QUEST-IS'25
QUANTUM ENGINEERING SCIENCES & TECHNOLOGIES FOR INDUSTRY & SERVICES

the interplay between quantum science and quantum engineering

Olivier Ezratty

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QUEST-IS, EDF Palaiseau, December 1st, 2025

#QEI
the quantum energy initiative

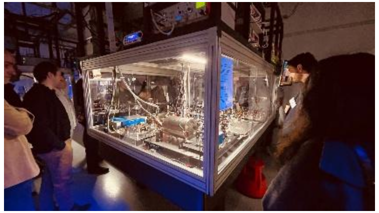
scientific development vs engineering

	scientific development	engineering
goal	**discover or explain new principles or phenomena**	**apply known principles and science to solve practical problems**

scientific development vs engineering

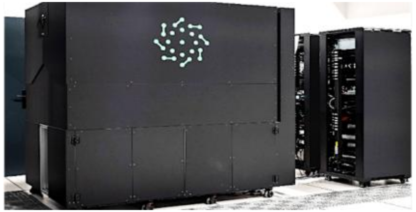
	scientific development	engineering
goal	**discover or explain new principles or phenomena**	**apply known principles and science to solve practical problems**
focus	understanding, modeling	designing, building, optimizing
methodology	hypothesis-driven, exploratory, small-scale experiments	**constraint-driven**, **solution-oriented**, design at practical scale
output	**theories, models, fundamental bounds, proofs, experiments**	**devices, systems, processes, products**
evaluation criteria	**scientific validity, novelty**, learnings, falsifiability	**functionality**, usefulness, efficiency, reliability, cost
time horizon	long-term, uncertain payoff	short-to-mid term, market-driven
economic constraints	variable, experimental setups	cost, manufacturability, user ROI

quantum engineering is a key enabler of the second quantum revolution



quantum science and research

- quantum physics
- condensed matter physics
- quantum photonics
- quantum cryptography
- quantum thermodynamics
- quantum metrology
- quantum information science



quantum technologies

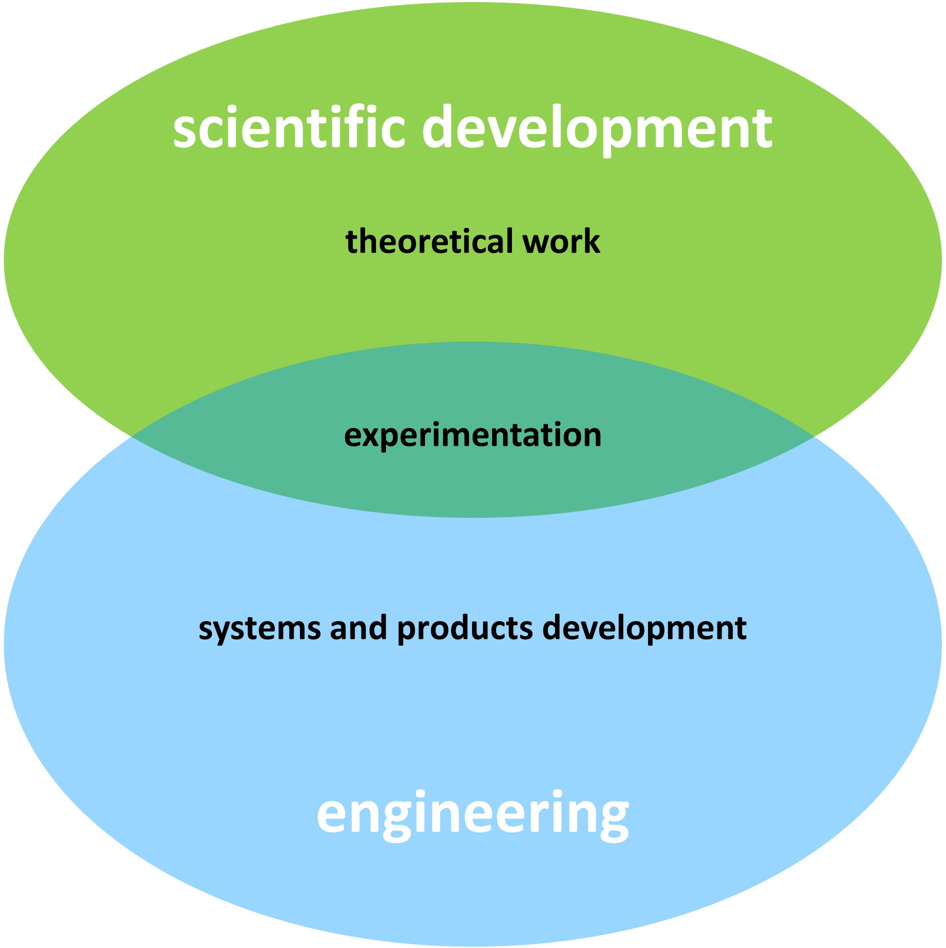
- quantum computers
- quantum key distribution
- quantum networks
- quantum sensors
- quantum matter
- classical enabling technologies

technology innovations

- products
- applications
- actual usage
- market outreach
- business and societal benefits
- economical impact

