CERN Quantum Communications activities

QUANTUM TECHNOLOGY INITIATIVE

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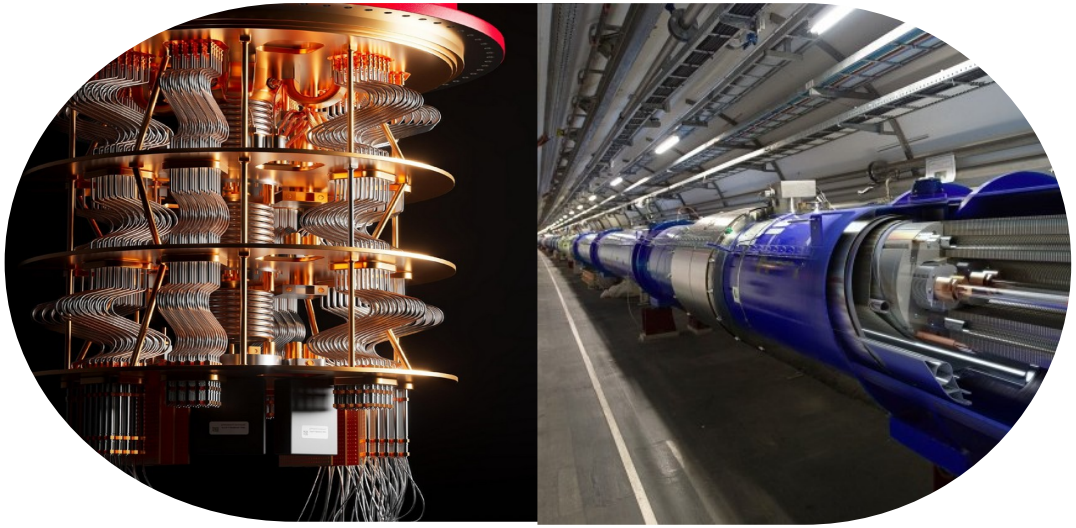
ISGC 2024 – Taipei TW
28th March 2024

CERN engagement in Quantum Technologies



QT4HEP

Develop technologies required by the CERN scientific programme

Integrate CERN to future quantum infrastructures

HEP4QT

Extend and share technologies available at CERN

Boost development and adoption of QT beyond CERN

CERN Quantum Technology Initiative (QTI): Phase 1, 2021-2023

Voir en français

CERN meets quantum technology

The CERN Quantum Technology Initiative will explore the potential of devices harnessing perplexing quantum phenomena such as entanglement to enrich and expand its challenging research programme

30 SEPTEMBER, 2020 | By Matthew Chalmers

The AEgIS 1T antimatter trap stack. CERN's AEgIS experiment is able to explore the multi-particle entangled nature of photons from positronium annihilation, and is one of several examples of existing CERN research with relevance to quantum technologies. (Image: CERN)

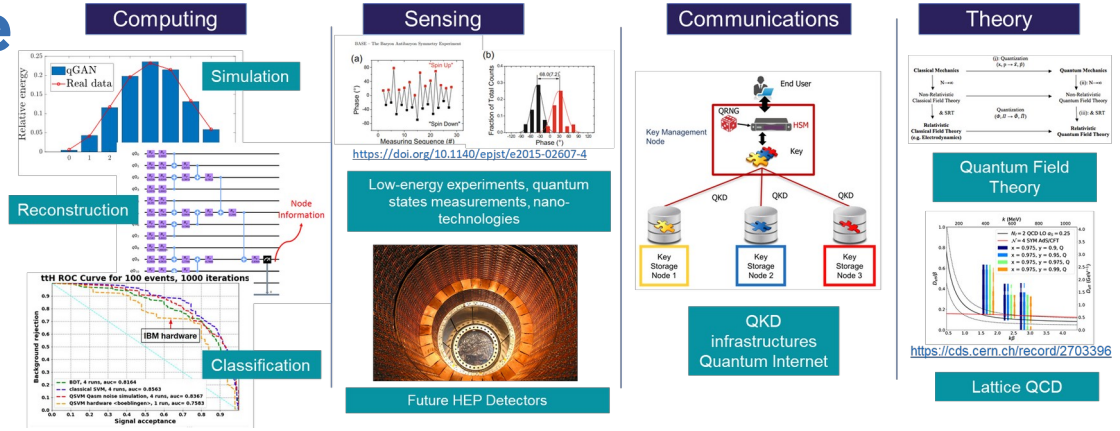
Main objectives

- Identify areas where CERN can make an impact
- Understand impact of quantum technology on CERN programme
- Collaborate with quantum initiatives in the CERN Member States
- Facilitate the collaboration across the HEP community the Quantum tech. community

QTI Roadmap:
https://doi.org/10.5281/zenodo.5553774

QTI1: An exploratory initiative

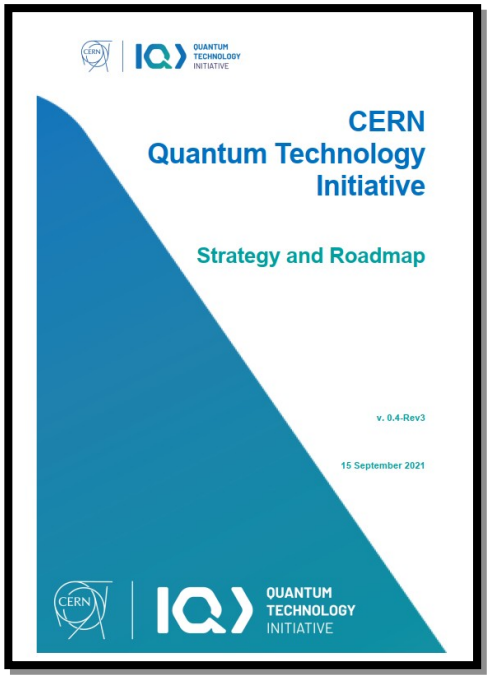
- Quantum simulation and HEP theory applications
- Quantum Computing
- Quantum Sensing
- Quantum Communication



CERN QTI Strategy and Roadmap

Developed at the beginning of the QTI Phase 1 with the CERN community and international experts. Reviewed and endorsed by the QTI AB Members and announced at the SPC and Council in September 2021. Formally published in September 2021 (https://zenodo.org/record/5846455#.ZFEwU4JBy4Q)

Four main high-level objectives covering science, technology, and collaboration, with detailed sub-goals



