AUDIT AND EVALUATION BRANCH

Evaluations of ISED Funding to the Perimeter Institute for Theoretical Physics and the Institute for Quantum Computing

REPORT

MARCH 2021

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Key Definitions

Theoretical physics explores the properties of the atom and studies the basic physical laws that govern the universe to develop new ideas about the essence of space, time, matter, and information.[1]

– Perimeter Institute for Theoretical Physics

Quantum information science harnesses and exploits the laws of mechanics in a quantum context to process information, examining the tiniest particles such as atoms, electrons, photons and the like.[2]

– Institute for Quantum Computing

Quantum technologies refers to the practical use of the science of quantum mechanics. This science reveals how energy and matter behave at extreme scales of atomic and subatomic particles.[3]

– National Research Council of Canada

The Perimeter Institute for Theoretical Physics

History

In 2000, the Perimeter Institute (PI) for Theoretical Physics was officially launched as an independent, not-for-profit organization in Waterloo, Ontario by creator of BlackBerry, Mike Lazaridis. The PI aims to conduct research, attract top-tier researchers, train the next generation of researchers, and build literacy and interest in theoretical physics in Canada. Innovation, Science and Economic Development Canada (ISED) has been providing funding to support the PI since 2002. The Science Research Sector (SRS) at ISED is responsible for managing the funding agreement with the PI.

Research Areas

The PI focuses on nine research areas in theoretical physics:

- Cosmology
- Mathematical Physics
- Particle Physics
- Quantum Fields and Strings
- Quantum Foundations
- Quantum Gravity
- Quantum Information
- Quantum Matter
- Strong Gravity

Research Initiatives

Aimed at supporting new ideas in theoretical physics, the PI has eight research initiatives underway:

- Causal Inference
- Centre for the Universe
- Clay Riddell Centre for Quantum Matter
- Discretuum to Continuum
- Event Horizon Telescope / Science at the Horizon
- Gravity Waves and Fundamental Physics
- Perimeter Institute Quantum Intelligence Lab
- Quantum Simulations of Fundamental Interactions
  (a joint venture with the Institute for Quantum Computing)

Overview of the Institute for Quantum Computing

The Institute for Quantum Computing

History

In close proximity to the PI, Mike Lazaridis established the Institute for Quantum Computing (IQC) in 2002 within the University of Waterloo. The IQC conducts research in quantum information science and technology, recruits leading researchers, provides students with opportunities to apply their knowledge, and promotes the applications of quantum research to Canadians. The IQC has been supported by ISED funding since 2009. The funding agreement with the IQC is managed by ISED's SRS.

Research Areas

The IQC has four multidisciplinary research areas of focus in quantum information science:

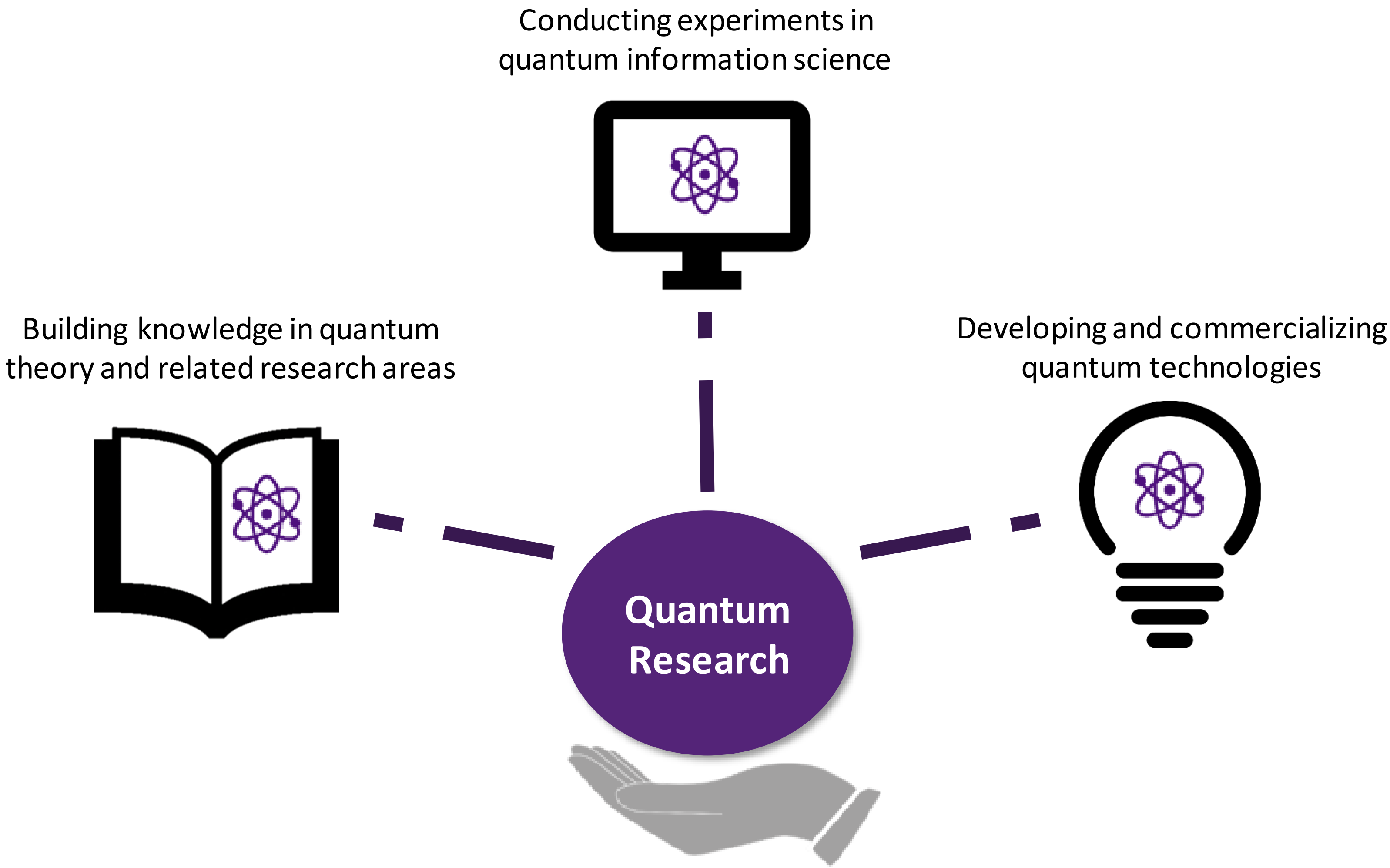
- Quantum Communication
- Quantum Computing
- Quantum Materials
- Quantum Sensing

The 'Quantum Valley' Vision

The IQC and PI are components of the 'Quantum Valley', a vision of Mike Lazaridis aimed at fostering an extensive scientific and technology ecosystem in Waterloo, Ontario. This vision of a 'Quantum Valley' brings together world-class researchers, state-of-the-art facilities, infrastructure, and training, as well as connections to investors and industry to support quantum research, technology development and commercialization in the region.

Research in the 'Quantum Valley'

Quantum research in Waterloo, Ontario is concentrated on the following:



Methodology

- *Evaluation Approach, Scope and Objectives*
- *Evaluation Questions and Areas of Assessment*
- *Data Collection Methods*
- *Limitations and Mitigation Strategies*

Evaluation Approach, Scope and Objectives

A joint reporting approach for the individual evaluations of ISED's funding to the PI and the IQC provides a strategic view of ISED's contributions to the research landscape in Waterloo, Ontario.

Evaluation Approach

The Audit and Evaluation Branch (AEB) conducted evaluations of ISED's funding to the PI and the IQC, as required under the *Financial Administration Act*. A joint evaluation approach was used to improve efficiency in evaluation resources and provide a strategic view of the research landscape in Waterloo due to the PI and the IQC's collaboration and partnership in broader research fields (e.g., quantum theory), and common outcome areas such as outreach and engagement, capacity building and training, and research advancement and application. The evaluations also adopted a results-based approach by examining the extent to which the PI and the IQC continue to individually make progress in these outcome areas, while also examining any elements of complementarity that exist between the two organizations. Although the evaluations were conducted and reported jointly, each organization was assessed independently. See Annex A for the PI logic model and Annex B for the IQC logic model.

Evaluation Scope and Objectives

The evaluations covered the period from 2016-17 to 2019-20 for the PI and from 2014-15 to 2019-20 for the IQC, which builds from the period examined in their previous evaluations.[4] The objectives of these evaluations were to assess the PI and the IQC in accordance with the Treasury Board Secretariat *Policy on Results*. The evaluations examined the relevance, performance, and efficiency of ISED's funding to the PI and the IQC.

Evaluation Questions and Areas of Assessment

The evaluation questions were strategically developed to ensure that the uniqueness of the PI and the IQC, as well as their complementarity, could be examined in the evaluation.

Relevance

Continued and Unique Need

1. To what extent is there a continued need for theoretical physics and quantum research?
   - To what extent does the PI and the IQC individually address a unique need?

Performance

Outreach and Engagement (short-term outcomes)

2. To what extent are the PI and the IQC contributing to educating the public and expanding interest in theoretical physics and quantum research in Canada?

Capacity Building and Training (medium-term outcomes)

3. To what extent are the PI and the IQC contributing to Canada being recognized as a place to study and conduct theoretical physics and quantum research?

Research Advancement and Application (long-term outcomes)

4. To what extent are the PI and the IQC contributing to Canada being positioned to take advantage of the economic and social benefits of theoretical physics and quantum research?

Efficiency

Program Delivery and Design

5. To what extent is ISED's program delivery model an efficient and effective approach to supporting the PI and the IQC in achieving their respective research objectives?
   - Are there alternative approaches that could support theoretical physics and quantum research?

Data Collection Methods

Multiple lines of evidence were used to assess the PI and the IQC in the areas of relevance, performance and efficiency, including both qualitative and quantitative research methods.

Case Studies

Four case studies were conducted based on research areas for each organization to support the overall evaluation. The case studies examined Strong Gravity, Cosmology, Quantum Matter and Quantum Information at the PI and all four of the IQC's research areas. They included a document review and surveys with Faculty members, totalling 31 completed surveys for the PI and 28 for the IQC.

Comparative Analysis

Research and analysis was conducted to identify comparable institutions in Canada and internationally, and compare them to the PI and the IQC in terms of their research areas, objectives and activities, funding profiles, and governance structure. The comparative analysis was based on a review of information and interviews.

Data Analysis

Performance data was also examined for each organization in order to assess the extent to which progress is being made towards achieving expected short-term, medium-term, and long-term outcomes. An analysis of the administrative and financial data from the PI and the IQC was also performed to assess efficiency.

Document Review

The review was comprised of pertinent literature as well as credible media sources to gain an understanding of the relevance of theoretical and quantum research in Canada and internationally, and the unique and continued need for the PI and the IQC. It was also comprised of key program and government priority-setting documents to support the assessment of performance and efficiency.

