We build quantum computers

High Performance Computing and Quantum Computing – Sixth Edition

Jani Heikkinen
Head of Business Development

Introduction to IQM

IQM

IQM builds and delivers quantum computers

OUR MISSION

We build world leading quantum computers for the well-being of humankind, now and for the future.

280+
experts

119
PhDs

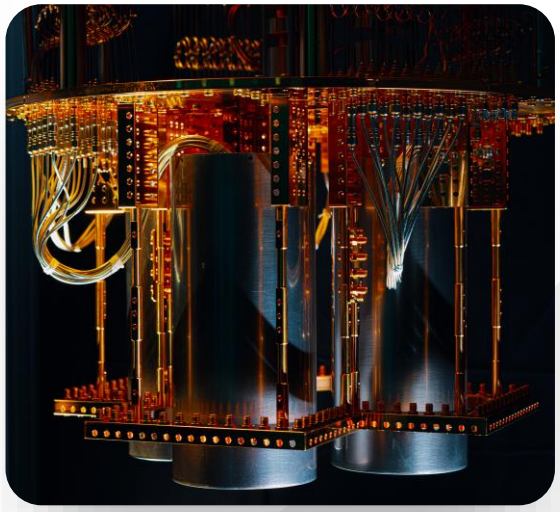
48
nationalities

On-premises & full access

3 systems sold and delivered

VTT 5/20-qubit system

Irz 20-qubit system



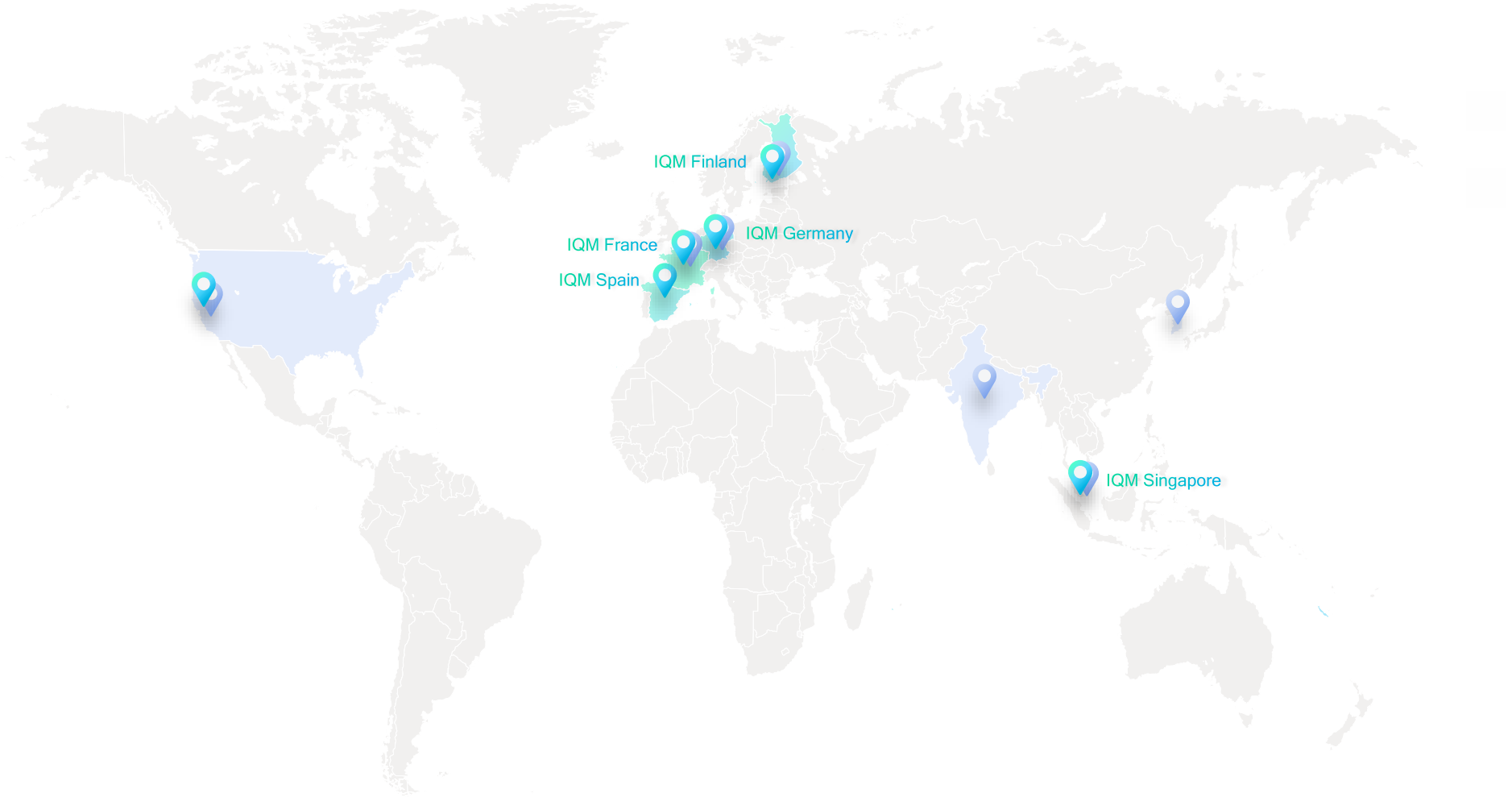
Full-stack solutions with **co-design**

Own facilities → **fast turnaround**

IQM's Private Foundry: **600 m2**

200M€+
funding

IQM Has Already Achieved a Global Footprint



IQM's registered office locations

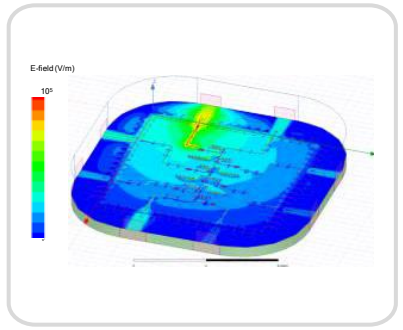
IQM's Partners' countries

IQM's Global Partnerships

VTT
BLUEFORS
EVIDEN an atos business
Allianz
AIRBUS
T Systems
SIEMENS
KEYSIGHT
NVIDIA
BEYOND LIMITS
TECH mahindra
NORMA

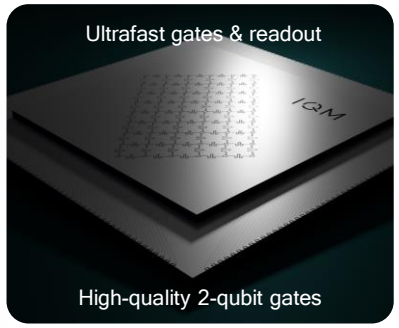
IQM: A Full-stack Quantum Computing Company

IQM's unique hardware capabilities:



01 Design of QC chipsets

02 Production of QC chipset



03 Best in class processors

04 System & HPC Integration

Vertical integration

IQM quantum computers are delivered fully functional and can be used with any common programming framework.

Innovative hardware-software Co-Design accelerates reaching quantum advantage
IP creation ensures business strategy (100+ patent families filed, 30 patents granted)

Hardware-Software gap

Hardware capabilities

Accelerated innovation cycle

Goal: Increase slope!

