Quantum 2030

THE DEPARTMENT OF NATIONAL DEFENCE AND CANADIAN ARMED FORCES

QUANTUM SCIENCE & TECHNOLOGY STRATEGY IMPLEMENTATION PLAN

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Quantum 2030: Quantum Science and Technology Strategy Implementation Plan

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Foreword

In January 2021, the Department of National Defence (DND) and the Canadian Armed Forces (CAF) released its first comprehensive strategy for adapting to an emerging and disruptive category of science and technology (S&T). The DND/CAF *Quantum S&T Strategy: Preparing for technological disruptions in the future operating environment* established a vision to strengthen the Defence team's preparedness for a future where quantum technology is prevalent in our operating environments.

The global defence and security context has rapidly changed since the DND/CAF Quantum S&T Strategy was released. The line between defence and security is blurring with increasing above- and below-threshold conflicts that threaten the rules-based international order. Cyber and outer space continue to be more important domains to defence and security. In June 2022, the Minister of National Defence announced that the systems used to defend North America and the Canadian Arctic will be modernized reflecting the latest advances in S&T. Quantum technologies are predicted to have a role to play in all of these domains.

Despite the ever-changing context, the need for defence and security science remains constant. The Defence team must ensure seamless interoperability with our allies while staying ahead of our adversaries. This requires immediate strategic action to build quantum capabilities, which Defence Research and Development Canada (DRDC) is well-positioned to advance as the federal leader in defence, safety and security S&T.

Given these considerations, I am pleased to present *Quantum 2030: The DND/CAF Quantum Science & Technology Strategy Implementation Plan. Quantum 2030* includes a mission-oriented research and development plan to achieving the goals laid out in the Quantum S&T Strategy, while providing guidance for the entire Defence team to continue adapting to the changing technology landscape.

As we look forward to the decades ahead, DRDC is prepared to support the Defence team and its safety and security partners in responding to future emerging technologies. *Quantum 2030* lays the groundwork that will inform continuous S&T efforts as we progress toward the future defence and security operating environment.

Dr. Jaspinder Komal
Assistant Deputy Minister (Defence Research and Development Canada)

Executive summary

Emerging quantum technologies promise to advance, disrupt, or enable new functionality for information technologies for a variety of military, safety and security applications. The Department of National Defence (DND), the Canadian Armed Forces (CAF) and Canada's allies can use these technologies to improve operations. In the hands of adversaries and bad actors, these same technologies can pose a threat.

To prepare for emerging quantum technologies, DND/CAF released the *Quantum Science & Technology Strategy: Preparing for Technological Disruption in the Future Operating Environment* (QSTS)[1] in January 2021. It guides DND/CAF's response to emerging quantum science and technology (S&T), ensuring the Defence team is well-prepared for the quantum-enabled future operating environment while supporting the academic and industrial quantum ecosystem that is already thriving in Canada.

While quantum technologies are still emerging, there is opportunity to invest in them: capitalizing on research and development (R&D), exploring countermeasures, and understanding their potential early. However, once they have emerged (i.e., are ready for operational use) the existence of certain technologies becomes a permanent feature of the threat landscape and could be used by bad actors against Canada or our allies. At the same time, Canada's allied defence peers are investing in quantum technologies across the spectrum of sensing, computing and communications. DND/CAF must stay ahead of potential adversaries and maintain interoperability with allies.

Since the release of the QSTS, technological trends have accelerated and governments around the world are increasingly investing in the global quantum ecosystem. Here in Canada, under the National Quantum Strategy (NQS) the Government of Canada is investing $360 million over seven years from fiscal year (FY) 2021/2022 to FY 2027/2028, to support Canada's quantum ecosystem.

Quantum 2030: The DND/CAF Quantum Science and Technology Strategy Implementation Plan is a call-to-action designed to enable the Defence team to identify and integrate quantum S&T considerations into planning efforts. The call-to-action spans five areas:

1. **Identify potential end-users and operations** that may be impacted by quantum technology. These end-users and operations will be targeted for additional quantum support and to implement the call-to-action.
2. **Train and up-skill implicated personnel** to create a base-level understanding of quantum, termed quantum literacy. Non-experts should be expected to make reasoned and evidence-based decisions related to quantum information S&T relevant to their roles.
3. **Continuously engage with Defence Research and Development Canada (DRDC)** on quantum efforts to increase harmonization in quantum investments across the Defence team in direct support of pillar 3 of the QSTS.
4. **Seize opportunities to drive practical experimentation** with quantum technologies through Government of Canada innovation programs to access state-of-the-art technologies.
5. **Engage directly with Canadian quantum experts in academia and industry.** The Canadian quantum ecosystem is recognized worldwide as being exceptional, and it is up to DND/CAF to leverage this civilian-sector advantage into a defence and security sector advantage.

In addition to the call-to-action, DRDC will lead the DND/CAF quantum S&T effort by undertaking a series of projects to advance technology

1 For a primer in quantum technology, how quantum technology may one day be used by defence and security, and a description of the DND/CAF comprehensive approach to transitioning quantum technologies into military capabilities, the reader is directed to the QSTS, available at https://www.canada.ca/en/department-national-defence/corporate/reports-publications/dnd-caf-quantum-science-and-technology-strategy.html

readiness level (TRL)[2] in four identified niche areas. A mission statement has been developed for each area with the goal of reaching TRL 7 (a prototype ready to be tested in the field) within seven years, that is, by the year 2030. Each mission identifies one specific quantum-related technology with high anticipated relevance to defence, safety and security.