Interviews

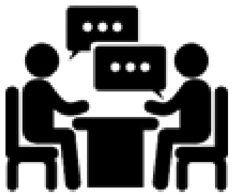
A total of 45 virtual interviews were conducted across the following stakeholder groups to gather diverse perspectives on the relevance, performance and efficiency of the PI and IQC: Management, Board of Directors, Scientific Advisory Committee, other players in the Waterloo region and research stakeholders.

Surveys

Online surveys were used to gather information on the perspectives of highly qualified personnel (HQP) which includes undergraduate and graduate students, as well as postdoctoral fellows at the PI and the IQC, to support the assessment of relevance, performance and efficiency. The completed surveys totaled 81 for the PI and 62 for the IQC.

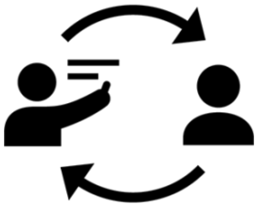
Limitations and Mitigation Strategies

The evaluation encountered the following limitations in regards to the methodologies.



Respondent Bias

The challenges and limitations associated with this evaluation include the potential for respondent bias and non-response error. Many interviewees are involved in program design and delivery or are direct beneficiaries. As such, the findings may be biased towards more favorable program outcomes. Several measures were taken to reduce the effect of respondent biases. For example, the purpose of the interview and strict confidentiality of responses were communicated clearly to participants. Further, interview data was cross-referenced across the different stakeholder groups for consistency and validation. Lastly, all findings were triangulated and validated with at least three other lines of evidence.



Attribution

Securing co-funding from other sources is a requirement for both the PI and the IQC, as per the current funding agreements with ISED. In addition, researchers at these institutes are also able to seek funding from other federal sources such as grants. It is therefore challenging to attribute the impact of specific research achievements directly to ISED's contribution. Further, given that researchers at the PI and the IQC work collaboratively with other researchers in Canada and internationally to advance their fields, it may be difficult to attribute Canada's overall success in these fields to a single organization. As a mitigation strategy, the evaluation examined each organization's contribution to the advancement of their respective research areas through the selected case studies to highlight their accomplishments.

Findings: Relevance

- *Need for Theoretical Physics and Quantum Research*
- *Need for the Perimeter Institute*
- *Need for the Institute for Quantum Computing*
- *Complementary Quantum Research Institutes*

Need for Theoretical Physics and Quantum Research

Finding: There is a continued need to support theoretical physics and quantum research in order to advance technology development and maintain Canada's competitiveness in these fields relative to other countries.

Need for research in theoretical physics

The document review and interviews found that theoretical physics is one of the lowest cost and highest impact areas of science.[5] It is cost-effective, primarily because the need for access to research infrastructure and equipment is lower than other areas of science. Interviews found that research in theoretical physics relies on collaborations among experts to generate new ideas. In addition to improving human understanding of the universe, such as how stars and the sun work, advancements and breakthroughs in theoretical physics led to discovering technologies such as radios and television. Cutting-edge infrastructure, including High Performance Computing, are also key elements underpinning research in theoretical physics. Today, theoretical physics has been linked to several new technologies such as solar cells, semiconductors, wireless internet and smartphone devices.[6]

The document review also suggests that since any technology relies on the laws of nature, the better those laws are understood, the more powerful the technologies that can be created. Innovation, the ultimate driver of long-term prosperity, therefore has its origins in knowledge generated from basic research such as theoretical physics.[7] Case studies indicate that research advances in theoretical physics produce new knowledge, often resulting in unanticipated technological, commercial and practical applications with unexpected timescales, as history continues to demonstrate. Further, the document review and case studies found that theoretical physics researchers have applied their skills and knowledge in sectors such as finance, cybersecurity, data science, artificial intelligence, biomedicine and quantum technologies.[8]

DID YOU **KNOW** ?

Specialized skills *that researchers in theoretical physics possess, such as mathematics, data modelling, software, and problem-solving, are being actively sought to support the response to the novel coronavirus (COVID-19), with researchers at the PI developing mutation tracking software, group testing methods, and models that track disease spread.*[9]

Need for quantum research

The document review and interviews indicate that quantum research, particularly quantum information science (QIS), is another high impact area, with the potential to produce quantum technologies. Quantum technologies are expected to impact existing sectors ranging from natural resources and communications, to health and finance by providing capabilities not available with today's technologies and enabling new solutions to existing problems.[10]

For example:

- **Communications:** Develop a globally secure network of communications underpinned by the laws of physics
- **Health:** Selection of promising drug candidates and improved MRI speeds at low cost
- **Big Data:** Improved machine learning and quantum artificial intelligence
- **Defense and Security:** Develop quantum encryption technologies, lighter satellites and stealth detection

In addition to creating new industries, QIS could generate significant economic benefits across many current sectors and industries. Literature suggests that by 2030, Canada's quantum industry will grow to $8.2 billion, employing approximately 16,000 people and generating $3.5 billion in returns for the government.[11] It further suggests that by 2040, when quantum technology is anticipated to reach 50% adoption, Canada's industry could be valued at $142.4 billion, producing 229,000 jobs and generating $55 billion in returns. Documents also indicate that research and development investments in QIS act as employment drivers, facilitating progress in science and technology across multiple disciplines and contributing to the development of a highly skilled workforce.[12]

DID YOU **KNOW** ?

*Research efforts in **quantum devices** at the Stewart Blusson Quantum Matter Institute have led to building, testing, and implementing an efficient, ultra-low-cost screening tool that, when it is ready, would enable on-the-go diagnostic testing for COVID-19 and future novel diseases.*[13]

Need for Theoretical Physics and Quantum Research

Need for support to maintain global competitiveness

Stakeholder perspectives suggest that Canada is currently a global leader in both theoretical physics, which is a core focus of the PI, and research in QIS, which is a primary focus of the IQC and includes theoretical and experimental components. Research at the PI also includes QIS, as well as several complementary areas. For example, the document review found that, internationally, the PI and the University of Waterloo rank 20th and 3rd, respectively, based on publications on the subject of quantum computing over the last decade, among other prestigious organizations such as Harvard University in the US, the Quantum Technologies Centre in Singapore, Oxford University in the UK, and ETH Zurich in Switzerland.[14] Further, Web of Science data indicates that the University of Waterloo is among the top five organizations in QIS research. The document review and interviews indicate that international competition in QIS research has increased in the last five years, challenging Canada's leadership, as countries such as China, the United States, and Australia launch national strategies and increase investments in this field.[15] Although the field of quantum is in early stages of producing technological impact, interview data and case studies suggest that research has advanced to the point that applications are beginning to emerge and the field is rapidly evolving.

Furthermore, documents indicate that support for theoretical physics and quantum research is aligned with the Government of Canada's priorities. It is aligned with the Innovation and Skills Plan's goal to equip Canadians with the tools, skills and experience they need to succeed by helping to maintain Canada's leadership role in fundamental research and attract top talent from around the world. Further, the priorities of the Minister of Innovation, Science and Industry's mandate letter include continuing to support innovation ecosystems across the country and investing in scientific research, with an appropriate balance between fundamental research to support new discoveries and the commercialization of ideas.[16]

DID YOU KNOW?

Canada ranks ***first*** *in physics and space science when it comes to key measures of research quality and impact, and* ***fifth*** *in quantum information science and technology based on number of publications and patent applications.*[17]

Need for the Perimeter Institute

Finding: The PI is unique in its breadth of theoretical physics research areas, role in connecting physics researchers, and distinct research environment. With its focus on theory, it plays a complementary role in quantum research relative to the IQC and their physical proximity facilitates collaboration and partnership.

Breadth in research areas

Interviews, the document review, and comparative analysis found that the PI is unique in Canada, and internationally, in its size and independent nature as a not-for-profit institute unaffiliated with a university, as well as in its breadth of research, particularly in its quantum areas. For example, interviews with international stakeholders noted the uniqueness of the PI's research in quantum fields and strings, and indicated it is a global expert in this area. Although universities in Canada may conduct similar research within their physics departments, interviews and the comparative analysis found that their research areas are not as comprehensive as the PI, nor are they focused entirely on theoretical physics. For example, the Canadian Institute for Theoretical Astrophysics at the University of Toronto focuses on modern astronomy and cosmology, which is one of nine research areas at the PI.

Connecting physics researchers

The PI plays a key role in connecting the Canadian physicist community, facilitating interactions between both theoretical and experimental physicists to strengthen physics research in Canada. Interviews and the document review found that the PI has established a collaborative network of physicists through its 'Affiliate' program in partnership with universities. As an 'Affiliate' at the PI, researchers have access to opportunities to participate in research activities, collaborations, and conferences. Data analysis found that between 2016-17 and 2019-20, the total number of affiliate members at the PI reached 119 across 34 institutions in Canada. Further, interviews and the document review indicate that the PI continues to develop relationships and grow its ties with experimental and observational institutes in Canada and internationally, providing a forum where theory can be tried and tested. For example, the PI has a partnership agreement with SNOLAB, an underground physics laboratory specializing in neutrino – weakly interacting, electrically neutral particles – and dark matter – a form of invisible matter existing in the universe that cannot be directly observed. The PI also has a partnership agreement with TRIUMF, Canada's particle accelerator centre, and maintains global connections with the Large Hardon Collider at the European Organization for Nuclear Research (CERN) and the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the US.[18]

Need for the Perimeter Institute

Unique research environment

The PI offers a unique environment for researchers. Surveys found that 90% of PI faculty respondents identified its cross-disciplinary research environment as one of the most common factors that led them to join the PI. For example, interviews and the document review indicate that the PI's environment in comparison to a university is defined by its minimal teaching and administrative requirements which enables researchers to focus their time entirely on their research activities. Further, interviews revealed that the symbiotic relationship with the IQC is another key characteristic of the PI's research environment. The quantum research at the PI is focused on theory and is complimentary to IQC's experimental research. Their proximity to one another facilitates collaborative activities and the achievement of common objectives in quantum research, as evidenced by case studies. For example, researchers at the IQC test the theories developed at the PI in their experiments, while the researchers at the PI provide theoretical insights into experimental observations made at the IQC. The document review identified the IQC as the PI's closest experimental partner and interviews confirmed that strong research coordination and collaboration exist between the two institutes, particularly in the PI's quantum information and the IQC's quantum computing research areas.[19] Further, surveys found that 50% of IQC faculty respondents indicated that access to the PI was a factor that led them to join the IQC.

Key component of the 'Quantum Valley' ecosystem

In the broader 'Quantum Valley', the PI plays a central role in advancing the objective to develop a vibrant quantum ecosystem that accelerates the development of quantum technologies through its focus on the theoretical aspects of QIS. For example, documents found that PI researchers are studying "cause and effect" within highly complex data sets through the PI's Quantum Causal Inference Initiative as part of the PI's quantum foundations research area, and this work, according to interviews, has attracted the interest of a large insurance company to discuss potential applications.[20] Documents and interviews indicate that the PI contributes to advancing QIS technologies and that its uniqueness comes in part from its close proximity not only to the IQC, but to the broader ecosystem that provides business, infrastructure, and commercialization support. Interviews also found that the PI's physical location in Waterloo is important in establishing a high concentration of talent and expertise in the region.

