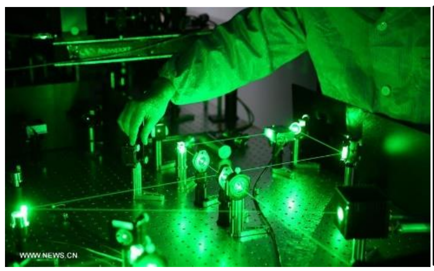
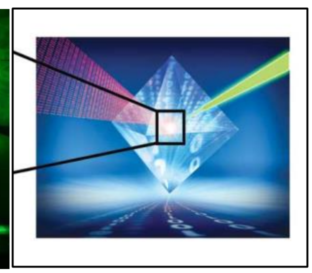
# Planning and Budgeting Committee (PBC)

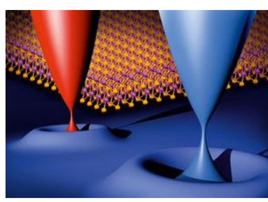
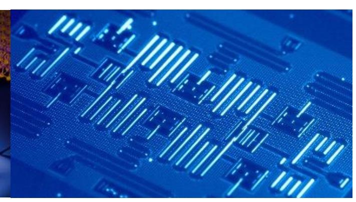
# Steering Advisory Committee

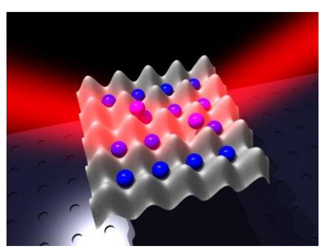
# on Quantum Science and Technology

## Final Report







**Presented to the Planning and Budgeting Committee General Assembly**

**February 2018**

*Preamble, Prof. Uri Sivan, Committee Chairman*

My heartfelt thanks to the committee members for their time and efforts invested in constructing the National Academic Quantum Science and Technology (QST) Program. Their expertise and the depth and scope of discussions have brought to the results presented below.

My thanks to the Planning and Budgeting Committee (PBC) members, particularly to the Chairwomen, Prof. Zilbershats, for her continuous trust in the committee and its objective. Special thanks to the PBC representatives accompanying the Committee: Dr. Liat Maoz, Ms. Nina Ostrozhko and Mr. Amir Gat for their extraordinary devotion and contributions throughout.

“The second quantum revolution”, which drove the PBC to declare QST as a priority field in its five-years plan, is underway. Testament to this are the expansive national and multinational programs announced by most developed countries and extensive commercial investments. The proposed program aims to lay down the academic foundation necessary for Israel to join this revolution. It leans upon the existing excellence and provides a roadmap of the steps necessary to significantly expand the scope of activity, improve research capacities and train a skilled workforce to set the revolution in motion in academia, industry and security sector.

An expansive academic program is critical to position Israel at the forefront of global research and development, but realizing its national potential also demands partnering with additional entities experienced in laying down the infrastructure necessary to develop the industry and security needs. At the meetings held with the Innovation Authority and Ministry of Defense, we realized that these entities have long since identified the essentiality of QST to the State of Israel and the need to develop an integrative national program. Therefore, from the onset, this academic program was formulated with appropriate interfaces with these entities, as well as other that will join; the proposed structure assumes establishment of a national program that will integrate all entities.

The harbinger of this collaboration will involve the establishment of a joint research fund by the PBC and Ministry of Defense, which would not be possible without the deep commitment of Dr. Moshe Goldberg, Dr. Nadav Cohen and Dr. Tal David from the Ministry of Defense and Prof. Beni Geiger and Dr. Tamar Jaffe-Mittwoch of the Israel Science Foundation.

Sincerely,

Prof. Uri Sivan

PBC QST Steering Advisory Committee Chairman

## *Preamble, Prof. Yaffa Zilbershats, PBC Chairwoman*

The strength of Israel’s science and academia undoubtedly leans on, first and foremost, outstanding academic researchers. To preserve and foster this prowess, significant efforts and investments are required, in ongoing purchasing and upgrading of research equipment and infrastructures, in generating an active and dynamic scientific community, in reinforcing international collaborations, in continuously improving training programs and in continuous recruitment of top-line faculty members. The current five-year PBC strategic program places emphasis on these elements and allocates significant funds to implement them.

Most of the investments are horizontal, but, in parallel, a limited number of fields was identified – disciplines which harbor immense breakthrough potential to Israeli research capacities and to global leadership. Failure to invest in these fields today will lead to lagging in the global race. One of these is Quantum Science and Technology (QST).

To draw up a comprehensive academic QST development program, the PBC appointed a Steering Advisory Committee comprised of leading scientists in various relevant subdisciplines. The committee was established in the summer of 2017 and worked intensively to prepare this report. The committee recommendations will be discussed by the PBC in their decision-making processes and will serve as a basis for establishment of a national program to promote QST, and to foster collaborations with other governmental ministries, especially via the National Infrastructure Forum for Research and Development (TELEM).

I and all my PBC colleagues, congratulate the Committee for its tireless efforts and professional work that led to this report.

I would like to thank the Committee chairman, Prof. Uri Sivan, who shepherded this work with interminable commitment, with much insight and professionalism, who always knew to provide good advice, and managed to engage all universities toward these common goals as well as our key future partners – the Ministry of Defense and the Innovation Authority. My sincerest thanks to the Committee members, for their noteworthy professionalism, and for their time, energy and expertise invested in promoting this important initiative.

Sincerely,

Prof. Yaffa Zilbershats

Planning and Budgeting Committee Chairwoman

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# 1. EXECUTIVE SUMMARY

**Background**

The past few years have witnessed the recognition that developments in fundamental and applied Quantum Science and Technology (QST) research have brought us to the brink of the "second quantum revolution". Such a revolution harbors immense potential for technological breakthroughs, with civil and security applications in computation, encryption, communication, imaging, materials, and more. As a result, many countries, continental organizations and international companies, have launched well-funded R&D programs in the field, with the aim of securing their place in the race for "quantum supremacy".

Extensive consultations with prominent figures in the Israeli academic system led the Planning and Budgeting Committee (PBC) of the Council of Higher Education (CHE) choose, as part of its multi-year strategic plan for 2017/8-2022/3, QST as one of four focal areas. Following this decision, a Steering Committee has been appointed to formulate a national academic program for the development of QST in Israel's higher education system – the resulting program is detailed in this report. Following are the main findings of the report and main recommendations.

**QST in Israel**

- University reports count 144 researchers involved in core QST research, and an additional 56 involved in QST-related research areas. Approximately half of the researchers are physicists, and the remaining are from engineering, chemistry, computer science and mathematics departments. Core QST researchers are mentoring 471 graduate students (198 MSc and 273 PhD students) and 122 postdoctoral fellows.
- Extensive research is being conducted in the quantum sensors and quantum materials fields, and significantly less in quantum computing, quantum communication and quantum simulators as well as fundamentals of quantum theory with technological implications.
- The percentage of Israeli researchers excelling in the QST field is high compared to both other countries and to other physical and engineering disciplines in Israel. This is particularly true with respect to young researchers in the field.
- The average Israeli core QST scientist has a relatively high scientific output and impact; a significant percentage (10-15%) has outstanding scientific output and impact.
- QST-related courses are integrated in programs for physics degree or degrees combining physics and another discipline. In other degrees, the status varies between institutions, with a small selection of courses and minimal exposure of non-physics students to QST – particularly in undergraduate studies, but also in advanced degrees. Within the physics departments, exposure to topics such as quantum computation or quantum encryption and communication is limited.
- As of the report date, 4 universities have established research centers dedicated to QST – Hebrew University (HUJI), the Technion, Ben Gurion University (BGU) and Bar Ilan University (BIU). In the remaining universities, research is conducted in centers dedicated to related disciplines, and QST centers are being planned. The existing centers provide research infrastructure, student training, research community (at times, an influential center of gravity for the broad Israeli community), encourage knowledge sharing and collaborations between members, constitute a framework for research collaborations with

security sectors and industry, as well as a framework for international collaborations in research and training programs.

**University development programs**

All universities in Israel have announced their plans to develop the field in the coming five years, and beyond. In some universities, the plan reflects established institutional strategy, while in others, the thinking process has been accelerated by the PBC initiative and the establishment of a National Steering Committee. Development programs include recruitment of new faculty members in the field, purchase and upgrading large research infrastructure, recruitment of technical manpower, development of training programs and support of advanced degrees.

**Main impediments to development of QST in Israeli academia**

- **A shortage of research students impedes a significant increase in the number of faculty members and industry researchers.** The committee analysis concluded that without directed intervention, the number of (non-emeritus) faculty members involved in core QST research will grow in the next 5 years by approximately 18% (i.e., 24 faculty members). Most of this growth is expected to be limited to the engineering departments. Growth in other disciplines is projected to be small or negligible.
  The reasons for this include: a shortage of faculty members outside physics or engineering; and in the computer science and engineering fields, also competition with industry over outstanding students. The projected growth in the number of faculty members is less than half the combined recruitment plan of all institutions (54 faculty members). Therefore, most of the growth potential in the next few years lies in attracting faculty members and post-docs from adjacent fields.
- **Narrow student training** and limited exposure to QST outside of physics departments (primarily during undergraduate studies, but also in advanced degree programs). This poses an obstacle both to building a trained workforce, suitable and compatible with domestic market and security needs, and to establishing the next generation of quality faculty in the field.
- All universities suffer from **shortage in adequate research infrastructure**.
- **Shortage of high-level international postdoctoral fellows**, in accord with the general shortage in natural sciences in Israel.
- **Limited interdisciplinarity** and research collaborations within and between institutions, which forms a barrier to coping with complex challenges requiring a range of expertise and knowledge.
- **Difficulty in recruiting quality technical staff:** regulatory limitations limit the salaries to values considerably lower than the average pay in industry.
- **Low industry involvement:** The number of Israeli companies involved in this field is minimal, which results in lack of industry funding, on the one hand, and difficulty in transferring knowledge and training of industry employees, on the other hand.

**The academic program - vision and goals**

The Committee set forth a double vision:

- **Reinforcement of Israel's basic and applied QST research capabilities and academic excellence in a sustainable manner.**
- **Establishment of the academic foundations for collaboration with governmental and industrial parties to ensure economic prosperity and security of the State of Israel in areas reliant upon QST.**

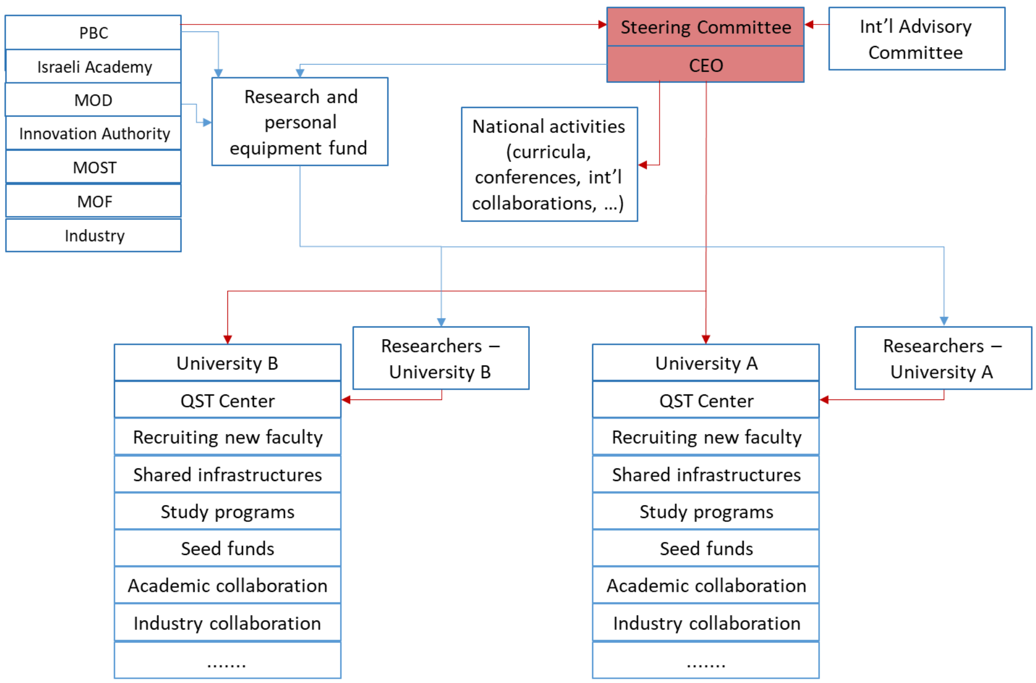
Development of the QST is of prime importance to the State of Israel. The academic plan detailed below should thus be seen as a first and essential step in the development of a comprehensive national plan in collaboration with the Innovation Authority and the Ministries of Economy, Defense and Finance as well as relevant industries. From the academic-scientific perspective, partnership with the Ministry of Science, Technology and Space and with the Israeli Academy of Sciences and Humanities can also be expected. Similarly, additional government offices may express interest in such partnership, including the Prime Minister's Office and the National Cyber Security Authority, Ministry of Communication and others.

The Committee is convinced that the national academic program should be constructed, from the start, as a central and pioneering leg in a broad national program encompassing all stakeholders. Details regarding the possible interests of all participants and their connection to the broad national program are presented in section 6 of this report. The program proposed by the Committee is constructed such that it can be immediately implemented, as a first step toward its expansion from the academic to the national level. Considering the globally growing competition in the field, the Committee recommends its immediate implementation.

This vision of industry-security-academia integrated program gave rise to the following central goals of the program:

1. **Expansion and reinforcement of the scientific community** involved in basic and applied QST research. Expansion of the community by recruiting new faculty members, attracting faculty members from other disciplines, and increasing the number of doctoral and postdoctoral fellows.
2. Establish the necessary **research infrastructure** for academic and industry research and allocate the manpower and other resources required to conduct competitive, cutting edge research.
3. Expansion of QST **training**, adjustment of curricula and promotion of interdisciplinary training programs for students and young researchers, to train a skilled workforce for both industry and academia. These efforts will focus on students studying in faculties other than Physics, e.g., Engineering and Computer Science departments.
4. Set up the academic ground necessary to develop industry and reinforce Israel security. **Development of the academia-industry-security interface:** shared research infrastructure, promotion of collaborations, knowledge generation and transfer, incentives for external investments in academic research in the field, incentives for cross-disciplinary mobility of personnel, innovation and ideas.
5. **Formation of an Israeli community by encouraging cross-disciplinary academic collaborations** to foster significant breakthroughs in the field and collaborations with industry and government ministries.

Following is the administrative structure proposed for the national academic program




MOD – Ministry of Defense, MOST – Ministry of Science and Technology, MOF – Ministry of Finance

The committee proposes that the program will be managed by a national steering committee serving as a board, and, in addition to the committee chairman, will include academic experts in the field, PBC representatives and Israel Academy of Sciences and Humanities (IASH) representatives, as well as representatives of other government/industry bodies, who will contribute significant funds to the program. The program will be run by a lean managerial team, led by the steering committee chairperson – a prominent academic figure, and a professional CEO. The steering committee will be aided by an International Scientific Advisory Committee, which will consult and monitor the program implementation. The national academic activity will be advanced via the three channels described below and other channels that will be established, if necessary.

### Main components of the academic program

To reach the above-mentioned goals, the committee generated an academic development plan that focuses on three implementation channels. The total budget required for its implementation is estimated at 600M NIS for 5 years, as detailed below:

| Implementation channel | Objective/Use | Estimated costs for 5 years | |
|---|---|---|---|
| **A. Research and Personal Equipment Fund (PBC-MOD Joint program)** | ISF-managed research fund | 50M NIS | **Total: 75M NIS** |
| | Via ISF: purchase of dedicated equipment for labs of winning grantees | 25M NIS | |
| | MOD (Maf'at) managed research fund | **25M NIS** | |
| **B. Support of Institutional Research Centers** | Recruitment of new faculty members and setting up labs for them | 120M NIS | **Total: 420M NIS** |
| | Purchase and upgrade shared research infrastructure | 200M NIS | |
| | Technical manpower | 70M NIS | |
| | Development of study programs, scholarships etc. | 30M NIS | |
| **C. National activity, management and unexpected expenses** | • National platforms for development of scientific-technological aspects<br>• Increase number of outstanding international postdoctoral fellows coming to Israel<br>• QST training of research students from other disciplines<br>• Joint national programs with industry<br>• International conferences<br>• International collaborations<br>• Create dynamic database of program indicators<br>• Create database of Israeli QST researchers abroad | **Total: 80M NIS** | |

A. **Research and personal equipment fund:** To promote academic research and to attract outstanding researchers from QST adjacent fields, a dedicated research fund is being established with a total budget of 100 million NIS over the coming five years. The fund is being established in collaboration with and with a matched donation from the PBC and MOD. 75 million NIS will be managed as a dedicated program in the framework of ISF and 25 million NIS will be managed by Maf'at (MOD). The ISF-managed research fund will support research and purchase of equipment dedicated for research laboratories on a competitive basis. The fund will be open to researchers of all research universities and will accept joint proposals of 1-5 research groups. When evaluating the research proposal, some advantage will be given to joint applications of groups from various disciplines, in accordance with the program goals. The fund will support 3-year research programs, with an option of an additional two years.
The budget allocated to this dedicated ISF program, i.e., 75M NIS over five years, was determined with the aim of maintaining an approximate 30% grant success rate, as in other ISF programs, thus retaining standards of excellence.

B. **Support of institutional research centers:** most of the funding will be allocated to development of research centers (existing or planned) at various universities. This channel is intended to support: recruitment of new faculty members and establishment of labs for them, promoting integration of researchers from adjacent QST disciplines, establishment and upgrading of research infrastructure catering all Israeli researchers and industry, development of training and continued education programs in collaboration with the industry and others. Support of these university centers will be granted on a competitive basis, following evaluation of submitted institutional proposals.

C. **National activities, management and unexpected expenses:** This channel is intended to address the shared national needs of both researchers and institutions. These will include:
   1) Participation in the establishment of national platforms and testbeds for R&D in areas such as quantum communication, sensors, and more.
   2) Increase the number of outstanding international postdoctoral fellows in Israel – either by establishing an exclusive and dedicated scholarship program or by opening a national center for international short-term visitors.
   3) Adequately address training of research students from other QST disciplines – particularly, establishment of a national program that will offer dedicated MSc/PhD QST-related courses throughout the country – courses that are generally not available at each individual institution. Such courses will be delivered one day a week over one year.
   4) Run national programs in partnership with industry, specifically, establish of a support fund that will assist integration of industry researchers in academic research.
   5) Run international conferences.
   6) Collaborate with national programs in other countries, and with the European Flagship program.
   7) Build a dynamic database of program success indicators.
   8) Build a database mapping the Israeli QST researchers living abroad.

**Summary**

The second quantum revolution is underway and harbors opportunities for partakers and risks for stragglers. The academic system stands at a good starting point with regards to the level of research and researchers but suffers from significant deficits. Failure to address these deficits may impact future academic achievements, and more importantly, the ability of the State of Israel to cope with the economic and security challenges posed by the revolution and to benefit from the projected advantages. This report analyzes the current academic activities, identifies the bottlenecks and outlines the academic component of the national program designated to enable integration of the State of Israel in this revolution, both via research reinforcement and enhancement and by training QST-skilled personnel who will feed into industry. To leverage the full potential, the academic program must be accompanied by an economic and defense program. To this end, the academic program was constructed, from the onset, with appropriate interfaces with complementary programs that focus on such aspects. The State of Israel is late in capitalizing on these trends and brings a limited scope of activity, on the academic levels, and even more so, in industry. As development processes are slow, time is of the essence.

# 2. BACKGROUND

## 2.1 Background and purpose of appointing the committee

As part of its multi-year strategic program for higher education for the years 2017/8-2022/3, the CHE/PBC has selected, after extensive consultations with prominent figures in the academic system, to concentrate its efforts in the development of large-scale research infrastructure in four complementary research fields. These fields, which will benefit from significant and steady national investment in their development over the next five years and beyond, are projected to bring to a quantum leap in Israeli research capacities, Israel's international position and the global knowledge forefront in the field.

One of these four fields is **Quantum Science and Technology (QST).**

In order to advance the PBC initiative to develop QST research, and particularly QST research infrastructure, the PBC decided in its meeting of 28.6.17 to establish a steering committee to **formulate and recommend a national program for development of QST in Israel's higher education system, in accordance with selected topics, and to aid in spearheading and implementing it**. Details of the Committee Mandate are provided in section 3.

## 2.2 The second quantum revolution

Quantum theory describes phenomena and behavior of small-scale physical systems. The significance of quantum effects hence rises as mechanical, electrical or optical devices become smaller, and as measurement precision of the systems increases. Over the past century, quantum theory[1] has successfully explained the structure of matter – the atom, molecule, chemical interactions, solids, crystals, and the like. Quantum theory has provided the foundation for developments such as the transistor, laser, light detectors, rapid communication, precise clocks which stand at the foundation of satellite navigating systems, medical imaging

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[1] Quantum Physics – Some fundamental concepts

The foundations of quantum physics were already developed at the turn of the early 20th century, and sparked a conceptual revolution regarding the nature of the universe and matter, the laws governing it and also the essence of science.

The term "quantum" means a discrete quantity – a basic unit. One of the fundamental principles of quantum physics states that certain measurable physical sizes can receive one of a series of discrete values, which differ from each other by the intervals of the "quantum" characteristic of that system. For example, the energy levels of atoms can obtain only certain discrete values and not continuous values.

In addition, quantum theory states that as objects get smaller and less energetic, their "quantum effects" become more significant: a wave behaves also as a flux of particles and particles also exhibit wave-like characteristics ("**wave-particle duality**"); particles are defined using functions with probabilistic and not deterministic interpretation ("**wave function**"), and at any moment before being measured, they exist in multiple states at the same time – each with a different probability between 0 and 100% ("**the superposition principle**"). In contrast, when being measured, a particle takes on a single state, at a certainty of 100% ("**wave function collapse**"). There are pairs of particle-associated values (e.g., its position and speed), such that it is impossible to know them both with absolute certainty at the same time ("**Uncertainty principle**").

