NATO
OTAN
Science for Peace and Security (SPS) Programme

Quantum Technologies and the Science for Peace and Security Programme

Foreword
by **David van Weel**

At the Copenhagen Quantum Conference in September of 2023, NATO Secretary General Jens Stoltenberg pointed out that NATO "has always adapted to and adopted new technologies to keep our people safe" and that "with the rapid spread of disruptive technologies, we must adapt further and faster than ever before, including in the field of quantum." He also underlined the importance of close collaboration between the public, private and academic sectors in this endeavour.

My Division addresses a wide range of Emerging and Disruptive Technologies (EDTs) in addition to quantum, such as artificial intelligence, robotics and autonomous systems, big data analytics, space technologies, and new advanced materials. Quantum-based technologies, however—unlike most other EDTs—are still in their nascent stages, and have the potential to fundamentally alter the way we view Euro-Atlantic and global security.

For example, a fully functioning, full-scale quantum computer could revolutionize the fields of encryption and communication and make current methods of securing information obsolete. Similarly, future quantum-sensing technologies will provide precise Position, Navigation and Timing (PNT) in GNSS-denied environments, with no need for satellites or ground stations, working anywhere—indoors, underground or underwater.

With technological innovations set to have such paradigm-shifting impacts in the near future, governments around the world have issued or are currently developing national quantum strategies; and NATO is in the process of ensuring that the Alliance is able to integrate quantum technologies into its existing security framework and also able to protect against adversarial use.

With the creation and implementation of its own Quantum Strategy, and by fostering the development of a transatlantic quantum community, NATO aims to harness the power of quantum technologies for the security of the Alliance.

The Science for Peace and Security (SPS) Programme is poised to play a significant role in developing cutting-edge quantum technologies, by building opportunities for practical cooperation among NATO allies and partner countries on security-related science and innovation.

As quantum technologies become an increasingly central focus for NATO and national administrations around the globe, SPS is expanding its portfolio of activities in quantum communications, quantum sensing as well as in quantum computing.

In 2023 alone, the SPS Programme has successfully completed two quantum-focused Multi-Year Projects, and has engaged nearly 40 universities and research institutes in NATO allied and partner countries in 12 research collaborations that are still in progress as of November 2023. The Programme has also supported five events on a variety of quantum-related topics and is planning to convene three more in 2024 to address current quantum research issues.

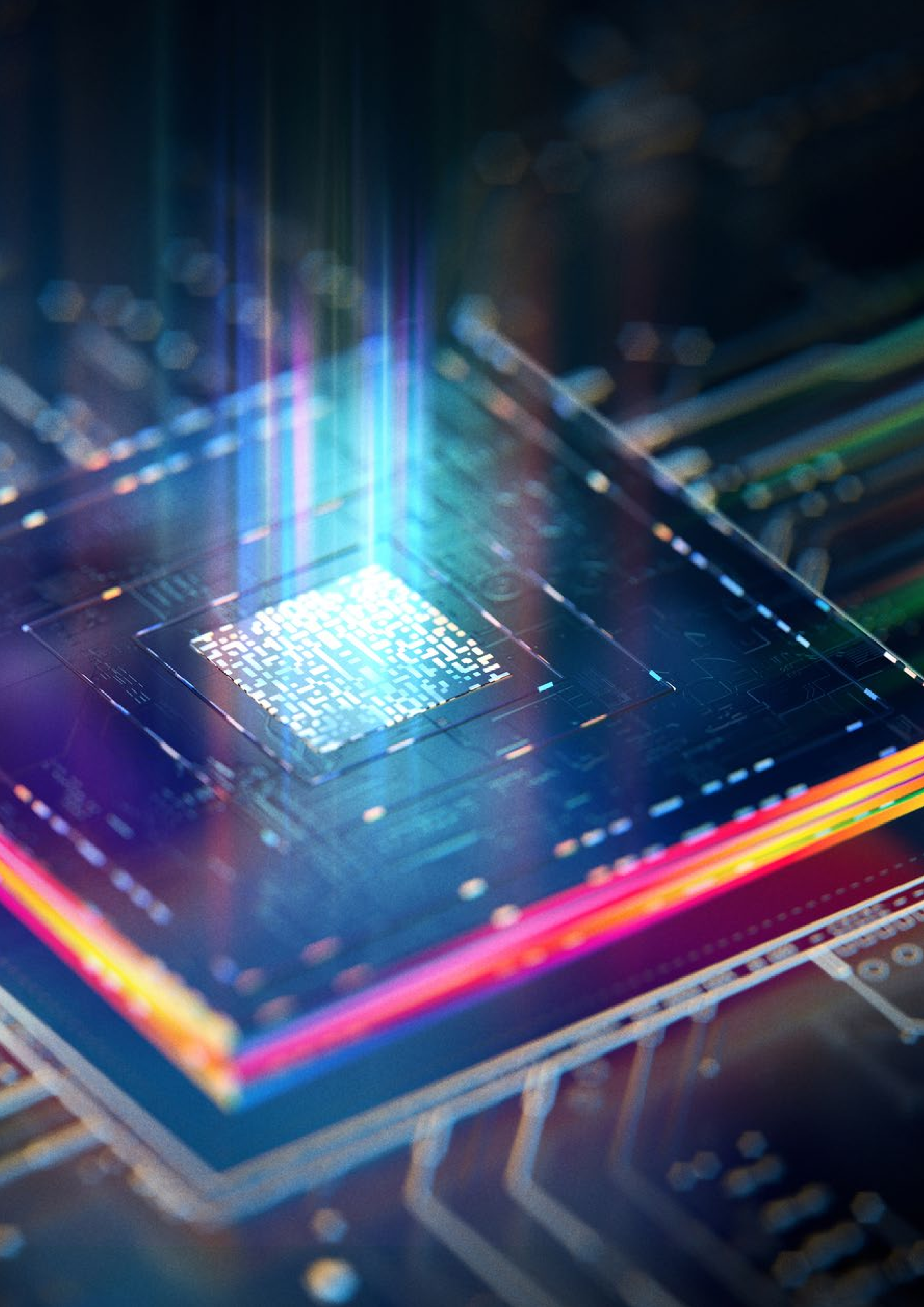
Keep reading to explore the work the SPS Programme has been supporting in the field of quantum technologies to date. I hope this report will inspire you and your communities to understand and investigate these topics, and to consider submitting your own research proposal to the SPS Programme.

