



The challenges of scaling the cryogenic infrastructure for quantum computing

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Summary

1. Brief summary about quantum technologies news
2. How to scale-up cryogenics ?
3. Challenges of scaling cryogenics for quantum computing
4. CRYONEXT development program

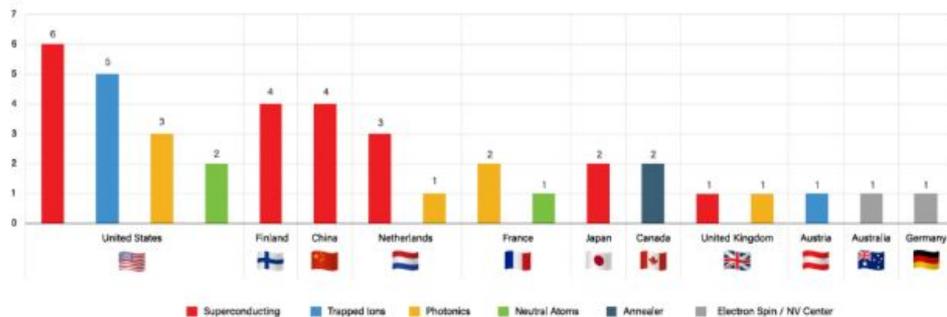
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2025 - Quantum Year

Sources 2025:
MIT analysis and Qu. tech. Monitor (Mc Kinsey)



Commercially available QPU models per country



Market size and value at stake: QC companies began a shift toward revenue generation, earning an estimated \$650 million to \$750 million in 2024.

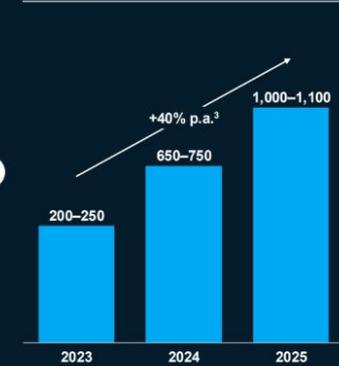
Quantum technology market size scenarios in 2035 and 2040

Based on existing development road maps and assumed adoption curve

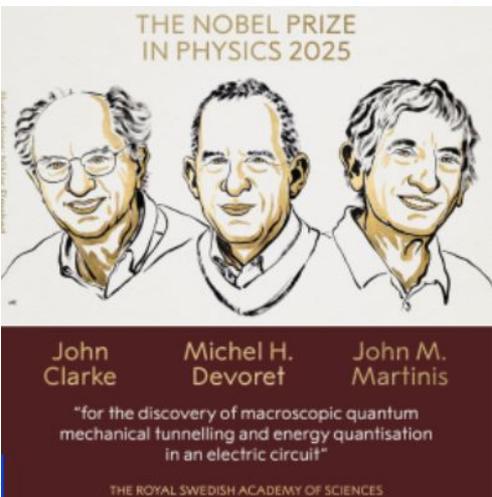
	QC	QComm	QS ¹
2035	\$28B-\$72B	\$11B-\$15B	\$7B-\$10B
2040	\$45B-\$131B	\$24B-\$36B	\$18B-\$31B

Potential economic value² from QC in 2035:
~\$0.9T-\$2.0T
Potential value driven by four industries by 2035: global energy and materials, pharmaceuticals and medical products, financial industry, and travel, transport, and logistics

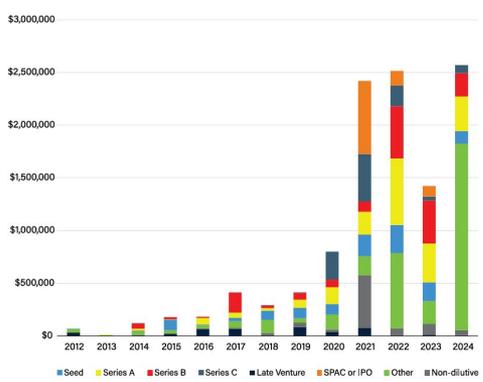
Revenue estimates of QC companies, \$ million



1. Approach for QS updated through clusters of use cases based on recent development, announcements, and breakthroughs.
2. Economic value is defined as the additional revenue and saved costs that the application of QC can unlock.
3. For annum.
Source: Crunchbase; expert interviews; Oxford Economics; PitchBook; Quantum Computing Report; S&P Capital IQ; McKinsey analysis