Quantum physics takes on an increasingly dominant role as we attempt to understand Nature, define and construct processes, equipment or devices at high spatial or temporal resolutions or at low energies. In contrast, measurement and application of quantum effects are quite challenging in the macroscopic environment in which we live and act (with regards to temperature, spatial distances etc.).

techniques, such as MRI and others. It has been tested in many experiments and has reached unprecedented precision in the agreement between prediction and experimental findings.

In the past few years, the realization has emerged, that theoretical and experimental research in this field has brought us to the brink of the "second quantum revolution".[2] While the first quantum revolution, arose from the understanding of quantum mechanics and technological development for overall control of quantum states of systems, the second revolution leans upon the understanding of the interaction between distinct system degrees of freedom (e.g., individual photons and atoms) and development of technologies to control them. These capacities will enable, and to some degree already enable today, producing computers significantly stronger than currently available, encrypted tap-proof communication, simulation of systems too complex to compute with existing computers, sensing at higher sensitivity than current techniques, development of materials with unique characteristics, and more.
Recognition of the immense potential harbored in the second quantum revolution has brought to vast public and private investments (see Appendix 7B). The European Union recently launched a "flagship program" encompassing 1 billion Euro for the coming five years. USA, China, Canada, Japan, Germany, UK and other countries have announced national programs to promote quantum technologies, and, according to the McKinsey report, in 2015 alone, 1.5 billion Euro were invested in non-classified quantum technologies worldwide. In addition, vast investments, have been made by security authorities and billions of dollars of investments by huge enterprises, including Google, Microsoft, IBM, Intel and Alibaba[3].

The revolution is underway and, in order to benefit from its fruits, the State of Israel must appropriately and rapidly prepare itself. This preparation includes academia, governmental authorities, led by the Ministry of Defense and the Innovation Authority, and industry. The aim of this report is to formulate an academic development plan and to indicate the essential interfaces with other authorities.

### 2.3 "Quantum Science and Technology" – Demarcating the discipline

The research areas included in the second quantum revolution are broad and combine various disciplines – physics, engineering, computer science, mathematics and chemistry. To focus the national efforts, the committee has decided to limit the research that will be supported by "QST" to theoretical or experimental research pertaining to the following categories:

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[2] In contrast to the "first quantum revolution" which gave rise to the above-mentioned inventions – e.g., the transistor, light sources and solid-state-based lasers, GPS navigation systems, and others.

[3] Below are some recent examples of the race toward quantum supremacy:

- In 2017, Alibaba announced 15 billion USD spendings on research in quantum computing, IOT, data analysis and artificial intelligence.
- In January 2018, IBM presented a 50 qubit processor prototype at the CES exhibition
- In January 2018, Intel also presented an experimental chip – a 49-qubit processor dubbed "Tangle Lake".
- In January 2018, Microsoft released Q# - a language for writing quantum algorithms, as part of its quantum development package. The company also invested in development of a topological quantum computer.

1. Quantum computing
2. Quantum communication
3. Simulation by quantum systems
4. Quantum devices and sensors, such as atomic clocks, magnetic field sensors, and quantum acceleration sensors
5. Quantum materials, such as topological materials and quantum engineered materials displaying unique properties
6. The fundamentals of quantum theory, baring future technological implications
7. Innovative quantum science and technologies

Below is a popular description of the main challenges in each of the above categories:

- **Quantum computing:** the quantum computing model is based on quantum theory principles, particularly on the fact that in the quantum world systems can be in a mixed state (superposition), until measured. A popular example is of Schrodinger's cat that is in a superposition of live and dead states, until measured. In place of common bits, which take the value of 0 or 1, the quantum computer makes use of qubits, which simultaneously have values of 0 and 1 – each with a different probability (superposition). Such a computer is expected to solve certain problems more efficiently than the best possible algorithm for a standard computer. Development of a quantum computer is currently still in the research stage. The existing technology has still not adequately matured to build a computer superior to standard computers, however the massive governmental and industrial investments promise continuous progress. There are substantial reasons to assume that such a computer, when (and if) developed, will set the stage for the most significant breakthroughs in the world of computing and encryption in the coming decades. The challenges we are facing are in understanding both how to advance the construction of such a computer, despite the significant challenges involved, and the potential applications of such a computer. Research in quantum computing includes experimental and theoretical aspects of quantum systems which can process quantum data, including error correction, understanding the shortcomings and the computational and algorithmic capacities of such systems, as well as the broader understanding of quantum computing complexity concepts with respect to more general physical systems.
- **Quantum communication, quantum encryption and information security:**
  Quantum theory principles enable generation of an encrypted communication channel, fully tap-proof. As said, one of the basic principles of quantum theory is that measurement of a particle causes the collapse of its wave function, namely, collapse of its superposition of various states to one single state. Quantum encryption exploits this principle such that someone who is tapping is essentially measuring a mix of information-bearing states and modifies them. The two sides – the encryptor and the recipient can therefore uncover him. In addition, there are methods for switching quantum encryption keys, flipping a quantum coin, quantum random number generators and other cryptographic techniques, where one of the main theoretical and practical challenges is to discover other possible applications of the advantages of quantum communication and cryptography. Of note, all the listed applications have far-reaching uses, with impacts on secure communication, information security and privacy preservation. Their application in physical systems also poses many experimental and theoretical challenges, such as error correction, system verification and others.

Application of quantum communication and encryption is particularly advanced, and encrypted quantum communication systems, including quantum communication to satellites already exist.

- **Simulation by quantum systems:** Quantum simulators are analog computers based on the laws of quantum physics, which enable simulation of the properties of materials or chemical compounds (or to solve complicated physical equations), which, due to their complexity, cannot be computed neither with sophisticated computers, nor with general quantum computers, when built. Currently, several platforms used to construct such simulators are being researched, including ultra-cold atoms in optical crystals, trapped atoms, arrays of superconducting qubits, or quantum dots and photons. Quantum simulators are an intermediate step toward full quantum computing, hoping that such simulators could be used even without error correction. The possible applications are expansive and include computation of diverse chemical and physical systems.
- **Quantum devices and sensors:** Since quantum phenomena are highly sensitive to external perturbations, they can be used as devices to measure and sense various effects, such as magnetic fields, temperature, acceleration and others, as well as for highly accurate time measurement ("atomic clocks"). By harnessing various quantum phenomena, electronic and electro-optical devices can also be constructed, based on new principles, primarily on the use of a small number of photons and/or atoms. These devices will require less energy and will enable continued miniaturization processes. Moreover, exploitation of unique quantum resources, such as entanglement and squeezing, will enable measurement sensitivity and precision beyond the limitations of classical sensors.
- **Quantum materials:** It is possible to design and manufacture new materials, with novel and exotic physical characteristics, deriving from quantum phenomena leveraged to a microscopic level. For example, materials in which there is a strong correlation between microscopic degrees of freedom, resulting in new characteristics; There are materials in which the electronic wave function takes on certain topological characteristics that affect electrical conductivity, heat conductivity and the optical activity of the material. Aside from the importance of such materials in a range of applications, they may also turn essential for quantum computing, quantum communication, and quantum sensor and simulator applications.
- **Principles of quantum theory, with future technological implications:** Quantum technology enables and relies upon the fascinating interaction between questions seemingly at both ends of the spectrum: questions which relate on the one hand to the deep and even philosophical foundations of quantum theory, and, on the other hand, to practical and experimental questions. Understanding the relationship between the two has proven itself time and again, as insights and breakthroughs in the basic science, led to surprising inventions and applications.

There is no doubt that the future holds scientific and technological breakthroughs that are still difficult to predict. These will be addressed by category 7 above.

### 2.4 National programs across the globe

In the past few years, a significant number of countries and organizations throughout the world have designated large funds to QST and begun to develop comprehensive programs to promote it. This was done with the understanding that significant breakthroughs in this field will spearhead new solutions for contemporary global challenges, induce significant economic growth and lead to competitive security advantages. Various governments across the globe, led by the USA[4], China[5], Canada, Japan, Germany and the UK, have announced national programs to advance quantum technologies. According to a 2015 McKinsey report[6], in 2015 alone, 1.5B Euro were invested in non-classified quantum technologies research worldwide. The countries leading in spending were USA, spending 360M Euro, China 220M Euro, Germany 120M Euro, the UK 105M Euro and Canada, spending 100M Euro. The combined European Union expenditure was approximately 550M Euro. Following is a diagram exhibiting the 2015 investments made by various countries (in millions of Euro):

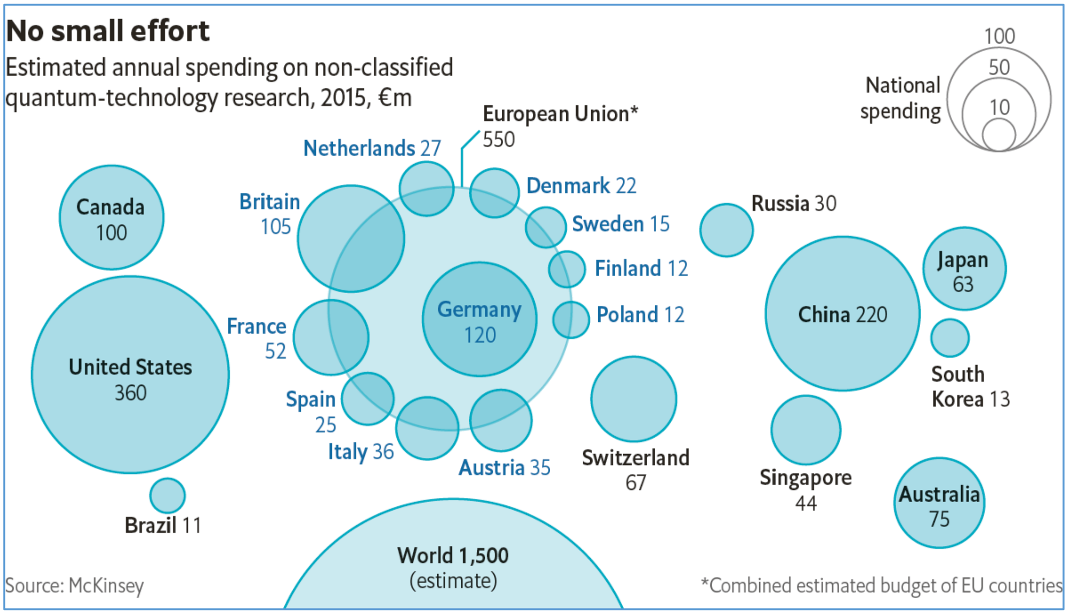



**Diagram 2.1:** Estimated 2015 spending on non-classified quantum technologies in various countries (millions of Euro)

An additional McKinsey analysis described, in addition to budget, the number of researchers authoring publications in the field in the years 2013-2015, by country:

[4] For details: Advancing Quantum Information Science: National Challenges and Opportunities, A joint report of the Committee on Science and the Committee on Homeland and National Security of the National Science and Technology Council, July 2016
[5] Review article of the initiative can be found, for example, in Chinese Efforts in Quantum Information Science: Drivers, Milestones, and Strategic Implications - Testimony for the U.S.-China Economic and Security Review Commission, March 16th, 2017, John Costello
[6] The main findings are quoted in the March 2017 issue of The Economist, under Quantum Leaps

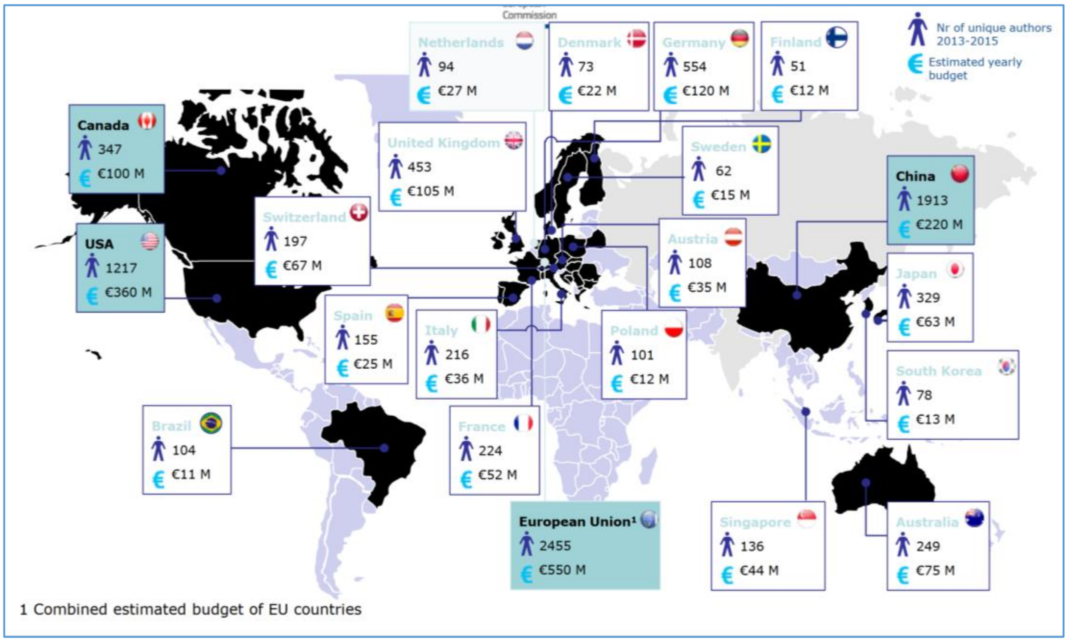



**Diagram 2.2:** Number of different scientists authoring publications in the field during the years 2013-2015, and annual spending on non-classified research in the field in 2015 (millions of Euro)

Again – as separate countries, China and the USA take the lead; However, when considering the combined expenditures of the EU states, the EU leads, with almost 2,500 active researchers in the field.

As of 2015[7], China and the USA are also the global leaders in the number of patent applications in the field:

[7] March 2017 The Economist

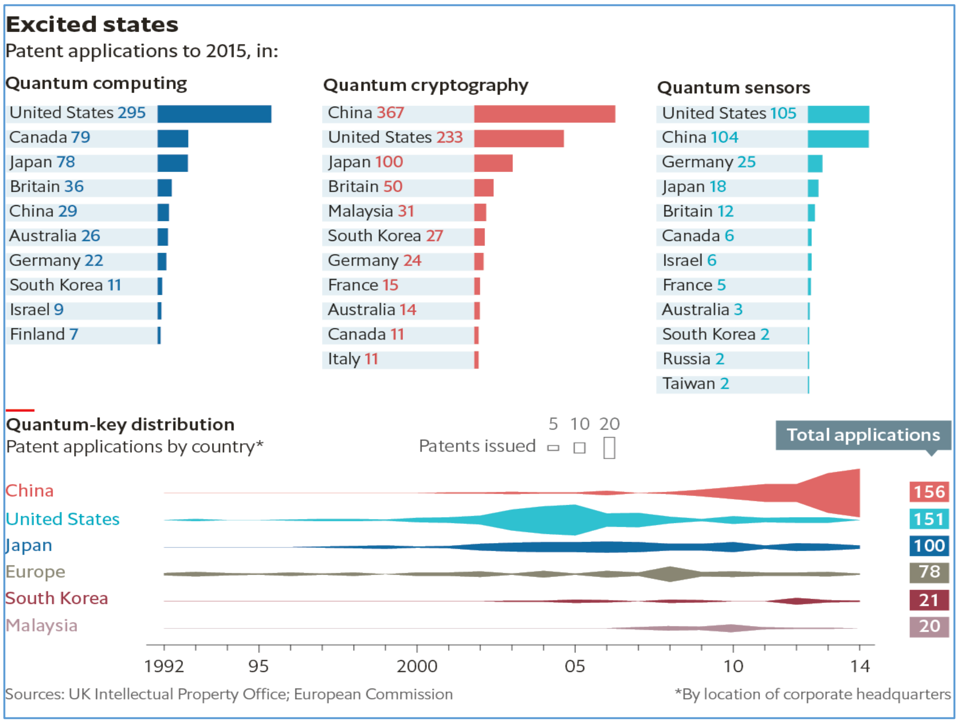



**Diagram 2.3:** Number of patent applications in 2015, per discipline and country and number of quantum-key distribution patent applications by country and year; 1992-2015.

In 2016, following some of these national initiatives, and in parallel to others, the **European Union** launched a large-scale new program in the field – the Quantum Flagship[8] initiative, with the goal of transforming Europe to a leading player in the second quantum revolution, so it can benefit from significant industrial development in the field. In the framework of this program, the European Commission will invest 1B Euro in a project which will begin in 2019 in a ramp-up phase, and will continue in 2021 in a full-scale phase (in addition to extra individual country investments).

Appendix 7B presents a short description of the key national initiatives in several leading countries. While we, unfortunately, were unable to find information regarding national spending on QST during 2016-2017, detailed below are the magnitudes of multi-year national programs in QST recently announced by several countries/organizations:

- **European Union:** €1B for 5 years (+country funds)
- **United Kingdom:** £270M[9] for five years (+£ 30M from national security sources)
- **Germany:** €300M for 10 years
- **The Netherlands:** €135M for 10 years

Of note, large commercial enterprises, including Google, Microsoft, Intel, Toshiba, Alibaba and IBM invest significant resources to advance the field and develop applications. The magnitude of the industrial spending is unknown but is estimated at several billions of dollars a year[10].

[8] Details: Quantum Manifesto, A New Era of Technology, May 2016
[9] Equivalent to approximately 300M Euro (1GBP ~1.1Euro)
[10] In October 2017, Alibaba alone announced a $15B investment in research and development of quantum computing, IOT, information analysis and artificial intelligence.

# 3. ISRAELI ACADEMIA – CURRENT STATUS

## 3.1 Research activity and training in various institutions

Quantum theory stands at the base of modern science, particularly in the areas of physics and electrical engineering. Therefore, there's a considerable number of researchers in Israeli academia who directly or indirectly work on quantum physics, and both undergraduate and graduate courses are available, primarily in physics departments.

The institutions differ from one another in the scope of their involvement in the field, the variety of sub-disciplines, the scope of student training, and the variety of departments in which research is conducted. In some institutions, research in the field developed naturally (researchers chose to work in the field), and in some, the instution took deliberate decisions to develop the area, by establishing research centers, acquiring research infrastructure and recruting faculty.

This chapter describes in some detail the current academic status of QST in Israel – independently and in comparison to the world. The main information sources for the summary to be presented below included institutional reports (in response to the Committee questionnaire and meetings held between Committee members and researchers and institutional administrative representatives – see details in chapter 4), PBC and Central Bureau of Statistics (CBS) data, research fund grant statistics and bibliometric analysis of publications and citations.

### 3.1.1 Research centers in Israeli universities

To date, four universities have QST-dedicated research centers: **The Hebrew University** (Quantum Information Science Center, established in 2011, 26 faculty members), **Ben-Gurion University** (Center for Quantum Information Science & Technology[11], established in 2014, 28 faculty members[12]), **Technion** (Center for Quantum Science Matter and Engineering, established in 2016, 40 faculty members), and **Bar-Ilan University** (Quantum Entanglement Science and Technology (QUEST), established in 2016, 7 faculty members).

The other universities have research centers in nearby areas, and plan to establish QST centers:

**Tel Aviv University** has a research center that deals with a much broader area (LMI – Light Material Interaction Center, established in 2016, 17 faculty members), and plans to establish a QST center in the coming year (approximately 25 faculty members). Much research in QST is being conducted at the **Weizmann Institute of Science** (WIS), however, to date, it has no dedicated research center. Two such research centers are

[11]The Center sees its uniqueness in positioning itself in the interface between basic and applied science

[12]The institute noted that 50 faculty members expressed their wish to be contributing members of the center

expected to be established in the coming years: "Institute for quantum Science and Technology" and "Institute for Advanced and Intelligent Materials", which will host a "Quantum Materials" unit.

**Ariel University** has The Schlesinger Family Center for Compact Accelerators, Radiation Sources & Applications (FEL) (8 faculty members) and the Materials Research Center (10 faculty members). It plans to establish a QST R&D center under the FEL.

**Haifa University** is currently in the final stages of establishing the "Theoretical Physics and Astrophysics Research Center of Haifa University", which will, in the coming years, consolidate the QST research at the university and will include 4 faculty members.

The existing centers generally provide a research community for its members (and at times, serve as centers of gravity for the entire Israeli QST community), foster knowledge exchange and collaborative research, provide a framework for research collaborations with government offices or with industry, as well as a framework for international collaborations in research, scholarship and training programs.

**a)** **Existing research infrastructure:** Research facilities available for researchers in most institutions are decentralized and include micro and nano-science and technology centers (if they exist), with advanced fabrication equipment. In some institutions, the facilities also include materials centers (with characterization and synthesis infrastructure), photonics labs, electron microscopy centers, etc. The infrastructure centers generally service the institute researchers (i.e., do not function as national centers), although some centers have equipment that serve the industry and researchers from other institutes in 20-30% of the total usage time. The existing infrastructure partially supports QST activity but requires significant upgrading and capacity expansion to support advanced research in the field.