David van Weel
Assistant Secretary General
for Emerging Security Challenges

Introduction

As the security challenges facing the Euro-Atlantic region become more complex, the Science for Peace and Security (SPS) Programme is supporting a growing portfolio of activities aimed at testing the boundaries of quantum technologies and their impact on the rapidly evolving global security landscape across three domains: quantum communications, quantum sensing and quantum computing. In the context of quantum communications, collaborations between scientists from NATO and partner nations supported by the Programme continued to explore systems for encryption and secure transmission of information focusing the potential of Quantum Key Distribution (QKD) and Post-Quantum Cryptography (PQC) in real-world environments. One recent project is designing, analysing and looking to implement a number of potential architectures, and associated use cases, for the establishment of a secure cryptographic communication, integrating PQC and QKD technologies on distributed network infrastructures.

The Programme also supported activities on quantum sensing, focusing on the detection of chemical and biological agents exploiting entanglement property of photons. In the field of quantum computing, SPS has focused on basic enabling scientific research, like spintronics – a research field aimed at the exploitation of the quantum mechanical property of the electrons' spin - and other quantum-enabling technologies, like single photon counters or frequency conversion technologies for quantum application. The list of activities is reported below.



Quantum Communications

Communication networks are a fundamental part of today's information technology infrastructure. The rapid advance of quantum technologies are impacting the requirements and capabilities for securely communicating over such networks, and are currently resulted in two main research thrusts:

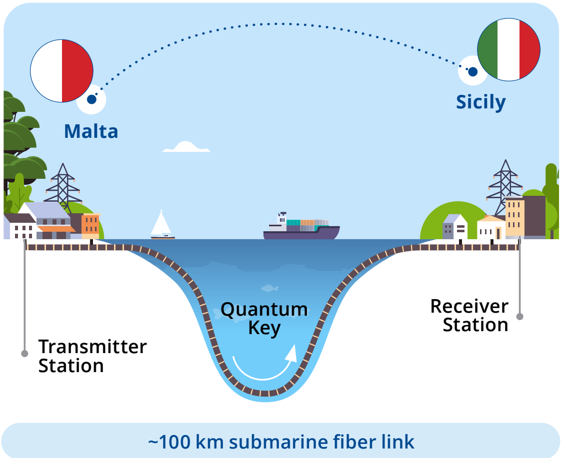
Quantum Key Distribution (QKD) is a secure communication method that exploits quantum mechanics to distribute and share keys necessary for cryptographic protocols. Information is encoded on single photons and relies on the quantum characteristics of the photon to remain secure and private between communicating parties. This is due to a fundamental feature of quantum systems: by observing photons, or disturbing them in any way, quantum characteristics are altered and communicating parties are made aware of potential attackers.

