French National Quantum Strategy

MetriQs-France

National Program on Measurement, Standards and Evaluation of Quantum Technologies

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TQCI Seminar « Application-oriented benchmarks for quantum computing »
Palaiseau – 11 May 2023

FRANCE 2030 — anr agence nationale de la recherche — RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité — LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

MetriQs-France

National Program on Measurement, Standards and Evaluation of Quantum Technologies

- **Quantum Computing**
- Quantum Sensing
- Quantum Communications
- Enabling Technologies

Develop, exploit, and promote **measurement capabilities of reference**, validated and harmonized, for characterization and performance assessment of quantum technologies with **reliability, impartiality and comparability** : metrology, test & evaluation, international standardization…

→ **Innovation**

→ **Establishment of the quantum industry**

➢ Measurement and Testing Infrastructure

- Platform of reference for quantum metrology at LNE, LNE-SYRTE, LNE-Cnam in the French Metrology Network
- Network of trusted platforms for characterization and testing

➢ Thematic R&D collaborative projects Promotion & exploitation actions

- National research organizations
- Large companies
- SMEs / Startups
- AFNOR
- LNE

BACQ: Application-oriented benchmarks for quantum computing

Developing an **objective**, **long-lasting**, **widely shared** measurement instrument, to serve as a **common reference**, for the evaluation of the quantum computing practical performance, by considering benchmarks close to real applications, meaningful for industrial end-users.

⇒ **Measuring the progress towards a practical quantum advantage**

→ Overall comparison between different quantum computing solutions and with classical computers

→ Assets determination of one quantum computing solution for a specific application

An extended Working Group

Established in Feb. 2022

A core group with general interests

~ 40 participants *(nat. research org., univ., associations, gov. agencies,* ***Teratec*** *as lead, …)*

- Scientific reflection
- Strategic orientation
- Consultations with industry *(technology providers and end-users)*
- EU & International cooperation
- Communication and promotion

BACQ R&D collaborative project

- - **3.9 M€ budget** (incl. 2.5 M€ funded by France 2030) / **3 years** (from Q2 2023**)**
  - **6 partners** (**Thales** as coord., Eviden, CEA, CNRS, Teratec, LNE) for **7.2 FTE / year**
- - A **polyvalent suite of benchmarks** addressing (to start):
    - Optimization (including **Q-Score/MAXCUT**)
    - Linear systems solving
    - Quantum physics simulation
    - Prime factorization
  - **Multi-criteria aggregation and analysis** (computational and energetic), transparent and fully interpretable, from technical criteria **to high-level operational indicators**
  - For **all quantum machines**, analog to gate-based machines, NISQ to FTQC
  - Towards an **open-access tool**
- - **Collaboration with stakeholders worldwide** (QPU providers, academic teams…)
  - **Cooperation/Dialogue with other initiatives** EU and international (QED-C, QuIC…)
  - **Promotion to standardization** e.g. CEN-CENELEC JTC22 / WG 3 QCS

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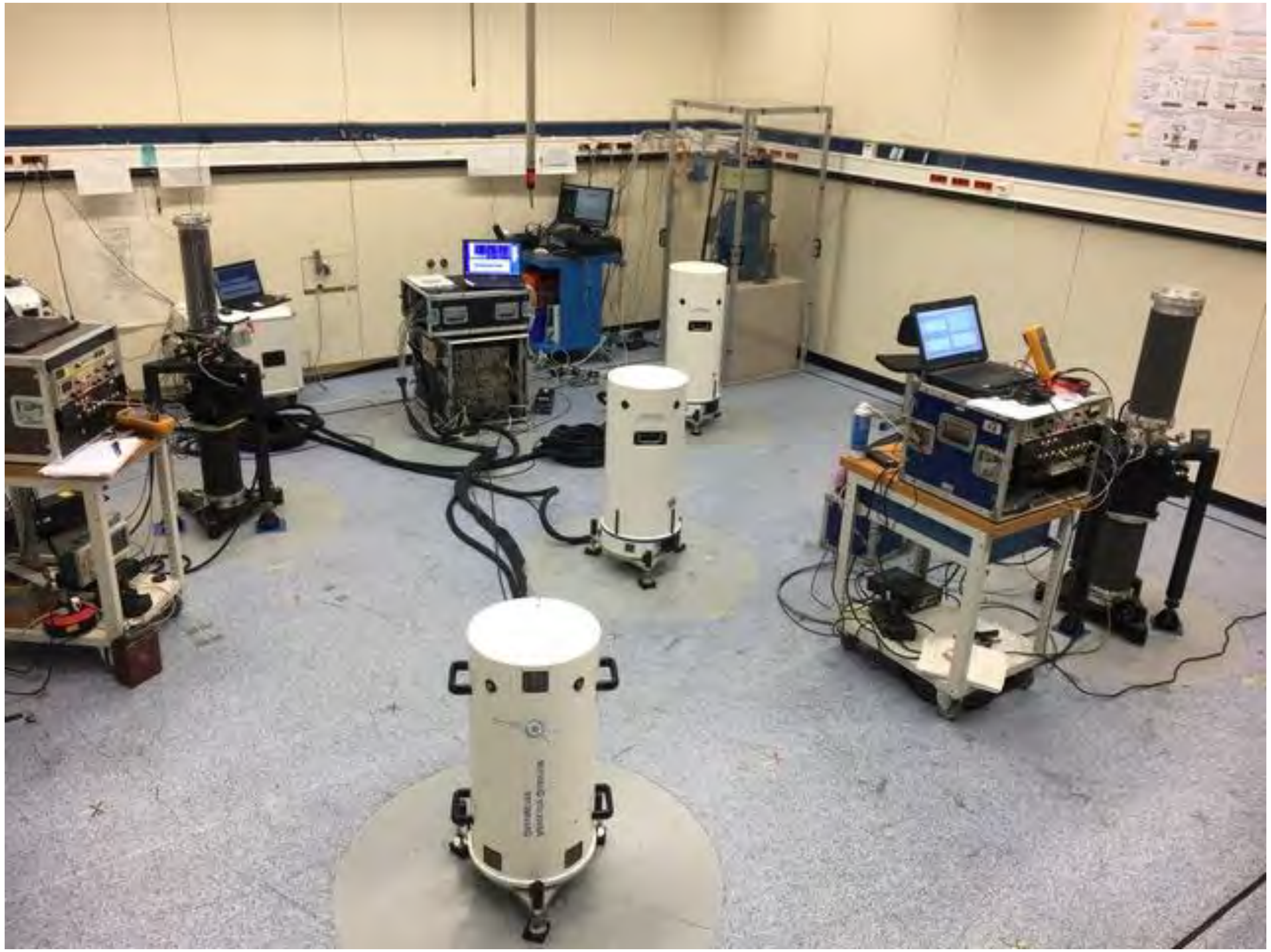


MetriQs-France

National Program on Measurement, Standards and Evaluation of Quantum Technologies

BACQ

Applications-Oriented Benchmarks for Quantum Computing

LNE, THALES, EVIDEN, CEA, CNRS, TERATEC

May 11th 2023

BACQ PROJECT

- Part of LNE MetriQs-France Program supported by the French National Quantum Strategy
- **Global Budget: 4 M€** including **2.5 M€ France 2030** funding
- Objective:
  - R&D Project, funded by MetriQs-France (France 2030), to elaborate full benchmarks integrated in a « testbed », to be deployed by quantum computers providers and users
  - Promotion at international level
- Partners
  - Coordinator: THALES
  - Partners: CEA (LIST, IPhT, PHELIQS), EVIDEN, CNRS, TERATEC, LNE
- Duration: 36 months
- Outputs
  - Fast Track on Q-SCORE metrics
  - Prototype of applications-oriented benchmarks
  - Multi-criteria model of quantum computers notation

MetriQs-France & BACQ Phases

Main Goal

- With the goal of developing a reliable, objective and long-lasting measurement instrument for the performance of quantum computers in terms of applications, BACQ aims to develop all the benchmarks constituting the corresponding "testbed", to exploit and promote it internationally. The project is part of the National program on measurement, standards and evaluation of quantum technologies MetriQs-France.

2 Phases of deployment

- A first phase consists of identifying and developing the first elements (software bricks) of the first candidate demonstrations (at TRL 3) which will then make it possible to specify the testbed. This first step is the main part of the project.
- A second phase will then be necessary to develop the testbed and make it usable by the community (TRL >5).

BACQ: Applications-Oriented Benchmark & Multi-criteria Approach

Drawbacks of existing benchmarks

- A number of initiatives exist to benchmark the performance of quantum computers. Examples include Quantum VOLUME and CLOPS from IBM, SupermarQ from Super-Tech or Quantum LINPACK from Berkeley Lab and QED-C Benchmarks. The metrics used in these approaches are relatively technical and require some knowledge of the underlying technologies. They often do not provide operational indicators of the performance of the different families of algorithms executed on the different existing quantum platforms.

Main advantages of BACQ: End-Users-Oriented Multi-Criteria Benchmarks

- We will therefore seek to go back to higher-level metrics, meaningful for industrial users. The proposed approach therefore aims to initiate a multi-criteria analysis approach in order to help such an evaluation of the different quantum solutions. THALES jointly provides a methodology and a **“MYRIAD” tool for this aggregation of low**-level technical metrics towards the qualities of services of interest to the user.

4 types of application problems will be studied to develop benchmarks:

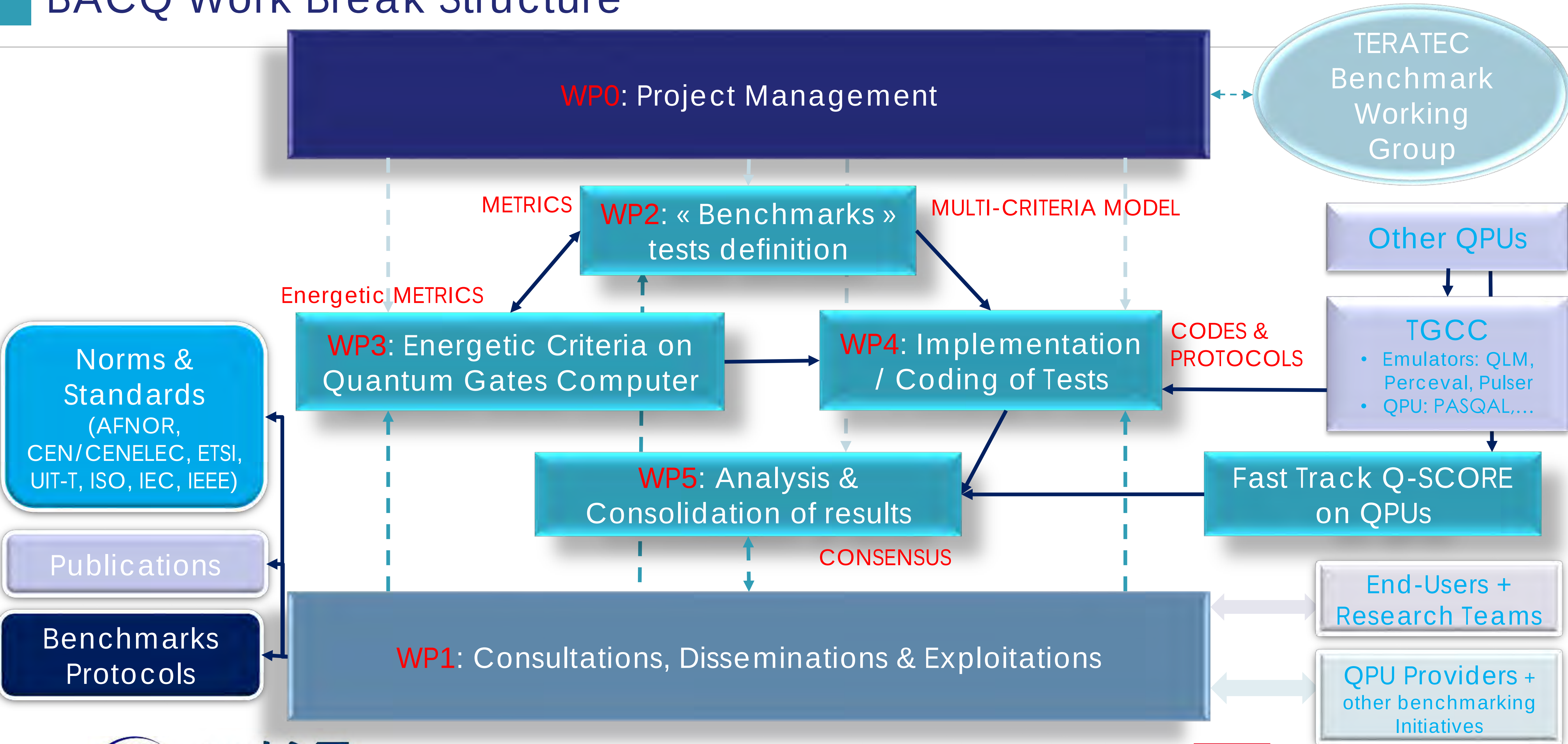
Quantum physics model simulation, linear systems, optimization and factorization.