T1 - Scientific and Technical Development and Capacity Building

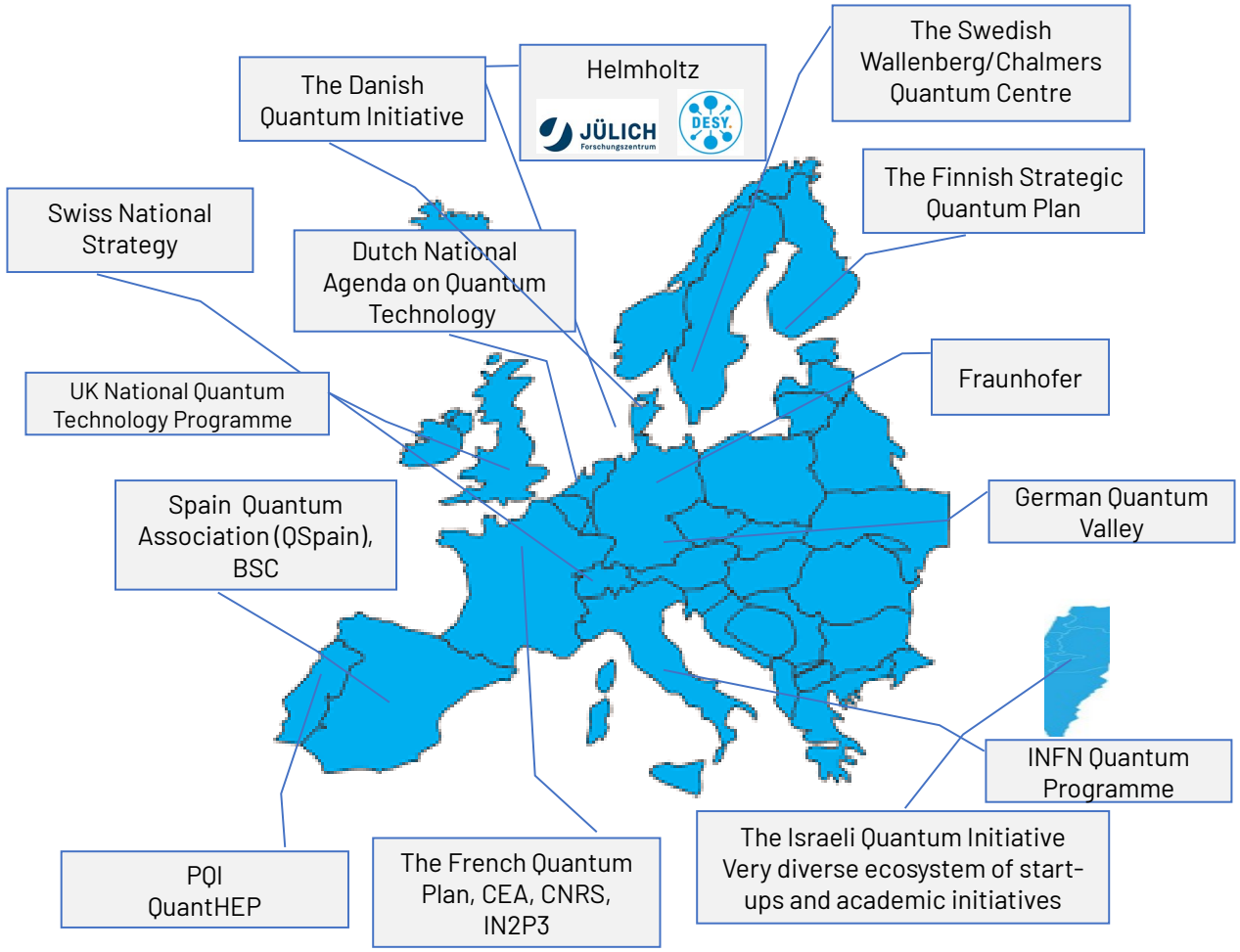
T3 - Community Building

T2 - Co-development

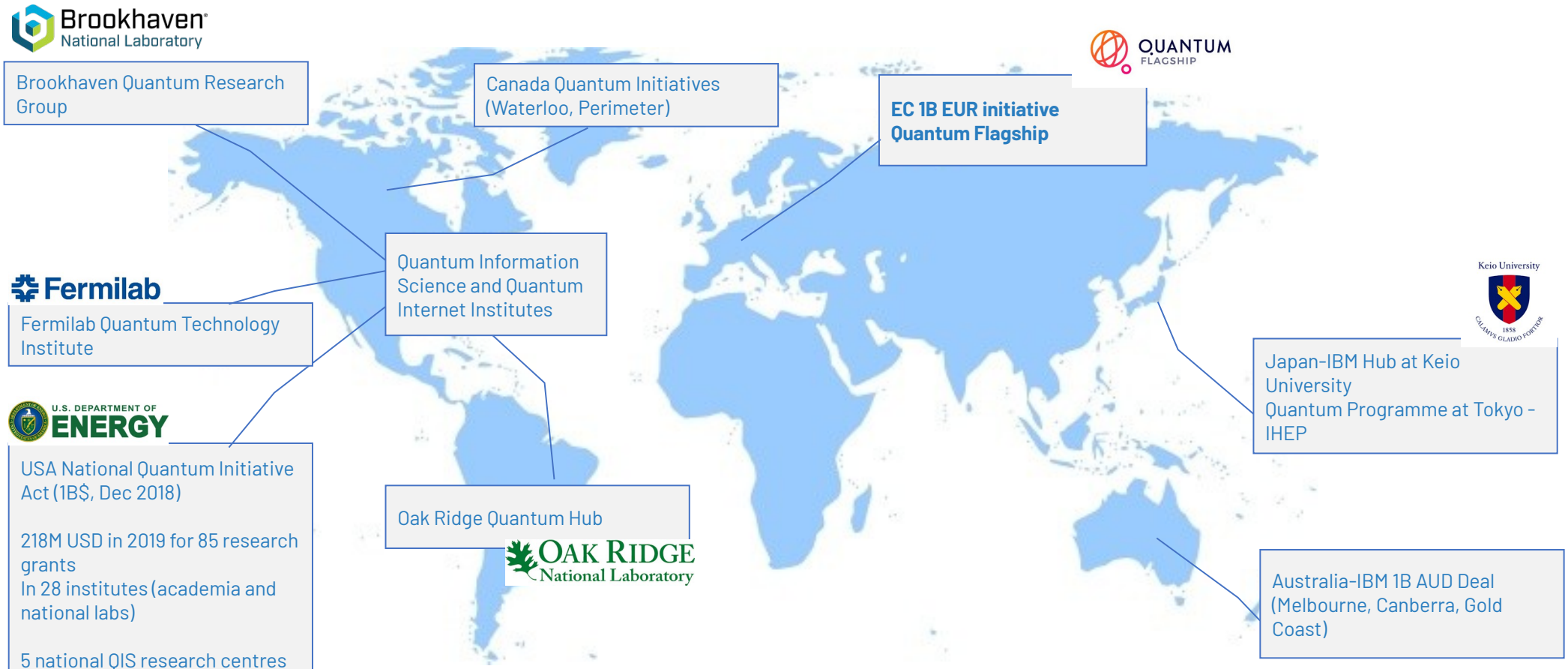
T4 - Integration with national and international initiatives and programmes

Alignment with Member States Initiatives

- Established relations with many initiatives, research labs, universities, companies in the Member States and beyond
- Liaised with national initiatives based on existing connections and through the expert **Advisory Board**
- Presented the QTI to international initiatives, including the European Quantum Flagship and similar initiatives in other Countries
- Set up joint collaborations and common programmes with entities in the Member States (all projects have at least an external participant)