Quantum technology funding landscape by round, 2012-2024



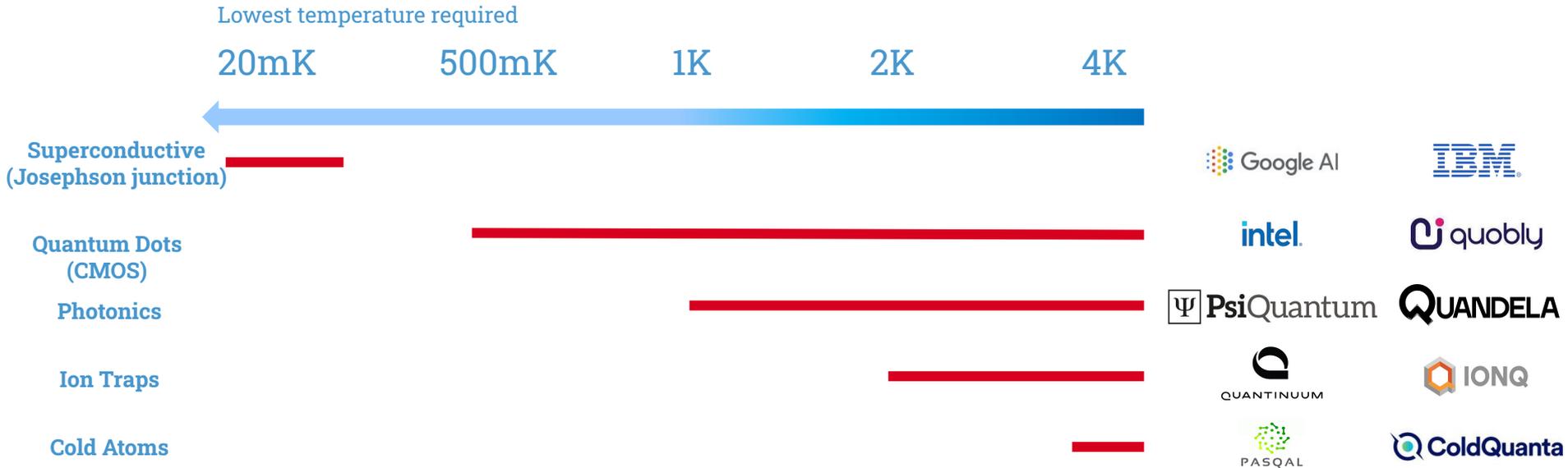
National investments announced to date total about \$54 billion.

Estimated and directional

Note: Includes investments through April 2025. Limited transparency on commercial activity in China, excludes the recent \$136B announced investment toward emerging technologies due to unclear relevance for QT. Excludes \$90M Swedish investments toward research and innovation, and US-Swedish investment of \$40M toward next-generation networks, AI, quantum technology, and educational science within STEM areas. The boundaries and names shown on maps do not imply official endorsement or acceptance by McKinsey & Company. Source: Press search

