France Quantum
conference

the scientific and technology challenges of FTQC

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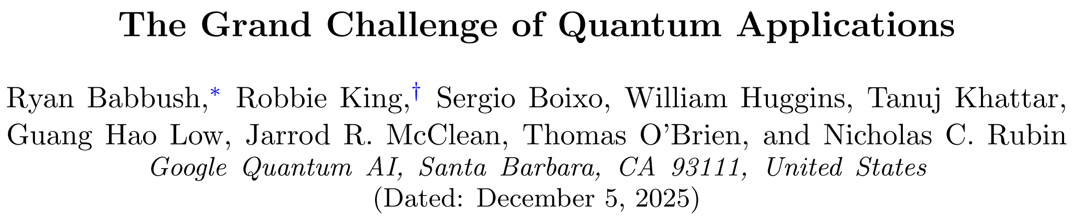
France Quantum, Paris, 16 juin 2026

#QEI
the quantum energy initiative

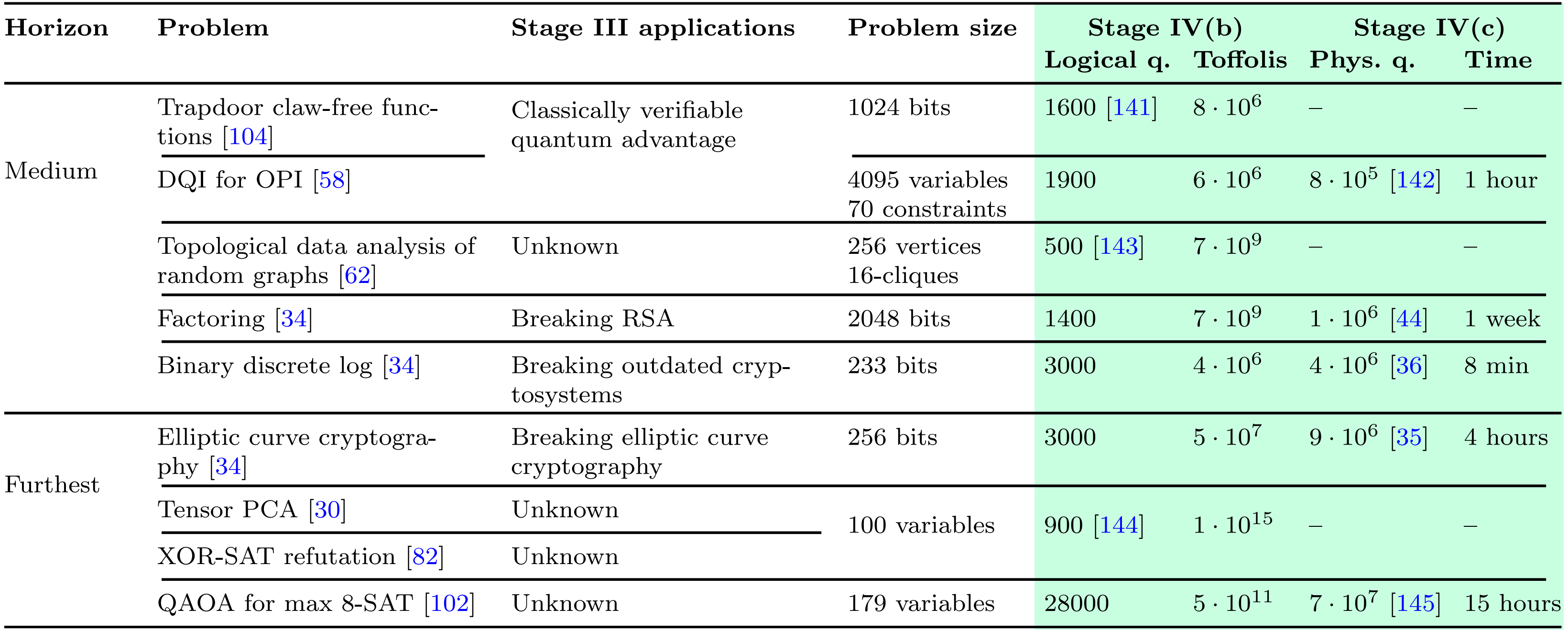
FTQC application needs



The Grand Challenge of Quantum Applications

Ryan Babbush,[*] Robbie King,[†] Sergio Boixo, William Huggins, Tanuj Khattar,
Guang Hao Low, Jarrod R. McClean, Thomas O'Brien, and Nicholas C. Rubin
Google Quantum AI, Santa Barbara, CA 93111, United States
(Dated: December 5, 2025)

arxiv.org/abs/2511.09124



Horizon	Problem	Stage III applications	Problem size	Stage IV(b)		Stage IV(c)	
				Logical q.	Toffolis	Phys. q.	Time
Medium	Trapdoor claw-free functions [104]	Classically verifiable quantum advantage	1024 bits	1600 [141]	$8 \cdot 10^6$	–	–
	DQI for OPI [58]		4095 variables 70 constraints	1900	$6 \cdot 10^6$	$8 \cdot 10^5$ [142]	1 hour
	Topological data analysis of random graphs [62]	Unknown	256 vertices 16-cliques	500 [143]	$7 \cdot 10^9$	–	–
	Factoring [34]	Breaking RSA	2048 bits	1400	$7 \cdot 10^9$	$1 \cdot 10^6$ [44]	1 week
	Binary discrete log [34]	Breaking outdated cryptosystems	233 bits	3000	$4 \cdot 10^6$	$4 \cdot 10^6$ [36]	8 min
Furthest	Elliptic curve cryptography [34]	Breaking elliptic curve cryptography	256 bits	3000	$5 \cdot 10^7$	$9 \cdot 10^6$ [35]	4 hours
	Tensor PCA [30]	Unknown	100 variables	900 [144]	$1 \cdot 10^{15}$	–	–
	XOR-SAT refutation [82]	Unknown					
	QAOA for max 8-SAT [102]	Unknown	179 variables	28000	$5 \cdot 10^{11}$	$7 \cdot 10^7$ [145]	15 hours

FeMoCo resources estimation trend

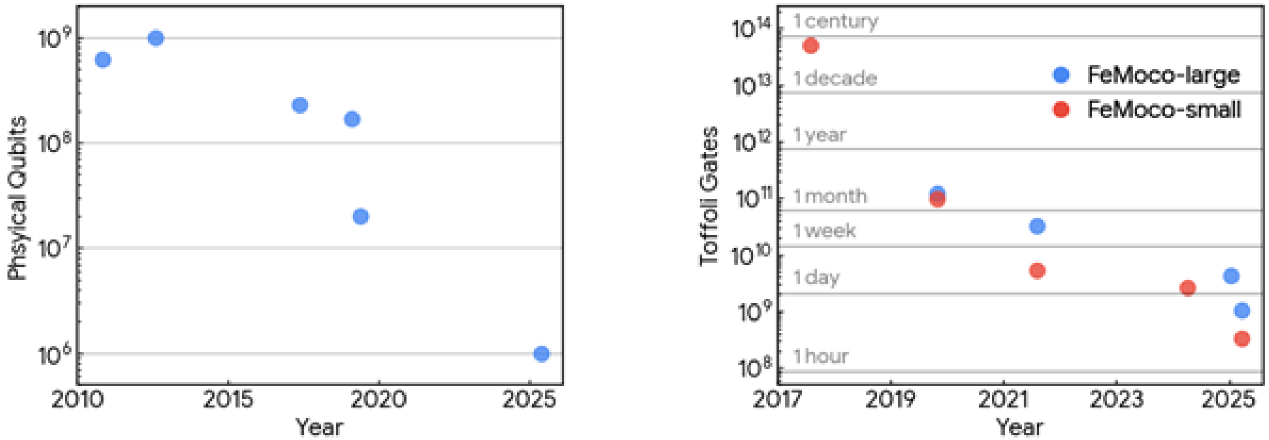


FIG. 2. These figures illustrate that Stage IV research has reduced the resources required to solve important problems by many orders of magnitude over the last decade as function of publication year in both space such as for breaking 2048 bit RSA encryption (left), and time as approximated by the Toffoli count estimating the ground state energy of FeMoco to chemical accuracy for "small" 54-orbital [137] and "large" 76-orbital active spaces [126] (right). The left plot includes Refs. [44, 138–141] and the right plot includes Refs. [41, 43, 137, 142, 143].

