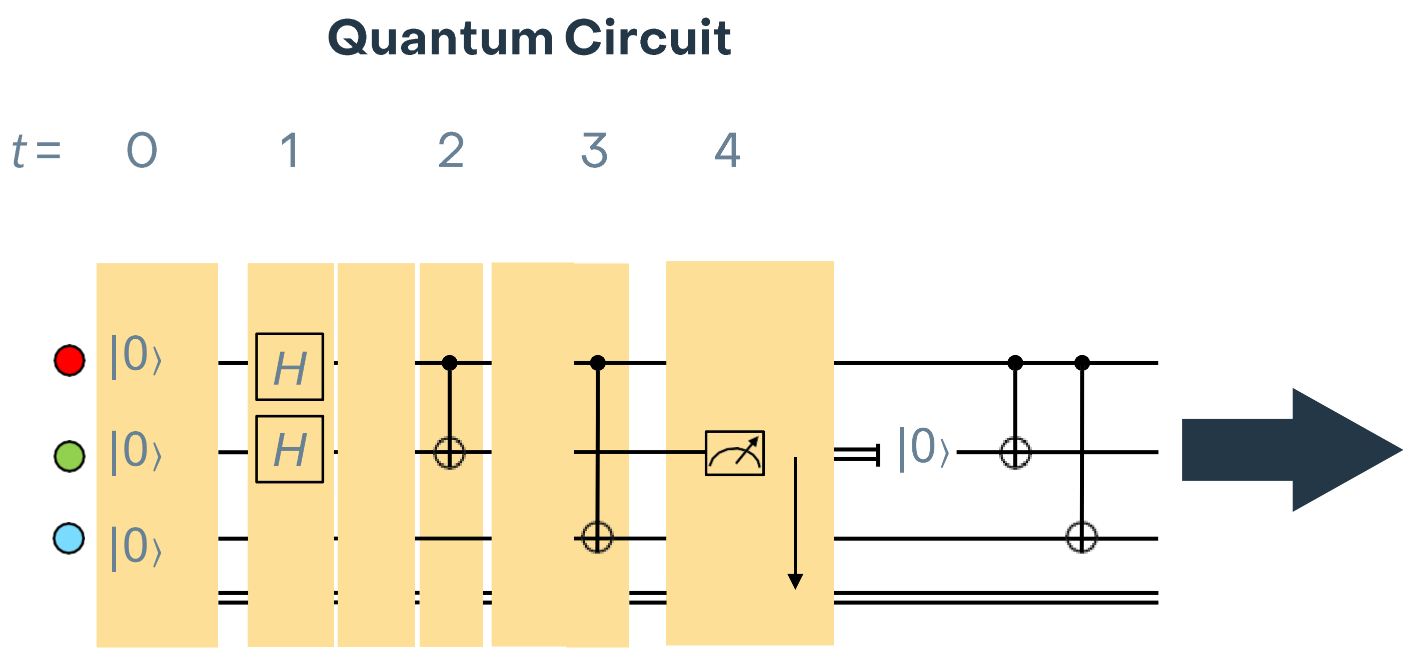


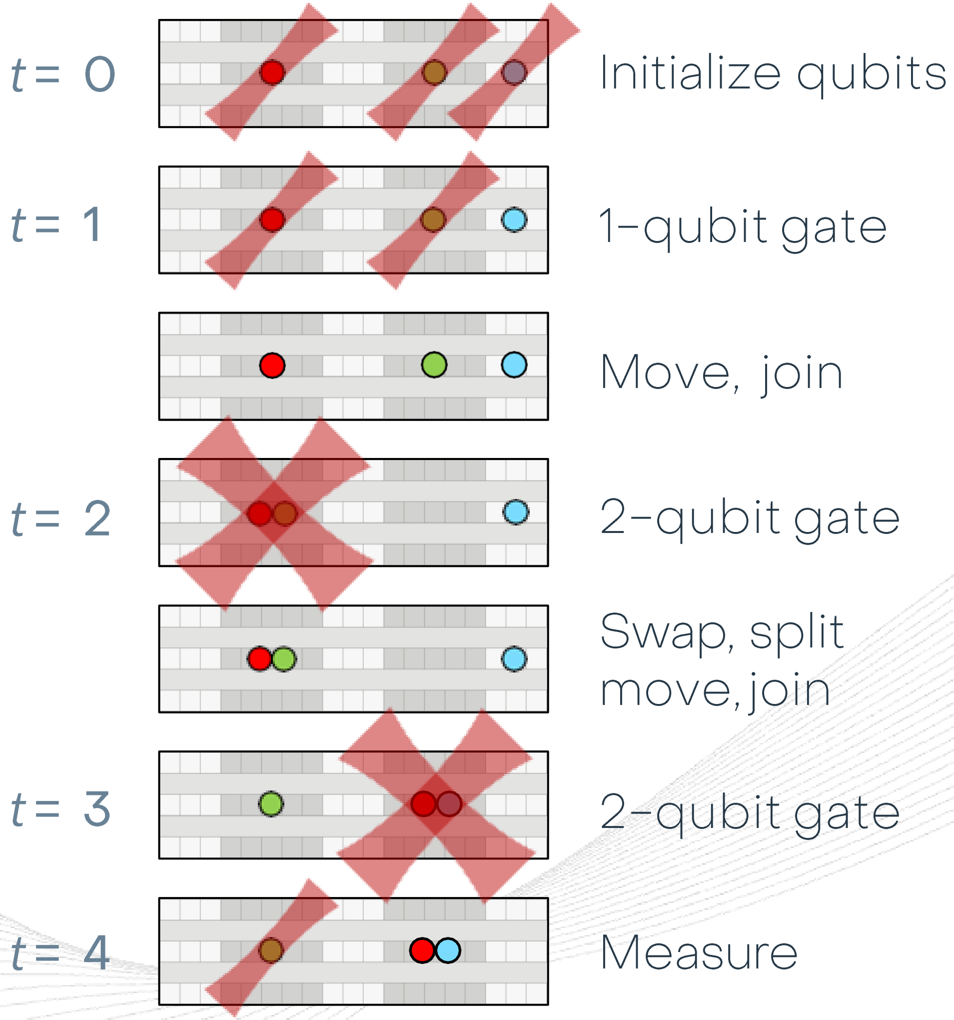
Swap

Ions are carefully manipulated to reorder positions



Physical Implementation

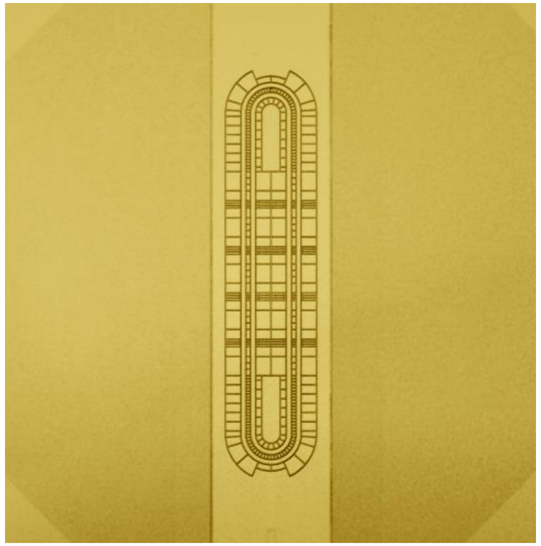




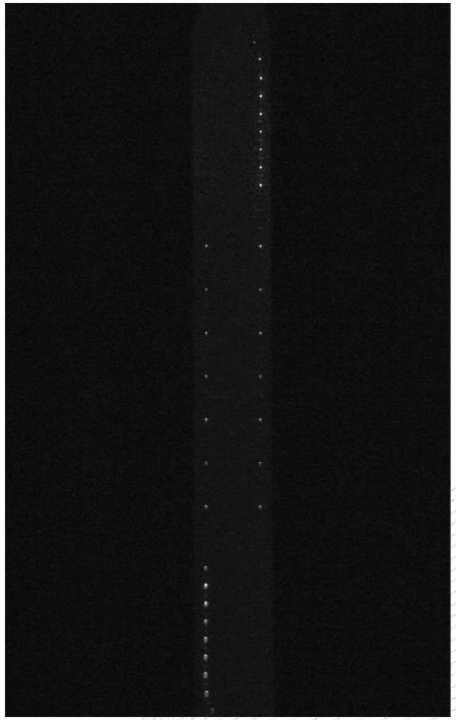
Scaling High Quality Qubits

Industry Leading Performance

- **32 Qubits – globally entangled at high fidelity**
- 1Q Fidelity 99.998%
- 2Q Fidelity 99.8%
- SPAM 99.8%