Cryogenics for Quantum Computing : Technologies

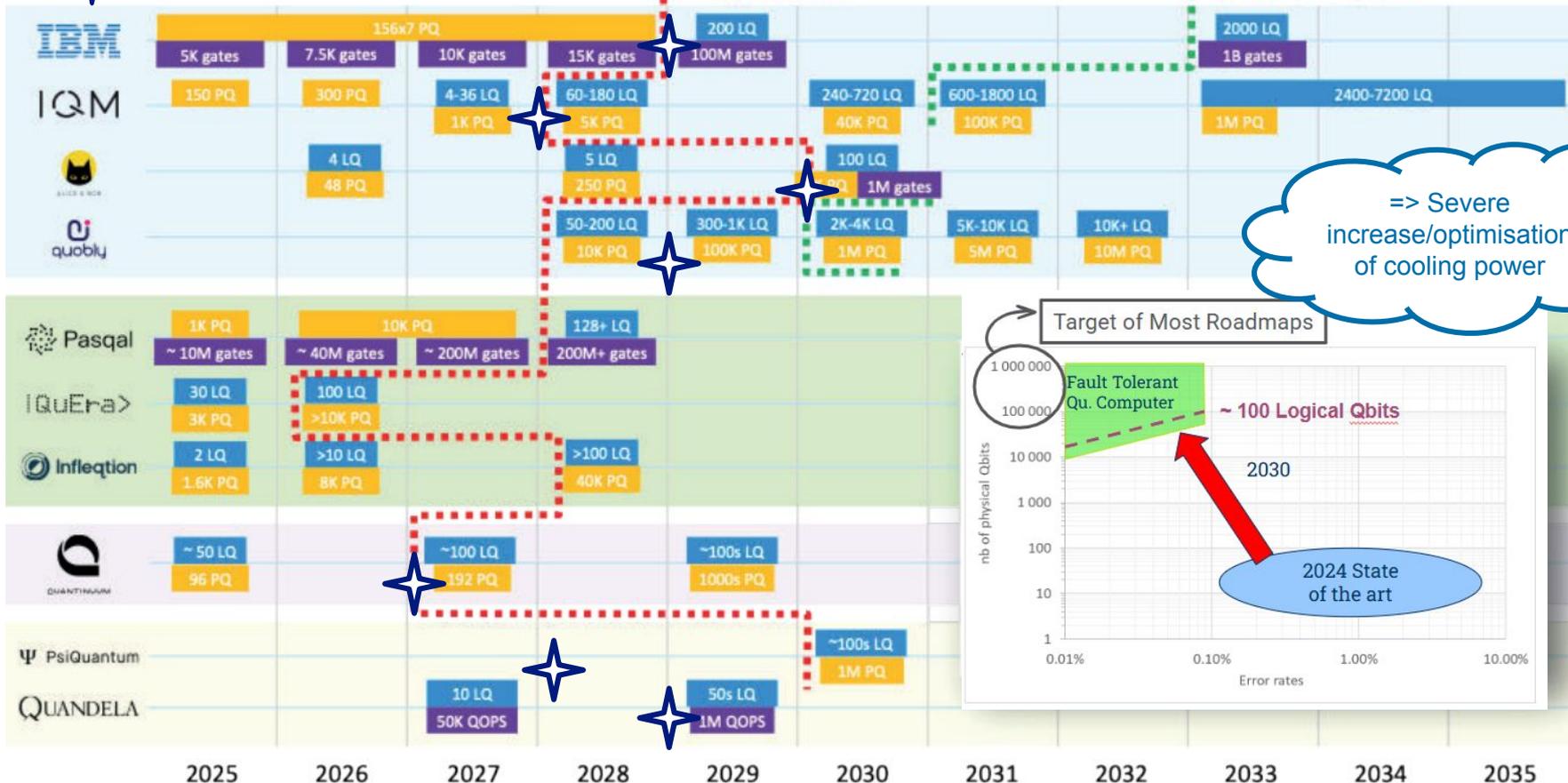
- The promise is to unlock computing speed by using quantum entanglement.
- After intense R&D activities, many actors (start-ups, Big Tech) have ambitious roadmaps and are working to **industrialize and up scale solutions** ... to reach the **Fault Tolerant Quantum Computer**.
- Several technologies are on the run, **all requiring cryogenic temperatures**.