The Grand Challenge of Quantum Applications by Ryan Babbush, Robbie King, Sergio Boixo, William Huggins, Tanuj Khattar, Guang Hao Low, Jarrod R. McClean, Thomas O'Brien, and Nicholas C. Rubin, arXiv, November 2025.

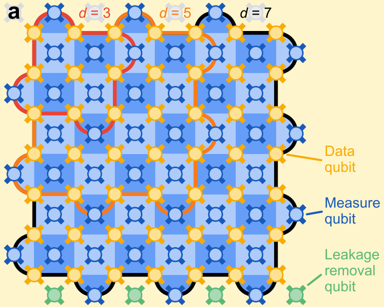
positioning QEC vs FTQC

fault tolerance quantum computing (FTQC)

- support logical gates on a universal gate set.
- avoid error propagation and amplification.
- fault-tolerant results readout.

error correction on logical qubits (QEC)

tens to thousands physical qubits per logical qubits



error rate ≈10^{-4} to ≈10^{-18}

- qubit connectivity.
- physical qubit operations fidelities (>99.9%).
- error correction codes.
- cost of deterministic or heralded photon generation (for photon qubits).
- logical gates implementation.
- error syndrome detection.

QEC/FTQC software + hardware components

software support

- **error suppression and detection**
- **real-time error syndrome detection and correction**
- **compilation-transpilation-optimization**
- **resource estimations**

	logical memory qubits						**logical gates**		
	Pauli error correction	leakage error correction	qubit loss errors correction	spatially correlated errors correction	erasure error correction	defect errors correction	single-qubit Clifford logical gates	two-qubit logical gate (*)	magic-state preparation (T) and teleportation
toolbox	surface and color codes other qLDPC codes concatenated codes stabilizers	leakage reduction unit	atom replenishment	flag qubits (used also in other circumstances) gap engineering (hardware design in superconducting qubits)	conversion to Pauli errors	code patching	Pauli frame tracking H and S gates	lattice surgery or transversal gate SWAP handled in compiler	magic state distillation magic state cultivation asynchronous generation code switching post-selection (not scalable)

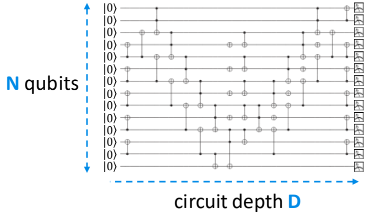
hardware support

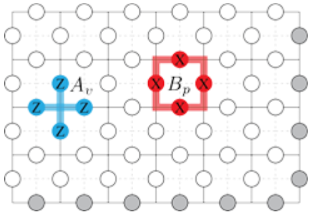
- **qubit physical gate fidelities >99.9% at scale**
- **qubit connectivity**
- **qubit control calibration**
- **qubit fast non demolition measurement**
- **gates and readout speed**
- **scaling QPU with interconnect and gate teleportation + circuits partitioning**

(*) not using post-selection which doesn't scale with deep circuits.

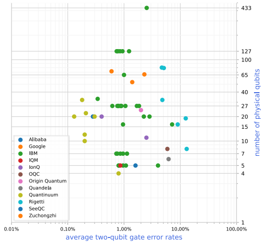
🟪	**purple**	supporting software components
🟩	**green**	QEC support.
🟦	**blue**	FTQC logical gates support.
⬜	**grey**	QEC and FTQC hardware enablers.

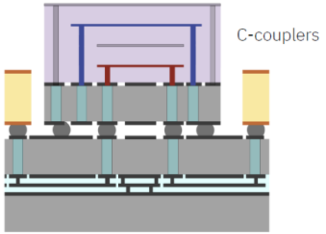
how FTQC ressource estimates work





>99.9%





algorithm breadth (N) and depth (D)

logical qubits # (N)

logical qubit error rate $< \frac{1}{N \times D}$

T gates #

error correction codes and FTQC implementation

physical qubits fidelities

physical qubits connectivity

algorithm independent

algorithm dependent

 # physical qubits / logical qubit

compiler, transpiler and optimizer efficiency

QEC classical overhead

physical gate and readout times

computing time + total # of physical qubits

# of logical qubits and gates + logical qubit fidelities

depends only on the algorithm

physical qubits and computing time estimates

depends on hardware + software

energetic costs

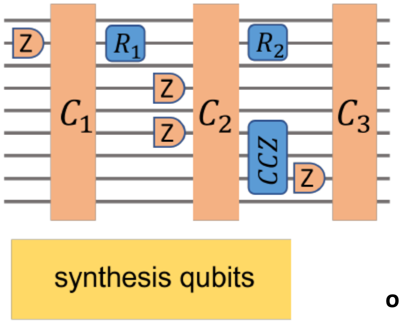
local vs non-local QEC codes

	local codes	non-local codes
typical QEC codes	surface codes (Google)	qLDPC variants, gross code (IBM)
qubit connectivity	nearest neighbors (Google, electron spins)	non-local, either bounded (IBM Loon) or not bounded (ions, atoms)
QEC time overhead	proportional to code distance	constant
Clifford logical gate	in the classical compiler with Pauli frame tracking, lattice surgery	with transversal logical gates
non-Clifford gates	T-state factory + lattice surgery to T state teleportation	T-state factory + transversal teleportation
physical gate speed	≈ 10 ns to 300 ns (superconducting qubits)	≈ 10 ms to 100 ms (when shuttling ions or atoms)
circuit speed ratio	1 (superconducting)	1/10 (atoms/ions) or <1 (superco) (cheaper hardware with atoms / ions)

circuit implementation

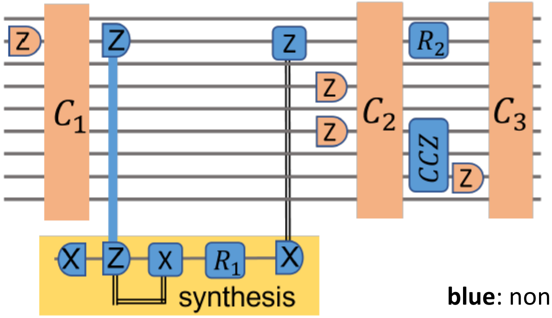
(for nearest neighbour connectivity codes)

(a) initial circuit



C_1, C_2, C_3 are subcircuits made with Clifford gates (X, Y, Z, H, CNOT, SWAP).

(b) Step 1: Rotation by measurement

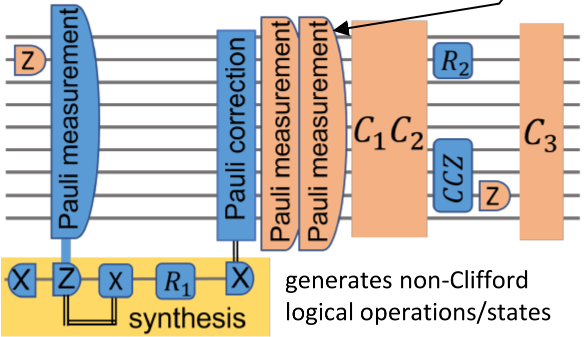


Z rounded shapes on one side are multiqubit ZZ measurements (the second qubit not always being represented).

orange: CNOT and single-qubit measurement.