Post-quantum cryptography (PQC) builds on mathematical problems that are considered intractable, even in the presence of large-scale quantum computers. PQC protocols are designed to run on classical computers and networks, without the need to upgrade network infrastructure.

Quantum Key Distribution

Secure Quantum Communications through Submarine Optical Fibre Link between Italy and Malta (SEQIM)

(G5485 MYP – Consiglio Nazionale delle Ricerche, Italy; University of Malta – 2018-2022)



The "SEQIM" multi-year project successfully developed a prototypical quantum key distribution link between Italy and the island of Malta utilising existing telecommunications infrastructure. It has provided the first quantum key distribution link between two different countries through a submarine dark-fibre link, guaranteeing secure communications between Italy and Malta. The project also served as a testing ground for future innovations, and the foundation it laid is now helping to reinforce the protection of governmental institutions, data centres, hospitals, energy grids and a range of critical infrastructure. Additionally, its prototype is making further development in telecommunications possible, providing a template for industrial-grade systems and products for quantum networks and a wide range of dual-use applications.

Quantum Cybersecurity in 5G Networks (QUANTUM5)

(G5894 MYP – VSB Technical University of Ostrava, Czechia; University of Sarajevo, Bosnia and Herzegovina – 2021-2024)

"Quantum Cybersecurity in 5G Networks (QUANTUM5)" is a multi-year project, launched in 2021, bringing together researchers from the VSB Technical University of Ostrava in Czechia and the University of Sarajevo in Bosnia and Herzegovina. The project aims to demonstrate practical applications of Quantum Key Distribution (QKD) in 5G networks, developing simulation tools and practical guidelines for further inclusion of quantum technologies in 5G networks and beyond.

Implementation Vulnerabilities in QKD Components for Fiber and Drone Applications

(G6026 MYP – California State University Los Angeles, USA; Ben Gurion University of the Negev, Israel; Istituto Nazionale di Ricerca Metrologica, Italy – 2023-2026)

The goal of the multi-year project "Implementation Vulnerabilities in QKD Components for Fiber and Drone Applications", launched in 2023, is to use next-generation components to identify loopholes in quantum key distribution technology and propose protocols and/or algorithms able to minimize the risk of eavesdropping both on fiber and free-space optical (drone) channels. Scientists at American, Italian and Israeli research institutes are using machine learning and artificial-intelligence techniques to future-proof the transmission of information, protecting it from increasingly advanced hacking systems.

QSCAN – Quantum-enabled secure multiparty computation for space surveillance tracking

(G6158 MYP – IT Instituto de Telecomunicações, Portugal; AIT Austrian Institute of Technology – 2023-2026)

To solve privacy issues related to usage of third-party data, the "QSCAN – Quantum-Enabled Secure Multiparty Computation for Space Surveillance Tracking Project", launched in 2023, will implement a quantum-enabled Secure Multiparty Computation (SMC) protocol for conjunction analysis, which will increase security for multiparty communications. Researchers at the Portuguese IT Instituto de Telecomunicações and the AIT Austrian Institute of Technology will work toward this result through the generation and distribution of oblivious keys, allowing for fast and secure multiparty computation. This multi-year project will demonstrate the SMC protocol for Space Surveillance Tracking

within the Portuguese Quantum Communication Infrastructure, currently in development in the city of Lisbon under the supervision of the Portuguese National Security Office.

Post Quantum Cryptography

Quantum-safe Authenticated Group Key Establishment

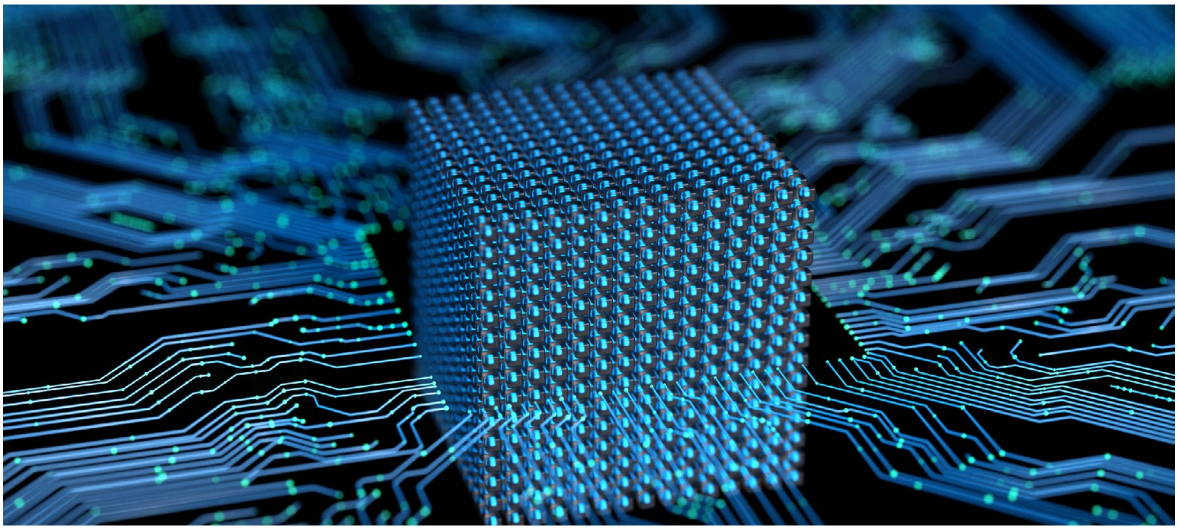
(G5448 MYP – Slovak University of Technology; University of Malta; Universidad Rey Juan Carlos, Spain; Florida Atlantic University, USA – 2018-2022)