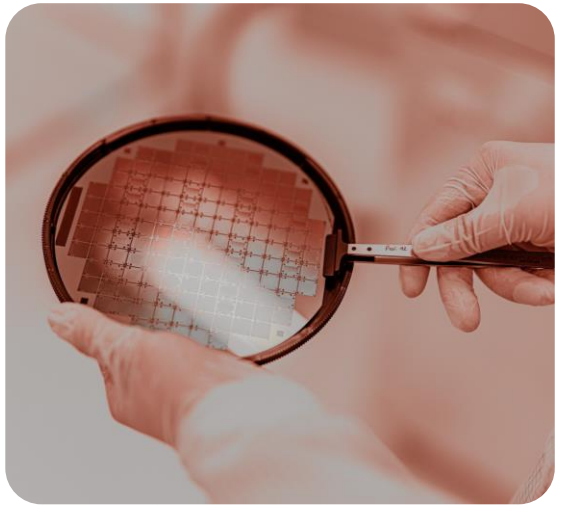
Grow hardware capabilities as fast as possible through complete in-house know-now

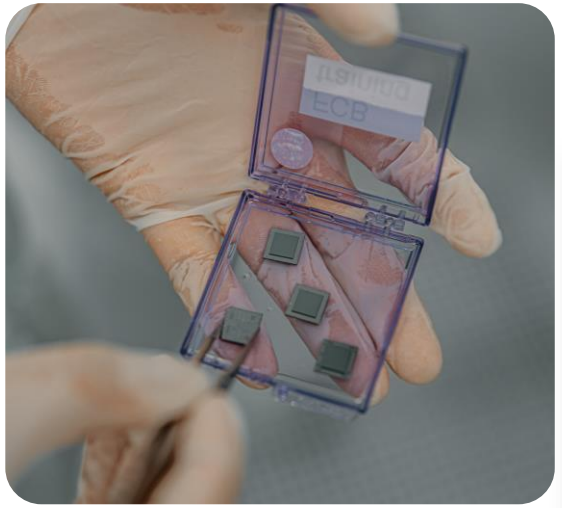
2024

2026

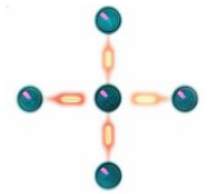
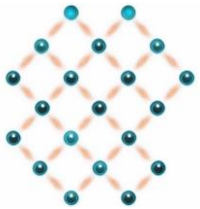
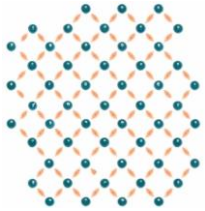
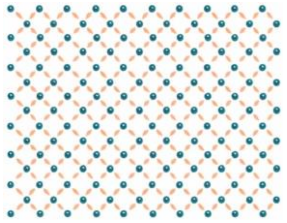
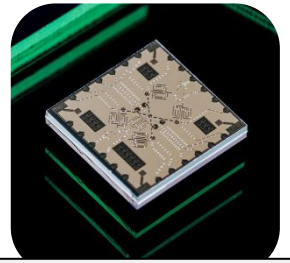
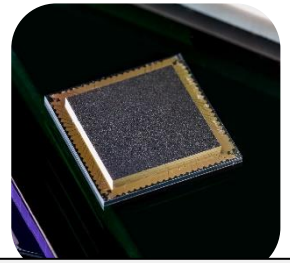
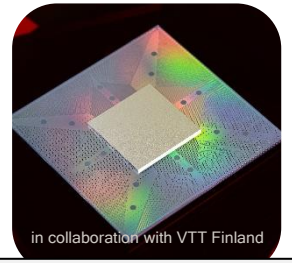
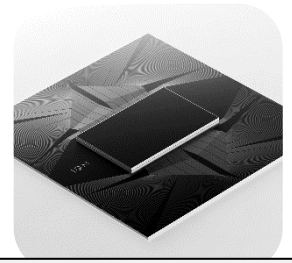
Strategic Advantage: Private Quantum Foundry in Europe

- 200 mm fabrication facility optimized for QPU piloting and production
  - Location: Espoo, Finland
  - Investment: € 20 Million
  - Area: 560 m2
- Advantages:
  - Accelerates design & production cycle
  - Guarantees production stability
  - Know-how generation and possibility for foundry service
  - Reinforces the in-house developed quantum design automation
- Capabilities
  - Fabrication, new material research, 3D integration, product delivery





IQM Quantum Processor Generations

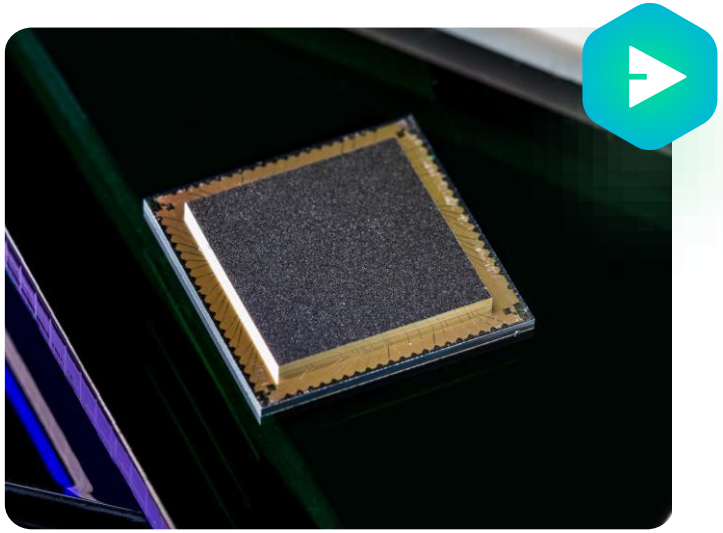
	IQM QPU with 5 qubits	IQM QPU with 20 qubits	IQM QPU with 54 qubits	IQM QPU with 150 qubits
QUBIT COUNT	5 data qubits 4 coupler qubits 9 qubits in total	20 data qubits 30 coupler qubits 50 qubits in total	54 data qubits 90 coupler qubits 144 qubits in total	150 data qubits 266 coupler qubits 416 qubits in total
BROAD AVAILABILITY	Since 2022 (*)	Since 2023 (*)	Expected in 2024 (*)	Expected in 2025 (*)
QPU LAYOUT				
				

QC: Quantum Computer, QPU: Quantum Processing Unit, (*) Subject to change with average system lead times of 1 year

IQM is Demonstrating Best-in-class Quality and Accuracy

Fidelity is a measure of the accuracy or quality of a quantum operation or quantum computation.

- If the fidelity of logic gates is too low, calculations will fail because errors will accumulate faster than they can be corrected.
- IQM's long-distance tunable coupler* is crucial for achieving high fidelity.



* F. Marxer et al., arXiv preprint arXiv:2208.09460 (2022) and 2 patents currently pending

QPU's Architecture

IQM-20 QPU contains 20 computational qubits and 30 tunable coupler qubits (in total 50 physical qubits).

Tunable coupler for qubits separated by distances up to 2 mm*:

- ✓ lower qubit-to-qubit crosstalk → faster gates, higher fidelity
- ✓ create space for individual readout resonators → faster readout, lower errors

Latest results for 20-qubit Quantum Processor

Qubit count	20
1Q fidelity	median 99.91 % best 99.944 ± 0.003 %
2Q fidelity	median 98.25 % best 99.1 ± 0.3 %
Quantum volume* (Classical simulation complexity)	16
Q-score* (Size of combinatorial optimisation task solved)	8
Largest GHZ genuinely entangled state*	9

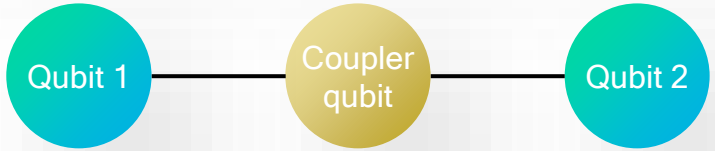
On par with leading US companies

* measured with readout-error mitigation

Tunable couplers vs. Fixed frequency couplers

Tunable coupler architecture

chip QBs = # computational QBs < # physical QB
(e.g. 5 qubit chip = 9 physical qubits)



Coupler qubit works as a switch, can fully turn off interaction

Advantages

- ✓ Possibility to completely switch off interaction between qubits
- ✓ Faster gates, higher fidelity
- ✓ Low idling errors

Drawbacks

- ✗ More physical qubits for an N qubit chip
- ✗ More lines, more complex system, more expensive BOM
- ✗ More challenging design and build

Fixed frequency coupling architecture

chip QBs = # computational QBs = # physical QB
(e.g. 5 qubit chip = 5 physical qubits)

Constant interaction between qubits even when idling

Advantages

- ✓ Easier to design and manufacture the QPU
- ✓ Easier to build the system, easier to calibrate the system
- ✓ Less lines per qubit
- ✓ Cheaper BOM

Drawbacks

- ✗ High idling error, degrade performance
- ✗ Slower gates due to the need of lower interaction strength to minimize leakage
- ✗ Lower fidelity

IQM Product and Service Portfolio

On-premises / Product delivery

IQM Spark™

- 5-qubit superconducting quantum computer for research and education
- Full control of your experimental setup
- Under one million euros

On-premises / Product delivery

IQM Radiance™

- State-of-the-art on-premises offering
- Deliver more computational value with a lower environmental footprint
- Integration-layer to HPC centres

Service provider

IQM Services

- Education and executive trainings
- Consulting services


INTRODUCING
IQM Spark™
YOUR TURNKEY SOLUTION FOR
QUANTUM RESEARCH AND EDUCATION.
IQM
*Artist's conceptual rendering. Actual product design may differ.