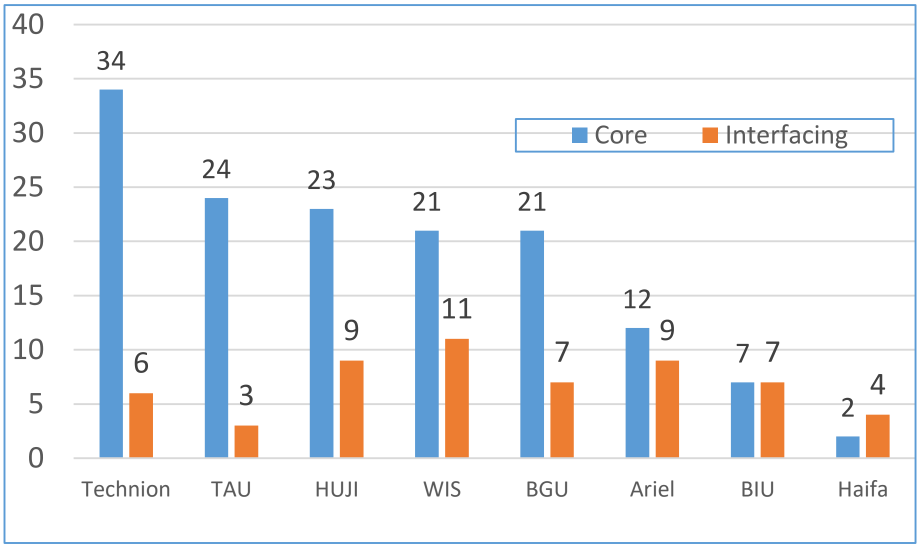
**b)** **Budgets:** The four existing QST centers differ from one another in their budget sources and magnitude. The **BIU** and **BGU** centers lack designated budgets, rather, each researcher in the center recruits his own budget (in BIU, for example, these individual budgets sum up annually to approximately 2.5M NIS). At **HUJI**, apart from the individual researcher budgets, the university allocates an annual sum of 100K NIS, which this year was increased to 300K NIS. In addition, the center was awarded by MOD 1.5M NIS for one year for a pivotal project of quantum communication. At the **Technion**, aside from individual researcher funds (which in the past two years totaled to about 15M Euro), donations designated for the Center totaled to approximately 8M dollars up to today.

**c)** **Center activities consolidate and form a research community:** All centres organize and initiate national and international meetings. Some also conduct symposia, workshops and summer schools for research students, weekly seminars, and outreach lectures for the public. The BGU center also produces high-level chips for labs around the world, and some centers avail some of their research facilities to the community.

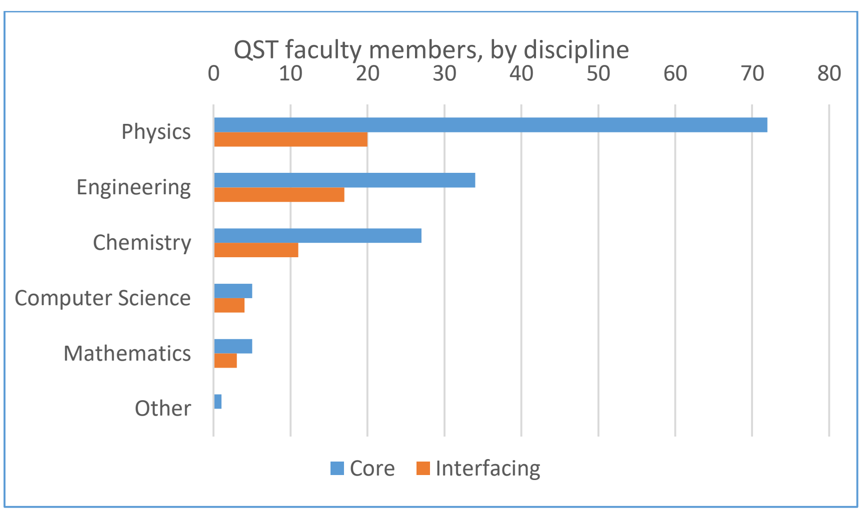
### 3.1.2 Scope and quality of the research in Israel

#### 3.1.2.1 Researchers and research students

University reports state that there are currently 144 core QST researchers and another 56 involved in peripheral QST research[13]. Core QST researchers are mentoring 471 graduate students (198 MSc, 273 PhD) and 122 postdoctoral fellows. As some reports count researchers who do not actually deal with core QST research, we estimate the actual number of core QST researchers to be around 110 and the corresponding number of actual graduate students to be 380. Below is the breakdown of these researchers – per the institutional reports:



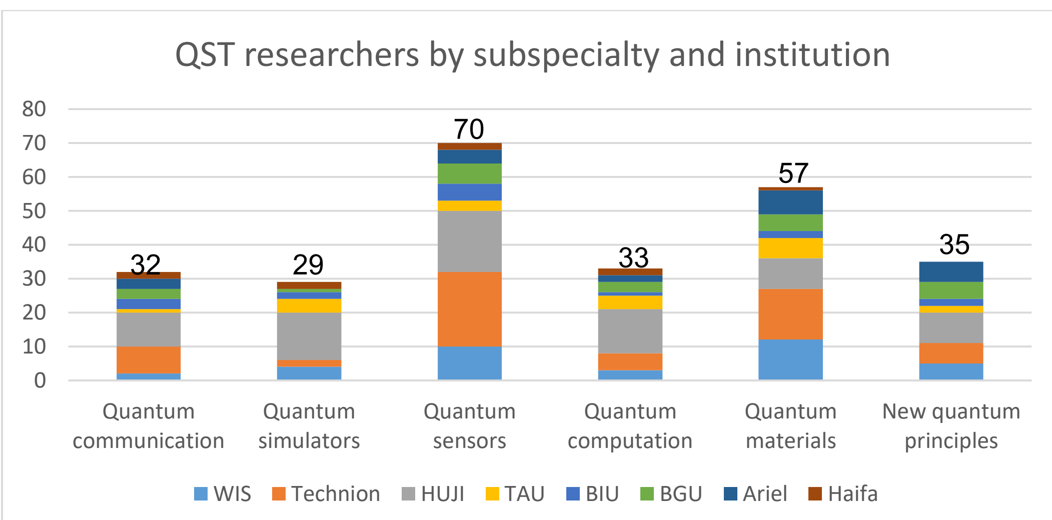

**Graph 3.1:** Breakdown of core QST and QST-interfacing researchers by institution. Total: 144 core faculty members (including 11 Profs emeriti) and 56 peripheral (interfacing).




[13]Data were taken from institutional reports, and therefore include researchers classified as belonging to core or peripheral disciplines, even though the committee would have classified them as peripheral/unrelated, respectively. Note that the presented numbers include emeriti professors.

| | Core Faculty | Core Students | | | | Faculty peripheral |
|---|---|---|---|---|---|---|
| | | MSc | PhD | Postdoc | Total | |
| **Physics** | 72 | 85 | 122 | 52 | 259 | 21 |
| **Engineering** | 34 | 68 | 79 | 26 | 173 | 17 |
| **Chemistry** | 27 | 32 | 50 | 38 | 120 | 11 |
| **Computer Science** | 5 | 5 | 5 | 1 | 11 | 4 |
| **Mathematics** | 5 | 2 | 13 | 5 | 20 | 3 |
| **Other** | 1 | 6 | 4 | 0 | 10 | 0 |
| **Total** | **144** | **198** | **273** | **122** | **593** | **56** |

**Table and graph 3.2:** Breakdown of core QST and QST-peripheral researchers by department. Breakdown of core QST and QST-peripheral research students by department.




**Graph 3.3:** Core QST and QST-peripheral researchers, by QST subfield

Taken together, most research in Israel is performed within the physics departments and relatively little is conducted in the computer science and mathematics departments. In addition, much research deals with quantum sensors and quantum materials, and significantly less with quantum computation, quantum communication, quantum simulators and innovative quantum theory principles with technological implications[14].

An additional interesting analysis focuses on the academic career stage of researchers in QST. Following is a breakdown of the core faculty members by career stage and proximity to retirement age as per our estimations:

| | Total Core Faculty | Emeritus | Expected to retire in the next 5 years | Expected to retire in the next 5-10 years | Expected to retire in >10 years |
|---|---|---|---|---|---|
| Physics | 72 | 3 | 8 | 6 | 54 |
| Engineering | 34 | 4 | 0 | 4 | 27 |
| Chemistry | 27 | 4 | 5 | 0 | 19 |
| Computer Science | 5 | 1 | 1 | 0 | 3 |
| Mathematics | 5 | 0 | 2 | 0 | 3 |
| Other | 1 | 0 | 1 | 0 | 0 |
| **Total** | **144** | **11** | **17** | **10** | **106** |

**Table 3.4** Core faculty members by career stage and proximity to retirement age

This analysis will be of use when assessing the expected changes in the number of faculty members in the coming years.

In addition, it is interesting to consider the gender breakdown of QST researchers. Here, we can see a picture similar to that seen in the general science community, with a low representation of women among faculty:[15]

[14]Of note, the quantum materials and quantum sensors fields are very broad. Therefore, many more researchers, including some who were classified as core QST researchers, although they aren't, will tend to classify their research as belonging to these subspecialties.

[15] The percentage of women in the QST sector is slightly lower than the general percentages of female faculty members in relevant disciplines. However, it must be emphasized that a small sample size was considered here, therefore, the statistical error is significant. The percentage of female faculty members in universities in 2013 (with the exception of WIS, whose reports combine faculty members with research associates, thus distorting the picture),

| | Core Faculty | Peripheral Faculty | Potential Faculty | Total |
|---|---|---|---|---|
| **Total** | **144** | **55** | **11** | **210** |
| **Men** | 135 | 50 | 9 | 194 |
| **Women** | 9 | 5 | 2 | 16 |
| **% Women** | 6% | 9% | 18% | 8% |

**Table 3.5:** QST researchers (core, peripheral, potential) by gender

#### 3.1.2.2 International comparison of research scope, priority and quality

It is difficult to find data that provide an accurate indication of the scope and quality of research in Israel versus abroad, especially since QST, per the committee's definition, encompasses several standard classification areas and subspecialties (physics, various type of engineering, chemistry, computer science, mathematics – and their associated subspecialties[16]). Thus, several indirect indications, from which the QST research scope and quality can be inferred, will be presented in this section. The full set of data is provided in Appendix 7.E.

##### a) Bibliometric analysis[17]

- **Priority indices[18]:** In the years 2007-2011, the disciplines of highest priority in Israel were clinical medicine (23%), **physics (11.4%), chemistry (7.2%) and engineering (6.4%),** the last three being relevant to QST.
  When compared to other countries[19], it is apparent that of the topics most relevant to QST disciplines: Israel had a higher priority for **physics, mathematics and computer science as compared to the global average;** in engineering, the priority was identical, while in chemistry and materials science, priority was lower.
- **Quantity/scope indices:**
  A key measure for scope of activity is the number of Israeli publications in a field and their relative percentage of the global and OECD publications in that field.
  Table 4e in Appendix 7.E shows that in comparison to other research disciplines, **the volume of activity in Israel during 2007-2011 was particularly high in mathematics (1.74% of global publications) and computer science (1.70% of global publications) and also high in physics (1.34% of global publications).** In materials science, chemistry

was between 7-15% in physical sciences, between 5-11% in mathematics and computer science, between 10-21% in engineering and architecture.

[16]Most existing bibliometric analyses are performed according to the Thompson Reuters classification, which includes 22 research areas and approximately 250 subspecialties.

[17] Data from "Research output and development in Israel: international comparison of scientific publications 1990-2011", Dr. Daphna Getz, Dr. Avishag Gordon, Dr. Noa Lavid, Yair Even-Zohar, Iris Eyal, Ela Barazani, Shmuel Neeman Institute for Advanced Science and Technology Research, August 2013.

[18] Priority is defined as the percentage of publications in a discipline relative to all scientific publications in the country.

[19] The data are presented in Appendix E, Table E3

and engineering, the volume of activity was lower (0.51%, 0.65% and 0.78% of global publications, respectively).

When analyzing trends over several years (comparison between the periods 2007-2011 and 2002-2006), it is apparent that the relative volume of Israeli activity in the OECD, increased in computer science and materials science, and slightly declined in the other relevant fields.[20]

The number of publications can be normalized by the size of the population in each country. When doing so, it can be noted that in the years 2007-2011, mathematics was the only area in which Israel is a global leader in the number of publications per capita[21].

- **Quality indices**

  (i) Citations per publication

If we consider the average number of citations per Israeli publication compared to the global or OECD count, during 2002-2006 and during 2007-2011, we obtain the following results:

| | Area | 2007-2011 | | 2002-2006 | |
|---|---|---|---|---|---|
| | | Avg. Israeli Cit/Pub relative to world avg. | Avg. Israeli Cit/Pub relative to OECD avg. | Avg. Israeli Cit/Pub relative to world avg. | Avg. Israeli Cit/Pub relative to OECD avg. |
| ⇩⇩ | Materials Science | 1.59 | 1.31 | 1.66 | 1.42 |
| ⇩⇩ | Space Science | 1.53 | 1.37 | 1.57 | 1.43 |
| ⬆⬆ | Plant & Animal Science | 1.46 | 1.27 | 1.36 | 1.22 |
| ⇩⇩ | Physics | 1.42 | 1.20 | 1.46 | 1.27 |
| ⬆⬆ | Geosciences | 1.32 | 1.14 | 1.17 | 1.03 |
| ⇩⇩ | Agricultural Sciences | 1.30[11] | 1.10 | 1.40 | 1.25 |
| ⬆⬆ | Molecular Biology & Genetics | 1.30 | 1.18 | 1.15 | 1.08 |
| ⇩⇩ | Chemistry | 1.29 | 1.05 | 1.35 | 1.12 |
| ⬆⬆ | Microbiology | 1.25 | 1.09 | 0.96 | 0.89 |
| ⬆⬆ | Biology & Biochemistry | 1.24 | 1.10 | 1.11 | 1.02 |
| ⇩⇩ | Pharmacology & Toxicology | 1.15 | 1.02 | 1.24 | 1.15 |
| ⬆⬆ | Clinical Medicine | 1.13 | 1.03 | 0.92 | 0.87 |
| ⬆⬆ | Economics & Business | 1.11 | 1.05 | 1.06 | 1.03 |
| ⬆⬆ | Immunology | 1.06 | 0.98 | 0.85 | 0.81 |
| ⬆⬆ | Neuroscience & Behavior | 1.06 | 0.99 | 1.01 | 0.97 |
| ⇩⇩ | Engineering | 1.01 | 0.97 | 1.19 | 1.11 |
| ⬆⬆ | Psychiatry/Psychology | 1.00 | 0.96 | 0.94 | 0.92 |
| ⇩⇩ | Environment/Ecology | 0.98 | 0.89 | 1.00 | 0.92 |
| ⇩⇩ | Computer Science | 0.96 | 0.90 | 1.69 | 1.55 |
| ⇩⇩ | Mathematics | 0.96 | 0.88 | 1.12 | 1.01 |
| ⬆⬆ | Social Sciences, general | 0.94 | 0.88 | 0.74 | 0.71 |

**Table 3.6:** Average number of citations for Israeli versus global and OECD publication during 2002-2006 and during 2007-2011

[20] Narrowing down to the OECD counterbalances the dramatic effect of inclusion of East Asian countries into the academic research arena (especially China and India). When looking at trends of the volume of Israeli activity in relation to the rest of the world, a reduction in all disciplines, apart from one (space science), is seen.

[21] Presented data can be found in the Shmuel Neeman Institute report, ibid.

As seen, the **average number of citations-per-publication in material science, physics and chemistry is higher in Israel as compared to the global and OECD averages in these areas** (Israel ranks #5 in materials science, #11 in physics and #10 in chemistry). In engineering, the Israeli average is similar to the OECD average (Israel ranks #23 in the global ranking) and in computer science and mathematics the Israeli average is slightly lower than the global and OECD ones (global ranking of #20 and #26, respectively)[22].

Analysis of the citations per publication normalized for the **nanoscience & nanotechnology[23] sub-field** shows that during the years 2007-2011, Israel ranked as high as #6 in the international listing for this index (data are provided in Table E5 in Appendix E).

(ii) Most cited papers

Analysis of the number of globally most cited papers in the various disciplines, number of Israeli publications in this list, and their percentage per field in the years 2001-2011 (data in Table E.6, Appendix E), shows that the four leading fields in Israel with respect to this index are: space science (#1), molecular biology and genetics (#2), computer science (#3) and physics (#4) – the latter two are relevant to QST.

**Following is a table summarizing the findings of the bibliometric analysis:**

| | Area priority relative to the world | Scope of activity in the area in Israel relative to the world | Publication quality in the area in Israel relative to the world |
|---|---|---|---|
| **Physics** | High | High | Citations per publication high (#11); very high percentage of most cited papers worldwide |
| **Engineering** | Low | Not High | Citations per publication ~ world average |
| **Chemistry** | Low | Not High | Citations per publication high (#10) |
| **Materials Science** | Low | Not High; on the rise with respect to the OECD | Citations per publication very high (#5) |
| **Computer Science** | High | Very high (and on the rise with respect to the OECD) | Citations per publication slightly lower than world average; very high percentage of most cited papers worldwide |
| **Mathematics** | High | Very High World-leading in number of citations per capita | Number of citations per publication slightly lower than world average |
| **Nanoscience and nanotechnology** | N/A | N/A | Very high number of citations per publication (#6) |

**Table 3.7** Bibliometric analysis of QST-related research areas

[22] For comparison, when averaging over all disciplines, Israel ranks #14 in the global ranking of this index.

[23] Analysis of additional relevant subspecialties from earlier years can be be found in previous Shmuel Neeman Institute reports, e.g., Computer Science – Theory and Methods, Computer Science – Interdisciplnary Applications and Optics from 2004-2008 in the "Research and development output in Israel: Scientific publications in an international comparison:, Dr. Daphna Getz, Yair Even Zohar, Bella Zalmonovitz, Dr. Eran Lak, April 2011 report.

### b) ERC[24,25] grant winning statistics

The European ERC grants are prestigious, with grantees recognized as leaders in their field (relative to their age group). Therefore, they serve as an interesting indicator of research quality in the field in each country, and can be used to compare between countries.

- Of the 144 faculty members classified by research universities as core QST researchers, 39 won ERC grants for QST-related research in the years 2007-2016. Below is a breakdown of these grantees by discipline, institution, years and grant type.

| Institution | Physics | Engineering | Chemistry | Computer Science | Mathematics | Total |
|---|---|---|---|---|---|---|
| **Weizmann Institute** | 11 | 0 | 5 | 0 | 0 | **16** |
| **Technion** | 3 | 2 | 0 | 0 | 0 | **5** |
| **Hebrew University** | 4 | 1 | 2 | 1 | 3 | **11** |
| **Tel Aviv University** | 1 | 3 | 0 | 0 | 0 | **4** |
| **Bar Ilan University** | 1 | 1 | 0 | 1 | 0 | **3** |
| **Ben Gurion University** | 0 | 0 | 0 | 0 | 0 | **0** |
| **Ariel University** | 0 | 0 | 0 | 0 | 0 | **0** |
| **Total** | **20** | **7** | **7** | **2** | **3** | **39** |

**Table 3.8:** Core QST researchers awarded ERC grants, by institution and discipline, 2007-2016

[24]Note that proposals sometimes receive almost identical scores, resulting in rejection of very high quality proposals (especially because the number of awardees each year for each committee is small). Therefore, this index is slightly problematic, and it would be interesting to also consider the number of proposals that reached the final assessment stage of each committee as an index.

[25]There are three types of grants: Starting grant = StG – grants for early-career researchers, within 2-7 years of completing their PhD; Consolidator Grant = CoG – grants for young principal researchers, within 7-12 years of completing their doctorate; Advanced Grant = AdG – grants for established researchers, over 12 years after completing their PhD.

| | StG | AdG | CoG | Total |
|---|---|---|---|---|
| **2007** | 0 | 0 | 0 | **0** |
| **2008** | 0 | 4 | 0 | **4** |
| **2009** | 0 | 1 | 0 | **1** |
| **2010** | 0 | 2 | 0 | **2** |
| **2011** | 1 | 0 | 0 | **1** |
| **2012** | 0 | 1 | 0 | **3** |
| **2013** | 1 | 4 | 1 | **9** |
| **2014** | 8 | 1 | 2 | **11** |
| **2015** | 3 | 2 | 2 | **7** |
| **2016** | 3 | 1 | 0 | **4** |
| **Total** | **19** | **17** | **6** | **42** |

**Table 3.9:** ERC grants to core QST researchers, by year and grant type[26], 2007-2016

As shown, the number of grantees was particularly high at the Weizmann Institute and Hebrew University. The number grew significantly in the years 2013-2016. Most grantees in this period were early-career researchers (StG).

To compare Israel with other countries we performed two analyses:

(i) **Comparison of total number of grantees of all grant types in the years 2007-2016:**

An international comparison of the number of ERC grantees in the years 2007-2016 in Physical Sciences and Engineering (PS&E) (total: 3,196) which used the word “quantum” in their research description (total: 623)

- Of the 623 quantum-related grants, 27 (which are 5%) were awarded to Israelis. In this index, Israel ranked #8, together with Austria (data in Table E.7 in Appendix E). **Namely, among ERC grantees in QST, a high percentage were Israelis**, in spite the enormous difference in the size of research community in Israel versus other countries.

[26]The overall number here is 42 and not 39, as in the previous table, due to researchers who were awarded two ERC grants each.

- This index can be compared to the relative strength of each country in PS&E at large; of the 3,196 grants, 134 (i.e. 4%) were awarded to Israeli researchers, again ranking Israel #8 (see data in Table E.8, Appendix E).
  **Namely, QST is even stronger than PS&E at large in Israel.**
- The percentage of PS&E grants which are QST-related (i.e. with the word "quantum" appearing in the research description) can serve as an additional national index. When looking at this index in the same 10 countries, Israel ranks higher (#5) than for the previous indices. **Namely, of the PS&E grants awarded to Israeli researchers, a higher percentage relative to other countries, are in QST** (see data in Table E.9, Appendix E).

(ii) **Focus on the quality of young QST researchers in recent years:**
An international comparison of **2013-2016 StG** ERC grantees in the PS&E sector (total: 628), who used the world "quantum" in their research description (total: 120).