1. **Quantum-enhanced radar**
   DRDC will build and field-test a prototype quantum-enhanced long range radio frequency transmission and detection system within the next seven years.
2. **Quantum-enhanced light detection and ranging (LiDAR)**
   DRDC will build and field-test a prototype quantum-enhanced LiDAR system within the next seven years.
3. **Quantum algorithms for defence and security**
   DRDC will demonstrate a quantum algorithm solving a defence and/or security problem with advantage over classical computing within the next seven years.
4. **Quantum networking**
   DRDC will work with partners to build and demonstrate a communications network capable of transmitting quantum information over long ranges and employing theoretically unhackable quantum protocols, within the next seven years.

The mission-oriented approach focuses on building prototype systems. Success in these missions will need multidisciplinary teams to design a working system. DRDC will need to collaborate with partners in academia, the private sector, and across the Government of Canada.

The missions will be carried out over three phases. The first phase (year one, FY 2023/2024) includes targeted growth, including recruiting highly qualified personnel (HQP), training for non-quantum experts, and additional capacity in the form of an expanded strategic advice function. The second phase (years two to four, FY 2024/2025 to FY 2026/2027) includes detailed milestone mapping and formal endorsement of the missions, and related scientific projects in support of each mission. The third and final phase (years five to seven, FY 2027/2028 to FY 2029/2030) will see field tests and demonstrations that expedite early adoption of quantum technologies.

By the year 2030, the quantum technology landscape and marketplace will be considerably different than it is today. *Quantum 2030* is designed to strike a balance between pursuing promising technological niches, and enabling an agile approach. As DND/CAF's first comprehensive S&T strategy implementation plan, *Quantum 2030* will also inform DND/CAF's future emerging technology postures.

Photo by Corporal David Veldman, Canadian Armed Forces

The Northern Lights can be seen beyond His Majesty's Canadian Ship (HMCS) HARRY DEWOLF during Cold Weather Trials near Frobisher Bay on February 21, 2021.

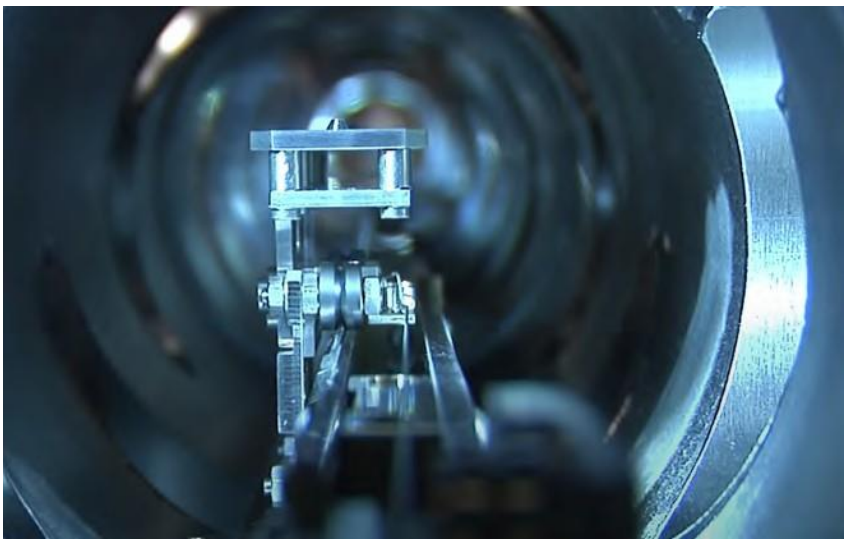
2 For more information, see the Annex – technology readiness levels.

Part 1:

INTRODUCTION

Emerging quantum technologies promise to advance, disrupt, or enable new functionality for a variety of military, safety and security applications. These include object detection, positioning, navigation and timing (PNT) in Global Positioning System (GPS)-denied environments, chemical, biological, radiological, and nuclear (CBRN) threat detection, secure communication, resource and logistics optimization, code-breaking, and advanced materials and medical research. Employed by DND/CAF and Canada's allies, these can present opportunities to improve defence, safety and security operations. In the hands of adversaries and bad actors, these same technologies can pose a threat to Canadian and allied forces, Canada's critical infrastructure, and Canadian prosperity and safety.

Since the release of the QSTS, technological trends have accelerated and the importance for the Defence team to prepare for disruptive quantum technology has only grown. The role of information technology in conflict, such as cyber and hybrid warfare, is likewise growing. Emerging technologies, including quantum technologies, are maturing more rapidly than expected, and it is increasingly important for DND/CAF to adapt to the changing operating environment.

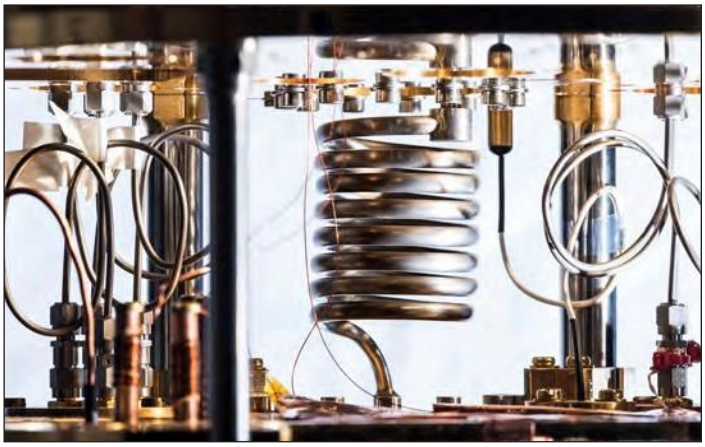


The recognition that quantum technologies are likely to not only spur significant economic growth, but also disrupt defence, safety and security operations has resulted in governments investing heavily in quantum technology. The private sector is adapting to the potential that quantum technologies promise with a number of start-ups pioneering quantum solutions, and enterprises across different sectors making significant investments in quantum R&D.