generic constraints

- talent
- funding
- competition
- evaluation
- patentability

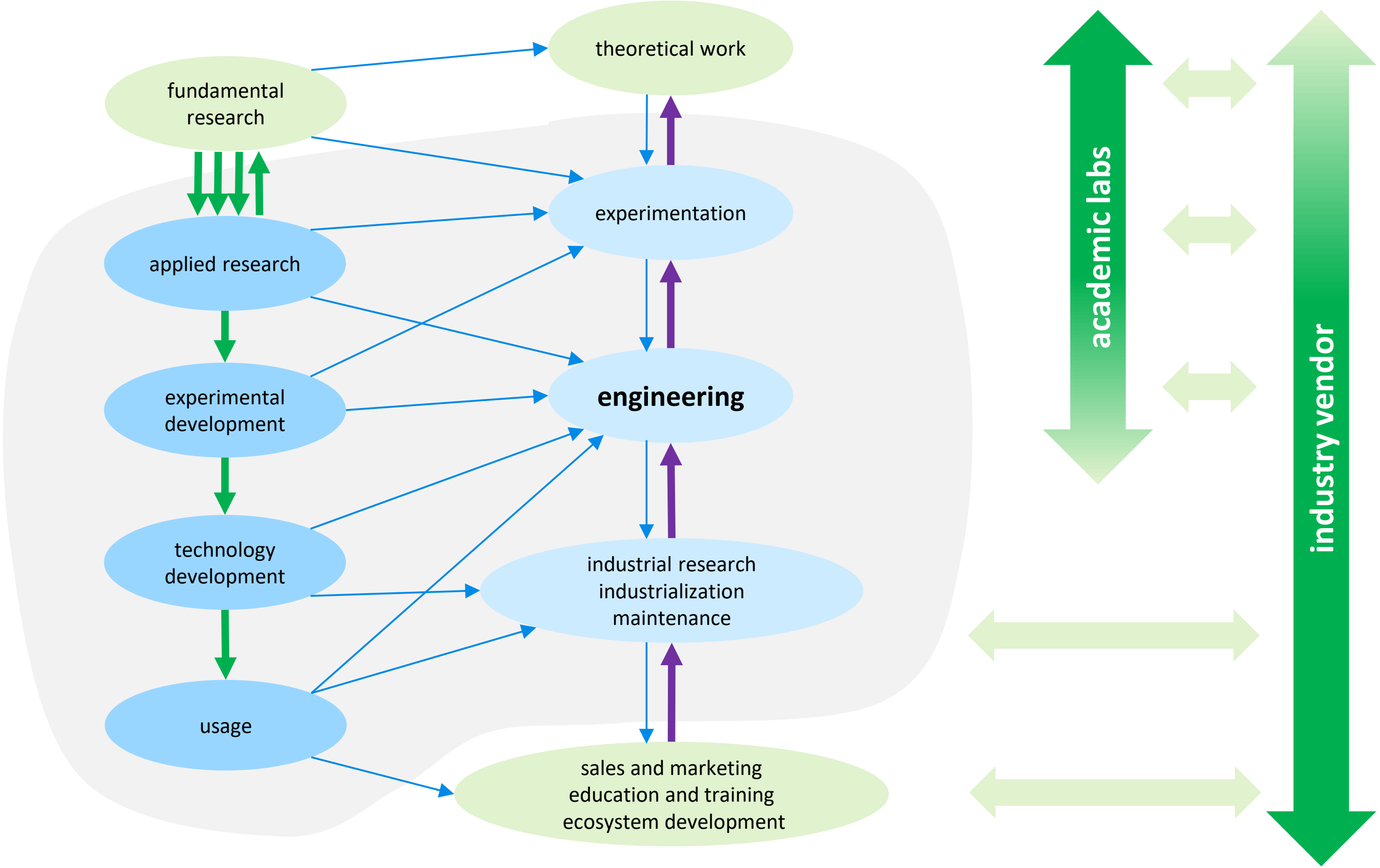


specific constraints

- find good questions
- advance science
- falsifiability
- publish

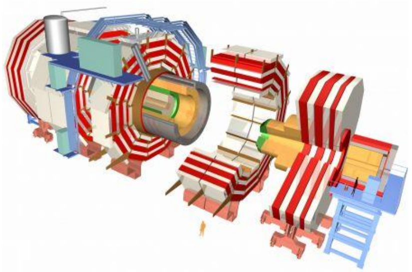
- project milestones
- enabling technologies
- multi-skills integration
- reproducibility

- user needs (UX, TCO, ROI)
- roadmaps
- investors pressure
- market size
- economies of scale
- scaling manufacturing
- business models

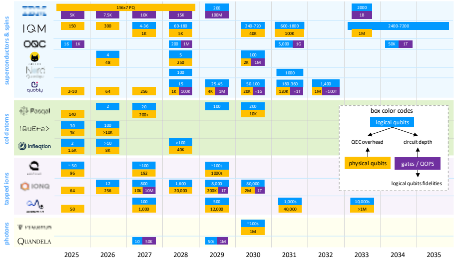

theoretical work
fundamental research
experimentation
applied research
engineering
experimental development
technology development
industrial research
industrialization
maintenance
usage
sales and marketing
education and training
ecosystem development
academic labs
industry vendor

quantum engineering

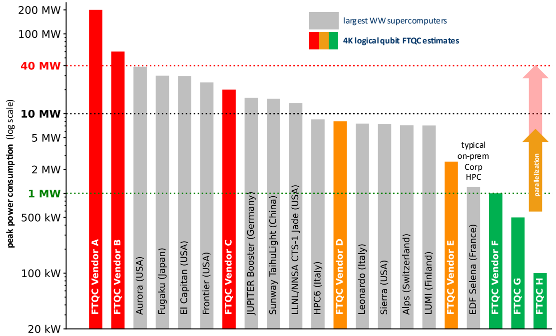
examples and learnings



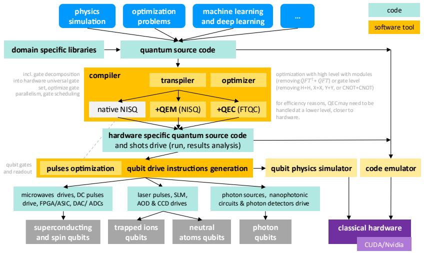
engineering @ CERN LHC



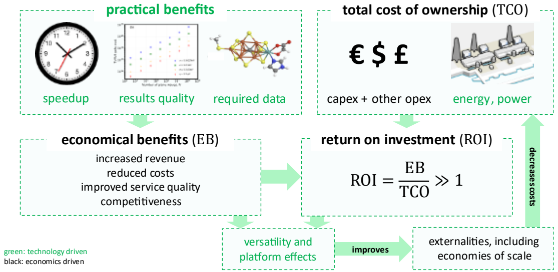
FTQC engineering



energetics engineering



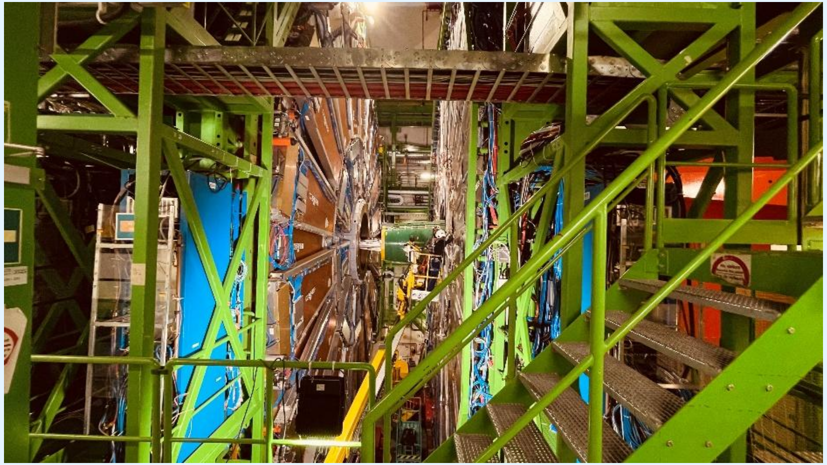
software engineering



economics and engineering

science and engineering at CERN LHC

how fundamental research benefits from engineering



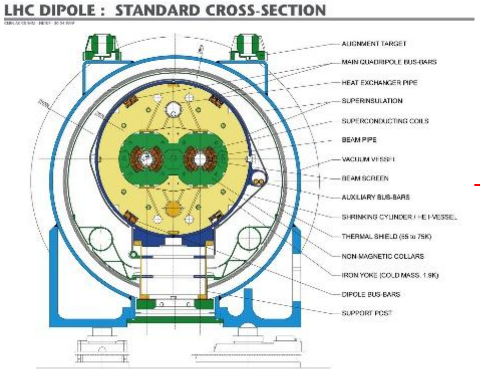

arXiv > hep-ex > arXiv:2503.21366

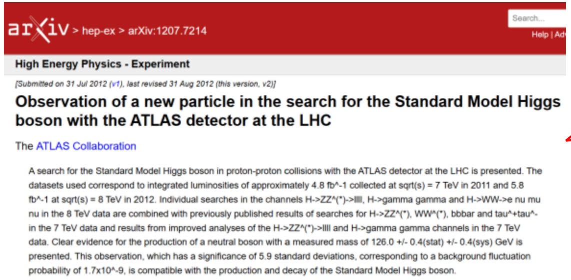
High Energy Physics - Experiment

[Submitted on 27 Mar 2025 (v1), last revised 6 Apr 2025 (this version, v2)]