BACQ Re-Use by LNE MetriQs-France Program

BACQ testbed operation under the supervision of LNE will aim to:

- Enable the users to perform assessment of quantum computers by their own and analysis of the results with explicable, transparent and impartial protocols.
- Use the results obtained on the tested machines to refine the definition of the testbed.
- At medium term, enable to establish and maintain a performance list over time with consent of the participants : access to the results and right to examine them before any publication.
- Develop communication and presentation material for the project (manifestos, brochures, publications, website, seminars, etc.) to encourage adhesion and participation.
- Set up European and international dialogue on the subject of benchmarking quantum computers to build common practices.
- Promote the developed benchmarks in international standards, with regard to the specifications of quantum machines and their evaluation methods.

BACQ Work Break Structure



Transversal contributions to BACQ

WP0: Project Management

Steering the study and ensure the coherence with the national strategy.

- Management and coordination
- Coordination avec LNE & MetriQs-France
- Coordination avec Groupe de Travail

Transversal contributions to BACQ

WP1: Consultations, Disseminations & Exploitations

Ensure the relevance and visibility of the project, share its ambitions with other initiatives at global level.

- State of the art and scientific intelligence
- Consultations with industrial stakeholders
- Dialogue in Europe and abroad
- Normalisation and standardisation
- Dissemination and communication

BACQ Workpackages Objectives

- WP0 Project Management: This WP is in charge of managing the project on a daily basis but also of interacting with the WG in France to ensure the consistency of the work carried out with the national ambitions and strategy.
- WP1 Consultations, Dissemination & Exploitation: This WP aims to ensure the visibility of the project at the national and international level, to promote its results and to share its ambitions with other studies in progress at the global level.
- WP2 Benchmarks Tests Definition: The objective of this WP is to identify the different algorithmic approaches adapted to “benchmark” tests. For this, the WP partners will help identify the criteria and divide them into different classes (criteria linked to the problem addressed by a benchmark, criteria linked to the method or to the different calculation methods and criteria linked to the machines). And finally, identify the generic multi-criteria approach to build an aggregate score
- WP3 Energetic Criteria: The objective of the WP is to propose, simulate and test energy efficiencies for useful algorithms studied in this project. The lot will study in detail the case of a gate-based machine performing a simple algorithm such as solving a linear system. This is about creating models and optimizations using tools and data from multiple levels of description.
- WP4 Implementation/Coding of Tests: This lot of tasks is at the heart of the project insofar as the objective here is to implement (code) and develop on real quantum machines (possibly in parallel with the use of emulators) the test protocols that will have been proposed for all the tasks of WP 2.
- WP5 Analysis & Consolidation of results: This WP consists of collecting the codes and the first experimental results carried out in WP 4. Then it will carry out a critical and statistical analysis of the results. These results will be consolidated through successive refinements with feedback from QPU vendors on how to best utilize QPUs.

Planning

Lots/Tâches		Mois																																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Lot 0: Pilotage Etude																																					
T0.1	Gestion et coordination de l’étude												D												D												D
T0.2	Coordination avec LNE & MetriQs-France												D																								
T0.3	Coordination avec Groupe de Travail (GT)												D												D												D
Lot1: Consulations, Disséminations et Exploitations																																					
T1.1	Etat de l’art et veille scientifique												D												D												D
T1.2	Consultations avec les parties prenantes												D												D												D
T1.3	Dialogue en Europe et à l’international												D																								
T1.4	Normalisation & standardisation												D												D												D
T1.5	Disséminations et Communications																																				
Lot2: Définition des tests de benchmark																																					
T2.1	Définition des problèmes									D									D																		
T2.2	Définition des critères par problème												D																								
T2.3	Définition de la note agrégée multi-critères															D					D																
Lot3: Critère énergétique par estimation de ressources pour la résolution d’algorithmes simples sur machines à portes																																					
T3.1	Estimateur analytique de critère énergétique																		D																		
T3.2	Modèle numérique énergétique du processeur																																				D
T3.3	Pilotage working group IEEE Energétique quantique																								D												D
Lot4: Analyse et Consolidation des résultats																																					
T4.1	Mise en place de l’accès aux simulateurs/ émulateurs/calculateurs																																				
T4.2	Développement et codages Benchmark machines analogiques																														D						D
T4.3	Développement et Codage Benchmark machines à portes																								D						D						D
Lot5: Analyse et Consolidation des résultats																																					
T5.0	Fast track Benckmarks																																				
T5.1	Tests avec des partenaires extérieurs																								D												
T5.2	Collecte et consolidation des résultats obtenus																														D						
T5.3	Analyse et synthèse des performances sur machines testées																																				D

BACQ Applications-Oriented Problems for End-Users

Simulation of Quantum Physics models

Optimization

Linear Systems Solving

Factorization (Hamiltonian version)

Initial Metrics provided by partners

Simulation of Quantum Physical Models

- Q-Score Many-Body (Eviden)
- Many-Body Fidelity (CEA-DRF)

Optimization

- Q-Score Max-Cut (Eviden)
- Accuracy indexed by noise level (THALES)
- Compilation-dependant criteria (THALES)
- Probability of obtaining the optimum(CEA-LIST)
- Min case/Max case Gap wrt Optimum (CEA-LIST)
- Size of problem in number of variables, number of Qbits to solve the problem, Class of problem addressed (CEA-LIST).

Linear systems Solving

- Accuracy indexed by noise level (THALES)
- Compilation-dependant criteria (THALES)
- Probability of solving the Problem, Number of variables and precision in Qbits.(CEA-LIST)
- Algorithm-dependant Energetic criteria (CNRS)

Factorization

- Probability to factorize(CEA-LIST)
- Size in Qubit of the calculated number (CEA-LIST)

Generic

- Computation Time
- Latency
- Throughput

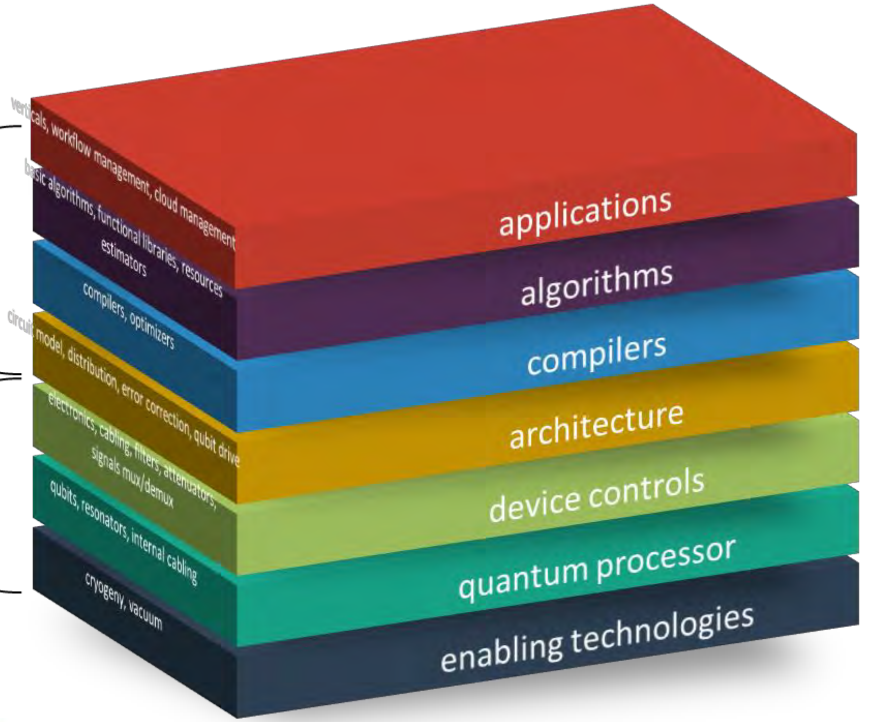
Defining resource efficiency

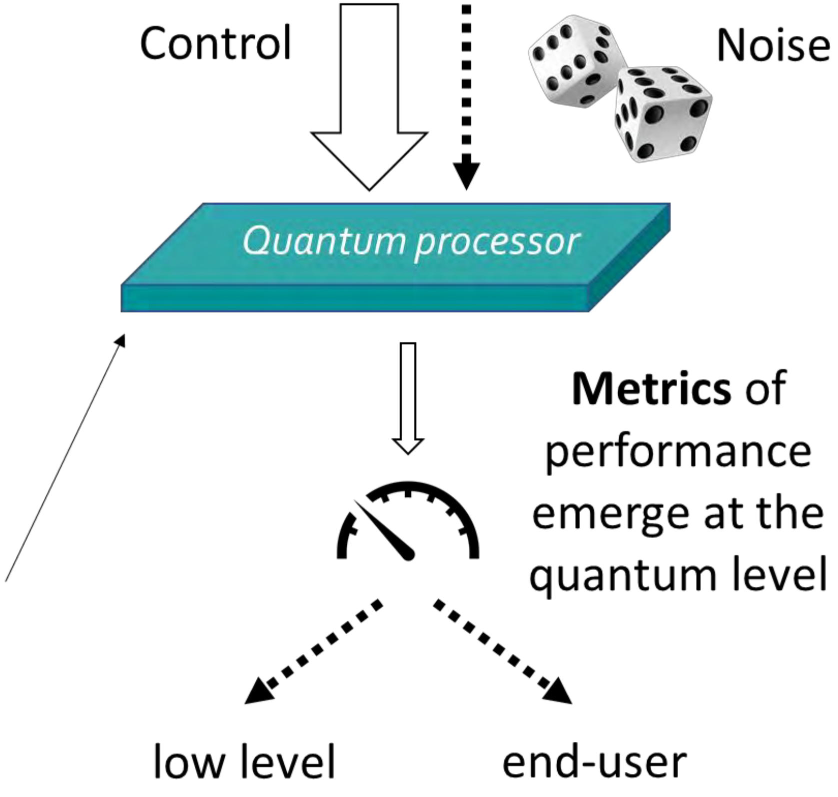
Mandates **resources** at all levels of the stack (hardware dependent or agnostic)

Resource efficiency = Metric of performance/Resource cost

Hardware agnostic

Hardware dependent





Metrics of performance emerge at the quantum level

Benchmark Metrics for QPU and Quantum Algorithms

Drawback of existing Quantum Benchmarking Rules/Tools

- Very technical metrics → CLOPS (IBM) | Quantum LINPACK (Berkeley Lab) | SupermarQ Suite (Super-Tech) | QED-C (USA)

Metrics

For the 3 QPUs

- Error impact / accuracy
- Latency
- Throughput
- Accessibility :
- Programming
- Supported applications
- Power Consumption

For algorithms for dedicated resources

- Advantage
- Input
- Noise
- Scaling
- Accuracy
- Non-linear
- Output
- Flexibility

How to aggregate all these metrics to compare several quantum solutions?

How to obtain an overall assessment interpretable for end-users?

BACQ

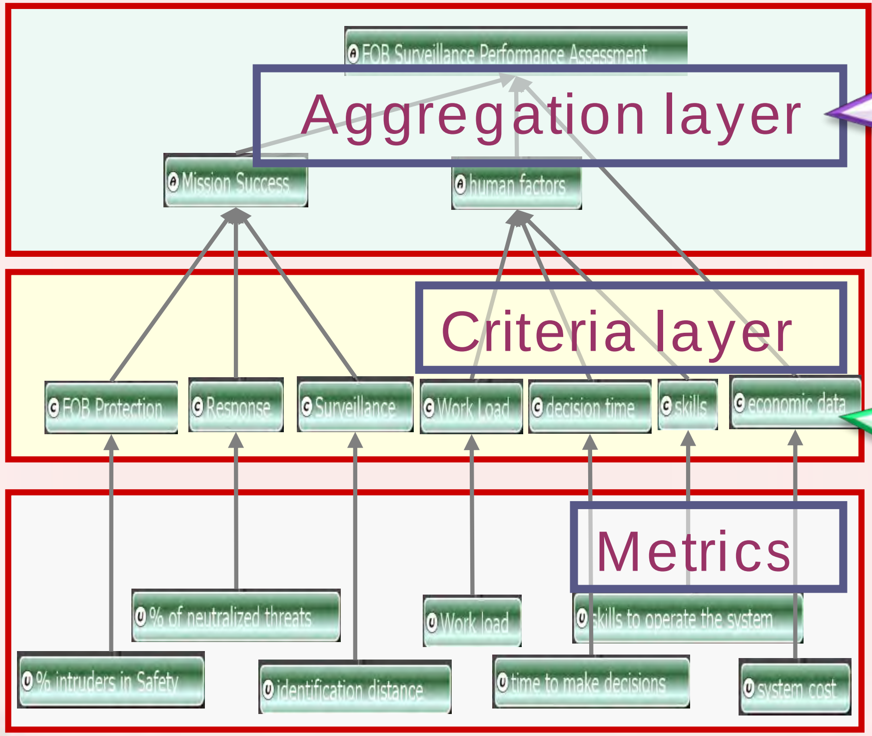
Use of Multi-Criteria Decision Aiding

- MYRIAD = methodology + Tool
- Already used with French MoD DGA and NATO

MYRIAD approach at a glance

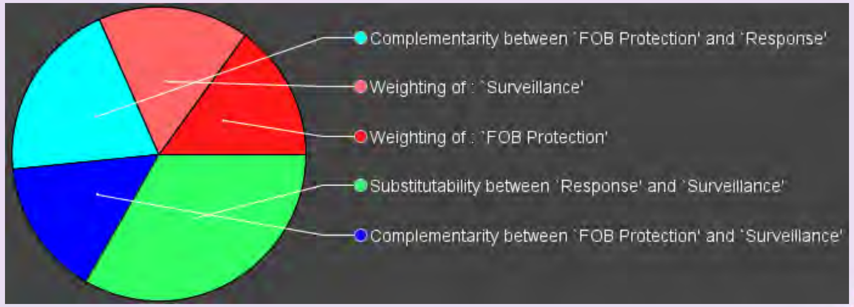
STEP 1: Problem formalization and construction of the evaluation function