The Leiden CF1400 dilution refrigerator at the University of Waterloo Institute of Quantum Computing provides an ultra-low temperature platform for developing quantum devices.

Canada is a leader in the development of quantum science and technologies in large part due to early investments by the private and public sectors. The NQS establishes the Government of Canada's commitment to growing and sustaining a world-class domestic quantum technologies ecosystem. Budget 2021 announced $360 million over seven years starting in FY 2021/2022 to launch the NQS, led by Innovation, Science and Economic Development Canada (ISED). The NQS will amplify Canada's strength in quantum research and grow our quantum technologies, companies and talent. Released in January 2023, the NQS outlines investments under three pillars: research, talent and commercialization. By coordinating investments and outcomes across all three, Canada can strengthen its quantum advantage and advance its scientific and technological sovereignty in this area. With a strong focus on collaboration, the NQS also guides efforts along missions in key areas of quantum technology.

NQS investments will be delivered primarily through existing Government of Canada programs such as the National Research Council of Canada (NRC) Challenge Programs and Natural Sciences and Engineering Research Council of Canada (NSERC) Alliance Grants. The Quantum Research and Development Initiative (QRDI), a new program of approximately $9 million over five years beginning in FY 2023/2024, is designed to enable inter-departmental quantum R&D on federal government mandates and priorities to address issues important to Canadians.



A closeup view of a dilution refrigerator.

Quantum 2030: The DND/CAF Quantum Science and Technology Strategy Implementation Plan is the follow-up to the QSTS and identifies concrete actions for the Defence team to achieve the goals outlined in the QSTS by the year 2030. *Quantum 2030* aligns with the NQS and other Government of Canada policies and strategies, and complements the plans of Canada's allies.

Quantum 2030 identifies niche areas, in the form of four quantum missions to be achieved by 2030, to focus internal S&T capability investment. Other quantum S&T efforts beyond the missions will continue through partnerships and programs such as Innovation for Defence Excellence and Security (IDEaS), the Canadian Safety and Security Program (CSSP), and Innovative Solutions Canada (ISC).

Part 2:

CURRENT DND/CAF QUANTUM EFFORTS

As the S&T advisor to the Defence team, DRDC has been investigating applications of quantum phenomena to solve defence, safety and security problems for years. Additionally, as quantum technologies are maturing, the Defence team is adapting. There are several DND/CAF efforts underway to adopt, adapt to or prepare for emerging quantum technologies which can be categorized into three mutually reinforcing pillars as laid out in the QSTS. These, along with new investment and focus on targeted areas, form the foundation for the *Quantum 2030* plan.

PILLAR 1 - Transition quantum technologies into Defence capabilities

The QSTS identified quantum sensors as a strategic priority for DND/CAF due to their relevance to operations. This work is well underway and *Quantum 2030* establishes a seven-year plan to invest in strategic types of quantum sensors, bringing them to high TRL and optimizing promising solutions for defence purposes.[3]

DRDC conducts research using a variety of quantum technologies to improve situational awareness in defence, safety and security contexts. Through partnerships and programs such as IDEaS, CSSP and ISC, DRDC currently supports research in quantum-enhanced PNT and CBRN hazard detection, among others. DRDC is planning expanded facilities, in part, to grow its capability to perform this kind of research.

Defence peers are investing in building quantum computing capability even though there are many unknowns in how the field will progress. Through the ISC testing stream, DRDC has obtained access to a prototype quantum computer. This early exploratory research will form the basis of continued investigation into quantum computing with a renewed focus on quantum algorithms for defence and security.[4]

Canada is a world leader in pioneering space-based quantum communications technology. DRDC supports the Quantum EncrYption and Science Satellite (QEYSSat) mission led by the Canadian Space Agency (CSA).[5]

Quantum countermeasures include efforts which may or may not employ quantum technology, to adapt to the threat that emerging quantum technologies pose. Exploring countermeasures for emerging quantum technologies is a strategic action identified in the QSTS; investigating

3 See quantum missions 1 and 2 for more details about DRDC plans to accelerate the transition of two specific types of quantum sensors into defence capabilities: quantum-enhanced radar and quantum-enhanced LiDAR.

4 See quantum mission 3 for more details about plans for quantum algorithms research.

5 See quantum mission 4 for additional plans for defence-specific quantum communications research.


Getty Images


Photo by James Clark, DRDC/DND

countermeasures for the associated technology is a key aspect of each of the missions of *Quantum 2030*.

The quantum computing threat to secure communications is a pressing national security concern. Implementing countermeasures to protect sensitive Defence team communications before the threat is realized by a quantum computer, and while assuring interoperability with allies, will be a key DND/CAF undertaking. The Communications Security Establishment (CSE) defends Government of Canada networks and provides advice and recommendations for other departments and agencies. DND/CAF including CSE are working together and with Canada's allies to implement post-quantum cryptography (PQC) following the development of standards. These standards are being designed to protect future sensitive communications from cryptographic attacks by an adversary with a sufficiently powerful quantum computer, while assuring interoperability with allies at all times.

PILLAR 2 -
Establish and sustain strong partnerships in quantum technologies

Canada has a world-class quantum ecosystem based in academia and industry. It is important for DND/CAF to invest in the domestic quantum industry, not only to leverage the talent toward enhancing defence capabilities, but also to protect it and de-risk innovation. Without support from DND/CAF, firms developing defence- and security-relevant technology would have no choice but to move to countries whose militaries are willing to invest in their development and/or supply chains. This would have economic and safety/security consequences for Canada, such as increased cost for DND/CAF to interoperate with allies or Canadian-developed quantum technology used by potential adversaries. It is also important for DRDC to participate in international standards discussions for emerging quantum technologies, lending its expertise in defence innovation and representing Canadian interests globally.

