CERN
Quantum Technology Initiative

Strategy and Roadmap

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1 Executive Summary

Quantum technologies have the potential to revolutionise science and society as early as the next five to ten years but require resources that are not mainstream today. CERN can be at the forefront of this revolution, setting up collaborations within the Member States, as well as international initiatives. Through such endeavours, we can work to develop new computing, detectors, and communications systems, in addition to advancing knowledge of quantum systems and fundamental physics. The Quantum Technology Initiative is based on more than two years of pilot collaborations and investigations — primarily in quantum computing — related to possible applications that are core to activities in high-energy physics (HEP).

Over the past few years, knowledge and technologies have evolved considerably; dedicated support for research and development in quantum technologies has become part of national and international research agendas. The time has come for CERN to engage more formally with such activities. Thanks to its role in HEP and more broadly in European and international scientific research, CERN has compelling requirements for its future instruments and infrastructures, which represent very valuable application use cases. This puts CERN in a unique position to catalyse interests and investigations to act as a hub for innovation and knowledge creation and sharing, and to have a long-lasting impact on applying quantum technologies to high-energy physics (HEP) and beyond.

The CERN Quantum Technology Initiative has defined a medium- and long-term roadmap and research programme in collaboration with the HEP and quantum-technology research communities. Together, we will establish joint research, educational and training activities, set up the supporting resource infrastructure, and provide dedicated mechanisms for exchange of both knowledge and technology.

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2 Motivations and Opportunities

Quantum technology is an emerging field of physics and engineering, which relies on the principles of quantum physics. It is about creating practical applications — such as quantum computing, quantum sensors, quantum cryptography, quantum simulation, quantum metrology or quantum imaging — based on properties of quantum mechanics, especially quantum entanglement, quantum superposition and quantum tunnelling.

Over the past 20 years, since the emergence of the concept of quantum technologies (QT)[1], quantum technologies have made great strides: they have gone from laboratory experiments to becoming a multi-disciplinary field of research and development in science and engineering. In particular, the last five years have seen a tremendous acceleration driven by advances in quantum computing and the potential it can offer in the acceleration of complex computing problems, in some cases even enabling computational solutions for the first time.

Today, quantum technology can be organised into at least four main domains of R&D and applications relevant for HEP and other sciences:

Quantum Computing and Algorithms

Quantum effects, such as superposition and entanglement, can be used to build devices that increase the computational efficiency of the solutions to certain classes of computational problems beyond the limits achievable with classical systems based on logical bits. The range of problems that can potentially be addressed goes from

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[1] Gerard J. Milburn, Schrodinger's Machines: The Quantum Technology Reshaping Everyday Life, W H Freeman & Co. (1997)

optimisation and simulation to novel applications of machine and deep learning. However, such problems have to be reformulated to exploit the nature of quantum devices and new algorithms designed to work with today NISQ computers and future fault-tolerant systems.

Quantum Theory and Simulation

Well-controlled quantum systems are used to simulate or reproduce the behaviour of different, less accessible many-body quantum phenomena, thanks to the reduction in computational complexity offered by quantum devices[2]. Complex theoretical physics problems that are not reachable today with classic computational approaches within and beyond the Standard Model of Physics could be tackled by future quantum computers, but also by alternative classical simulation methods developed in quantum information science, i.e. tensor network methods able to attack simulation with sign-problem.

Quantum Sensing, Metrology, and Materials

The high sensitivity of coherent quantum systems can be used to design new classes of sensors. Detectors ranging from instruments measuring nanoscale local information to devices relying on planetary-scale coherence can significantly improve precision and enable new measurement protocols. Ion and particle traps, crystals, and new nanomaterials can open the way to increasingly efficient quantum devices.

Quantum Communication and Networks

Single or entangled photons and their quantum states can be used to implement provably secure communication protocols across fibre-optic networks, or, potentially, quantum memory devices able to store quantum states. Applications range from

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[2] Richard Feynman, Simulating physics with computers Int. J. Theor. Phys. 21 467 (1982)

security and privacy to future distributed quantum computing infrastructures and quantum internet.

Besides these four main domains of R&D, cross-cutting areas are emerging that bring together elements of more than one domain, potentially supporting a wide range of scientific and technological applications. For example, quantum software and algorithms — or a combination of quantum sensors, network software and communication protocols — can be brought together to create potentially very precise, large-scale detector systems.

The move from devices that only rely on quantum mechanics effects (e.g. lasers, semiconductors, imaging devices, etc.) to devices that allow manipulating and controlling those effects to perform computations or design communication protocols has recently been defined as the "second quantum revolution"[3]. The potential of this revolution has triggered a flurry of national and international initiatives to fund and perform scientific and technology research.

Detailed lists of high-level international initiatives are available in many publications[4]. Among the significant examples of particular relevance to CERN Member States and the LHC experiments collaborations are Europe's Quantum Flagship initiative (https://qt.eu/) and its Strategic Research Agenda (SRA) released in March 2020[5]; the QuantERA Programme[6]; the UK National Quantum Technology Programme[7]; the German Quantum Technology Programme of the Government (BMBF)[8], Fraunhofer[9],

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[3] Lars Jaeger, The Second Quantum Revolution: From Entanglement to Quantum Computing and Other Super-Technologies, Springer (2018)

[4] https://iopscience.iop.org/journal/2058-9565/page/Focus_on_quantum_science_and_technology_initiatives_around_the_world

[5] https://qt.eu//app/uploads/2020/04/Strategic_Research-_Agenda_d_FINAL.pdf

[6] https://quantera.eu/

[7] http://uknqt.epsrc.ac.uk/

[8] https://www.quantentechnologien.de/

[9] https://www.fraunhofer.de/en/research/key-strategic-initiatives/quantum-technology.html

Helmholtz Association[10], and other German centres; the French Quantum Plan[11]; the Dutch National Agenda on Quantum Technology[12] implemented through the Quantum Delta NL programme[13]; the quantum technology agendas launched by the Foundation for Polish Science[14]; the Hungarian National Quantum Technology Program (HunQuTech[15]); the US National Quantum Initiative[16]; the Russia Digital Economy National Program for Quantum Technologies[17].

A number of joint collaborations are already being created across the HEP community, such as the German-Canadian Helmholtz network for quantum computing, hosted at DESY and TRIUMF laboratories. CERN has in place several pilot investigations and projects with leading academic and research centres and industry. It also supports the creation of national quantum initiatives with statements of interest and direct advisory roles, as for example the US National Quantum Institutes programme.

Companies such as Atos, IBM, D-Wave, Google, Honeywell, or Microsoft are setting up collaboration between industry and academia to promote and speed up research and applications of quantum technologies. Emerging start-ups bring innovation in all aspects of quantum technologies, from quantum algorithms and software, to sensors, cryogenic technologies, and quantum repeaters.