- Of these 120 grants awarded, 10 (which make 8%) were awarded to Israeli researchers. Israel ranks #4 in this index, after Germany, France and the UK (see data in Table E.10, Appendix E). Namely, despite the relatively small size of the research community in Israel, **when focusing on the young outstanding QST researchers in recent years, Israel is extraordinarily strong,** and is positioned immediately after countries with significantly larger research communities.
- This index can be compared to the relative strength of young PS&E researchers in each country in recent years. Of the 628 such grants, 7% were awarded to Israeli researchers, and Israel ranks #5. **Namely, in the past few years, the young Israeli QST researchers are even stronger than the young Israeli PS&E researchers at large.**
- The percentage of 2013-2016 StG PS&E grants which are QST-related (i.e. with the word "quantum" appearing in the research description), can also serve as an additional index. In the same 11 countries, Israel received a relatively high percentage of QST-related grants (22% of these Israeli StG grants were related to QST, ranking Israel #4 of the 10 leading countries in this index after Denmark, Austria and Germany - data in Table E.12 Appendix E). **Namely, of the PS&E grants awarded to young Israeli researchers, a relatively high percentage, in comparison to other countries, is in QST.**

### c) H-index analysis

The h-index[27] is a common, albeit controversial, academic index measuring a researcher's scientific output and impact. We analysed h-index values of the 144 researchers classified

[27]The h-index is an index attributed to an individual researcher, attempting to express a combination of his/her scientific output and scientific impact (manifested by citations per publication). The researcher is assigned an index h if he/she published h articles, each being cited at least h times. This index was proposed in 2005 by Hirsch – a physicst at UCSD. As a scale of magnitude, according to Hirsch, for physicists, h~12 is a typical h-index value for being granted tenure at a leading research university, h~18 is a typical value for obtaining full Proffesorship, h~15-20 is a value appropriate for membership in the American Physical Society and h>45 is appropriate for membership in the American Academy of Science. Estimates show that after 20 years of research, a successful scientist will have h~20, an outstanding scientist h~40 and an exceptional scientist h~60.
Of note, this index has several characteristics, drawbacks and limitations that must be taken into consideration: (a) it is difficult to use it to compare researchers in different fields due to the different citation practices in the different fields; (b) the index is naturally biased in favor of senior researchers and against young researchers; (c) the index is low for researchers with few publications, even if they are extraordinary in their scientific importance; (d) the index does not consider the researcher's position in the list of authors; (e) the index is influenced by self-citations.
The analysis conducted in this section assumes that the h-indices of QST researchers, even if in different disciplines, can be compared. However, it is clear that there are still differences in citation practices between disciplines, which limits validity of the proposed analysis.

by universities as core QST. Below is the distribution (x axis – ranges of h-index values; y axis – number of researchers whose index falls within the range):

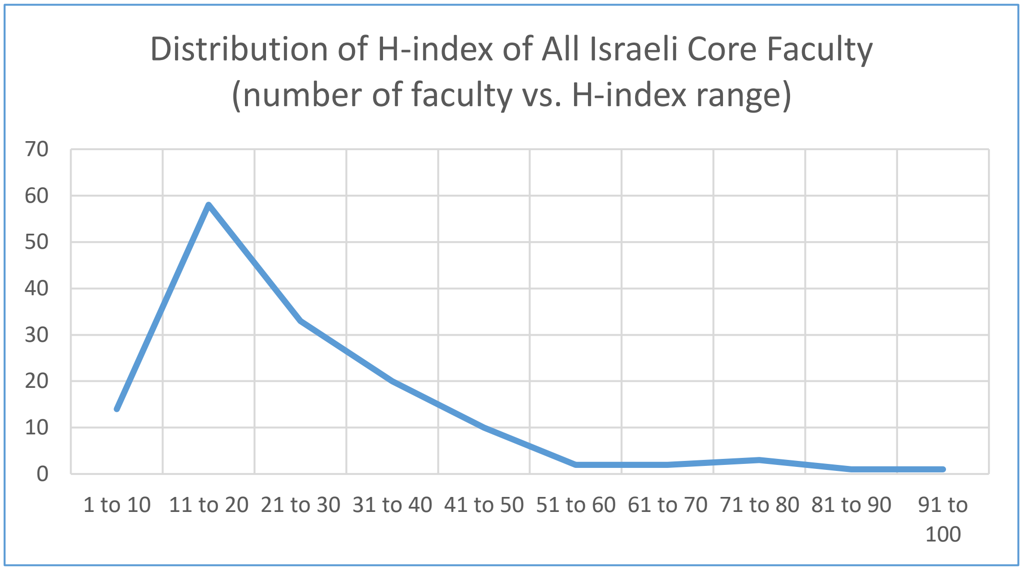



**Diagram 3.10:** Distribution of number of Israeli core QST researchers by h-index

Two distribution characteristics should be noted:

i. **The average h-index of all researchers is 25 – a relatively high value** (see measure of comparison in footnote 27), and the most probable h-index is in the 11-20 range. This value is affected by the fact that many researchers in QST are young academically speaking (approximately 75% have more than 10 years until expected retirement).
ii. The maximal h-index is 94. **Nineteen researchers (13% of the core QST researchers) had an index of 41 or above,** which, as said, is considered an index of outstanding scientists after 20 years of scientific activity (see footnote 27). Namely, **Israel has a relatively high rate of outstanding researchers.**

### 3.1.2.3 Main conclusions

Following are the conclusions of the analyses presented in the previous sections with regards to the scope and quality of academic QST research in Israel. These will serve as the basis for the national plan detailed in section 5:

(a) According to institutional reports, there are currently around **144 core QST researchers in Israel** of whom 11 are professors emeriti. **The committee considers about 110 researchers as being a more realistic estimate.**
(b) **Most QST research in Israel is conducted in physics departments,** and little in computer science and mathematics.
(c) Much research is being conducted on **quantum sensors and quantum materials,** and significantly less on quantum computation, quantum communication, quantum simulators and innovative principles of quantum theory with technological implications.
(d) 1. In a global comparison, Israeli researchers are very active in **computer science, mathematics and physics**.
2. The average Israeli publication in material science, nanoscience and nanotechnology, chemistry and physics is highly cited.

3. **Computer science and physics** are excelling in Israel: the percentage of Israeli publications among the most highly cited publications worldwide is very high.

(e) **The percentage of outstanding Israeli QST researchers is very high as compared to other countries, and as compared to other PS&E areas in Israel.** This is especially true considering **young researchers in the field.**

(f) **The average Israeli core QST researcher has a relatively high scientific output and impact; a high percentage of them (10%-15%) are outstanding** with regards to scientific output and impact.

### 3.1.3 New researchers – projected demand

**In the coming 5 years,** several researchers are expected to retire while new researchers are expected to be hired. These researchers include:

(a) PhD students (years 3, 4, 5) and postdoctoral fellows in the field who will be hired as new faculty members in Israel.

(b) PhD students (years 3, 4, 5) and postdoctoral fellows working in nearby fields, who will choose to continue their research in QST and will be hired as new faculty members in Israel.

(c) Faculty members currently in proximal fields, who will choose to switch their research focus to core QST areas.

(d) A small number of non-Israeli faculty members or Israeli PhD students studying abroad

We estimate, based on the data and assumptions presented in Appendix 7C, the following numbers for categories a-c in the coming 5 years (2017/8-2022/3) [28]

- Retirements: approximately 17 core QST scientists are expected to retire, as per the following breakdown:
  - Approximately 8 in physics
  - Approximately 0 in engineering
  - Approximately 5 in chemistry
  - Approximately 1 in computer science
  - Approximately 2 in mathematics
  - Approximately 1 in "other"
- New researchers from category (a): approximately 42, as per the following breakdown:
  - Approximately 13 in physics
  - Approximately 21 in engineering
  - Approximately 5 in chemistry
  - Approximately 1 in computer science
  - Approximately 1 in mathematics
  - Approximately 1 in "other"

[28] Several reservations with regards to this analysis should be mentioned:

(a) We assumed that the ratio of the number of doctoral students to the number of new QST faculty members will be similar to that of the broad research areas of the faculty members (physical sciences, engineering & architecture, computer science and mathematics); **However, when considering current trends, it seems that QST disciplines can expect lower ratios (i.e., more hirings)**

(b) The sample size is small, thus, significant error is possible.

Without intervention, the following numbers of core QST faculty members expected in the coming 5 years are:

| Discipline | Core Faculty 2018 | Projected core faculty in 5 years(2023) |
|---|---|---|
| Physics | 69 + 3emeriti | 74 (+7%) + 11 emeriti |
| Engineering | 30 + 4 emeriti | 51 (+70%) + 4 emeriti |
| Chemistry | 23 + 4 emeriti | 23 (+0%) + 9 emeriti |
| Computer Science | 4 +1 emeriti | 4 (+0%) + 2 emeriti |
| Mathematics | 5 | 4 (-20%) + 2 emeriti |
| Other | 1 | 1 (+0%) + 1 emeriti |
| Total | **133 + 12 emeriti** | **157 (+18%) + 29 emeriti** |

**Table 3.11:** Projected number of core QST faculty members in the coming 5 years, by discipline

Therefore, **without directed intervention, an 18% increase in the number of QST faculty members (non-emeriti) is expected. This is less than half of the total recruitment plan of all institutions and, therefore, a deficit is expected. Most of this growth is expected to be in engineering. In other fields, the growth is expected to be small or negligible.** An increase in the number of faculty members in QST in the next five years can therefore be primarily fed by category (c) researchers, i.e., current faculty members in proximal fields who will choose to switch their research focus to QST.

If we extend our outlook and consider **the coming 10 years**, the number of retirements is expected to increase to 27, and new researchers joining the field will be of three types:

(a) Current doctoral students (years 1, 2), current MSc students (years 1, 2) and BSc students in their third year of studies, who will be hired as new academic faculty members in Israel within the next 10 years.
(b) Faculty members currently in proximal fields, who will choose to switch their research focus to QST.
(c) A small number of non-Israeli researchers or Israeli PhD students studying abroad.

Of course, these numbers will be critically influenced by long-term intervention.

### 3.1.4 Training programs

**BSc:**

Various courses in QST are always included in the BSc curriculum of physics and of degrees combining physics with other fields. In other fields, the picture varies between institutions but in general, introductory QST courses are not mandatory and there aren't enough such courses. Therefore, students in disciplines other than physics are barely exposed to QST[29].

**Graduate degrees:**

The status is slightly better for graduate degrees. Aside from physics students exposed to this area[30], students from other disciplines, who need to learn about QST topics for their research, are usually sent by their mentors to take such courses around the campus. In most institutions, these advanced courses are primarily offered by the physics department.

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[29]Relevant faculties at the Technion do offer courses in quantum mechanics but these have to be upgraded and adapted so they are offered as dedicated courses for students from the various faculties. The Faculty of Chemistry offers quantum mechanics courses. Since approximately 1/3 of the electrical engineering students at the Technion are also enrolled in the physics program - most of them are adequately exposed to QST. There is hardly any training in computer science and computer engineering.

Hebrew University offers 5 quantum-related courses given each year, which are open to non-physics students (3 for electrical engineering and computer engineering students – quantum optics, introduction to quantum mechanics for engineeers, quantum technnologies; quantum chemistry and its applications for chemistry students and introduction to quantum computation for computer science students). There are also courses given once every two years.

Tel-Aviv University

- Bachelors in electrical engineering includes a mandatory course - "quantum physics and solid state". More advanced courses such as "electronic devices" and "introduction to lasers" are partly based on this course.
- In the materials science and engineering program in the Chemistry department, "quantum mechanics and chemical bonds" is a mandatory course in the fourth semester.
- In the Chemistry department, "quantum mechanics and chemical bonds" is a mandatory course, as well as an advanced course - "quantum chemistry". A course in spectroscopy. Electives – quantum dynamics, solid state of quantized nanoscopic systems.

The university currently has about 50 students studying Electrical Engineering and Physics who therefore, study high-level quantum physics. There are about 50 students studying computer science and electrical engineering who are not exposed to QST (aside from one course in fields and waves, which is inadequate), and there are about 250 students who are studying electrical engineering alone, and who are not exposed to QST. In computer science, there is currently one quantum computation course, which is offered once in two years.

The university is considering opening a new course in quantum information for computer science/electrical engineering/mathematics students, and possibly, an online introductory course on the fundamentals of quantum theory.

At Bar Ilan University, physics-engineering double-major students study advanced quantum physics with physicists, as well as modern optics and lasers. These students, like physicists, participate in summer research labs which expose them to QST research. All electrical engineering students take a basic course in quantum theory. Solid state, semiconductor devices, modern lasers and optics courses are offered for those specializing in optical engineering.

At Ben-Gurion University the following courses are offered: Charge and energy transport through nanoscale systems, photovoltaic and solar energy uses, advanced quantum mechanics. Researchers in QST have emphasized the need to teach electrical engineering students more topics since currently, quantum mechanics 2 is not offered/not suitable for engineering students.

At Haifa University, during the 2018 Spring semester Prof. Shay Giron will teach a trial course in "quantum computation" for mathematics students. This course is given for the first time in the university.

[30] Hebrew University is unique in that it launched an MSc Physics program (and applied physics) with subspecialty in quantum technology and information.

Therefore, in most cases, the courses will presume basic knowledge in the field, and will not be suitable for non-physics students. In addition, courses such as quantum computation theory (which should be offered by the computer science department) or quantum electronics, are usually missing.

In this respect, a few exceptions should be noted: at Tel-Aviv University, an introductory course in "quantum electronics" is offered to electrical engineering students; in chemistry – quantum chemistry and advanced courses such as fundamentals of magnetic resonance, introduction to solid state theory, quantum electrodynamics and advanced spectroscopy and solid state of quantized nanoscopic systems; in computer science – a course in quantum computation is offered every few years.

Of note, an MSc physics degree is still not offered in Ariel University. therefore, mainly advanced courses such as quantum chemistry and quantum electronics are offered there for MSc. There are plans to open courses in advanced quantum mechanics and field theory.

## 3.2 Strategic plans in the various institutions for the coming 5 years

In response to the Committee's request for information from the various universities, all universities reported plans to invest in development of QST in the coming 5 years, to continue developing existing centers or to establish new dedicated centers. In some universities, such plans are part of an already existing strategic institutional program, while in others, the PBC and the Committee's activities catalyzed thinking processes on this.

Following is the overall projected expenditure in the coming 5 years, as per university reports (excluding research student and post-doc scholarship costs):

| | Number | Projected cost (M NIS) |
|---|---|---|
| Recruitment of academic staff | 54 | 150 |
| Infrastructure equipment (excluding construction) | | 265 |
| Additional technical staff | 52 | 85 |
| **Total** | | **500** |

**Table 3.12:** Summary of cost of new faculty recruitment, infrastructure and technical staff, as per university reports of development plans within the next 5 years

Priority of QST development: Haifa University sees QST as a potential growth engine for the university, with priority similar to a number of other development programs, and all other research universities see it as a growth engine of higher priority than other institutional development programs.

Following is a short summary of statements of intent sent by university presidents to the Committee:

**a. Hebrew University**

- Recruitment of approximately 10 researchers (7 experimentalists and 3 theoreticians)
- Establishment and upgrade of several supporting infrastructures for experimental QST research, including a thin-layer quantum interface characterization and production lab, electronics and control lab, time synchronization system and combing laser, and upgrade of the mechanical workshop.
- Recruitment and training of 6 new engineers.
- Expansion of the QST MSc program to other faculties (beyond physics and applied physics). This program is already in a test-run and in about one year, teaching and training quality will be assessed, and improvements will be proposed. Efforts will be invested to recruit students to support the desired scope of research.
- Establishment of a post-doc hub to attract and recruit outstanding post-docs.
- Establishment of multidisciplinary groups by small internal seed grants to enable researchers to assess feasibility of collaborations.
- Continued development of international collaborations with IQST (The ULM University and MPQ Quantum Center in Stuttgart) and with ETH, and expansion of joint scholarship programs.
- Promote industry entrepreneurship via HU-START and the TTO (the general university START support system dedicated to such initiatives). Consolidation of the above support system with respect to applied research and establishment of dedicated QST companies in this framework.

**b. Technion**

- Recruitment of 7 new faculty members in the field: 2 senior and 5 young.
- Upgrade and expansion of existing research infrastructure, primarily with regards to fabrication of 2D and superconducting materials, upgrade of fabrication capacities in the nanoelectronics center, material characterization, upgrade of the electronic microscopy center and upgrade of quantum optics characterization systems.
- Recruitment and training of 5-10 engineers.
- Development of updated study programs for engineering undergraduate degrees, aiming to deepen the knowledge in various QST areas.
- Fellowships for postdocs
- Seed funding to initiate both internal and external collaborations in Israel and worldwide.
- Continued and reinforced international collaborations as well as collaborations with industry and security sector.

**c. Bar-Ilan University**

- Recruitment of 10 new faculty members working on quantum technologies – in physics, engineering, computer science and applied mathematics departments.
- Establishment of a center for the institute (a new building or allocation and renovation of an existing building)
- Purchase shared equipment for the new center (lithography, nanofabrication, microscopy, diamond growth, etc.).
- Recruitment of 10 engineers and research staff for new research labs, shared equipment center and new teaching labs.
- Prepare several new study programs integrating physics, engineering and computer science for a degree in quantum engineering and for a subspecialty in quantum computation.

- Scholarships for research students and postdocs.
- Establishment of a competitive support fund to promote assessment of feasibility of cross-disciplinary studies between members of the center.
- Hosting international visitors to promote existing and new collaborations.
- Support members of the center in establishing collaborations with industry and security sector in the framework of existing support at the university.

d. **Ben-Gurion University**
- Recruitment of at least 4-5 new faculty members in the field.
- Establishment of new QST labs and clean rooms in new buildings in the north campus.
- Establishment of shared labs and pan-university facilities.
- Continued collaboration with the industry (including with companies in the science park near the campus) and with the security sector.

e. **Tel Aviv University**
- Establishment of a QST-dedicated research center within 1-2 years.
- Recruitment of approximately 6-8 physics, electrical engineering, chemistry and computer science faculty members – around half experimentalists and half theoreticians.
- Purchase of a transmission electron microscope (TEM) and other research infrastructures.
- Recruitment of two lab engineers.
- Improvement of the training program – addition of advanced courses to physics, electrical engineering and chemistry curricula, development of a new undergraduate course in quantum computation algorithms will be considered, development of an online course (MOOC) on quantum theory principles will be considered.
- Awarding 5-10 post-doc scholarships in the field.
- Promotion of seed grant allocations mostly financed by external funds.
- Promotion of international research collaborations with initial internal funding.
- Continued promotion of collaborations with industry and/or security sector.

f. **Weizmann Institute**
- The Institute is currently establishing 2 relevant centers, to be completed in the next two years: (a) A QST center – will be located in the Faculty of Physics and will include 3 hubs – solid state QST, atomic, molecular and optical physics (AMO) QST, QST theory; (b) Advanced and Smart Materials Center, which will include a "Quantum Materials" unit – the Advanced Materials Center will be situated in the Faculty of Chemistry.
- Recruitment of approximately 5 new faculty members in the field.
- Establishment of centralized research infrastructure, including a new nanofabrication facility, advanced electron microscopy, advanced photonic fabrication tools, central clock facility, optical frequency scanner, and others.
- Recruitment of approximately 10 staff scientists and engineers.
- Promotion of cross-disciplinary collaborations on campus and continued establishment and promotion of international collaborations (e.g., the joint conference with ETH).
- Expansion of collaborations with the industry and security sector.

g. **Ariel University**

- Establishment of a QST research and development center under the umbrella of the Accelerators Center.
- Recruitment of approximately 6 new faculty members.
- Infrastructure purchase and upgrade, including a nanotechnology fabrication system, hoods, recycling/helium liquid system and femtosecond laser amplifier.
- Recruitment of 3 new engineers and a technician.
- Addition of courses to the graduate level curriculum, and later, additional courses such as quantum computation.
- Scholarships for 5 postdocs and approximately 20 MSc and PhD students in various disciplines (physics, electrical engineering, chemistry, mechatronics, computer science).
- Promotion of cross-disciplinary research.
- Reinforcement of existing international collaborations and establishment of new ones.
- Continued collaboration with the security sector and Atomic Energy Commission and formation of collaborations with the industry.

h. **Haifa University**

- Establishment of the "Center for Theoretical Physics and Astrophysics – Haifa University" is in its final stages. The center will consolidate QST research at the university over the coming years.
- Haifa University is currently assembling a group of QST theoreticians. The institution plans to recruit an additional 5 new faculty members in theoretical physics, mathematics and computer science.
- Significant upgrade of computation capacities at the university by expanding the existing multi-processor computer cluster.
- Recruitment of a research engineer dedicated to providing support, and recruitment of a center administrator.
- Double the physical area of the center infrastructure.
- Promotion of collaborations with researchers abroad.
- Outreach lectures for the public.

### 3.3 National impediments and deficits

The meetings held in the framework of the Committee's activities uncovered several issues that hinder development of the field in academia in Israel. Below are the primary bottlenecks:

- **Deficient research infrastructure** – a deficit in advanced fabrication and characterization infrastructure was noted in all institutions. In addition, a deficit was noted in a broad national infrastructure, in particular with regards to time and frequency distribution and a national platform for conducting quantum communication experiments.
- **Teaching infrastructure** – training a skilled workforce requires exposure to the experimental aspects of QST as part of the degree. Currently, this is lacking in all institutions and in all degrees.
- **Low presence of computer scientists and mathematicians in the field**.

- **Shortage in research students in the field who will serve as a quality pool for significant increase of the number of faculty members in QST[31].** This is particularly true in disciplines such as chemistry and mathematics, which do not include many QST faculty members who can mentor students. In computer science and engineering, this limitation is further compounded by competition with the industry – academic stipends are significantly lower than the average pay in industry and many BSc and MSc graduates leave academia.
- **Shortage in student training programs integrating relevant knowledge sectors, already noted at the undergraduate level**: optimal undergraduate QST training should include basic courses in two or more relevant QST areas (e.g., physics and computer science or physics and electrical engineering). In addition, outside of the physics departments, there is practically no QST exposure in undergraduate or graduate degrees. Some computer science/engineering/chemistry departments oppose to broadening the training. Physics departments also often do not expose their students to topics such as quantum computation, and generally, students do not learn fundamental concepts in computer science/engineering/chemistry. This narrow undergraduate training poses an obstacle to both training a suitable and updated workforce for the industry and in establishing the next generation of quality faculty in QST.
- **Shortage in high-level international postdocs** (similar to the general deficit in natural sciences in Israel).
- **Limited multidisciplinarity** and limited research collaborations (intra and inter-institutional) makes it difficult coping with complex challenges requiring a range of skills and knowledge.
- **Difficulty recruiting quality technical staff:** due to regulatory limitations, salaries are significantly lower than those in industry.
- **Low industry involvement:** Low industry investments on the one hand and difficulty in transferring knowledge and skills to industry, on the other hand.