DRDC is working to build strong links with Canadian quantum expertise in industry and academia. For example, the IDEaS program plays a key role in how DND/CAF identifies partners and innovative solutions for defence problems. IDEaS has provided funding to Canadian quantum innovators through competitive projects and is scoping collaborative Innovation Networks focused on defence applications of quantum S&T. There is a potential for additional quantum calls for proposals in the future. The Defence and Security Science and Technology (DSST) program has ongoing projects supporting research in a diverse set of defence-relevant quantum areas.

Finally, DRDC has sponsored several challenges through ISC to support the development of specific quantum technologies by Canadian private or academic groups. These challenges are ongoing.

DND/CAF, through DRDC, works closely with other government departments and agencies (OGD/A) through existing memoranda of understanding (MOUs), as well as through several interdepartmental committees. These mechanisms enable DND/CAF to support research projects with defence, safety and security applications, as well as coordination across government to build partnerships and to support training of quantum-specialized HQP in areas of relevance to defence needs.

DRDC maintains strategic contacts and works with various organizations around the world with a focus on leveraging and contributing to the development of mutually beneficial quantum technologies. For example, DRDC is working with United States (US) partners in areas related to quantum communications.

The Defence team collaborates with the Five Eyes international community and The Technical Cooperation Program (TTCP). DRDC also participates in the North Atlantic Treaty Organization (NATO) Quantum Group, which provides DND/CAF connections to quantum technology companies in NATO nations. These mechanisms enable international government collaboration on shared R&D priorities.

LiDAR system mounted on vehicle for testing at DRDC Valcartier.

PILLAR 3 -
Bring coherence to quantum S&T investments across DND/CAF

Development of *Quantum 2030* has been a process in harmonization in direct support of pillar 3 of the QSTS. As part of the implementation of *Quantum 2030*, ongoing work will be undertaken to sustain this harmonization. *Quantum 2030* does not pre-determine every quantum activity for the next seven years; it aims to empower the Defence team's quantum initiatives, enabling innovation and adaptability where appropriate, and providing clear guidance about strategic areas based on the best available evidence.

Photo by James Clark, DRDC/DND

The Contested Urban Environment 2018 experiment (CUE 18) aims to investigate new and emerging technologies that could improve the effectiveness of military personnel operating in complex urban environments while reducing risk to both military forces and civilians.

Part 3:

QUANTUM S&T STRATEGY IMPLEMENTATION PLAN

The plan to achieve the goals in the three pillars of the QSTS is divided into two sections: a call-to-action for DND/CAF to continue to prepare for the quantum-enabled future operating environment; and, a plan for DRDC to lead the Defence team S&T response in this field of emerging and potentially disruptive technology.

CALL-TO-ACTION FOR THE DEFENCE TEAM

Gender-based Analysis Plus (GBA+), diversity and inclusion, and national, economic and research security considerations will be embedded in all quantum-related work in accordance with existing Government of Canada policy.

Quantum technologies are often described as "emerging"; thus the Defence team response is time-sensitive. When quantum technologies are in development (i.e., low TRL) there is a prime opportunity to invest in them, capitalizing on R&D, exploring countermeasures, and understanding their potential early. However, once they have emerged (i.e., are ready for operational use) the existence of certain technologies becomes a permanent threat, since they could be used by bad actors against CAF members, Canadians, or our allies. At the same time, Canada's allied defence peers are investing in quantum technologies across the spectrum of sensing, computing and communications. Not only must we stay ahead of potential adversaries, DND/CAF must maintain interoperability with allies. With these considerations in mind, the following actions should be incorporated into planning efforts:

1. **Identify potential end-users and operations** that may be impacted by quantum technology. These end-users and operations will be targeted for additional quantum support and to implement the call-to-action. These are areas that are expected to be impacted by quantum sensing, quantum computing, and quantum communications, respectively:
   - Any type of sensor (a device that builds situational awareness by measuring aspects of the environment) may, in principle, be improved by the integration of advanced quantum components. This includes but is not limited to: cameras (thermal/infrared, optical), radio/radar detection and imaging, magnetometers, gravimeters and PNT systems, and CBRN hazard detection.
   - Users of high performance and cloud computing services, as well as data analysts employing artificial intelligence (AI) and machine learning (ML) or other techniques to solve complex problems such as logistics or other optimizations, should consider how future quantum computers could impact operations. Plans to integrate quantum computing services into existing and future cloud computing strategies should be developed at classified and unclassified levels. While commercial quantum computers are not yet ready for full deployment, the Defence team must prepare for sudden unexpected technological progress in the field.

Recent S&T developments highlight the rapidly approaching convergence of quantum and AI/ML. The successful implementation of the QSTS, in particular in leveraging the full potential of quantum computing for data analytics, will need a strong foundation of organized, accurate and well-governed data, making the DND/CAF Data Strategy[6] a key guiding document.

- Teams that work with cybersecurity and information systems will be impacted by the quantum computing threat to secure communication. Cybersecurity and communications operations, including space-based communications, will soon need to implement countermeasures. Plans to implement PQC are being developed in collaboration with allies.

2. **Train and up-skill implicated personnel** to create a base-level understanding of quantum technology, termed quantum literacy. Non-experts should be expected to make reasoned and evidence-based decisions related to quantum S&T relevant to their roles.
   - The NQS is investing in developing and retaining quantum expertise in Canada, as well as in accessing global pools of talent to meet Canada's current and future needs.
3. **Continuously engage with DRDC** on quantum efforts to increase harmonization in quantum investments across the Defence team in direct support of pillar 3 of the QSTS.
   - DRDC has built strategic relationships with the quantum technology community, both in Canada and abroad. The Defence team is encouraged to work with DRDC to identify potential partners to leverage as its quantum S&T capability grows and to provide specific training and recruiting opportunities.