Long-Baseline Atom Interferometry

Antun Balaz, Diego Blas, Oliver Buchmueller, Sergio Calatroni, Laurentiu-Ioan Caramete, David Cerdeno, Maria Luisa Chiofalo, Fabio Di Pumpo, Goran Djordjevic, John Ellis, Pierre Fayet, Chris Foot, Naceur Gaaloul, Susan Gardner, Barry M Garraway, Alexandre Gauguet, Enno Giese, Jason M. Hogan, Onur Hosten, Alex Kehagias, Eva Kilian, Tim Kovachy, Carlos Lacasta, Marek Lewicki, Elias Lopez Asamar, J.Luis Lopez-Gonzalez, Nathan Lundblad, Michele Maggiore, Christopher McCabe, John McFerran, Gaetano Mileti, Peter Millington, Gavin W. Morley, Senad Odzak, Chris Overstreet, Krzysztof Pawlowski, Emanuele Pelucchi, Johann Rafelski, Albert Roura, Marianna S. Safronova, Florian Schreck, Olga Sergijenko, Yeshpal Singh, Marcelle Soares-Santos, Nikolaos Stergioulas, Guglielmo M. Tino, J. N. Tinsley, Hendrik Ulbrich, Maurits van der Grinten, Ville Vaskonen, Wolf von Klitzing, Andre Xuereb, Emmanuel Zambrini Cruzeiro




arXiv > hep-ex > arXiv:1207.7214

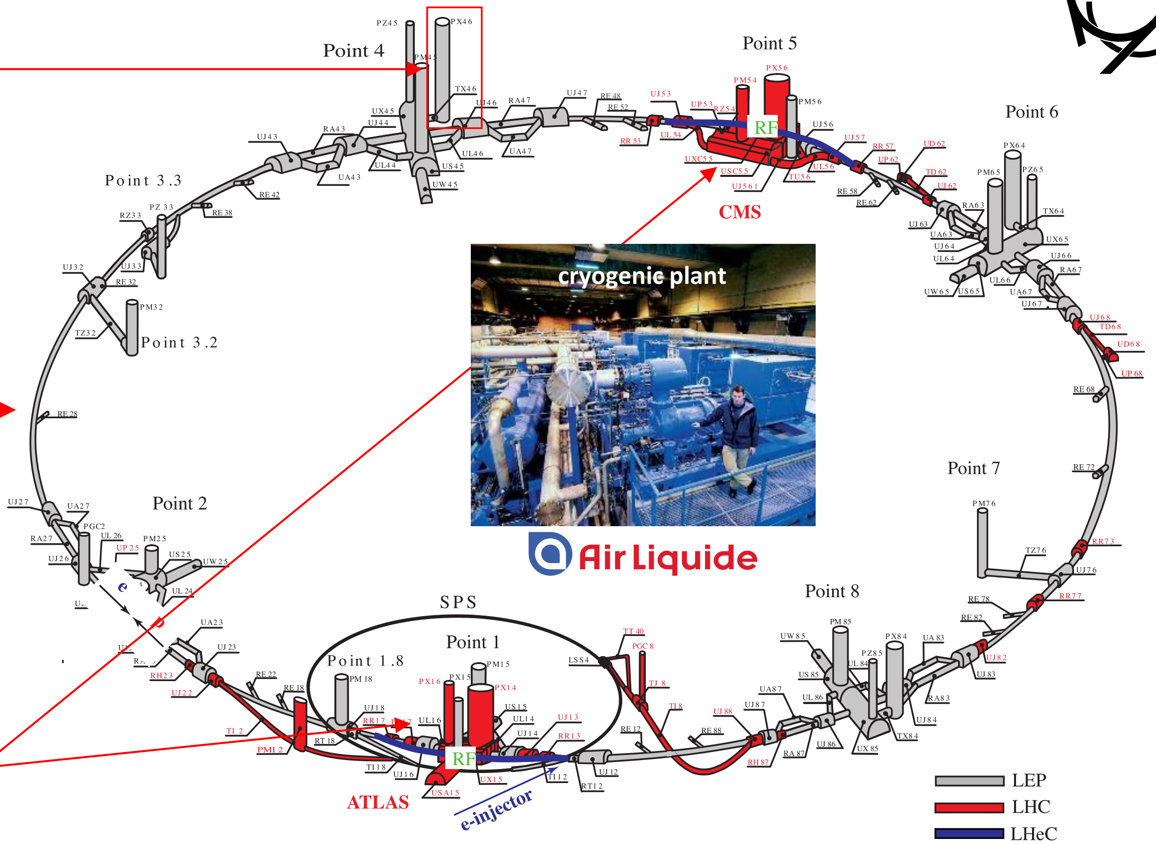
High Energy Physics - Experiment

[Submitted on 31 Jul 2012 (v1), last revised 31 Aug 2012 (this version, v2)]

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC

The ATLAS Collaboration

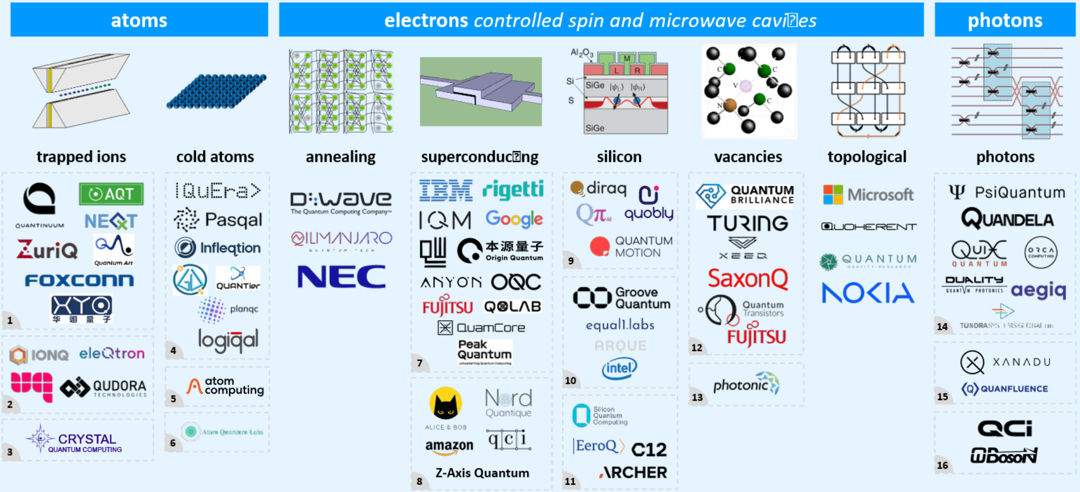
A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^-1 collected at sqrt(s) = 7 TeV in 2011 and 5.8 fb^-1 at sqrt(s) = 8 TeV in 2012. Individual searches in the channels H->ZZ^(*)->llll, H->gamma gamma and H->WW->e nu mu nu in the 8 TeV data are combined with previously published results of searches for H->ZZ^(*), WW^(*), bbbar and tau^+tau^- in the 7 TeV data and results from improved analyses of the H->ZZ^(*)->llll and H->gamma gamma channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 +/- 0.4(stat) +/- 0.4(sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7x10^-9, is compatible with the production and decay of the Standard Model Higgs boson.