CERN's challenging scientific research programme could benefit greatly from the application of quantum technologies. For example, such technologies could play an important role in supporting the design of new sophisticated types of detectors, or in

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[10] https://www.helmholtz.de/en/research/quantum-technologies/
[11] https://www.gouvernement.fr/en/quantum-plan
[12] https://quantumdelta.nl/TUQ/wp-content/uploads/2020/04/NAQT-2019-EN.pdf
[13] https://quantumdelta.nl
[14] https://www.fnp.org.pl/en/;
[15] https://wigner.hu/quantumtechnology/en/node/1
[16] https://www.congress.gov/bill/115th-congress/house-bill/6227
[17] https://www.nature.com/articles/d41586-019-03855-z

accelerating the computing workloads of the physics experiments and developing models to explore physics beyond the Standard Model (BSM).

Furthermore, the broad range of specialised technical expertise found at CERN, puts the laboratory in a unique position today to take a prominent role in the development of quantum technologies in almost all of its core domains, not only for its own research programmes but also as a general contribution to the advancement of science and technology.

To prepare for such a possibility, it is necessary for CERN to organise a comprehensive R&D and academic collaboration programme beyond the initial best-effort explorations, covering the different needs of the Organization and the HEP community.

To implement such a vision, the **CERN Quantum Technology Initiative was established in September 2020** to structure and coordinate collaborative R&D, innovation, and education activities with the HEP community and with the many international public and private initiatives within its Member States and beyond.

3 The CERN QTI Strategy and Roadmap

3.1 Main Objectives and Expected Results

The CERN QTI Roadmap defines and guides the activities of the Initiative during its first three years and lays the foundations for a continuous programme of R&D and collaborations for the mid- and long-term. The strategy is based on four top-level objectives:

> ### *T1 - Scientific and Technical Development and Capacity Building*
>
> Quantum Technologies are a relatively recent field of research and development with promising potential to support fundamental research at CERN and for the HEP community. To define and materialise such potential, **a programme of focused R&D projects will be established** to identify the areas where quantum advantage can be reached over time, quantify the expected impact on HEP research, and highlight where CERN and HEP scientific knowledge and technology needs to be further developed in collaboration with the international community.
>
> *Expected results*: creation of a quantum computing infrastructure of resources, tools, knowledge, and collaborations; creation of quantum computing skills in the HEP community, identification of areas of potential quantum advantage; development of new detection and algorithmic approaches for typical HEP problems.
>
> *Ways to measure impact*: number of collaborations between CERN and Institutes in the Member States and beyond; scientific publications; progressive adoption of new methodology as part of the HEP R&D activities (both experiment and theory).

T2 - Co-development

Quantum technologies are a strategic asset in scientific, industrial and social agendas of CERN Member States and beyond. Innovation and competitiveness in the development of new efficient technologies and the growth of competences and knowledge are a critical objective. The design, development, and exploitation of **enabling technologies** is a fundamental component of future innovation. **CERN will work in close collaboration with academic and industrial partners to exploit its knowledge and technologies in unique areas** such as applied quantum algorithms, quantum state sensors, cryogenics, electronics, optical devices and photon sources, and computing networks, further develop such technologies and enable an efficient transfer of knowledge from research to industry.

Expected results: knowledge creation and transfer from CERN into applications and products; creation of joint projects, start-ups, and public-private collaborations.

Ways to measure impact: number of companies and laboratories in the Member States and beyond having agreements with CERN to develop new IP assets and exploitable results; exploitable assets released under open source or open access licences.

T3 - Community Building

Research on Quantum Technologies is a multi-disciplinary field where computer science, mathematics, engineering, application experts must interact and work in close collaboration to enable innovation. CERN has traditionally played a fundamental role in building and supporting international collaborations across diverse communities. **The CERN QTI will actively promote collaboration and organise activities to support community building through a variety of**

means, such as technical events, education opportunities, technical dissemination, publications, etc. **CERN will play a reference role in building a quantum technology community within HEP**, but also provide opportunities for exchanges with other disciplines and areas of application. **It will provide a neutral ground of collaboration across and beyond Member States, promoting open international collaboration** for the advancement of quantum science and technology.

Expected results: increase collaboration and knowledge in the community in the field of quantum computing; support the evolution of education and professional development programmes to include quantum technology skills.

Ways to measure impact: number of events; number of people reached; number of collaborations in education and training activities.

T4 - Integration with national and international initiatives and programmes

Although CERN and the HEP community have been developing quantum technologies for many years as part of their fundamental research programmes, the specific focus on quantum technologies as a way of providing more efficient computing devices, more sensitive sensors and detectors, or more secure communication infrastructures is very recent. Many initiatives and funding programmes exist individually in most Member States and at an international level. **The CERN QTI will work in close collaboration with existing and future initiatives and align its activities with international roadmaps and objectives**. This has the two-fold objective of providing opportunities to integrate CERN and HEP objectives in international agendas and to actively contribute to the further development of a broader quantum technology vision for the future.

> *Expected results*: alignment of research and development activities with major priorities and interests of the HEP community and the quantum technology communities in the CERN Member States and relevant international programmes.
>
> *Ways to measure impact*: participation in international programmes; joint projects across and beyond CERN Member States; inclusion in events, publications, and communication channels of other initiatives.

3.2 Quantum Computing and Algorithms

Technology to build computing devices using quantum-mechanical effects has seen a tremendous acceleration in the past few years. Quantum computing uses qubits instead of bits. These are built in a variety of ways, from ion traps and superconducting circuits to impurity spins and linear optical elements.

The promising advantage of quantum computers over classical devices lies in the possibility of using quantum superposition effects of n qubits to perform exponentially growing (2n) computations in parallel. This effect makes it possible to reduce the computational complexity of certain classes of problems, such as optimisation, sampling, combinatorial or factorisation problems.

Over recent years, quantum algorithms, characterised by lower computational complexity than their classical counterparts, have been discovered. Shor’s algorithm, for example, can factor integers exponentially faster than any classical one; Grover’s element search in unstructured databases exhibits quadratic speedup. These algorithms require large scale fault-tolerant quantum computers. However, today we have only access to NISQ hardware dominated by short coherence time (noise), small number of qubits (from a few tens up to few thousands, in the case of quantum annealers) and limited lattice connectivity (in most cases, only the nearest neighbouring qubits interact). Furthermore, the initial simplification that more qubits equate to more performance is being replaced with more realistic metrics that take into account the hardware, software and applications characteristics (such as Atos Q-Score or IBM Quantum Volume).