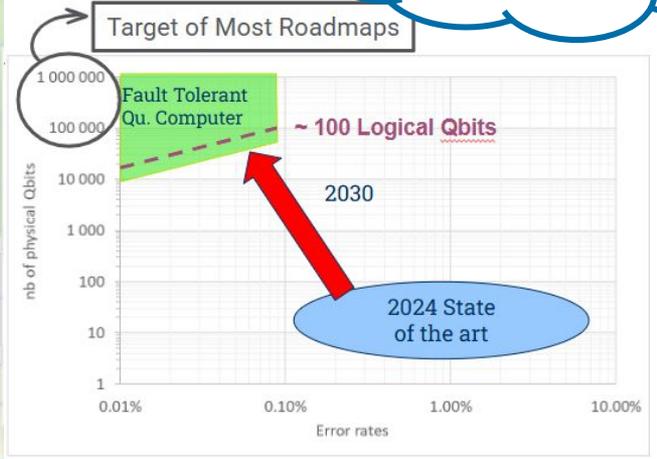
Scaling through End-users Roadmaps

logical qubits
physical qubits
gates / QOPS

✦ First Quantum Large Scale System



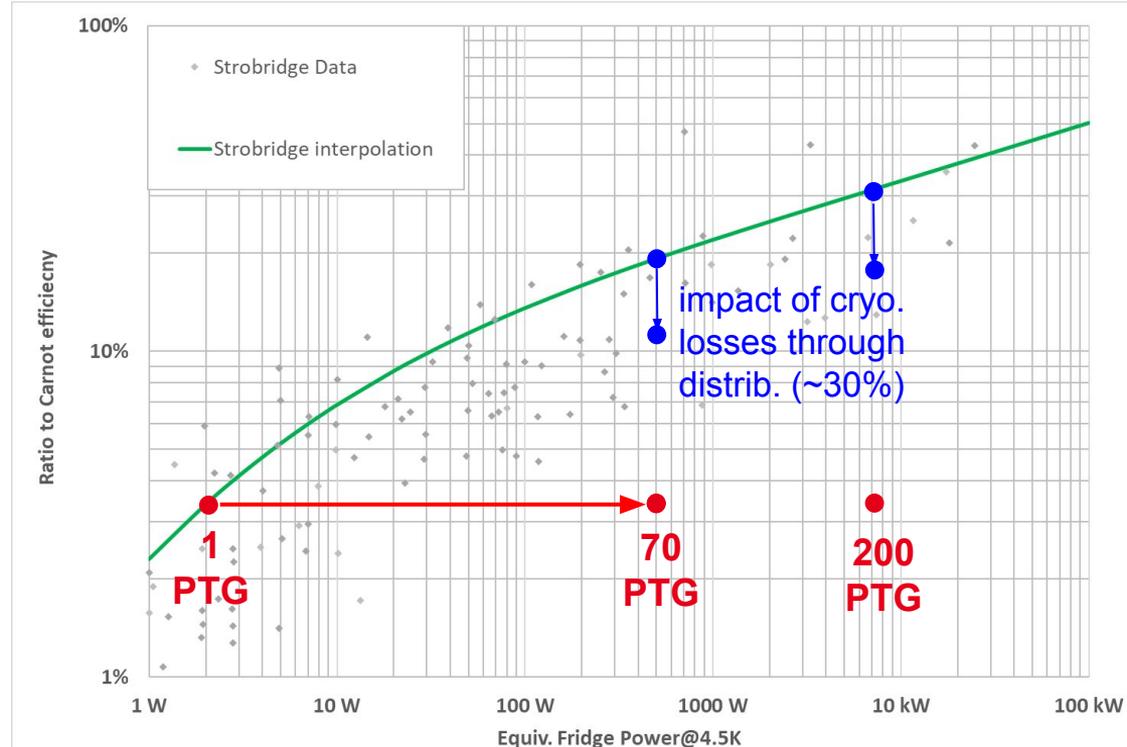
=> Severe increase/optimisation of cooling power



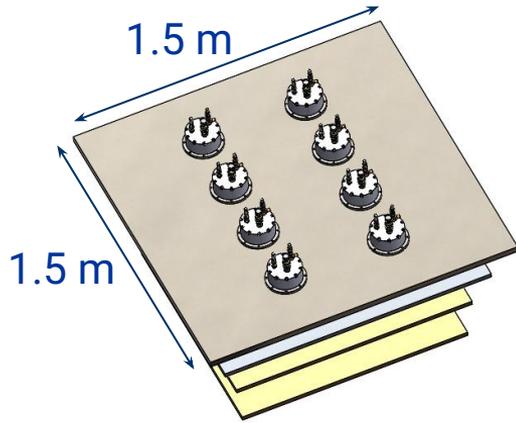
Which cryogenics for scaling ?

- Cryogenics MUST SUPPORT the needs of **multiplying low-temperature cryostats and their interconnection** + increase of cooling capacity by **one to several orders of magnitude** compared to the state of the art.
- One Pulse Tube Gas (PTG) (typically 7 W @4.2 K) demonstrates approx. an efficiency of **~ 4% of Carnot eff.**
- A “farm” of numerous cryostats with PTG : same efficiency of **~ 4% of Carnot**

- **Solution** : dev. of a **centralized refrigeration system** with an efficiency of **~ 16% of Carnot**
 - Equivalent to a system with 70 to 200 PTGs for 4 times lower elec. consumption
 - The gain largely exceeds the impact of thermal losses in the distribution network (- 30%) of a centralized source.



Inspired by recent developments of large cryostats ...