6 Available at https://www.canada.ca/en/department-national-defence/corporate/reports-publications/data-strategy/data-strategy.html

Photo by James Clark, DRDC/DND

Michael Franz, DRDC/DND

An uncrewed ground vehicle was used to collect samples from radiological threats detected using uncrewed aerial vehicles, during the Radiological Dispersal Trial at DRDC Suffield.

- To facilitate harmonization across the Defence team, the existing DRDC-led quantum working group (QWG) membership includes researchers, quantum technology end users, policy analysts and other personnel. The QWG is an example of a forum where knowledge on quantum S&T is being shared across DND/CAF, quantum S&T activities are discussed at the working level and opportunities to leverage Defence team advancements are identified in support of pillar 3. Ongoing membership and management of the QWG will evolve over time to reflect the needs of the Defence team.

4. **Seize opportunities to drive practical experimentation** with quantum technologies through Government of Canada innovation programs to access state-of-the-art technologies.
    - This will include the use of ISC, CSSP and IDEaS.
    - The NQS is expected to increase opportunities to advance quantum technologies into defence capabilities by working with OGD/A, via QRDI for example, and by collaborating with Canadian industry and academic partners through other funded programs.
5. **Engage directly with Canadian quantum experts in academia and industry.** The Canadian quantum ecosystem is recognized worldwide as being exceptional, and it is up to DND/CAF to leverage this civilian sector advantage into a defence and security sector advantage.
    - While it is important for the rest of the Defence team to engage continuously with DRDC to seek defence-oriented science advice and avoid duplication of work, this does not preclude end-users and operations that may be impacted by quantum technology from engaging directly with external stakeholders and building their own relationships.

Photo by Cpl Valérie Duclos-Péloquin, 34 Brigade Group, Canadian Armed Forces

QUANTUM MISSIONS

To advance DND/CAF capability in identified niche areas, DRDC has identified a series of projects to advance quantum technology. A mission statement is included below for each specific area with the goal of reaching TRL 7 (a prototype ready to be tested in the field) within seven years, that is, by the year 2030. Success in these missions will need multidisciplinary teams to design working systems; DRDC will need to collaborate with partners in academia, the private sector, and across the Government of Canada.

Each mission identifies one specific quantum-related technology with a high degree of value to defence, safety and security: quantum-enhanced radar, quantum-enhanced LiDAR, quantum algorithms, and quantum networking. The missions were chosen to provide DRDC with specific technology areas to focus investment in order to realize pillar 1 of the QSTS: transition quantum technologies into Defence capabilities. Each mission also contains an emphasis on countermeasures in support of pillar 1.2.

To facilitate building stronger partnerships in support of pillar 2, the missions were chosen based on Canadian and DRDC strength areas, complementarity with allied nations' strength areas, likelihood of success, the need to perform at least part of the work internally due to sensitivity, and to build capability in areas of high anticipated relevance to future defence operations.

The mission-oriented approach builds Defence team cohesion in support of pillar 3.

The missions do not negate DND/CAF support for research in other areas of quantum S&T relevant to defence and security where work by external partners in allied nations and/or the private sector will advance, with continued Defence team participation in the capacity of testing and exploratory early adoption, such as through IDEaS, CSSP, ISC or other investment vehicles.

Before fully embarking on the missions as they are described here, the first step is to perform detailed scientific milestone mapping and feasibility studies on each of the areas identified. Following this step, the missions can be refined and planned as a program to carry out a series of projects to advance quantum technologies for defence and security. More details about the phased approach is included in the next section.

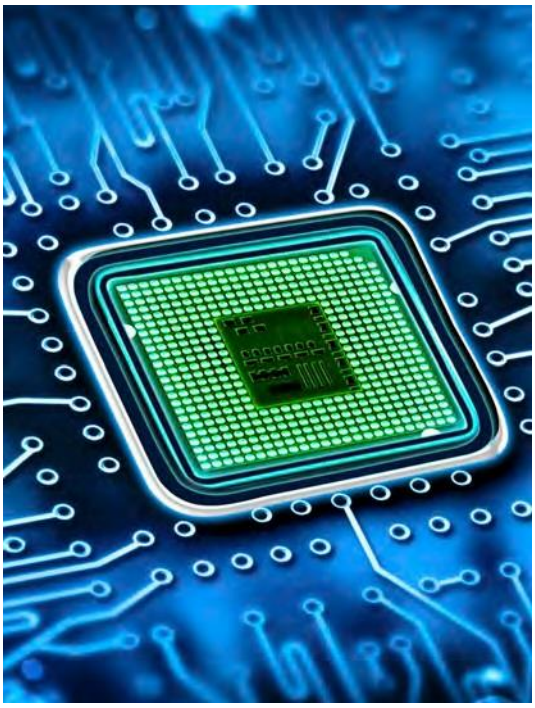


Photo: Getty Images/iStockphoto

Photo by James Clark, DRDC/DND

A magnetic anomaly detection trial at the Canadian Forces Maritime Experimental Test Ranges in British Columbia.

MISSION 1: QUANTUM-ENHANCED RADAR

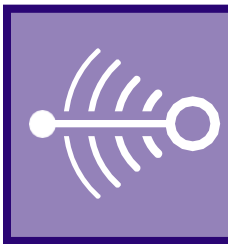
QUANTUM SENSING

DRDC will build and field-test a prototype quantum-enhanced long range radio frequency transmission and detection system within the next seven years.

The story of radar is one of continuous improvement. It has been observed that the radar systems used during the Second World War would be useless in a defence context today, thanks to the continuous improvements made in the decades since. Today, radar is the key technology behind the joint US and Canadian North Warning System used to defend North America from threats entering Canadian airspace from the north. As radar technology progresses, future applications and additional capabilities may employ quantum-enhanced components.