These limitations have sparked intense R&D towards the design and optimisation of NISQ algorithms that demonstrate quantum advantage over current hardware, intense research on noise mitigation and correction, and hardware-software co-development. Early experiments have shown promise and projected roadmaps for practical quantum computers are moving from being not less than 20 years away to being as close as the next 5 years.

The QTI Quantum Computing and Algorithms roadmap includes the following objectives:

Objective	Contributes to top level objective(s)
C1: Formalise and extend the existing catalogue of use cases and examples of possible applications of quantum computing to HEP workflows and algorithms.	T1
C2: Collect and share information about existing resources, tools, libraries, and collaborations across the community. Set up R&D projects to adapt or design algorithms for quantum platforms and benchmark their current and potential performance.	T1, T3

C3: Identify and coordinate access to computing resources in collaboration with other institutes or companies. Design and deploy a distributed infrastructure for quantum computing and simulation, based on existing distributed computing expertise, to make resources and tools easily accessible to researchers, thus enabling investigations to be performed as part of community projects.	T1, T2, T4

Current and Future Activities

Based on the vision highlighted by the three main objectives listed above, several activities have started or have been planned for the coming years. The first set of activities concerns the **investigations on quantum algorithms for different HEP workflows** (*C1*), focusing in particular on quantum machine learning and direct simulation of quantum systems (in collaboration with the theory area). The second objective (*C2*) is being concretised in a series of projects targeted at **studying algorithms optimisation with respect to quantum hardware features and benchmarking** of the different simulators, frameworks and tools. A third set of activities is directly related to objective *C3* and revolves around the **design of a distributed infrastructure to enable easy access** to computing and simulation resources (quantum and classical).

> #### *Quantum Algorithms for HEP Workloads and Quantum Machine Learning*
>
> In HEP, data is generated from quantum processes. Even after measurement, quantum correlations between the produced particles can be probed by, e.g., studying the angular distribution of their momenta. The angular correlations between the measured momenta of the particles are a direct consequence of the underlying laws encoded in the amplitude, or equivalently in HEP jargon, the matrix

element of the physical process. Theoretically, these amplitudes are computed in the context of the Standard Model of Particle Physics using Quantum Field Theory techniques. The common assumption is that, when designed accordingly, quantum models will be able to naturally deduce these inherently quantum correlations in the data leading to higher model performance with respect to classical models.

Quantum machine learning (QML) could become among the most exciting applications of quantum technologies. However, machine learning algorithms are designed to analyse large amounts of data, and they can be considerably different from commonly studied computational tasks. In a NISQ perspective, the challenge related to data and problem dimensionality is important, at the same time, the definition of a quantum advantage for QML approaches can be redefined beyond the simple acceleration/speed-up. Despite the difficulty related to training a model to convergence in a quantum setup, QML could exhibit higher representational power with respect to classical models, and therefore present an advantage in terms of training sample size and/or final accuracy, especially in particularly complicated scenarios, such as those related to generative models.

For this reason, several projects have been launched to better understand the application of quantum approaches to machine learning for HEP data processing. Examples include signal/background classification problems (***Quantum SVM for Higgs classification, QML algorithms for classification of SUSY events***), reinforcement learning for dynamic optimisation of complex systems (***Quantum Reinforcement Learning for accelerator beam steering***) and quantum generative models for simulation and anomaly detection (***Quantum Generative Adversarial Networks for detector simulation***, ***Quantum Generative Models for Earth observation***, ***Quantum Generative Models for ab-initio calculation of lepton-nucleon scattering***).

In the same context, different projects will investigate the optimisation and adaptation of well-known quantum algorithms, such as Grover's search, to HEP data processing. For example, the project ***Quantum Algorithms for Event Reconstruction*** at the CMS detector (***Q-Track***) is under way and focuses on accelerating, through QC, the TICL framework for HGCAL event reconstruction.

Algorithm Optimisation and Benchmarking

With limited qubit counts, connectivity and coherence times of the present quantum computers, the quantum circuit optimisation is crucial for making the best use of those devices. In addition to the above algorithmic studies, this activity intends to study novel circuit optimisation protocols and error mitigation strategies to exploit at best near term quantum devices. As an example, the project ***Quantum Gate Pattern Recognition and Circuit Optimisation***, has developed an initial protocol, composed of two techniques - pattern recognition of repeated sets of gates and reduction of circuit complexity by identifying computational basis states, that demonstrates a significant gate reduction for a quantum algorithm designed to simulate parton shower processes.

Another critical aspect to achieve the goals described by objective C3 is a systematic approach to benchmarking algorithms, platforms and in the future full-stack quantum systems. This is particularly important given the increasing number of quantum hardware systems and simulators that exist today. They are provided in a variety of open-source, commercial, cloud or on-premises installation mechanisms. The different implementations exploit technologies or architectures that make different algorithms and applications more or less performant, more or less suitable. In this context, the project ***Automated Benchmarking and Assessment of QUantum Software (ABAQUS)*** is intended to design and implement an automated algorithm benchmarking system based on a public database of algorithms, configurations, and platforms. The possibility of sharing such information across a broad community of researchers and creating a "crowd-

> sourced" collaborative platform would ensure a rapid evolution of computer science and technology.

> ***Design of a Distributed Infrastructure for Quantum Computing***
>
> Introducing quantum computing technology in HEP workloads requires a fundamental shift in how algorithms and applications are designed and implemented compared to classic software stacks. Easy access to a variety of hardware and software solutions is essential to facilitate the R&D activity. With the project ***Distributed Quantum Computing Platform***, CERN aims at implementing the key aspects outlined by objective *C3*, namely building a distributed platform of quantum computing simulators and hardware in open collaboration with academic institutes, resources and technology providers; facilitating access to these resources for the CERN and HEP community; contributing to defining and implementing the layers of future full-stack quantum computing services.

3.3 Quantum Theory and Simulation

Richard Feynman is famously quoted for his statement that "Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy." Therefore, it is only natural that physics and HEP are considered an area where quantum devices could make a difference in simulating complex dynamic interactions or multi-body systems.

Many classes of problems used in chemistry, condensed-matter physics or HEP can be simulated by means of well-controlled quantum systems. In HEP, quite a few possible applications have been investigated in recent years, especially in the context of gauge theories and their applications to dynamic problems (e.g. heavy-ion collisions), topological problems (e.g. CP violation), or high-baryon density configurations (e.g. modelling of neutron stars).

One possible approach is to design simulation strategies that apply different techniques, a mix of classic and quantum methods, to different parts of the problems and focus the attention on those areas that are computationally intractable using standard techniques. An example of this approach is the application of quantum circuits to describe the quantum properties of parton showers as a complementary technique to more classical Markov Chain Monte Carlo methods.