- Structuration phase
  - -Identify relevant metrics
  - -Organize them in a tree

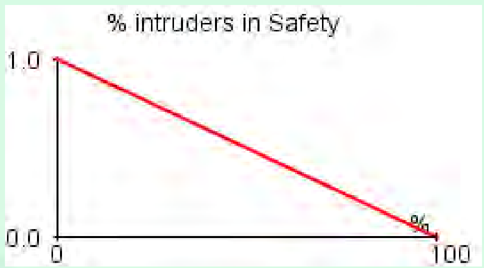


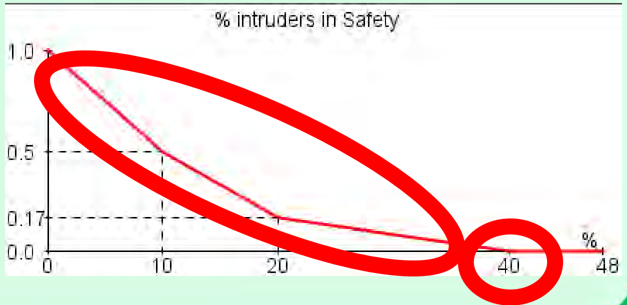
- Aggregation of normalized scores
  - -Representation of complex decisions

Elicitation: Learn model from examples of solution comparisons



- Criteria = normalisation
  - -Elicitation: 2 references + Intensities of pref





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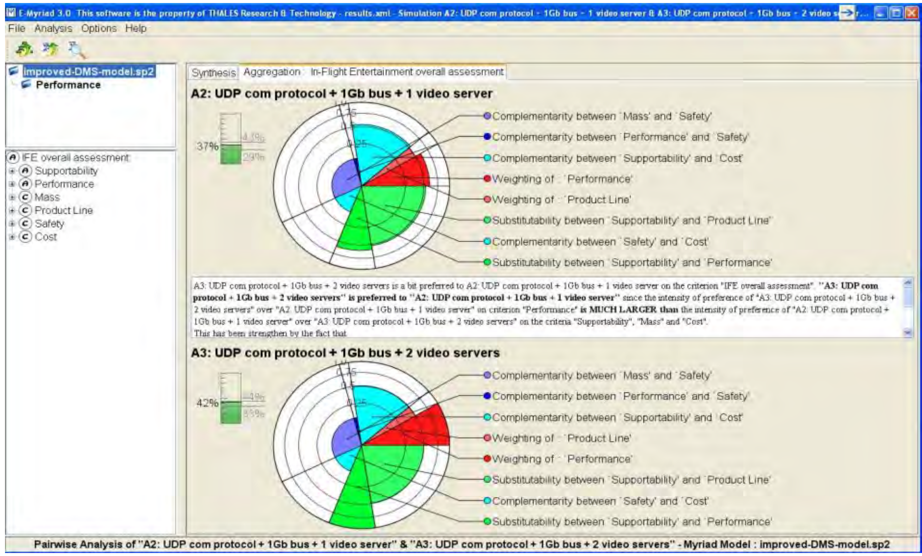
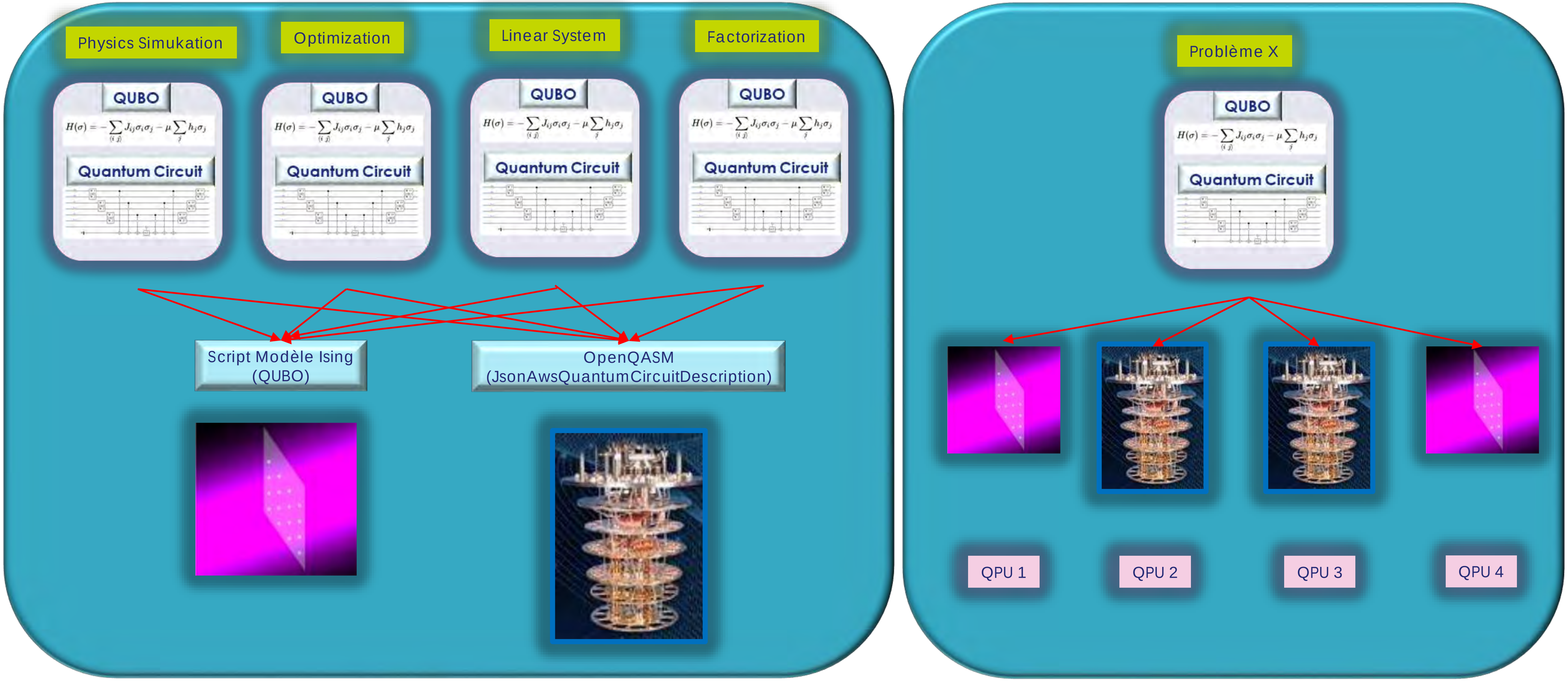
MYRIAD approach at a glance

STEP 2: Application of the evaluation function on quantum solutions

- **Model intrinsically interpretable**
  - Hierarchical where each node makes sense
  - All nodes have the same semantics (good ➔ bad)
  - Interpretation of aggregation nodes
- **Explainability**
  - Local explanation
    - Graphical explanation of aggregation
  - Global explanation
    - Feature attribution
    - Worth to improve
    - Sensitivity analysis



QPUs Benchmarks jointly on all problems or for one problem



THALES

Building a future we can all trust

FRANCE 2030

EVIDEN an atos business

cea

RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité

cnrs

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BACQ

Partners Contribution

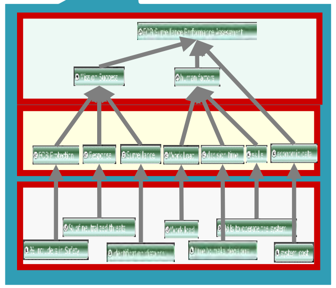
LNE, THALES, EVIDEN, CEA, CNRS, TERATEC

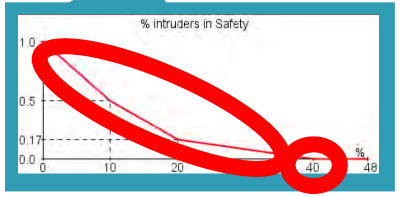
THALES contribution in BACQ: KPI aggregation with MYRIAD

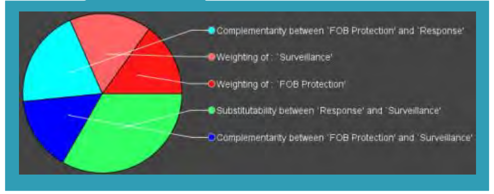
MYRIAD at a glance

Problem Formalization: KPI identification → KPI normalization → KPI aggregation

Performance assessment: Notation assessment → Notation explanation







MYRIAD added-values

- Aggregate all KPIs into a unique quality score …
- **… making it** possible to rank solutions
- Representation of interacting criteria
- Model constructed from preferences of experts
- The model is fully interpretable
- Explanable of the evaluations
- The model can be shared among stakeholder

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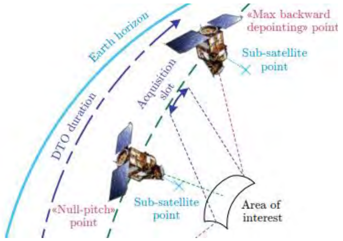
Research focus at Thales Research and Technology

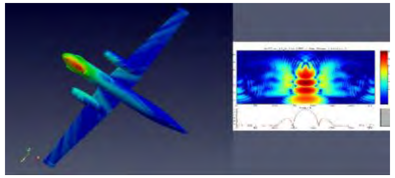
Classical research tracks

Optimization



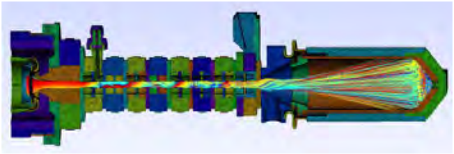
- ❑ Scheduling
- ❑ Mission planning

Deterministic methods



- ❑ Electromagnetic simulations

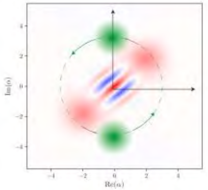
Monte Carlo methods



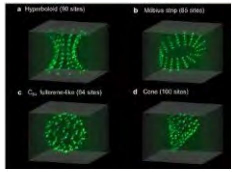
- ❑ Electromagnetic simulations with charged particles

Quantum research tracks

Understanding hardware



- ❑ cat qubits

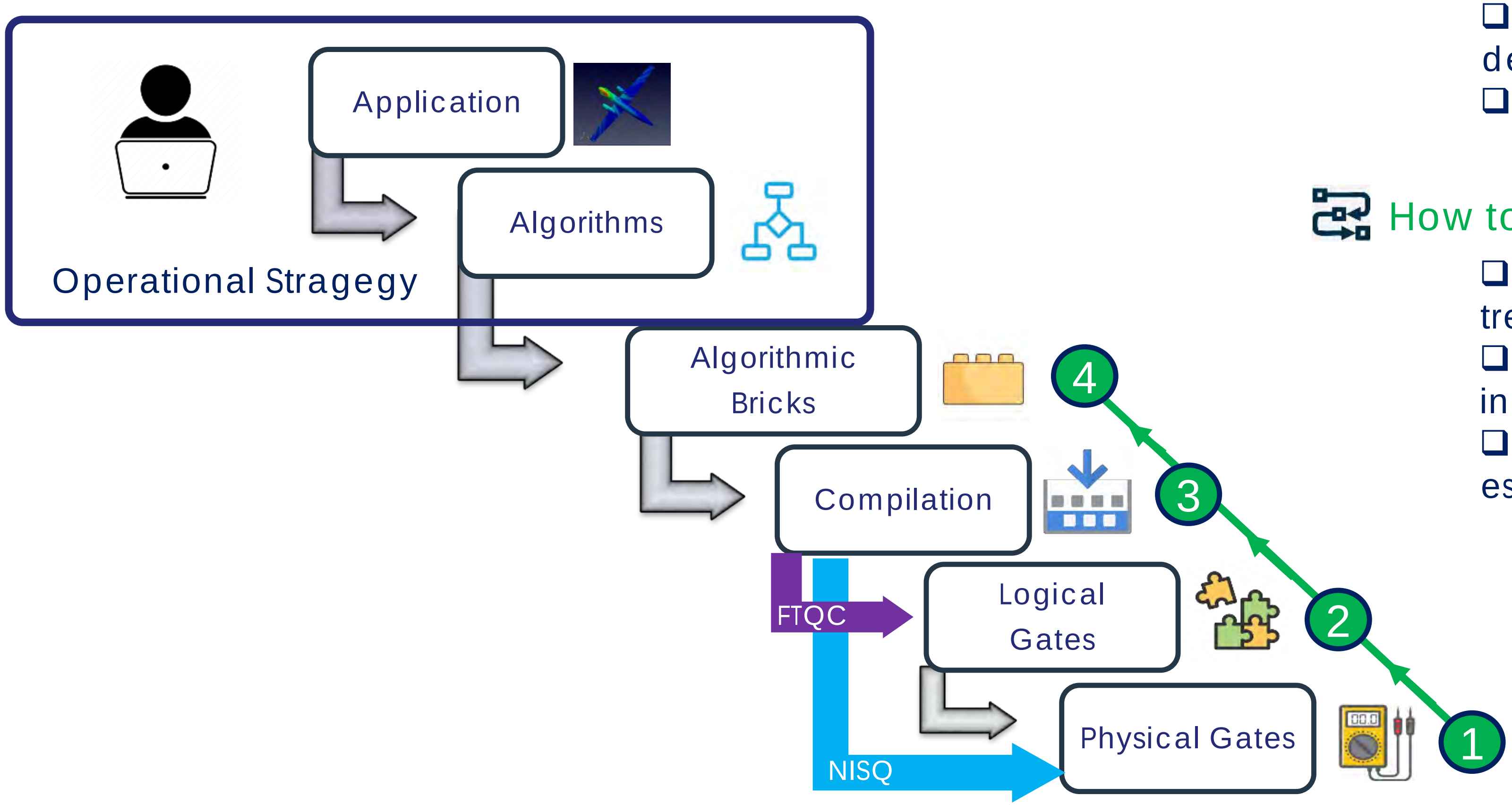


- ❑ cold atoms

Algorithms

- ❑ Increment algorithms with use case specificities

Benchmarking: WHY and HOW?