Air Liquide

FTQC engineering

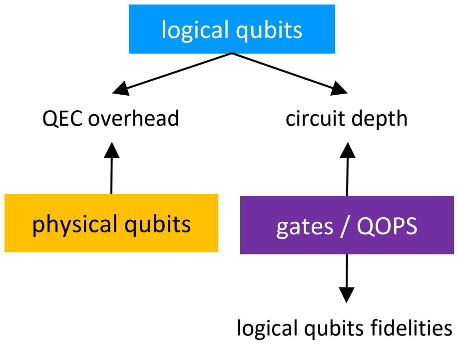
full-stack components integration to deliver on the promises of FTQC



what should we have in FTQC roadmaps?

basic features

- # logical qubits.
- supported circuit size / logical error rates.
- # physical qubits.



engineering “features”

- supported range of applications.
- clock speed and QLOPs/s.
- planned QEC codes and methods.
- processor size & reliance on QPU interconnect.
- peak power consumption in W.
- components operating temperature.
- QPU weight and size.
- temperature variability.
- components MTBF.
- capex/opex cost structure.

operational metrics

QEC/FTQC engineering

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)

Google Willow in 2024

compilation-optimization

resource estimations and optimizations

real-time error syndrome detection

code switching

logical memory qubit

single-qubit logical gate

two-qubit logical gate (*)

magic-state preparation (T) and teleportation

leakage error correction

correlated errors correction

qubit connectivity

qubit control calibration

qubit fast non demolition measurement

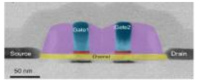
qubit physical gate fidelities >99.9% at scale

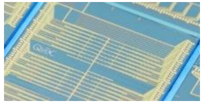
scaling QPU with interconnect and gate teleportation + circuits partitioning

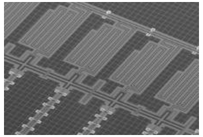
(*) not using post-selection which doesn't scale to deep circuits.

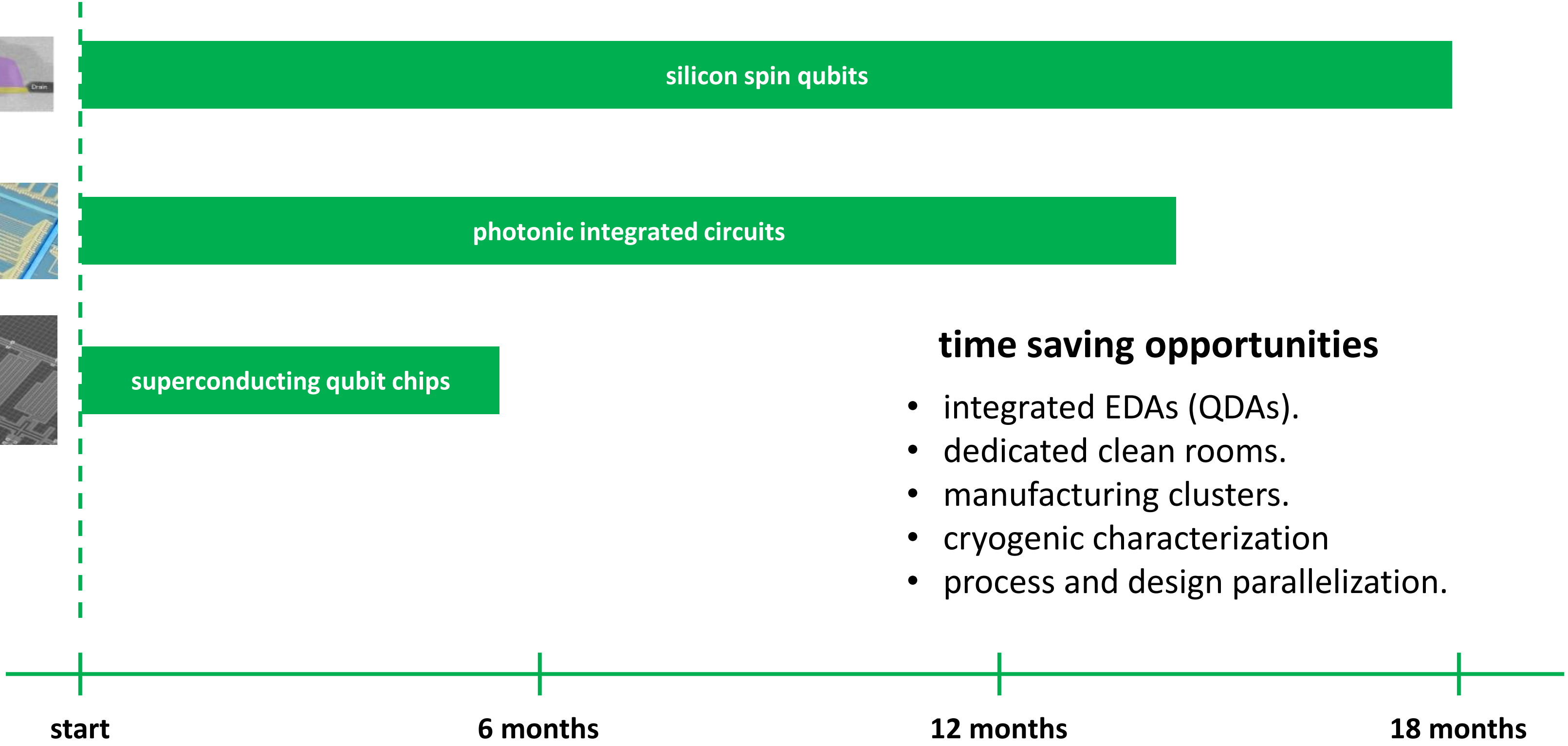
blue	QEC basic component.
green	FTQC component.
grey	QEC hardware enablers.

chips "design to test" iteration cycles









time saving opportunities

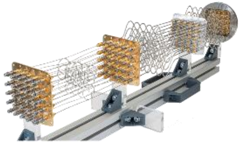
- integrated EDAs (QDAs).
- dedicated clean rooms.
- manufacturing clusters.
- cryogenic characterization
- process and design parallelization.

enabling tech engineering trade-offs

control and readout signals multiplexing ⟷ ? ⟷ control signals quality

room temperature electronics ⟷ ? ⟷ cryo-electronics ⟷ ? ⟷ cryogenics scaling

QPU scaling ⟷ ? ⟷ cabling scaling



quantum computing energetics engineering

system architecture using reductionist and holistic optimizations under multiple constraints