DRDC works with partners to design and test quantum-enhanced radio-frequency emitters and detectors. These could one day be used in a quantum-enhanced radar system. Such technology, still early-to-mid TRL, could enable detection of 'stealth' aircraft, be itself an undetectable mode of detection (stealth detection), as well as improve imaging resolution. The work will require improvement in quantum signal processing and the expertise of multidisciplinary teams.

Along with research in developing the technology, DRDC will conduct research into countermeasures for quantum-enhanced radar.



MISSION 2: QUANTUM-ENHANCED LIDAR

QUANTUM SENSING

DRDC will build and field-test a prototype quantum-enhanced LiDAR system within the next seven years.

LiDAR is similar to radar, but works with coherent light sources such as lasers. The improvement in quantum optics sources and detectors over the past decades, including quantum-entangled sources, means that the improved sensitivity that comes from leveraging quantum effects can be used to improve LiDAR.

Areas of DRDC expertise and active research include underwater imaging, imaging through obscuring or scattering media (fog, smoke, nets, etc.), and hostile optics detection. This mission is an opportunity to push the limit on what is already a DRDC and Canadian strength.

Along with research in developing the technology, DRDC will conduct research into countermeasures for quantum-enhanced LiDAR.

MISSION 3: QUANTUM ALGORITHMS FOR DEFENCE AND SECURITY

QUANTUM COMPUTING

DRDC will demonstrate a quantum algorithm solving a defence problem with advantage over classical computing within the next seven years.

There have already been demonstrations of real-world logistics operations improved through the use of a combination of Big Data, AI/ML and quantum computing. The non-quantum aspect of this work is significant: the data must be collected, organized and analyzed, and the AI/ML algorithms must be integrated with the quantum computer. These non-quantum information technology investments will be necessary to fully leverage the new hardware capabilities of quantum technology. This means supporting access to the high-quality, well-governed, well-architected, and appropriately classified data on which AI/ML depends, and building multidisciplinary R&D teams.

DRDC researchers possess expertise in using high-performance computing platforms to solve computational problems in partnership with Defence team partners. DRDC has secured access to a prototype quantum computer to begin exploring potential applications, and researchers have explored the use of cloud-accessible commercially available quantum computing platforms to solve defence, safety and security problems. With the success of this mission, quantum algorithms will be developed and put to the test of improving efficiency of logistics using quantum-enhanced AI/ML or solving other computational problems.

Along with research in developing the technology, DRDC will conduct research into countermeasures to quantum algorithms.

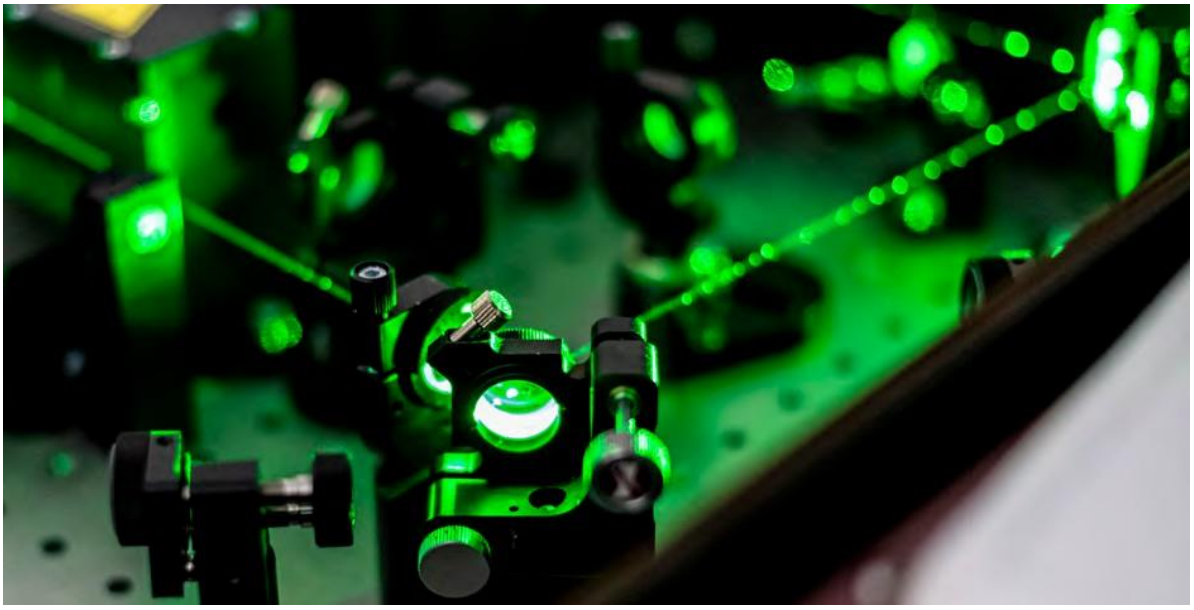
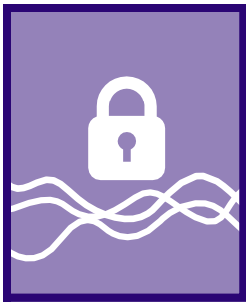


Photo: Getty Images/iStockphoto



MISSION 4: QUANTUM NETWORKING
QUANTUM COMMUNICATIONS

DRDC will work with partners to build and demonstrate a communications network capable of transmitting quantum information over long ranges and employing theoretically unhackable quantum protocols, within the next seven years.

The role of information technology and cybersecurity is increasingly important in defence and national security, from protecting Canada's critical and space-based infrastructure to securing sensitive communications. The quantum computing threat to secure communication grows closer with the advances in quantum computing seen every year. It is a question not of if, but when quantum computers will break current cryptographic protocols, and DND/CAF must be prepared when it does.