Motivations

- ❑ Assess which algorithm can run on a given device with a given precision/fidelity
- ❑ Understand the technologies better

How to proceed

- ❑ Litterature review for each technology treated
- ❑ Extract relevant information for error impact in the NISQ regime
- ❑ Level up on error correction for resource estimation in LSQ regime

from hardware to restults

Physical metrics

Goals

→ Quantify the errors of the physical systems with probabilities of occurance
→ Deduce the link with final gate fidelities given by providers

→ Take into account the specificities of each architectures

→ State preparation easier on some architectures

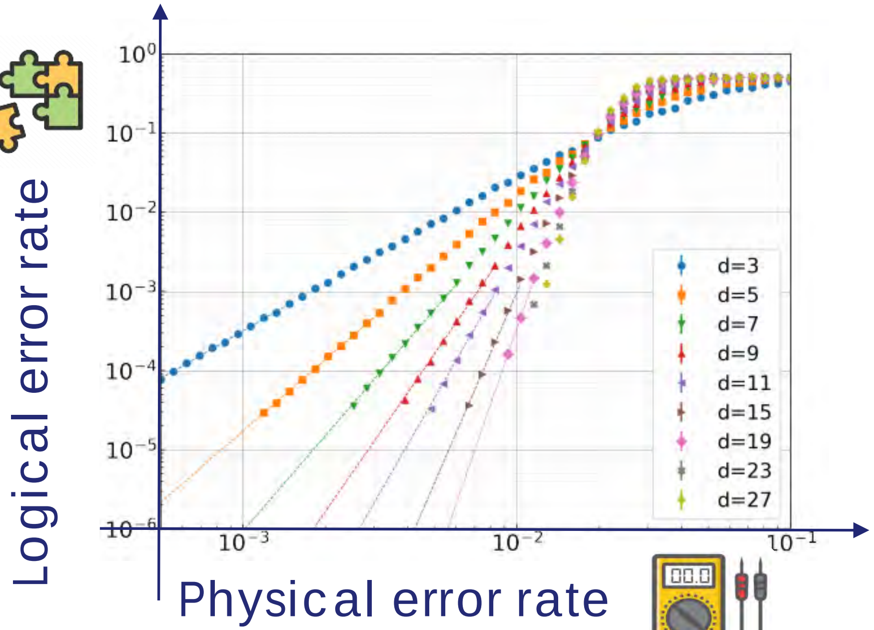
→ Not the same native gates

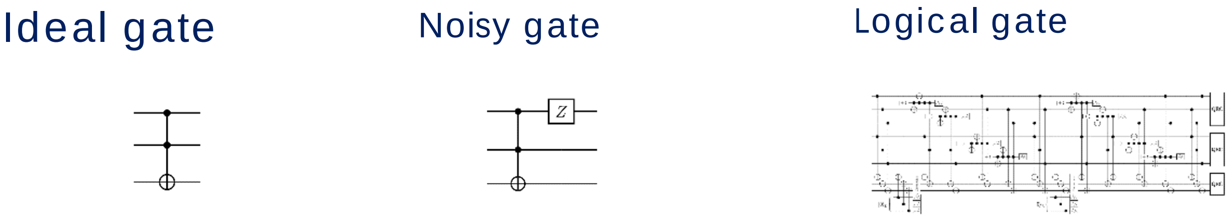
→ Not the same types of errors

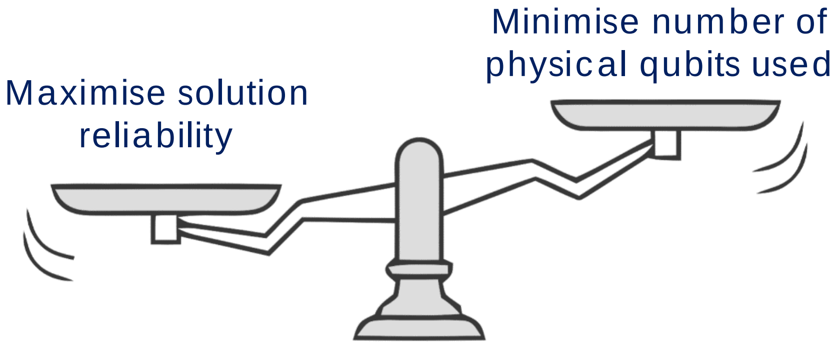
Logical metrics

Goals

→ Take into account error correction codes
→ Estimation of the overhead of the number of physical qubits
→ Minimize overhead by identifying which algorithmic bricks are resilient to errors







for each algorithmic brick

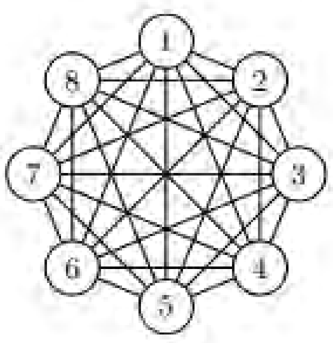
Error Rates and Resource Overheads of Repetition Cat Qubits, Jérémie Guillaud, Mazyar Mirrahimi, 2020

ALICE & BOB

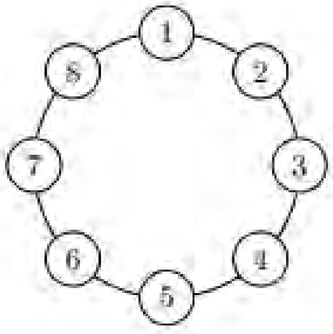
Compilation metrics

Goals

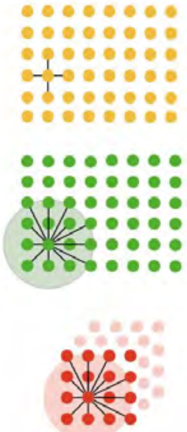
→ Routing overhead estimation (number of SWAP operations needed)
→ Study the connectivity of providers' hardware

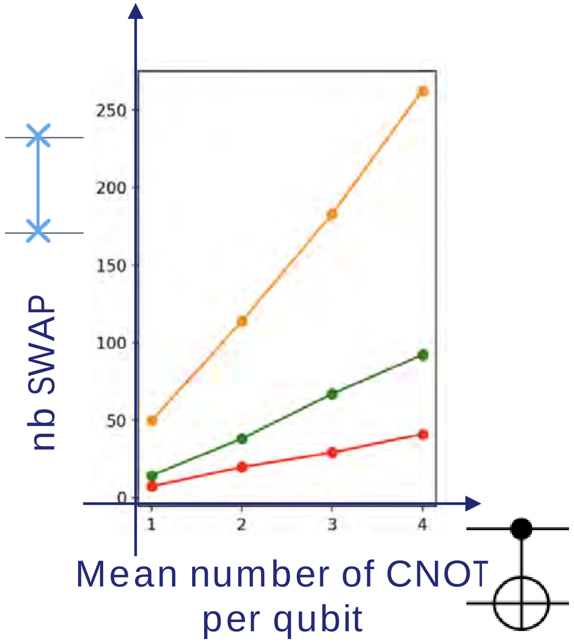


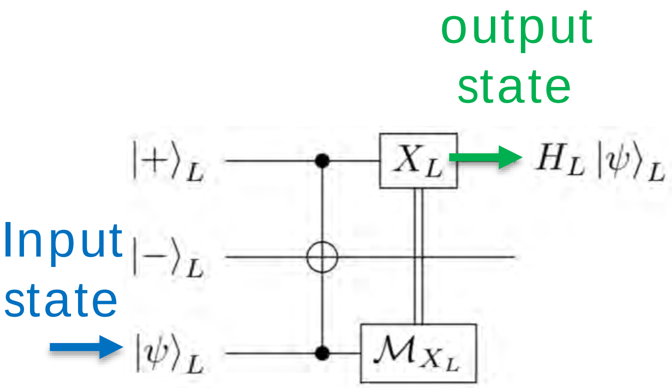
Full connectivity assumed



Real hardware connectivity







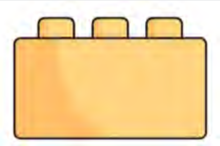
Hadamard gate

On the qubit routing problem
Alexander Cowtan, 2019

Quantum Computing with Neutral Atoms,
Loic Henriet et al., 2020

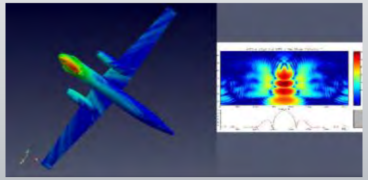
Repetition cat-qubits: fault-tolerant quantum computation with highly reduced overhead, Jérémie Guillaud, Mazyar Mirrahimi, 2019

Algorithmic Bricks

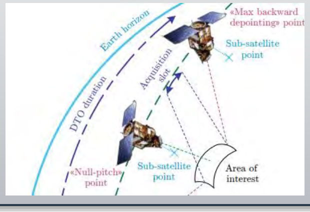


Selection of relevant sub routines for:

→ Partial Differential Equations



→ Optimization



FTQC regime

HHL

- Phase Estimation
- Target encoding
- Solving matrix controlled unitary
- …

NISQ regime

Quantum Approximate Optimization algorithm

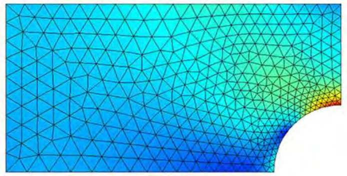
- Variational ansatz

Variational Quantum Linear Solver

- Solving matrix controlled unitary
- SWAP test
- …

THALES contribution to BACQ: Metrics

- Focus on two applications: electromagnetic simulations & optimization problems
- Focus on NISQ & FTQC QPUs
- Definition of two metrics following 3 phases:
  - 1st phase:
    - Evaluation of physical characteristics of a selected set of QPUs to better understand noise origins (with the help of QPU providers) & noise modelling.
  - 2nd phase:
    - Study of the impact of physical errors on a set of logic algorithm bricks.
    - Identification of error correction codes supported by each QPU.
    - Estimation of the induced overhead on the algorithm bricks.
    - Evaluation of the impact of error propagation on real QPU machines.
    - Definition of a performance metrics related to the noise level & computing accuracy.
  - 3rd phase:
    - Study of the impact of these observations on more complex algorithm compilation (according to connectivity constraints).
    - Test and measures on real QPU machines.
    - Definition of an overhead metrics due to the compilation.