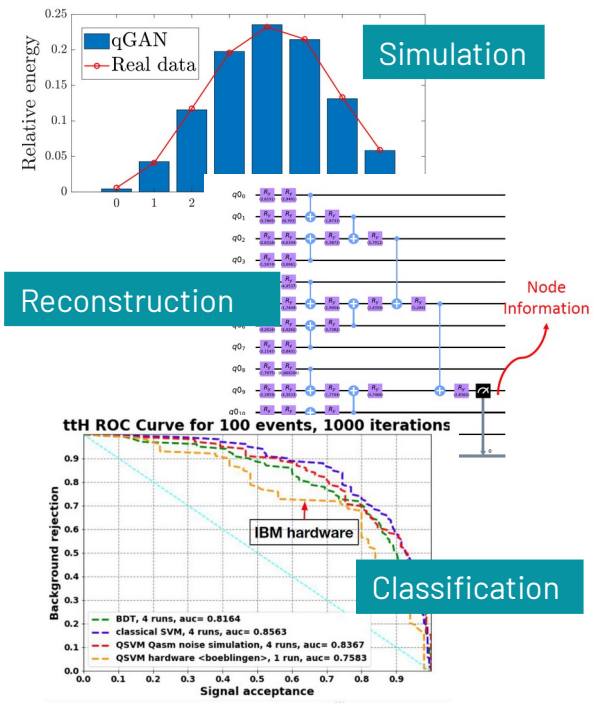


Alignment with Worldwide Initiatives and Investments

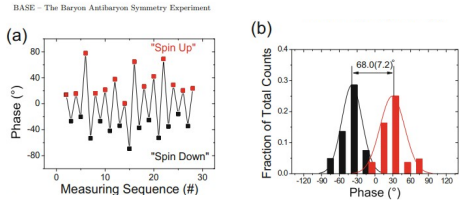


Areas of Investigation

Computing

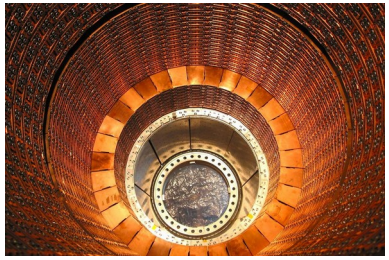


Sensing



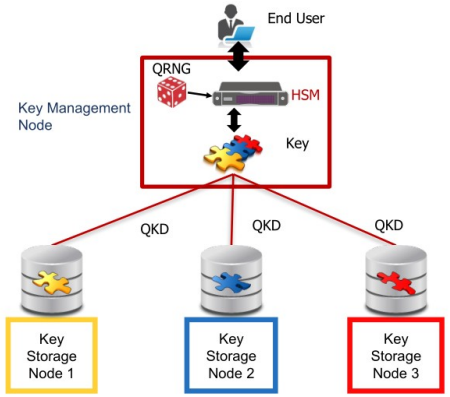
https://doi.org/10.1140/epjst/e2015-02607-4

Low-energy experiments, quantum states measurements, nano-technologies



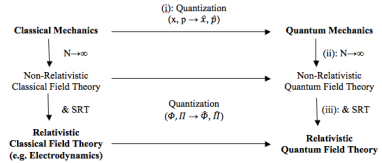
Future HEP Detectors

Networks/Comms

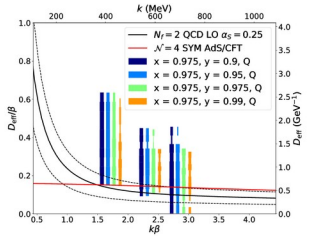


Quantum networks, QKD applications

Theory



Quantum Field Theory



https://cds.cern.ch/record/2703396

Lattice QCD

Many pilot projects already started as part of the **CERN openlab quantum** programme (https://openlab.cern/quantum)

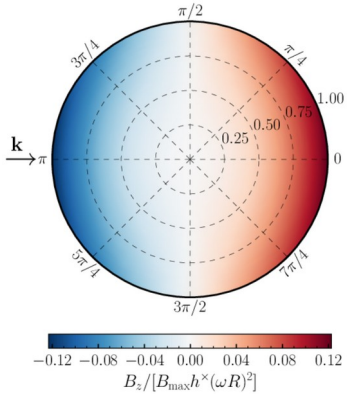
Initial results (I)

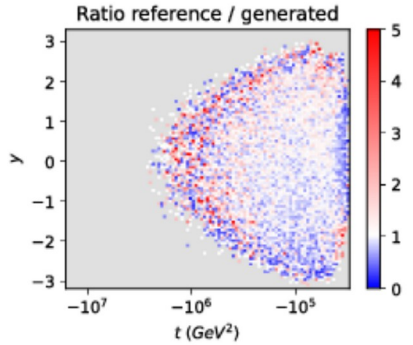
Quantum Theory and Simulation

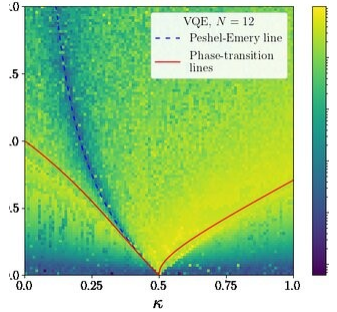
- QC applications to LQCD scalability (small lattices, long range)
- Quantum sensing for atom interferometry of GW and DM
- Atomic clocks for new physics searches

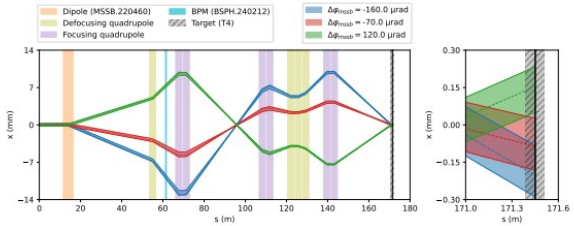
Quantum Computing and Algorithms

- Quantum algorithms for event generation, detector simulation, data processing
- Characterization of different classes of algorithms for robustness, noise behavior
- Quantum computing infrastructure (simulators and devices) to support all CERN projects









Initial results (II)

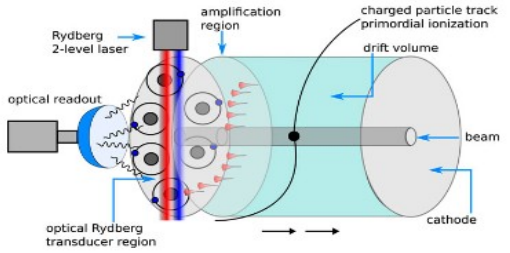
Quantum Sensing, Metrology and Materials

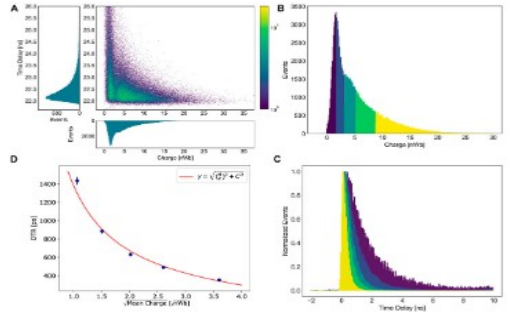
- Quantum dots with different nanomaterials and embeddings
- Procedures to transfer graphene layers nanostructures for gaseous detectors
- AMO-based DAQ and experiment control systems (AEgIS, ArtiQ) achieving dramatic speed-up in working procedures and automation