Need for the Institute for Quantum Computing

Finding: The IQC plays a leading role in Canada's efforts to develop quantum technologies, conducting multidisciplinary research in QIS that includes a combination of work in theory and experiments. Its research is unique in the 'Quantum Valley' ecosystem and complements the strengths that have emerged at institutes in other regions of Canada.

Multidisciplinary research environment

Interviews and documents indicate that the IQC contributes to developing a quantum ecosystem through its ability to attract researchers and private sector interest, conduct high quality research in QIS, and demonstrate the potential of quantum technologies through experimentation and early applications. IQC advances progress towards developing viable quantum technologies through its multidisciplinary research environment that crosses several disciplines including physics, mathematics, computer science, engineering, and chemistry, as well as its focus on conducting research across the spectrum of theory, experiments and early applications. For example, researchers at the IQC are leading efforts in quantum simulations, which is rich for collaboration between theory and experiment. This work is based on theories that describe how particles interact at the most fundamental level and literature suggests that it is leading to the development of novel quantum methods. In 2019, these research efforts spurred a joint venture with the PI, the 'Quantum Simulations of Fundamental Interactions' (QFun) research initiative, which brings together researchers across disciplines aimed at developing new, quantum-based methods and tools that will enable simulating, exploring, and understanding quantum phenomena. Data analysis and interviews found that 53% of IQC faculty are theorists, while 41% are experimentalists, with the remaining 6% indicating that they are both. In addition, surveys noted that the IQC's interdisciplinary research environment was one of the most common reasons for joining the IQC.

Key component of the 'Quantum Valley' ecosystem

The IQC is a key component of the Quantum Valley and its location in the Waterloo region is important not only for advancing its objectives, but for developing the region's quantum ecosystem. Literature has identified Waterloo as a "stand-out example" of a big vision for quantum research and technology.[21] According to interviews, the proximity to the PI and the location of the IQC in 'Quantum Valley' provides researchers with access to business and commercialization support, opportunities for academic and industry collaboration, and a high concentration of regional talent. Further, case studies found that in 2020, UK Research and Innovation and NSERC's Canada-UK Projects on Quantum Technologies program awarded three out of eight projects to IQC researchers in the areas of quantum computing and quantum secure communications, highlighting the IQC's leadership role in Canada.[22]

Complementary Quantum Research Institutes

Regional and complementary strengths in quantum research

Although the evaluation identified the IQC as a leading player in QIS, it also noted other regional concentrations of quantum research activity across Canada that are contributing to a national quantum research landscape, particularly at the University of British Columbia's Stewart Blusson Quantum Matter Institute (SBQMI) and the Université de Sherbrooke's Institut Quantique (IQ). Further, the Canada First Research Excellence Fund (CFREF), led by the tri-agencies (i.e., Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council of Canada and the Social Sciences and Humanities Research Council of Canada), supports Canadian universities in developing their existing strengths into world-leading capabilities. The CFREF awarded grants to the IQC in 2016-17, and to both the SBQMI and IQ in 2015-16, through their respective universities. It was found from documents and the comparative analysis, that these three institutes have unique strengths.[23] For example, the SBQMI specializes in quantum materials and device development while Sherbrooke's IQ specializes in quantum electronics and engineering. Interviews also suggest that these institutes view the IQC as having complementary strengths, particularly in quantum computing, quantum communication and quantum sensing areas that have resulted in major advancements, according to case studies.

In terms of collaboration between institutes, interviews found that it is on an as-needed basis, such as joint research projects and publications. Literature indicates that while Canadian institutes collaborate less in comparison to countries such as the UK, this is in part due to the great physical distances between centres of activity.[24] Interviews and the comparative analysis noted that the CFREF has facilitated collaborative activities, and as of March 2019, the three institutes are collaborating on five new joint research projects expected to accelerate advances towards quantum breakthroughs. The institutes are also working to share infrastructure through the 'Quantum Co-lab' initiative and minimize research duplication by hosting annual conferences to encourage collaboration between individual researchers. In light of rising international competition, interviews noted that there is an opportunity to foster greater collaboration across quantum institutes at Canadian universities.

The CFREF allocated a total of $176.3 million over 7 years to advance quantum research efforts at Canadian universities.

Recommendation: ISED SRS should monitor the quantum research landscape in Canada more broadly, including the complementary strengths that are evolving at research institutes across Canada.

Findings: Performance

- *Outreach and Engagement Results*
- *Capacity Building and Training Results*
- *Research Advancement and Application Results*

Finding: The PI continues to deliver effective outreach and engagement programs that target diverse audiences in Canada and internationally. The PI has also prioritized promoting physics to youth in an effort to grow interest in this field and build a diversified talent pool of next-generation researchers.

Engaging the general public in order to increase scientific literacy

The PI's public outreach efforts are extensive, according to the document review, data analysis, and interviews. In 2017, the federal government selected the PI to lead 'Innovation150', a national outreach campaign in partnership with organizations such as the IQC to highlight Canadian innovation. This included the PI's 'Power of Ideas' travelling exhibition, which engaged over 140,000 students across 390 Canadian communities, including those in remote and indigenous regions, and led to a spin-off exhibition in Ontario. The PI has hosted 6 to 9 public lectures annually, inviting researchers from around the world to present on physics topics. The document and data review found that all lectures, to date, have amassed ≈4.65 million views. Further, in 2010, the PI launched 'Inside the Perimeter', a semi-annual magazine that highlights the PI's activities.

Interviews indicate that the PI has also made efforts to communicate the value of theoretical physics to the private sector through fundraising activities and discussions with business leaders who remain current on the PI's research activities. Survey results indicate that there are a few faculty members at the PI whose knowledge dissemination efforts target the business community. To support those interested in pursuing private sector opportunities, the document review and interviews found that the PI launched its 'Career Trajectories' conference series in 2018-19 to provide students and researchers with the opportunity to network with industry players and learn about potential non-academic career options.

Data indicates that 97% of participants in the PI's public lectures over the evaluation period were inspired to learn more about science, technology, engineering and mathematics (STEM).[25]

Training educators to teach physics to youth and build the next generation of researchers

The PI's efforts to build the next generation of researchers are focused primarily on high school programming and educational modules as indicated by the document review, data analysis, and interviews. The PI's International 'Summer School for Young Physicists' (ISSYP) reaches a diverse cohort of high school students. From 2016-17 to 2019-20, 160 students from across Canada and around the world explored topics in theoretical physics through the ISSYP and the PI achieved gender parity in participants each year. During this time period, 50% of the ISSYP participants were from other countries. To date, the ISSYP has trained 865 students across 61 countries. Data suggests that 95% of ISSYP alumni indicated that their experience at the PI positively impacted their attitude toward science, while 69% noted that their attendance had inspired them to pursue a career in physics or math. Furthermore, the PI's 'Inspiring Future Women in Science' annual conference aims to address gender imbalance in STEM. It provided 665 female high school students in Canada with the opportunity to connect with and receive mentorship from successful women pursuing STEM careers.

The PI offers free, online educational modules that provide educators with resources to teach physics to students. From 2016-17 to 2019-20, these modules, which are available in other languages, reached ≈9.7 million students annually worldwide, and since 2006, have facilitated ≈59 million student interactions across 106 countries. The PI engages teachers primarily through its 'Perimeter Teacher Network', which is composed of over 100 teacher trainers worldwide who train high school educators on how to use the PI's educational resources to teach physics. The PI uses a 'train-the-trainer' model by training teachers to provide workshops to other educators in their home districts. From 2016-17 to 2019-20, it delivered 641 workshops. It also offers an 'EinsteinPlus Teacher Training Camp', which introduces high school teachers to the PI's educational resources and teaching methods. Since 2016, the PI has also collaborated with more than 450 teacher educators to deliver 25 workshops to Indigenous communities.

The PI delivered 641 workshops between 2016-17 and 2019-20, and together with its teacher training camp, trained a total of ≈18,300 educators during this time period, half of which were educators from countries outside of Canada.[26]

Raising awareness and visibility of research activities within the scientific community

The PI increases awareness and visibility of its research within the scientific community. Evidence from interviews and surveys indicate that PI researchers' publications are one of the primary ways that the PI engages with the scientific community, and that without PI publications, Canada's standing and visibility would drop internationally. Further, bibliometrics confirm that Canada's citation impact would have fallen from first to fourth in 2019 without the PI.[27] In addition to peer-reviewed publications, a survey of the PI's faculty found that members engage the scientific community primarily through conferences, seminars, and colloquia as well as lectures and presentations that provide opportunities to share current research while engaging in knowledge exchange and facilitates collaboration. The comparative analysis found that that these activities are unique to the PI and that there is no other institute in Canada that leads similar activities. Data suggests that from 2016-17 to 2019-20, the PI hosted an average of ≈300 scientific talks per year. In the same time period, the PI hosted an average of 16 workshops and conferences per year, with 799 participants annually. The document review suggests that these activities covered the latest developments, challenges, and advances in theoretical physics.[28]

The document review also found that the 'Perimeter Institute Recorded Seminar Archive' (PIRSA) extends the PI's reach beyond those directly participating in its in-person activities. The PIRSA is an online archive of all seminars, conferences, workshops and courses. As of January 2020, the PIRSA contained 12,750 recordings, with 400 to 800 new videos added each year. Data suggests that from 2016-17 to 2019-20, PIRSA recordings produced 700,000 to 900,000 views annually. Further, documents and interviews suggest that the PI intends to launch a five-year project called 'SciTalks.ca' to provide an open-source software toolkit that would allow any institution to establish their own standardized and searchable repository of institutional talks. The ultimate objective of this project is to link institutional repositories from around the world into a single, searchable platform.

Subscribers across all social media platforms have risen 264% and PI's YouTube engagement has been highly successful, with the total number of video views rising annually from ≈900,000 in 2016-17 to ≈2.5 million in 2019-20.[29]

Finding: The outreach and engagement programs at the IQC are effective at raising interest in quantum information science among the Canadian general public, particularly diverse high school and undergraduate students. Further, the IQC's outreach with the business community is primarily focused on pre-commercialization activities.