IQM Spark™: Empowering Quantum Exploration

Your turnkey solution for quantum research and education.

- Full control of your 5-qubit superconducting quantum computer
- Enhance your research and development
- Foster the next generation of quantum experts

Artist's conceptual renderings. Actual product design may differ.

Technical specifications

Processor: 5 qubits	Guaranteed	Typical
Single-qubit gate fidelity	≥ 99.7%	≥ 99.9%
Two-qubit gate (CZ) fidelity	≥ 96%	≥ 98%
Single-qubit gate duration	≤ 60 ns	≤ 40 ns
Two-qubit gate (CZ) duration	≤ 100 ns	≤ 60 ns
Readout fidelity*	≥ 92%	≥ 95%
Quantum volume*	≥ 8	≥ 8
Q-score*	≥ 4	≥ 5

*with TWPA option ordered.

Property	5-qubit configuration
Water cooling	15 kW
Air conditioning	1 kW
System floor footprint	1.3 m x 5.0 m (In the standard layout)*
Minimum ceiling height	290 cm

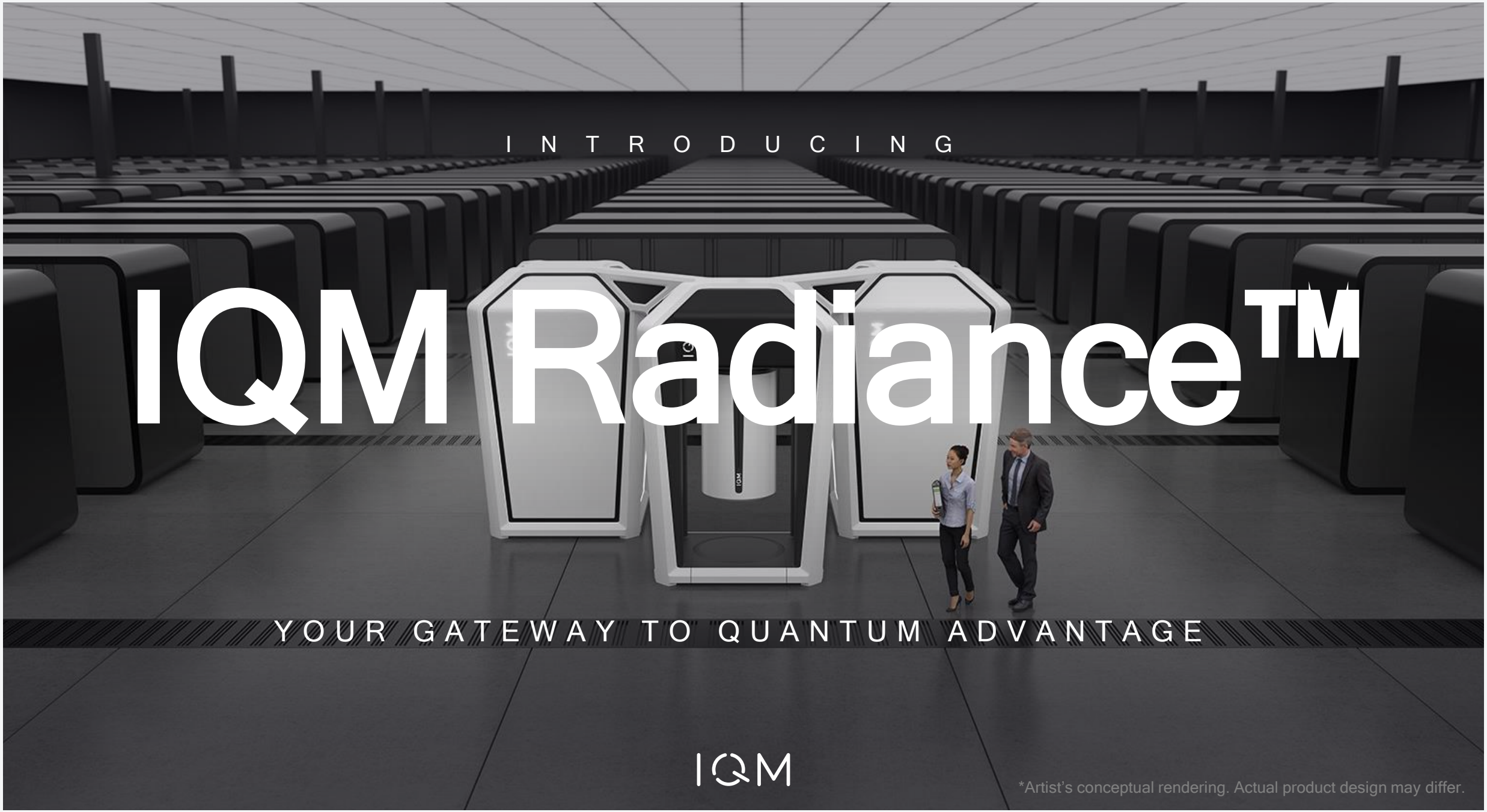
Software Packages	Interface type	Intended user
Cirq on IQM	Python	Human
Qiskit on IQM	Python	Human
EXA experiment	Python	Human
Computation Control	RESTful HTTP	Machine
IQM Station Control	Non-RESTful HTTP	Machine

Ready for your extraordinary journey into quantum computing?

Contact us today for a free personalized demo and transform quantum education and research for the better!

↗ https://meetiqm.com/products/iqm-spark/

Learn more


INTRODUCING
IQM Radiance™
YOUR GATEWAY TO QUANTUM ADVANTAGE
IQM
*Artist's conceptual rendering. Actual product design may differ.