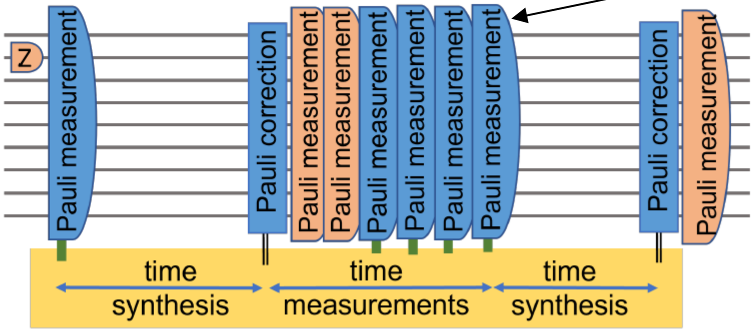
blue: non-destructive joint two-qubit Pauli measurement (XX or ZZ).

(c) Step 2: eliminating Clifford C_1

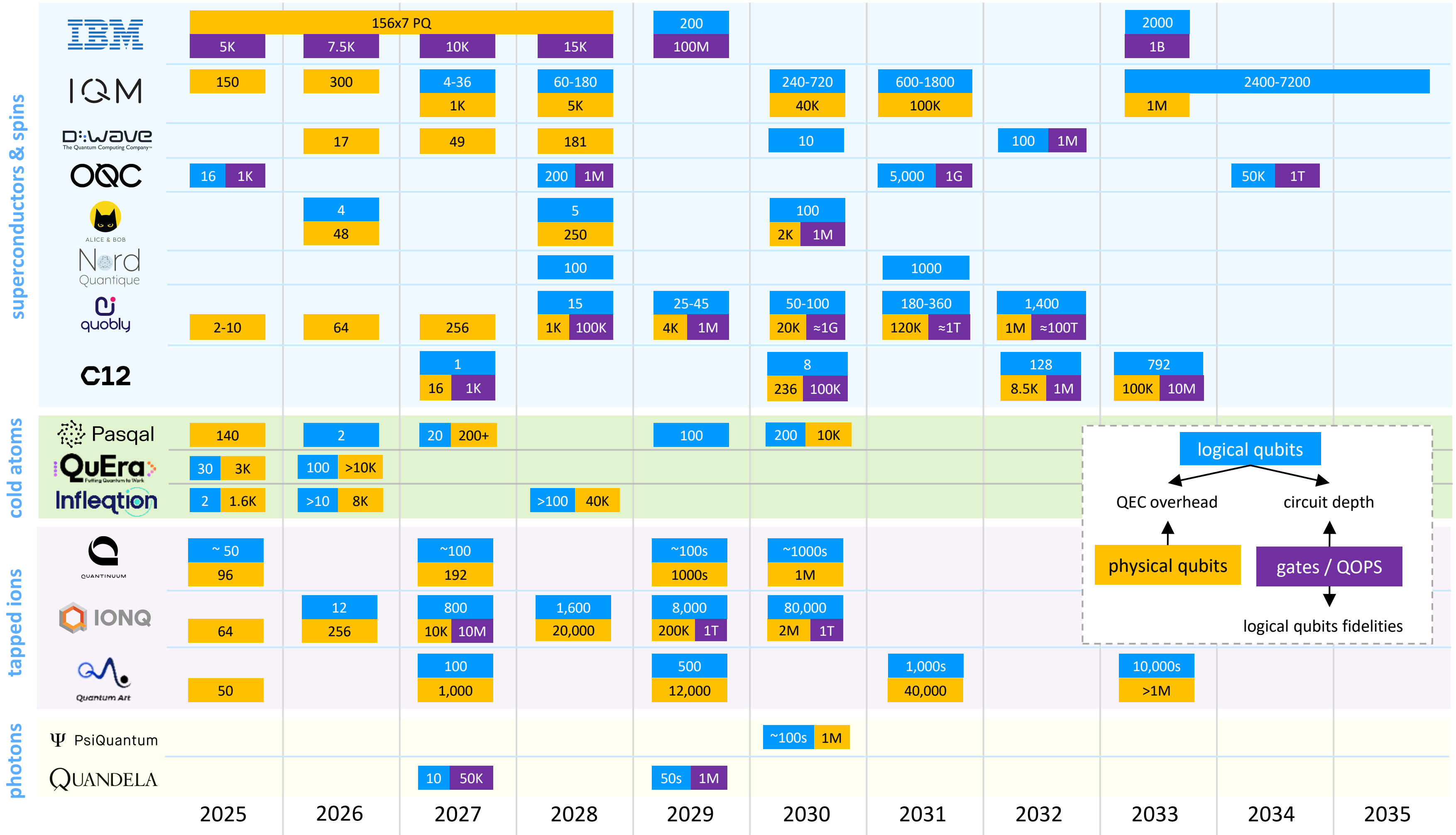


generates non-Clifford logical operations/states

(d) Step 2: all Clifford unitaries eliminated



source: Assessing requirements to scale to practical quantum advantage, by Michael E. Beverland and Alexander Vaschillo et al, arXiv, November 2022.



		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
superconductors & spins	IBM	🟨 156x7 PQ 🟪 5K	🟪 7.5K	🟪 10K	🟪 15K	🟦 200 🟪 100M				🟦 2000 🟪 1B		
	IQM	🟨 150	🟨 300	🟦 4-36 🟨 1K	🟦 60-180 🟨 5K		🟦 240-720 🟨 40K	🟦 600-1800 🟨 100K		🟦 2400-7200 🟨 1M		
	D-Wave The Quantum Computing Company		🟨 17	🟨 49	🟨 181		🟦 10		🟦 100 🟪 1M			
	OQC	🟦 16 🟪 1K			🟦 200 🟪 1M			🟦 5,000 🟪 1G			🟦 50K 🟪 1T	
	ALICE & BOB		🟦 4 🟨 48		🟦 5 🟨 250		🟦 100 🟨 2K 🟪 1M					
	Nord Quantique				🟦 100			🟦 1000				
	quobly	🟨 2-10	🟨 64	🟨 256	🟦 15 🟨 1K 🟪 100K	🟦 25-45 🟨 4K 🟪 1M	🟦 50-100 🟨 20K 🟪 ≈1G	🟦 180-360 🟨 120K 🟪 ≈1T	🟦 1,400 🟨 1M 🟪 ≈100T			
	C12			🟦 1 🟨 16 🟪 1K			🟦 8 🟨 236 🟪 100K		🟦 128 🟨 8.5K 🟪 1M	🟦 792 🟨 100K 🟪 10M		
cold atoms	Pasqal	🟨 140	🟦 2	🟦 20 🟨 200+		🟦 100	🟦 200 🟨 10K					
	QuEra Putting Quantum to Work	🟦 30 🟨 3K	🟦 100 🟨 >10K									
	Infleqtion	🟦 2 🟨 1.6K	🟦 >10 🟨 8K		🟦 >100 🟨 40K							
tapped ions	QUANTINUUM	🟦 ~ 50 🟨 96		🟦 ~100 🟨 192		🟦 ~100s 🟨 1000s	🟦 ~1000s 🟨 1M					
	IONQ	🟨 64	🟦 12 🟨 256	🟦 800 🟨 10K 🟪 10M	🟦 1,600 🟨 20,000	🟦 8,000 🟨 200K 🟪 1T	🟦 80,000 🟨 2M 🟪 1T					
	Quantum Art	🟨 50		🟦 100 🟨 1,000		🟦 500 🟨 12,000		🟦 1,000s 🟨 40,000		🟦 10,000s 🟨 >1M		
photons	PsiQuantum						🟦 ~100s 🟨 1M					
	QUANDELA			🟦 10 🟪 50K		🟦 50s 🟪 1M						