## 3.4 Collaboration with the Ministry of Defense (MOD)

For several years now, the Ministry of Defense has been funding QST research. The funds are usually awarded to individual researchers, however, recently, this support has been expanded to establish a national demonstrator in quantum communication (by HUJI). Most research funds are allocated by Maf'at and some by the Committee for Atomic Energy and American security organizations.

The security aspect constitutes a central rationale for development of this field in Israel and the program detailed in sections 5, 6 relates to this aspect.

## 3.5 Collaboration with Industry

Most collaborations with industry are on an individual and not institutional level. A large portion of such collaborations relate to security related industries – including Rafael and Accubit, Elbit and the Aerospace industry/Ramta, Elta Systems[32].

[31] See quantitative analsysis in section 3.1.3
[32] It is difficult to assess from the reports whether the collaborations are QST-related or involve researchers in the institutional research centers but from other disciplines.

Additional collaborations between researchers and Israeli and multi-national companies include Melanox, Intel, Google, GM, Vilantis, Makhteshim Adama, Qlight (bought by Merck), Northrop-Grumman and various start-up companies[33]. Clearly lacking were collaborations with global companies such as Google, Microsoft and IBM, which invest considerable resources into quantum computation research and development.

The industrial aspect and collaboration with the Innovation Authority are central components of the national plan detailed in sections 5, 6.

### 3.6 Interface with the European Flagship program

As mentioned in section 2.4 and as presented in Appendix 7B, the EU announced the Quantum Flagship program, under the umbrella of the European Horizon 2020 Research and Innovation program (H2020). In the Quantum Flagship program, the European Commission will invest approximately 1B Euro over 5-10 years. Since Israel is an associated country of H2020, all European flagship calls will be open to Israelis as well, which is expected to leverage national Israeli investments in QST.
The EU has already begun to invest in the quantum sector. This began with a 36M Euro joint program (2016-2017) for the union and interested countries (QuantERA), and a preliminary call to establish a 0.5M Euro Coordination and Support (CSA) Action.
Currently, the ramp-up stage of the flagship program (2018-2020) has begun. Calls have been and are being announced: for the CSA (2M Euro in 2018), and the Flagship Research and Innovation Actions (130M Euro in 2018, of which 110M Euro is for leveraging knowledge transfer from academia to industry and 20M Euro for continuation of long-term research projects). In addition, a 15M Euro call to establish a Quantum Key Distribution Testbed has been announced. Subsequent activity is expected in the QuantERA 2019 program. Starting in 2020, the program will enter its full-fledged phase and a series of new calls is expected. In the framework of its activities, the EU has established a High-Level Steering Committee (HLSC) in collaboration with leading academic researchers and representatives of leading companies in the field. In June 2017, the committee published its Quantum Technologies Flagship Final Report.
On a national level, ISERD[34] – the Israel-Europe Directorate for Research Innovation – ensures representation of Israel in the various program management committees – those that currently exist and those that are planned. To date, all funders are represented in the Board of Funders (BoF), which, together with the European Commission, form a decision-making authority. Beneath it is the High-Level Steering Committee. Once the flagship stage commences, this entity will be exchanged by the Strategic Advisory Board, which will be responsible for strategic guidance. Below it are the Coordination & Support Action (CSA) and Science Engineering Board (SEB), in charge of networking and coordination.

[33]See above

[34]ISERD is an inter-office organization established by the PBC of the CHE, Ministry of Economy, Ministry of Science and Technology, Ministry of Finance and Ministry of Foreign Affairs. Its main roles are:

- Promotion of Israel-Europe collaborations in thematic and/or binational R&D programs
- Activity in the various institutions of European R&D programs
- Managements of an extensive network of contacts with parallel European agencies
- Assistance in identifying collaborators in Israel and Europe
- Training and monitoring regarding research proposals

The National Quantum Coordinator Network (NQN) was established as part of the activities of the current CSA, which assists CSA administrators in building and planning the activity structure of the flagship program and provides recommendations regarding various points which should be developed in the framework of the program.
Israel has a representative in the NQN (Prof. Nadav Katz – HUJI), who helped represent Israeli positions toward publication of the flagship program. Later, appointment of Prof. Nir Davidson (WIS) to the HLSC was proposed to the program directors in Brussels. ISERD, in coordination with PBC, the Ministry of Economy, MOD and other stakeholders, is working on integrating Israeli representatives also in other boards and committees.
The combination of a national program together with a pan-European one, has the potential to significantly impact the Israeli research community. Of note, the EU expects to see integration and synergy between the national program of each country and that of the EU and will give this fact particular weight in the score of future calls.

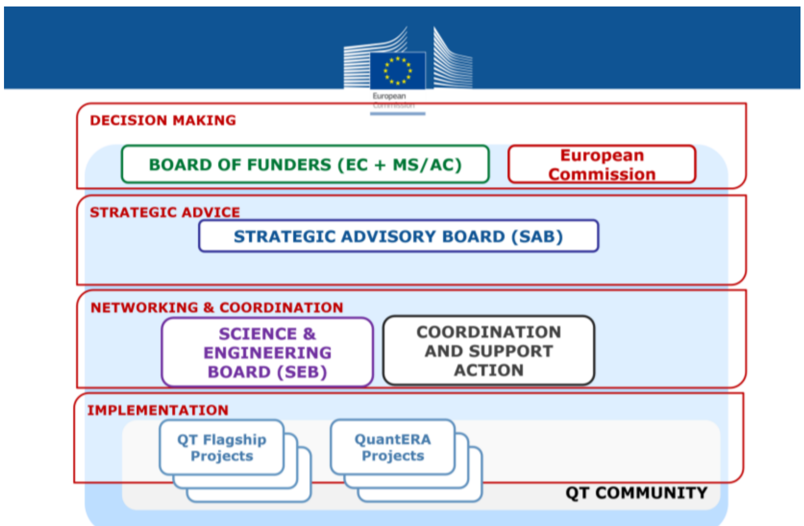


**Figure 3.13** Governance structure proposed by the FET flagship on Quantum Technologies

# 4. COMMITTEE ACTIVITIES

## 4.1 Appointment of the Committee and its mandate

At its meeting held on 28.6.17 the PBC decided to appoint a steering committee to **formulate and recommend a national program for development of QST in Israel's higher education system and to aid in spearheading and implementing it.** Its mandate was:

1. Scientific demarcation of the disciplines included in "QST".

2. Identification and prioritization of the research needs of the relevant academic community in Israel to promote QST in the coming five years and forward-looking to the coming decade.

3. Assist in identifying and locating partners to promote QST (e.g., MOD, the Innovation Authority and Ministry of Economics, private industry, philanthropists and the like) and maintaining collaboration with these partners.

4. Assist in consolidating the budgetary framework for dedicated support in QST in the coming 5 years, including the internal budget allocation for each of the identified needs.

5. Recommend relevant implementation mechanisms.

6. If necessary, participate in forums related to the Quantum Flagship, and in other international forums as relevant.

7. Accompany implementation stages of the program and provide continuous advice, as needed.

The Committee members were selected due to their senior academic positions in a range of relevant QST subdisciplines and from a variety of relevant institutions. In addition, the Committee includes two PBC representatives. The committee chairman, Prof. Uri Sivan from the Technion is a senior academic researcher with experience in leading large-scale research infrastructure projects. The list of Committee members is presented in Appendix 7A of this document. The Committee was coordinated and assisted by PBC staff.

All Committee members signed a non-conflict of interest statement. The Steering Committee chairman and its members were appointed to their respective roles by the PBC chairwomen for a period of 3 years, until 28.6.20, with an option of extending it for an additional three years.

## 4.2 Committee mode of operation

### A. Process

The Committee met on the following five dates: 24.7.17, 25.9.17, 23.11.17, 4.1.18, 8.2.18. Between meetings, the committee members conducted discussions via email.

A private website was set up for the committee's work, which enabled sharing materials between the professional PBC staff and the Committee members. The Committee invited representatives of the various research universities to some of its meetings to present their institutional activities. Interested Committee members joined the chairman in tours of the universities. In these tours, the chairman met with the research community in all institutions, as well as with the presidents or their representatives. The Committee chairman met with the vice-president-for-research forum, presented the program to them and obtained feedback; the PBC chairwoman, who is a member of the committee, presented the program to the university presidents forum.

In addition, the committee invited representatives of the Ministry of Defense and the Innovation Authority to its meetings, to learn of the wider national activity in the field and to identify possible interfaces.

The committee sent questionnaires to the university presidents. These questionnaires requested mapping out the status of QST in the university and the development plans of the university for the coming 5-10 years. The responses were discussed by the Committee members and assisted them in formulating the plan detailed below.

### B. Topics discussed by the committee

- QST – definitions and characteristics
- Mapping out similar initiatives worldwide
- Mapping out relevant bodies in Israel
- Collection and mapping out the academic status in Israel, the institutional plans and needs
- Assessment of the obstacles hindering development of QST
- Program goals
- National program structure
- Different aspects of the support policy and the balance between them
- Various platforms to advance the field
- Student and industry employees training
- Interface with government bodies and industry
- Recommendations and work plan

## 4.3 List of entities and people with whom the committee consulted

A. Academic institutions:

**Hebrew University**

Administration: Prof. Re'em Sari (VP Research)

Researchers: Professors Nadav Katz (head of QST Research Institute), Dorit Aharonov (committee member), Ronnie Kosloff (committee member), Alex Retzker, Yossi Paltiel, Yaron Bromberg, Hagai Eisenberg, Michael Ben-Or, Simcha Korenblit, Hadar Steinberg, Ronen Rappaport

**Ben-Gurion University**

Administration: Prof. Rivka Carmi (President), Prof. Dan Blumberg (VP Research), Sharona Rittberg (Director of Research Authority).

Researchers: Professors Ibrahim Abdulhalim, Amnon Aharony (committee member), Ora Entin, Yigal Meir, Shlomi Arnon, Rami Burstein, Yuval Golan, Eytan Grosfeld, Yonatan Dubi, Doron Cohen, Avishai Carmi, Or Satat, Ron Folman, Alina Karabchevsky, Reuben Shuker, Moshe Schechter and Dr. Meni Givon

**Weizmann Institute**
Administration: Prof. Daniel Zajfman (President), Prof. Michal Neeman (VP Research).
Researchers: Professors Ady Stern (committee member), Roee Ozeri (committee member), Moti Heiblum, Ofer Firstenberg, Amit Finkler, Shahal Ilani, Oren Tal, Shimon Levit, Nir Davidson, Barak Dayan, Dan Oron, Eli Zeldov, Yuval Oreg, Yuval Gefen, Karen Michaeli, Binghai Yan

**Bar-Ilan University**
Researchers: Professors Michael Rosenbluh, Avi Pe'er (committee member), Emanuele Dalla Torre, Richard Berkowitz, Aviad Friedman, Efrat Shimshoni

**Tel-Aviv University**
Administration: Prof. Yossi Klafter (President), Prof. Yaron Oz (Rector), Prof. Yoav Henis (VP Research).
Researchers: Professors Ady Arie (committee member), Moshe Ben-Shalom, Moshe Goldstein, Tal Ellenbogen, Pavel Ginzburg, Oded Hod, Amir Goldbourt, Guy Cohen, Tal Schwartz, Avner Fleisher, Yoram Dagan, Alon Bahabad, Roni Ilan

**Technion**
Administration: Prof. Peretz Lavie (President), Prof. Adam Shwartz (Senior VP), Wayne Kaplan (VP Research), Development Committee
Researchers: Professors Gadi Eisenstein, Moti Segev (committee member), Netanel Lindner, David Gershoni

**Ariel University**
Administration: Prof. Michael Zinigrad (Rector)
Researchers: Professors Aharon Friedman, Konstantin Borodianski, Michael Zovkov, Eliyahu Farber, Albina Musin, Haya Kornweitz, Shmuel Shaham, Shmuel Zilberg, Moshe Einat, Ariel Naos, Maya Radion

**Haifa University**
Researchers: Prof. Ofir Alon

B. **Israel Science Foundation (ISF)** – Prof. Benny Geiger (Chairman), Dr. Tamar Jaffe-Mittwoch (CEO), Prof. Ronnie Kosloff (Academic board member of the foundation; committee member)

**C. Government ministries and administrative entities**

**Maf'at/MOD**
Dr. Danny Gold (Maf'at head), Dr. Moshe Goldberg, Dr. Nadav Cohen, Dr. Tal David

**The Innovation Authority**
Dr. Ami Applebaum (Chief Scientist and Chairperson), Aharon Aharon (CEO), Ilan Peled, Dr. Aviv Zeevi

**Prime Minister's Office**
Eli Groner (Director General), Prof. Avi Simchon (The National Economic Council director)

**ISERD**
Nili Shalev (CEO), Dan Seker

**Ministry of Science**
Dr. Fadil Salih

**The Israel Academy of Sciences and Humanities**
Prof. Joshua Jortner, Prof. Ya'akov Ziv

**Other**
Prof. Isaac Ben-Israel, head of the Yuval Ne’eman Workshop for Science, Technology and Security and Director of the ICRC - Blavatnik Interdisciplinary Cyber Research Center at TAU and chairman of the Israeli Space Agency in the Ministry of Science Technology and Space.

**Representatives of relevant foreign governmental ministries and international entities**
Prof. Tommaso Calarco and Prof. Jurgen Mlynek – European Flagship representatives
Senior representatives of the NSFC (Natural Science Foundation of China):

i. Prof. Shen Yan, VP
ii. Prof. Feng Feng, DG, Bureau of International Cooperation
iii. Ms. Di Ming, Director of Division, Bureau of personnel
iv. Prof. Ni Pei-gen, Program Officer, Dept. of Mathematical and Physical Sciences

# 5. NATIONAL ACADEMIC QST PROGRAM*

The following two chapters expound on the **academic** QST program structure, as per the PBC's request from the Committee. However, as said, the Committee believes that expansive national program is necessary, including collaboration of the academia with other government ministries, so that Israel will be able to significantly benefit from the fruits of the second quantum revolution.

No doubt, the academic program presented in this report, will constitute a central component of such a broad national plan, and, therefore, several additional administrative structures, that will be able to serve as a foundation for such a comprehensive national program, are mentioned in sections 5 and 6.

### 5.1 Vision

***A. Reinforcement of Israel's basic and applied QST research capabilities and academic excellence in a sustainable manner .***

***B. Establishment of the academic foundations for collaboration with governmental and industrial partners to ensure economic prosperity and security of the state of Israel in areas reliant upon QST***

** "QST" relates to the following areas: quantum computation; quantum communication; simulation via quantum systems; quantum devices and sensors; quantum materials; the principles of quantum theory with future technological implications; innovative QST*

### 5.2 Main tools to realize the vision and its projected impact in the coming 5 and 10 years

1. **Expansion and reinforcement of the scientific community** involved in basic and applied QST research. Expansion of the community by recruiting new faculty members, attracting faculty members from other disciplines, increasing the number of doctoral and postdoctoral fellows.
2. Establish the necessary **research infrastructure** for academic and industry research scientists and set up of the resources required to conduct competitive, excellent and novel research.
3. Expansion of QST **training**, adjustment of curricula and promotion of interdisciplinary training programs for students and young researchers, to train a skilled workforce for both industry and academia. These efforts will focus on students studying in faculties other than Physics, e.g., Engineering and Computer Science departments.
4. Set up the academic ground necessary to develop industry and reinforce Israel security. **Development of the academia-industry-security interface:** shared research infrastructure, promotion of collaborations, knowledge generation and its transfer, incentives for external investments in academic research in the field, incentives for cross-disciplinary mobility of personnel, innovation and ideas.

5. **Formation of an Israeli community by encouraging cross-disciplinary academic collaborations** to foster significant breakthroughs in the field and collaborations with industry and the security sector.

## 5.3 Description of the program

### 5.3.1 Program components and required budget

The proposed program structure is detailed in Figure 5.1. The structure includes an administrative tier and the three planned academic implementation channels: Individual research and equipment fund, Independent university research centers, and National activity. The structure assumes significant enlistment of governmental ministries and industry to establish the program. With time, and if necessary, the proposed structure can be modified to establish a broader program with additional partners and activities.

The program will be managed by a national steering committee, which will serve as the board, in which all funders will be represented, and a small administrative team directed by an expert. The steering committee will assist in outlining the program agenda and monitor its implementation. The board will be assisted by an International Scientific Advisory Committee (SAC). Implementation of the national program will be carried out along the three flow lines described below, alongside additional implementation modules that will be established in the future, if needed. The estimated overall budget required for the academic program is estimated at 600M NIS over 5 years, as detailed below.

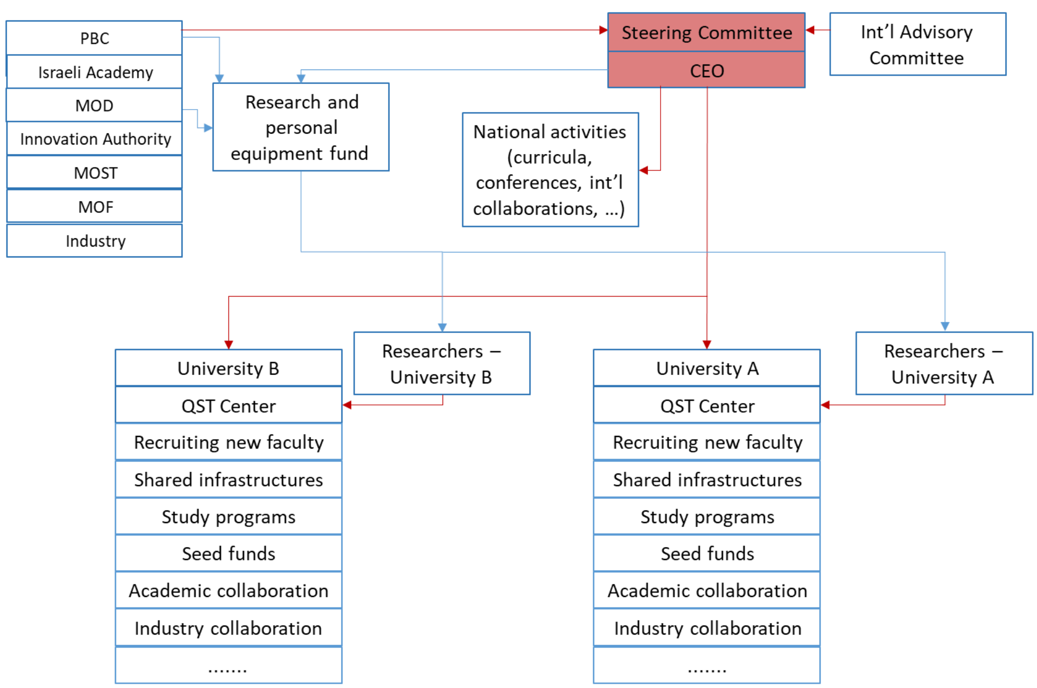


**Figure 5.1:** National academic program structure

#### 5.3.1.1 Research and personal equipment fund

To support academic research, upgrade research laboratories, and adapt them for research in the field, **a dedicated 100M NIS research fund,** allocated over the coming five years, is currently being set up. The fund is being established in collaboration by PBC and MOD (Maf'at) with equal contribution.

Of the overall sum, 75M NIS will be managed as a dedicated program by ISF (Israel Science Foundation) and 25M NIS will be managed by Maf'at. The research fund will be competitively allocated to fund research projects and purchasing of dedicated equipment for research labs, as is common in the ISF and Maf'at, respectively. The fund will be open to research universities and to submission of joint proposals of 1-5 research groups. Multidisciplinary proposals will be given an advantage.

The fund will support 3-year research programs, with a possibility of extension for an additional two years. Grantees will be allowed to request an increase in budget of up to 50% to purchase dedicated equipment.

The ISF-allocated fund size of 75M NIS over five years, was set in order to keep the 30% success rate, as accepted in the ISF, thereby maintaining the high threshold of excellence of grantees[35].

#### 5.3.1.2 Support of institutional research centers

The lion share of the resources will be channeled toward development of centers at the various universities. This channel will support the following activities:

- Recruitment of new faculty members and establishment of new labs for them. Recruitment will be via the faculties/departments, as they see fit.
- Encouragement of integration of researchers from other fields into QST research
- Establishment and upgrade of research infrastructures that will service all researchers in Israeli academia and industry
- Recruitment or improvement of technical workforce and scientific assistants
- Maintenance of infrastructure equipment and relevant training of researchers and industry employees
- Graduate degree and postdoc scholarships
- Drawing up and adapting study programs that will confer the necessary knowledge for QST R&D
- Seed funding for new research, emphasizing multi-disciplinarity and innovation
- Training and specialty programs in collaboration with the industry
- Development of intellectual property
- Collaboration with the industry, mutual exposure of industry needs and academic capabilities

[35] Assuming an avearge grant per PI (principal investigator) ranging between 400-600K NIS/year, this budget will be able to fund grants for five years, with the first three years beginning with three rounds of submission – once per year (each for 5 years), to between 30-47 research groups. Assuming a 30% success rate, 90-156 research groups will submit proposals, which matches the number of QST researchers in Israel.

- Collaboration with academic institutions in Israel and abroad, as well as with international programs
- Organization of meetings, schools, etc.