IQM Radiance™: Your Gateway to Quantum Advantage

Q3/2024

54 QUBITS

+ 90 coupler qubits

Upgradable to 150-qubit system

Q1/2025

150 QUBITS

+ 266 coupler qubits

Upgradable to higher performance QPU

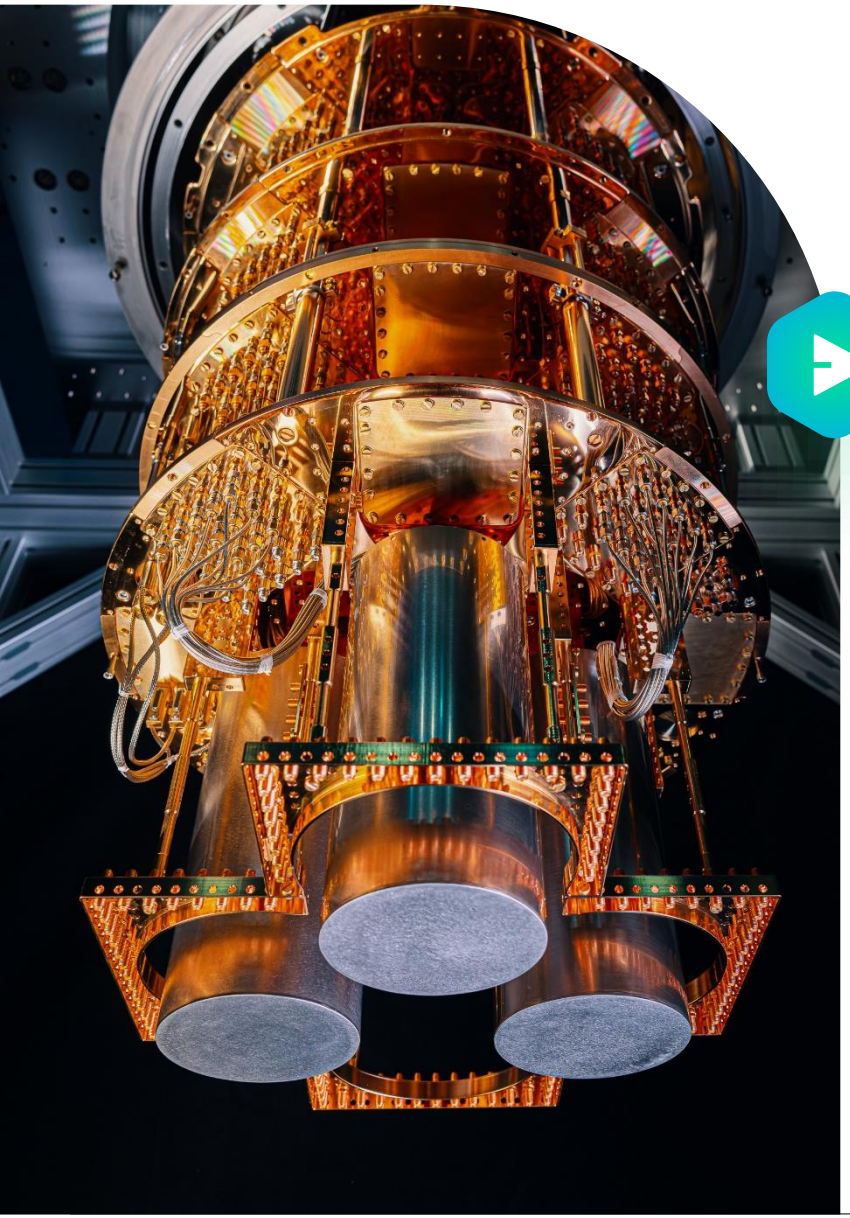
Artist's conceptual renderings. Actual product design may differ.

IQM Radiance unleashes the potential of quantum computing, delivering tangible value to users.

Quantum utility:
potentially solve problems with less computing time, or power, or more accurately than comparable classical devices

Business value:
solve real-life problems by executing simulation, optimization, and quantum machine learning algorithms.

Preparing the future:
delve into fault-tolerant quantum computing, experimenting with error correction codes and logical qubits.



Why choose IQM for your on-premises quantum computer?

Full and secure access

IQM grants you complete and secure hardware access, accelerating research and driving innovation.

Low-latency data transfer

Having quantum computers on your premises ensures low-latency data transfer between classical and quantum systems.

Technology sovereignty

IQM offers quantum hardware which can be regularly upgraded to deliver technological sovereignty.

Sustainable alternatives

Quantum technologies deliver a sustainable alternative to growing computational needs.

Full-stack system integrator

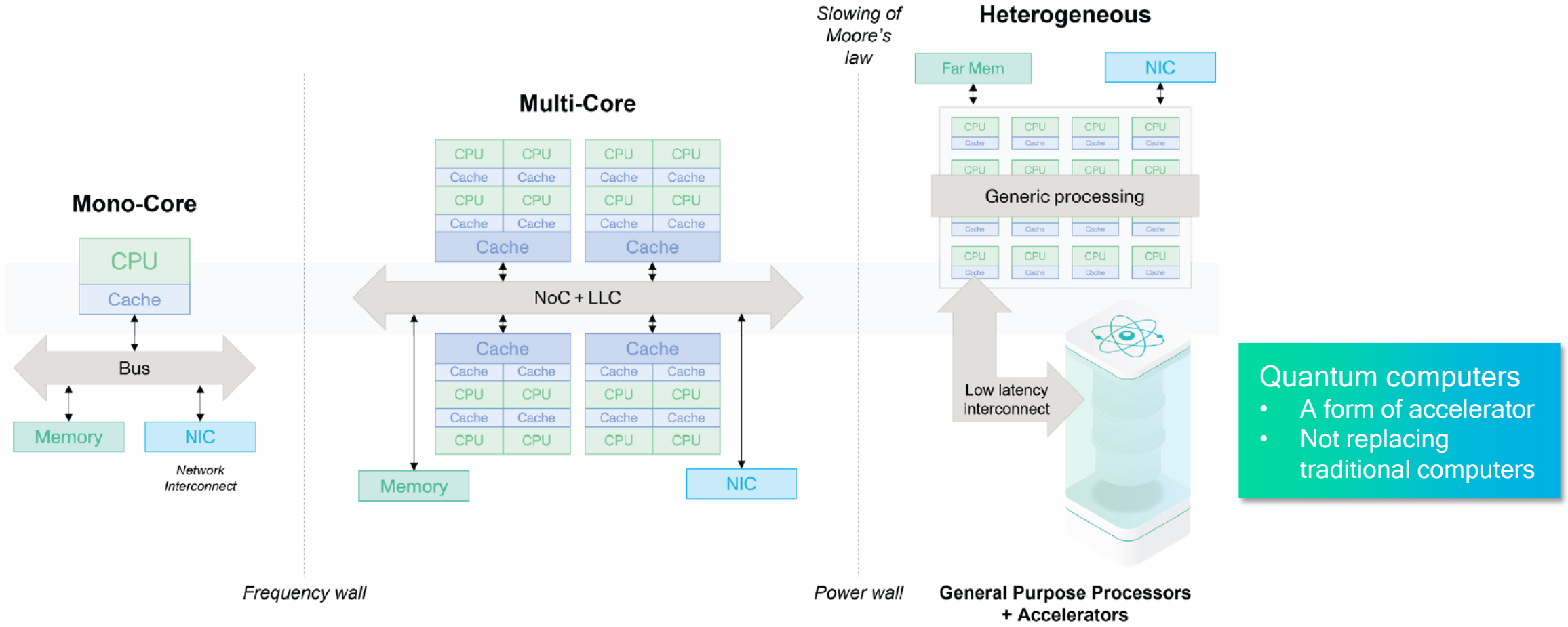
As a full-stack integrator, IQM expedites your quantum ecosystem development, thanks to our experience in building national quantum programs and quantum accelerators.

Made in Europe

We have the largest quantum hardware team in Europe, comprising of world-renowned quantum experts. We are not red taped by restrictions such as ITAR.