🟦 logical qubits

QEC overhead

circuit depth

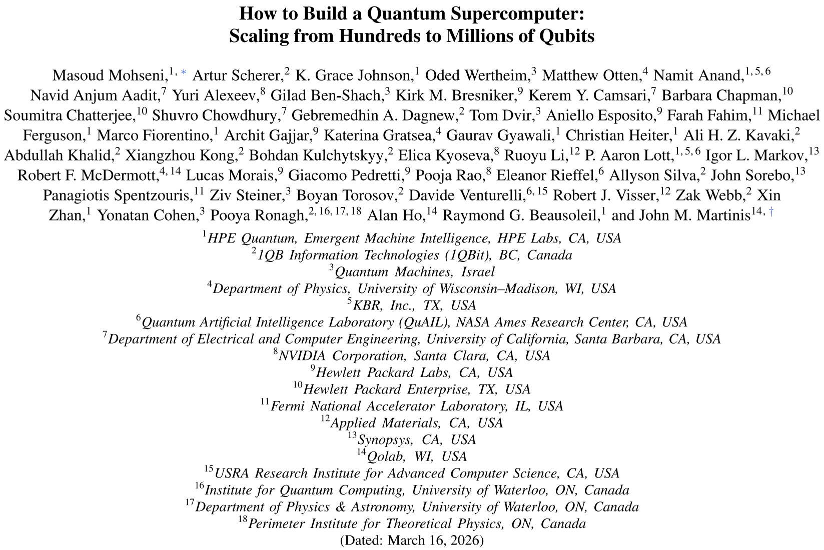
🟨 physical qubits

🟪 gates / QOPS

logical qubits fidelities

(cc) Olivier Ezratty, June 2026.

FTQC blueprints



How to Build a Quantum Supercomputer: Scaling from Hundreds to Millions of Qubits

Masoud Mohseni,[1,*] Artur Scherer,[2] K. Grace Johnson,[1] Oded Wertheim,[3] Matthew Otten,[4] Namit Anand,[1,5,6] Navid Anjum Aadit,[7] Yuri Alexeev,[8] Gilad Ben-Shach,[3] Kirk M. Bresniker,[9] Kerem Y. Camsari,[7] Barbara Chapman,[10] Soumitra Chatterjee,[10] Shuvro Chowdhury,[7] Gebremedhin A. Dagnew,[2] Tom Dvir,[3] Aniello Esposito,[9] Farah Fahim,[11] Michael Ferguson,[1] Marco Fiorentino,[1] Archit Gajjar,[9] Katerina Gratsea,[4] Gaurav Gyawali,[1] Christian Heiter,[1] Ali H. Z. Kavaki,[2] Abdullah Khalid,[2] Xiangzhou Kong,[2] Bohdan Kulchytskyy,[2] Elica Kyoseva,[8] Ruoyu Li,[12] P. Aaron Lott,[1,5,6] Igor L. Markov,[13] Robert F. McDermott,[4,14] Lucas Morais,[9] Giacomo Pedretti,[9] Pooja Rao,[8] Eleanor Rieffel,[6] Allyson Silva,[2] John Sorebo,[13] Panagiotis Spentzouris,[11] Ziv Steiner,[3] Boyan Torosov,[2] Davide Venturelli,[6,15] Robert J. Visser,[12] Zak Webb,[2] Xin Zhan,[1] Yonatan Cohen,[3] Pooya Ronagh,[2,16,17,18] Alan Ho,[14] Raymond G. Beausoleil,[1] and John M. Martinis[14,†]

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[5] *KBR, Inc., TX, USA*
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[8] *NVIDIA Corporation, Santa Clara, CA, USA*
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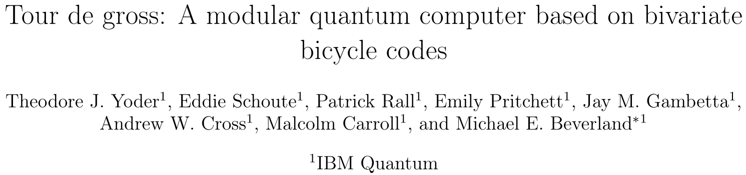
[14] *Qolab, WI, USA*
[15] *USRA Research Institute for Advanced Computer Science, CA, USA*
[16] *Institute for Quantum Computing, University of Waterloo, ON, Canada*
[17] *Department of Physics & Astronomy, University of Waterloo, ON, Canada*
[18] *Perimeter Institute for Theoretical Physics, ON, Canada*
(Dated: March 16, 2026)

https://arxiv.org/abs/2411.10406 (91 pages)

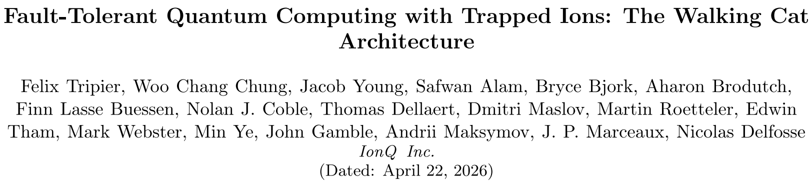


Tour de gross: A modular quantum computer based on bivariate bicycle codes

Theodore J. Yoder[1], Eddie Schoute[1], Patrick Rall[1], Emily Pritchett[1], Jay M. Gambetta[1], Andrew W. Cross[1], Malcolm Carroll[1], and Michael E. Beverland[*1]

[1] IBM Quantum

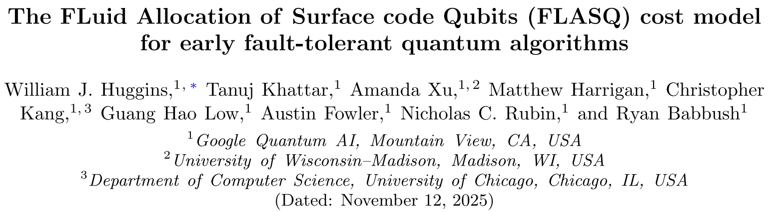
https://arxiv.org/abs/2506.03094 (68 pages)



Fault-Tolerant Quantum Computing with Trapped Ions: The Walking Cat Architecture

Felix Tripier, Woo Chang Chung, Jacob Young, Safwan Alam, Bryce Bjork, Aharon Brodutch, Finn Lasse Buessen, Nolan J. Coble, Thomas Dellaert, Dmitri Maslov, Martin Roetteler, Edwin Tham, Mark Webster, Min Ye, John Gamble, Andrii Maksymov, J. P. Marceaux, Nicolas Delfosse
IonQ Inc.
(Dated: April 22, 2026)

https://arxiv.org/abs/2604.19481 (110 pages)



The FLuid Allocation of Surface code Qubits (FLASQ) cost model for early fault-tolerant quantum algorithms

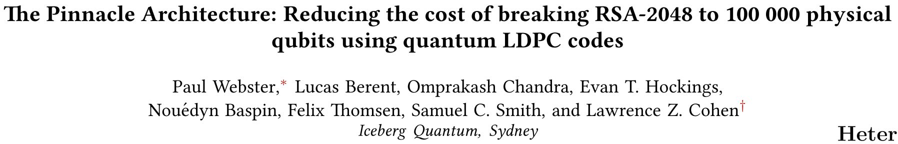
William J. Huggins,[1,*] Tanuj Khattar,[1] Amanda Xu,[1,2] Matthew Harrigan,[1] Christopher Kang,[1,3] Guang Hao Low,[1] Austin Fowler,[1] Nicholas C. Rubin,[1] and Ryan Babbush[1]