Educating the general public to raise interest in QIS

Over the evaluation period, the IQC's notable efforts to engage the general public included its exhibition events, in-person public lectures, and a growing online presence, as indicated by the document review, data analysis and interviews. Data suggests that the IQC exhibitions have been the most impactful in terms of reach. In 2017, the IQC participated in 'Innovation150', a national scientific outreach program led by the PI. The IQC's contribution included a 4,000 square foot bilingual exhibition designed to engage visitors of all ages in core quantum concepts. The IQC exhibitions, including the IQC's 'Quantum: The Exhibition Series'; 'Quantum: The Pop-up Exhibition Series'; and the 'Visitors to Lights Illuminated Exhibition' reached ≈938,000 Canadians. Documents indicate that parts of the tour was also delivered to remote and underrepresented communities such as Iqaluit, as well as those in Europe and Asia.[30]

In addition to these exhibitions, over the evaluation period, the IQC conducted 285 public outreach activities that reached over 15,000 members of the general public. Of these activities, the top three most impactful in terms of number of events and participants reached were high school laboratory visits, public lectures from world renowned researchers, and educational sessions for youth. Other activities included open houses, school visits, science fairs, webinars, and workshops. According to interviewees, IQC's outreach activities have been effective in engaging the general public and have contributed to increasing awareness and interest in QIS as well as STEM overall.

The IQC's online presence continues to grow, with its total followers across all social media platforms having increased by 305% over the evaluation period.[31]

Engaging youth in QIS and training educators on introducing the topic in classrooms

The IQC's focused efforts to engage youth, particularly high school students, is notable. It has also made concerted efforts to encourage women and girls to pursue QIS, and STEM broadly. It has conducted 12 STEM events for girls and women in elementary and high schools, reaching a total of 568 students. In January 2018, the IQC hosted the first-ever 'Girls in STEM' event in partnership with the City of Waterloo, providing girls with the opportunity to engage with successful women in STEM careers. Further, the IQC's 'Quantum Cryptography School for Young Students' (QCSYS) invites ≈40 Canadian and international high school students to the IQC each year to explore QIS and data suggests that this training program achieves gender parity. From 2016-17 to 2019-20, the total number of applications in the QCSYS rose from 210 to 309.

Furthermore, interviews and the document review found that the IQC engages the teaching community through workshops and training sessions to teach educators how to introduce QIS in their classrooms. In 2015-16, the IQC launched 'Schrödinger's Class', a workshop that trains Canadian and international high school educators on how to integrate QIS into teaching curriculums. Data suggests that in 2018-19 and 2019-20, the program received a total of 102 applications for ≈39 available spots. Documents also indicate that the program reaches a broader teaching community beyond the immediate participants using a multiplier effect, with participants in 2019-20 indicating that on average, each one would share the material learned in the program with 22 other teachers.[32] The IQC also hosted 30 training sessions and workshops for teachers during the evaluation period, totaling 1,100 participants.

Data suggests that 92% of participants in the IQC's 'Quantum Cryptography School for Young Students' indicated that it enticed them to seek further information on how to pursue a future in QIS.[33]

Transferring knowledge of QIS within the scientific and business communities

The document review and data analysis indicate that the IQC engages the scientific community primarily through its program of seminars, colloquia, conferences, and workshops. These events address current topics in QIS and provide a forum to stimulate collaborations. Data indicates that the IQC conducted 554 outreach events to the scientific community, the majority of which were seminars and/or colloquia, reaching a total of ≈4800 participants. Over the evaluation period, faculty members at the IQC, on average, were invited to participate in a total of 126 conferences annually as well. In the last five years, IQC researchers have given over 44 talks, representing 13% of all break-through research presented at the international conference on Quantum Information Processing, an annual meeting for QIS research worldwide.

The IQC has also made efforts to engage the business community through its pre-commercialization activities such as tours and visits, industry meetings with faculty members, and outreach at industry conferences. Furthermore, interviews, documents and data found that the 'Transformative Quantum Technologies (TQT) program' – an initiative funded by the CFREF to support research at the IQC – plays a role in industry engagement. Data indicates that over the evaluation period, the IQC engaged industry through 4 symposia, 3 educational sessions, and 13 meetings with private sector firms reaching a total of 445 participants. The IQC also conducted 139 industry tours and visits with companies such as Microsoft, Nokia, and ISARA. It was noted in interviews that as quantum technologies begin to emerge, there will be an opportunity for the IQC to expand its pre-commercialization activities by engaging first adopters of technology and facilitating connections with researchers, as well as increasing the private sector's awareness of the ways in which QIS could address industry challenges. Surveys revealed that many IQC researchers use commercialization avenues such as the 'Quantum Valley Investments Fund', launched in 2013 to support the commercialization of breakthrough technologies in QIS, as well as the 'Waterloo Commercialization Office', which offers support and expertise to package and convert research innovations into commercially viable products and services. Further, surveys found that 43% of respondents are presently not pursuing commercialization opportunities, for reasons such as the significant time investment required, the research being at a low technology readiness level, or the current research focus is on quantum theory.

Surveys of IQC faculty suggest that 57% of respondents are interested in commercialization opportunities, with all having indicated a level of satisfaction with the IQC's private sector outreach activities.

Finding: The PI has been effective in leveraging diverse Canadian and international talent through its ability to cross-appoint researchers in collaboration with partnering institutions and its offering of unique recruitment programs. It continues to build its research capacity and provide world-class training in theoretical physics.

Access to a high-quality, productive research environment

The PI is making a significant contribution to Canada's leadership and reputation in theoretical physics, drawing in exceptional talent through its competitive research programs and high quality of research, as documents and interviews suggest. Bibliometric analysis supports this assessment, showing that the PI's research contribution is vital to Canada's rank as first in physics and space science.[34] The document review and data analysis found that the total number of publications produced by PI-affiliated researchers since inception has risen from ≈4600 in 2016-17 to ≈6300 at the end of 2019-20, and as of July 2020, these papers have appeared in more than 250 journals. Furthermore, cumulative citations continue to rise as these papers have been cited ≈290,000 times.

The PI attracts world-class theoretical physicists through its unique structure, which surveys and interviews indicate is defined by its minimal teaching and administrative requirements such as mandatory grant writing. This creates an attractive environment that allows researchers to focus entirely on their research activities. For example, documents indicate that the PI hosts one of the largest, if not the largest, group of independent postdoctoral fellows in theoretical physics in the world granting them full autonomy to pursue independent research programs.[35] Data shows that the total number at any one time has increased from 59 in 2016-17 to 84 in 2019-20, across 32 countries. The comparative analysis and interviews suggest that the PI's research environment is unique in comparison to other institutes around the world. Further, infrastructure at the PI optimizes theoretical physics research and training. For example, it includes a purpose-built facility with collaboration spaces and resources, learning and conference facilities, and state-of-the-art computing resources, including access to high performance computing and computational scientists.

In 2019, Canada's performance via percentage of papers in the top 1% of most highly cited publications would have fallen from first to fourth if the publications by PI researchers were excluded.[36]

Leveraging and attracting talent using collaborative recruitment programs

The PI leverages global talent through its ‘Associate’ and ‘Affiliate’ programs. Its ‘Affiliate’ program is intended to strengthen the Canadian physics research community by allowing faculty from Canadian universities to make regular, informal visits to collaborate with the PI’s resident researchers and attend its events. Over the evaluation period, the PI had up to 119 ‘Affiliates’ across 34 organizations each year, predominantly within Canada. In addition, the PI’s ‘Associate’ program works with nearby institutions to make joint faculty hires. In 2019-20, data found that it jointly recruited three ‘Associate’ faculty with the IQC. Data indicates that the IQC and the University of Waterloo represent the highest proportion of any partner institution. The PI and the IQC have also offered joint postdoctoral fellowships. Documents and interviews indicate that joint recruitment programs are critical tools in establishing the PI, and therefore Canada, as a global leader in theoretical physics.

The comparative analysis found that collaborations in theoretical physics are predominantly at the researcher-to-researcher level stemming from interactions at the PI. Interviews and documents indicate that the PI’s research environment is enhanced by its scientific visitor programs which connect Canadian and international physicists by providing opportunities for visiting scientists to collaborate with resident researchers through short-term and extended visits. The PI’s main visiting programs include the ‘Distinguished Visiting Researcher Chairs’ and ‘Visiting Fellows’ programs which attract researchers from institutions around the world to deliver talks, collaborate and attend conferences. It also includes the ‘Simons Emmy Noether Fellows’, a visiting program launched in 2013 that provides young to mid-career females with the opportunity to conduct research at the PI and advance their careers through scholarly and research outcomes. Documents also indicate that ≈1000 scientists visit the PI each year through these visiting programs or through invitations to participate in research collaborations or other activities.[37]

The PI has 12 agreements signed with research centres in Canada and abroad to promote research collaboration in areas of common interest and to encourage scientific exchange visits.

Recruiting and training diverse students through world-class academic programs

The PI's training programs attract talent to Canada. Surveys found that nearly 90% of HQP respondents indicated they had greatly increased their knowledge of theoretical physics at the PI, with 70% specifically noting a great increase in knowledge of quantum research. These respondents also highlighted the development of technical skills at the PI such as computational techniques in machine learning and computer coding. Data indicates that the PI trains graduate students through its 'Perimeter Scholars International' (PSI) program – a one-year Master program that provides an overview of theoretical physics, emphasizing quantum phenomena at all scales – and its PhD program. The total number of resident PhD students in training grew from 53 in 2016-17 to 77 in 2019-20, from 39 countries. During that time, the percentage of PhD students reporting non-Canadian citizenship ranged from 80 to 90%. Through its PSI program, the PI trained 116 students from 48 countries, with nearly 40% of students identifying as female. Of these PSI graduates, 86% pursued PhD studies, of which 31% chose to continue at the PI. Documents indicate that the PSI program is the PI's primary source of talent for the PhD program and since 2015, approximately two-thirds of the PhD students at the PI were graduates of the PSI.[38] In 2020-21, the PI achieved a 100% acceptance rate in terms of offers made to students for admission into the PSI program. Moreover, the PI also reports that the strength and volume of PSI applications allows it to lead in pursuing gender balance in its graduate programs.

In 2018-19, the PI launched its 'Undergraduate Theoretical Physics Program' offering undergraduate students a two-week summer immersion in research, talks, and events at the PI. In its first year, it attracted applications from 76 countries and has served as a recruitment tool, with 6 students from the first cohort recruited into the PSI program. Over the evaluation period, the total number of undergraduate students at the PI at any one time has more than doubled, from 20 in 2016-17 to 55 in 2019-20. It has also nearly achieved gender parity, as 47% of participants to date have identified as women.

While the first cohort of the PI's master program in 2009 was 20% women, data analysis found that the 2019 cohort was 50% women, a major accomplishment for a graduate physics program.

Finding: The IQC has been effective at building its capacity to undertake research through its access to state-of-the-art infrastructure and the 'Quantum Valley' ecosystem. It continues to attract diverse talent, support the training of next-generation quantum researchers, and facilitate international collaboration in QIS.

Access to state-of-the-art research infrastructure

The IQC provides researchers with access to state-of-the-art infrastructure and equipment necessary to advance QIS research. Interviews and documents indicate that the IQC's faculty start-up packages, which provides support to acquire start-up equipment, high quality laboratories and facilities, and infrastructure in the broader 'Quantum Valley' are all essential for not only attracting researchers, but also in enabling and advancing experimental QIS research. Data revealed that the IQC attracted 10 new quantum experimentalists over the evaluation period, reaching its target, and provided them with support to set up new laboratories in the Quantum-Nano Centre, demonstrating its commitment to building research capacity.