Deterministic methods (Finite Element)

CNRS Contribution to BACQ: Energetic Benchmarks for Gate-Based

Goal: propose and simulate energetic benchmarks

- Energy is critical for competitivity and sovereignty
- Currently no energetic benchmark for quantum computing => France can take a leadership
- Challenges: methodologic (interdisciplinarity), strategic (acceptation of the benchmark)

MNR (metrics noise resource)

- Under study: a simple gate-based quantum machine
- Build up of a systemic *hardware-agnostic* approach

D3.1 List of control parameters and algorithmic resources for a gate-based quantum machine performing a simple task. Design and exploitation of an Algorithmic Resource Estimator for the studied problem (M18)

D3.2 Optimization of the algorithmic efficiency for a fixed noise and effective relation to the energetic performance of the machine (M36)

Working group Quantum Energy Initiative @ IEEE

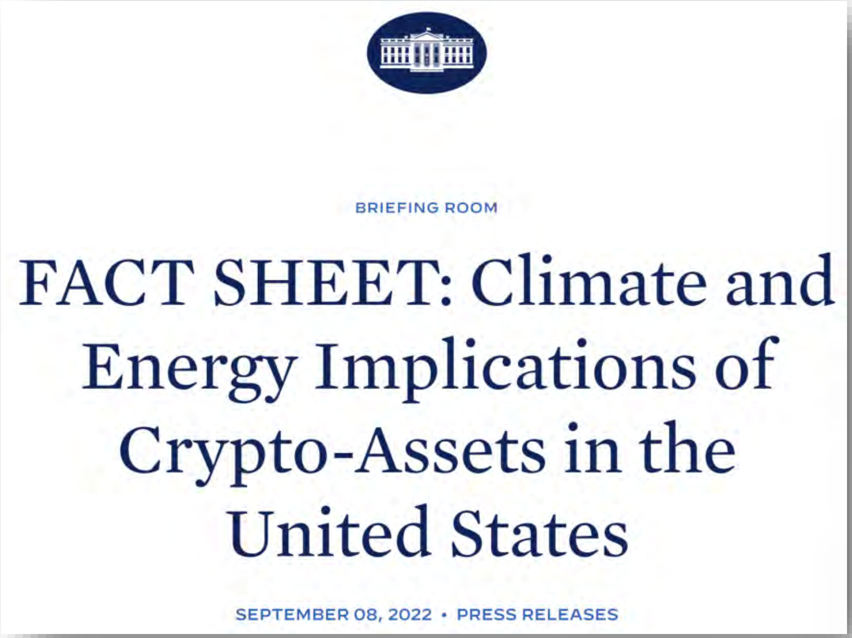
- D3.3 (M12, M24, M36): Proposition of frameworks and contribution of the validation of the standard

#QEI the quantum energy initiative

IEEE SA STANDARDS ASSOCIATION

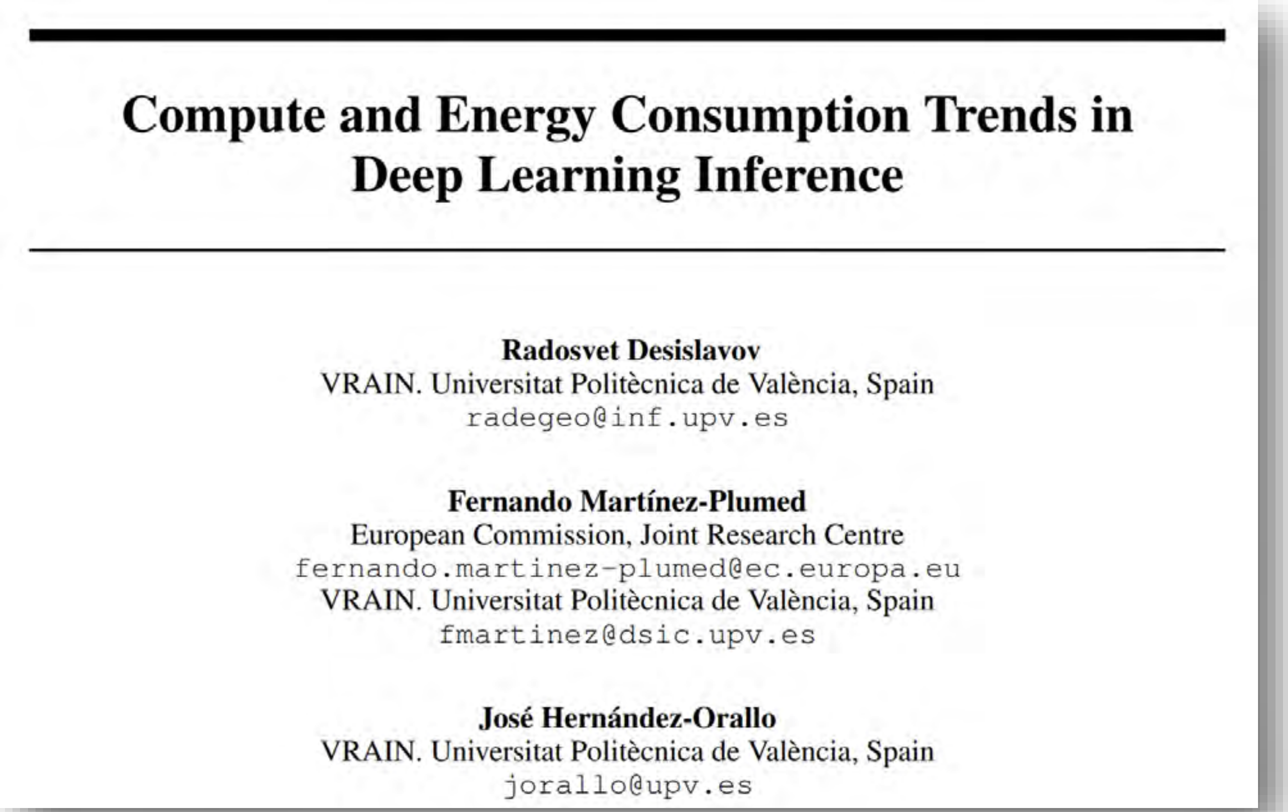
Digital technologies are energy hungry

ICT global electricity consumption in 2020: **11%** (Puebla et al, 2020).


BRIEFING ROOM

FACT SHEET: Climate and Energy Implications of Crypto-Assets in the United States

SEPTEMBER 08, 2022 • PRESS RELEASES


Compute and Energy Consumption Trends in Deep Learning Inference

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https://arxiv.org/abs/2109.05472

https://www.whitehouse.gov/wp-content/uploads/2022/09/09-2022-Crypto-Assets-and-Climate-Report.pdf

How about quantum technologies?

RESEARCH-ARTICLE

Energy Cost of Quantum Circuit Optimisation: Predicting That Optimising Shor's Algorithm Circuit Uses 1 GWh

Authors: Alexandru Paler, Robert Basmadjian Authors Info & Claims

ACM Transactions on Quantum Computing, Volume 3, Issue 1 • March 2022 • Article No.: 3, pp 1–14 • https://doi.org/10.1145/3490172

https://dl.acm.org/doi/10.1145/3490172

energy hog?

or energy saver?

Is quantum computing green? An estimate for an energy-efficiency quantum advantage

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[2]*Dipartimento di Fisica e Astronomia "G. Galilei" & Padua Quantum Technologies Research Center, Università degli Studi di Padova, Italy I-35131, Padova, Italy*
[3]*INFN, Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy*

(Dated: May 25, 2022)

https://arxiv.org/abs/2205.12092

Quantum Energy Initiative vision paper

PRX QUANTUM
a Physical Review journal

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Perspective Open Access

Quantum Technologies Need a Quantum Energy Initiative

Alexia Auffèves
PRX Quantum **3**, 020101 – Published 1 June 2022

Article References No Citing Articles PDF HTML Export Citation

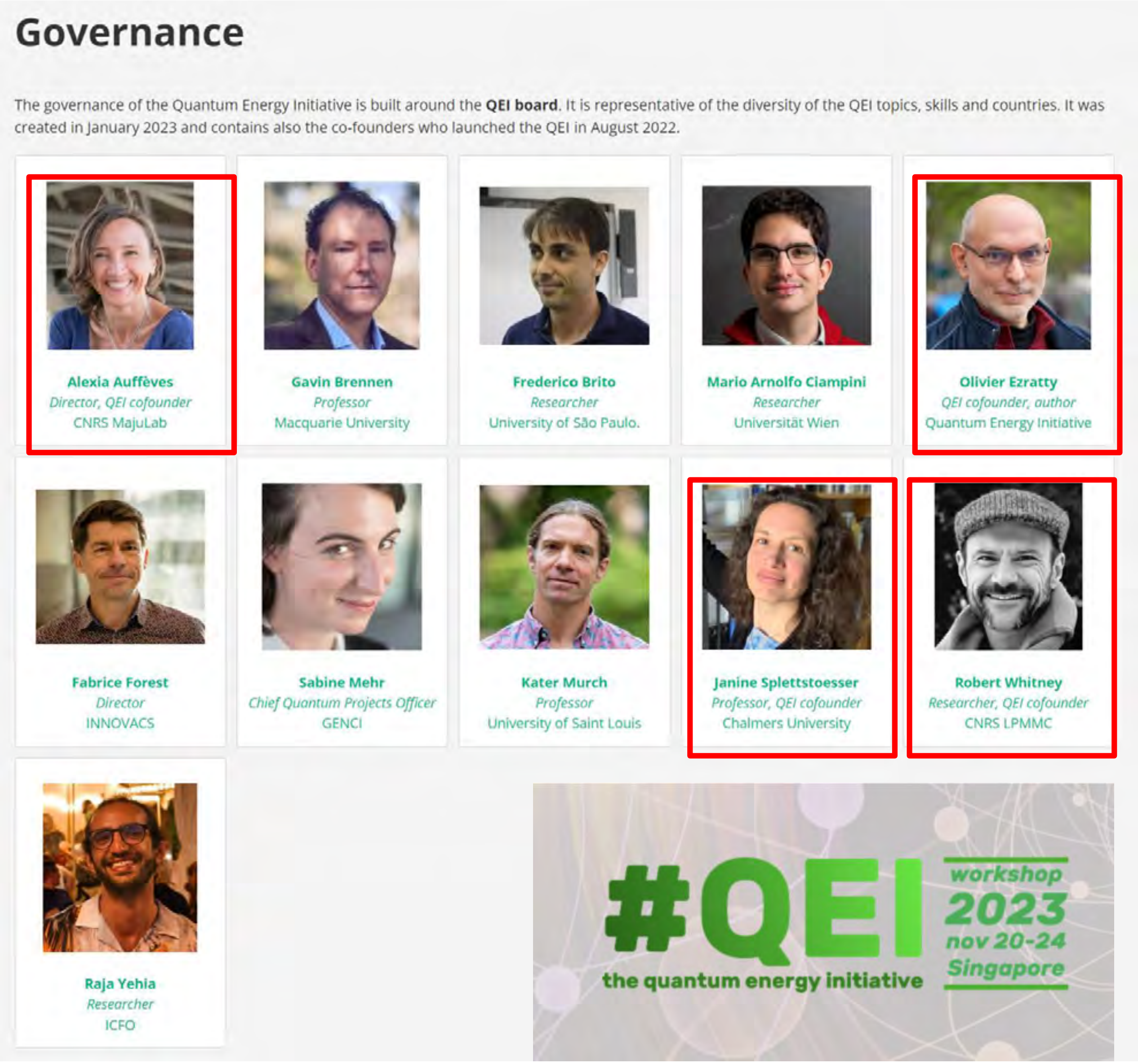
ABSTRACT

Quantum technologies are currently the object of high expectations from governments and private companies, as they hold the promise to shape safer and faster ways to extract, exchange, and treat information. However, despite its major potential impact for industry and society, the question of their energetic footprint has remained in a blind spot of current deployment strategies. In this Perspective, I argue that quantum technologies must urgently plan for the creation and structuration of a transverse quantum energy initiative, connecting quantum thermodynamics, quantum information science, quantum physics, and engineering. Such an initiative is the only path towards energy-efficient, sustainable quantum technologies, and to possibly bring out an energetic quantum advantage.

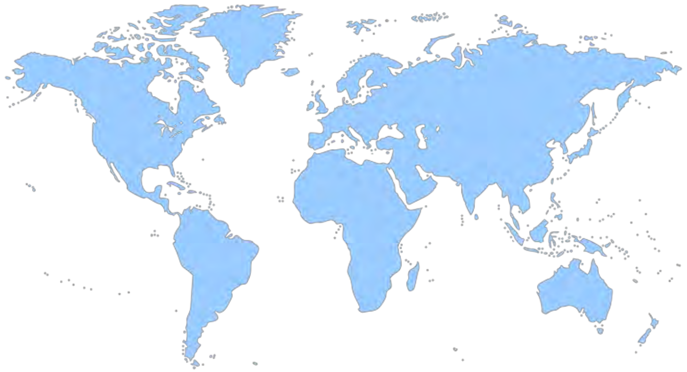
Timeline

Jun 22 Vision paper
Aug 22 QEI website and Manifesto
Jan 23 QEI board
May 23 300 participants, 48 countries, 28 partners
May 23 Kickoff of QEI WG@IEEE
Jun 23 YouTube channel
Nov 23 First QEI workshop, Singapore

www.quantum-energy-initiative.org
https://qei2023.sciencesconf.org/

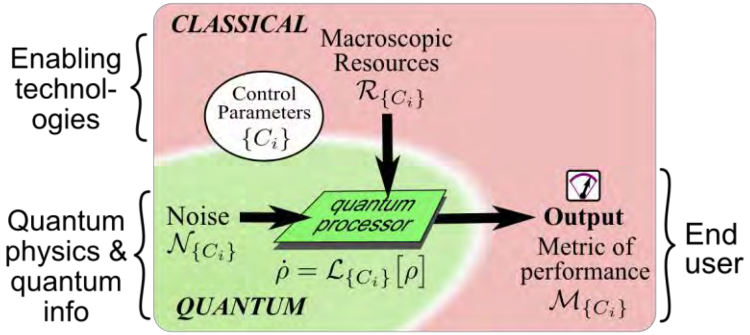


Goals & missions

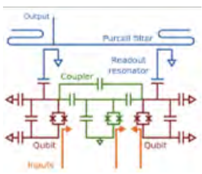


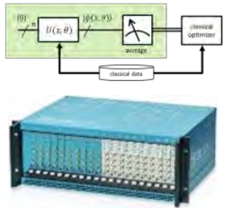
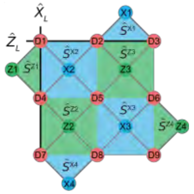
Create a **worldwide community** working on quantum technologies energetics associating fundamental research and industry vendors.