Example of a DR square design with 8 PT Cryomech 425 as precoolers

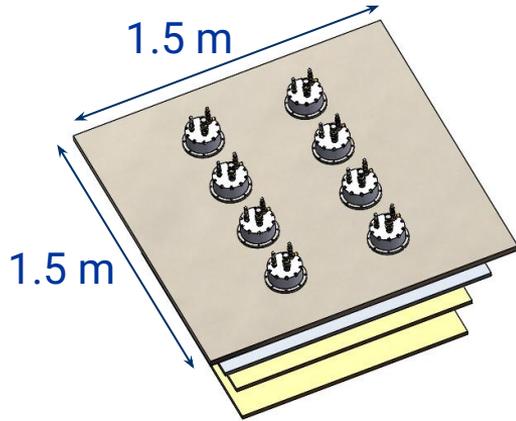
⇒ ~ 22 W@4K + 0.4 kW@45K

13 modules with 104 PTs in total

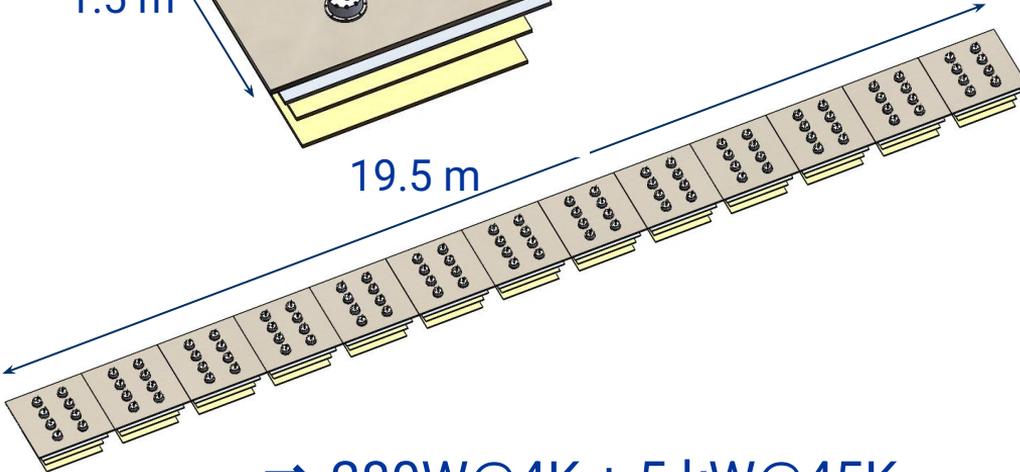
⇒ ~ 280 W@4K + 5 kW@45K
(750W@4.5K)

Pulse tubes are very structuring for cryostats (at interface and inside)

... an idea of first demonstration of scaling-up of cryogenics



⇒ $22\text{W}@4\text{K} + 0.44\text{kW}@45\text{K} \rightsquigarrow$ 108 kW elec.



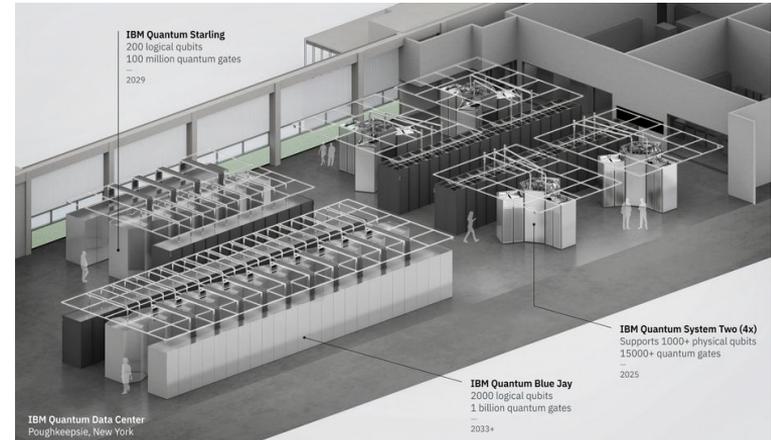
⇒ $280\text{W}@4\text{K} + 5\text{ kW}@45\text{K}$
⇒ 1 350 kW elec.



Liq. Helium based architecture with a single cryoline
⇒ $850\text{ W}@4\text{K} + 2\text{ kW}@70\text{K}$
($1050\text{W}@4.5\text{K}$) ⇒ 350 kW elec.

Opportunities of scaling-up of cryogenics for Quantum

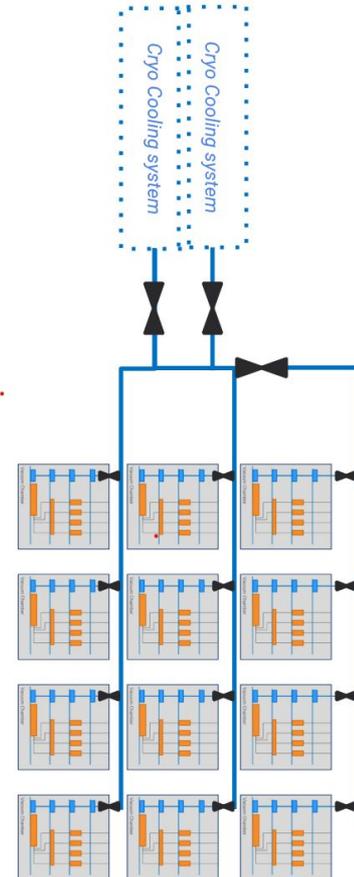
- Reliable and proven solutions exist at small scale and for R&D needs
- But important to anticipate scaling to serve future end-user needs with :
 - **Efficient** architecture thanks to REX on scientific instrument (like CERN) and industrial cryogenics (Liquid Helium Production)
 - **Continuous improvement** on cabling/signal transmission (inside and between cryostats)
 - **Integration** constraints inside a Quantum Data Center
 - Adequate **cold power interfaces**
 - **More industrialised** cryo-plants for digital market
- These developments can serve other future cryogenic applications (fusion, superconductivity for electricity transport, ...)