Fundamental to establishing secure communication channels is the execution of a protocol that authenticates all involved users and devices and establishes a common secret key among them. This is referred to as authenticated group key establishment (AGKE), and the goal of the "Quantum-safe Authenticated Group Key Establishment" multi-year project, which ran from 2018 to 2022, was to design and implement an AGKE solution which would provide security against an adversary with access to large quantum-computing resources. Collaboration between Slovak, Maltese, Spanish and American universities developed a constant-round AGKE with strong provable security guarantees, employing a post-quantum key establishment mechanism. The protocol was successfully implemented in the C programming language, and a sample application was shown in a live demonstration involving five nations. The protocol also provides a number of countermeasures against practical real-world attacks, including the support of a hardware security module that is responsible for all cryptographic computations involving secret data.

Intermediate and Advanced Course on Post-Quantum Cryptography

(G5972 ATC – Tubitak Bilgem National Institute of Electronics and Cryptology, Türkiye; War College of the Armed Forces, Azerbaijan – September 2022)

This Advanced Training Course, which took place in Baku, Azerbaijan, in September of 2022, brought together a wide range of experts from five NATO allies and partner countries to explore recent developments in the field of quantum technologies. A particular focus of the course was post-quantum cryptography, which attempts to develop methods to secure data against attack from a quantum computer. The "Intermediate and Advanced Course on Post-Quantum Cryptography" introduced participants to current technologies, challenges and opportunities, and the abstract mathematical structures fundamental to quantum and post-quantum technological developments.

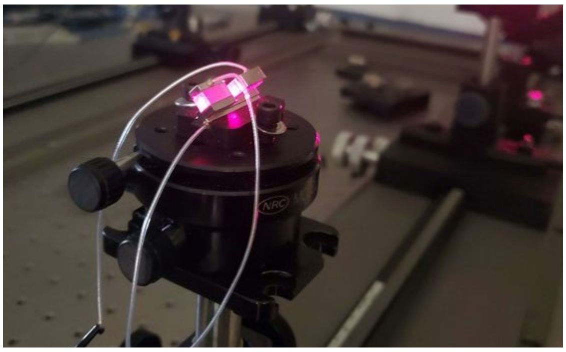


Combination of Quantum Key Distribution and Post Quantum Cryptography

Secure Communication via Classical and Quantum Technologies

(G5985 MYP – University of Alabama in Huntsville, USA; VTT Technical Research Centre, Finland; Institute of Physics, Slovak Academy of Science; University of Technology in Bratislava, Slovakia; Universidad Rey Juan Carlos, Spain – 2023-2026)

Post-quantum cryptography (PQC) and quantum communication, including quantum key distribution (QKD), offer different capabilities for securing sensitive transmission. However, the two research communities have engaged in minimal collaboration. Launched in 2023, the "Secure Communication via Classical and Quantum Technologies" multi-year project is designing, analysing and looking to implement a cryptographic protocol for secure group communication on distributed, hybrid networks, integrating PQC and QKD as available on the distributed network infrastructures.