Following the call to “make [simulations of nature] quantum mechanical” is not an easy task. Fortunately, many aspects of quantum devices can be understood rigorously using tools already well established in theoretical particle physics. By bringing together theoretical and experimental expertise, CERN has a unique capability to act as a catalyst for breakthroughs in quantum technologies also capitalising on expertise in the CERN Theory Department (CERN-TH).

The CERN QTI Quantum Theory and Simulation roadmap includes the following objectives:

Objective	Contributes to top level objective(s)
I1: Identify possible applications of quantum simulations relevant to HEP, particularly in the realm of collider physics and simulations of the QCD phase diagram, with the aim of supporting worldwide experimental efforts to probe and measure both Standard Model and beyond the Standard Model physics.	T1

I2: Assist the Computing and Sensing activities in identifying theoretically promising regions of parameter space in which quantum technology could provide an advantage over classical methods	T1, T3
I3: Benchmark the current and potential performance of quantum simulations against state-of-the-art classical computations, drawing on the high-performance computing (HPC) expertise of CERN-based lattice QCD experts and the HPC group.	T1, T2, T3
I4: Host workshops, summer institutes and visitors, drawing on the infrastructure and expertise of the CERN Theory divisions with the goal of establishing global collaborations with other institutes, national labs and companies and identifying the quantum technology best suited for the applications at hand	T3, T4

Current and Future Activities

Modern day particle physics is currently at a crossroads, where progress depends on ever-increasingly precise experimental measurements and theoretical predictions. Additionally, with the most-promising extensions of the Standard Model ruled out or heavily disfavoured, there is a massive landscape of possible beyond the Standard Model (BSM) models to test. While quantum technology holds the promise of allowing the HEP community access to previously untested physics, it is not yet clear which quantum technology is best suited for this goal, nor even which open questions in particle physics can be best addressed with quantum methods, instead of classical methods. Objective *I1* of the Theory and Simulation is, therefore, to **provide the theoretical background necessary to make these decisions and start**

identifying the most promising areas of investigation. Objective I2 provides the **natural links between the physics and fundamental science applications and the necessary expected developments from other areas of quantum technologies, such as computing and sensing**, introducing a specific aspect of co-development within the QTI strategy. Realistic assessments of the investigations performed as part of the R&D activities need to be made to monitor progress and **identify the most promising technological areas beyond what is classically possible today or in the near future**. Such activities are the focus of objective *I3*. Finally, collaboration and knowledge sharing represent a critical aspect in this emerging field of research and the organisation of focus, specialistic events must be assured as part of objective *I4*.

Physics Theories Simulation

Quantum field theories, by their nature, are rife with infinities. To connect theoretical predictions from QFT calculations to experimental results, these infinities must be dealt with via a process called regularisation and renormalisation. The only known generic method for doing so non-perturbatively is by implementing the field theory on a lattice, i.e. by discretising space-time. An additional benefit of working on a lattice is that it allows one to simulate the theory on a computer, providing first-principle calculations of the properties of strongly coupled theories, including QCD.

This numerical simulation of Euclidean space-time correlation functions currently provides the only ab-initio method for extracting information about low-energy QCD/nuclear physics, with quantifiable errors. Current lattice QCD simulations allow for the measurement of light hadron masses, scattering parameters for certain few-body scattering events and the spectrum of several light hadrons. However, due to the limitations of Monte Carlo importance sampling, there are many questions that cannot be addressed with these tools, including the nature of the QCD phase diagram, particularly for large nuclear density, the real time behaviour of quarks-gluon plasmas and even the masses of any but the lightest hadrons and nuclei.

The limitations of Monte Carlo also affect our ability to learn about the properties of high-energy QCD, including the structure of parton showers, as seen in LHC collisions. The ***Lattice Gauge Theory Simulation*** project will investigate if and how quantum devices and methods, rather than traditional Monte Carlo methods, may allow many of these questions to be explored. Another area taking centre-stage in physics research today is the **physics of neutrino oscillation** (periodic conversions of one neutrino flavour into another during propagation). The project ***Quantum Simulation of Collective Neutrino Oscillations*** will explore some of the least understood aspects of neutrino oscillations, as for example their dynamics in extreme environments such as supernova cores, where neutrino densities are so high that neutrinos influence each other so that the flavour evolution equations become highly non-linear. As this is intrinsically a quantum mechanical process, the goal of this project is to develop methods for simulating collective neutrino oscillations on a quantum computer.

Applications of Quantum Machine Learning

Quantum machine learning (QML) algorithms are a **promising approach to certain classes of applications in HEP phenomenology and theory**, for example using variational quantum circuits and novel model architectures, which could benefit from the quantum hardware representation. The main motivation behind this planned activity is to identify potential benefits of QML in HEP in terms of performance, precision, accuracy, and power consumption when compared to the current classical state of the art counterparts.

We will target **applications on practical primitives for near-term quantum devices as well as advanced procedures for future, fully-fledged universal quantum computers**. Research activities will include the development of hybrid classical-quantum models based on variational quantum circuit optimisation and data re-uploading techniques, and the identification of new hardware designs which may accelerate QML performance. An important goal of this activity is the joint development of open-source libraries of quantum machine learning models designed for the hep-ph and hep-th applications based on open collaboration across the community. This activity is the natural bridge between the Theory and Simulation area and the Quantum Computing area of the CERN QTI.

Interactions between Theory and Sensing

Many developments stemming from advances in quantum technologies have opened up new parameter spaces for the search for BSM physics, with particular implications in searches for symmetry violations, searches for unknown interactions, searches for ultra-light dark matter particles or fields, and precision determinations of masses or binding energies. In many cases, it is only the availability of a new technology that allows initially exploring, and then subsequently systematically investigating these new parameter spaces, requiring development of dedicated highly sensitive detection schemes. In many cases, technologies relevant to quantum computing (e.g. ion traps, *section 3.2*) or quantum communication (*objective N2*) form the basis of measurements sensitive to new fundamental physics or to violations of symmetries. Reaching ultimate sensitivities often requires scaling such devices far beyond the initial proof-of-principle, an area in which expertise in designing, producing, and assembling large-scale devices — as is the case for high energy particle physics — may become crucial. At the same time, guidance from theory can help identify particularly interesting topics, can help avoid duplication, and can indicate overlap with more sensitive searches that may have been carried out via other technologies (objective *I2*).

3.4 Quantum Sensing, Metrology and Materials

Progress in particle physics relies on appropriate detection techniques, and while for high-energy experiments, a large degree of standardisation has occurred over the last decades, new detector approaches enabled by quantum technologies are increasingly opening up new parameter spaces in low energy particle physics. At the same time, some of these technologies might also allow for higher sensitivity detectors at high energies.