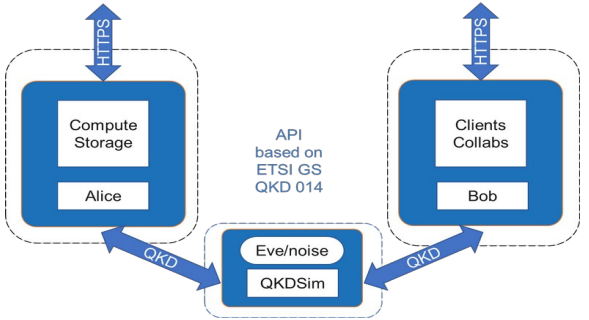
Quantum Communications and Networks

- A Quantum Key Distribution simulator with noise and attacks simulation
- Applications of QKD protocols to distributed data analysis with end-to-end privacy
- Tests on QKD hardware and fibre links

Figure 5







History and timelines

The QTI2 proposal

Capitalise on the achievements of Phase 1 to lay the foundation for a realistic programme focused on “centres of competence” in areas of existing, recognised CERN strengths and strategic objectives

Define objectives integrated in CERN’s existing scientific programme that support both CERN research and (future) operational goals while contributing to general QT development (QT4HEP and HEP4QT)

Keep building on the collaboration with and support of the Member States to grow capacity and competitiveness in quantum technologies by co-developing and sharing results

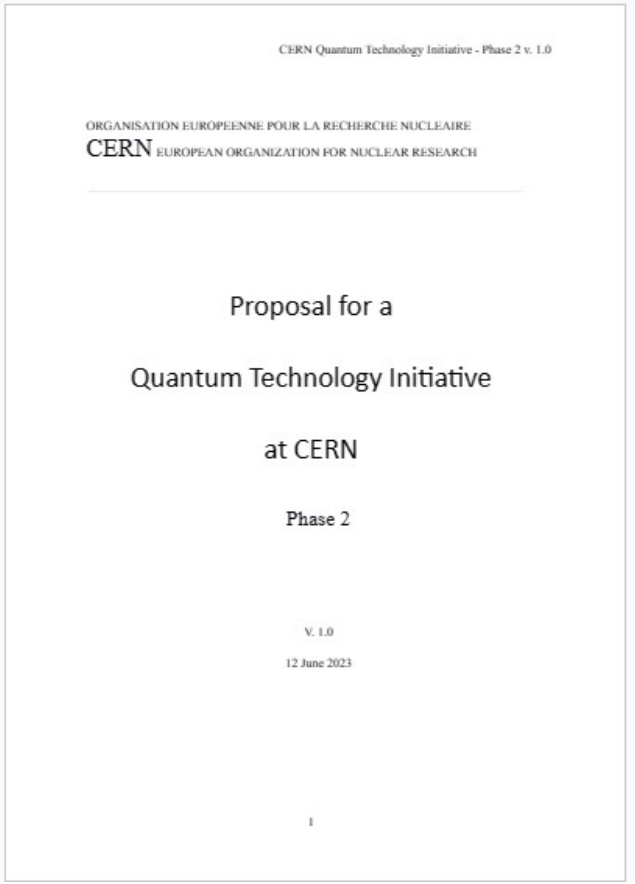
Attract collaborations, partnerships, investments to move the technology forward in visible, impactful directions for applications in HEP while supporting a range of scientific, industrial, and societal applications.

The QTI2 factsheet

QTI 2

- Designed in H1 2023
- Formally approved in June 2023
- Start date: January 2024
- Duration: 5 years
- CERN Departments: IT, EP, TH, BE, EN, SY, IPT

- Total budget: 10M from CERN, 5M from complementary projects and initiative


CERN Quantum Technology Initiative - Phase 2 v. 1.0

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal for a

Quantum Technology Initiative

at CERN

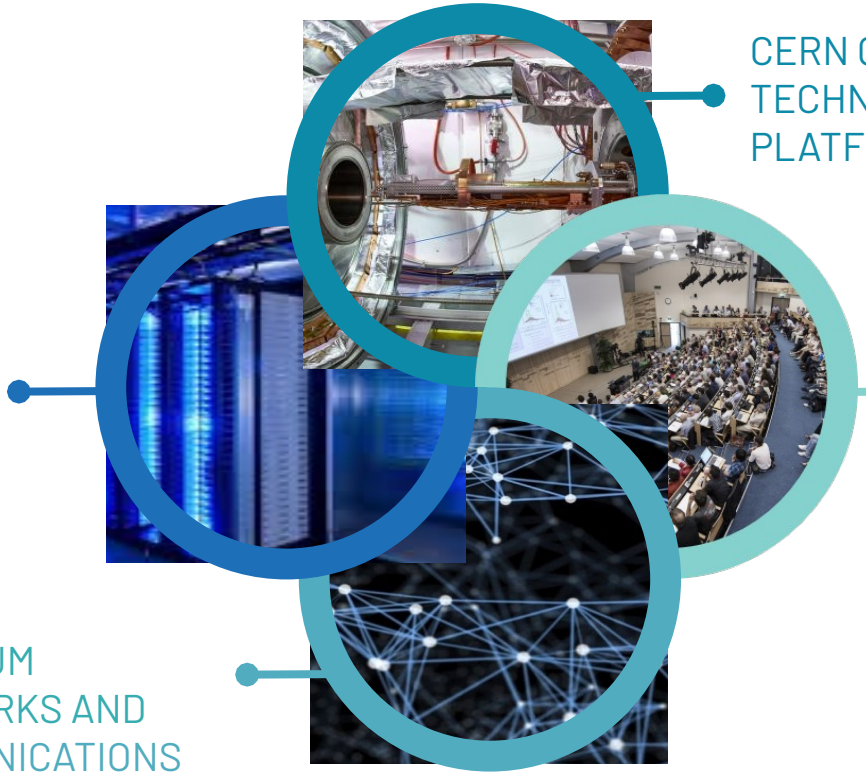
Phase 2

V. 1.0

12 June 2023

1

QTI2: four Centres of Competences



CERN QUANTUM TECHNOLOGY PLATFORMS

HYBRID QUANTUM COMPUTING AND ALGORITHMS

COLLABORATION FOR IMPACT

QUANTUM NETWORKS AND COMMUNICATIONS

CERN | QUANTUM TECHNOLOGY INITIATIVE

CC1: Quantum Computing

Lead: IT department
Participants: TH, EP, LHC experiments, BE (accelerators operations)

Activities

- Integration in the EU and US HPC+QCS infrastructures
- Development of hybrid classic+quantum algorithms for theoretical and experimental physics in collaboration with TH, EP and the LHC experiments
- Simulation of high dimensional classical / quantum systems (with TH)
- Software stacks for quantum devices calibration and control systems
- Investigations of distributed quantum computing, resource optimisation, green quantum computing