HPC Challenges

Compute architecture evolution



Quantum computers
- A form of accelerator
- Not replacing traditional computers

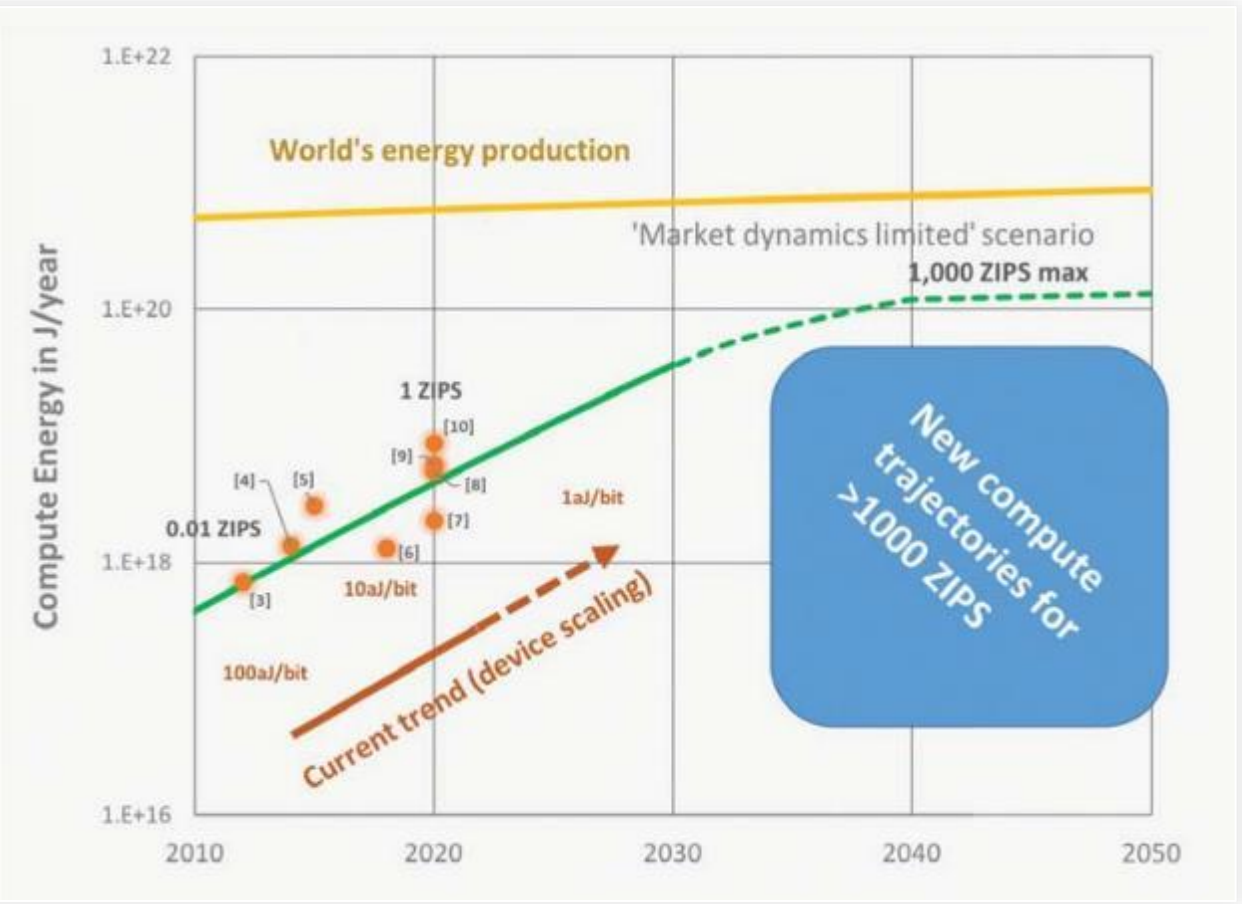
Image source: European Processor Initiative (EPI), and Sipearl

There is no way we are going to make it using conventional computers

IQM is part of the quantum energy initiative to explore the energy effectiveness of quantum computing.

There are signs for a so called “Quantum Energy Advantage”

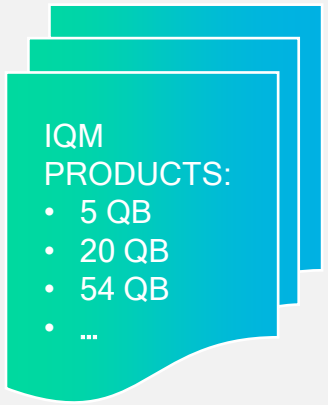
#QEI
the quantum energy initiative



Quantum Sustainability

Current:

- 5 QB -> 15 kW
- 20 QB -> 32 kW
- 54 QB -> 34 kW
- 150 QB -> 49 kW
- …



- Converging to ≈ 3.5×10^{-1} kW / QB

OPTIMIZE — ≈ 500 QB
- Higher electronics integration
- Cryocooler / compressor efficiency
- Cryogenic HW and cabling density

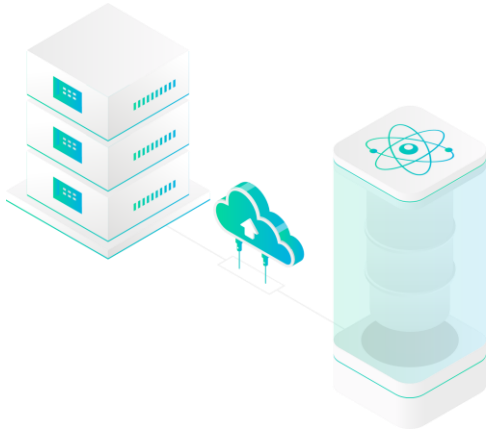
DEVELOP — ≈ 2000 QB
- Cryogenic electronics
- Wing and signal heat load reduction
- Cryocooler power need decrease

DISRUPT — ≈ 5000 QB
- On-chip electronics
- Heat load minimization per Qubit
- Highly integrated cryo system

Electronics	≈ 1.3×10^{-1} kW / QB	≈ 2.0×10^{-2} kW / QB	≈ 5.0×10^{-3} kW / QB	≈ 1.0×10^{-3} kW / QB
Cryostat vacuum and pumping system	≈ 2.3×10^{-2} kW / QB	≈ 6.0×10^{-3} kW / QB	≈ 1.0×10^{-3} kW / QB	≈ 6.0×10^{-4} kW / QB
Cryo cooler / compressor	≈ 2.3×10^{-1} kW / QB	≈ 7.8×10^{-2} kW / QB	≈ 2.6×10^{-2} kW / QB	≈ 5.0×10^{-3} kW / QB
Total	≈ 3.8×10^{-1} kW / QB	≈ 1.0×10^{-1} kW / QB	≈ 3.3×10^{-2} kW / QB	≈ 6.8×10^{-3} kW / QB

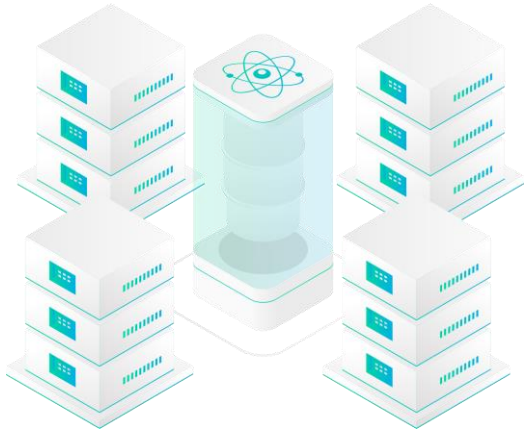
Hybrid Classical-Quantum Architectures

Hardware considerations: locality



Remote access

+ Easy access to multiple technologies.
- Data security.
- Shared access. Pay-as-you-go | oversubscribed systems.
- Possible 3rd party hosting and maintenance.



On-premises

+ Same high-speed network.
+ Data security.
+ Improved execution efficiency for heterogeneous workflows.
- Maintenance by specialized staff.
- Acquisition cost.

On-node

+ Ultimate performance.
+ Advanced access to, e.g. memory.
- Requires significant leaps in QC tech.