[1] *Google Quantum AI, Mountain View, CA, USA*
[2] *University of Wisconsin–Madison, Madison, WI, USA*
[3] *Department of Computer Science, University of Chicago, Chicago, IL, USA*
(Dated: November 12, 2025)

https://arxiv.org/abs/2511.08508 (60 pages)

new FTQC resource estimates

Iceberg Quantum

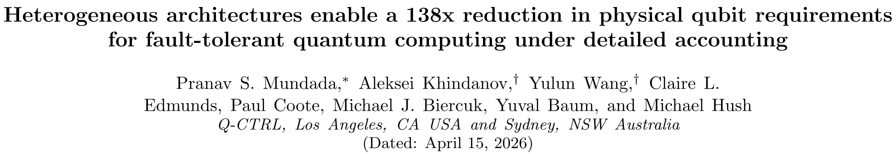


The Pinnacle Architecture: Reducing the cost of breaking RSA-2048 to 100 000 physical qubits using quantum LDPC codes

Paul Webster,[*] Lucas Berent, Omprakash Chandra, Evan T. Hockings,
Nouédyn Baspin, Felix Thomsen, Samuel C. Smith, and Lawrence Z. Cohen[†]
Iceberg Quantum, Sydney

https://arxiv.org/abs/2602.11457

Q-CTRL

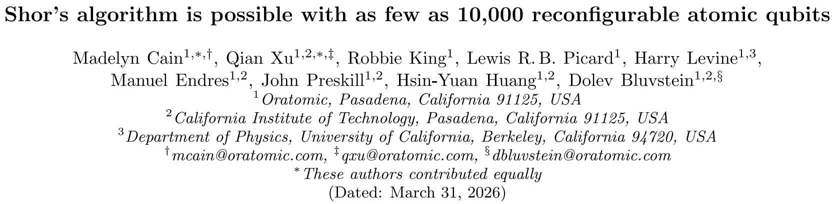


Heterogeneous architectures enable a 138x reduction in physical qubit requirements for fault-tolerant quantum computing under detailed accounting

Pranav S. Mundada,[*] Aleksei Khindanov,[†] Yulun Wang,[†] Claire L. Edmunds, Paul Coote, Michael J. Biercuk, Yuval Baum, and Michael Hush
Q-CTRL, Los Angeles, CA USA and Sydney, NSW Australia
(Dated: April 15, 2026)

https://arxiv.org/abs/2604.06319

Oratomic



Shor's algorithm is possible with as few as 10,000 reconfigurable atomic qubits

Madelyn Cain[1,*,†], Qian Xu[1,2,*,‡], Robbie King[1], Lewis R. B. Picard[1], Harry Levine[1,3],
Manuel Endres[1,2], John Preskill[1,2], Hsin-Yuan Huang[1,2], Dolev Bluvstein[1,2,§]
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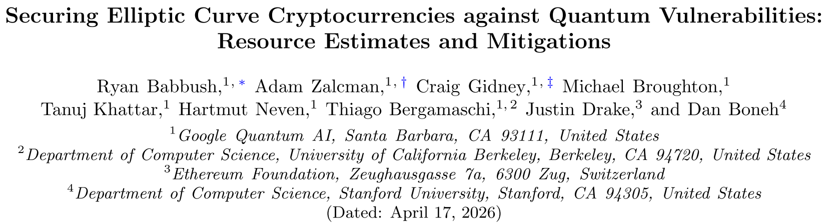
[*] *These authors contributed equally*
(Dated: March 31, 2026)

https://arxiv.org/abs/2603.28627v1

Google



Securing Elliptic Curve Cryptocurrencies against Quantum Vulnerabilities: Resource Estimates and Mitigations

Ryan Babbush,[1,*] Adam Zalcman,[1,†] Craig Gidney,[1,‡] Michael Broughton,[1]
Tanuj Khattar,[1] Hartmut Neven,[1] Thiago Bergamaschi,[1,2] Justin Drake,[3] and Dan Boneh[4]
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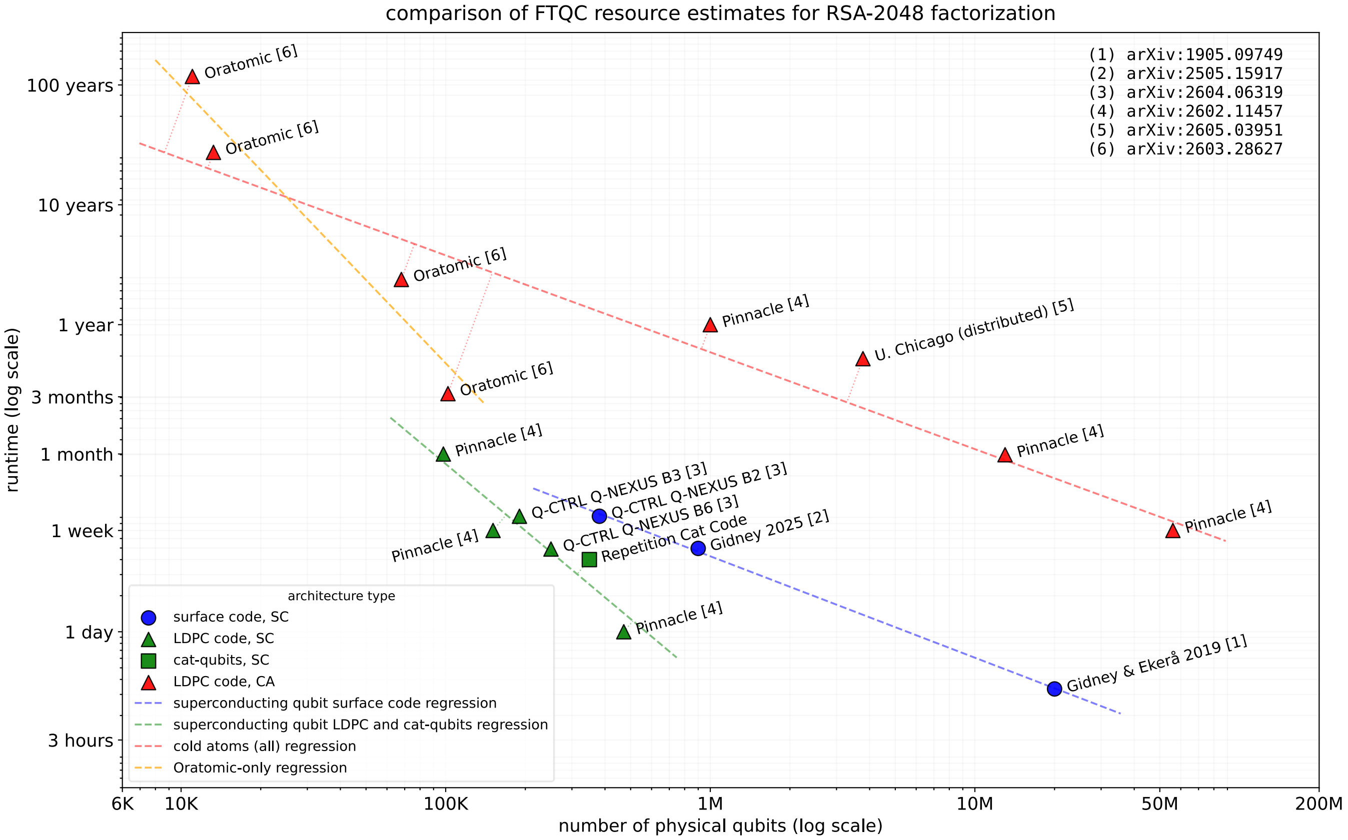
(Dated: April 17, 2026)

https://arxiv.org/abs/2603.28846

FTQC space-time trade-offs



source: Olivier Ezratty, May 2026

#QEI

the quantum energy initiative

quantum-energy-initiative.org/

QEI 2025 (Grenoble) and 2026 (Barcelona)

why

- ICT energy consumption is growing fast.
- most quantum technologies will add an incremental energetic cost to existing ICT.
- it is time to work on this as quantum technologies and applications are designed.
- ethical and responsible innovation imperative.