Expected results (What)	Expected impact (Why)
Agreements and joint development with EuroHPC, EuroQCS centres and technology providers	Facilitate CERN participation in the establishment of the future HPC/Quantum infrastructures in the Member States. Ensure HEP requirements are taken into account and supported
Contributions to and support of the development of classic/quantum algorithms for HEP/Particle Physics use cases	Classic/Quantum algorithms represent a considerable paradigm shifts in simulation and data analysis, algorithms, libraries, common tools, and skills need to grow over time
Contributions to the characterisation of algorithms and noise models for different qubit implementations	Quantum computing is an early stage technology where CERN skills and scientific approach can have a significant impact

CC2: Quantum Sensors

Lead: EP (Experimental Physics) department
Participants: TH, EN, SY

Activities:

- Exotic atoms and ions as qubits and Dark Matter sensors
- Atomic and nuclear clocks as sensors for new, feeble interactions
- Cryogenics and RF cavities for axion and Gravitational Wave searches
- Development and characterisation of multi-qubit systems with superconducting cavities, ion traps and isotopes
- Quantum sensors for millicharged particles and for HEP
- Quantum data acquisition

Expected results (What)	Expected impact (Why)
Development of innovative technologies for different CERN programmes (BSD searches, physics beyond colliders, GW, etc.)	Quantum technologies are opening new lines of research with great potential to go beyond the current state of the art. This QTI CC consolidates several activities in a coherent programme
Co-develop and adapt CERN technologies as building blocks of quantum devices	Promote and exploit CERN know-how, contribute to growing quantum capacity in the Member States in areas of unique value, demonstrate CERN excellence

CC3: Quantum Communications

Lead: IT department
Participants: IT, BE (Control systems, White Rabbit)

Activities

- CERN Quantum Network Hub and exchange point setup, quantum networks and time/frequency synchronisation protocols
- Deployment of experiments and applications for time distribution, frequency dissemination, quantum interferometry, support for quantum key distribution, and distributed quantum computing

Expected results (What)	Expected impact (Why)
Update and upgrade the CERN network infrastructures to carry time, frequency, and quantum signals	Time and frequency distribution networks are a top priority of many scientific research strategies including Particle Physics, CERN needs to support future programmes
Support the deployment of distributed experiments using the T/F/Q signals	Co-develop and validate the network and protocol layers with experiments to ensure it is "fit-for-purpose"
Establish CERN as a node of the future distributed European quantum infrastructure in collaboration with relevant international initiatives (GEANT, EuroQCI) and national institutes	Ensure CERN keeps being part of the development and deployment of distributed infrastructures for science

CC4: Collaboration

Lead: IT department
Participants: CERN, GESDA

Activities

- **Outreach and education**
  - OQI has an explicit mission of promoting outreach and education around the use of quantum computing for science and society. This is supported the long tradition of the CERN School of Computing, the CERN openlab Summer Student Programme and many other recognised activities
- **Science and technology collaborations**
  - The OQI will support up to 20 demonstrators across the world of how quantum computing can accelerate solutions for high-impact challenges. The IT Department provides overall project portfolio management and the coordination of the relations with quantum computing providers.

CERN QTI Phase 2: Quantum communications

QUANTUM
NETWORKS AND
COMMUNICATIONS

Quantum Network Infrastructures

CERN has traditionally been the lead in the design and deployment of network infrastructures for the HEP community in the past 20+ years, both locally and as part of the worldwide LHC grid

CERN was part of early quantum networks experiments already 10+ years ago

There is a strategic and practical interest in taking part in the ongoing international network deployment initiatives to build the future network infrastructures able to carry quantum, time and frequency signals

Much work is already being done by European and international network providers, both nationally (national metrology institutes) and internationally (GEANT, the EU QCI initiative)

Quantum Communications and CERN

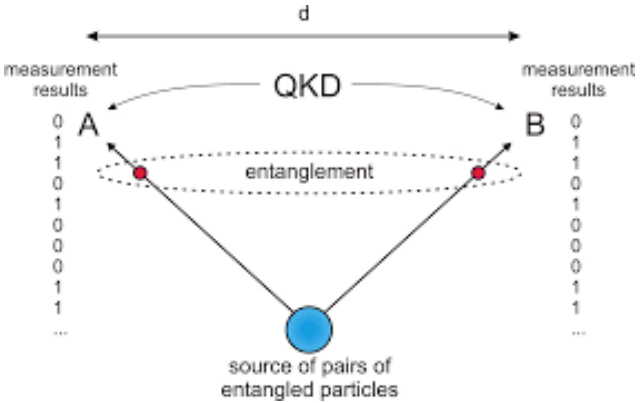
John Bell was a theoretical physicist at CERN when he published his work on Bell's inequalities and the Bell's Theorem in 1964

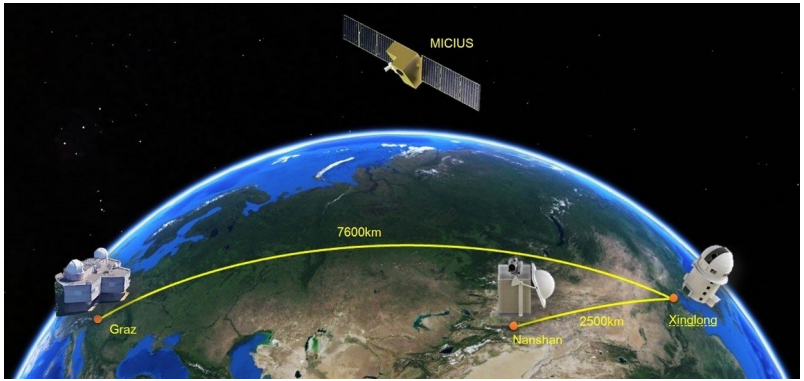
- A test of the "spooky action at a distance"

Work on extending the distance of range of quantum communication channels already had CERN involved 2009-2011 as part of the SwissQuantum project

Research in QTI 1 at CERN focused on:

- Building expertise in quantum infrastructure technologies (mainly QKD)
- Generation and distribution of quantum random numbers for simulation, security, etc.
- Laser technologies
- Experimental and theoretical work on quantum optics





Time and Frequency Distribution Networks

Interest in Time and Frequency Distribution networks is currently much greater for the HEP community than QKD, although the physical requirements of the network are very similar

The QTI 2 program focuses explicitly on setting up this type of capability

Requests for providing T&FDN is not new, it has been discussed for a few years now, but until now it was not possible to have the necessary resources allocated

More recently however the HEP community has started large-scale initiatives to go beyond the state of the art in generating and distributing ultra-precise clock signals for future dark matter experiments