Documents and interviews found that the IQC also contributes funding to support the University of Waterloo's 'Quantum Nanofabrication and Characterization Facility' (QNFCF), a world-class facility that provides researchers across Canada with access to fabrication tools and equipment to run experimental tests and build devices. In 2019-20, the QNFCF reported 32,894 hours of independent lab equipment use, the highest use in one year, and documents suggest that in that same year, 195 researchers from 59 different research groups across Canada used QNFCF equipment, suggesting that the facility has a broad reach beyond the Waterloo region. Documents indicate that developments continue to be made to research infrastructure at the University of Waterloo, for example, with the addition of its new 'Quantum Exploration' space, which is a demonstration area intended in part, to facilitate engagement between industry and academia.[39]

Data suggests that the demand for access to the University of Waterloo's Quantum Nanofabrication and Characterization Facility has increased in the last four years, with an average annual growth of 46% from 2016-17 to 2019-20.

Attracting high calibre faculty and graduate students

The IQC attracts and recruits high-calibre researchers at all levels and is regarded as an international destination of choice for QIS research. Surveys found that the critical mass of top-quality researchers was one of the most common reasons for joining the IQC. Further, ≈50% of researchers surveyed indicated that the opportunity to access the researchers at the PI was an important factor for choosing the IQC. Its support for lab start-up activities was another important factor, also noted by ≈50% of survey participants. Over 65% of HQP reported that they were attracted by the opportunity to receive mentorship from researchers at the IQC. Data and literature indicate that, collectively, researchers at the IQC produce, on average, 146 publications annually. Cumulative citations have reached 47,564, exceeding the IQC's goal of 35,000 citations by 2019. Most recently, in 2019-20, Web of Science data indicates that two papers by an IQC researcher were placed in the top 1% of the academic field of mathematics based on their citations.

In terms of recruitment of talent, the IQC is on track to meet its target of 39 faculty by 2023. Over the evaluation period, data suggests that it recruited on average, two new faculty members per year, increasing its faculty size from 23 members in 2014-15 to 32 in 2019-20. Data also indicates that the IQC reached its target of 65 postdoctoral fellows, from 46 in 2014-15 to 65 in 2019-20. In terms of graduate student recruitment, the IQC is exceeding its target of 165 as the total number of graduate students in training at any one time increased from 126 in 2014-15 to 203 in 2019-20, representing a 61% growth rate overall. Over the evaluation period, the IQC received an average of 292 applications annually to its 'Collaborative Quantum Information' graduate program', with a target of 200 applications. Notably, the IQC experienced a significant increase in applications in the last year, rising from 268 in 2018-19 to 528 in 2019-20. Data also found that ≈54% of students currently enrolled in the IQC's graduate program or supervised by IQC faculty were international students, suggesting a diverse group of students. Further, just under 20% of students enrolled or supervised by IQC faculty identify as female.

Over the period covered by the evaluation, the IQC successfully hired three women faculty members, improving the faculty gender balance from 4.3% in 2014-15 to 12.5% in 2019-20.

Unique training programs for researchers across all levels of education

The IQC's training programs contribute to recruiting talent. Nearly 70% of undergraduate students in the IQC's 'Undergraduate School on Experimental Quantum Information Processing' (USEQIP) from 2017 to 2019 indicated that, they were interested in pursuing the IQC's graduate program. Further, nearly 75% of postdoctoral fellows that participated in the IQC's 'Quantum Innovators Math and Science' program from 2017 to 2019 indicated they would consider the IQC as a destination for their scientific career.[40] The training programs at the IQC benefit participants by increasing their knowledge in QIS and developing the skills necessary to succeed in this field. The IQC hosts training programs that target researchers across all levels of education. Documents suggest that these programs offer high school and undergraduate students the opportunity to explore QIS, while providing a forum for graduate students and postdoctoral fellows to discuss and receive specialized training in topics such as quantum cryptography and quantum communications. Further, data indicates that 85% of USEQIP participants felt that the program gave them the tools needed to begin investigating the quantum information field.

According to surveys, all HQP respondents reported that acquiring research experience in the form of new knowledge and technical skills was a benefit from working on research at the IQC. When asked to specify a notable skill they acquired, survey responses were diverse, highlighting QIS specific knowledge and skills such as learning quantum security proof and microfabrication techniques, to developing transferable skills such as critical thinking and scientific project management abilities. The IQC also explores options to enhance its training programs. For example, interviews indicate that the IQC is developing a new one-year course-based Master's program to prepare graduates for careers in the quantum industry. Furthermore, in response to industry demand for workforce training, the IQC is developing a micro-credential learning platform to build awareness and knowledge of QIS.

Nearly 75% of 'Quantum Key Distribution Summer School' participants at the graduate and postdoctoral level indicated that the program gave them a solid foundation in relevant approaches and techniques, enabling them to perform their own independent research.[41]

Facilitating researcher-to-researcher collaborations

The IQC facilitates researcher-to-researcher collaborations by creating an environment that provides individuals with the opportunity to identify new partnerships. Surveys indicate that 97% of IQC faculty and 82% of HQP respondents were satisfied with their opportunities to develop collaborations for their research. Regarding the types of collaborative activities, faculty and HQPs were most likely to indicate involvement in a joint research project or peer-reviewed co-publication for both their national and international collaborations. Further, data analysis found that IQC faculty were involved in 1,246 collaborations, 82% of which were joint publications. Notably, surveys indicate that the most frequent collaborations are with researchers at the University of Waterloo and the PI. Survey data and interviews suggest that research collaborations with other quantum institutes in Canada is minimal. However, the comparative analysis found that quantum institutes are interested in exploring and discussing additional opportunities for collaboration with the IQC, beyond what is being facilitated by the CFREF.

These surveys also indicate that, internationally, participants were most likely to identify collaborations with researchers in North America and Europe. Further, surveys and interviews highlighted the importance of the IQC's scientific visitor program in creating an environment for researchers to identify potential collaborations. Data indicates that faculty members reported an average of 88 active or ongoing collaborations annually across 78 unique organizations. Over the evaluation period, the IQC hosted, on average, ≈139 scientific visitors per year. In each year, these visitors came from an average of 108 unique organizations. Overall, 86% of visitors have come from outside of Canada. Furthermore, documents found that the IQC has a total of 13 signed agreements with universities and international organizations to facilitate collaborative research and exchange visits.[42] For example, in 2016-17, the IQC established an agreement with the Beijing Computational Science Research Center to promote possibilities for educational cooperation by conducting joint research and exchanging postdoctoral fellows.

Data indicates that nearly 70% of all publications by researchers at the IQC were co-authored in collaboration with international researchers.

Finding: The PI has contributed to major scientific breakthroughs in theoretical physics and continues to advance the field. Further, its research in quantum theory is leading to applications in artificial intelligence and supporting start-up companies in quantum computing, with an increasing number of PI researchers applying their knowledge in the private sector.

Contributing to scientific breakthroughs and applying knowledge and skills

Since 2016, documents indicate that 62 major prizes and honours have been awarded, recognizing major scientific discoveries by PI researchers, including seven New Horizons Prizes ("the Oscars of Science"), more than any institution worldwide. Case studies found that the PI and its researchers are continuing to advance research in theoretical physics and contribute to scientific breakthroughs by solving long-standing questions and exploring new questions and ideas. For example, among the research results generated at the PI since 2016-17, surveys of faculty and HQP found that over 90% of total respondents indicated that their research enabled new questions to be asked or ideas to be explored. In addition, 71% of faculty respondents indicated that their research enabled a long-standing question or challenge to be solved. Literature also suggests that research at the PI is having a notable impact on scientific advancement, with 4.7% of PI papers being in the world's top 1% of those most highly cited.[43] This percentage is more than double that of the entire Canadian physics and space science dataset, which is 2.2%, and is nearly five times that of the global average, which is 1%.

Although the current PI logic model (see Annex A) does not include an outcome related to the impacts or applications of theoretical physics research, aside from publications, case studies identified notable examples from collaborations with experimental research institutes and the private sector. Further, surveys found that at least one researcher at the PI was granted intellectual property rights. Notably, 10% of faculty respondents indicated that their research led to involvement with technology start-up companies, including Universal Quantum Devices, Quantum Benchmark, QuantumLaf Inc, and Xanadu, suggesting that there is unexpected interest in private sector opportunities by PI researchers. The document review found that 12% of past postdoctoral fellows who left the PI between 2015 and 2020 pursued opportunities in the private sector in careers such as finance, data analysis, and technology start-ups.[44] Similarly, surveys found that many current HQPs at the PI are applying their knowledge and skills in the Canadian private sector and 12% of total HQP respondents intend to do so after completing their studies.

The next section presents examples of research results achieved by the PI from 2016-17 to 2019-20.

Strong Gravity

Cosmology

Quantum Matter

Quantum Information

Research in strong gravity strives to understand both the theoretical and observational aspects of systems in which gravity is very strong.

The 'Event Horizon Telescope' (EHT) Initiative was created in 2015 to support the PI's efforts on the EHT, a collaboration involving 13 partners and more than 50 institutions around the world. The EHT is a virtual Earth-sized telescope that aims to capture images of 'black holes', which are points in space where gravity is very strong. In 2019, the EHT produced a scientific breakthrough – the first image of a black hole's 'event horizon', which is the theoretical boundary that prevents all matter, even light, from escaping the black hole. Case studies found that researchers at the PI contributed to the EHT by focusing on the science utilization of the data generated, which provided access to the dynamical environment that surrounds black holes. This work involved creating mathematical models and developing key analysis software that provided the foundation for the results reported in the publications presenting the image of a black hole on galaxy Messier 87 (M87), which literature indicates is the strongest evidence to date on the existence of the event horizon.[45]

In 2019, the PI launched its Gravity Waves and Fundamental Physics initiative to seek novel ways of harnessing observations to answer fundamental physics questions. Researchers are obtaining predictions that will help advance gravitational wave detectors. For example, PI researchers have shown how black holes can diagnose the presence of new particles, giving signatures that can appear in the Laser Interferometer Gravitational Wave Observatory (LIGO) or any future gravitational wave telescope.

DID YOU KNOW?

*M87 is a galaxy with the most **powerful** known source of radio energy, and at its heart exists a black hole – this is the same black hole that was captured as an image by the EHT.*

***Four** prestigious prizes that recognize research excellence were each awarded to two researchers at the PI for their major contributions to the scientific breakthrough made by the EHT.*

Research in cosmology aims to understand the constituents and history of our universe, and the rules governing its origin and evolution.

In 2017, the PI created the Centre for the Universe (CFU), an initiative focused on cosmology. The CFU complements the Waterloo Centre for Astrophysics at the University of Waterloo, which focuses mainly on experimental observation. Case studies indicate that both Centres recognize that the most important advances happen when they collaborate. Data found that the PI is involved in 12 collaborations in experimental observation. For example, the PI participates in the Canadian Hydrogen Intensity Mapping Experiment (CHIME), a radio telescope located in British Columbia, in collaboration with the National Research Council and over 50 Canadian researchers. Compared to traditional radio telescopes, the CHIME is potentially much more powerful and generates significantly more data.