what

- build **new** science and engineering.
- create full-stack methodologies and standards to evaluate, optimize, and benchmark quantum technologies energy consumption.
- change the rules of the game.

how

- QEI scientific board (8).
- QEI community (>700 participants from 81 countries).
- QEI workshops (2023 in Singapore, 2025 in Grenoble, 2026 in Barcelona, 2027 in Lisbon).
- QEI IEEE standards WG.
- ≈30 industry partners including IBM, Quandela, etc.

#QEI
the quantum energy initiative

pillars

science and engineering

- quantum thermodynamics and energetics.
- classical information thermodynamics.
- solid-state physics, quantum optics, quantum control, and quantum interfaces.
- quantum information theory and protocols: communications, algorithms, QEC/FTQC fundamentals.
- quantum metrology and sensing.

- QEC/FTQC full-stack implementation.
- quantum devices manufacturing.
- enabling technologies scaling.
- quantum network and QPU interconnect infrastructure.
- quantum software engineering and FTQC-HPC integration.
- quantum sensors.

interdisciplinarity
hardware + software
resource estimates

- IEEE QEI standard.
- benchmarking standards.

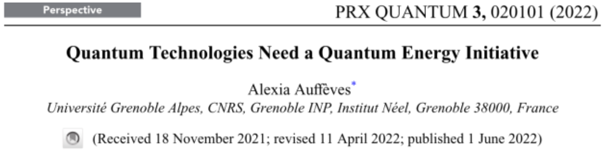
- economic impact analysis.
- help projects funding.

- ethics and sustainability.
- policy makers outreach.

ecosystem

non-exhaustive inventory

the initial call



Perspective

PRX QUANTUM **3,** 020101 (2022)

Quantum Technologies Need a Quantum Energy Initiative

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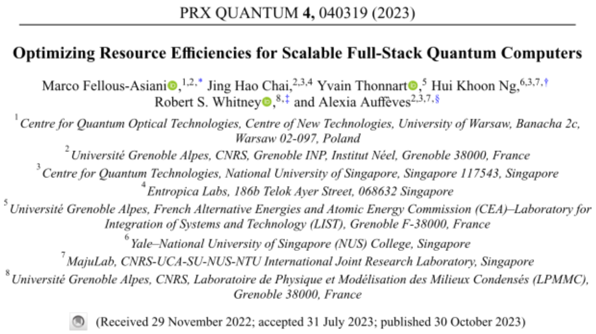
(Received 18 November 2021; revised 11 April 2022; published 1 June 2022)

prxquantum 3.020101

a first full-stack methodology



PRX QUANTUM **4,** 040319 (2023)

Optimizing Resource Efficiencies for Scalable Full-Stack Quantum Computers

Marco Fellous-Asiani,[1,2,*] Jing Hao Chai,[2,3,4] Yvain Thonnart,[5] Hui Khoon Ng,[6,3,7,†]
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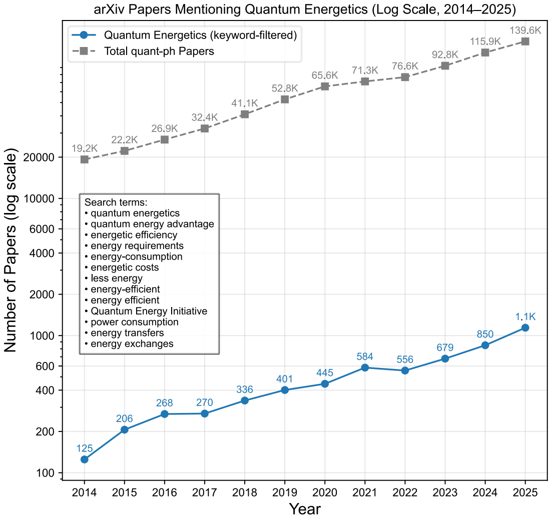
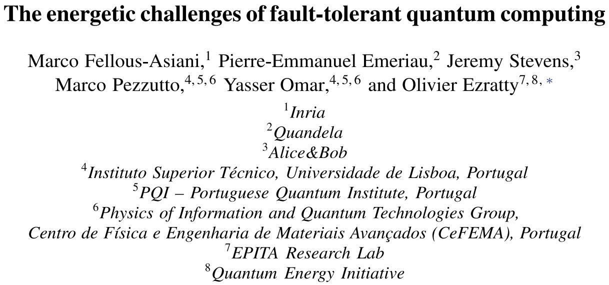
a nascent academic field



expanding work on FTQC



The energetic challenges of fault-tolerant quantum computing

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in preparation

standardization

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IEEE P3329 Quantum Energy Initiative (QEI) Working Group

Title: Standard for Quantum Computing Energy Efficiency

Scope: This standard defines energy efficiency metrics for quantum computing (gate-based, quantum annealing, quantum simulation). It compares the performance of the computation to its energy consumption. The performance is defined at the quantum level and at the end user level. The definition applies to all Quantum Bit (qubit) technologies, including the classical and quantum control chains, to various quantum processors, both Noisy Intermediate Scale Quantum (NISQ)-era and fault-tolerant, as well as to quantum annealers and simulators.

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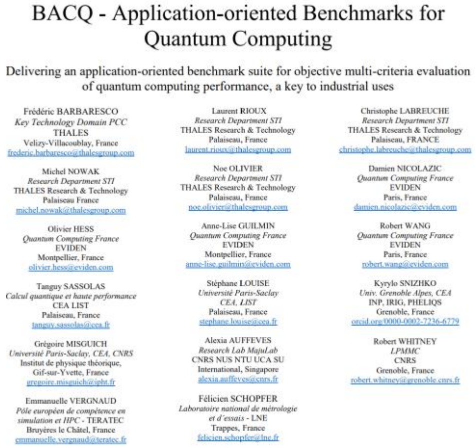
Vice Chair

https://sagroups.ieee.org/qei/

benchmarking



BACQ - Application-oriented Benchmarks for Quantum Computing

Delivering an application-oriented benchmark suite for objective multi-criteria evaluation of quantum computing performance, a key to industrial uses