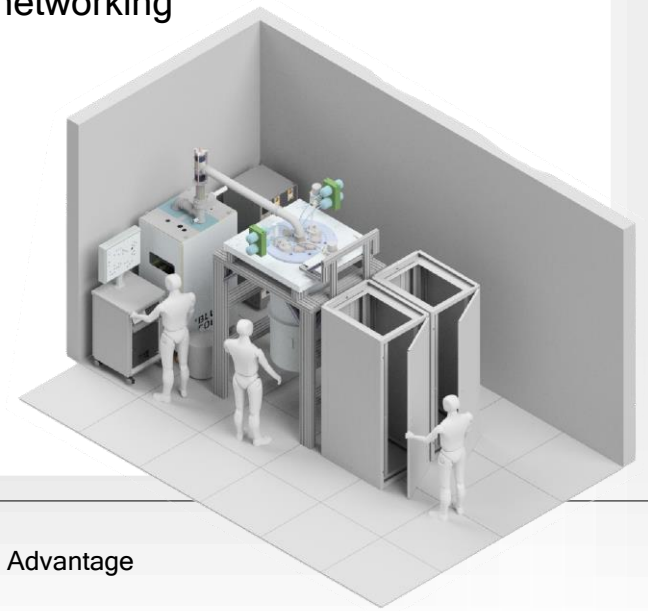
IQM Solution

Steps to build the future of HPC

Hardware of a HPC integrated quantum computer

TRADITIONAL LAB LAYOUT

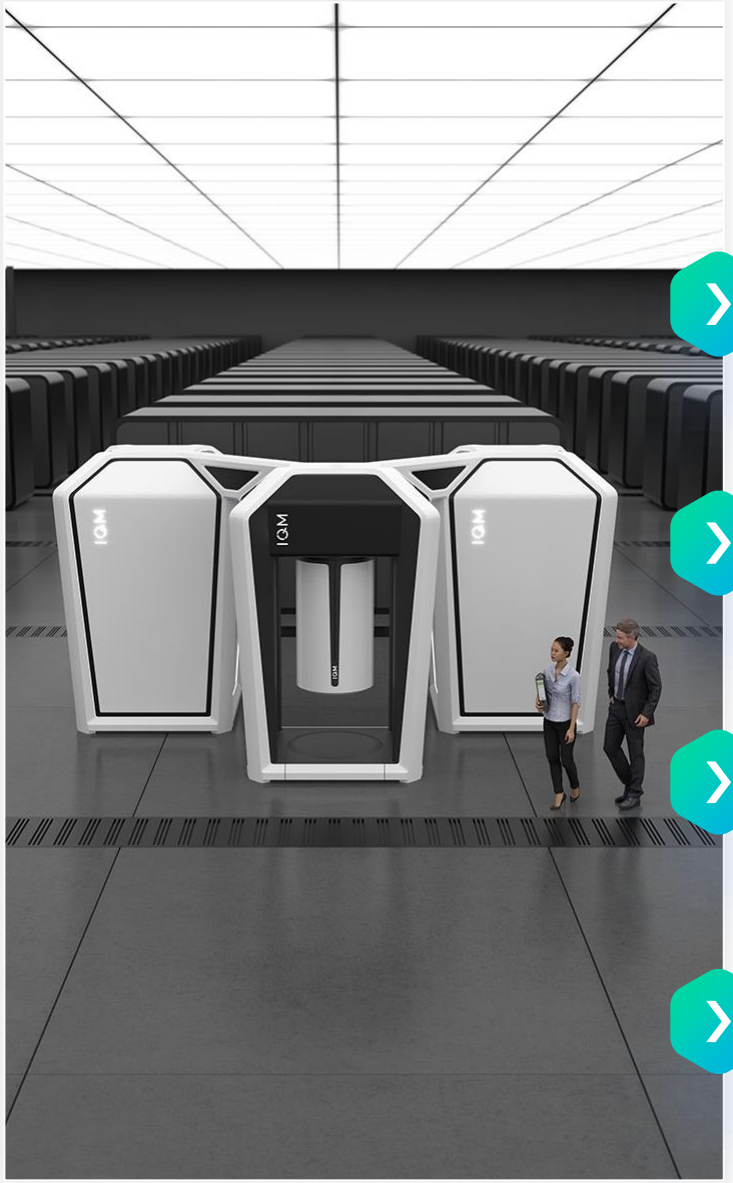
- "An assembly of laboratory equipment“
- Custom layout for each space
- 4 different electrical supplies
- 3 connections to clean filtered cooling water
- Site access to CDA standard compressed air
- Liquid nitrogen filling by user
- Fiberoptic networking



HPC INTEGRATED PRODUCT

- "Just bring power, network, and water," a product suitable for datacenters
- Framed and fits a standard 3m pitch isle of hardware
- Unified power with internal distribution and 3-phase load balancing.
- Internal LN2 and clean dry air generation and filling*.
- Wider range of compatible cooling water due to an internal secondary loop*.
- Sub-structure to install into standard 60cm pitch false floor with nominal weight limits*.
- Network connectivity by Ethernet
- Internal metrics for system maintenance and health checks

*optional, site dependent



Hybrid Classical-Quantum Algorithms

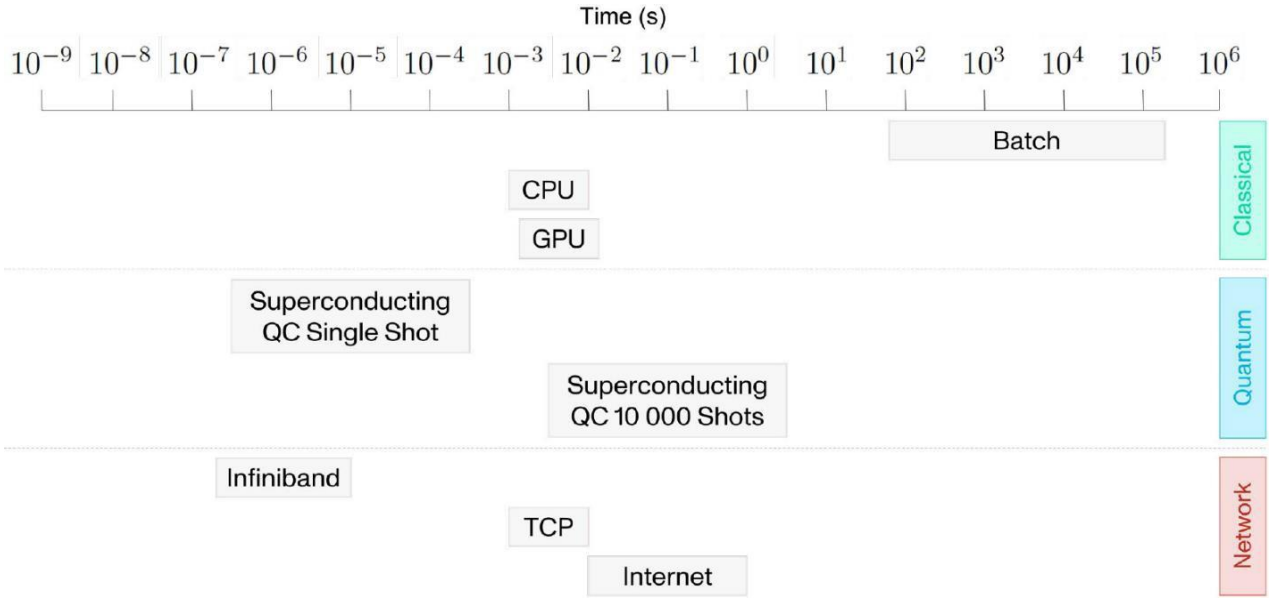
QUANTUM ADVANTAGE

- Quantum advantage has been theoretically demonstrated on a number of algorithms, but only a small number of applications were explored so far
  - Most developments to date have focused on algorithms running only on quantum computers
- Combining classical and quantum computers is likely to produce many algorithms with a quantum advantage
  - e.g. Variational Quantum Algorithms
- Integrating quantum computing into HPC requires a similar approach to other accelerators we have seen in the past
  - The classical host is the computer which requires tasks to be computed using the accelerator
- The benefits associated to different types of algorithms are highly dependent on the hardware interface between the supercomputer and the quantum accelerator

Hybrid Classical-Quantum Architectures

Software considerations

- System-wide Quantum Resource Management is key to maximize the usage of resources and prevent conflicts between users
  - Quantum computing integrated with HPC creates new constraints:
    - the exclusivity of resources
    - the bounded execution time of quantum algorithms in current systems
    - the indivisibility of a single shot - resources cannot be preempted
  - Classical jobs are in the order of magnitude between seconds and days whereas quantum shot are several orders of magnitude shorter
    - Batch schedulers are not equipped to handle that