Case studies and interviews found that researchers at the PI have developed several algorithms for analyzing the CHIME data and implemented them as software. The result was a 'fast radio burst' (FRB) search that ran 100x faster, which opened up the possibility of new searches and experiments. FRBs are bright, ultra-brief radio signals from outside our galaxy that have perplexed researchers since their discovery in 2007. Canada's CHIME telescope has discovered over 1000 FRBs compared to the 79 FRBs found cumulatively by all other telescopes, making it the world's best detector of FRBs. In addition, the CHIME has also worked with industry partner, Advanced Micro Devices (AMD), to test next-generation computer chips.

DID YOU KNOW ?

*The CHIME is being upgraded to improve its angular resolution of FRB scans by a factor of **100,000**, powered by new software.*

*With **8x** the statistical power, the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD) is being developed as a follow-up to the CHIME.*

Strong Gravity

Cosmology

Quantum Matter

Quantum Information

Research in quantum matter studies the behaviour of a system with many particles, also known as 'many-body' systems.

The PI launched the 'Perimeter Institute Quantum Intelligence Lab' (PIQuIL) in 2018, the first artificial intelligence (AI) lab formed directly out of a physics institute. This PI-based lab now includes partnerships between the PI, 1QBit, Vector Institute and the National Research Council. Research at the PIQuIL spans machine learning and quantum matter, applying computer algorithms to study complex systems that have many interacting particles. AI refers to the simulation of human intelligence in machines, and machine learning is a form of AI that enables a system to learn from data rather than through explicit programming.

Case studies, documents and interviews suggest that researchers at the PIQuIL collaborate with experimental quantum computing laboratories, including the IQC, as well as top machine learning theorists and practitioners. Further, collaborations with top academic and industry players, such as the IQC, Harvard, Google, and IBM, provide the PIQuIL with unique access to the most advanced quantum hardware. The PIQuIL is actively developing next-generation AI software for scientific research and industry. Literature indicates that its researchers have published their results in peer-reviewed journals.[46] Case studies found that these researchers have also developed an open source platform (e.g.,QuCumber) and algorithms for AI-enabled discovery.

DID YOU KNOW?

__Five__ researchers at 1QBit, a quantum computing start-up company based in British Columbia, were relocated to the PIQuIL to take advantage of its unique training, skills building opportunities, and research synergies.[47]

Communitech Data Hub, a __start-up__ incubator in Waterloo, is the PIQuIL headquarters.

Strong Gravity

Cosmology

Quantum Matter

Quantum Information

Research in quantum information exploits the uniquely quantum laws in an effort to understand and use the properties of the quantum world.

Research in quantum information at the PI is in cooperation with the IQC. The experimentally driven research at the IQC in this area complements the theoretically focused research at the PI, and interviews indicate that collaboration is mutually beneficial.

Case studies and interviews suggest that 'quantum error correction and fault tolerance quantum computation' is an active topic. It involves encoding 'qubits' – the fundamental unit of quantum information – and studying the techniques needed to verify information and protect against errors that occur in quantum computing. While no fully convincing demonstration of fault tolerance has been made to date, documents and literature indicate that researchers, affiliated with both the PI and IQC, have identified a principled criterion that must be satisfied for an experiment to successfully demonstrate fault tolerance.[48] It is likely that the first demonstration will become a standard benchmark when attempting to build large quantum computers. This area has also resulted in industry connections and the launch of start-up companies by researchers affiliated with both the PI and the IQC.

DID YOU **KNOW** ?

100% *of the PI's associate faculty in quantum information are also faculty at the IQC, and its postdoctoral fellows are cross-appointed.*

In 2019, the 'Qfun' research initiative was launched as a ***joint venture*** *between the PI and the IQC to capitalize on advancements that are occurring in quantum technologies.*

Recommendation: ISED SRS should collaborate with the PI to develop metrics for tracking and reporting its impacts on experimental research and private sector applications.

Finding: Although quantum technology development is in early stages, the IQC has made experimental advances in QIS. Start-up companies, patents and quantum products have also emerged as a result of research at the IQC, particularly in areas such as quantum computing and quantum sensing.

Advancing QIS research and progressing towards technology development

Case studies found that the IQC is making progress towards developing technological applications. Surveys of IQC faculty members found that nearly 65% of respondents indicated that their research made significant progress towards the development of at least one technological application. While roughly 1/3 of faculty respondents indicated they had not explored, developed, or applied practical applications for their research, the remaining faculty respondents indicated they had engaged in direct or indirect technology transfer for new or improved commercial products, processes or services (e.g, patenting). Further, nearly 25% of HQP respondents indicated that they had pursued security applications (e.g., more secure communication networks). As of 2019-20, data indicates that IQC faculty collectively hold 47 patents, and an additional 94 patents are pending approval.

As outlined in its logic model (see Annex B), the IQC provides its researchers with pre-commercialization support in the form of workshops, courses, training, and mentorship. Case studies found that IQC researchers are progressing towards commercialization by launching start-up companies. The total number of IQC start-ups rose from 3 in 2014-15 to 14 by 2019-20, which interviews indicate is due to an increased focus on application and technologies in the QIS field. Moreover, documents and data indicate that IQC graduates are increasingly pursuing opportunities in the private sector. Since 2014-15, the proportion of IQC graduates working for industry has more than doubled, from 16% to 33%.[49]

The next section presents examples of results achieved by the IQC in each of its research areas.

Research in quantum computing harnesses the quantum behaviour of atoms, molecules and nanoelectronic circuits for a radically different, and fundamentally more powerful way of computing.

Case study surveys suggest that the highest proportion of faculty members at the IQC work in quantum computing, as three in four indicated that they conduct their research in this area with many working in additional QIS areas. Similar to the PI researchers in quantum information, researchers in quantum computing at the IQC appear to cover a myriad of different research topics.

For example, IQC researchers have conducted experiments that use and control currently existing quantum processors (which have limitations) to simulate phenomena in physics. This has allowed researchers to determine if phenomena predicted in theory actually exist in reality and may lead to simulations of problems in physics that were previously considered impossible to solve. In 2019-20, an IQC researcher used a quantum processor to simulate a property in quantum gravity that had been primarily theoretically-based.[50]

DID YOU KNOW ?

*The PI and the IQC together make up one of the **world's largest** and most prolific collections of QIS theorists and experimentalists.*[51]

*IQC researchers have begun **simulating** quantum phenomena that have been primarily theoretical, such as quantum gravity, a current research area of focus at the PI.*[52]

Quantum Computing

Quantum Sensing

Quantum Communication

Quantum Materials

In 2019-20, case studies found that IQC researchers developed a new method called 'cycle benchmarking' to measure and correct errors that occur in quantum computing, setting the standard for comparing quantum technologies and their qualities today. This method is considered a breakthrough in the global effort to develop a quantum computer and interviews note that it is the global standard for error correction and characterization. IQC researchers developed this method into a software that eventually led to their start-up 'Quantum Benchmark'. Case studies indicate that this software has had a notable impact on how quantum devices are tested and contributes to the development of quantum computing performance standards globally.

Case studies also suggest that advancements are being made by IQC researchers in quantum computing algorithms. Research in quantum computing algorithms focuses on understanding potential applications of universal quantum computers and the currently available, early-stage quantum devices that have limitations. Interviews and documents indicate that researchers at the IQC have developed new models for quantum computing including algorithms that can outperform any classical algorithm, and this work was published in *Science*. Case studies found that quantum computing research at the IQC also focuses on other topics, such as understanding and classifying the problems that quantum computers could solve in the near and medium-term, and simulating quantum computers via classical computers.

DID YOU KNOW ?

Technology companies such as Google and IBM are using the quantum error correction ***software*** *that was developed by IQC researchers.*[53]

Three products have been brought to ***market*** *through IQC start-up companies, providing software packages in quantum error correction, quantum-safe cryptography, and quantum-related services.*[54]

Research in quantum sensing applies quantum mechanics to develop new sensors with significant increases in sensitivity, selectivity and efficiencies.

Case studies and interviews indicate that IQC researchers are continuing to make progress towards developing and commercializing quantum sensors, and are launching start-up companies. Researchers have developed a new quantum sensor prototype with the capability to outperform existing commercial technologies. This new sensor is expected to yield benefits for sensing applications, including improved dose monitoring for cancer treatments. For example, a health practitioner could precisely monitor doses in cancer treatment, ensuring that the dose provided is sufficient to kill the cancer cells without killing healthy ones. Other benefits include higher resolution 3D imaging, improved imaging from space, and laser remote sensing. This new sensor is based on semiconductor nanowires that can detect single particles of light – a single photon – with high speed and efficiency over an unparalleled wavelength range. Currently, no commercially available device is able to do this. Having proven itself within the lab, this quantum sensor prototype is being packaged with electronics and portable cooling for testing outside of the laboratory, with an objective of commercializing in the next 3 to 5 years. Case studies suggest the quantum sensor is transitioning from the research group to their start-up company, Single Quantum Systems, with a planned launch in 2021.

DID YOU KNOW ?

Quantum sensing currently has the greatest range of existing and potential technological ***applications*** *out of all QIS areas and is the most likely to yield benefits in the near-term.*[55]

IQC researchers have succeeded in developing a new quantum sensor prototype, which is described as a ***next-generation*** *quantum sensor.*

Additional evidence from interviews and the document review show that other researchers are also producing quantum sensing devices that have potential benefits in many application areas. For example, an IQC researcher is currently working collaboratively with the University of Waterloo's School of Optometry to develop a structured light microscope that could enable optometrists to image and track the physiology of the eye in order to detect degeneration in the central area of the retina before the onset of symptoms. This researcher's quantum sensing company, High Q Technologies LP, was launched in 2018 and brings expertise to the microbiology community. Documents indicate its sensors are 100,000 times more sensitive than existing technologies.[56]

Interviews and documents indicate that progress has also been made to develop 'quantum radar' technology. Quantum radar relies on a sensing technique called 'quantum illumination' to detect and receive information from objects, but this has only been explored in the laboratory and not in the field. The document review showed that in 2018-19, IQC researchers in collaboration with researchers from Université de Sherbrooke and Defence Research and Development Canada (DRDC) succeeded in completing the first experimental demonstration of quantum-enhanced noise radar which may have practical applications for current radar technology.[57] Researchers showed the quantum process outperforms a classical radar by a factor of 10, allowing for the detection of objects that are smaller, faster and farther while making the radar itself less detectable.

DID YOU **KNOW** ?

IQC researchers are developing a quantum sensing ***device*** *that will detect degeneration in the eye.*

The Department of National Defence invested ***$2.7 million*** *in an IQC-led project to develop quantum radar technology that would allow isolating objects such as missiles with unparalleled accuracy.*

Research in quantum communication aims to develop ultra-secure communication channels and global quantum networks by leveraging the power of the quantum world.