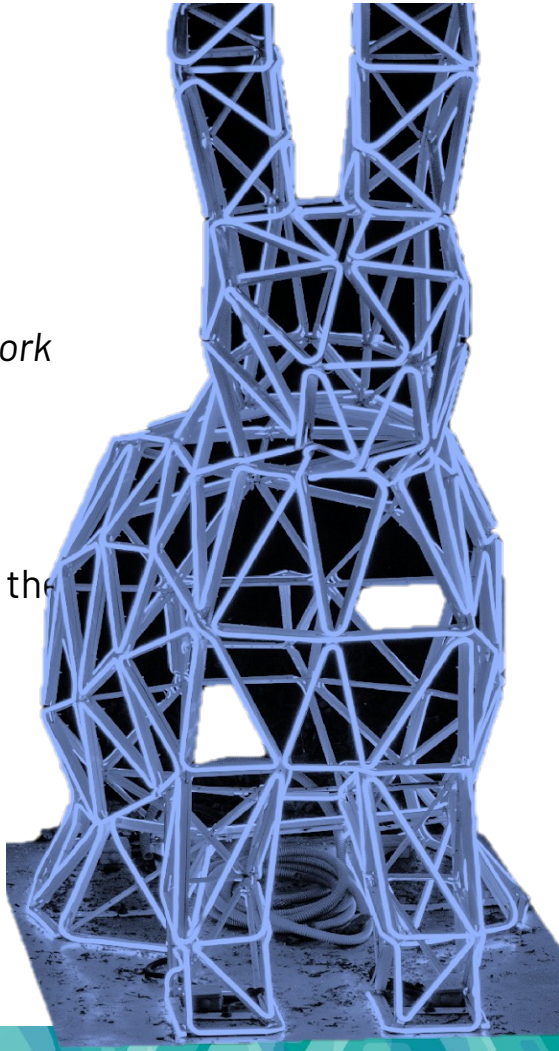
Unique CERN expertise

White Rabbit technology for time synchronisation in a network

Future ***time and frequency distribution (for scientific applications and also as part of quantum devices control systems) and quantum networking protocols (****such as entanglement swapping and teleportation) require, in many cases, the nodes of the network to be synchronised to picosecond level. CERN's White Rabbit technology is well suited to achieve this [1].*

Discussions with companies such as **Creotech (PL)** and **BT (UK),** and with National Metrology Institutes (such as **SYRTE (FR)**, **INRiM (IT), METAS (CH)** and **NIST(US)**) about the use of White Rabbit for the control plane of quantum networks.

Joint R&D projects as part of the future **White Rabbit Collaboration.**



[1] https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=934604

CC3 Quantum Network Hub for Research

- CERN Quantum Networks and Communications Hub setup;
- development of protocols for time/frequency distributions and synchronisation, absolute time references;
- support for deployment of experiments and applications requiring precise time distribution, frequency dissemination, quantum interferometry, quantum key distribution; support for quantum-safe communications;
- support for hybrid and distributed quantum computing

Objective 1

Set up the CERN Quantum Networks Hub

Quantum Key (QKD), Quantum Communication

- set up a test environment, to gain experience with required network capabilities and equipment
- use of White Rabbit for key synchronization
- interconnect with other NRENs Quantum networks

Optical Time and Frequency Distribution

- identify experiments needing it, reach them with optical connections connect to metrology institutes in Europe. GEANT is planning an European network and is interested in a collaboration

Objective 2

Deployment of experiments and applications

Deployment of a service with appropriate SLAs where CERN can act both as a producer of time and frequency signals and as a consumer, and the provisioning of such service to supported experiments

As part of a larger infrastructure involving European and national metrology institutes and network providers

Start with neighbouring countries (Switzerland, Italy, France)

Time-Frequency Network Project Proposal

GEANT Time and Frequency Network

- The CLONETS-DS (CLOck NETwork Services - Design Study) project has completed and published its findings

- CLONETS-DS recommended the building of a European-wide time-frequency network

- GEANT Time and Frequency Incubator has explored using GEANT funds for this purpose

- Goal of GN5-2 funding: Prepare a GEANT funding proposal to build a core time-frequency network (C-TFN)

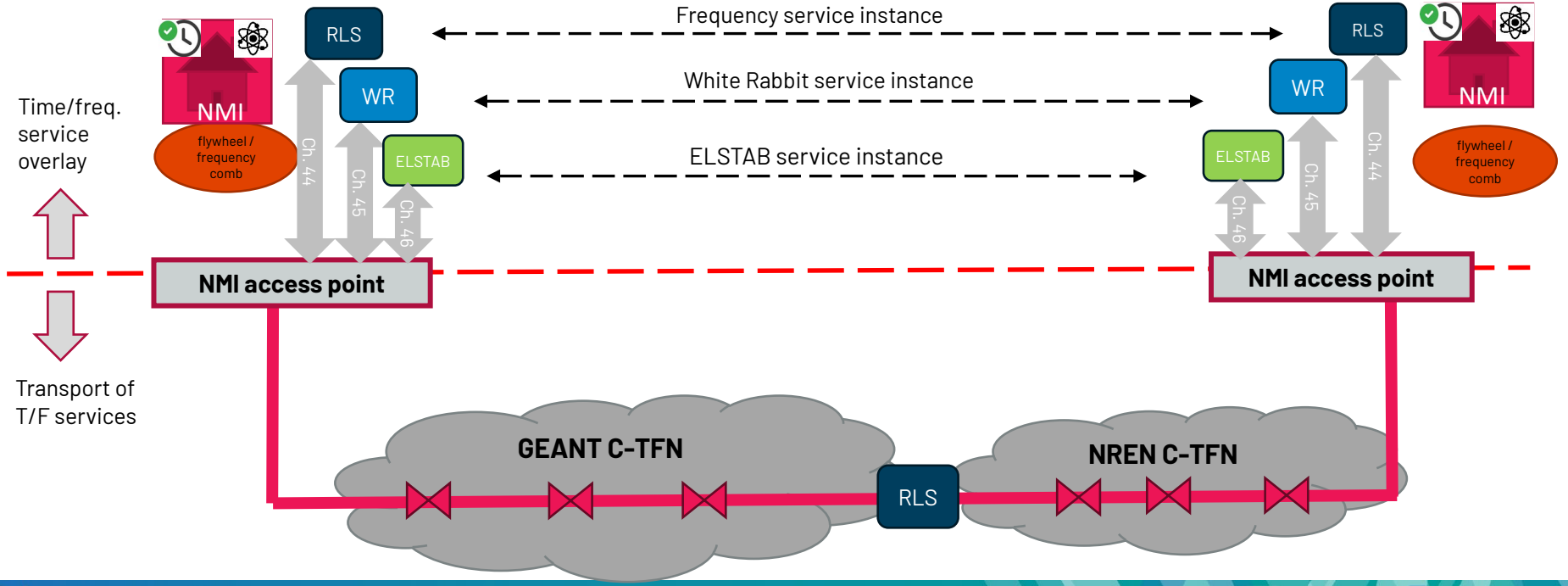
Transport layer vs. time and frequency layer