What are the technical challenges to overcome to develop an industrial system architecture ?

- Technical Challenge #1 : **Efficient and reliable centralized helium refrigeration unit**
Meeting industry (IT) expectations regarding reliability and energy efficiency
- Technical Challenge #2 : **Cryogenic circulation and distribution system**
Ensuring optimal interfacing between the distribution and usage points (connections, thermal links) while considering the operational constraints of the cryostats
- Technical Challenge #3 : **Connection of the objects to be cooled to the fluid distribution system => Functional interface modules** compatible with quantum integration
- Technical Challenge #4 : Cabling adapted to centralized and rackable architectures
Incorporating solutions specifically designed for quantum applications

A new cryogenic architecture to meet the unique requirements of quantum computing is required



CRYONEXT - French Program for Quantum Cryogenics

⇒ **Quantum National Strategy / ANR Program** - 34 M€ during 6 years involving 16 academic partners and 14 industrial stakeholders through 7 projects

- Project 1 - Cryostat Farm and new cryogenic architectures
- Partners : CEA, CNRS, Air Liquide, Radiall, Viqthor
- End user community : Quantum start-ups and industry
- Status of the Program :
 - Phase 1 : Closed (Roadmap preparation)
 - Phase 2 : Go/NoGo nov. 2025 (R&D activities)
 - Phase 3 : Go/NoGo beginning 2028 (Demonstrator production)
- In present Phase 2, 3 main parts :
 - Capitalization (Cryogenics, data center) and Specification / Use case
 - Design and qualification of key techno-bricks and architectures
 - Pre-Development of a demonstrator



**Test infrastructures at
CEA & CNRS**



Technical challenge # 1

Reliable and Efficient Helium Refri. Unit (HeRU)

=> TCO (Invest. Costs + Operation Costs + Maintenance Costs)
 => a good way to evaluate and developer the right solution

- Solution PTG**

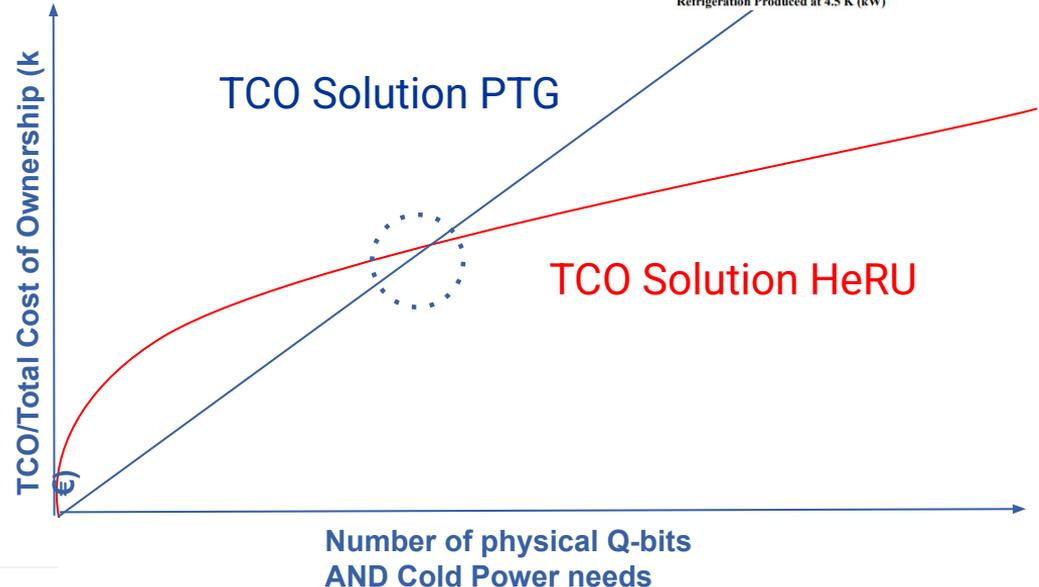
Nb PT (CAPEX) +
 Elec. Consump (OPEX)
 Maintenance costs
 ~ α nb physical Qbits