When quantum computers emerge, their processing power will be able to break encryption codes used by current technology to protect private and sensitive data. Quantum key distribution (QKD) technology was created to respond to this threat by ensuring the confidentiality of information transmitted between two parties. Information is transmitted using individual particles of light called 'photons' and the laws of quantum physics to create private encryption keys between users. QKD enables two parties to produce a shared secret key known only to them, which can then be used to encrypt and decrypt messages. A unique property of QKD is its capacity to detect the presence of any third party trying to intercept the key. Documents suggest that ground-based QKD devices are commercially available today, but their capacity is limited by reliance on ground fibre optic cables that limit distance to 200 kilometres.[58] Satellite-based QKD systems offer the best approach for surpassing this distance limitation with today's technology. Case studies and interviews found that the IQC's efforts towards demonstrating ultra-secure communications via global satellites have advanced and are contributing to the ultimate objective of establishing a globally secure quantum communication network.

DID YOU KNOW ?

In the early 2000s, researchers at the IQC and the PI ***collaborated*** *and successfully demonstrated QKD.*

IQC researchers developed ***new tools*** *and techniques to analyze QKD protocols based on optical communication devices that are compatible with mainstream telecommunications infrastructure.*[59]

The document review found that Canada's Quantum Encryption and Science Satellite (QEYSSat) mission aims to demonstrate QKD technology in space and is expected to launch in 2022. In 2017-18, researchers at the IQC developed a prototype receiver that successfully demonstrated the first QKD transmissions from a ground transmitter to a quantum 'payload' – an entangled photon source – on a moving aircraft. This showed that the technology was viable. Following this proof of concept, the CSA awarded a $30M contract to Honeywell in 2019 for the design and implementation phase of QEYSSAT that seeks to perform a technological demonstration of QKD in space.

Further, in 2020, IQC researchers were successful in the new Canada-UK Quantum Technologies Competition, run jointly by UK Research and Innovation and the Natural Sciences and Engineering Research Council of Canada (NSERC) with an aim to accelerate the development of quantum technologies and provide demonstrable evidence of their impacts on the economy and society. The IQC will collaborate with academic and private sector partners in Canada and the UK to demonstrate quantum technology's ability to protect commercial and national communications networks. Researchers will seek to integrate a quantum transmitter on QEYSSat to demonstrate links between ground stations in Canada and the UK. The potential application of this technology includes enhanced privacy and the protection of commercial and national communication networks based on unbreakable security codes.

DID YOU KNOW ?

The Canadian Space Agency awarded the IQC ***$1.5 million*** *in 2017 to be the scientific lead for Canada's Quantum Encryption and Science Satellite (QEYSSat) mission.*

The UK-Canada Quantum Technologies Competition is the ***first*** *industry-led partnership between any two countries to develop quantum technologies.*

Quantum Computing

Quantum Sensing

Quantum Communication

Quantum Materials

Research in quantum material involves engineering material with unique quantum properties to develop advanced quantum processors and devices.

Case studies, interviews and documents suggest that the IQC has made some advances in quantum materials research over the evaluation period. For example, researchers at the IQC demonstrated a device with an extremely large response to a magnetic field, which could potentially lead to advances in the development of quantum technologies. This device uses a combination of two-dimensional (2D) quantum materials which have properties that help to build quantum devices. Interviews suggest that this experimental work could be a breakthrough for magnetic memory technology and other applications including high-capacity energy storage and zero-loss electricity transmission.

IQC researchers also worked with the National Institute for Standards and Technology to demonstrate a new method to study magnetic materials. Furthermore, IQC researchers measured a very large, local magnetic field and generated a current of electron 'spin' – a quantum property that describes a rotating electron – in a new quantum material. Documents indicate that this discovery opens the way to electronic devices that leverage the spin of electrons which are more energy efficient and quicker than existing technology.[60]

DID YOU KNOW ?

To support Canada's response efforts to ***COVID-19****, the IQC's Quantum Fabrication and Characterization Facility, critical infrastructure for quantum materials research, is being used to study the efficacy of reused masks as well as the antiviral coatings on fabrics used in N95 masks.*

Findings: Efficiency

- *Program Delivery and Design*

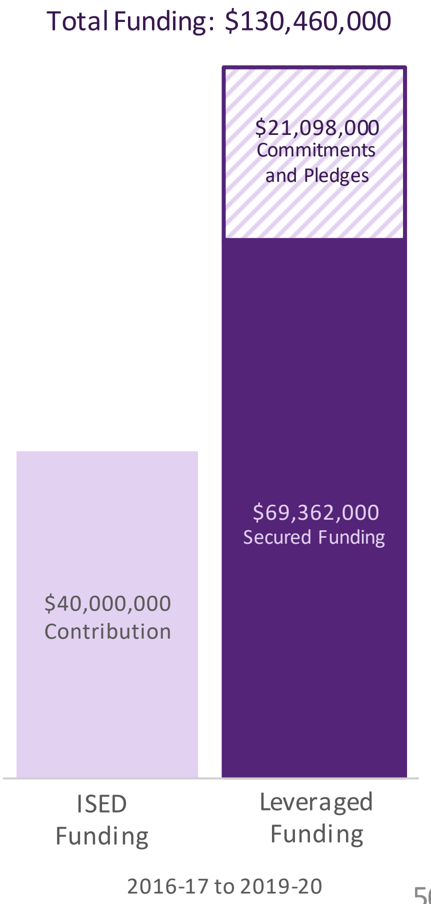
Perimeter Institute Program Delivery and Design

Finding: ISED funding has supported the PI in attracting financial investments from the private sector. Further, ISED funding has provided the PI with flexibility to pursue new research initiatives, thereby making the public-private partnership an effective approach for supporting research in theoretical physics.

Public-private funding to support research in theoretical physics

Since its inception, the PI has been the recipient of significant public and private investments. ISED and the Government of Ontario have each committed $10 million per annum in a series of five-year agreements spanning 2007 to 2022. Its third five-year funding agreement with ISED is set to end in 2021-22. Documents and interviews indicate that the PI is the foundation of the Waterloo region's 'Quantum Valley' ecosystem and it helped to catalyze the creation of the IQC. Overall, the PI contributes to ensuring that Canada remains globally competitive in theoretical physics and QIS research. Documents and interviews also indicate that the co-location of the PI and the IQC is effective and promotes efficiency in advancing research objectives by creating a symbiotic relationship whereby theorists and experimentalists can interact and work together.

Data indicates that ISED funding made up 31% of the PI's total funding, which includes approximately $21 million in commitments and pledges as well as $69 million of secured funding from private donors such as corporations, foundations and philanthropists, to be received beyond 2019-20. Interviews suggest that ISED funding is crucial in securing investments from other sources, including provincial government and the private sector. It was also noted in interviews that ISED funding helps sustain the PI at its current scale and enables it to pursue multiple research areas in theoretical physics simultaneously. The public-private partnership approach also provides the PI with the flexibility to pursue unique research opportunities quickly and efficiently to position Canada at the forefront of research advancements and breakthroughs. Interviews could not identify an alternative approach that is more effective than the public-private funding model, which is a synergy between government, industry, and philanthropy. In particular, interviews found that the combination of public and private financial support provides private donors with assurance of strong stewardship and oversight; ensures alignment of activities with the broader public interest; and enhances the overall impact of the public sector's investment.



Unique organizational structure and access to federal programming

The comparative analysis found that the PI has a more diversified funding model relative to other Canadian theoretical physics institutes that exist within academic institutions. However, given the independence of the PI from a university, as a not-for-profit research institute, documents and interviews found that it is more limited in access to traditional federal funding opportunities that support post-secondary research (e.g., NSERC).[61] As such, its researchers are primarily supported by the funding secured by the PI. ISED's support therefore appears to play a key role in addressing funding gaps in federal programming for a not-for-profit research organization such as the PI that has similar research areas to what would be observed at post-secondary institutions. Funding from ISED has enabled the PI to offer a unique research environment with the opportunity to minimize administrative and teaching requirements for its researchers. Interviews and documents found that ISED funding has been effective at providing the PI with the flexibility to pivot its research agenda and adapt its suite of research initiatives quickly, ensuring that Canada remains competitive in theoretical physics research.

Data analysis found that PI researchers collectively received ≈$9.8 million in research grant funding from 2016-17 to 2019-20, which included funding from NSERC and the Canadian Institute for Advanced Research (CIFAR). However, many researchers at the PI do not have access to the same federal support as university researchers who can seek support from multiple NSERC programs. More specifically, they are limited by eligibility rules of Canadian granting programs. In terms of NSERC funding programs, documents and interviews indicate that PI researchers are only eligible for the NSERC Discovery Grants program, and even so, with significant restrictions (e.g., can be used only to fund students). For example, PI faculty can only apply through their faculty position at their home institution, and the grant funding flows directly to that institution, not to the PI. Notably, from 2015 to 2019, PI researchers were collectively awarded ≈$2 million in NSERC Discovery Grants. Survey respondents also indicated that this grant may be sufficient for supporting a faculty member's graduate students, but a key limitation is that it cannot be used to support postdoctoral fellows, which data suggests represented 60% of the PI's resident research community in 2019-20. Surveys also found that the PI's financial support is critical for covering expenses related to postdoctoral fellows as well as visitor researchers. Further, case studies indicate that the PI has collaborated with the National Research Council to leverage top postdoctoral fellows and students who will advance research in two areas at the PI, artificial intelligence at the PIQuIL and cosmology through the CHIME telescope.

Surveys found that of the PI faculty who indicated that they have received federal funding outside of PI support, 100% of the participants noted it was in the form of an NSERC Discovery Grant.

Institute for Quantum Computing Program Delivery and Design

Finding: ISED funding has supported the IQC in advancing its research objectives and establishing expertise. Further, the public-private partnership is an effective approach for supporting quantum research in Canada.

Public-private funding to support quantum research

Budget 2009 allocated $50 million over 5 years to the IQC to support the construction and establishment of a new world-class research facility. Budget 2014 renewed funding for $14.975 million over 3 years and again in Budget 2017 for $10 million over 2 years. Most recently, funding was renewed for $15 million over 3 years in Budget 2018, beginning in 2019-20. Documents indicate that the IQC also received operational funding support through the Government of Ontario, which ended in 2018-19. Data indicates that from 2014-16 to 2019-20, the IQC leveraged funding from other sources valued at ≈5 times that of total ISED funding. The IQC's secured funding of approximately $153 million includes investments from other federal departments and agencies, provincial government and private sector.