- Memory Fidelity 99.98%
- Measurement cross-talk error 0.0005%
- All-to-all connectivity
- Mid-circuit measurement with conditional logic
- Qubit reuse
- Parametrized angle 2Q gate included in native set



H2 ion trap



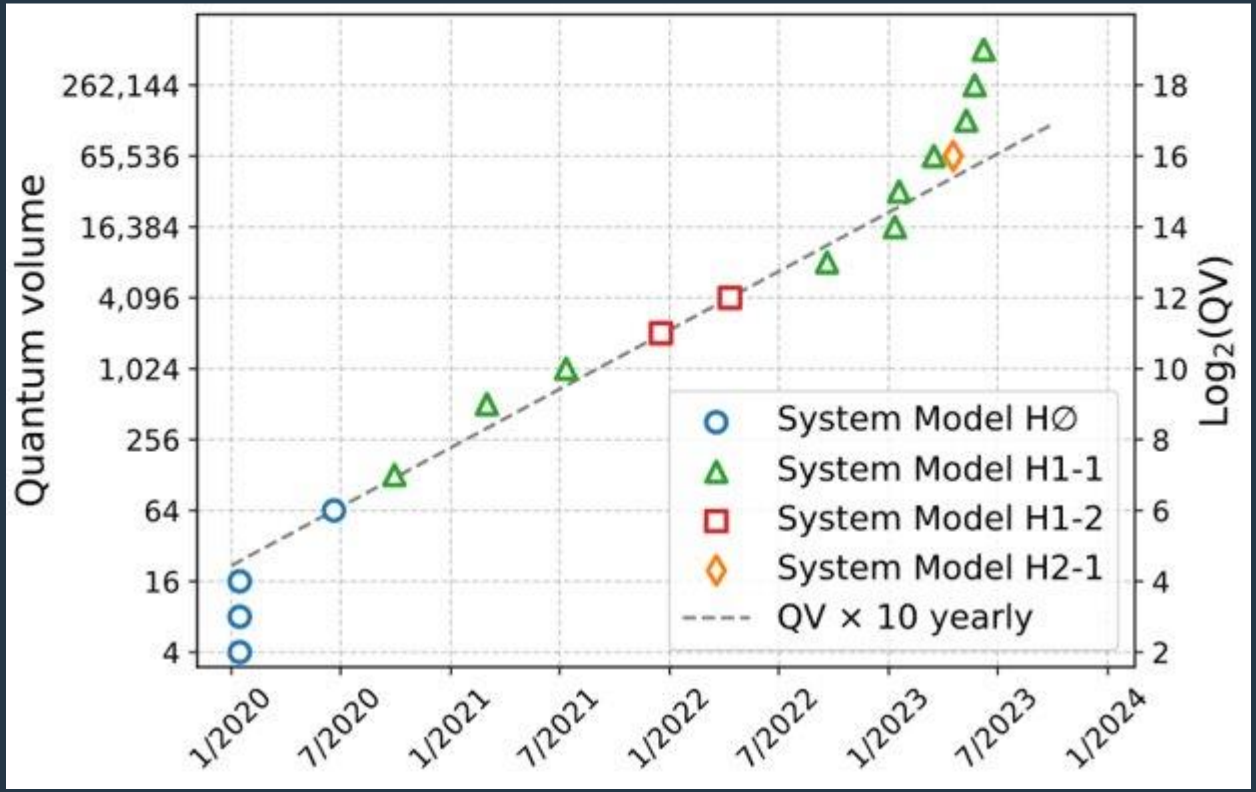
32 qubits transporting around

Roadmap for Quantum Hardware Improvement

Quantinuum's quantum computer has achieved a Quantum Volume (QV) of 2^{19}, equivalent to 524,288.