(a) Metric-Noise-Resource (MNR) methodology for the full-stack of a quantum computer

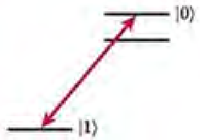
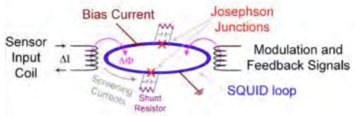


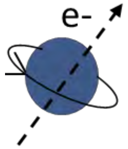
Propose **optimization methodologies, frameworks** and **benchmarks** for quantum technologies, enabling technologies and software engineering

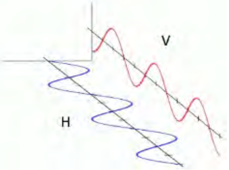


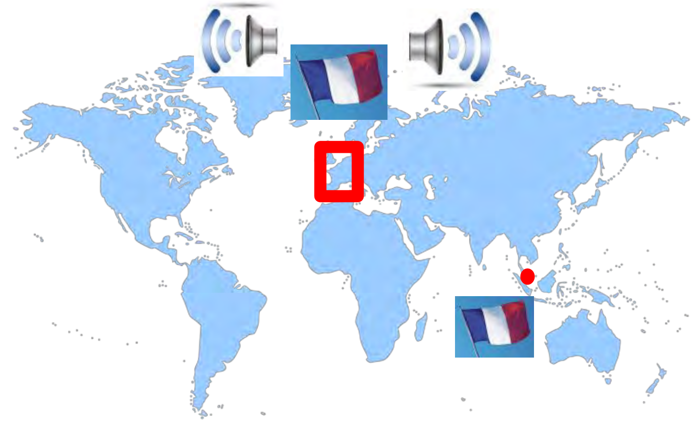
Create a new **transversal line of research** and **collaborative projects**.





Cover **all qubit types**, **programming paradigms**, and other quantum technologies (communications, sensing)



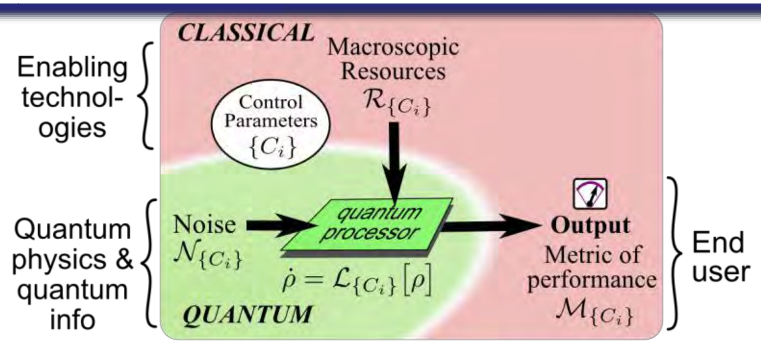
#QEI the quantum energy initiative

IEEE SA STANDARDS ASSOCIATION

CNRS | QET>

Optimizing resource efficiencies for scalable full-stack quantum computers

Marco Fellous-Asiani,[1,2,*] Jing Hao Chai,[2,3] Yvain Thonnart,[4] Hui Khoon Ng,[5,3,6,†] Robert S. Whitney,[7,‡] and Alexia Auffèves[2,6,§]



Goal

- Take a lead in the definition, simulation and tests of energetic benchmarks

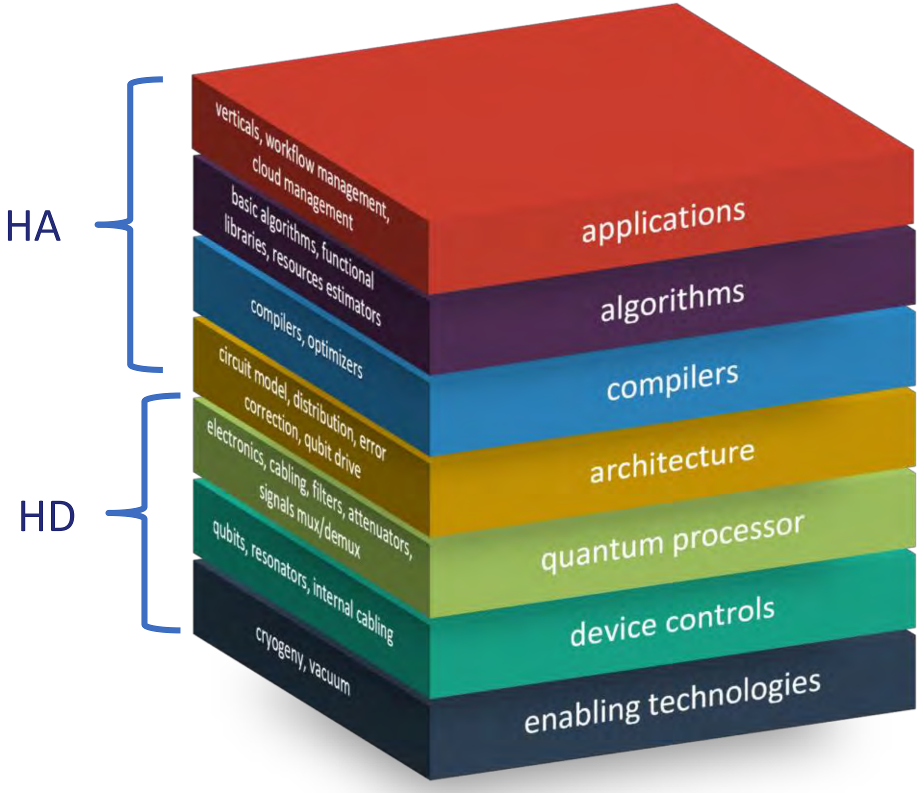
Challenges

- Energetic efficiencies are hybrid figures of merit: interdisciplinary methodology
- Standards only matter if they are used => acceptance

Strengths

- Methodology already proposed and applied in the CNRS|QET> team
- Worldwide connections already established (QEI/IEEE/|QET>)

Methodology and scope



Efficiency = Metric of performance/Resource cost

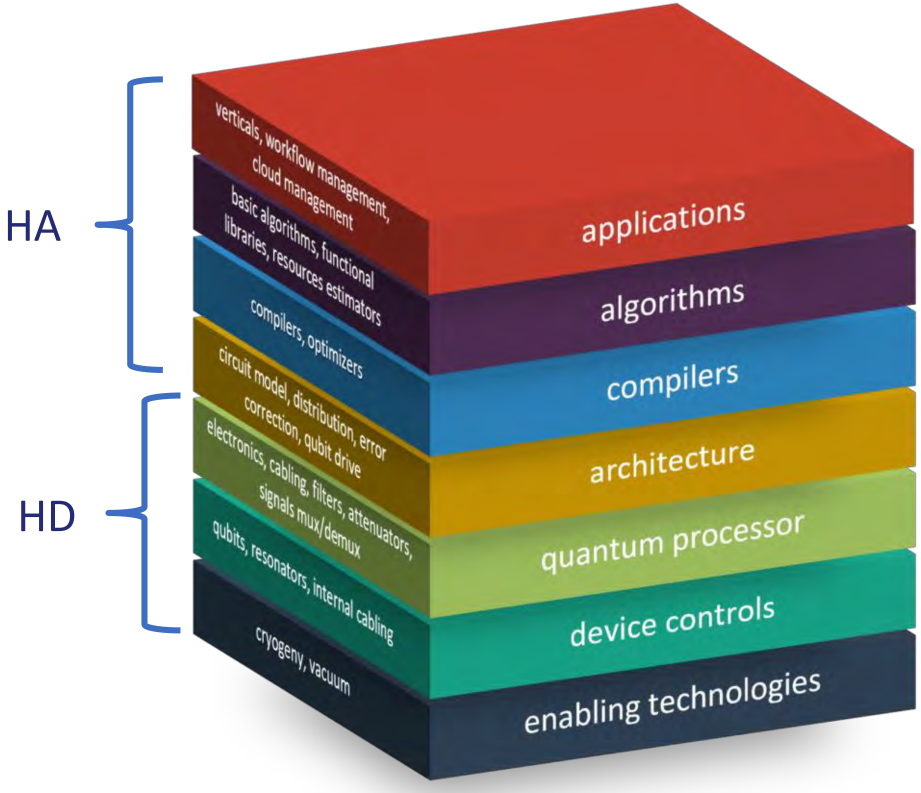
- **Metrics** can be defined at low level or end user level. They characterize a specific use case. They depend on control over **noise** at the quantum level
- **Control** depends on **resources**
- **Resources** can be hardware-agnostic (HA) or hardware-dependent (HD). **Energy** is a HD resource. HD resources feedback on **noise** => Coupled problem, to be treated in a holistic approach (in other projects)

In BACQ, we consider a simple algorithm and focus on the HA side of the stack

- end-user metrics
- HA resources

The connection with energy is made in an effective way.

Tasks and Deliverables



Tâches	
T3.1	Analytic estimator of energetic efficiency (CNRS) Define and produce analytic expressions of energetic efficiencies for a gate based quantum machine performing a simple algorithm
T3.2	Numerical model of quantum processor (CNRS) Create a numerical model of the quantum processor, and integrate Hardware Dependent parameters in an effective way.
T3.3	Steering of the IEEE QEI WG (chair A. Auffèves)

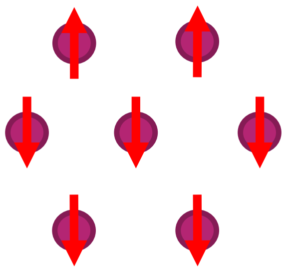
Livrables		Responsable	Echéance
D3.1	List of control parameters and algorithmic resources of a gate-based machine performing a simple algorithm.	CNRS	M18
D3.2	Optimization of the algorithmic efficiency for fixed noise and effective relation with the energetic performance of the machine	CNRS	M36
D3.3.1-3	Relation to the IEEE QEI WG, proposition of frameworks and contribution to the acceptance of the energetic standard	CNRS	M12, M24,M36

CEA contribution to BACQ: Metrics Elaboration

Gate-based and analogue simulations of condensed-matter inspired quantum many-body models

CEA/DRF: IPhT & IRIG/Pheliqs

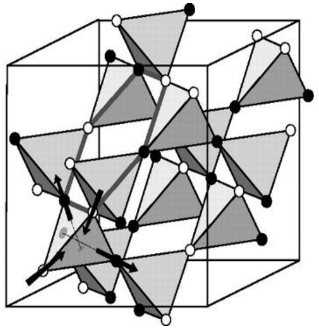
- Idea: develop metrics to quantify the capacity of a quantum machine to simulate difficult and physically relevant quantum problems (example: quantum phase transitions).
- Criteria: many-body fidelity of state preparation (target non-trivial N-qubit entangled states), accuracy of dynamics simulation, accuracy of extracting physical quantities of interest.



Gate-based and analogue application for optimization, linear system solving and (Hamiltonian-based) integer factorization CEA/DRT : LIST/DSCIN

- Idea: develop metrics to evaluate quantum computers on several classes of optimization problems (from easy-sparse, to difficult-dense problems), linear systems (at different sizes), and integer factorizations (with an increasing complexity)
- Criteria: probability of finding the optimum or distance to optimum (optimization), size, complexity and sparsity of the associated problem;

Simulations of quantum many-body problems



- Quantum physics problems
  - Condensed matter / solid-state physics
    superconductivity, correlated electrons , quantum magnetism, electronic transport, new phases of matter
  - Chemistry (electronic structure of molecules, reaction mechanisms)
  - High energy Physics (nuclear physics, gauge theories, …)
- … are exponentially hard for classical computers (generically)

reason: exponential growth of the Hilbert space dimension with the number of particles

- Some promising quantum algorithms
  - Analog quantum simulations
  - Gate-based approaches
    Variational quantum eigensolver (VQE), Trotter-based calculation of the dynamics, …

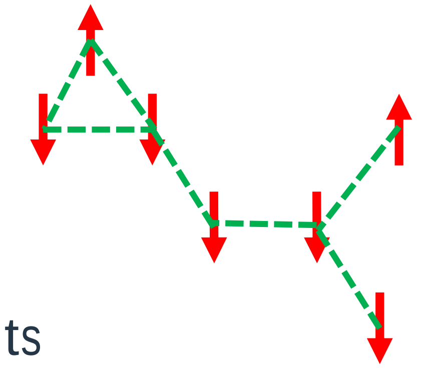
Simulations of quantum many-body problems

- Goal: develop metrics to quantify the capacity of a quantum machine to simulate difficult and physically relevant quantum problems (examples: previous slide)
- Criteria:
  - many-body fidelity of state preparation (target non-trivial N-qubit entangled states)
  - accuracy of hamiltonian dynamics simulation
  - accuracy of extracting physical quantities of interest
- Actors: 2 academic labs. of the Direction de la Rech. fondamentale (DRF) of CEA
  - Institut de Physique Théorique (IPhT - Saclay)
  - PHotonique ELectronique et Ingénierie QuantiqueS (IRIG/PHELIQS)

Approaches to quantum modelling of many-body systems

What is an analog quantum simulator ?