Total Cost Ownership

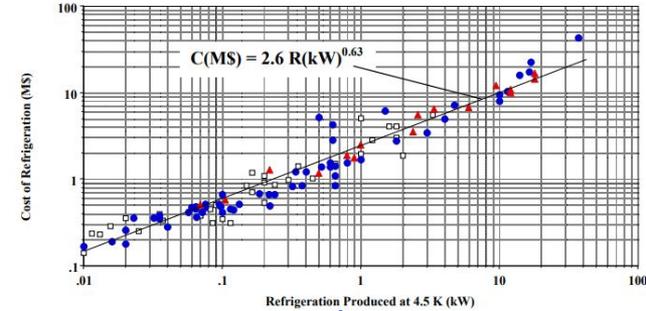
- Solution centralized HeRU**

HeRU Cost (CAPEX)
 Elec. Consump (OPEX)
 Maintenance costs ~ non linear
 + HeRU efficiency is improved with cold power

Total Cost Ownership



Source : M. Green - AIP Conf. Proc. 985, 872–878 (2008)

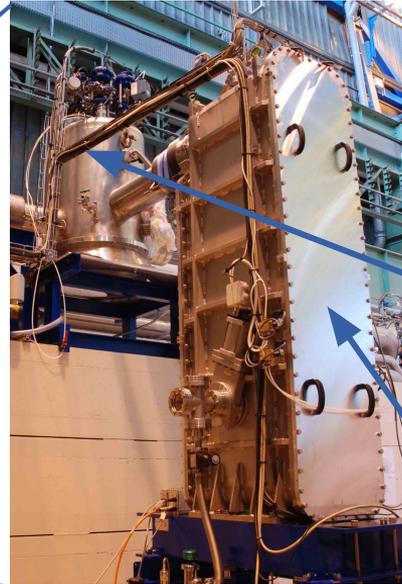
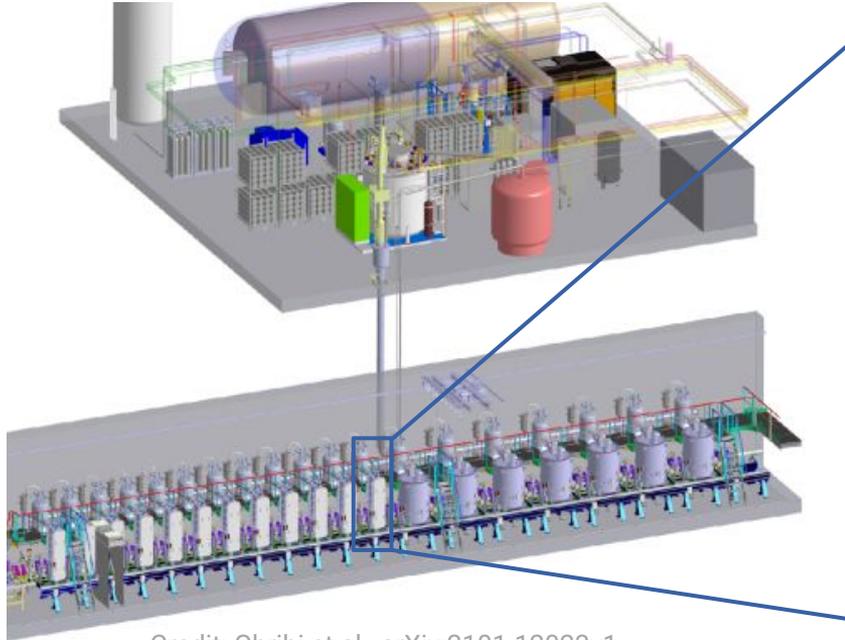


Technical challenge # 2

Cryogenic distribution and circulation system inspired from scientific infrastructures

Psi-quantum configuration

Example of Linear distribution system with LHe : Spiral2 (GANIL) with 19 cryostats with 19 Distribution Boxes (DB) and a single Multi-Cryoline



Distribution Boxes (DB) with valves, PSV, Pressure, Temperatures

Application Cryostats :
Single or multiple Cryostat for Cavities, Magnets or Quantum Computers