**The committee estimates that these activities will require 420M NIS over the next five years[36], of which:**

- 120M NIS to recruit new faculty[37]
- 200M NIS to purchase and upgrade infrastructure equipment[38], of which:
  - Materials manufacturing infrastructure – approximately 50M NIS
  - Materials characterization infrastructure – approximately 60M NIS
  - Device manufacturing infrastructure – approximately 60M NIS
  - Photonics manufacturing infrastructure – approximately 10M NIS
  - Time and frequency infrastructure – approximately 15M NIS
  - Electronics and mechanics infrastructure – approximately 5M NIS
- 70M NIS for technical manpower[39]
- 30M NIS for equipment maintenance, study curricula development, establishment of student labs, scholarships for postdocs and fellows, seed grants for innovative studies and collaborations with industry, IP generation and protection, and other uses

Support of university centers will be provided on a competitive basis, in response to proposals submitted and evaluated by the steering committee, with the assistance of the international advisory scientific committee.

The steering committee, with the assistance of the international advisory scientific committee (SAC) will monitor, on an annual basis, progress of funded programs and will approve or modify the designated budget, in accordance with implementation progress.

[36]As detailed in section 3, Table 3.12, the overall projected institutional spendings for new faculty recruitment, infrastructure and technical manpower over 5 years is about 500M NIS. According to our calculation, the proposed budget is sufficient

[37] In Table 3.11, we projected that within 5 years, the non-emeriti core QST community will grow from 133 to 157 researchers (+18%), and when including Profs. emeriti, from 145 to 188 (+30%). Some of the Profs. emeriti will clearly not be active, so the expected growth is actually lower. A realistic estimation is 20-25% growth of the community in the coming 5 years. Since the true number of core QST researchers is actually lower than that reported by the institutions, and is estimated by the Committee to be 110, the community is expected to grow by approximately 25 researchers. Doubling the community growth in the next 5 years to 50 researchers (160 researchers in 2023), will be considered a major success. The requested budget assumes recruitment of 40-45 faculty members in 5 years in all universities (an estimation between the realistic and optimal scenarios), of which approximately 2/3 will be experimentalists (recruitment costs of approximately 4M NIS per researcher) and 1/3 will be theoreticians (recruitment costs of approximately 350K NIS per researcher).

[38]This estimate is based upon institution responses to questionnaires regarding their infrastructure purchase and upgrading plans and based upon the experience gained in the national nanotechnology program. The institutions estimated their infrastructure needs at an overall sum of 265M NIS.

[39]Based upon an estimated recruitment of 40 engineers and lab scientists during this period in all institutions, and an average salaray expenditure of 350K NIS per year.

#### 5.3.1.3 National activity, management and reserve

This implementation channel aims to address the national needs common to all researchers and institutions. These activities include:

- Program management costs (administrator + administrative assistance) as well as expenses of organizing the annual monitoring meeting (including flight costs of the scientific advisory committee, printing fees, surveys, etc.)
- Increase the number of outstanding international post-docs in Israel
- Establishment of a post-doc scholarship fund for Israelis going for a post-doc in leading institutions abroad
- Adequately addressing QST training of students from various disciplines, including the creation of a joint national framework for complementary graduate courses
- National programs in collaboration with industry, such as establishment of a support fund assisting industry researchers integration in academic research
- Holding international meetings
- Collaboration with national programs in other countries and with the European Flagship Program
- Construction of a database that maps the Israeli QST researchers living abroad to bring them back to Israel
- Construction of a dynamic database for the various indices detailed in section 5.5
- Reserve - to develop new programs

**The committee estimates a budget of 80M NIS over five years is required for this channel.**

### 5.3.2 Administrative structure, timelines and program range

#### 5.3.2.1 Potential partners

Development of QST is of prime importance to the State of Israel. As detailed in the background section of this report, the “second quantum revolution” harbors tremendous economic–commercial potential, as well as cardinal security potential, explaining the global race to “quantum supremacy”.

Therefore, the natural partners for development of QST in Israel should be the Innovation Authority and the Ministry of Economy, as well as the Ministry of Defense and the Ministry of Finance. From the academic-scientific perspective, partnerships with the Ministry of Science and with the Israeli Academy for Sciences and Humanities are expected. Further, additional government ministries may take interest in partnerships, including the Prime Minister’s Office and the National Cyber Authority, Ministry of Communication and others.

Therefore, the committee believes the national academic program must be constructed from the onset as a primary component in a broader national program that includes all stakeholders. Details regarding the possible interest of various partners and their connection to a broader national program, is presented in Section 6 of this report. However, the committee emphasizes the need to launch the academic program without delay.

#### 5.3.2.2 National Steering Committee

The steering committee will be chaired by a reputable Israeli scientist with management experience. The committee makeup will include academic experts in the field, PBC representatives and Israeli Academy for Sciences and Humanities representatives, as well as representatives of ministries/industry, which will participate with significant funds in the realization of the program.

The Steering Committee (or a committee it appoints) will be responsible for evaluating the proposals submitted by the institutions in response to calls, and for allocating funds. Their work will be supported by the Scientific Advisory Committee (SAC). The National Steering Committee will convene at least twice a year to be updated on program progress and to delineate the plan of action for the subsequent period. One such meeting will be held with the SAC and will focus on program progress in all implementation channels. In preparation for this meeting, all institutions will submit a report relating to implementation of the program in the preceding year and the work plan for the coming year. All centers will present the key points of their reports at these meetings and Maf'at and the ISF will report on the status of the joint fund. Following the meeting, the national work plan for the coming year will be reassessed and the budget and its allocation will be updated.

#### 5.3.2.3 Program administration

The program administration will include the Steering Committee chairperson and a professional administrator, both salaried. They will be accountable for implementing the program set forth by the Steering Committee, communication with the SAC, fostering and maintaining relations with the international community, initiation of new activities and management of the joint aspects of the program, resource recruitment and addition of partners to the program, as well as monitoring implementation of program aspects relating to the grants fund and institutional centers. The program administration will be responsible for organizing the annual monitoring meeting and for preparing a report consolidating the findings.

#### 5.3.2.4 Scientific Advisory Committee (SAC)

The SAC will be chaired by a reputable Israeli QST scientist. The board will include 2-3 additional high-stature foreign QST scientists, who, together, cover different core and applied QST disciplines, and, if possible, a world-leader from industry (e.g., a senior executive from IBM, Google, Microsoft, etc.).

The SAC will assist the Steering Committee in evaluating institutional proposals, monitoring their implementation and in directing the various implementation modules of the national plan. For this, the board will convene once a year to meet with the National Steering Committee, whose purpose is detailed in section 5.3.2.2.

#### 5.3.2.5 Institutional Centers

Institutions participating in the program will establish QST-dedicated centers that will consolidate all QST activities and will be in continuous contact with the national program director. The center's director will be a reputable QST scientist who will be appointed by the university president. Aside from the director, the center will establish a management committee comprised of researchers representing various areas of activity.

The center director will consolidate all the institutional QST activity and will submit a development plan in response to a call, will manage all aspects of the joint activities in the field, will compose an annual report and will present it to the National Steering Committee and the SAC each year.

### 5.3.2.6 Program monitoring and regulation

Owing to the broad and long-range nature of this program, which is expected to have an extensive impact on the academia, industry and security sector, it is critical to establish from the start monitoring and regulation mechanisms as well as measurable milestones. In addition, since the field is dynamic and involves many players across the globe – countries, various members and organizations, it is important that the program be flexible and open to changes and adaptations in accordance with the developments in Israel and abroad.
In accordance with determination of the program goals and the specific indicators, the National Steering Committee, together with the SAC will set up concrete support and regulation mechanisms and milestones for each element of the program and institutional plans. Proposed indicators are detailed in section 5.5.

### 5.3.2.7 Timeline

To derive maximal benefit from the program, to synergize with global initiatives (such as the European Flagship) and to position Israel at a good starting point in the "global race toward quantum supremacy", the program must be implemented as soon as possible. It is recommended to implement the program in a modular fashion, so that delay of one component will not delay implementation of others.
The existence of a national academic program, as detailed in the present report, is of pivotal significance in developing connections and collaborations with other countries and with the EU.
It seems as if the first channel – "research and personal equipment fund" can be launched as soon as possible, owing to the progress in negotiations between PBC and Maf'at and the ISF. A call is estimated for the Spring of 2018 and the first round of grants in the beginning of 2019.
The second channel of the program (support of institutional center activities) requires coordination between additional partners and discussions with institutions. In addition, this channel will require establishment of managing entities and the SAC detailed above. Therefore, a call for submission of institutional development plans is expected for no earlier than the summer of 2018, institutional proposals will be submitted in the fall of 2018 and funding will begin in Spring 2019.
The third channel, national activities, also requires establishment of entities detailed above. It is very important to appoint a program director as soon as possible. The national activities will begin gradually and will depend on the rate of establishment of partnerships and fundraising. A realistic estimation sees launch of this channel in the Spring of 2018.

### 5.3.2.8 Sustainability beyond five years

Full realization of investments in the program will require a period longer than five years. The fruits of the proposed program will only be reaped in 5-10 years from its launch: time ranges in which the graduate students trained in the framework of the program will be recruited as new faculty members in Israel, a time span in which research programs will mature and discoveries, as well as associated patents, will be realized through companies and industrial developments. Many of the significant fruits of the nanotechnology program, like this one in its scope, potential and development stage at launching, were only reaped 5-10 years after initiating the program. Therefore, it is critical to ensure, already at this stage, that the many investments made in this program will be long-range and that the program will continue beyond the first five years.
For this reason, several mechanisms should be considered in all channels:
<u>Research grants</u>: This component is constructed from the outset, such that the grants will be awarded during the first five years and will continue afterwards as well (each grant can be awarded for up to 5 years).

Institutional centers: One could think of mechanisms such as a maintenance fund, which the center will allocate for the its future sustainability; future funding mechanisms for use of national research infrastructures, or services offered to the industry and security sector.

National activity: The National Steering Committee will need to ensure, as much as possible, the sustainability of each of the relevant initiatives. For example – funding for the graduate program can be given in advance for several rounds, each for a period of 5 years; likewise, postdoc fellowships or grants for short-term visiting scientists, etc.

**However, it is important that the establishing entities consider in advance the following five years, so they can plan the first ten years and derive the maximal return on the enormous monetary and manpower investments.**

### 5.4 Program tenor and operating point for resource allocation

A national program inherently balances between broad and equal support and promotion of excellence. The committee is of the unequivocal opinion that excellence and competitiveness must be emphasized, while allocating a certain small portion of the resources to broad support (while evaluating the potential of improvement) to enable extensive development of the field. In addition, the Committee calls for the Steering Committee and program director to focus on the areas listed in section 2.3 and to be wary of fanning out to other areas, even if they contain the word "quantum". As described in the previous section, most of the budget will be assigned to institutional centers. Support of these centers will be given, as said, on a competitive basis, following submission of proposals evaluated by the Steering Committee and the international SAC. The Committee recommends that the budget for each center be determined in accordance with the quality of the proposal, assigning a large weight to excellence.

To enable long-term planning and optimal exploitation of resources, the budget determined after the evaluation will be allocated from the onset for five years, pending annual reporting of institutional program developments and reaching milestones. Significant changes in the plans will require approval from the Steering Committee.

The budget will be allocated to the centers for (a) recruitment of new academic faculty members and establishment of labs for them, as well as for (b) additional research and teaching goals as delineated by the institutions and as described in section 5.3.1.2.

The Committee has discussed how to ensure excellence and competitiveness in budget allocations. One suggestion raised was that the budget for goal (b), which will be, as said, approximately 2/3 of the overall institutional center budget, will be allocated from the start, to each center, after a competitive evaluation, for a period of 5 years (of course, with changes that could be made following the program monitoring feedback). However, the budget for goal (a), which, as said, will be approximately 1/3 of the overall budget to the institutional centers, will be allocated – the small portion (approximately 20%-30%) to each institution, together with the funds for goal (b), as per the recruitment plan proposed by the institute, while the main part (approximately 70%-80%) will be allocated annually on a competitive basis, as per academic excellence of the candidates, regardless of the institution to which the candidate is affiliated – similar to the process used in the "Alon scholarships" program. The objective of this is to ensure academic quality and relevance to QST of most new faculty members, but also to provide each institution with a certain degree of autonomy in recruiting faculty, as each institution will be allocated a minimal recruitment budget which will enable it to expand its activities in this area.

**In any case, the Steering Committee will need to later consider and decide regarding the proper allocation mechanisms.**

### 5.5 Program progress indicators

Each of the goals can be assigned indicators – quantitative indicators that can be directly measured using existing tools, as well as qualitative indicators or those requiring development of a new measurement tool.

The directly measured quantitative indicators require collection of data from the start of the program to enable monitoring progress over time. **The Committee recommends that the Steering Committee to be established should immediately begin constructing a mechanism for collection of such data.** Thereafter, goals (absolute or relative – relative to past development of QST, relative to other areas in Israel or relative to the world) will have to be defined.

All indicators touch upon different impact circles – ranging from the researchers, institutions of higher education, the higher education system in Israel, to the Israeli society and economy and contribution to global knowledge at large.

Note that some of these indicators can already be assessed after completion of the first 5 years of the program, but others will require a longer period to mature and measurable results can only be expected after approximately 10 years.

**(I) GOAL: Expansion and reinforcement of the scientific community involved in basic and applied QST research. Expansion of the community by recruiting new faculty members, attracting faculty members from other disciplines, increasing the number of doctoral and postdoctoral fellows.**

Quantitative direct indicators:

1. Number[40] and quality[41] (e.g., h-index) of core QST principal researchers (PI). Number and quality
   a) (e.g., h-index) of QST-related PI, all to be broken down by theoreticians/experimentalists; researchers in each discipline; how many were trained in the field, how many switched the focus of their research, how many relocated from abroad to Israel.
   b) Number and quality of publications (impact factor/citations)
   c) Number of ERC, other competitive research fund and prestigious prize winners in QST
   d) Number and quality of graduate students by level of degree (broken down to theoreticians/experimentalists; QST subfields)
   e) Activity as a scientific community – number of conferences, seminars, summer schools etc.

[40]In table 3.11, we estimated that within 5 years, the non-emeriti core community will grow from 133 to 157 researchers (+18%), and when including Profs. emeriti, from 145 to 188 (+30%). Some of the Profs. emeriti will clearly not remain active, namely, the expected growth is smaller. A realistic estimation sees the community growing in the next five years by approximately 20-25%. Since the true number of core QST researchers is smaller than that reported by the institutions and is estimated by the Committee to be 110, the community is expected to grow by approximately 25 researchers. Doubling the growth rate of the community during the next five years to 50 researchers (160 researchers in 2023), will be considered an outstsanding success. Increasing the number of core researchers to 170 over the next ten years is a befitting goal and increasing to 210 will be considered an extraordinary achievement.

[41] If we look, for example, at Graph 3.10 which presents the distribution of core researchers in Israel by h-index, or in any similar graph describing the number of researchers as a function of scientific quality, we hope to bring to an elevation of the entire graph by this program – its maximal value will move to the right and the right “tail” will increase more than the graph as a whole.

New qualitative and quantitative indicators:

a. Increased awareness of graduate students and QST-related researchers to QST research possibilities in Israel
    - Improved attractiveness of Israeli academia to promising international researchers in the field, branding of Israeli research and international awareness of Israeli academia and the initiatives being taken in the field
    - Allocating resources appropriate for upgrading existing research labs and for integrating researchers from other fields
    - Provision of appropriate integration packages for new researchers
    - Increased exposure of Israeli researchers to possible industrial and security applications of academic research. Generation of a sense that QST is a hot field.

**(II) GOAL: Establish the necessary research infrastructure for academic and industry research scientists and set up the resources required to conduct competitive, excellent and novel research.**

Direct quantitative indicators:

a. Number of relevant infrastructure centres in the institutions
b. Number of technical personnel operating the research infrastructure in the institutions
c. Scope of investment in improving and upgrading research infrastructures, including internal university spending

New qualitative and quantitative indicators:

- Service level provided by the infrastructure centers at each university to academic and industry researchers
- Scope of use of university research infrastructure by the industry

**(III) GOAL: Expansion of QST training, adjustment of curricula and promotion of interdisciplinary training programs for students and young researchers, to train a skilled workforce for both industry and academia. These efforts will focus on students studying in faculties other than Physics, e.g., Engineering and Computer Science departments.**

Direct quantitative indicators:

a. Number and variety of QST courses offered for the various levels of graduate degrees in the various faculties of the various universities.
b. Number and range of QST subspecialties offered in existing graduate degree programs
c. Existence of a national QST study program offering dedicated courses for graduate students
d. Number of short-term schools for students and young researchers

**(IV) GOAL: Formation of an Israeli community by encouraging cross-disciplinary academic collaborations to foster significant breakthroughs in the field and collaborations with industry and the security sector.**

Direct quantitative indicators:

a. Joint publications between researchers from different disciplines and institutions
b. Number of consolidating research groups (e.g., in submissions to European programs)
c. Number of submissions for grants awarded by the joint PBC-Maf'at fund via the ISF, activity and success of these groups
d. Number of conferences for researchers from the various QST disciplines

New qualitative and quantitative indicators:

- Promotion of large-scale initiatives of leading groups in the various QST disciplines

**(V) GOAL: Set up the academic ground necessary to develop industry and reinforce Israel security. Development of the academia-industry-security interface: shared research infrastructure, promotion of collaborations, knowledge generation and transfer, incentives for external investments in academic research in the field, incentives for cross-disciplinary mobility of personnel, innovation and ideas.**

Direct quantitative indicators:

a. Volume of annual infrastructure utility by non-academic entities in each institution
b. Number of QST submissions to Authority of Innovation knowledge transfer programs
c. Number of QST patent submissions and approvals
d. Number and scope of tech transfer from academia to industry
e. Number of QST start-ups established
f. Number of people switching between sectors. Students integrated in industry, on the one hand and number of industry employees participating in academic research or who were integrated in academia, on the other hand

New qualitative and quantitative indicators:

- Quality of cross-disciplinary collaboration and importance of their achievements

## 6. *PROGRAM COMPONENTS AND IMPACT ON ISRAELI ACADEMIA*

### 6.1. Training workforce

The main output of research universities is a skilled workforce at three levels of training: Bachelors, Masters and PhD.

a. **Bachelors** – BSc graduates relevant to the QST include scientific faculty graduates (physics, chemistry, computer science, mathematics) and engineering faculty graduates (electrical, mechanical, materials, chemical) or joint degrees between these faculties. Except for physics graduates, and combined majors involving physics, and to some extent chemistry graduates, the current undergraduate training does not expose students to the physics background required for QST. On the other hand, students exposed to QST generally lack basic knowledge in other disciplines, such as computer science, engineering and chemistry. Expansion of the pool of graduates with basic knowledge in the field is critical to developing quantum-related industry, as well as to expanding the pool of students continuing to advanced studies in QST.
**To achieve this objective, the Committee recommends providing incentives to add relevant topics to the academic curriculum at the engineering and computer science faculties/departments**. **In parallel, the Committee recommends funding QST-related undergraduate projects in all faculties/departments.**

**b. Advanced degrees** – MSc and PhD graduates constitute the main pool of industrial research manpower. The findings of the survey conducted in the universities indicate that there are currently 198 core QST MSc students and 273 PhD students. Assuming that MSc takes two years and a doctorate 4 years, and assuming a minimal drop-out rate, approximately 100 MSc students and approximately 70 PhD[42] students finish their studies each year. Of the 100 MSc students, 60 carry on toward a PhD, leaving only 40 who join the workforce. It is difficult to project industry needs. However, seeing that the advanced degree QST graduates are immediately hired by industry, and realizing we must already now build up a workforce that will enable integration of Israel in the second quantum revolution, **the country must significantly increase the number of advanced degree students and improve their training**. Such measures will also assist in achieving the necessary expansion of the number of QST faculty members as well as the scope of academic research, leading also to IP generation and commercialization. **In other words, significant increases in the volume and level of academic activities is a prerequisite to development of a QST industry.**

c. **Expanded curriculum** – here, as well, curricula integrating physics with another discipline[43] most adequately address training, albeit, still deficient. The optimal combination depends on the subfield – areas that deal with quantum computation require integration of physics with computer science, areas relating to sensors require combination of physics with electrical engineering, etc. Most curricula do not offer an appropriate selection of courses[44]. In theory, physics courses are open to all students, however, the knowledge gap generated already during undergraduate studies, makes these courses very difficult for

[42]The number 70 includes 60 MSc students each year who carry on towards a PhD and approximately 10 in a direct PhD track.
[43]As well as the dedicated HUJI program.
[44] In recent years, a course in quantum information has been added in some universities, but important courses are still lacking, such as algorithms and complexity for physicists, some of which can be taken at other aculties/departments. Other study programs, especially the engineering ones, do not provide an appropriate selection of courses.

non-physics students. In particular, except for dedicated programs at HUJI, and, to some extent, physics study programs, there is no organized track for systematic acquisition of QST knowledge. The deficit is distinct in mathematics and computer science faculties/departments, areas which harbor great potential for advancing QST. Similarly, the lack of quantum mechanics training in electrical engineering, materials engineering and other faculties is quite distinct, which makes it difficult for these students to integrate in QST.

d. **Establish a joint graduate study program for QST** – the variety of courses and expertise in the various universities are limited due to lack of critical mass of researchers. To address this limitation, the Committee recommends designing a national study program that will offer a broad range of courses to all graduate students in Israel. The courses will be consolidated to one day per week, over one year (and may be continued with focused mini-courses in the winter/summer), which will provide 8 credit points. An academic commission, comprised of representatives from all universities, will be appointed to compose a list of courses and to choose the lecturers from all universities (these teaching hours will count toward their mandatory institutional teaching obligations). This program will be open to all graduate students in all universities, and universities will be required to recognize the credits toward the student's degree.
**A predetermined number of outstanding students** (approximately 15-20 per class of all institutions) could be officially accepted to the program and receive an addition to the stipend. This aims to grant the program prestige, to increase the program's exposure among BSc graduates, and to attract top graduates from all departments and universities.