The next closest reported QV is 512.

Quantinuum has increased the QV by a factor of 10 every 12 months and believes they can continue with this for the next several years.



QUANTUM COMPUTING SOFTWARE

Noisy intermediate scale quantum (NISQ)

CONSTRAINTS:

50 – 100 qubits

High error rates

Low coherence time

Limited error correction

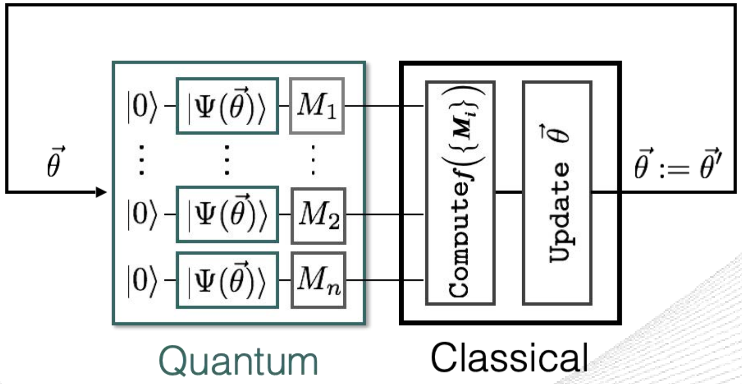
Connectivity

Basis gate set

NISQ ALGORITHMS:

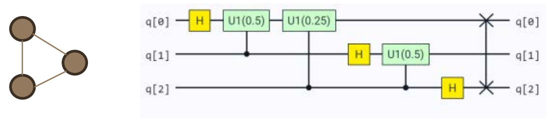
Hybrid quantum + classical

Small circuit depth

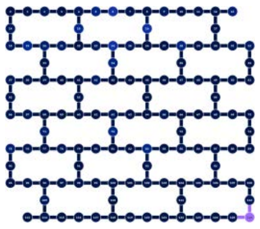


Typical Quantum Algorithm Workflow on a Gate-model Quantum Computer

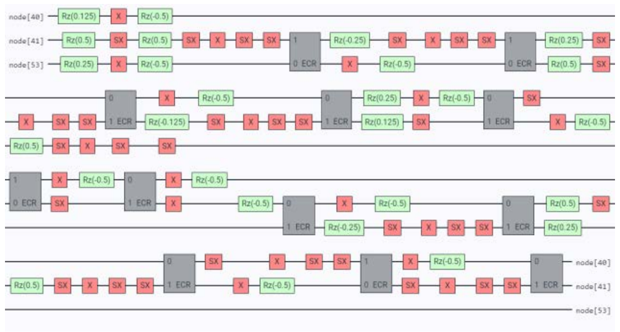
e.g. QFT



e.g. TKET



Native gateset:
ECR, ID, RZ, SX, X



Use Case

Application Software

Quantum Circuit

All-to-all qubit connectivity
Universal gateset

Quantum Circuit Compiler

Native gateset
Qubit connectivity
Qubit error
Gate errors
More…

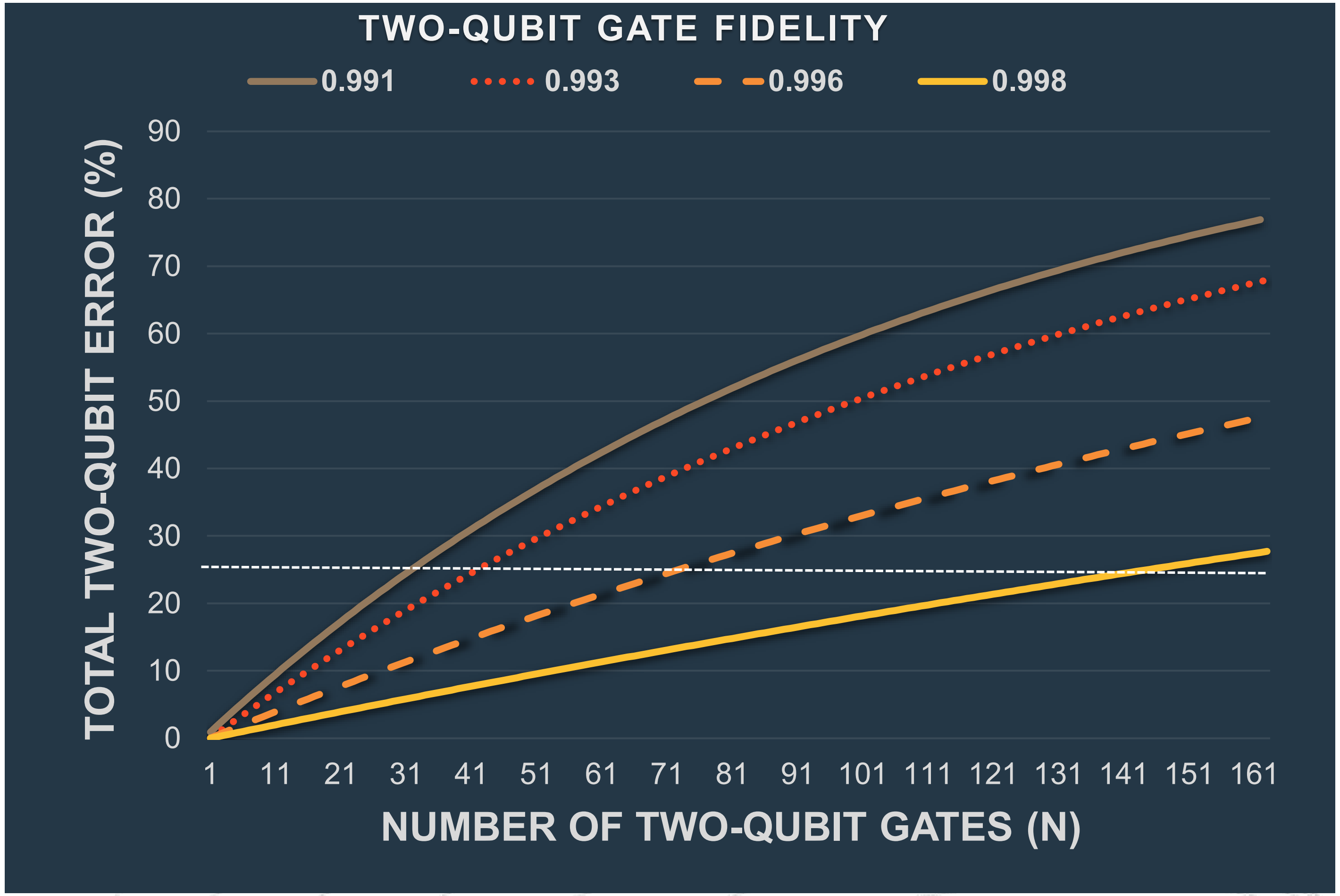
Machine Code

Quantum Simulator

Quantum Processor

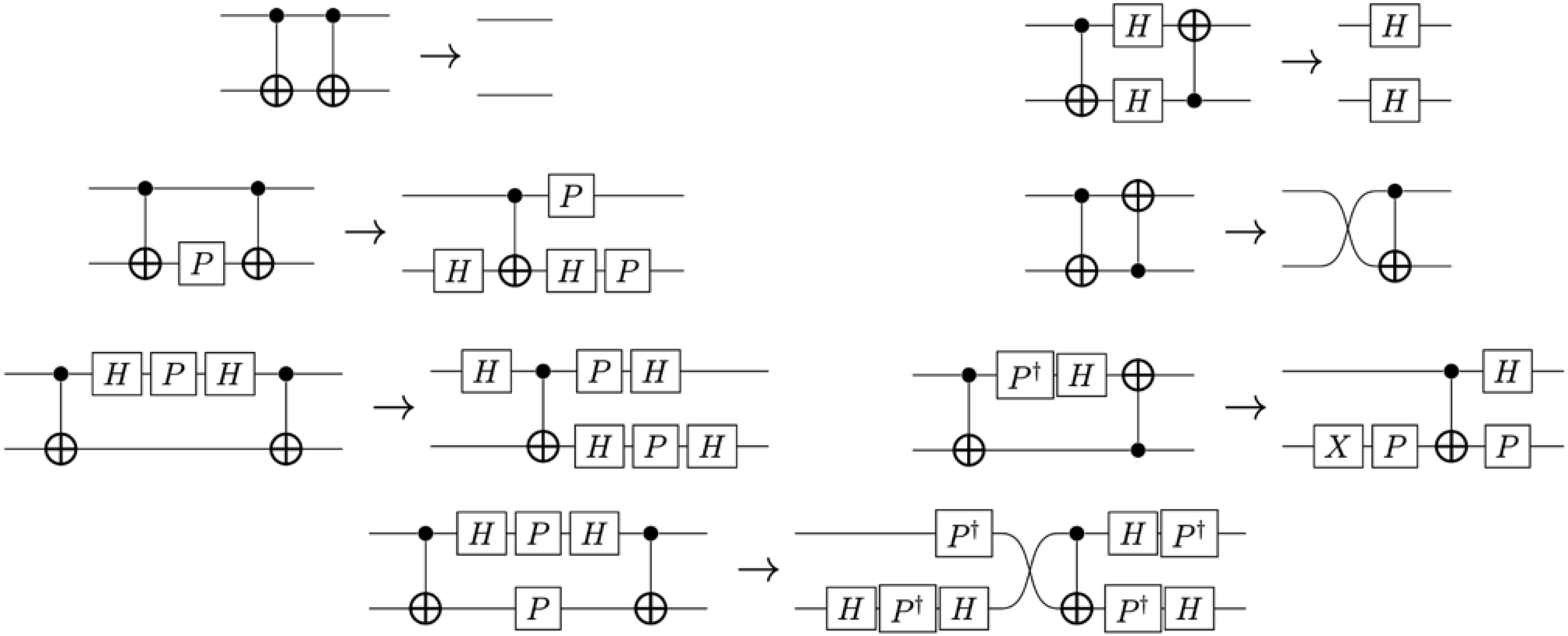
Quantum Computing Stack

TWO-QUBIT GATE ERRORS



$$\% \, Error = (100\%)(1 - Fidelity^{N})$$

Example circuit optimization



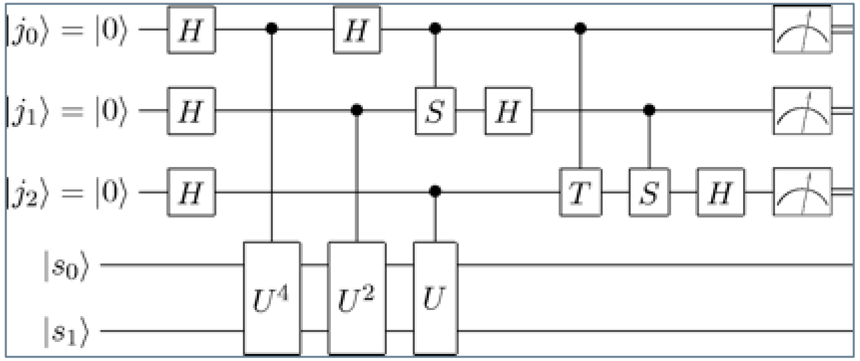
For more technical detail see arXiv:2003.10611

Example routing problem

IBM MELBOURNE

4 qubit coupling max

QUANTUM CIRCUIT



5 qubit coupling

Routing

PROBLEM

At each time step a pair of qubits need to interact but are not adjacent.