NMIs

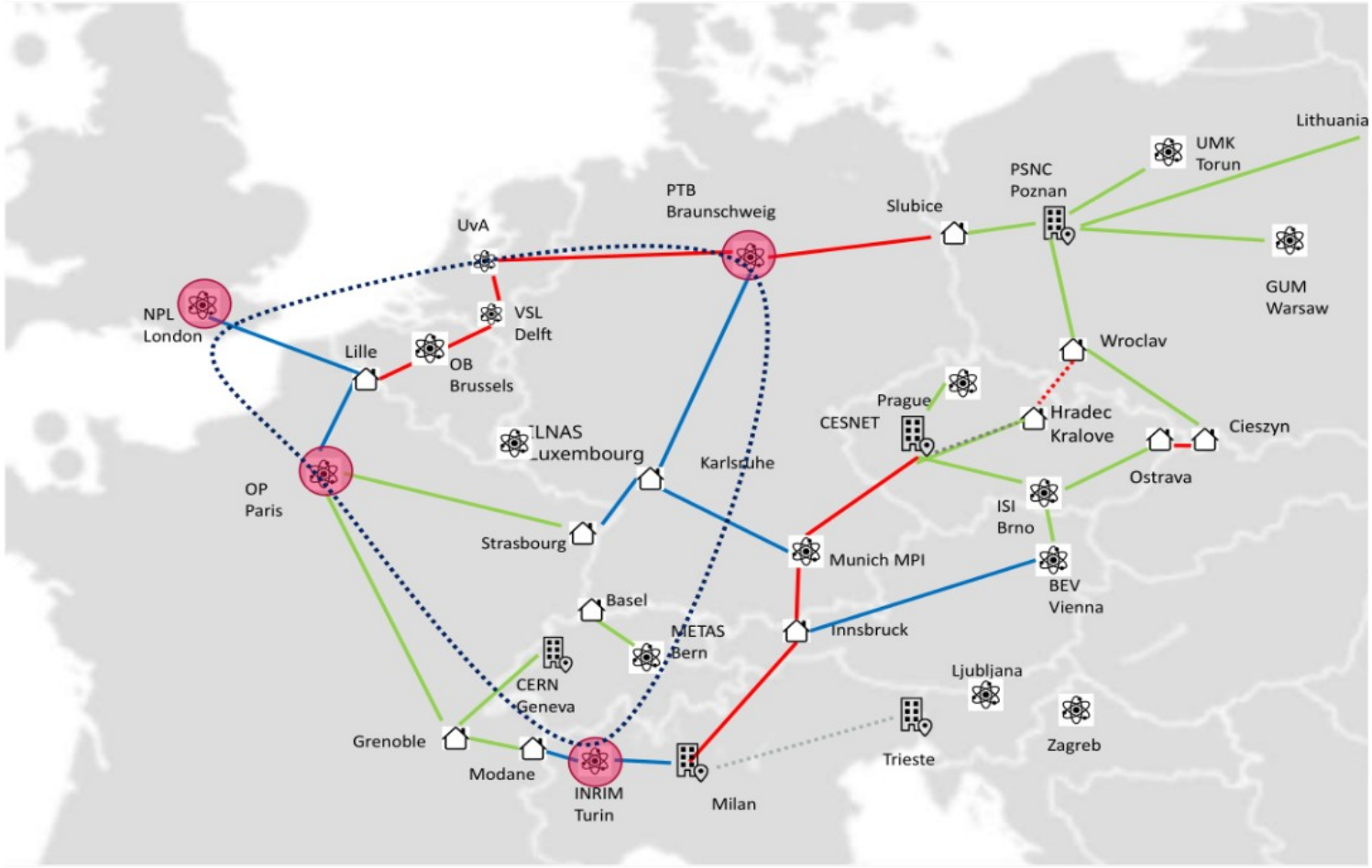
- Build, own and operate the T/F equipment: Flywheels, counters, frequency combs
- Retain ownership of time/frequency
- Generate and measure time/frequency
- Terminate T/F services

GEANT, NRENs

- build, own and operate transport links: fibre, amplifiers, access points, intermediate RLS
- Provide a service to NMIs to carry T/F services



Proposed solution



Solution:

- Red lines are proposed for GN5-2
- These will interconnect national 'islands' of frequency networks
- Support redefinition of the SI second
- Primary users are national frequency reference providers
- Secondary users are research institutes that connect via their national frequency provider

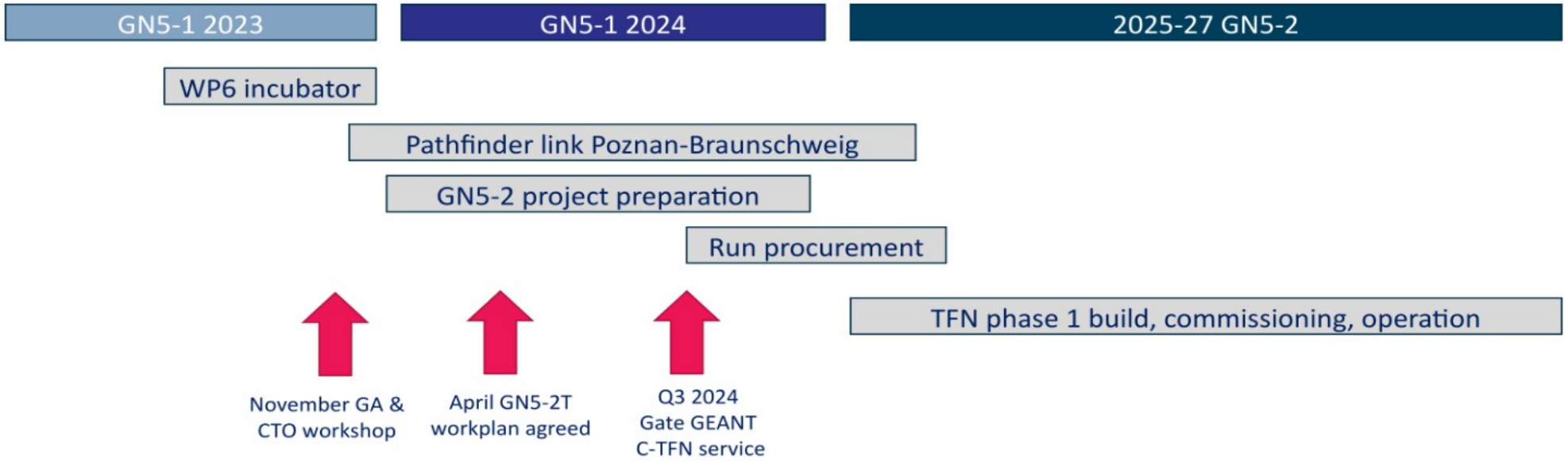
NMI Frequency reference

Research institute

Hut for housing RLS

Work phases

- May-Dec 2023: Incubator study
- Jan 2024 to June 2025: Pathfinder link
- Jan 2025- July 2027: Build TFN Phase 1
- After July 2027: TFN Phase 2 (funding not yet identified)