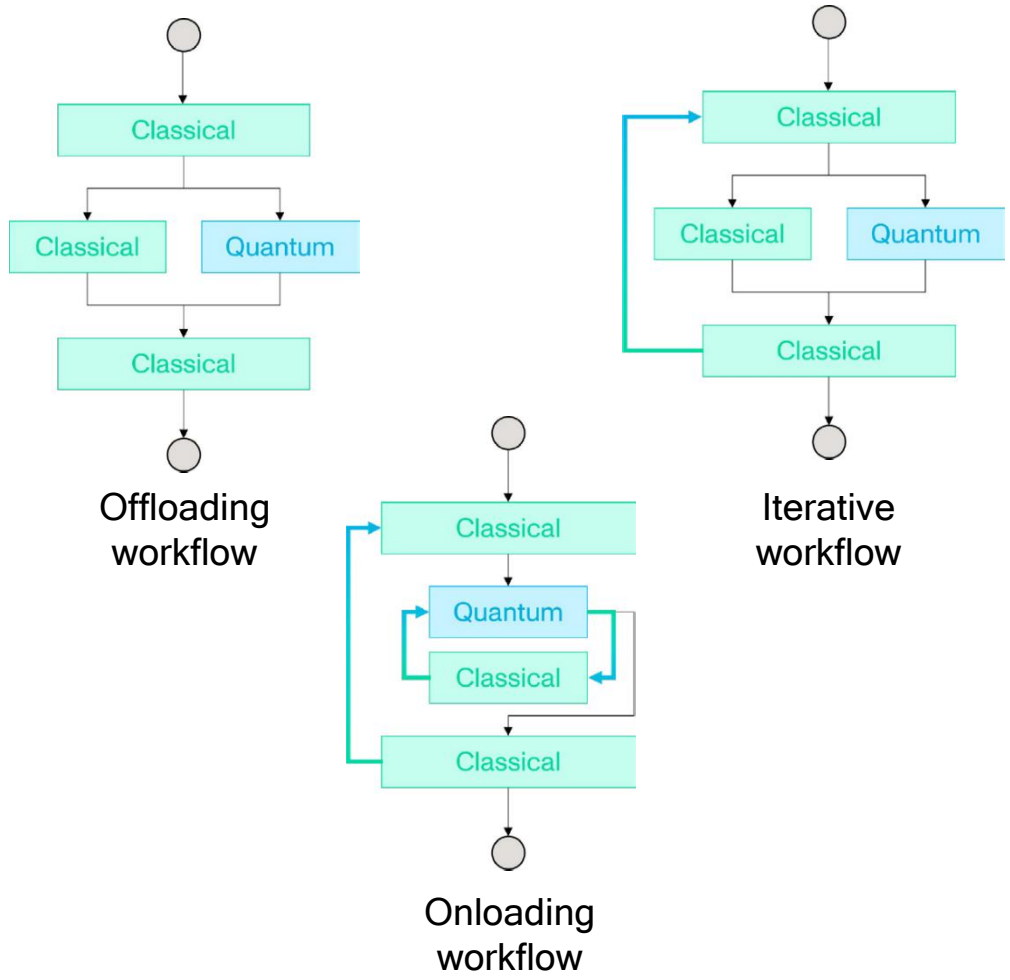


SW Integration for Hybrid Classical-Quantum Algorithms

REVISITING COMPUTING

Successful integration of a quantum accelerator into the HPC environment relies on the HPC user community learning to rethink their problems considering quantum resources:

- Rethinking workflows
  - Which part of the workflow can take benefit from quantum acceleration?
- Rethinking the use of direct solvers
  - Many problems in classical computing are using iterative solvers, but quantum algorithms behave more like direct solvers
- Rethinking numerical models
  - Including the underlying mathematical model



Abstraction layers, Interfaces & Standards

FUTURE HETEROGENEOUS HPC+QC SYSTEMS

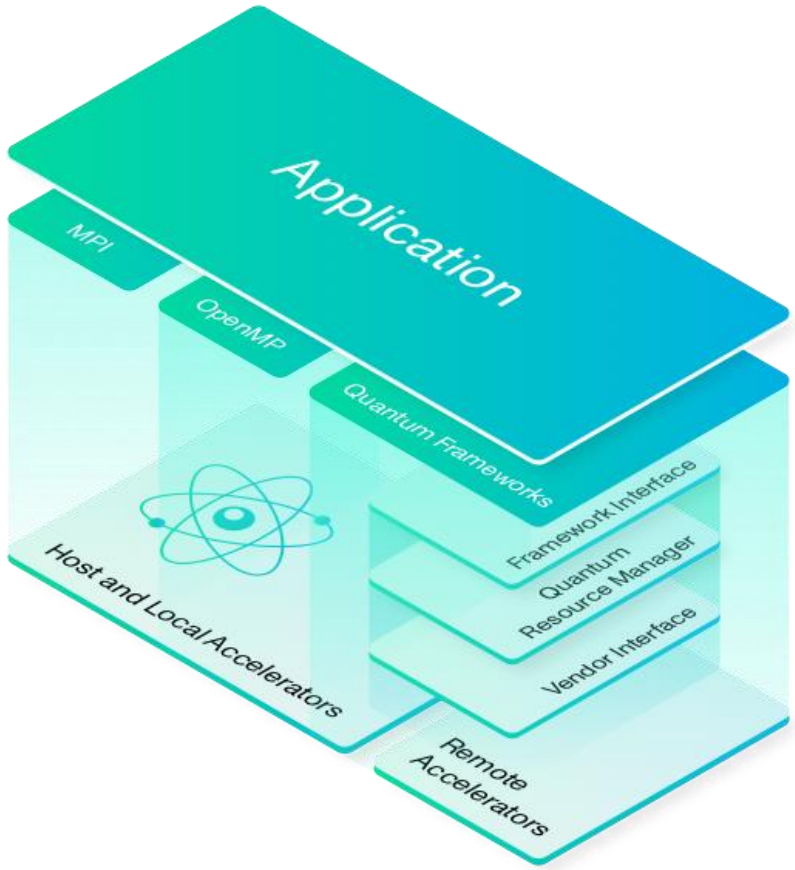
Multiple Quantum Accelerators will be available.
Need for standardization of interfaces.

FRAMEWORK INTERFACE

Allows quantum frameworks to target the quantum resource manager.
Quantum algorithm optimization moved below this layer.
Reduces barrier for user engagement.

VENDOR INTERFACE

Exposes abstraction layers for the control of the QC hardware.
Must support system management tasks for the resource manager.
Likely needs to be upgraded to improve performance.



WHITEPAPER

Bringing quantum acceleration to supercomputers

http://meetiqm.com/uploads/documents/IQM_HPC-QC-Integration-Whitepaper.pdf

Martin Ruefenacht, Bruno G. Taketani, Pasi Lähteenmäki,
Ville Bergholm, Dieter Kranzlmüller, Laura Schulz, Martin Schulz


IQM Leibniz-Rechenzenturm der Bayerischen Akademie der Wissenschaften

MAY 2022

Bringing quantum acceleration to supercomputers

MARTIN RUEFENACHT[1], BRUNO G. TAKETANI[2], PASI LÄHTEENMÄKI[3], VILLE BERGHOLM[3], DIETER KRANZLMÜLLER[1], LAURA SCHULZ[1], AND MARTIN SCHULZ[1,4]

[1] Leibniz Supercomputing Centre, Garching near München, Germany
[2] IQM, Nymphenburgerstr. 86, 80636 Munich, Germany
[3] IQM, Keilaranta 19, 02150 Espoo, Finland
[4] Technical University of Munich, Garching near München, Germany

Education and executive trainings

IQM Academy

- https://academy.meetiqm.com/
- Free online resources to learn about quantum computing.
- Interactive curriculum, tips & tricks for using IQM hardware, and much more.

Executive Masterclass

- This masterclass will teach you a solid understanding of quantum computing vocabulary, use-cases and help you gain an understanding about quantum computing opportunities for your company

Quantum Computing Certificate Workshop

- Key concepts of quantum computing, the quantum computing landscape and get the chance to engage in hand s-on exercises.
- Experts from IQM and Atos will accompany you on your journey.

Technical Deep Dives

- You have specific needs for your quantum computing journey?
- Together with you we will assess the educational needs, create a custom learning path, and deliver engaging learning experiences that will fit the learning style of your company.