Interviews indicated that ISED funding to the IQC has supported its ability to secure investments from other sources, particularly from private sector investors that view federal funding as a signal of Canada's support for quantum research. Interviews also indicate that the public-private partnership is important for the IQC given its efforts to translate research into commercialization. Further, evidence suggests that ISED funding has enabled the IQC to make longer-term faculty hires and offer start-up packages for labs and equipment. It has also supported salaries for technical staff at the Quantum Nanofabrication and Characterization Facility and provided resources for outreach activities. Notably, interviews indicated that ISED funding has supported the IQC's ability to attract funding from NSERC and CFREF, and according to case studies, the Department of National Defense and Canadian Space Agency as well.

Access to funding opportunities for quantum researchers in Canada

In 2016-17, the IQC, via the University of Waterloo, was awarded $76.3 million in federal funding through the CFREF to implement the Transformative Quantum Technology (TQT) program. Documents and data found that the 'Quantum Quest Seed Fund', an initiative of the TQT program, provides funding for IQC researchers, as well as the broader Waterloo community, to develop new ideas and applications for quantum devices. With respect to other federal support, documents indicate that quantum researchers have received funding through programs such as the Strategic Innovation Fund (SIF) and the Innovation Superclusters Initiative.[62] For example, through the SIF, an IQC start-up company, High Q Technologies, received $6.5 million in 2019-20 to develop new quantum technologies that could enable life-saving treatments for illnesses. Other companies that conduct quantum research activities, such as ISARA, Cognitive Systems and the Quantum Valley Ideas Lab were funded by the SIF as well. Furthermore, the Digital Technology Supercluster has supported talent development projects in quantum computing in partnerships with the UBC, Microsoft, and quantum computing company, D-wave.

The document review and interviews found that IQC researchers have access to funding from a variety of sources, including non-governmental funding from the CIFAR and the Canada Foundation for Innovation (CFI). The comparative analysis found that NSERC, CFI, CIFAR and respective provincial governments appear to be common sources of funding for researchers at other quantum institutes across Canada. However, these other sources do not provide the same type or scale of support as ISED and CFREF funding. For example, CIFAR provides support for QIS by funding the creation of a research network through workshops and conferences. According to interviews, CIFAR provides approximately $25,000 per researcher, but is valuable due to its flexibility in allowing researchers to repair equipment when needed. Moreover, interviews suggest that without ISED funding, the IQC may not have been able to establish expertise, pursue research in multiple areas of QIS, or conduct larger-scale quantum research.

Surveys indicate that of the faculty respondents who received federal government support for research activities, 60% were financially supported through the CFREF-funded Transformative Quantum Technology program at the University of Waterloo.

Conclusions

Perimeter Institute

Institute for Quantum Computing

There is a continued need to support theoretical physics and quantum research in order to advance technology development and maintain Canada's competitiveness in these fields relative to other countries.

Relevance

The PI is unique in its breadth of theoretical physics research areas, role in connecting physics researchers, and distinct research environment. With its focus on theory, it plays a complementary role in quantum research relative to the IQC and their physical proximity facilitates collaboration and partnership.

The IQC plays a leading role in Canada's efforts to develop quantum technologies, conducting multidisciplinary research in QIS that includes a combination of work in theory and experiments. Its research is unique in the 'Quantum Valley' ecosystem and complements the strengths that have emerged at institutes in other regions of Canada.

The PI and the IQC have demonstrated results in outreach and engagement; capacity building and training; and research advancement and application.

Performance

The PI continues to deliver effective outreach and engagement programs that target diverse audiences in Canada and internationally. It has also prioritized promoting physics to youth in an effort to grow interest in this field and build a diversified talent pool of next-generation researchers. The PI has been effective in leveraging diverse Canadian and international talent through its ability to cross-appoint researchers in collaboration with partnering institutions and its offering of unique recruitment programs. It continues to build its research capacity and provide world-class training in theoretical physics. The PI has contributed to major scientific breakthroughs in theoretical physics and continues to advance the field. Further, its research in quantum theory is leading to applications in artificial intelligence and supporting start-up companies in quantum computing, with an increasing number of PI researchers applying their knowledge in the private sector.

The outreach and engagement programs at the IQC are effective at raising interest in quantum information science among the Canadian general public, particularly diverse high school and undergraduate students. Further, the IQC's outreach with the business community is primarily focused on pre-commercialization activities. The IQC has been effective at building its capacity to undertake research through its access to state-of-the-art infrastructure and the 'Quantum Valley' ecosystem. It continues to attract diverse talent, support the training of next-generation quantum researchers, and facilitate international collaboration in QIS. Although quantum technology development is in early stages, the IQC has made experimental advances in QIS. Start-up companies, patents and quantum products have also emerged as a result of research at the IQC, particularly in areas such as quantum computing and quantum sensing.

Conclusions

Perimeter Institute

Institute for Quantum Computing

The public-private partnership is an effective and efficient approach for supporting theoretical physics and quantum research in Canada.

ISED funding has supported the PI in attracting financial investments from the private sector. Further, ISED funding has provided the PI with flexibility to pursue new research initiatives, thereby making the public-private partnership an effective approach for supporting research in theoretical physics.

Efficiency

ISED funding has supported the IQC in advancing its research objectives and establishing expertise. Further, the public-private partnership is an effective approach for supporting quantum research in Canada.

The findings from the evaluations produced two recommendations.

Performance

ISED SRS should collaborate with the PI to develop metrics for tracking and reporting its impacts on experimental research and private sector applications.

Relevance

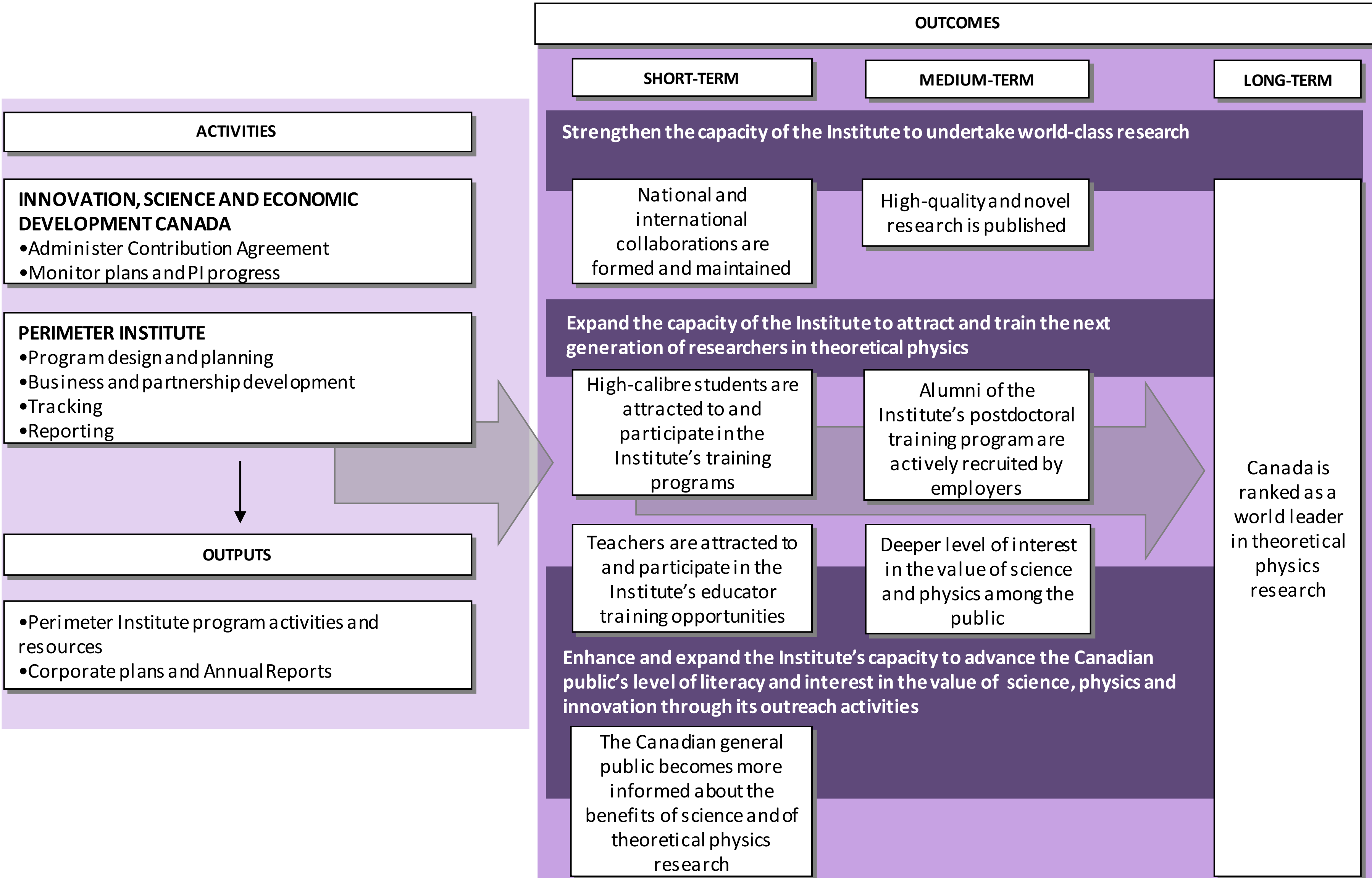
ISED SRS should monitor the quantum research landscape in Canada more broadly, including the complementary strengths that are evolving at research institutes across Canada.

Appendices

- *Logic Models*
- *Endnotes*

Annex A: PI Logic Model

The evaluation of the PI was based on the outcomes outlined in the 2016-17 logic model.



Annex B: IQC Logic Model

The evaluation of the IQC was based on the outcomes outlined in the 2014-15 logic model.

ACTIVITIES

INNOVATION, SCIENCE AND ECONOMIC DEVELOPMENT CANADA
- Administer Contribution Agreement
- Monitor plans and IQC progress

INSTITUTE FOR QUANTUM COMPUTING
- Conducting research in QIS
- Recruitment of new faculty and postdoctoral fellows to the IQC
- Training of young researchers
- Lab start-up activities
- Scientific and educational outreach
- Pre-commercialization work

OUTPUTS

- Expanded number and size of collaborations and research networks, new projects
- Increased number of researchers attracted to the IQC / new IQC members
- Expanded courses, labs and graduate program enrollment, increased opportunities for students to learn and apply new knowledge in practical settings
- Minor research equipment
- Scientific conferences and lectures (Canada and abroad)
- Workshops, visits to the IQC, presentations, website, communications and outreach conferences
- Pre-commercialization workshops, courses, training and mentorship opportunities

OUTCOMES

SHORT-TERM

- Increased knowledge in quantum information science and technology
- Support and create opportunities for students to learn and apply new knowledge
- Improved research facilities
- Increased awareness and knowledge of quantum information science and technology and IQC (both in the quantum information community and amongst Canadians)
- Increased awareness among IQC researchers of commercialization opportunities

MEDIUM-TERM

- Canada is branded as a place to conduct research in quantum information technologies
- Canada is positioned to take advantage of the economic and social benefits of research through seizing opportunities to commercialize

LONG-TERM

- Canada is branded as a place to conduct research in quantum information technologies

Endnotes

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