#QEI

the quantum energy initiative

full-stack energetic costs decomposition

quantum physics & quantum energetics

qubit gates and readout operations

cost of fighting noise with error correction

engineered dissipation

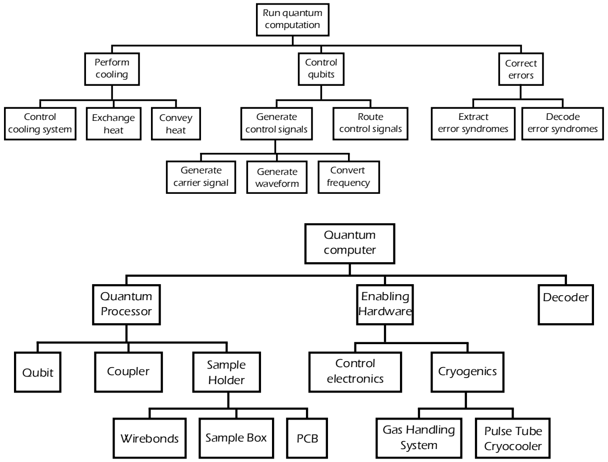
…

	ions and neutral atoms	photons	superconducting & spin qubits
classical computing	**classical part of quantum algorithms** ansatz preparation, data loading, block encoding, cost function computing, data access, networking, post-processing		
	code compiling (or minor embedding in analog modes) and **run-time execution drive** (including number of shots)		
	error syndromes detection and QEC drive (FTQC) and/or **quantum error mitigation & suppression** (NISQ)		
electronics and photonics	**gate calibration**, tuning control electronics		
	room temperature electronics and controls, including QPU interconnect FPGA, ASICs, DAC/ADCs, AWG, mixers, tone pulses generation; lasers, SLMs, AODs, CCD and photonic circuits controls		
	lasers		**low-temperature active electronics** JPA, TWPA, HEMT, cryo-CMOS, SFQ, mux/demux
	SLMs, AODs CCD/CMOS sensors, ion traps	**photon sources and detectors**	**low-temperature passive electronics** cables, attenuators, filters
cooling and vacuum	**laser cooling** (water/air)		**dilution cryostat** – 15mK to 1K
	4K compressor for dilution, vacuum chambers, cryopumps, photon sources, photon detectors		
	4K compressor cooling (water/air)		
	ultra-vacuum pump	**vacuum pump**	

energetic systems architecture approach

1. **functional and product breakdowns** →
2. **estimate baseline resources**
3. **optimize energy efficiency under constraints**
4. **mix reductionist and holistic approaches**
5. **handle operational trade-offs**
6. **measure and benchmark**
7. **integrate an economical view**

detailed in next slide



credit: Jeremy Stevens, Alice&Bob

FTQC energetics paper (in preparation).

The energetic challenges of fault-tolerant quantum computing

Marco Fellous-Asiani,[1] Pierre-Emmanuel Emeriau,[2] Jeremy Stevens,[3] Marco Pezzutto,[4,5,6] Yasser Omar,[4,5,6] and Olivier Ezratty[7,8,*]

[1]*Inria*
[2]*Quandela*
[3]*Alice&Bob*
[4]*Instituto Superior Técnico, Universidade de Lisboa, Portugal*
[5]*PQI – Portuguese Quantum Institute, Portugal*
[6]*Physics of Information and Quantum Technologies Group, Centro de Física e Engenharia de Materiais Avançados (CeFEMA), Portugal*
[7]*EPITA Research Lab*
[8]*Quantum Energy Initiative*

from baseline estimates to optimizations

what

baseline resources

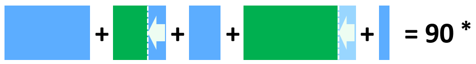
- use state of the art existing technologies.
- adding individual components resources.
- evaluate or measure idle, average and peak power.

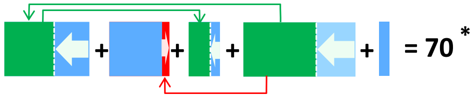
reductionist optimizations

- account for future enabling technology developments.
- component level optimization.
- doesn't affect other components performance.
- doesn't add more noise.

holistic optimizations

- interdependent optimizations.
- side effects on noise and task success metrics.
- various energy vs computing time or space-time trade-offs.





examples

- all active components.
- classical computing (circuit preparation, compiler, error correction, post-processing, …).

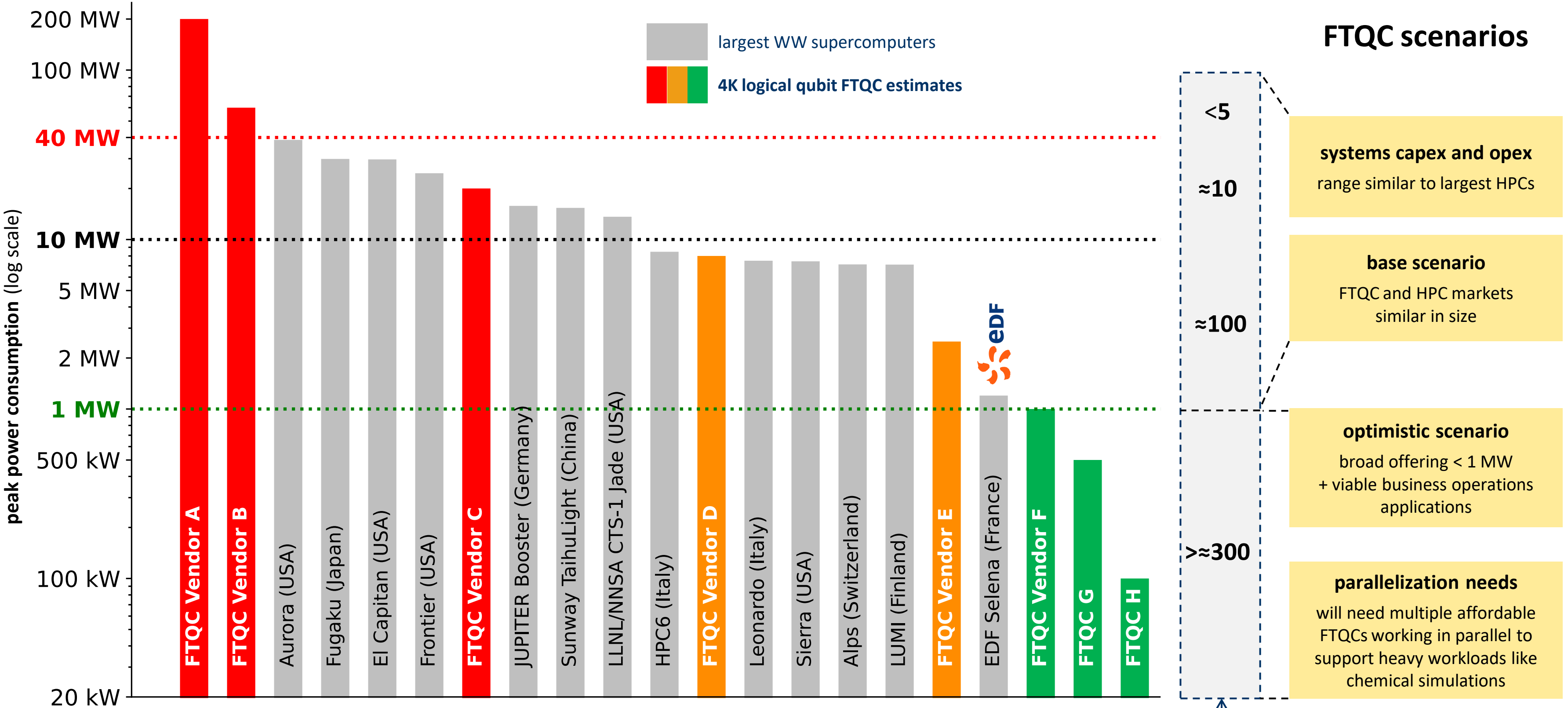
- cryogenics.
- control electronics.
- cable dissipation.
- compiler efficiency.