**e.** **Training deficit in experimental QST.** Student labs and projects currently offer practically no relevant practical experience in QST. Therefore, the Committee allocated a significant budget to **add relevant courses and upgrade graduate student labs.**

**f.** **Research training –** active participation in cutting-edge research constitutes a central element of training graduate researchers. The scope of training, and, to a certain extent its quality, are currently limited by the number of faculty members in QST, and by the deficient research infrastructure, both in research labs as well as in infrastructure centers. To overcome these obstacles, the Committee recommends taking the following measures: **(1) allocating significant resources to recruitment of new faculty and establishment of advanced research labs for them; (2) allocating resources to upgrade research laboratories; (3) allocating resources to attract faculty members from other fields and adapting their research labs for QST research; (4) allocating significant resources to purchase and upgrade infrastructure equipment; (5) financing employment of advanced technical workforce and design of a promotional track for them; (6) allocating resources to fund long (several months) visits of Israeli students in leading research labs abroad.**

### 6.2 Leveraging research potential

**Increasing the number and quality of foreign postdoctoral fellows –** central elements relating to broadening outstanding research potential are detailed in section 6 above. In addition, the Committee considered increasing the number and quality of foreign postdocs. Postdocs are a key element in research progress in leading countries. Unfortunately, in all natural sciences, Israel has a hard time bringing large numbers of quality postdocs from abroad. This difficulty is the result of: distance from the "main science hubs" (from leading areas in the USA and EU) and the implications on the chance of obtaining a position afterwards in a leading institution; security situation and political issues in Israel; visa problems (particularly, work opportunities for spouses who are not entitled to citizenship); stipend (which usually does not compete with leading institutions around the world); and in certain areas – the quality and availability of research equipment and infrastructure.

Since it will be difficult to adequately address most of these elements, the Committee proposes two possibilities – each with its drawbacks:

**a.** Establishment of a prestigious (manifested by grant sum and branding) grant program for QST postdocs. Joint postdoctoral work between an Israeli and non-Israeli lab can be considered to enable grantees to draw nearer to the "scientific hubs" in the USA or EU.

**b.** Establishment of an international visitors' center for periods of 6 months and longer, from PhD students to postdocs and all levels of academic faculty. This initiative will set the stage for converting Israel to an international QST hub and will enable flow of international scientists to Israel, as well as collaborations. In the long-run, such a center is expected to also increase the success of post-doc programs, such as that described above in (a).

### 6.3. Interaction with the industry and security sector

**Updating knowledge of industry and defense scientists and engineers** – many industry scientists and engineers were never exposed to the basic knowledge necessary for QST research and to up-to-date theoretical and experimental tools. Outdated knowledge is obviously a general problem, but, in the current context, takes on greater dimensions due to the minimal QST training during studies and because of the rapid rate of development of research in the field. To cope with this problem, the Committee recommends taking the following measures:

- **Organization of QST conferences and workshops intended for the industry and security forces.** The objective of these conferences is to expose industry and industrial researchers to the potential of this field. In addition, it is important that academic scientists invite lecturers from industries such as IBM, Intel, Google, Microsoft where there is already extensive activity in the field.
- **Establishment of a fund that will support integration of individuals from the industry and defense forces into academic research** for one or two years, whether it be as a supplementation or as part of an advanced degree.
- **Establishment of a mechanism that will make it easier for academics to spend a sabbatical year in industry or security efforts.**
- **Exposure of faculty and students to the challenges of the relevant industries and security bodies.** Apart from the applicative ideas that will inevitably arise during such meetings, unmediated meetings will also assist in formation of discourse productive for both sides.
    A. **Establishment of advanced infrastructures and knowledge hubs for industrial use** – apart from the improved research capacities and student training, all infrastructure and operating expertise will be available for use by the industry. Already today, many companies, especially start-up ones, utilize academic infrastructures. A rough estimate, based on numbers from the nano centers, claims that approximately 20% of the hours of academic infrastructure operation is used by the industry.
    B. **Intellectual property, start-up companies and tech transfer to industry** – it is obviously difficult to project the scope of intellectual property, the number of start-ups

and the scope of academia-to-industry tech-transfer deals during the period of the proposed program. These numbers can perhaps be estimated based on the achievements of the National Nanotechnology Program which was implemented over the years 2005-2016, and during which, approximately $380M were invested in universities, one-third of which was from the government (of note, this investment was leveraged by the academia to recruit $900M from research funds).

During this period, apart from the academic achievements, the program promoted the following commercial achievements[45]:

- 888 approved patent filings
- Launching of 120 start-ups, of which 60 were active in July 2017, the date the National Nanotechnology Program Committee published its report
- 272 academia-to-industry knowledge-transfer agreements
- 1,942 joint academia-industry projects

Despite these achievements, one of the lessons learned from this program was that technology transfer to large enterprises was only partially successful and did not lead, to date, to establishment of large nano oriented companies. The reasons for this caveat can be analyzed, but the immediate conclusion for the proposed quantum program is that this aspect should be considered at the onset. One means of ensuring this is by recruiting one or more of the enterprises in this sector (Microsoft, Google, IBM, Intel, Alibaba), as well as activity in Israel at early stages of the program. In addition, a joint consortium of Israeli companies and academia should be considered.

[45]National Nanotechnology Committee Report, July 2017

## 7. APPENDICES

### A. Committee Members

- Prof. Uri Sivan, Faculty of Physics, Technion – Chairperson
- Prof. Yaffa Zilbershats, PBC Chairwoman
- Prof. Yeshayahu Talmon, PBC member, Faculty of Chemical Engineering, Technion
- Prof. Dorit Aharonov, School of Engineering and Computer Science, Hebrew University
- Prof. Amnon Aharony, Physics Department, Ben-Gurion University
- Prof. Ady Arie, Faculty of Engineering, School of Electrical Engineering, Tel-Aviv University
- Prof. Roee Ozeri, Faculty of Physics, Complex Systems Department of Physics, Weizmann Institute of Science
- Prof. Avi Pe’er, Department of Physics, Bar-Ilan University
- Prof. Ronnie Kosloff, Department of Physical Chemistry, Hebrew University
- Prof. Moti Segev, Faculty of Physics, Technion
- Prof. Ady Stern, Faculty of Physics, Condensed Matter Physics Department, Weizmann Institute of Science

## B. Some national programs around the world

### 1. China

Primary motivation:

- Secured communication
- Economic competitiveness – advanced technologies with production capacity and human capital can ensure global market leadership in quantum information solutions
- Strategic military competitiveness – primarily relating to quantum communication, with big data and AI capacities
- China's president, Xi Jinping already expressed interest in the field in 2013 and at the party congress in November 2015, announced "quantum communication" as a high-priority project until 2030 to foster significant breakthroughs
- Estimated national investments in the sector in 2015: approximately €220 M EU
- In China's 2016-2020 multi-year R&D plan, quantum information and quantum control were flagged high-priority, under "Basic research related to national strategic needs"
- In 2016-2017, 6 research missions were indicated:
    - Related electronic systems
    - Small quantum systems
    - Artificial band-gap systems
    - Quantum communication
    - Quantum computation
    - Quantum precision measurements
- From May 2015, quantum computation was indicated as a priority topic in the Chinese "Made in China 2025" technology commercialization program

**China's quantum program: principle achievements to date**

- **Quantum computation**
    - Academia – USTC scientists developed a semi-conductor quantum chip that will enable quantum operations and data processing (08/16); succeeded in realizing and measuring 600 pairs of entangled quantum particles (08/16); developed precise logic quantum gates for quantum control (10/16)
    - Industry – extensive efforts in the Alibaba Quantum Computing Lab. Set goals for 2020 to achieve coherent manipulation of 30 qubit; for 2030 – a quantum computer prototype with 50-100 qubits
- **Encryption and Quantum communication**
    - 8/16 – launching of first quantum satellite – Micius: established a quantum key distribution network with the transmission of quantum information between the satellite and multiple ground stations (part of QUESS-quantum experiments at space scale program from 2011)
    - 9/16 – Pan Jianwei of USTC (did his doctorate at Zeilinger, Vienna) published demonstration of quantum teleportation of photons in an optical fiber to a distance of 12.5 km
    - 6/17 – Pan Jianwei demonstrated quantum entanglement with a satellite at a total satellite-ground distance of 1600-2400 km, and entanglement distribution of over 1200 km between relay stations
    - 7/17 **-** Beijing-Shanghai quantum network (2,000 km) conducted a successful experiment – the experiment was conducted between 200 different terminals in Jinan, in a network covering a few hundred km$^2$
    - 1/18 – the quantum satellite Micius demonstrated quantum key distribution between China and Australia, a distance of 7,600 km apart
- **Quantum sensing**

- September 16 - a group of scientists at CETC, together with Pan Jianwei of USTC and scientists from the University of Nanjing, realized a single-photon radar based on photon entanglement, which can sense targets at distances of up to 100 km (5 times that reported until then)

## 2. USA

Considerably increased academic activity has been seen in the past few years. Below is a graph describing the rise in the number of Quantum Information Science-related publications over the years 2000-2015, by subdisciplines (Information, Computing and Communication):

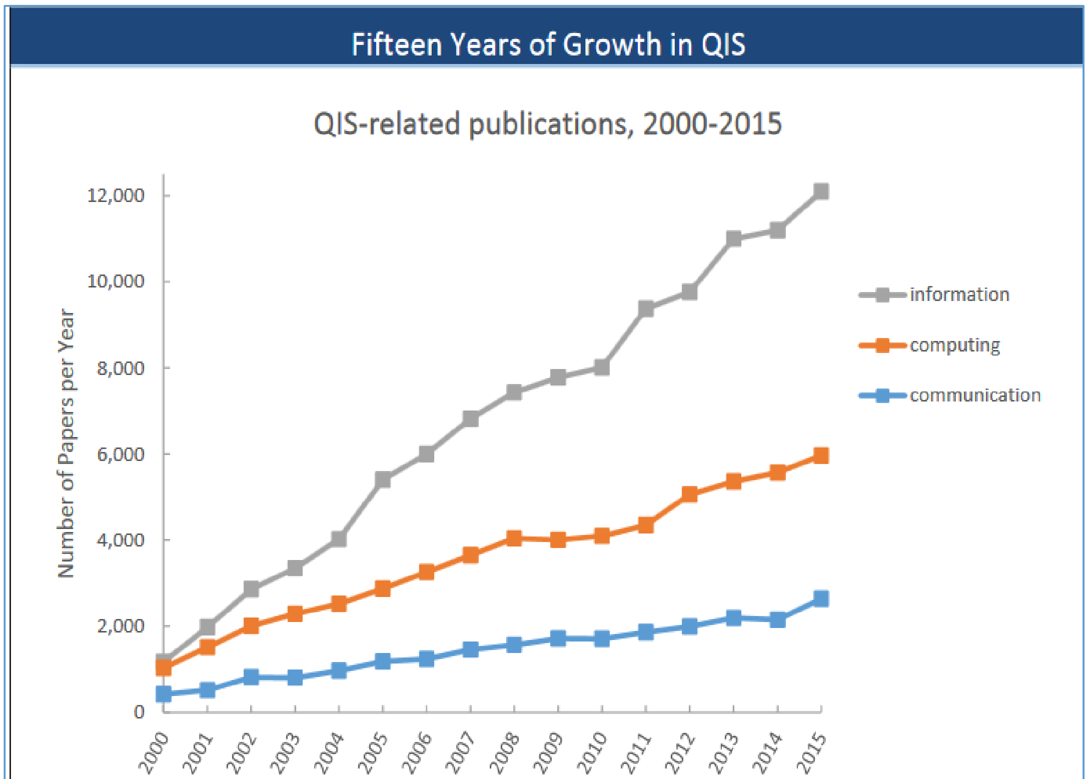


*Figure 1. A Google Scholar search for publications (excluding patents and citations) containing the terms "quantum information," "quantum computing," and "quantum communication" illustrates how the field has grown in recent years.*

**Graph B1.** Increase in number of QIS (Quantum Information Science)-related publications authored by American scientists over the period of 2000-2015, by subdiscipline (Information, Computation, Communication).

<u>In 2008, the federal QIS vision was stated:</u>

*The United States will create a scientific foundation for controlling, manipulating, and exploiting the behavior of **quantum matter** and identifying the physical, mathematical, and computational capabilities and limitations of **quantum information processing** systems in order to build a knowledge base for this 21st century technology.*

*To succeed, the US must identify the critical scientific elements and target them as **research** priorities, **train** a new generation of scientists in the underlying sectors that contribute to QIS, and share results and **coordinate** efforts.*

**<u>Federal support of QIS</u>:**

- Over 20 years of support
- In 2016, approximately $200M annually
  - Ongoing support of basic research (DOD and Office of the Secretary of Defense, NIST and NSF)
  - Support of projects (DARPA, IARPA)
- In 2017, the DOE also plans to support QST
- Strong alliance with the 2015 National Strategic Computing Initiative (NSCI)

| Entity | Support |
|---|---|
| **DOD** | • Focus on security applications (precision navigation, secure quantum clocks and networks)<br>• **In 2011-2015, the OSD funded 12 Multidisciplinary University Research Initiative (MURI) awards – for especially long periods of time: periods needed for complex group projects**<br>(projects of 2+3 years with funds of $½ M - $1M per year)<br>• In 2016, the OSD will fund the Tri-Service Quantum Science and Engineering Program (QSEP) to construct a scalable quantum network prototype, quantum memory and sensitive quantum sensor applications<br>• Additional programs in ONR, ASO, AROSR, including academic collaborations (e.g., Maryland University)<br>• DARPA supports and is supporting specific projects, such as QuSAR for sensors, OLE for simulators, QuEST for particularly innovative projects and Detect to model and produce photonic detectors |

| | |
|---|---|
| **DOE** | • In the past decade, development of expertise in the QST sectors relevant to them<br>• From 2017, a core program relating to application of simulators and quantum computation for critical DOE issues<br>• Workshop on basic research in quantum materials for energy technologies |
| **IARPA** | • Support to promote quantum computation, such as:<br>• The Logical Qubits Program - overcome the limitations of current multi-qubit systems by building a logical qubit from a number of imperfect physical qubits<br>• Quantum Enhanced Optimization Program - harness quantum effects required to enhance quantum annealing solutions to hard combinatorial optimization problems.<br>• Forward-looking: Development of appropriate algorithms |
| **NIST** | • Programs over the past 20 years, already with impressive achievements<br>• The current program focuses on metrology (for quantum communication), quantum computation and quantum measurements<br>• 2016 – special program for quantum sensors<br>• 2017 – increased support of quantum computation<br>• Support of 2 centers at the University of Maryland |
| **NSF** | • Over a decade – Quantum Information Science and Revolutionary Computing “Physics” program<br>• Funding 2 research centers in the sector – in Caltech (since 2011) and in JQI in the University of Maryland (since 2008)<br>• 2016 – the Engineering Directorate selected Quantum Communication as the new discipline for the innovation program which supports multidisciplinary groups in paradigm-changing research<br>• New meta-program from 2017 - Connections in Quantum Information Science, for multi-disciplinary programs involving MPS (Mathematics and Physics), ENG and CISE (computers and engineering) |

**Table B.2:** Federal bodies supporting US-based centers

Impediments to optimal development of the sector (per NSTC 2016 report)

- **Institutional boundaries** – a lack of inter-departmental collaborations within and between institutions. A diverse range of skills and expertise are necessary to move ahead

- **Workforce education and training** – lack of adequate training in the field, outside of physics departments (computer science, applied mathematics, EE, system engineering)

- **Technology and knowledge transfer** – inadequate knowledge transfer to industry – no dedicated framework supporting conversion of a prototype from a lab into a marketable product; high estimated IP value; unsatisfactory connection between graduates and companies requiring specific skills.

- Materials and fabrication – inadequate availability of quantum material fabrication capacities (e.g., NV centers in diamond)

- **Level and stability of funding** - Arose from lack of coordination between federal agencies, which brought many good researchers to switch fields or to leave the USA

Forward-looking recommendations of NIST

A coherent, all-of-government approach that will include:

- Stable and sustained core programs that can be enhanced as new opportunities arise and restructured as impediments evolve

- Strategic investment in targeted, time-limited programs to achieve concrete, measurable objectives

- Continued and close monitoring of the field to evaluate the outcome of investments and quickly adapt programs to take advantage of technical breakthroughs

### 3. European Union

With the growing understanding of the economic potential harbored in the “second quantum revolution” the European Commission decided to strengthen commercialization of knowledge in the field and to foster growth of large industrial players in developing technologies. In April 2016, it published the Quantum Manifesto[46] which set forth the principles of developing the sector in Europe and which involved over 3,500 stakeholders, including scientists, research institutions and companies in

[46] http://qurope.eu/manifesto.

Europe. In response to the manifesto, in May 2016 the European Commission proposed launching a broad-scale and ambitious flagship program, whose goals were:

- Positioning Europe as a leading player in the second quantum revolution
- Consolidate resources and expand European scientific leadership and excellence in quantum research, including training the relevant skills
- Kick-start a competitive European industry in quantum technologies to position Europe as a leader in the future global industrial landscape
- Make Europe a dynamic and attractive region for innovative research, business and investments in QT, thus accelerating their development and take-up by the market
- Producing transformative technologies accessible to all

A high-level steering committee (HLSC), chaired by Prof. Jürgen Mlynek, was established in September/October 2016. The initiative's governance structure is described in section 3.6 of this report.

Four science and technology domains were selected to be included in the flagship initiative: quantum communication, quantum computation, quantum simulation and quantum sensors, to be enabled via basic science, education/training, software/theory and engineering/control.

### 4. UK

Program goal: "Create a coherent government, industry and academic quantum technology community that gives the UK a world-leading position in the emerging multi-billion-pound new quantum technology markets, and to substantially enhance the value of some of the biggest UK-based industries".

In 2013, George Osborn announced £270M governmental funding of the sector over 5 years; In 2014, the UK presented a 5-year QST program which includes establishment and support of 4 new QST-focused hubs: sensors and metrology (led by the University of Birmingham), Communication (York University), Networked QIT (Oxford), Imaging (Glasgow). Of the government investment (£270M over five years), 120M£ were allocated to the four hubs via the EPSRC, manpower, academia-industry collaboration and led by a university. Overall, there are 17 participating academic centers and 132 companies.

In addition, the Defense Science and Technology Laboratory (DSTL), together with the Ministry of Defense, announced investment of £30M to create national quantum timing, navigation and gravity imaging devices.

In 2016, UK announced an additional initiative to train skilled QT manpower.

A 12-member QT SAB, chaired by David Delpy of UCL, with academia and industry representatives, was established.

Main SAB recommendations:

- Investment in a 10-year program that will support academia, industry and other partners
- Continued investment in research infrastructure
- Private investment incentives
- University infrastructure accessibility to the industry
- Development of dynamic workforce
- Support of exchange of people, innovation and ideas between academia, industry and government
- Develop appropriate regulation and standardization
- Maintain a competitive advantage as a global supplier of quantum devices and systems and to continue playing a central, global role in technology development

Below are the central components of the program – research and technology, innovation, knowledge transfer, capital equipment and skill:


The government investment **(£270M over 5 years)** is currently allocated in 4 main support modules:

1. Sponsor 4 QST hubs, as detailed above
2. Grants to UK companies to identify and develop applications and markets for new technologies
3. Grants to industry-led projects
4. Centres for doctoral training

## 5. The Netherlands

1. In 2015, Holland announced a 10-year program to accelerate quantum computation development at the Quantum Technology Institute at DELFT University
2. A joint DELFT, Netherlands Organisation for Applied Scientific Research (TNO) , NOW, FOM, STW, and HTSM initiative
3. Joint funding of €135M over 10 years
4. Over 100 scientists, expected to double within 5 years
5. Several companies, including Intel ($50M over 10 years) and Microsoft, have already decided to partner with and support the center

## 6. Germany – QUTEGA initiative

- BMBF initiative announced in 5/16.
- Planned investment of approximately €300M over 10 years.
- Goal: to prepare for the EU Flagship Program.
- A 28-member scientific committee, was established, chaired by Prof. Dr. Gerd Leuchs, Director of the Max Planck Institute of Light Science in Erlangen.

- In 2017, the committee published a policy paper, presenting the following main points of the program:
  - Calls for proposals in 5 topics – quantum computation; quantum sensors; quantum communication; overlapping theoretical models; key quantum system technologies.
  - Recommended policy-implementing tools:
    - Promote R&D – more academia-industry collaborations by (a) fostering consortiums; (b) establishment of QST centers for large infrastructure and collaborations with industry, such as in Nano-technology; (c) mutual sabbaticals.
    - Structural measures – Training: engineering curricula; University structure: new academic positions in medium-size universities, reinforcement and guidance for new faculty; establishment of consolidating entity - federal and for all states, academia, industry and private investors.
    - Public relations and education – increased exposure of general public to “second quantum revolution”, school study material, exhibits, accessible online information.
- First steps:
  - Support of the first 3 pilot projects: magnetic sensors for man-machine interfaces, portable atomic clocks, quantum key distribution with cube-sats (industry-academia consortium).
  - The first project – development of an optical single ion clock, commenced in May ’17, led by Toptica Photonics. Overall investment of €6M over 3 years (4.5 from BMBF and 1.5M from industrial partners).
  - Call for proposals for quantum communication

### C. Projected number of QST researchers in the coming 5 years 2017/18-2022/23

The following calculation was made to estimate the number of QST researchers in the coming 5 years:

a) We assumed that the relevant candidates are currently doctorate students of core QST researchers in the various disciplines (physics, engineering, chemistry, computer science, mathematics, and others).[47]

b) We calculated the ratio between number of faculty recruitments per year and the number of PhD graduates per year in the 3 main disciplines: physical sciences[48], engineering[49], computer science and mathematics[50]. We used the annual average

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[47] The true candidates are actually be those who complete their postdoctoral fellowship within the next 5 years, and are currently in their first/second/third year of their post-doc, as well as those that are currently doctoral students in their 3rd, 4th or 5th year of their degree. Therefore, we are actually calculating the number of relevant candidates for the years 2020-2005. This is assuming that there will not be a big change in the number of QST doctoral students in the coming two years. In addition, it assumes that the average doctorate degree takes 5 years.