Several attempts to explore the application of specific experimental techniques stemming from the fields of quantum optics, nanocrystals or 2-dimensional materials to experiments in HEP have begun, while collaborations on topics relevant for low-energy particle physics approaches (with implications for BSM searches) in the areas of atomic interferometry, ultrasensitive cryogenic signal acquisition, and calorimetric detection of axions are being looked into.

The CERN QTI Quantum Sensing roadmap includes the following objectives:

Objective	Contributes to top level objective(s)
S1: Encourage the acquisition and dissemination of expertise on quantum sensing in areas specifically relevant to the fields of low- and high-energy particle physics.	T1, T2, T4
S2: Develop a selection of quantum sensing approaches, including small-scale AMO-type experiments, with emphasis on those particularly relevant to low energy particle physics measurements that may benefit from CERN infrastructure.	T1, T2, T4

S3: Identify particularly promising technologies, focusing on a small number of developments with potential specifically for novel applications in HEP.	T1, T2, T3, T4
S4: Set up common R&D projects and coordinate collaboration with other institutes or companies to adapt or develop both the technologies themselves as well as new test systems for quantum sensing approaches and benchmark their current and potential performance.	T1, T2, T3, T4

Current and Future Activities

The goal of developing quantum sensing techniques for particle physics is thus manifold: to **acquire expertise in sensor techniques** that are currently not relied upon in medium and high-energy particle physics (Objective *S1*); to **expand existing and develop novel technologies based on quantum sensors that are relevant to low energy particle physics** and its ability to explore heretofore only partly or not at all covered parameter spaces corresponding to low-mass / low-energy BSM particles or fields (Objective *S2*); and to **explore the possibilities provided by quantum technologies for detector developments relevant to HEP** (Objective *S3*). Given the breadth of technologies and possible approaches as well as of physics targets, **collaboration with a wide range of university and industrial partners** will also certainly be required (Objective *S4*).

As a notable example, **interferometric probes** (ranging from atomic systems to RF cavities to large-scale gravitational wave observatories) are uniquely sensitive to minute perturbations, such as those caused by interactions with dark-matter fields or gravitational waves, and have great potential to greatly enhance sensitivity to, and potentially exploration of, new physics. The development of the technologies required to **scale a number of these systems beyond the state of the art**, or to prepare a next-to-next generation of experiments that might be space-based, would benefit from the engineering experience and infrastructure that has permitted the building of large-scale experiments.

Currently, three ongoing investigations are being set up, as they provide opportunities for possible applications of quantum sensing to HEP environments. Naturally, **all activities involve external networks and their expertise**. Discussions on similar approaches focusing on developments relevant for low-energy particle physics that have a strong overlap with ongoing activities at CERN, such as (anti)atomic physics, nuclear physics, axion searches, have begun, and — as long as they are based on joint ventures with related developments outside CERN — have the potential to expand the particle physics parameter space that can be investigated at CERN.

> ***Graphene-Based Functional Structures and Nanostructures***
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> The first project, which will begin at the end of 2021, investigates Graphene-based functional structures and nanostructures for novel gaseous detectors. The unique properties of two-dimensional materials such as graphene as well as carbon-based nanostructures, including nanotubes, nanowires and quantum dots, offer exciting possibilities for next-generation detector systems, including wide-band photosensors. In the field of gaseous radiation detectors, these materials can be exploited to extend the sensitivity to wide energy ranges of incident radiation, selectively influence charge production and transport processes and extend the longevity in challenging operational conditions. In the context of this doctoral student project in the CERN EP-DT Gas Detector Development team, we propose to pursue next-generation gaseous detector concepts taking advantage of novel materials and nanostructures. The research aims at exploiting graphene and nanomaterials for next-generation gaseous detectors, including broadband

gaseous photodetectors, robust precise timing detectors and graphene-enhanced ion-backflow suppression, which holds great potential for gaseous Time Projection Chambers (TPCs). In addition, potential synergies with other CERN groups working on graphene, Diamond-Like Carbon (DLC) and nanostructures will be explored.

Control Systems for Quantum Optics

The second project (which began at the end of 2020) is porting experiment control systems currently being developed in the field of quantum optics to experimental investigations of possible symmetry violations in neutral atomic systems containing antimatter: antihydrogen, antiprotonic atoms and positronium. The first two systems are only available at CERN's Antihydrogen Decelerator facility, whereas positronium can be obtained from radioactive sources even in small laboratories. For all three systems, studies are ongoing or being prepared, benefiting from anti-hydrogen pulsed formation (2018) and long-lived positronium in Rydberg states (2015) and 23S metastable states (2019). Investigations with pulsed beams of positronium atoms of possible additional interactions, as well as possibly of 3-photon correlations in Ps decays, both using a novel approach (stemming from the field of atomic and molecular optics) for experiment control and data acquisition (Sinara), form the main thrust of the PhD project.

Quantum-Dot-Based Scintillators

There is a great demand today for ultrafast timing detectors, and in particular for scintillator-based detectors. Particle physics experiments running at future accelerator facilities count on such fast-timing detectors to cope with the high-event pileup due to the increase in luminosity and to enable particle identification capabilities. TOF techniques and event tagging with a minimum precision of 30ps can achieve pileup suppression by more than a factor of 10. The improvement of time resolution can be achieved with scintillators with a high photon density. Standard bulk scintillating materials are able to convert energy from high energetic impacts into optical photons at a rate of at most one photon per MeV per picosecond with approximately 50% efficiency which are nonetheless delayed by a rise time of the order of 100ps. This restricts the amount of information available within the first few picoseconds after the particle or gamma has interacted and is governed by the emission centre excited states decaying to their ground states with typical relaxation times of at least tens of ns. On the other hand, direct-band-gap-engineered semiconductor nanostructures show high potential for the emission of prompt photons due to the quantum confinement. In particular, the potential of materials based on semiconductor quantum dots/quantum wells such as CdSe, InGaN/GaN or perovskite nanocrystals (eg. XPbBr3) as scintillator or charged particle tracking for HEP detectors will be explored.

3.5 Quantum Communication and Networks

Experiments with quantum communication devices and protocols are not new at CERN. In 2009, the Organization already took part in the **SwissQuantum project, a public-private initiative to set up and operate over long periods of time a prototype quantum key distribution (QKD) layer**.

CERN plays an important role in regional and European Internet infrastructures at the physical layer. For example, it has hosted the **CERN Internet eXchange Point (CIXP) since 1996**, and it has been a driving force behind the evolution of the regional internet infrastructure. The CIXP is a founding member of the European Internet Exchange Point Association (Euro-IX). Technologies that are core to communications systems, like time synchronization or lasers, have been developed for CERN applications and then moved to other fields.

For the past 20 years, **CERN has played a leading role in the design, deployment, and operations of the Worldwide LHC Computing Grid (WLCG)**, at the base of the revolution that has led to modern distributed computing infrastructures and Cloud computing.