- moving electronics at cryogenic temperatures.
- using SFQ control electronics.
- changing qubit temperature.

system generic (power) or **task dependent with a success metric** (energy)

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

FTQC vs HPC power baseline estimates

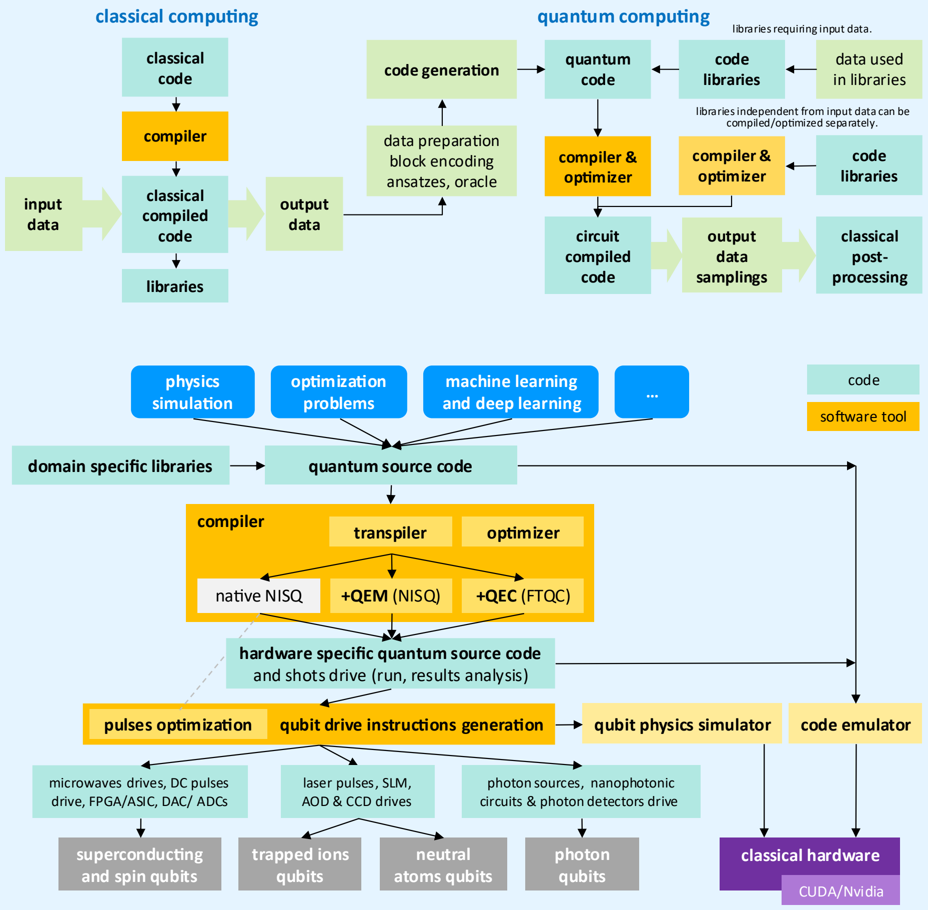


estimate base power for various FTQCs and actual for existing largest HPCs WW. HPC source: https://www.top500.org/lists/top500/2025/11/.
FTQC sources: official and unofficial vendor data, estimates with 4K logical qubits and 10^{12} gates support.

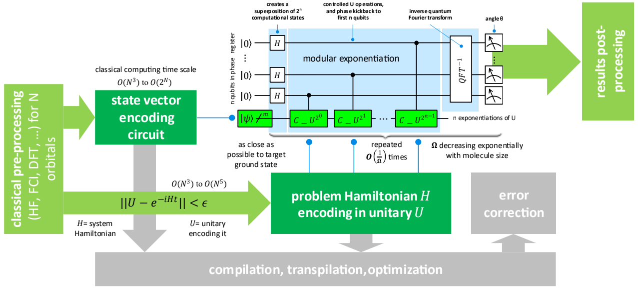
FTQC market in units using
HPC comparables

quantum software engineering

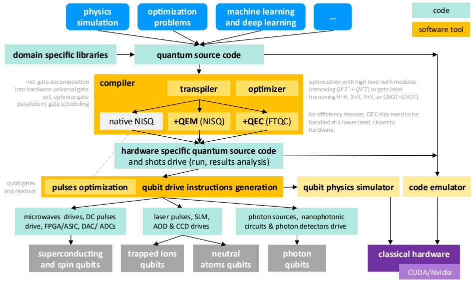
from quantum circuits to full-stack software engineering



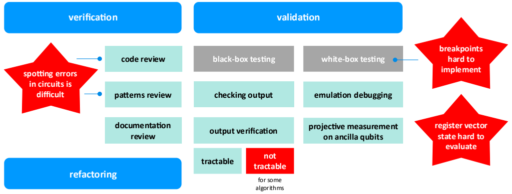
quantum software engineering



full-stack software solutions design



compilation chain



verification and validation

compilation-optimization

resource estimations and optimizations

real-time error syndrome detection

code switching

logical memory qubit

single-qubit logical gate

two-qubit logical gate (*)

magic-state preparation (T) and teleportation

leakage error correction

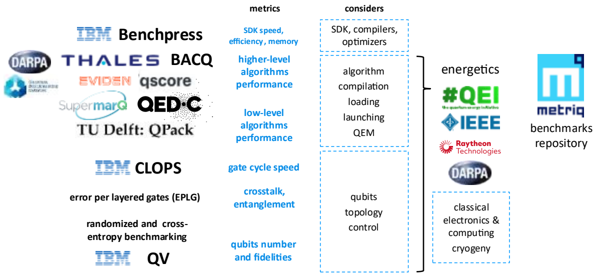
correlated errors correction

qubit connectivity

qubit control calibration

qubit fast non demolition measurement

error correction and fault tolerance



benchmarking

theory vs engineering

aspect	science	engineering
obtaining some quantum computing speedups	• complexity class theory. • theoretical speedup.	• accounting for prefactors. • resource estimates. • using real-life user data sets. • compare with best-in-class classical solutions.

« On overexcitable children

Xavier Waintal responds (tl;dr Grover is still quadratically faster) »

Of course Grover's algorithm offers a quantum advantage!

Unrelated Update: Huge congratulations to Ethernet inventor Bob Metcalfe, for winning UT Austin's third Turing Award after Dijkstra and Emerson!

PHYSICAL REVIEW X **14**, 041029 (2024)