[48] Including Chemistry, Organic Chemistry, Physical Chemistry, Industrial Chemistry, Physics, Nuclear Physics, Nanoscience and Nanotechnology, Geophysics, Geology, Oceanography, Hydraulics, Climatology, Marine Geology

[49] Including Construction, Geotechnology, Transport Engineering, Engineering and Environmental Architecture, Geodata Engineering, Water Resources Engineering and Management, Mechanical Engineering, Electrical Engineering, Communication Systems Engineering, Aeronautical and Space Engineering, Chemical Engineering, Biotechnology and Food Engineering, Industrial Engineering and Operations Management, Informations System Engineering, Systems Engineering, Nuclear Engineering, Agricutural Engineering, Biomedical Engineering, Interdisciplinary engineering studies, Polymer Engineering, Biotechnology Engineering, Product Quality Control, Energy Engineering.

[50] Including Mathematics, Statistics, Computer Science, Information System and Management.

university faculty recruitment statistics (average over 5 years 2010-2014) and 2014 PhD graduate statistics. The following ratios were obtained:

| | Average annual recruitment of new faculty | PhD graduates per year | Ratio |
|---|---|---|---|
| Physical Science | 22 | 202 | 11% |
| Engineering | 39 | 150 | 26% |
| Computer Science and Mathematics | 22 | 87 | 25% |

**Table C.1:** Ratio between number of new faculty members and number of PhD graduates per year in 3 main QST disciplines

c) We then multiplied the number of current PhD students of researchers in the core QST areas by the above ratios to obtain an estimate of the number of projected faculty recruitments in QST over the next 5 years[51]:

| | PhD students of core QST researchers | Ratio: recruited faculty / PhD graduates | projected faculty recruitments over the next 5 years |
|---|---|---|---|
| **Physics** | 122 | 11% | 13 |
| **Engineering** | 79 | 26% | 21 |
| **Chemistry** | 50 | 11% | 5 |
| **Computer Science** | 5 | 25% | 1 |
| **Mathematics** | 13 | 25% | 1 |
| **Other** | 4 | 25% | 1 |
| **Total** | **273** | | **42** |

**Table C.2:** Projected new faculty recruitments in the next 5 years

[51] Here, we assumed: (i) an average doctorate in these disciplines takes 5 years; (ii) we disregarded drop-out rates during doctoral studies; (iii) the faculty recruitment/PhD graduates ratio in QST secctor is similar to the ratio in the broader physical science, computer science and mathematics sectors; (iv) the faculty recruitment/PhD graduates ratio in "Other" areas (i.e., Humanities) is approximately 25%

d) From these, we subtracted the number of expected retirements in QST in the coming 5 years by discipline[52]:

| | Total number of core QST researchers | Profs emeritus among core researchers | Core researchers expected to retire within next 5 years |
|---|---|---|---|
| **Physics** | 72 | 3 | 8 |
| **Engineering** | 34 | 4 | 0 |
| **Chemistry** | 27 | 4 | 5 |
| **Computer Science** | 5 | 1 | 1 |
| **Mathematics** | 5 | 0 | 2 |
| **Other** | 1 | 0 | 1 |
| **Total** | ***144*** | **11** | **17** |

**Table C.3** Core researchers expected to retire within the next 5 years, by discipline

[52] Number of Profs emeriti and those expected to retire in the next 5 years was extrapolated from an individual assessment of 80% of the 144 researchers (in the various disciplines)

## D. Questionnaire sent to research universities

**Part A – Mapping current research activities and training**

**A. Research Center** – Does the institution have a research center or institute dedicated to QST or peripheral/partially overlapping fields?

If yes, please provide the following information regarding its current activities:

a. Center/Institution name:
b. Date established:
c. Number of faculty members:
d. Number of postdocs:
e. Number of technical manpower at the center (FTE) maintaining joint equipment and providing QST research services:
f. Annual budget:
g. Existing joint infrastructure centers and main equipment:
h. Main industry collaborations, if any:
i. Main collaborations with the security sector, if any:
j. Main international collaborations, if any:
k. Center's activities for academic QST community (e.g., conferences, workshops, schools, summer courses or mini-courses, and the like):

**B. QST-associated faculty members**

(I) Please fill out the attached Excel file in English (Faculty.xls)
   1) The "Core faculty" worksheet should include the list of faculty members whose core research is in QST. The information includes name, academic affiliation (faculty, department), research area, number of mentored students (MSc, PhD, post-docs)
   2) The "Peripheral faculty" worksheet should include the same information relating to researchers involved in research related to QST, but that QST is not at the core of their research.
   3) The "Potential faculty" worksheet should include the same information regarding non-QST researchers who may potentially expand to conduct QST research.

(II) Does your institution currently have a QST faculty recruitment plan? If yes, have academic positions been allocated for this purpose? How many?

**C. Main areas of research**

In which of the following areas is there research activity at your institution? Indicate number of researchers, academic affiliation and type of activity (theoretical/ experimental, system type – e.g., cold atoms or quantum optics):

1) Quantum communication
2) Quantum simulators
3) Quantum sensors
4) Quantum computation
5) Quantum materials e.g., topological materials, materials exploiting innovative quantum principles to control their properties
6) Innovative quantum theory principles with technological implications
7) Other topics you consider related to QST (provide details)

## D. Training activity

If exists, please briefly describe the QST training activity at your institution (or in collaboration with other institutions):

1) For non-physics BSc students:

2) For graduate students:

3) For post-docs:

**<u>Part B</u> – Needs and goals of institution leadership in QST development in the coming years**

As said, the PBC, via the Steering Committee, is diligently working on developing a national academic program to promote QST in the coming years. This program will have several components, the central ones being: (1) A competitive support fund for researchers and research groups in QST; (2) support of institutional QST centers/institutes. Assuming that component (2) will include PBC support as well as self-funding by the institutional centers, we are interested in understanding and delineating the needs and plans of each institution. For planning purposes alone, you may assume a 10M NIS annual budget funded by external sources – PBC and others, apart from the self-funding of each institution. We emphasize that this number should not be considered a commitment, rather a planning aid. In any case, the budget for each institution will be determined by several factors, including volume and scope of research activity in the field.

A. To what extend do you think QST can/should be a growth-engine for research development in your institution in the coming years? Please detail how you rank its priority as compared to other research areas in your institution.
   [ ] High priority relative to support of other development programs in the institution
   [ ] Similar priority to other development programs
   [ ] Other programs are given higher priority than this program

B. If you indicated that there is no center or institute dedicated to QST research or peripheral fields in your institution –
   Does the institution plan to establish such a center?
   If yes, when is it expected to be established?
   If no, how does the institution plan to develop QST?

C. Provide a scheme of your institution's 5-year plan, which contains sections such as those listed below, including budget magnitude (from internal and external sources):
   - New faculty recruitments (including equipment purchase for new members)
   - Purchase/upgrade of shared research infrastructure
   - Hiring and training technical support staff
   - Development of QST training programs
   - Doctoral and postdoc scholarships
   - Promotion of interdisciplinary research collaborations in QST
   - Promotion of high risk-high gain research
   - Promotion of international research collaborations
   - Promotion of collaborations with industry and security sector, and knowledge transfer in QST.

With regards to the first four items in the list, please also relate to the following points:

1. **Recruitment of new faculty in the next five years**:
   - What are the institution recruitment needs and capacities in QST in the coming 5 years?
   - What is the estimated equipment budget needed for the new recruits in the coming 5 years?

2. **Shared research infrastructure:** Please provide a list of infrastructure equipment items you would like to purchase for your institution over the next 5 years. Arrange them in order of priority. Indicate estimated cost for each item and the overall cost.

3. **Technical manpower:** Do you plan to expand your technical staff or their skillsets to address the institution's needs in the next 5 years? If so, please provide details and costs estimate.

4. **Training activities:** Do you see a need to change QST curricula and training for undergraduates and/or graduate students? If so, please detail the changes you think your institution will want to implement and the expected costs.

## E. Information regarding scope and quality of research in Israel

| Institution | Number of core faculty members | Number of peripheral faculty members | Number of potential faculty |
|---|---|---|---|
| **WIS** | 23 | 11 | 0 |
| **Technion** | 32 | 6 | 0 |
| **HUJI** | 23 | 9 | 3 |
| **TAU** | 24 | 3 | 3 |
| **BIU** | 7 | 7 | 5 |
| **BGU** | 21 | 7 | 0 |
| **Ariel** | 12 | 9 | 0 |
| **Haifa** | 2 | 4 | 0 |
| **Total** | ***144*** | ***56*** | ***11*** |
| | | **211** | |

**Table E.1** Number of QST researchers in the various institutions by proximity to QST – core, peripheral, potential

| Institution | Quantum communication | Quantum simulators | Quantum sensors | Quantum computation | Quantum materials | Innovative principles in quantum theory |
|---|---|---|---|---|---|---|
| WIS | 2 | 4 | 10 | 3 | 12 | 5 |
| Technion | 8 | 2 | 22 | 5 | 15 | 6 |
| HUJI | 10 | 14 | 18 | 13 | 9 | 9 |
| TAU | 1 | 4 | 3 | 4 | 6 | 2 |
| BIU | 3 | 2 | 5 | 1 | 2 | 2 |
| BGU | 3 | 1 | 6 | 3 | 5 | 5 |
| Ariel | 3 | 0 | 4 | 2 | 7 | 6 |
| Haifa | 2 | 2 | 2 | 2 | 1 | _ |
| ***Total*** | ***32*** | ***29*** | ***70*** | ***33*** | ***57*** | ***35*** |

**Table E.2.** Number of core QST and QST-peripheral researchers, by subspecialty

Data in tables E.3-E.6 are from “Research output and development in Israel: international comparison of scientific publications 1990-2011”, Dr. Daphna Getz, Dr. Avishag Gordon, Dr. Noa Lavid, Yair Even-Zohar, Iris Eyal, Ela Barazani, Shmuel Neeman Institute for Advanced Science and Technology Research, August 2013

| Discipline | Priority ranking in Israel | Priority ranking globally |
|---|---|---|
| Clinical Medicine | 1 | 1 |
| Physics | 2 | 3 |
| Chemistry | 3 | 2 |
| Engineering | 4 | 4 |
| Social Sciences, general | 5 | 7 |
| Biology & Biochemistry | 6 | 6 |
| Mathematics | 7 | 12 |
| Psychiatry/Psychology | 8 | 14 |
| Neuroscience & Behavior | 9 | 11 |
| Plant & Animal Science | 10 | 5 |
| Molecular Biology & Genetics | 11 | 13 |
| Computer Science | 12 | 16 |
| Materials Science | 13 | 8 |
| Environment/Ecology | 14 | 9 |
| Geosciences | 15 | 10 |
| Economics & Business | 16 | 18 |
| Space Science | 17 | 21 |
| Immunology | 18 | 20 |
| Microbiology | 19 | 19 |
| Pharmacology & Toxicology | 20 | 17 |
| Agricultural Sciences | 21 | 15 |

עיבוד של מוסד שמואל נאמן לנתוני Thomson Reuters

**Table E.3** Ranking various research disciplines’ priority in Israel and globally 2007-2011

| 2011-2007 | | | 2006-2002 | | | Field |
|---|---|---|---|---|---|---|
| Israel contribution to the field in OECD (%) | Israel contribution to the field globally (%) | No. of publications | Israel contribution to the field in OECD (%) | Israel contribution to the field globally (%) | No. of publications | |
| 0.67 | 0.46 | 599 | 0.81 | 0.65 | 554 | Agricultural Sciences |
| 1.33 | 1.07 | 3,190 | 1.42 | 1.25 | 3,290 | Biology & Biochemistry |
| 1.04 | 0.65 | 4,291 | 1.11 | 0.78 | 4,229 | Chemistry |
| 1.32 | 1.14 | 13,761 | 1.53 | 1.39 | 12,750 | Clinical Medicine |
| 2.22 | 1.70 | 2,001 | 2.08 | 1.73 | 2,540 | Computer Science |
| 1.16 | 1.03 | 1,056 | 1.45 | 1.37 | 850 | Economics & Business |
| 1.12 | 0.78 | 3,806 | 1.32 | 1.03 | 3,644 | Engineering |
| 0.90 | 0.72 | 1,190 | 1.03 | 0.88 | 1,032 | Environment/Ecology |
| 0.85 | 0.66 | 1,087 | 0.89 | 0.74 | 906 | Geosciences |
| 1.42 | 1.26 | 827 | 1.56 | 1.45 | 855 | Immunology |
| 0.87 | 0.51 | 1,365 | 0.79 | 0.54 | 1,114 | Materials Science |
| 2.44 | 1.74 | 2,812 | 2.71 | 2.15 | 2,383 | Mathematics |
| 1.08 | 0.86 | 825 | 1.14 | 1.02 | 749 | Microbiology |
| 1.62 | 1.39 | 2,182 | 1.58 | 1.45 | 1,826 | Molecular Biology & Genetics |
| 1.60 | 1.43 | 2,319 | 1.61 | 1.49 | 2,075 | Neuroscience & Behavior |
| 0.82 | 0.61 | 688 | 0.76 | 0.64 | 517 | Pharmacology & Toxicology |
| 1.95 | 1.34 | 6,825 | 1.98 | 1.52 | 6,548 | Physics |
| 0.98 | 0.74 | 2,298 | 1.15 | 0.96 | 2,382 | Plant & Animal Science |
| 1.88 | 1.76 | 2,539 | 1.90 | 1.82 | 1,943 | Psychiatry/Psychology |
| 1.38 | 1.22 | 3,428 | 1.48 | 1.36 | 2,320 | Social Sciences, general |
| 1.68 | 1.44 | 921 | 1.48 | 1.31 | 768 | Space Science |

**Table E.4** Number of Israeli publications by discipline and contribution to field in the world and for two time periods: 2002-2006 and 2007-2011

| 2002-2006 | | | | 2007-2011 | | | |
|---|---|---|---|---|---|---|---|
| | | # of pubs | Avg cit/pub normalized | | | # of pubs | Avg cit/pub normalized |
| 1 | USA | 10,678 | 1.5 | 1 | USA | 24,974 | 1.43 |
| 2 | **Israel** | 355 | 1.36 | 2 | Ireland | 529 | 1.43 |
| 3 | Netherlands | 746 | 1.23 | 3 | Switzerland | 1,689 | 1.36 |
| 4 | Austria | 384 | 1.2 | 4 | Netherlands | 1,734 | 1.34 |
| 5 | Denmark | 248 | 1.18 | 5 | UK | 4,502 | 1.24 |
| 6 | Germany | 3,683 | 1.18 | 6 | **Israel** | 890 | 1.21 |
| 7 | Sweden | 535 | 1.17 | 7 | Sweden | 1,282 | 1.19 |
| 8 | Hong Kong | 435 | 1.11 | 8 | Germany | 7,209 | 1.14 |
| | **OECD** | 29,054 | 1.1 | 9 | Singapore | 2,303 | 1.13 |
| 9 | Switzerland | 743 | 1.06 | 10 | Australia | 1,979 | 1.12 |
| 10 | Belgium | 602 | 0.99 | 11 | **OECD** | 66,130 | 1.1 |
| 11 | UK | 2,103 | 0.98 | | Hong Kong | 1,104 | 1.07 |
| 12 | Canada | 963 | 0.97 | 12 | Austria | 770 | 1.07 |
| 13 | Spain | 963 | 0.92 | 13 | Denmark | 650 | 1.07 |
| 14 | Australia | 583 | 0.83 | 14 | Canada | 2,612 | 0.98 |
| 15 | Japan | 4,236 | 0.81 | 15 | China | 17,162 | 0.96 |
| 16 | South Korea | 2,218 | 0.77 | 16 | Spain | 2,865 | 0.95 |
| 17 | Greece | 274 | 0.76 | 17 | Finland | 570 | 0.94 |
| 18 | China | 3,884 | 0.75 | 18 | Japan | 7,377 | 0.9 |
| 19 | France | 2,250 | 0.75 | 19 | Belgium | 1,299 | 0.9 |
| 20 | Finland | 217 | 0.74 | 20 | France | 4,852 | 0.84 |

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*The average citation/publication of each country in the table is w.r.t. the average citation/publication in the field, which was 1.07 in 2002-2006, and was 2.90 in 2007-2011*

**Table E.5** Average number of citations per publication normalized by the nanoscience and nanotechnology subspecialty for the time periods 2002-2006 and 2007-2011

| Discipline (ordered by number of most cited publications) | Number of most cited publications in database | Number of Israeli publications and their % of field |
|---|---|---|
| Clinical medicine | 20,704 | 340 (1.6%) |
| Chemistry | 11,962 | 127 (1.1%) |
| Physics | 9,170 | 210 (2.3%) |
| Engineering | 7,989 | 86 (1.1%) |
| Biology / biochemistry | 5,453 | 98 (1.8%) |
| Animal and Plant Science | 5,276 | 111 (2.1%) |
| Social Sciences | 4,726 | 42 (0.9%) |
| Material Sciences | 4,692 | 56 (1.2%) |
| Brain and Behavioural Sciences | 3,017 | 41 (1.4%) |
| Planetary Sciences | 2,906 | 43 (1.5%) |
| Environmental Sciences and Ecology | 2,822 | 24 (0.9%) |
| Molecular Biology and Genetics | 2,792 | 72 (2.6%) |
| Computer Sciences | 2,620 | 66 (2.5%) |
| Mathematics | 2,560 | 39 (1.5%) |
| Psychiatry / Psychology | 2,441 | 42 (1.7%) |
| Agriculture | 2,045 | 23 (1.1%) |
| Pharmacology & Toxicology | 1,906 | 17 (0.9%) |
| Microbiology | 1,687 | 30 (1.8%) |
| Economics and Business Administration | 1,659 | 23 (1.4%) |
| Space Sciences | 1,239 | 47 (3.8%) |
| Immunology | 1,207 | 13 (1.1%) |

**Table E.6** Number of most cited publications in the world in various disciplines, number of Israeli publications in this database, and their percentage of the total number of most cited papers in the discipline for the years 2001-2011

| Country | Number of PS&E grants relating to quantum | Number of overall PS&E grants relating to quantum | Rank |
|---|---|---|---|
| DE | 96 | 15% | 1 |
| FR | 89 | 16% | 2 |
| UK | 77 | 13% | 3 |
| CH | 57 | 10% | 4 |
| NL | 43 | 8% | 5 |
| SP | 41 | 7% | 6 |
| IT | 36 | 6% | 7 |
| IL | 27 | 5% | 8 |
| AU | 27 | 5% | 8 |
| SW | 15 | 3% | 9 |

**Table E.7** ERC grants in the PS&E field relating to quantum, by country

| Country | Total number of PS&E grants in the country | Percentage of total number of PS&E grants | Rank |
|---|---|---|---|
| DE | 458 | 14% | 2 |
| FR | 444 | 14% | 3 |
| UK | 507 | 17% | 1 |
| CH | 239 | 8% | 5 |
| NL | 228 | 7% | 6 |
| SP | 187 | 6% | 7 |
| IT | 360 | 12% | 4 |
| IL | 134 | 4% | 8 |
| AU | 76 | 2% | 10 |
| SW | 93 | 3% | 9 |

**Table E.8** ERC grants in PS&E fields, by country

| Country | Percentage of grantees related to quantum | Rank |
|---|---|---|
| DE | 21% | 4 |
| FR | 20% | 5 |
| UK | 15% | 8 |
| CH | 24% | 2 |
| NL | 19% | 6 |
| SP | 22% | 3 |
| IT | 10% | 9 |
| IL | 20% | 5 |
| AU | 36% | 1 |
| SW | 16% | 7 |

**Table E.9** Percentage of ERC grants related to QST and in PS&E sector, by country

| Country | Number of quantum-related StG grants in PS&E, by country | Percentage of quantum-related StG grants in PS&E | Rank |
|---|---|---|---|
| DE | 22 | 18% | 1 |
| FR | 19 | 16% | 2 |
| UK | 12 | 10% | 3 |
| IL | 10 | 8% | 4 |
| NL | 9 | 8% | 5 |
| CH | 8 | 7% | 6 |
| SP | 7 | 6% | 7 |
| AU | 6 | 5% | 8 |
| IT | 5 | 4% | 9 |
| DK | 5 | 4% | 9 |
| BE | 5 | 4% | 9 |

**Table E.10.** Quantum-related StG ERC grants in PS&E sector during 2013-2016, by country

| Country | Number of StG grants in PS&E, by country | Percentage of StG grants in PS&E | Rank |
|---|---|---|---|
| DE | 85 | 15% | 2 |
| FR | 90 | 14% | 3 |
| UK | 98 | 16% | 1 |
| IL | 45 | 7% | 5 |
| NL | 54 | 9% | 4 |
| CH | 39 | 6% | 6 |
| SP | 36 | 6% | 7 |
| AU | 17 | 3% | 10 |
| IT | 30 | 5% | 8 |
| DK | 7 | 1% | 12 |
| BE | 28 | 4% | 9 |

**Table E.11** Number of ERC StG grants in PS&E section, in 2013-2016, by country

| Country | Percentage of quantum-related StG PS&E grantees | Rank |
|---|---|---|
| DE | 23% | 3 |
| FR | 21% | 5 |
| UK | 12% | 10 |
| IL | 22% | 4 |
| NL | 17% | 7 |
| CH | 21% | 6 |
| SP | 19% | 8 |
| AU | 35% | 2 |
| IT | 17% | 7 |
| DK | 71% | 1 |
| BE | 18% | 9 |

**Table E.12** Percentage of quantum-related StG ERC grants in PS&E category during 2013-2016