Novel PQC standards are being developed to address this threat, and are under a great deal of expert scrutiny to assure their security. Nevertheless, it is theoretically impossible to prove whether any such algorithm is secure. The potential impact of a failure of new cryptographic standards is great, so there is scientific interest in understanding alternatives and complementary solutions, such as quantum-secured communications.

Quantum key distribution (QKD) is theoretically secure against some types of cryptographic attacks including quantum computing-based attacks, but has other vulnerabilities. QKD is not currently recommended to protect national security systems until significant technical hurdles have been overcome. From a scientific perspective, these hurdles are a scientific call-to-action, rather than an obstacle or deterrent to investing in R&D.

Beyond protecting digital communications, distributing quantum information is expected to have a multiplying effect on the capability of other quantum technologies. As quantum computing and sensing technologies mature, significant enhancement in performance is expected to arise by connecting systems to distribute the quantum resources of superposition and entanglement. It will be important for the Defence team to support and understand the security assurances of these systems.

This mission would see the construction of a quantum network and demonstrate quantum-encrypted communications such as email, instant messaging, voice and video calls. The goal of this mission is to connect multiple DND/CAF sites, demonstrating the feasibility of local as well as long-range ground-to-ground quantum channels. Locations will be chosen separated by sufficient distance that a particular component, called a quantum repeater, will be required to enable the reliable transmission of quantum information.

Having access to a working quantum network at a research facility will enable research directly in support of developing countermeasures and assurances to emerging quantum communications technologies. Understanding the vulnerability of quantum networks will enable improved security protecting Canadian interests, but also potentially enable new offensive capabilities against nations who deploy or come to rely on quantum networks.

This mission is designed to be highly collaborative and would benefit from the involvement of OGD/A. The Canadian academic and private sectors house significant expertise in this area and will be important partners in achieving success of the mission.

RISK IDENTIFICATION

Quantum 2030 is an ambitious, yet necessary, far-reaching plan with many components. Therefore it is not without risks. These risks, along with their mitigation plans, are described here.

Global talent squeeze

People are at the heart of everything the Defence team does. To keep pace with emerging quantum technologies, DND/CAF will need to ensure it has the best quality advice from HQP. At the same time, the operating environment is changing, and operators across DND/CAF will need to become familiar with the concepts of quantum technology as it pertains to their role; this is termed "quantum literacy" and developing this within the Defence team is an important aspect of *Quantum 2030*.

DND/CAF will continue to work with OGD/A and collaborate directly with external partners to ensure defence, safety and security needs for HQP and training are communicated to granting agencies and the wider federal family.

Infrastructure and equipment

As the Defence team's science, technology and innovation leader, trusted advisor, collaborative partner, and knowledge integrator, DRDC faces many competing priorities. DRDC continually operates at full R&D capacity at both classified and unclassified levels. Expanding quantum research efforts will create more demand for classified and unclassified R&D capability and advancing a quantum area comes at the potential cost of limiting DRDC effort in another scientific area.

While specific plans for expanding R&D capacity lie beyond the scope of *Quantum 2030*, the need for additional infrastructure and equipment is identified as a risk. The lead time to build and equip new research facilities is long, so planning efforts will need to start well in advance of additional capacity being needed.

Research security

As quantum technologies mature, there is increasing concern that bad actors may interfere with Canadian R&D efforts. Preventing or mitigating this is a Government of Canada priority.

One of the key roles of DRDC in the Canadian quantum ecosystem is to identify the research that is particularly sensitive from a defence and security perspective and ensure the knowledge is protected. Every initiative under *Quantum 2030* will, per Government of Canada policy, be subject to careful oversight to protect the security and integrity of Canada's research.

Research and development uncertainty

Due to the unpredictable progress of quantum technology R&D, there will be some degree of success and failure in R&D efforts. As a scientific organization DRDC must accept the inherent risk and tolerate some degree of failure at the project-level.

By building enough coordinated quantum capacity, DRDC will have the expertise to mitigate the occurrence or severity of failure, as well as learn from unproductive lines of quantum scientific enquiry, and pivot as needed. By working with a wide array of allies and partners, risk and reward can be distributed.

Ethical use of quantum science and technology

Quantum technologies promise to enable vastly improved performance in certain intelligence, surveillance and reconnaissance (ISR) and information processing functions. Therefore, to accompany the drive to develop new quantum technologies, DND/CAF will seek to understand the ethical implications of their use in defence, safety and security settings. These include but are not limited to the ethical considerations associated with bias in datasets used to train AI/ML, given the connection between quantum computing and AI/ML.

PHASED APPROACH TO QUANTUM MISSIONS

PHASE 1:
Transition to strategic approach to quantum
Year one (FY 2023/2024)

The first phase formally begins with the release of *Quantum 2030*. During this phase, DRDC will reinforce its capacity to provide enhanced strategic advice to the Defence team on emerging quantum technologies. For example, the Canadian quantum industry is expected to grow with the injection of significant NQS funding, and DRDC will need to monitor these accelerating developments. Research into the ethical development and use of quantum technology in the defence, safety and security context will be undertaken in partnership with OGD/A. Engagement with partners and allies will increase in quantity, magnitude and ambition.

In preparation of the quantum missions, Defence team wide strategic alignment and targeted growth will take place in this phase. DRDC will expand efforts to recruit scientists who can lead or support in the strategic areas identified in the quantum missions. Training and education for existing personnel will also be important to build quantum literacy across the Defence team.

PHASE 2:
Undertake projects that support *Quantum 2030*
Years two to four
(FY 2024/2025 through FY 2026/2027)

This phase captures the majority of the scientific work and will see the formal launch of the quantum missions. It should be noted that most of the scientific foundations to the missions already exist, and research will be conducted in parallel to the activities of the first two years.