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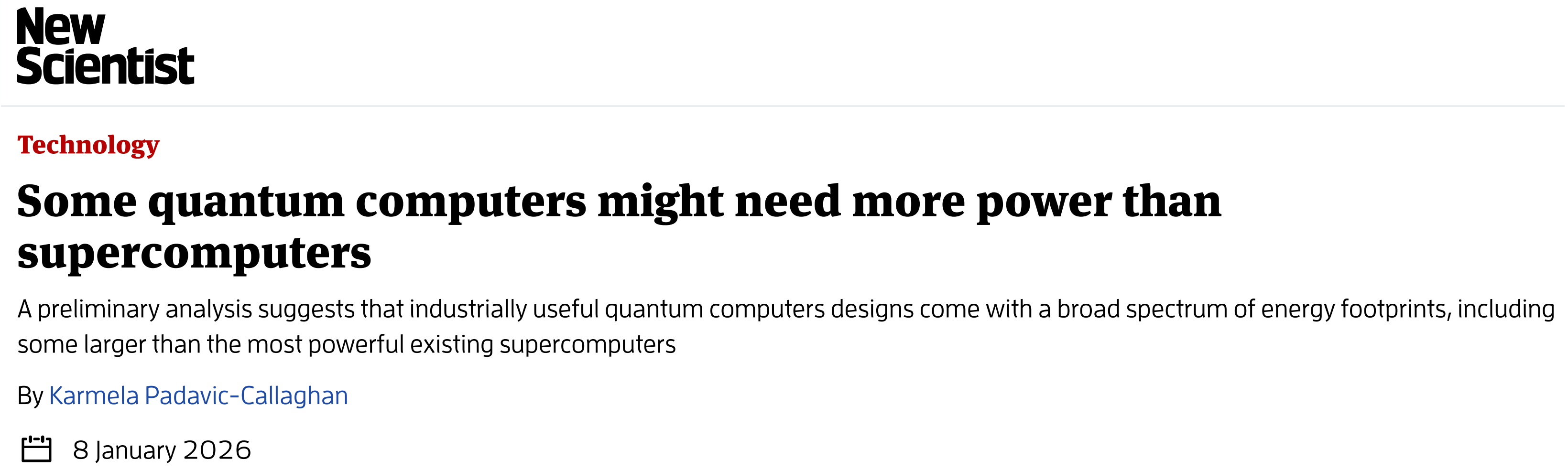
arxiv 2403.12205

looming energetic challenge



New Scientist

Technology

Some quantum computers might need more power than supercomputers

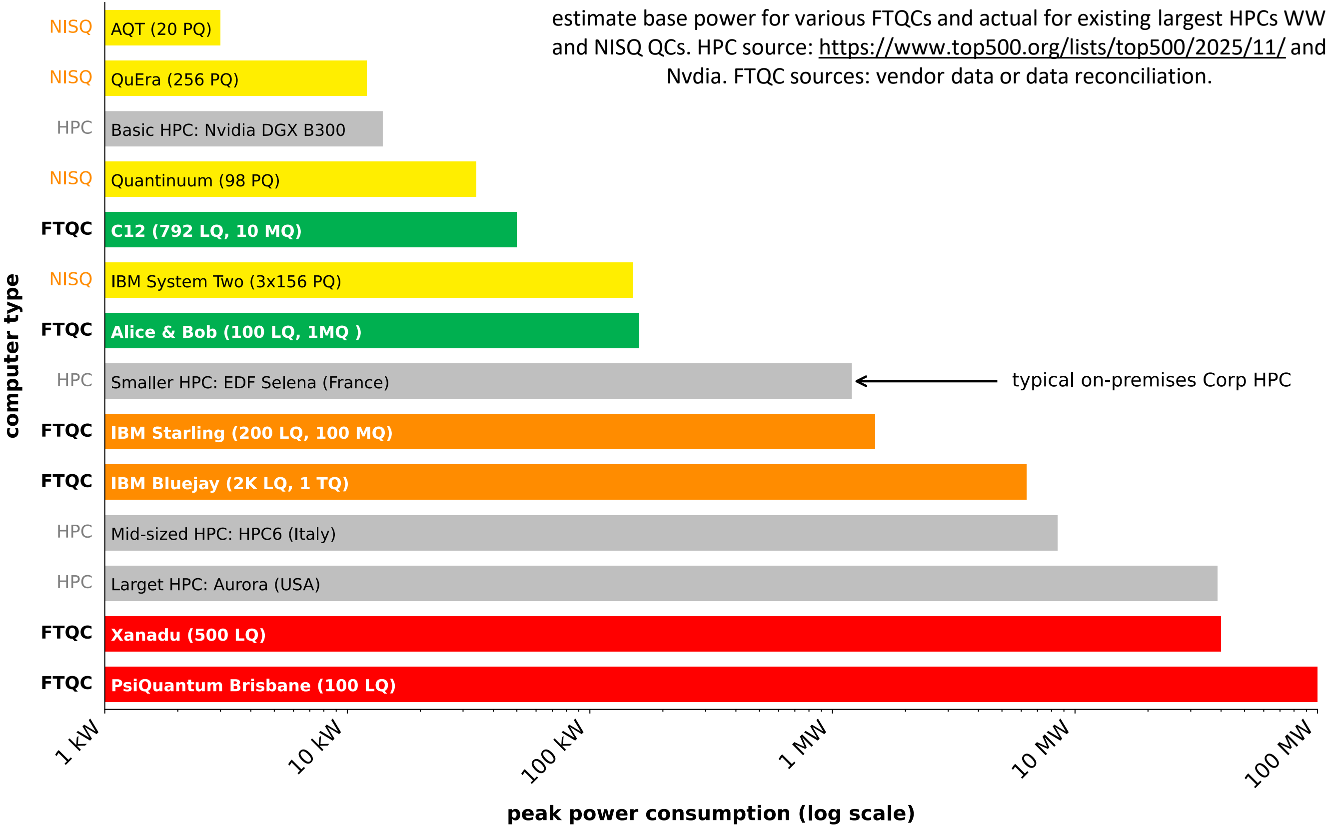
A preliminary analysis suggests that industrially useful quantum computers designs come with a broad spectrum of energy footprints, including some larger than the most powerful existing supercomputers

By Karmela Padavic-Callaghan

8 January 2026

https://www.newscientist.com/article/2509492-some-quantum-computers-might-need-more-power-than-supercomputers/