Taking part in technology investigations and supporting the deployment and operations of the future Quantum Internet would not only be a **natural extension of CERN’s current mission** but would also ensure that **CERN continues to play a central role in the future of European and international communication infrastructures**.

The CERN QTI Quantum Communication and Networks roadmap includes the following objectives:

Objective	Contributes to top level objective(s)
N1: Identify and support use cases for specific uses in collaboration with appropriate research and industry partners in area such as security, privacy protection, medical applications	T1, T2
N2: Identify, extend, co-develop CERN technologies relevant to quantum infrastructures, such as time synchronisation and clocks, photon sources, laser technology	T2
N3: Formalise CERN's participation in the pan-European quantum infrastructure, providing operational and technical support	T4

Current and Planned Activities

Investigations of the **potential impact of quantum networks on distributed computing and data analysis workflows** for HEP and other applications is the core of objective *N1*. This includes the co-design and testing of end-to-end scenarios using QKD and other related emerging encryption technologies. Objective *N2* focuses on the exploitation and further development of **technologies developed by CERN for control systems, accelerators operations, material science applications or civil engineering**. By definition, the deployment of international infrastructure requires **alignment and interoperations with network and technology providers, application developers and users**, and concertation in open initiatives. This is the focus of objective *N3*.

Confidential computing

The possibility of exploiting a large number of distributed resources to analyse heterogeneous data, especially for medical or biological applications, is hampered by the fact that often such data contains sensitive information or is protected by policies and usage agreements that do not allow the data to be shared. However, the recent pandemic and the many unsolved health challenges (HIV, neurological and mental conditions, overstressed healthcare systems, just to mention a few) require a **different approach to data collection, sharing and analysis**. Traditional approaches like (pseudo-)anonymisation require compromises between privacy preservation and information-content preservation.

Novel techniques to encrypt the data (such as homomorphic encryption) or move the data across provably secure connections might turn the tide. Projects like openQKD, part of the European Quantum Flagship strategy, and others are investigating the feasibility of large-scale QKD networks. CERN is currently involved in the development of an end-to-end QKD-based secure data analytics demonstrator, ***Quantumacy***, that proposes to advance the application of cryptographic techniques, federated learning and QKD to distributed data processing.

Discussions to set up joint research in this area are now taking place with infrastructure providers, such as GEANT in Europe, and domain experts in industry (IDQ) and research (PSNC in Poznań).

Communications technologies

Several technologies have been developed at CERN over the years to support specific needs of the Accelerators Complex, such as time synchronisation or alignment of physical components along the LHC 27 km path. Such technologies have applications outside their original intent, in particular in quantum computing and quantum communications.

A significant example is the White Rabbit (WR) technology developed at CERN to provide **sub-nanosecond accuracy and picoseconds precision of synchronisation** for the LHC accelerators chain. It was first used in 2012 and since then has been showcasing its diverse industrial applications outside the field of particle physics. In 2020, the Institute of Electrical and Electronics Engineers (IEEE) updated the Precision Time Protocol industry-standard (PTP), incorporating the White Rabbit PTP extension and thus maximising its adoption by industry and other partners in their pursuit to build innovative solutions to address world challenges.

This Ethernet-based technology, which ensures sub-nanosecond synchronisation and deterministic data transfer, is now deployed in numerous scientific infrastructures worldwide. It has shown its innovative potential by being commercialised and introduced into different industries, including telecommunications, financial markets, smart grids, space industry and of course quantum computing and communication. Discussions for further **co-development of this technology specifically for quantum communications** are taking place with industrial and research technology providers.

Another example is the possible applications of **structured laser beams**. A structured laser beam system, developed by a team of CERN surveyors in collaboration with the Institute of Plasma Physics in Prague (IPP), is currently already deployed in communications applications and there is interest in investigating the potential applications in quantum communications. The structured laser beam system is **capable of producing beams that are virtually non-diffractive over several hundred metres**, whereas systems currently available on the market produce such beams over a distance of only a few metres.

4 Coordination and Collaboration Activities

A fundamental objective of the the CERN QTI is to structure and align CERN efforts in quantum technologies with initiatives, activities, projects in the CERN Member States and beyond. Since its very inception, CERN has had a traditional role since its very inception as a hub for collaboration and a cradle for innovation and discoveries. The structure and governance of the CERN QTI have been designed to favour and exploit the large network of existing connections within and beyond the HEP community and to create opportunities to build bridges across different communities.

4.1 Governance

The governance structure of the CERN QTI has been designed to maximise the **integration of bottom-up participation and innovation with top-down guidance**. The Initiative is fundamentally a **research and development effort** to investigate the application of quantum technologies in typical CERN and HEP activities directly involving the researchers and providing direct opportunities for competence building. At the same time, **oversight and guidance** from the HEP community and experts in relevant national and international quantum programmes is needed to ensure alignment and co-development.

Based on these principles, the CERN QTI implements a layer of **knowledge and capacity building** based on joint projects integrated in different CERN departments and experiments and staffed with Doctoral and Post-Doctoral researchers. A **Coordination Team of CERN experts** led by a **Coordinator** sets priorities for projects and collaborations based on the strategy and roadmap described in this document and reports to the CERN Management. The Coordination Team is assisted by a **multi-disciplinary Task Force** providing technical, legal, IP management, and organisational support.

The initiative oversight is provided by an **Advisory Board** of quantum technology experts from the CERN Member States nominated by the CERN Council representatives. **Integration with HEP initiatives** (such as the HEP Software Foundation – HSF, or the European Committee for Future Accelerators – ECFA) is ensured by direct participation of their representatives in the coordination team or task force.