Opening the Black Box inside Grover's Algorithm

E. M. Stoudenmire[1] and Xavier Waintal[2]

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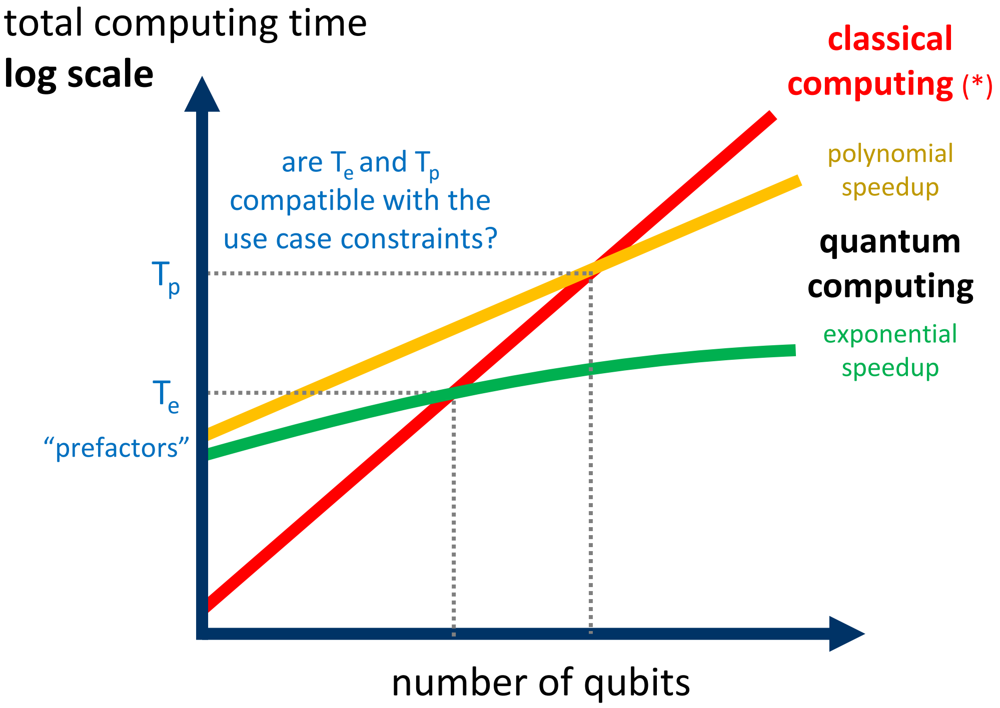
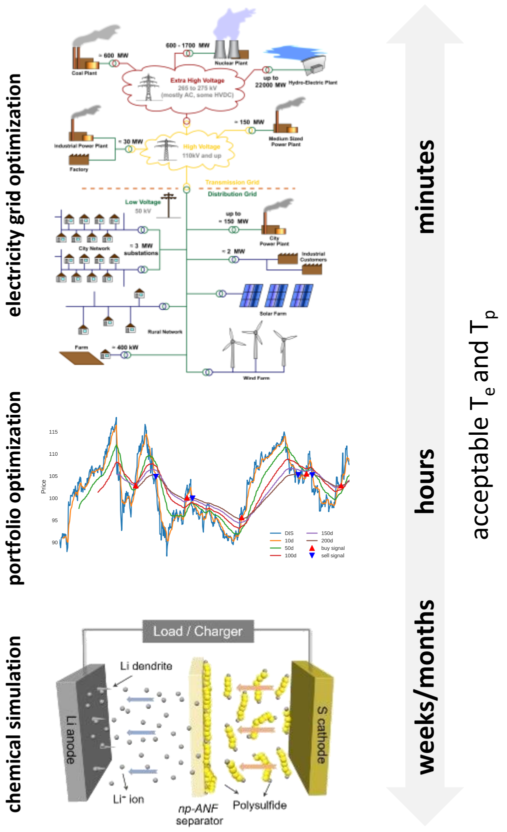
[2]*Université Grenoble Alpes, CEA, Grenoble INP, IRIG, Pheliqs, F-38000 Grenoble, France*

(Received 30 May 2023; revised 9 July 2024; accepted 5 August 2024; published 1 November 2024)

theoretical vs practical speedups

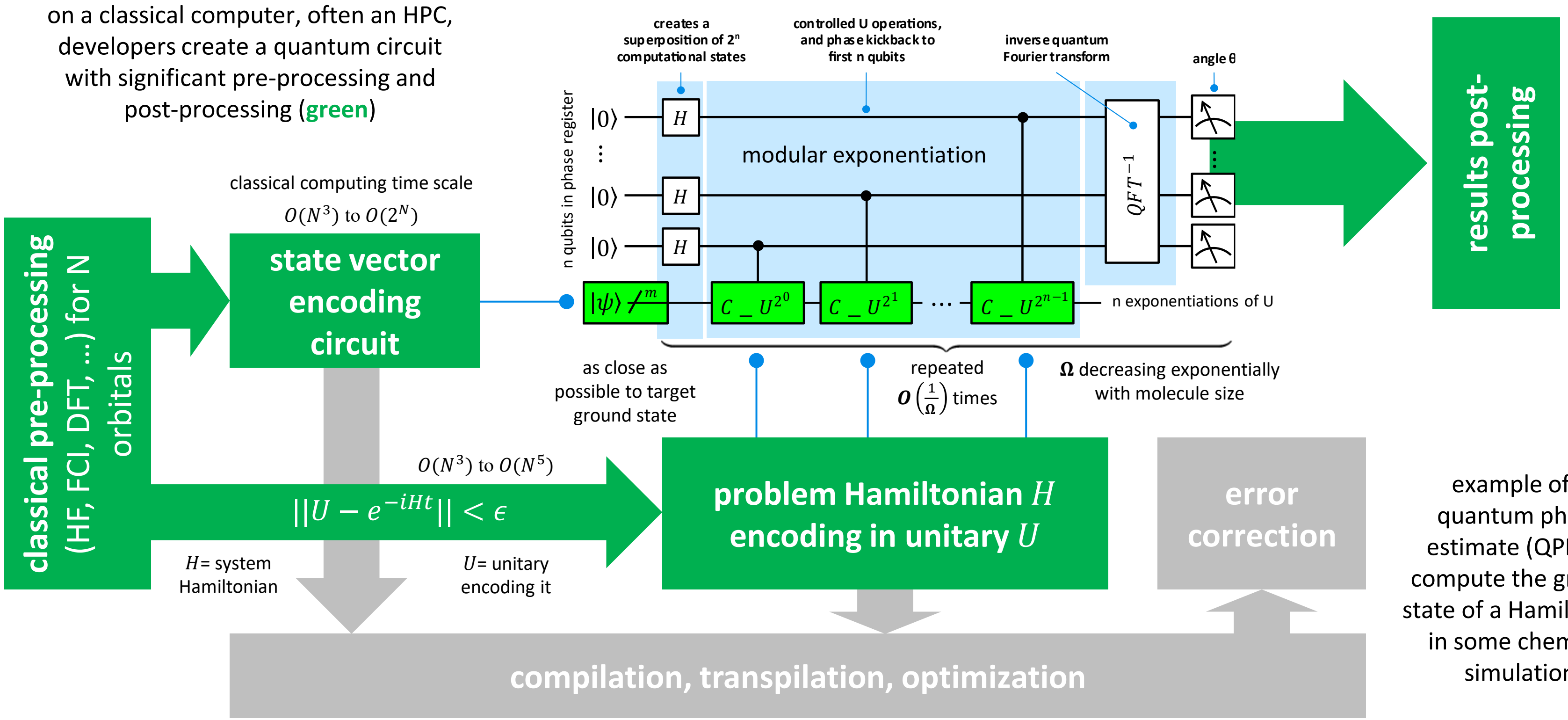




inspired by Opening the Black Box inside Grover's Algorithm
by E. Miles Stoudenmire and Xavier Waintal, PRX, November 2024.

(*) for a fair comparison, the classical computer can be as expensive and/or energy hungry as the QPU.

quantum algorithm full-stack engineering



example of a quantum phase estimate (QPE) to compute the ground state of a Hamiltonian in some chemical simulation

other classical costs in grey are algorithm independent

HPC QPU integration

- when is colocation mandated?
- what bandwidth is required?
- what HPC size next to QPUs?
- data center constraints?