Open Quantum Institute

OQI
Open Quantum
Institute

An initiative hosted by CERN, born at GESDA, supported by UBS

OQI Open Quantum Institute

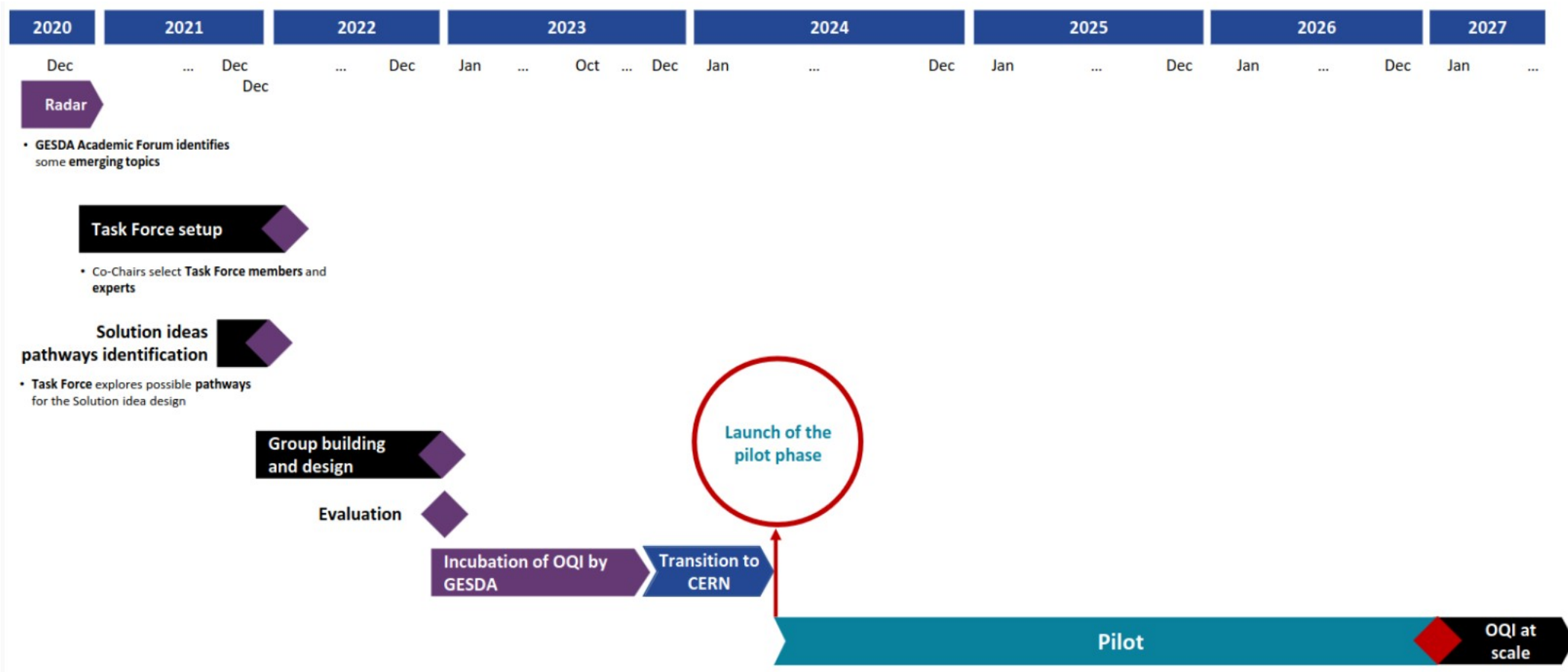
A new, three-year CERN-based programme that will make quantum computing resources and technical expertise available to projects designed to support the UN's Sustainable Development Goals (SDGs).

Hosted by CERN, the OQI has been designed by the Geneva Science and Diplomacy Anticipator (GESDA) in collaboration with some 130 experts and will be funded by UBS as lead impact partner. The announcement of the three-year pilot phase was made on 13 October during the 2023 GESDA summit and the programme will be fully embedded into CERN's wider Quantum Technology Initiative (QTI) as of 1 March 2024.

The OQI will be, de facto, the societal arm of the QTI

The overarching goal of the OQI is to find ways to enable quantum computing to have the widest possible societal impact by promoting and facilitating access to quantum computing resources and technical expertise. Through the OQI, cutting-edge nascent technologies will also become available to people from underserved regions, thus contributing to reducing a possible new digital divide.

OQI timeline



OQI goals

Activating multilateral governance for UN's SDGs

Providing a neutral forum to help shape multilateral governance of quantum computing for the Sustainable Development Goals

Access for all

Providing global, inclusive and equitable access to a pool of public and private quantum computers and simulators available via the cloud

Advancing capacity building

Developing educational tools to enable everyone around the world to contribute to the development of quantum computing and make the most of the technology

Accelerating applications for humanity

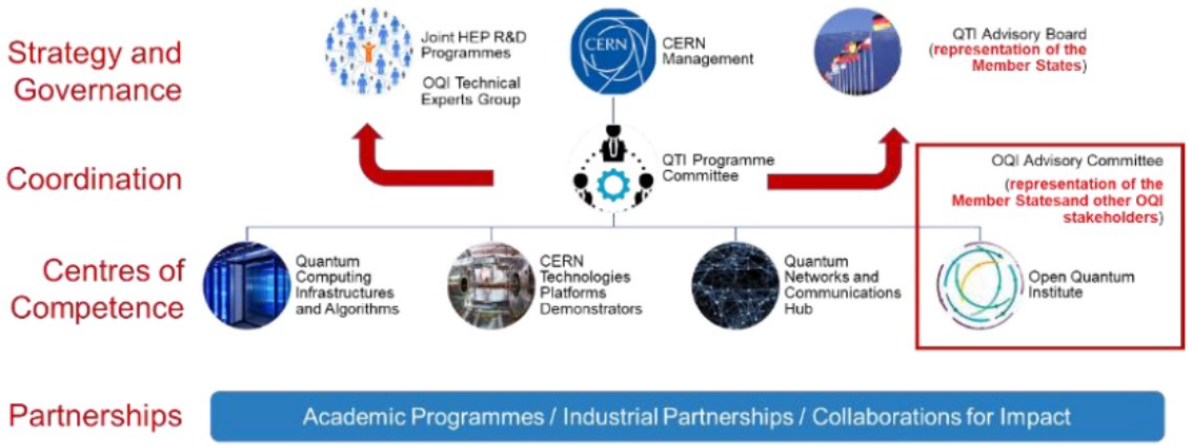
Realising the full potential of quantum computing by accelerating the use cases geared towards achieving the SDGs, thanks to the combined forces of researchers and developers, entrepreneurs, the United Nations, and large NGOs.

Hand-over of OQI to CERN

Overarching values and principles of CERN

CERN's core values are: integrity, commitment, professionalism, creativity and diversity

CERN is committed to the advancement of science and the wide dissemination of knowledge by embracing and promoting practices making scientific research more open, collaborative, and responsive to societal changes



CERN's goals include:

- To be a politically neutral voice for science, advocating investment in fundamental research and evidence-based policy
- To train a new generation of scientists and engineers
- To inspire and nurture scientific awareness in all citizens

Conclusions

Summary

QTI phase 1 successfully completed
QTI phase 2 has just started and will concentrate on Quantum Computing, Sensors, Communications, Outreach

Quantum Communications objectives:
- T&F distribution for Quantum communications and QKD using White Rabbit
- Quantum Communication hub
- Partner of GEANT Time and Frequency distribution network

QTI is in charge to deliver the Open Quantum Institutes objectives

References

QTI: https://quantum.cern/

OQI: https://oqi.gesda.global/

CLONETS-DS: https://clonets-ds.eu/

Questions?

QUANTUM
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