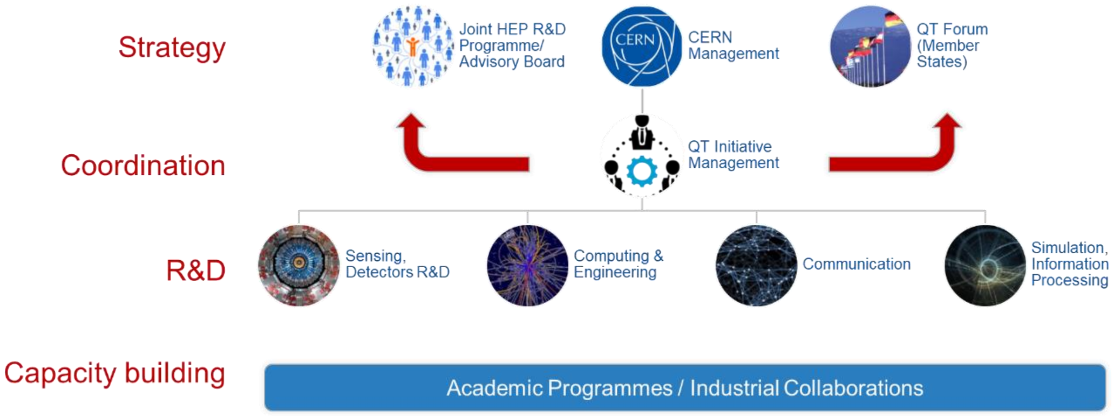

Figure 1: The CERN Quantum Technology Initiative governance model

4.2 Collaborations and Synergies

The CERN QTI has established, and actively seeks to establish, collaborations and synergies with relevant initiatives and bodies at many different levels. Most of the current research projects are run in direct collaboration with academic and research centres and companies in the CERN Members States and beyond, most notably the Quantum Technology Initiative at DESY in Hamburg, University of Oviedo Computer Science Department, ETHZ in Zurich and EPFL in Lausanne, Tokyo University, and more. All current projects are described on the CERN QTI website at https://quantum.cern.

CERN's traditional collaborative culture and the specific position of CERN as an international multidisciplinary scientific research centres put the Organization in an ideal position to act as a hub, an *honest broker*, for knowledge advancement and sharing across communities and to promote broader discussions about the development and use of quantum technologies for science and society.

CERN-wide Collaborations

Within CERN, the CERN QTI capitalises on the existing R&D and collaboration framework provided by the **CERN openlab[18] programme in the Information Technology Department**, where most of the initial investigations in quantum computing at CERN started in 2017. One of the first events on Quantum Computing for HEP was organised by CERN openlab in November 2018[19] with a broad participation of researchers, academia, and industry.

The CERN QTI activities and plans have been presented and are discussed with **scientific and technology bodies within CERN**, such as the EP department *Architects' Forum* and the *Computing Forum* organised by the *Directorate of Research and Computing*.

The **Theory Department** runs specialistic workshops on different relevant topics using, for example, the format of the **TH Institutes**, extended workshops intended to structure the TH visitor programme around topical themes, make the best use of resources, share them with the community, and coordinate the activities with those of other institutes, universities, or research centres. A dedicated TH Institute[20] was

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[18] https://openlab.cern
[19] https://indico.cern.ch/event/719844/
[20] https://indico.cern.ch/event/1015866/

organised in July 2021 to discuss the rapidly advancing field of quantum technology and the role this technology plays in particle physics.

The **CERN Knowledge Transfer Group** is also taking an active part in the CERN QTI, overseeing the identification of CERN technologies that can be used in quantum technologies applications, the management of IP, and the setup of appropriate conditions for technology transfer activities between CERN and third-party entities.

Collaborations with CERN Member States Institutes

To ensure alignment and integration with CERN Member States efforts direct contacts have been established with national quantum initiatives. Initial contacts and discussions have taken place among others with the *UK National Quantum Technology Programme and Quantum Hubs*, with *CEA and CNRS* in France, with the *Helmholtz Association* in Germany, with the *Israeli Quantum Technology Initiative*, with the *Swedish Quantum Centre in Wallenberg/Chalmers*, with the *quantum research communities in Portugal, Poland and Slovakia*, with representatives of the *Swiss national higher education institutes and quantum research centres*, with the *Quantum Technology programme of the Italian INFN*, with the Spanish *QSpain* initiative. With the support of the Advisory Board, CERN QTI members will progressively extend the map of discussions and collaborations making sure that all initiatives and programmes are fairly involved and represented.

European Initiatives and Organisations

At the European level, the CERN QTI has been presented to and discussed with the *EC Quantum Flagship* to foster both technical and community organisation activities. It is part of the CERN QTI strategy to ensure that CERN is involved with the EC framework programmes in different quantum-technology areas and to contribute to establishing an international vision for the evolution of technologies, applications, and funding programmes. CERN is today an Associate Member of the *QuantHEP project* funded under the *QuantERA programme* specifically to explore applications of quantum computing to HEP.

Participation in the activities of HEP-specific coordination bodies is ensured whenever possible by direct representation and participation. *The European Committee for Future Accelerators (ECFA)* recently pointed out that “quantum sensing technologies have demonstrated substantial impact on particle physics as well as on fundamental physics; with this and potential further impacts in mind, their development across the full range of existing (but also nascent) technologies should be promoted, and the corresponding developments in quantum technologies should be closely followed and adapted to particle physics wherever relevant.”

In September 2020, CERN and the *European Space Agency (ESA)* announced a joint research programme on Artificial Intelligence and Quantum Computing to support the two organisations’ future challenges in data and image analysis. The programme is being implemented by CERN openlab in Geneva and ESA Φ-lab in Frascati (Rome). The programme has been extended to other participants (such as *ECMWF* and *DLR*) and will investigate applications of quantum-machine-learning algorithms and quantum-inspired methods.

Early discussions on QKD applications are taking place with members of the *openQKD project* (such as *IDQ* and *PSNC in Poznan*) as part of existing collaborations, and with *GEANT*, the pan-European data network for the research and education community. CERN is currently hosting IDQ equipment used by the openQKD project and will actively pursue investigations and feasibility studies of integration with future quantum infrastructures.

Worldwide HEP Initiatives and Collaborations

As part of the objective to act as a hub for collaboration and innovation within and beyond the Member States, CERN QTI experts are participating in quantum technology discussions and programmes in other countries, like the USA, Japan, and South Korea. Proposals have been jointly developed as part of the *US Particle Physics Community Planning Exercise (Snowmass)* and preliminary discussions are taking place with *US National Laboratories* (namely *Oak Ridge* and *Fermilab*) for joint investigations as part of the US Quantum Science Institutes programmes. Joint R&D projects are in place with the physics community in Japan within the International Center for Elementary Particle Physics (ICEPP) at the University of Tokyo. Joint investigations of future applications of QKD networks for sensitive data processing are taking place with South Korean Institutes (SNUBH, KISTI).

It is an explicit goal of the CERN QTI Roadmap to extend the number of collaborations across different international communities. The effort to implement additional agreements and joint projects with Institutes across the international HEP community will therefore receive particular attention.

Collaborations with Industry

Industry plays a critical role today in the development and construction of quantum technologies. Companies such *Atos, IBM, Google, Honeywell, or Microsoft* have put in place R&D programmes to develop quantum computers and are rapidly moving from devices with a handful of qubits to roadmaps that foresee the availability of many hundreds of physical qubits as early as 2023. Close collaboration with industry to get early access to technology and conversely to transfer CERN know-how and technology through co-development efforts is therefore critical to the success of the CERN QTI roadmap. As of today, joint R&D projects and in some cases commercial agreements for procurement of quantum-computing capabilities have been set up. CERN is currently a **Hub Member of the IBM Q Network** and **Member of the Atos User Club** together with prominent research and academic centres, computing facilities and industries, such as *Fraunhofer, Juelich, LRZ, and Daimler in Germany, Brookhaven and Oak Ridge in the USA, Keio University in Japan, or Cambridge Quantum Computing in the UK*.