- Programmable Hamiltonian for interacting qubits. Example:



$$\hat{H}(t) = \sum_{i=1\ldots N} h_i(t)\,\hat{\sigma}_i^x + \sum_{i,j=1\ldots N} J_{ij}(t)\hat{\sigma}_i^z\hat{\sigma}_j^z$$

- Device allowing initializing, time-evolving and measures of the qubits
- Application: solid-state physics, chemistry, optimization, …

Digital approaches to quantum simulation

- Consider the same Hamiltonian, but instead of implementing it *physically*,
  - Use VQE to get its ground state
  - Use Trotterized system dynamics to simulate the evolution

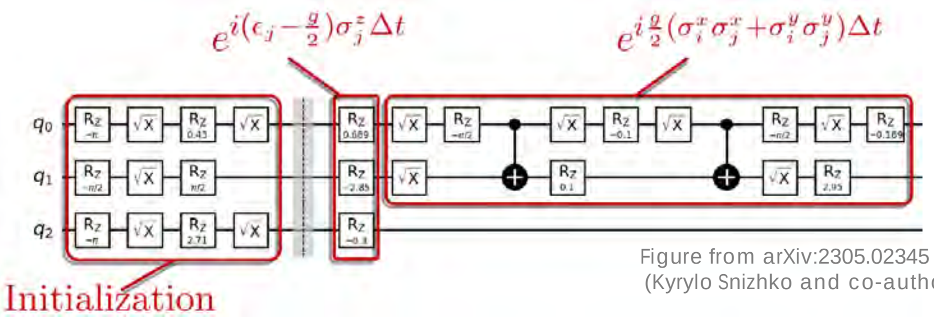


Figure from arXiv:2305.02345 (Kyrylo Snizhko and co-authors)

Targets

- Construct quantitative measures of the accuracy

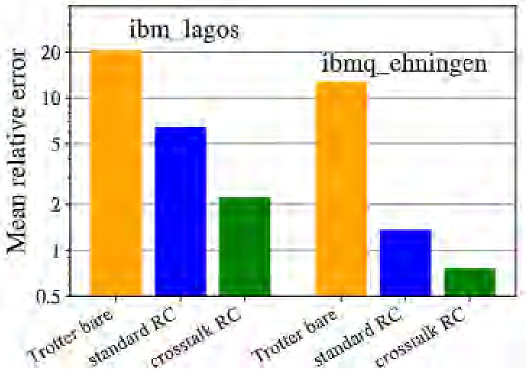


Figure from arXiv:2305.02345 (Kyrylo Snizhko and co-authors)

- Method: exploit some exactly solvable (spin) models to select/characterize relevant target states, compare the theoretical values of relevant observables with the measured ones.

- Key criteria:
  - accuracy of preparing a given target entangled state of N qubits
  - accuracy of simulating the system dynamics
  - measures of accuracy for **what's** physically important
    - Signatures of the phase transition in the model? (Scaling)
    - Accuracy of the critical indices?

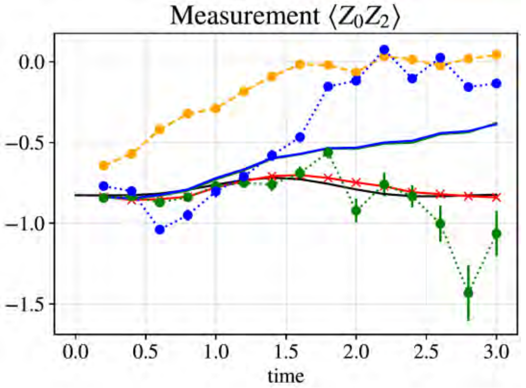


Figure from arXiv:2305.02345 (Kyrylo Snizhko and co-authors)

Quantum Computing for Optimization and Op. Research

- Optimization is a domain with a high level of expectancy toward QC
  - Analog Quantum Computing is taylored as a tool aimed at optimization problems
    - QUBO/2D-Ising are a tool for up to NP-hard optimization
    - No computational quantum advantage demonstrated
    - But still a possible « black box » optimizing device with quantum effects
  - Gate-based Q-Computers can utilize a simulation of the adiabatic th. : QAOA
    - Results are not so bad noiseless cases
    - The depth of the simulation (p-parameter) can probe the accuracy of real-world QPUs

- Optimization can have several classes of difficulties
  - Polynomial vs NP-hard
  - Sparce vs dense
  - Beyond QUBO : HOBO

- Goal : display a generalized vision of MaxCut/QuScore

Quantum Computing for Linear System Solving

- Linear systems are a potential disruptive field of application for QC
  - The HHL algorithm promises exponential speedup
    - But is basically unfeasible on non perfect Gate-based QPUs
    - Is not accessible to analog QPUs
  - A pragmatic approach is required to probe this field of application within the constraints of nowadays QPUs
    - Probably no computational quantum advantage
    - Maybe a perspective of future energy advantage for future QPUs

- Lot of parameters to probe
  - Number of equations
  - Sparcity of the system
  - Precision in bits
  - Etc.

- Goal : showing at least naive application even with imediate potential of advantage

Quantum Computing for Integer Factorizations

- Integer factorization is one of the holy grail of QC
  - The share existence of Shor's algorithm fostered the so-called Quantum Hype
    - But is basically unfeasible on non perfect Gate-based QPUs
    - Is not accessible to analog QPUs
  - A pragmatic approach is required to probe this field of application within the constraints of nowadays QPUs
    - No computational quantum advantage
    - Only a means to probe the efficiency of QPUs vs Noise
- Hamiltonian approach of the problem
  - Will work on any QPU
  - Probably with a low number of qubits
  - Better than the out-of-reach Shor's algorithm with the current state of the quantum hardware

- Goal : showing a result is better than not

- Future extension with noise-free QPU should take the relay when ready

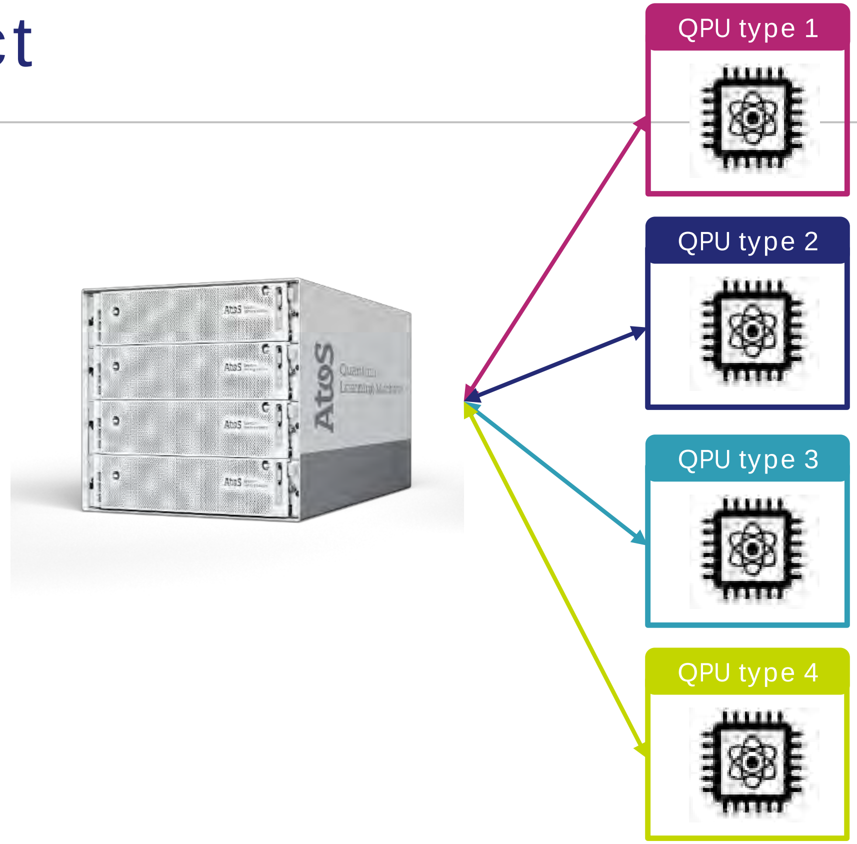
Eviden activities within BACQ project

On going work

- Leading Fast-Track (March 2023 - December 2023)

Future work with BACQ collaborators

- Define a new metric (Q-score manybody) and collect the metrics of other collaborators
- Make the partners QPU accessible to run tests on them
- Gather and analyse results of the runs



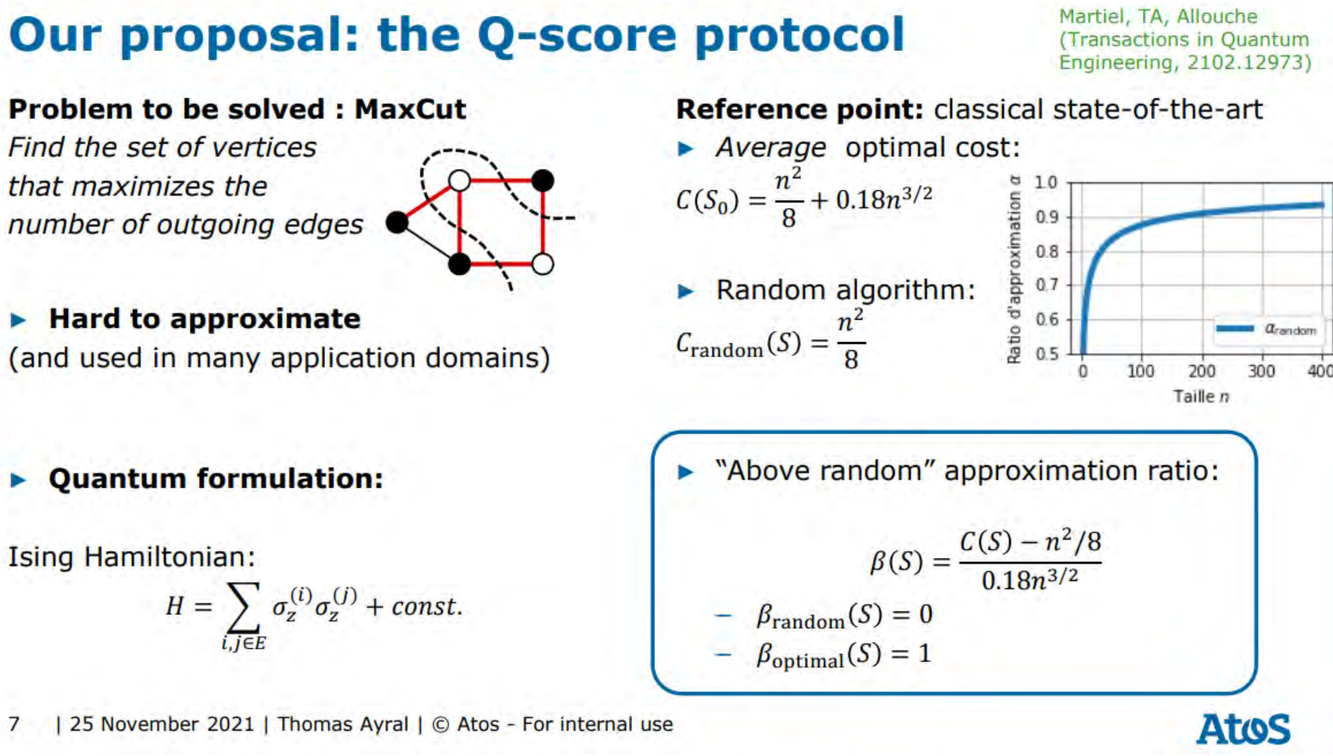
Eviden gains

- QLM is designed for interoperability and this project is an opportunity to prove it on an extensive set of various technologies of QPUs
- Extending the Q-score methodology to another metric (manybody) is an opportunity to remind its qualities and promote its adoption.