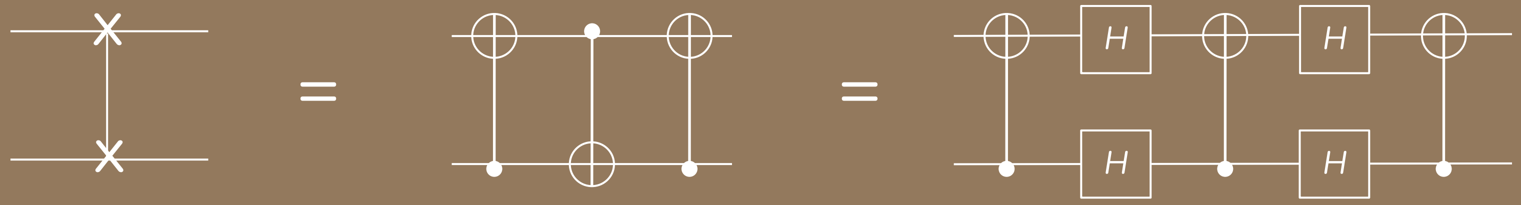
SOLUTION

Insert SWAP operations to move them closer together.

Very expensive! Need to do this optimally.

Difficult combinatorial problem — NP-hard.

SWAP Gate



INTRODUCTION TO TKET

QUANTINUUM

Quantum Information Scientist (End User)

- Use gate-level quantum computers to solve my problems
- Program a quantum computer in my favorite language
- Run my quantum algorithms efficiently
- Get the most accurate result while focusing on solving my problems

TKET as a universal SDK

TKET optimizes quantum circuits, reducing the number of required operations – essential for NISQ devices.

> 1,000,000 downloads

Front ends
High level interface

python
PENNYLANE
Q#
pyzx
Cirq

Build Circuits

pytket
python

TKET
C++ library

Rewrite Circuits
Solve for device constraints
Perform optimizations

Back ends
Quantum devices/simulators

QUANTINUUM
IBM
IONQ
aws
AQT
Microsoft
* NVIDIA/ cuQuantum
* under development

Execute Circuits

Get started with TKET, a universal quantum SDK

TKET is available for free on GitHub (https://gitub.com/CQCL/pytket) and is installed by

```
pip install pytket
```

The extension module interfacing pytket with the H-series is installed by

```
pip install pytket-quantinuum
```

and for interfacing with Qiskit and IBM Quantum install

```
pip install pytket-qiskit
```

QUANTINUUM

INTEGRATING OTHER QUANTUM TOOLKITS IS EASY

qiskit_to_tk(circuit)

Qiskit ⇄ TKET

tk_to_qiskit(circuit)

Other bidirectional conversions exist: Cirq, Bracket etc.

TKET has a default pass manager for each backend

```
get_compiled_circuit(circuit,optimization_level)
```

Level 0	Level 1	Level 2 (default)
Solves the device constraints without optimizing.	Additionally performs some light optimizations.	Adds more intensive optimizations that can increase compilation time for large circuits.

QUANTINUUM

TARGET A DIFFERENT BACKEND EASILY

```python
from pytket.extensions.qiskit import IBMQEmulatorBackend

backend = IBMQEmulatorBackend('ibmq_belem', hub ='partner-cqc', group ='internal', project ='default')
```

```python
from pytket.extensions.quantinuum import QuantinuumBackend

backend = QuantinuumBackend('H1-1E') # emulator
```

TKET CODING EXAMPLE: GOOGLE COLAB

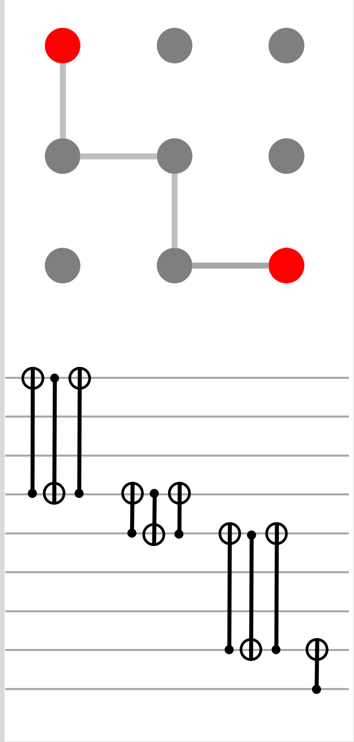
https://tinyurl.com/dtdrhvab

SUMMARY

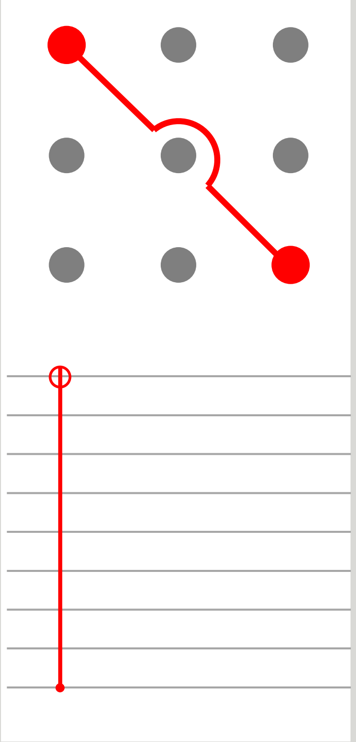
QCCD Architecture Differentiating Features