Dependable Classical-Quantum Computer Systems Engineering

Edoardo Giusto[*], Santiago Nuñez-Corrales[†], Phuong Cao[†],
Alessandro Cilardo[*], Ravishankar K. Iyer[‡], Weiwen Jiang[‖], Paolo Rech[§], Flavio Vella[§],
Bartolomeo Montrucchio[¶], Samudra Dasgupta[**], and Travis S. Humble [**]
[*]University of Naples Federico II, Italy - egiusto@ieee.org
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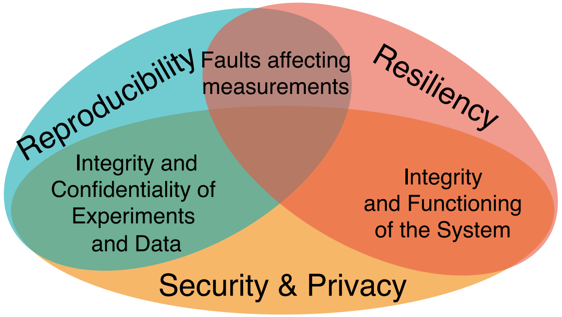
[§]University of Trento, Italy
[¶] Politecnico di Torino, Italy
[‖] George Mason University, VA, US
[**] Oak Ridge National Laboratory, TN, US



https://arxiv.org/abs/2408.10484

Integration of Quantum Accelerators into HPC: Toward a Unified Quantum Platform

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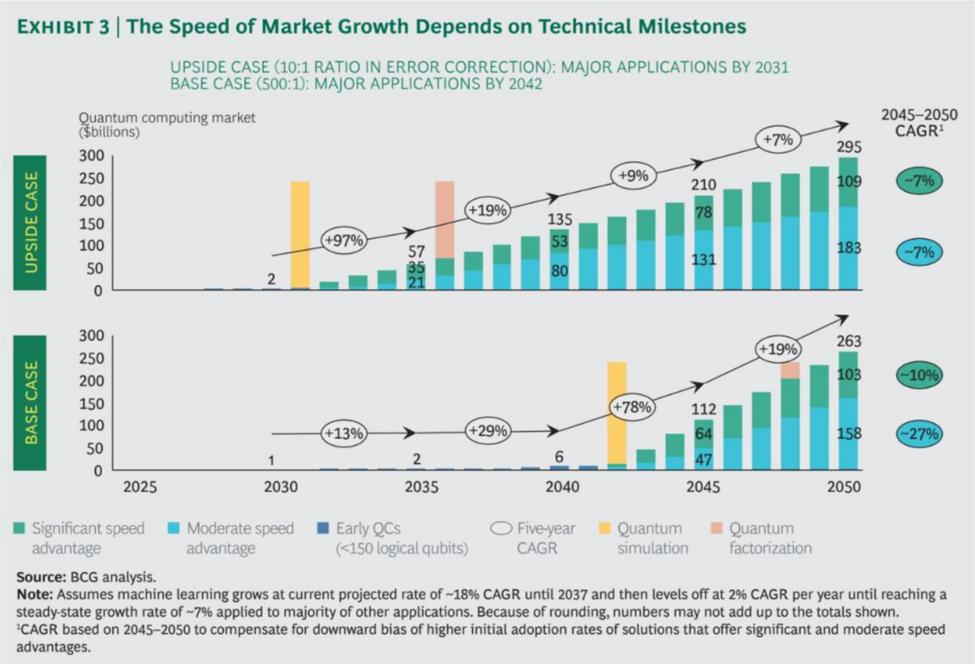
https://arxiv.org/abs/2407.18527

quantum software engineering tools

	academic experiments	industry applications tools
software tools	• pulse-level control (NISQ). • prototype SDKs. • Python notebooks. • custom emulators. • hardware-level qubit simulators. • tomography software tools. • research-oriented transpilers. • experiment data analysis tools. • data-analysis machine learning tools. • post-selection-based error correction.	• full-stack QEC and FTQC. • stable APIs and gate set • production-grade SDKs. • resource estimators. • quantum circuits partitioning tools. • hardened compilers and optimizers. • debugging, verification and certification. • telemetry and performance monitoring. • cloud/HPC operations. • job queuing and scheduling. • QPU time billing. • operational research tools.

quantum engineering and economics

TCO-ROI and externalities



Moore's law *duality*

technology

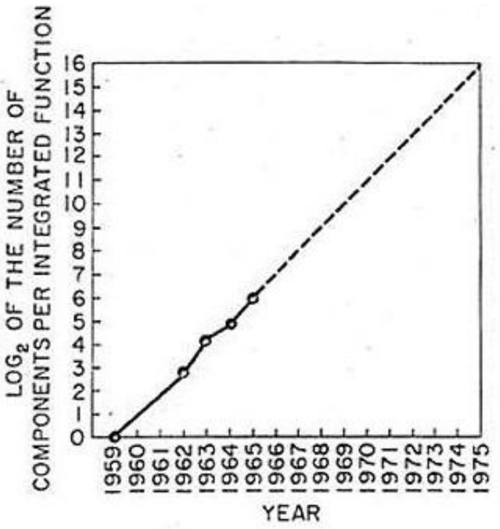


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

"complexity"
= # of transistors on a chip

The experts look ahead

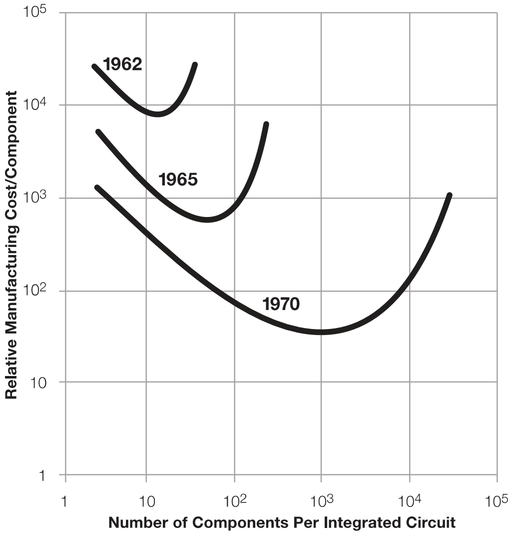
Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

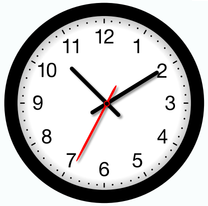
economics

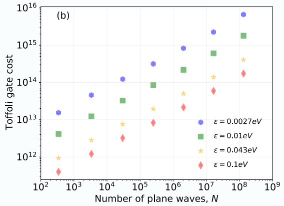


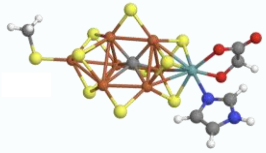
also, an economic driven law

from value to return on investment

practical benefits



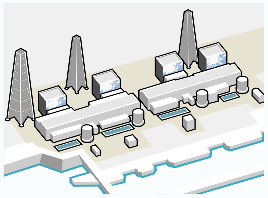




speedup · results quality · required data

total cost of ownership (TCO)

€ $ £



capex + other opex · energy, power

economical benefits (EB)

increased revenue
reduced costs
improved service quality
competitiveness

return on investment (ROI)

$$\mathrm{ROI} = \frac{\mathrm{EB}}{\mathrm{TCO}} \gg 1$$

versatility and platform effects

improves

externalities, including economies of scale

decreases costs

green: technology driven
black: economics driven

discussion

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now