Credit: Ghribi et al., arXiv:2101.12023v1

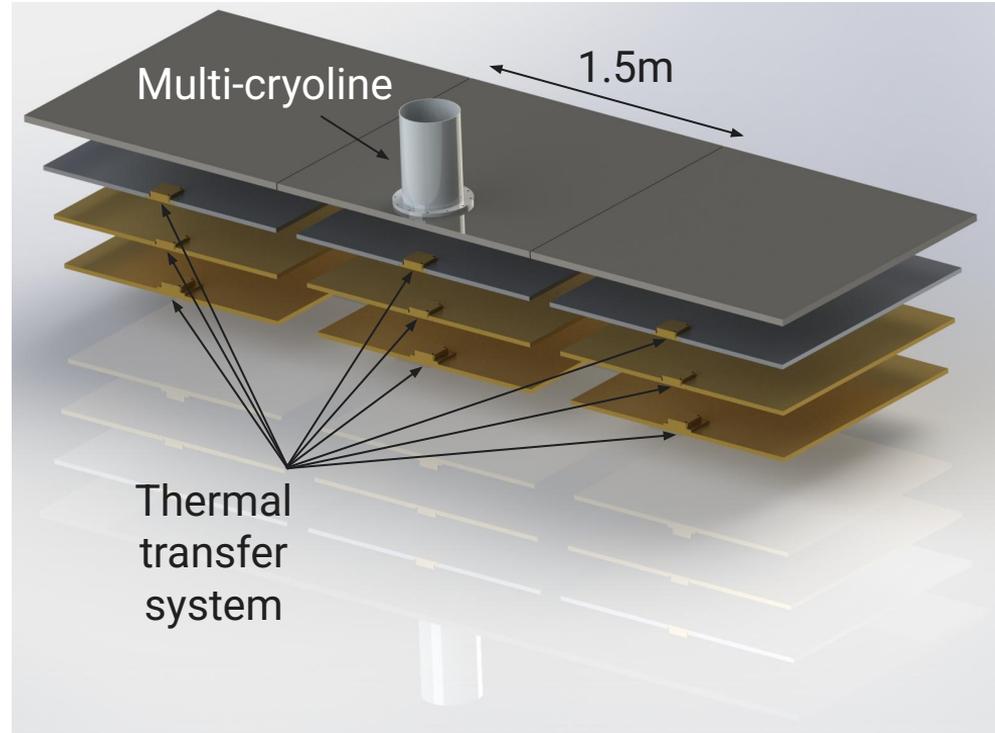
Technical challenge # 3

Cryostat connection to Cold Distribution System

Develop/qualify interface thermal transfer systems to provide the required cooling powers at the desired temperatures with a very small spatial footprint and compliant to the cryostat integration.

Inspired by the experience of scientific instruments, different complementary configurations have been identified and will be evaluated by the partners :

- Supercritical Helium Circulation
- Thermosiphon bath
- Two-Phase Circulation/Bath



Technical challenge # 4

Wiring suitable for centralized and rack-mounted architectures

As with cryogenic scientific experiments, the final solution must be **designed in an integrated manner**, and the cabling is part of the solution.

- Scaling up of cryostat farms: need for **dense, modular, low-dissipation wiring**, suitable for centralized and rack-mountable architectures.
- Development of **highly integrated RF/DC harnesses**, designed for industrial integration and optimized distribution within cryogenic farms." "These harnesses could be co-distributed with the cooling lines, facilitating cluster architecture (cryoclusters) and maintenance.
- Additional contribution on cryo-compatible optical interfaces, in support of future needs for photonic readout or synchronization.



Program summary : Scaling-up and make cryogenics operational for quantum technologies

A situation

Low Temperature Cryogenics :

- Key for quantum technologies
- Mostly Lab level
- No real integration effort
- Energy intensive

Needs

I. Integration of proximity cryogenics of quantum computer

II. Architecture and overall efficiency

III. Smart Operation

Objectives

Development of smart Exchanger to bring cold at the user

Co-dev with cabling, cold electronics specialist and chip integrator

Smart refrigeration processes (Transient, stable and degraded modes)

Efficient machines

Systemic approach

Ultra-efficient Transfer lines

Co-dev with end user (plug and play, coupling, control software)

Cold as a Service

Thanks to :

- **Cryonext French Program**
- Partnerships with other enabling technologies
- End-users

Conclusion

- ★ **High interest to envision He cryogenic system for scale-up**
 - Efficiency
 - Compactness
 - Reliability

- ★ **Development program (Cryonext in France) in place to address key scale-up challenges collaboratively between academics and companies for end users**

- ★ **Results of these developments will serve also other fields (Science, Fusion, Electricity transport, HPC Data Centers)**



Thank you Q&A