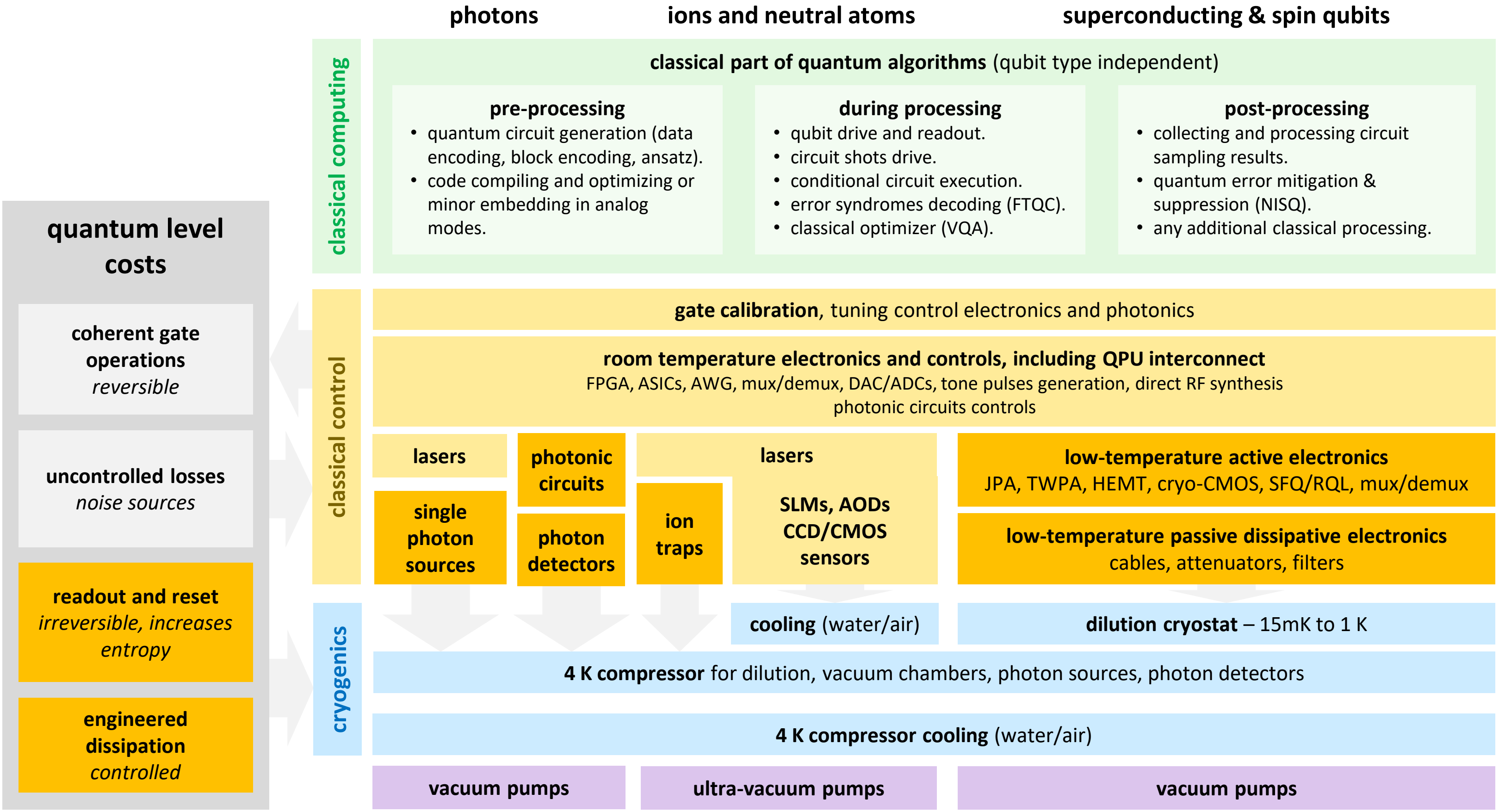
first FTQC vs HPC power estimates



estimate base power for various FTQCs and actual for existing largest HPCs WW and NISQ QCs. HPC source: https://www.top500.org/lists/top500/2025/11/ and Nvdia. FTQC sources: vendor data or data reconciliation.

source: Olivier Ezratty, May 2026

accounting for all energetic costs



photons | **ions and neutral atoms** | **superconducting & spin qubits**

quantum level costs

coherent gate operations
reversible

uncontrolled losses
noise sources

readout and reset
irreversible, increases entropy

engineered dissipation
controlled

classical computing

classical part of quantum algorithms (qubit type independent)

pre-processing
- quantum circuit generation (data encoding, block encoding, ansatz).
- code compiling and optimizing or minor embedding in analog modes.

during processing
- qubit drive and readout.
- circuit shots drive.
- conditional circuit execution.
- error syndromes decoding (FTQC).
- classical optimizer (VQA).

post-processing
- collecting and processing circuit sampling results.
- quantum error mitigation & suppression (NISQ).
- any additional classical processing.

classical control

gate calibration, tuning control electronics and photonics

room temperature electronics and controls, including QPU interconnect
FPGA, ASICs, AWG, mux/demux, DAC/ADCs, tone pulses generation, direct RF synthesis
photonic circuits controls

lasers

single photon sources

photonic circuits

photon detectors

lasers

ion traps

SLMs, AODs CCD/CMOS sensors

low-temperature active electronics
JPA, TWPA, HEMT, cryo-CMOS, SFQ/RQL, mux/demux

low-temperature passive dissipative electronics
cables, attenuators, filters

cryogenics

cooling (water/air)

dilution cryostat – 15mK to 1 K

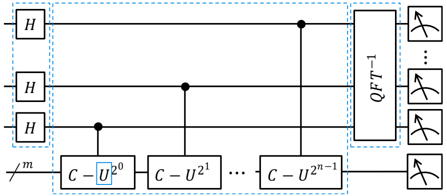
4 K compressor for dilution, vacuum chambers, photon sources, photon detectors

4 K compressor cooling (water/air)

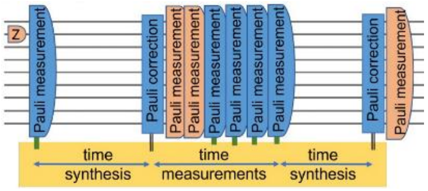
vacuum pumps | **ultra-vacuum pumps** | **vacuum pumps**

classical computing costs to consider

logical circuit



physical circuit



problem structure
problem data

classical bits

value of interest

- ground state
- excited state
- index value

classical computing tasks

quantum circuit generation

- problem reformulation
- includes data encoding in an input vector or an oracle

circuit compiling

- transpiling and optimization
- error correction and fault tolerance conversion (FTQC)
- circuit partitioning

real time error detection (FTQC)

batch manager

- controls multiple circuit execution
- distributed workloads

circuit shots post-processing

calibration

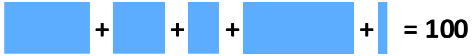
from baseline estimates to optimizations

holistic optimizations

reductionist optimizations

baseline resources

- include all active components.
- using existing state of the art technologies.
- sum-up the energy and power contribution of each component.

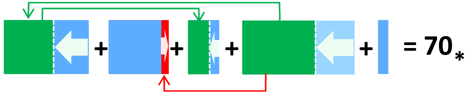


- optimize the consumption of individual components in the stack, without introducing more noise on the processor.

examples:

- improve cryogenic efficiency.
- reduce cable heat conduction.
- reduce the algorithmic cost without degrading its accuracy.

- interdependent optimizations.
- typically, introduce tradeoffs between spending less energy and introducing more noise.



examples:

- moving control electronics at cryogenic temperatures.
- multiplexing control signals.
- moving atoms to implement two-qubit gates and QEC.
- changing qubit temperature.

---

* % of baseline power or energy, for the sake of demonstration

key takeaways

- **FTQC** relies on solving a wealth of scientific and technical challenges.
- **progress is faster** on reducing algorithm costs than on the hardware.
- **FTQC power consumption** may become significant, depending on the qubit type.
- **energetic costs** spread over control electronics/photonics, cryogenics and classical error syndromes detection.
- **standardization** needed on the basics of energy/power evaluations, which can enable optimizations.

discussion

get the slides now!

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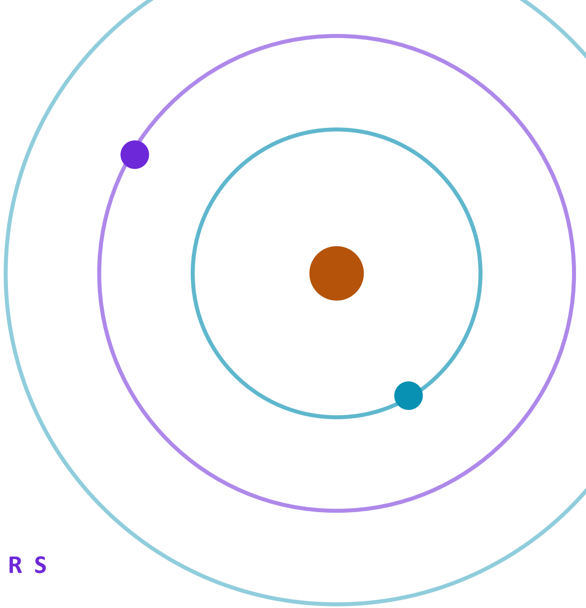

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IQC Chair

Impact of Quantum on Cybersecurity

2026 — 2031 · NEARLY 10 FOUNDING PARTNERS

QUANTUM ENGINEERING *becomes real*

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post-quantum

02
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engineering & resources

03
Education
engineers of tomorrow

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