All-to-All Connectivity

Nearest Neighbor

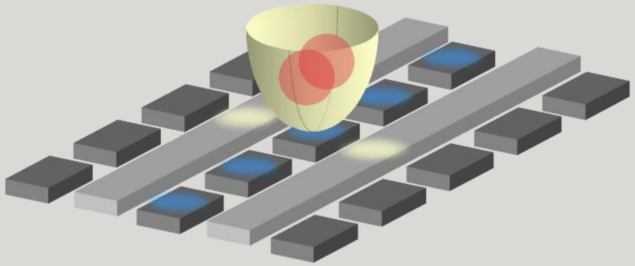


All-to-All



High-Fidelity Gates

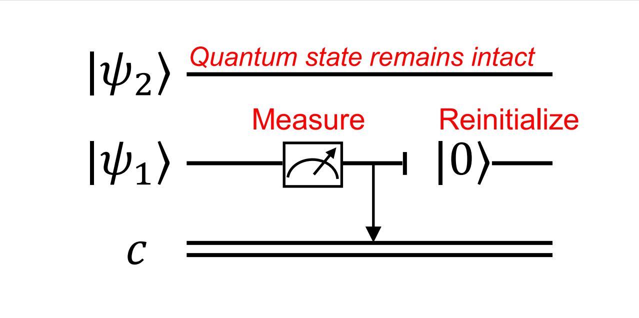
Isolated Gates = Scalable Gates



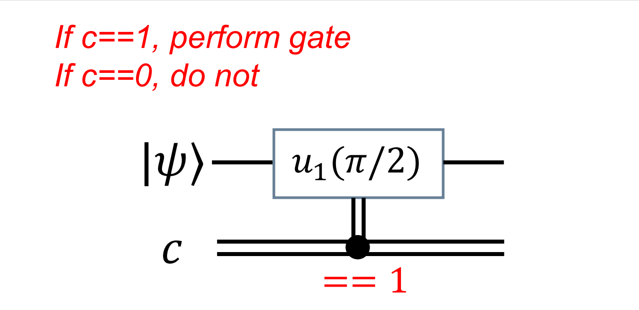
1Q infidelity	$< 3 \times 10^{-5}$
2Q infidelity	$< 2 \times 10^{-3}$
State preparation and measurement error	$< 2 \times 10^{-3}$
Measurement cross-talk error	$< 5 \times 10^{-5}$
Memory error per qubit at average depth-1 circuit	$< 6 \times 10^{-4}$

Qubit Measurement and Reuse

Measurement and reuse



Conditional logic



USE TKET!

```
pip install pytket
```

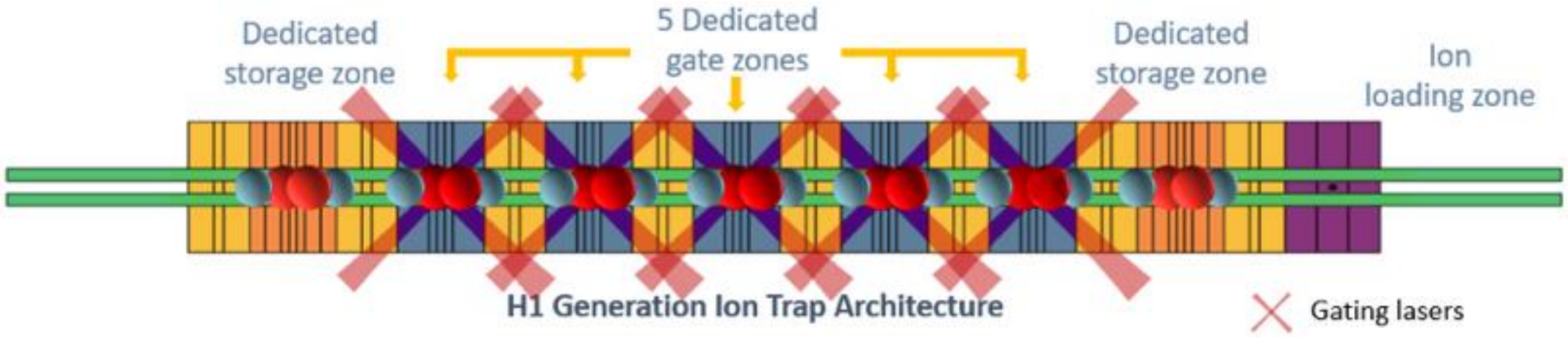
- State-of-the-art circuit compilation
- Retargetable
- Works with other libraries
- Application-specific tools
- Other software is built on top of TKET

Growing Quantum Ecosystem with Quantinuum

quantinuum.com

Quantinuum Trapped-Ion Architecture

Quantinuum's quantum charge coupled device (QCCD) architecture



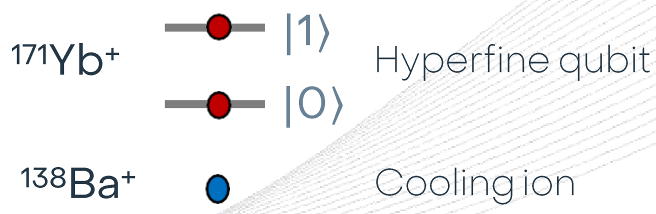
QCCD Requirements

1. Trap a large # of small ion crystals
2. Fast transport operations
3. Clock synchronization across trapping regions
4. Ability to trap 2 different ion species (1 for qubit, 1 for cooling)
5. Parallelization of transport and quantum operations

Architecture Features

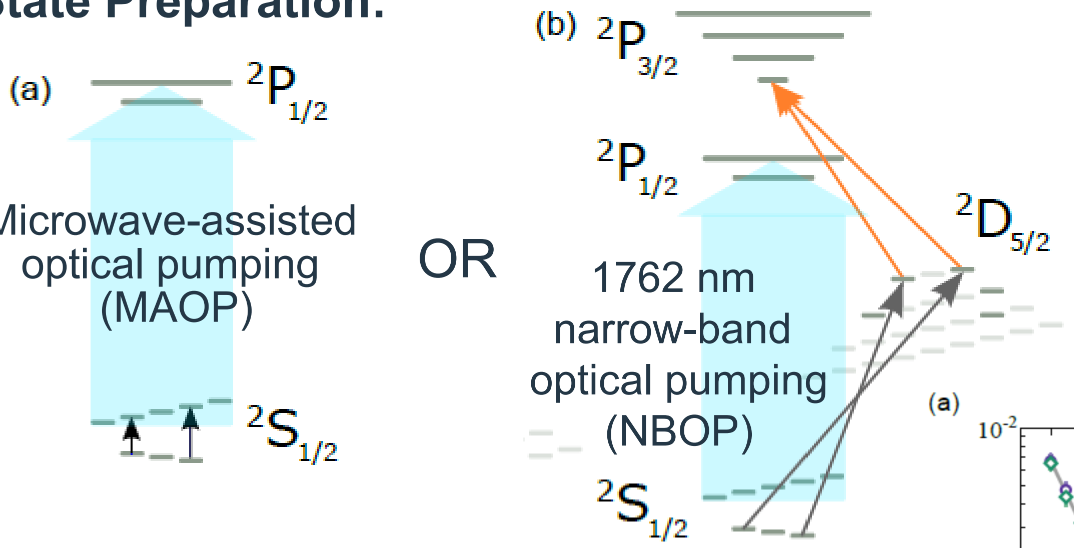
- Perfect qubits (Yb+ ions)
- Dedicated interaction zones (gating, storage & auxiliary)
- Short ion chains
- High fidelity quantum gates
- Ion transport within & across zones
- Split, combine & swap primitives
- Real-time control system