Q-SCORE Maxcut Metric

Q-SCORE Maxcut

- Q-score maxcut addresses a complex problem (maxcut) for which a quantum advantage is expected
- Q-score is scalable because the reference used to validate a success is an average on a random sample of graphs which is easily computed classically; despite individual graphs being complex to solve classically.
- The maxcut problem only has a meaning for a size of graph >= 5 vertices



EVIDEN an atos business

The Q-SCORE Protocol in Practice

a. For a size-n graph G:

i. Execute an algorithm to find a solution S

ii. Compute cost $C_G(S)$

b. Average costs: $C_n = \langle C_G(S) \rangle_G$ and compute $\beta(n)$

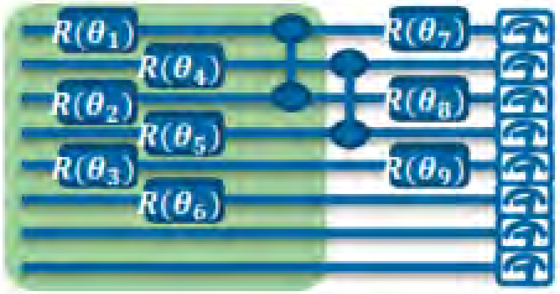
Quantum algorithm:

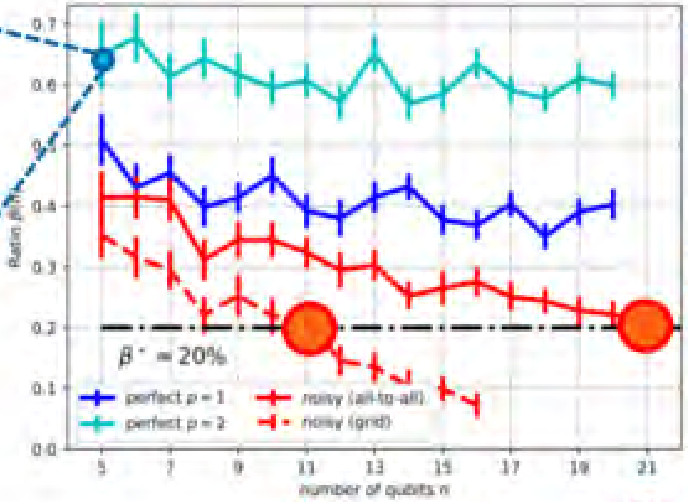
User's choice (gate-based, analog).

Here, variational algorithm ("QAOA")

$|\psi\rangle = U_{\vec{\theta}^*}|0\rangle$ with $\vec{\theta}^*$ minimizing $\langle \psi_{\vec{\theta}} | H | \psi_{\vec{\theta}} \rangle$

Preparation of $U_{\vec{\theta}}|0\rangle$





Q-score value

Without decoherence

The longer the preparation circuit ($p = 1 \rightarrow 2$), the higher the quality (constant w.r.t size)

With (simulated) decoherence

(here, depolarizing noise)

- Quality decreases with size
- Qubit connectivity plays a role (**compilation**)

Q-score : number of "useful" qubits to solve a difficult problem

Martiel, TA, Allouche (TQE, in press, 2102.12973)

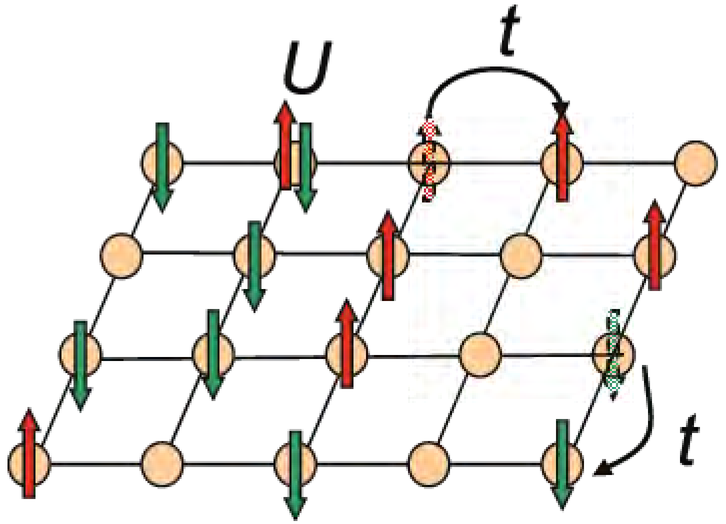
Usefulness | Scalability | Agnosticity

FRANCE 2030 · LNE Laboratoire national de métrologie et d'essais · anr agence nationale de la recherche · STRATEGIE NATIONALE QUANTIQUE · Teratec

RÉPUBLIQUE FRANÇAISE · cnrs · EVIDEN an atos business · cea · THALES Building a future we can all trust

What is the Q-score many-body metric?

- Q-score « many-body » mesures the ability of a quantum processor to solve the Hubbard model in 2 dimensions. This is a reference problem which is used to study the phase transition in materials.



- As Q-score « MaxCut », this problem is hard to solve using classical techniques, but several polynomial classical references could be chosen so that the metric can scale: Monte-Carlo algorithms (exact for Half-Filling : optimal reference point), or Hartree-Fock computations (minimal reference point).

- The Q-score could be the maximal number of orbitals above which the energy computed by the QPU is no longer competitive compared to these references. The precise definition of the criteria (equivalent to the weighted 29 Tflops for Wassenaar agreement) are yet to be determined during the BACQ project.

THALES
Building a future we can all trust

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MetriQs-France

National Program on
Measurement, Standards and Evaluation
of Quantum Technologies

RÉPUBLIQUE FRANÇAISE · LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS · LNE

BACQ
FAST-TRACK Q-SCORE

LNE, THALES, EVIDEN, CEA, CNRS, TERATEC

Presented by Anne-Lise Guilmin (EVIDEN)

Fast Track phase of BACQ initiative

Opportunity to introduce BACQ to potential partners

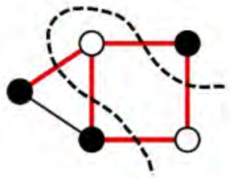
Gather early partners to join a preliminary phase test on an existing metric

- An application oriented metric for quantum computation is already defined: Q-score maxcut.
- It has been designed to be generic.
- As part of Fast-Track, we want to run it on various technologies and gain rapid experience on the Q-score evolutions required to universality and the challenges along the BACQ project.
- Q-score is a metric. It defines a way to score a QPU for a specific purpose. It does not specify how the QPU is supposed to achieve this purpose. In order to run Q-score, we first need to find an implementation which fits each machine we test.

What is the Q-score maxcut metric?

Problem to be solved : MaxCut

Find the set of vertices that maximizes the number of outgoing edges



- Q-score maxcut addresses a complex problem (maxcut) for which a quantum advantage is expected.

  The maxcut problem only has a meaning for a size of graph >= 5 vertices

- Methodology to assess if a QPU can solve a given size of graphs

  - Classically compute the average solution for a family of graphs of this size
  - Randomly choose n graphs among this family of graphs
  - Execute it on a quantum machine
  - Compute the quantum average and its standard deviation to the classical average

- Q-score is the maximal size of graphs that the quantum machine can handle

- Q-score is scalable because the reference used to validate a success is an average on a random sample of graphs which is easily computed classically; despite individual graphs being complex to solve classically.

The Q-score protocol in practice

- Running Q-score on various technologies requires to write an implementation of the maxcut problem for each qubit technology and each programming model (quantum gate, analog, annealing).

- New questions arrived:
  - Due to topology, some QPUs are able to run some graphs but not any graphs of a given size. How to rate them?
  - Today, QPUs are not able to solve bigger size of graphs than classical machines. How to assess the part of classical computing in a hybrid computation?

Partners contacted to participate in Fast-Track

Sorted by qubit technology

- Photonic
  - Psiquantum (Palo Alto, US)
  - Quandela (Massy, France)
  - QuiX (Enschede, The Netherlands) via TNO
  - Xanadu (Toronto, Canada)
- Superconductors
  - Alice & Bob (Paris, France)
  - Google (Santa Barbara County, US)
  - IBM (Cambridge, US) via TNO
  - IQM (Espoo, Finland)
  - OQC (Oxford, UK)
- Trapped ions
  - AQT (Innsbruck, Austria)
  - Quantinuum (Cambridge, UK)
- Spin qubits
  - C12 (Paris, France)
  - Siquance (Grenoble, France)
- Neutral atoms
  - Pasqal (Massy, France)
  - QuEra (Boston, US)
- Annealing
  - D-Wave (Burnaby, Canada) via TNO and FZJ
  - Fujitsu (Kanagawa, Japan) via Riken via CEA
  - NEC (Tamagawa, Japan) via Riken via CEA
- NV centers in diamond
  - Quantum Brilliance (Acton, Australia)

* Indirect access via collaborators to be discussed
* Collaboration under discussion

Partners contacted to participate in Fast-Track and interest points for future collaborations with BACQ initiative

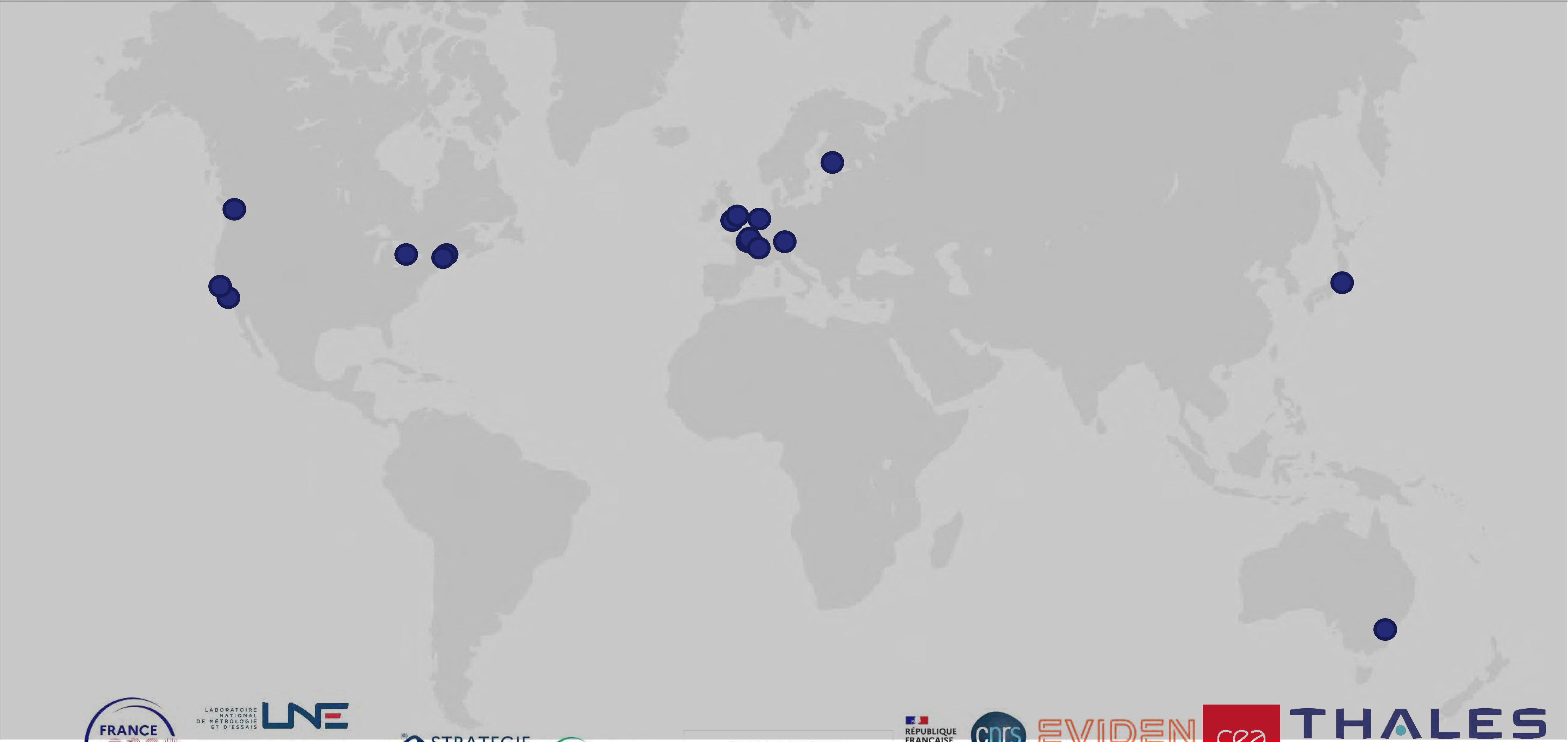


Image by rawpixel.com on Freepik

Done and on-going work

Past

- Q-score definition, by Atos [DOI: 10.1109/TQE.2021.3090207]
- Q-score maxcut on D-Wave, by TNO [DOI: 10.1109/QSW55613.2022.00017]
- Q-score maxcut on Pasqal emulator, by Pasqal [https://arxiv.org/abs/2207.13030]

Fast-Track achievement so far

- Q-score maxcut implementation on Quandela emulator

On going activities:

- Q-score maxcut implementation on IQM and Quantinuum emulators
- Q-score maxcut run on Quandela and Pasqal hardware
- Q-score maxcut run on a photonic hardware (when the machine is available in TGCC)
- Brainstorming with A&B around other possible Q-score metrics
- On-going discussions to formalize engagement with partners (MoU)

Invitation to participate

- BACQ is a 3-year project.
- Partners are welcome to test Q-score and other metrics to come.

If interested, please contact Félicien Schopfer and Frédéric Barbaresco

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- THANK YOU!

BACQ

Applications-Oriented Benchmarks
for Quantum Computers

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