Milestone mapping and technical feasibility studies of the missions will take place over the first year of phase 2 (year two), with plans in place by the end of year two. These types of studies for the quantum missions will allow detailed planning for transitioning prototype quantum technologies into defence applications. Upon completion of the feasibility studies and milestone mapping, the quantum missions can be refined to set realistic plans and outcomes. With technical plans in place, formal endorsement of the missions are to be sought in accordance with existing organizational processes.

The QSTS and *Quantum 2030* represent DND/CAF's first proactive and coordinated approach to an emerging and disruptive technology (EDT). Documenting lessons learned from the process to inform future EDT strategies, and supporting the implementation with timely advice as the quantum technology landscape evolves are valuable opportunities to maximize the likelihood of success and ultimately provide the Defence team with the best possible science advice. As part of regular business management, an implementation progress report will be developed for the end of phase 2 (year four).

PHASE 3:
Field tests and demonstrations that expedite early adoptions and transitions
Years five to seven
(FY 2027/2028 through FY 2029/2030)

The third and final phase is focused on field tests and early adoptions. By the end of this phase, advanced quantum technologies will reach the point where prototype field demonstrations can take place. Prototype technologies under each of the four missions will be demonstrated at TRL 7 by the end of phase 3.

With the conclusion of *Quantum 2030* implementation, a retrospective report will be written during year seven to document lessons learned and report on the progress of DND/CAF's strategic approach to quantum S&T.

Conclusion

Over the next 10 years, developments in EDTs are expected to transform the defence, safety and security landscape. These technologies pose significant opportunities and challenges to defence and security. To prepare for and adapt to the future operating environment, Canada and its allies are developing strategic approaches to EDTs that balance responsible use, accelerated adoption and protection against threats.

By the year 2030, the quantum technology landscape will look significantly different. Many technologies will be available for use in operations, while others will have failed due to engineering or commercial challenges. It is impossible to predict today which will succeed and which will fail; it will be important for DND/CAF to be able to pivot accordingly. Although it builds on years of work in the well-established and world-class Canadian quantum ecosystem, *Quantum 2030* is a new starting point for DND/CAF that will inform continuous improvement efforts toward the quantum-enabled future defence and security operating environment. The *Quantum 2030* plan will build capability, partnerships, and coherence across the Defence team to minimize future risks to successful and safe operations by taking strategic and evidence-based R&D risks today and in years to come.

Acronyms

AI	artificial intelligence
CAF	Canadian Armed Forces
CBRN	chemical, biological, radiological, and nuclear
CSA	Canadian Space Agency
CSE	Communications Security Establishment
CSSP	Canadian Safety and Security Program
DND	Department of National Defence
DRDC	Defence Research and Development Canada
DSST	Defence and Security Science and Technology
EDT	emerging and disruptive technology
FY	fiscal year
GBA+	Gender-based Analysis Plus
GPS	Global Positioning System
HQP	highly qualified personnel
IDEaS	Innovation for Defence Excellence and Security
ISC	Innovative Solutions Canada
ISED	Innovation, Science and Economic Development Canada
ISR	intelligence, surveillance and reconnaissance
LiDAR	light detection and ranging
ML	machine learning
MOU	memorandum of understanding
NATO	North Atlantic Treaty Organization
NQS	National Quantum Strategy
NRC	National Research Council of Canada
NSERC	Natural Sciences and Engineering Research Council of Canada
OGD/A	other government departments and agencies
PNT	positioning, navigation and timing
PQC	post-quantum cryptography
QEYSSat	Quantum EncrYption and Science Satellite
QKD	quantum key distribution
QRDI	Quantum Research and Development Initiative
QSTS	*Quantum S&T Strategy: Preparing for technological disruptions in the future operating environment*
QWG	quantum working group
R&D	research and development
S&T	science and technology
TRL	technology readiness level
TTCP	The Technical Cooperation Program
US	United States

Annex -
TECHNOLOGY READINESS LEVELS

The following definitions of technology readiness levels (TRL) are used throughout *Quantum 2030*. More information is available at Technology readiness levels[7]. There are nine TRLs, with 1 being the least ready and 9 being ready for deployment in real-life conditions.

Level 1: Basic principles of concept are observed and reported
Scientific research begins to be translated into applied research and development. Activities might include paper studies of a technology's basic properties.

Level 2: Technology concept and/or application formulated
Invention begins. Once basic principles are observed, practical applications can be invented. Activities are limited to analytic studies.

Level 3: Analytical and experimental critical function and/or proof of concept
Active research and development is initiated. This includes analytical studies and/or laboratory studies. Activities might include components that are not yet integrated or representative.

Level 4: Component and/or validation in a laboratory environment
Basic technological components are integrated to establish that they will work together. Activities include integration of "ad hoc" hardware in the laboratory.

Level 5: Component and/or validation in a simulated environment
The basic technological components are integrated for testing in a simulated environment. Activities include laboratory integration of components.

Level 6: System/subsystem model or prototype demonstration in a simulated environment
A model or prototype that represents a near desired configuration. Activities include testing in a simulated operational environment or laboratory.

Level 7: Prototype ready for demonstration in an appropriate operational environment
Prototype at planned operational level and is ready for demonstration in an operational environment. Activities include prototype field testing.

Level 8: Actual technology completed and qualified through tests and demonstrations
Technology has been proven to work in its final form and under expected conditions. Activities include developmental testing and evaluation of whether it will meet operational requirements.

Level 9: Actual technology proven through successful deployment in an operational setting
Actual application of the technology in its final form and under real-life conditions, such as those encountered in operational tests and evaluations. Activities include using the innovation under operational conditions.

7 More information is available at https://ised-isde.canada.ca/site/innovation-canada/en/technology-readiness-levels.