Quantum bits (qubits) are stored in the electronic states of Yb^+ ions



HIGH FIDELITY STATE PREPARATION AND MEASUREMENT

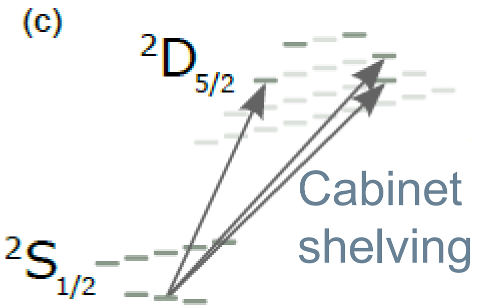
State Preparation:

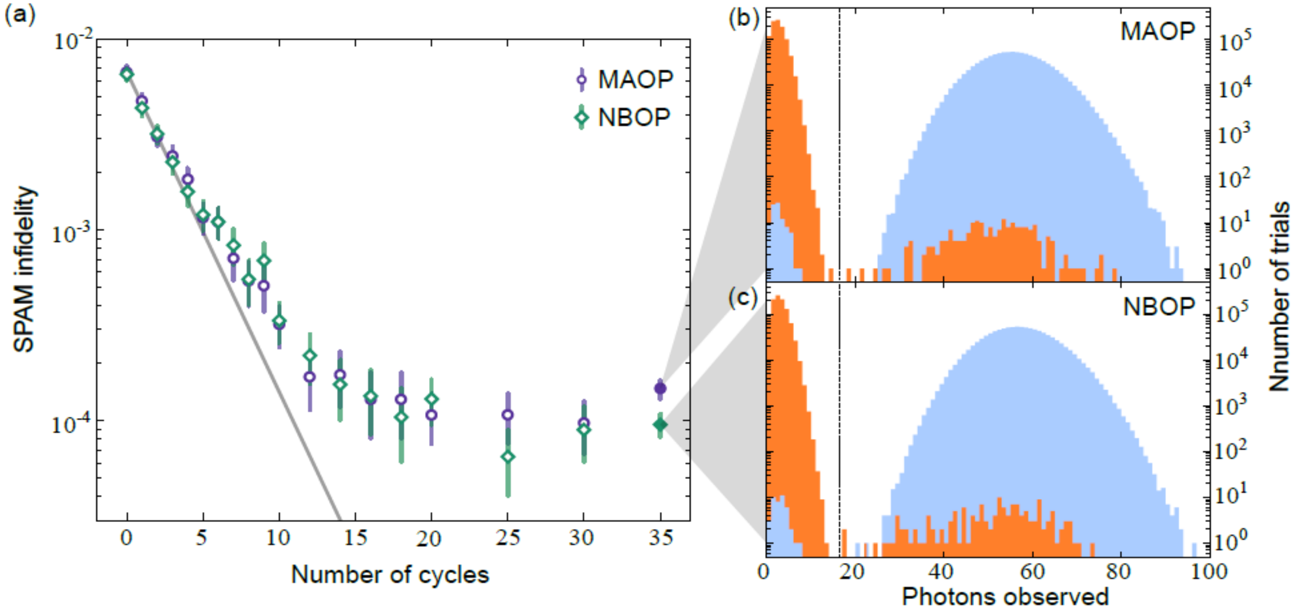


$^{137}Ba^+$

SPAM error: 9.6(1.4)×10^{-5}

Detection:



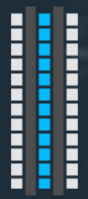


An, Fangzhao Alex, *et al.* High fidelity state preparation and measurement of ion hyperfine qubits with I > 1/2, *arxiv:2203.01920*.

Trap Scaling Roadmap

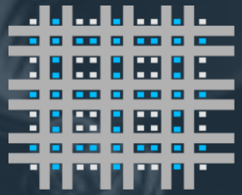
2020 → 2030 +

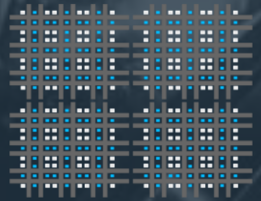
H1	H2	H3	H4	H5
POWERED BY HONEYWELL	POWERED BY HONEYWELL	POWERED BY HONEYWELL	POWERED BY HONEYWELL	POWERED BY HONEYWELL