4.3 Infrastructure and Computing Facilities

To support the R&D efforts in the CERN and HEP community working with the CERN QTI, the availability of **accessible quantum computing and quantum computing simulation resources** is required. As part of its capacity building objective (*T1*), the CERN QTI has set up the first instances of a **distributed, heterogeneous platform** composed of classic accelerated hardware, specialised quantum computing simulators and quantum computing cloud services.

Classic hardware and quantum simulators (specifically an **Atos QLM**) are currently hosted at CERN and can be accessed via a standard interface being developed, based on Jupyter notebooks technology. Quantum hardware is available via a three-year commercial agreement with **IBM** where **CERN has the role of Hub manager** and can onboard additional institutes for joint projects. Discussions to add members to the hub are currently underway with Institutes in the CERN Member States. Additional access to quantum hardware will become available as of Q4 2022 as part of the **CloudBankEU project**[21] led by CERN, which will make it possible to access cloud services from different providers (*Amazon, Google, Microsoft, Oracle, Orange, T-Systems, and more*) including quantum platforms.

The platform will be further developed with the participation of other HEP institutes with the objective to provide an easily accessible distributed infrastructure for researchers to get familiar with quantum computing and deploy R&D projects. It will be complemented by the **assessment and benchmarking tools provided as part of the ABAQUS project** and will form the base for discussing possible implementations of **software tools and interfaces with an increasing level of abstraction** as typical today of classic computing resources.

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[21] https://ngiatlantic.eu/news/large-hadron-collider-lhc-farmers-how-society-will-reap-benefits-second-ngiatlanticeu-open

4.4 Education, Training, and Knowledge Sharing

Given the R&D and sometimes still speculative nature of quantum technologies and its longer-term impact, a solid educational and training programme must be at the core of the Initiative. The CERN QTI implements most of its R&D activities as **a PhD-level programme, as part of the existing CERN DOCT scheme** and in collaboration with relevant academic institutes with proven expertise in the field. This approach allows to create synergies between CERN and academic institutes active in the quantum technology fields and to start creating knowledge and skills for future activities.

A programme of exchanges in the form of **visiting professorships and scientific associates** is being established as a further mechanism of knowledge sharing across institutes and to build expertise within the Organization. Experts from universities can spend periods from a few weeks to several months at CERN as part of the ongoing projects, interact directly with the research teams, and deliver specialistic courses and lectures.

Education and training events are being organised in collaboration with selected academic and industry partners to speed up the establishment of a solid foundational layer of competencies across the different CERN R&D and engineering activities. Proven expertise in the organisation of academia-industry training programmes is already available at CERN through frameworks such as CERN openlab and is already provided to the CERN QTI. A first **introductory course about quantum computing**[22] took place in November and December 2020 in collaboration with the University of Oviedo that showed the size of interest in quantum technologies across

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[22] https://indico.cern.ch/event/970903/

the world with more than 1,500 live participants and more than 14,000 offline viewers in many of the proposed lectures. The course material has even been translated into Russian by volunteers for Russian-speaking audiences.

Given that the subject of quantum technologies might be very new in many education institutes or companies, we have the opportunity to look at **new ways of delivering courses and share information**. Modern, interactive forms of education might complement traditional courseware material offered by academia. A notable example of this approach is the **QPlayLearn**[23] initiative in Finland, where the approach based on multimedia, gamified learning resources aims at reaching and motivating students as early as high school. The CERN QTI is discussing with QPlayLearn about a collaboration to design content and organise targeted education and innovation events.

A critical aspect of the activities of the CERN QTI is the establishment of **co-development collaborations** between research and industry to advance the state of the art and to exploit the specific areas of expertise at CERN. The CERN QTI — in direct collaboration with existing CERN structures, such as the Knowledge Transfer Group[24], CERN openlab[25], or IdeaSquare[26] — shares knowledge and builds innovation primarily via two mechanisms, **the creation of a network of industrial collaborations within and outside the HEP community** based on specific **IP management policies**; and **the maximisation of dissemination and adoption of its research outcomes** by the publication of research outcomes through scientific journals but also specialised media outlets, or social-media channels. Any commercially exploitable result will be subject to appropriate IP management,

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[23] https://qplaylearn.com/
[24] https://kt.cern/
[25] https://openlab.cern
[26] https://ideasquare.cern/home

including protection mechanisms where applicable (e.g. patenting) and the definition of appropriate licensing policies.

5 Glossary

NISQ	Noisy Intermediate-Scale Quantum: used to refer to quantum computing systems with a limited number of qubits (50-1000) not allowing effective error correction.
Noise	Noise in quantum computers is due to disturbances of the environment on the system qubits that cause loss of coherence and therefore information.
QKD	A method that leverages the properties of quantum mechanics, such as the no cloning theorem, to allow two people to securely agree on a key (OTP – One Time Pad). A key in this context is a secret code-word that is shared only between you and the person you are trying to communicate with. This secret code-word can then be used to encrypt messages such that they can be transmitted without being read by a malicious third party.
Qubit	The fundamental unit of computation of quantum systems. Whereas a classical bit can be in two states (either zero or one), a quantum bit or qubit can be in a sort of zero state and in a one state at the same time. This situation is called a superposition of (quantum) states.
Quantum Advantage or Quantum Supremacy	For a given problem, the improvement in run time for a quantum computer versus a conventional computer running the best known conventional algorithm.

Quantum Error Correction	Quantum error correction combats the information loss due to environmental disturbances in the computational state of the system by taking such state and spreading it out over an entangled state over many qubits. This entanglement allows outside classical observers to observe and remedy disturbances without observing the computational state itself, which would collapse it.
Quantum Turing Machine or Universal Quantum Computer	A Quantum Turing machine (QTM), also a universal quantum computer, is an abstract machine used to model the effect of a quantum computer. It provides a very simple model which captures all of the power of quantum computation.
Quantum Repeaters	Quantum repeaters enable long distance communication over a quantum network beyond the typical limits of an optical fibre that can transmit a qubit over roughly 100 kilometres. Quantum repeaters can be thought of as a series of short entangled links connecting the two points. The quantum information can then be teleported through these links and arrive safely at its destination.
Quantum Sensor	A quantum sensor is a device that exploits quantum correlations, such as quantum entanglement, to achieve a sensitivity or resolution that is better than can be achieved using only classical systems. A quantum sensor can measure the effect of the quantum state of another system on itself