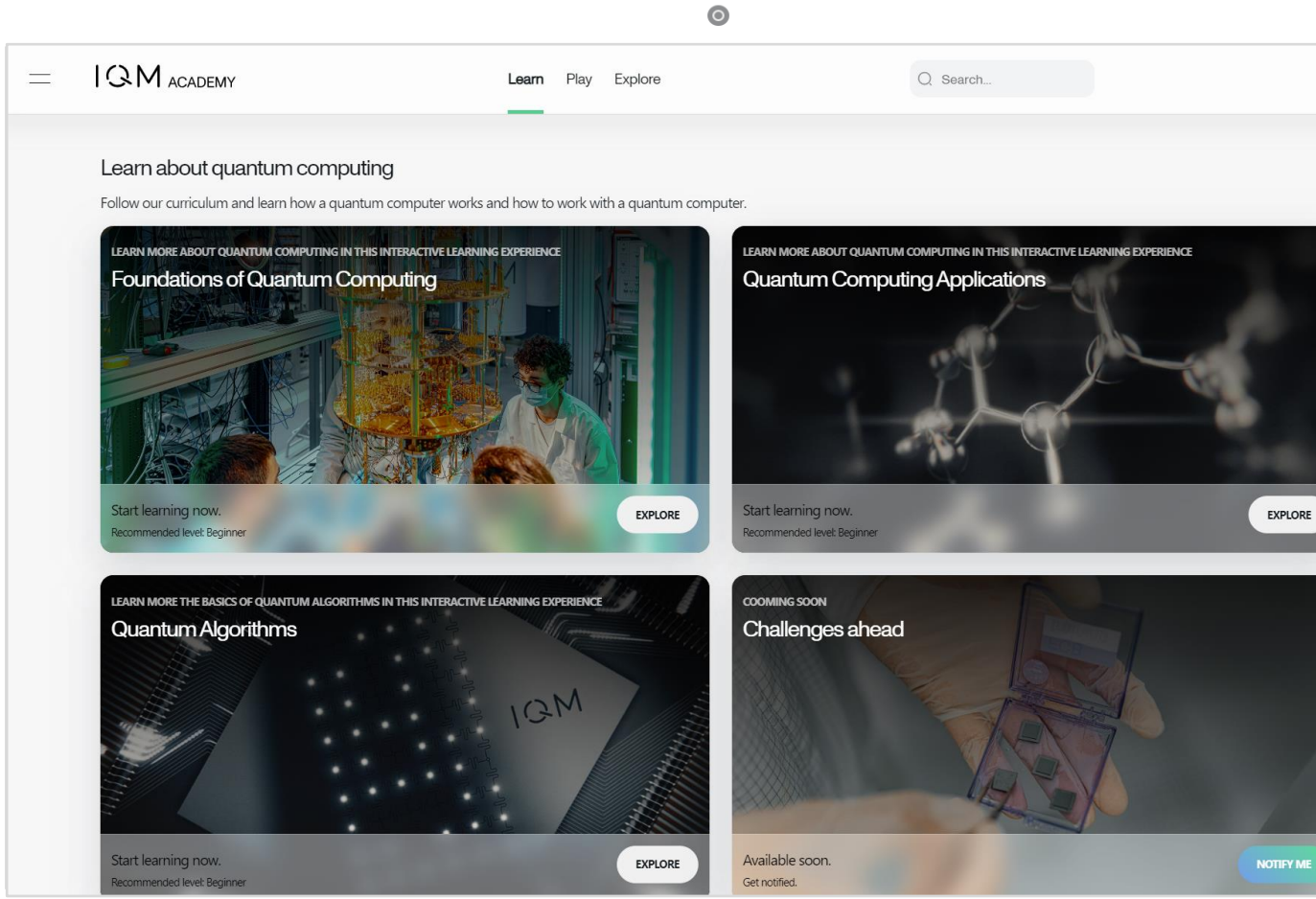
IQM Academy

Gain a thorough understanding of quantum computing and its applications.

- A free curriculum and learning platform for anyone
- Easy to pick up, no previous knowledge required
- Highly interactive and engaging

Start today on

https://academy.meetiqm.com/



IQM is exploring early applications

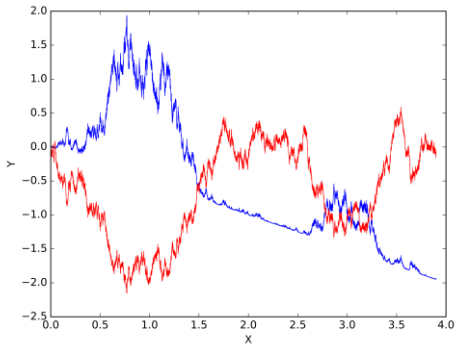
IQM is currently investigating several use-cases for advantage and co-design, organized in two work lines:

Machine Learning

Quantum Reinforcement Learning, Quantum Reservoir Computing

Application: Financial fraud detection

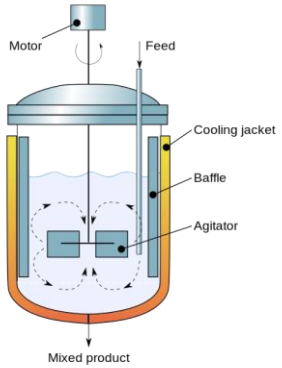
Our partners and clients: A financial institution and Multiverse



→ Develop a quantum-accelerated AI-based PoC for financial fraud detection problems

Application: System/machine control and optimization

Our partners and clients: Siemens, Fraunhofer, and FAU



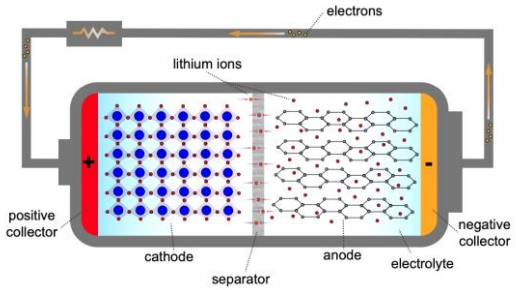
→ PoC for quantum reinforcement learning algorithm to find human-understandable control policy

Fermionic Simulation

Quantum Monte Carlo, Dynamical Mean Field Theory

Application: Battery optimization, transition metal oxides (TMO)

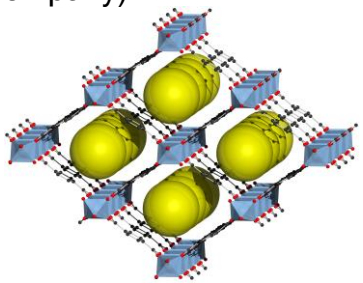
Our partners and clients: An automotive company and German Aerospace Center (DLR)



→ PoC for battery toy model to study chemical properties of TMOs used as cathode materials

Application: Metal-organic framework (MOF) simulation for carbon capture

Our partners and clients: Unannounced collaboration with chemical research company (and energy company)



→ PoC study of interaction between CO2 and the constituents of the MOF

IQM is exploring early applications

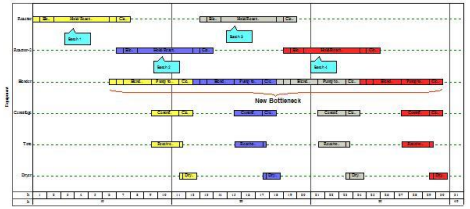
IQM is currently investigating several use-cases for advantage and co-design, organized in two work lines:

Optimization

Quantum Approximate Optimization Algorithm

Application: Power plant outage scheduling

Our partners and clients: a national electric company



- → Investigation of quantum solutions to highly constrained problems
- → PoC scheduling problem solved with amplitude amplification
- → QAOA approach to be investigated

Application: Trajectory optimization

Our partners and clients: a national contractor

- → QASIC approach for optimization (co-design)

Partial Differential Equations (PDE)

Variational quantum circuits

Application: Climate simulations

Our partners and clients: Quanscient, DLR

- → Perspective paper about the use of QC for climate research
- → Speed-up PDE simulations, model tuning, analysis & evaluation