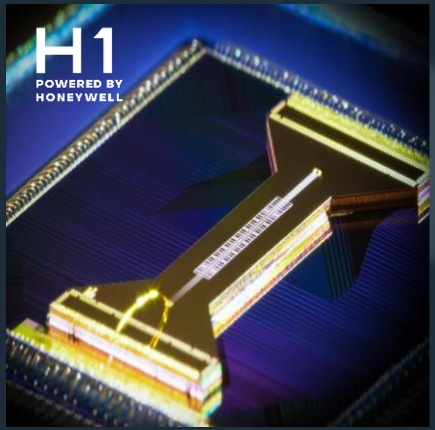

LINEAR


PARALLEL GATE ZONES

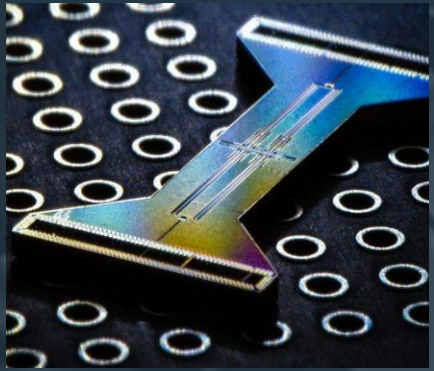

GRID


INTEGRATED OPTICS

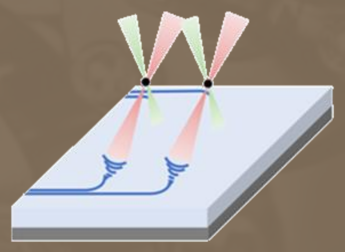

LARGE SCALE



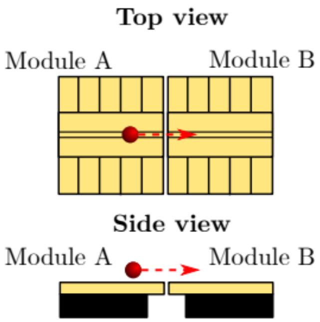
Grid Trap Prototype



Photonic Waveguides & Couplers



Modular, Tiled Traps

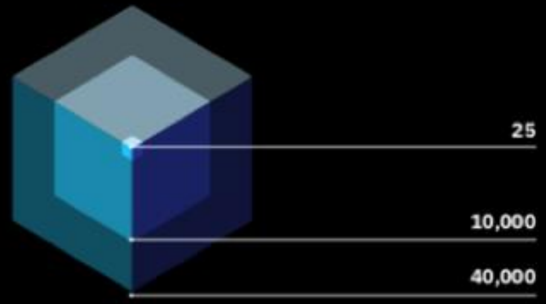


Akhtar et al, (Sussex/Universal Quantum)
arxiv.org/pdf/2203.14062.pdf

QUANTINUUM

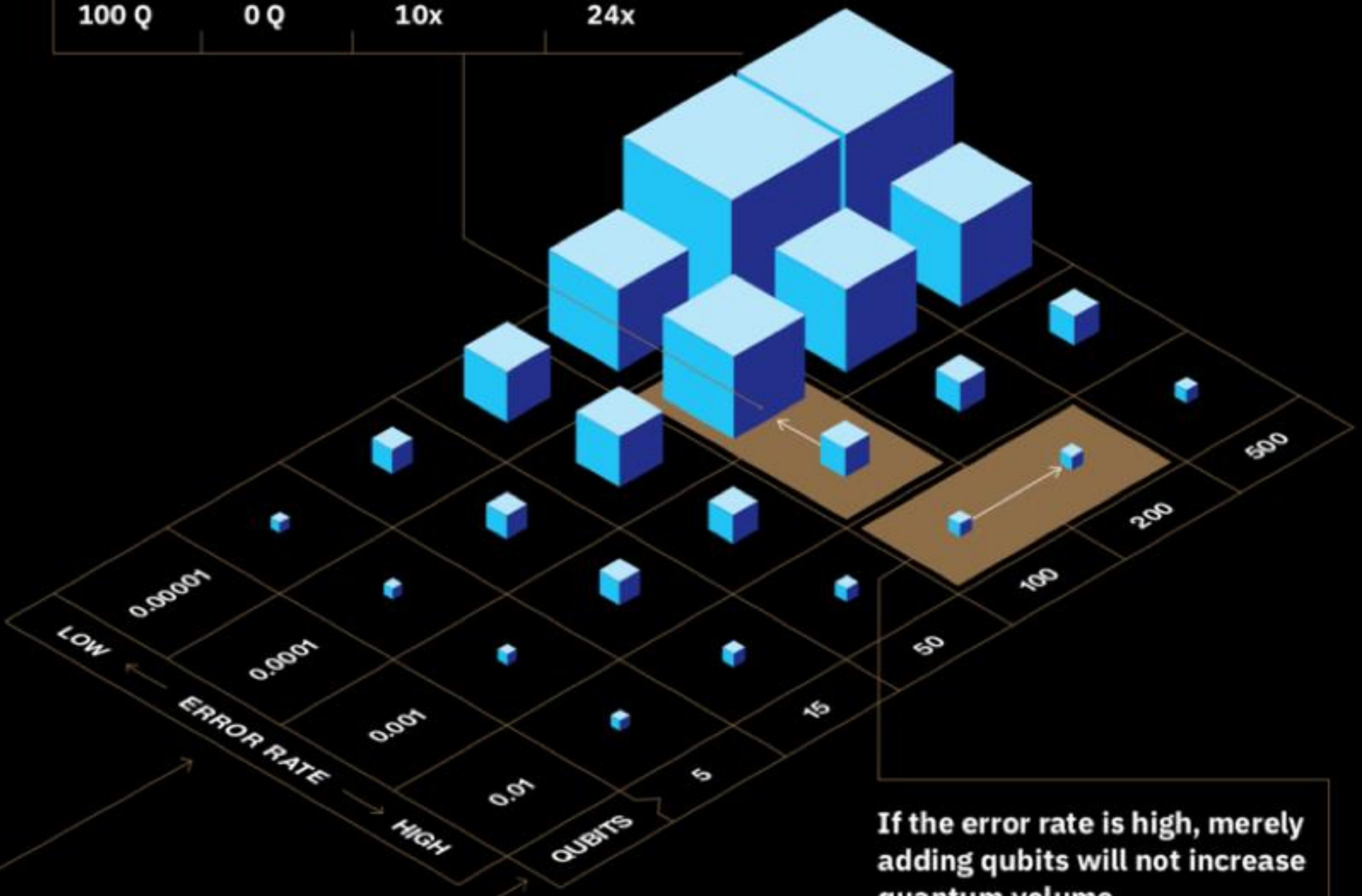
Understanding Quantum Volume

The volume of a cube is determined by its qubit count and error rate. The greater the volume, the more powerful the machine.



Improving the error rate can increase quantum volume even when the number of qubits remains the same. For example:

QUBITS EXISTING	QUBITS ADDED	ERROR RATE DECREASE	QUANTUM VOLUME INCREASE
100 Q	0 Q	10x	24x



The Quantum Volume Matrix

Error Rate (Y-AXIS)
An expression of how well the device can implement arbitrary pairwise interactions between qubits

Qubits (X-AXIS)
The number of qubits active in the system

If the error rate is high, merely adding qubits will not increase quantum volume.

QUBITS EXISTING	QUBITS ADDED	ERROR RATE DECREASE	QUANTUM VOLUME INCREASE
100 Q	100 Q	0x	0x