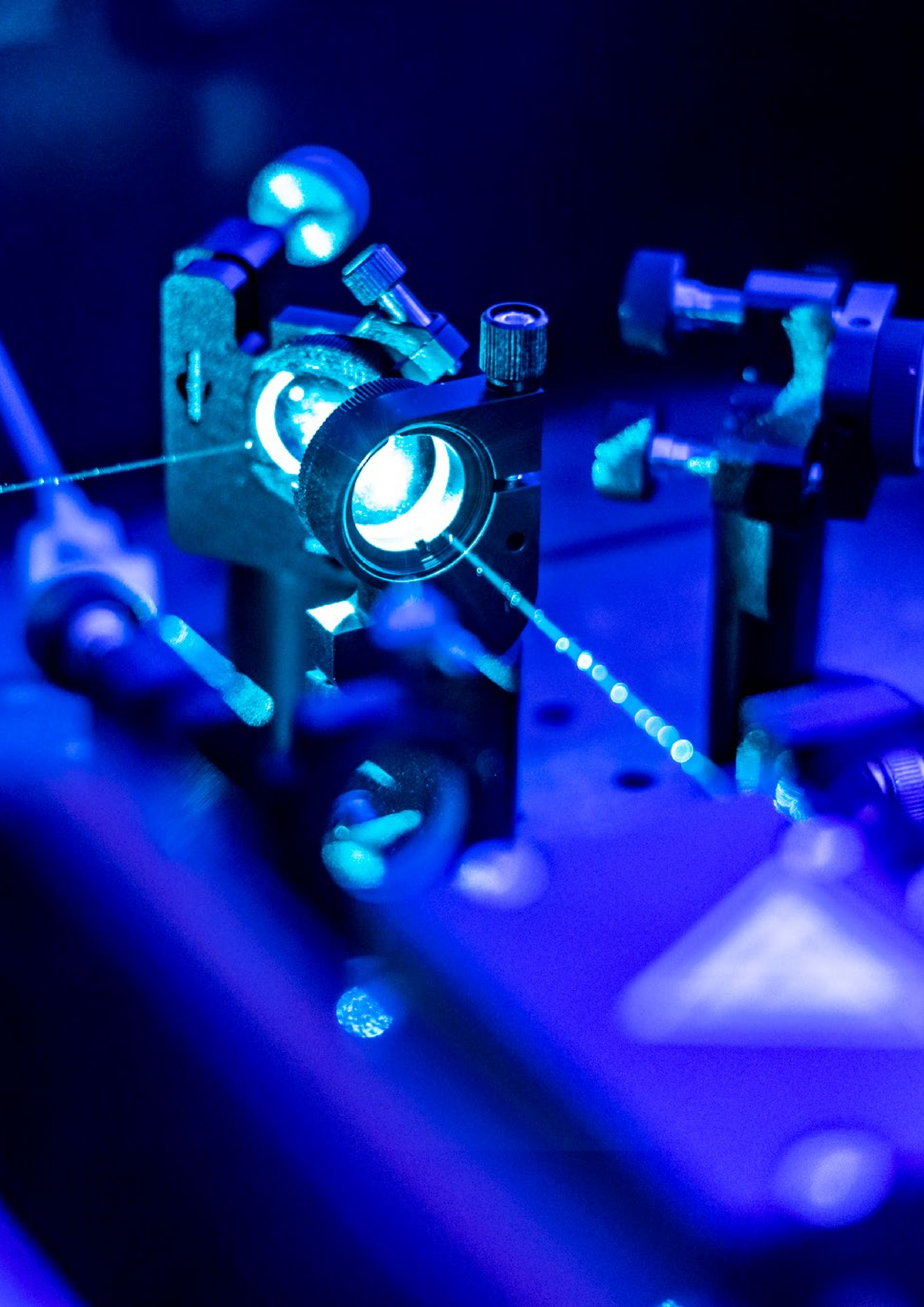


Traditional cryptographic protocols commonly assume a network topology that offers connections among most parties, including broadcast channels. Quantum links, on the other hand, are by default point-to-point, and establishing secure group communication is non-trivial. This project is developing a security model that allows the design of cryptographic protocols for secure group communication on a hybrid network structure comprising PQC and QKD components. Going beyond the theoretical stage, a prototype of the identified solution on a distributed hybrid network will be implemented, and the integration of PQC and QKD components will be demonstrated in two countries. Additionally, the project seeks to integrate work on PQC and QKD implementations, ensuring direct collaboration of young researchers with a classical cryptography background and young researchers with a quantum physics background, in order to ensure the maximum benefits for the scientific community at large.

Cybersecurity in the Era of Quantum Computing: Threats and Challenges

(G6123 ASI – Polish Academy of Sciences; Mohammed V University in Rabat, Morocco – 2024)

In April 2024, experts from the Institute of Theoretical and Applied Informatics – Polish Academy of Sciences and the Mohammed V University in Rabat, Morocco, will convene the "Cybersecurity in the Era of Quantum Computing: Threats and Challenges" Advanced Study Institute. The event will be hosted in Ifrane, Morocco, and will bring together researchers from 13 NATO allies and partner countries. The lectures in the event will address recent developments in quantum algorithms and protocols for secure data encryptions, quantum key distribution for secure quantum communications, and quantum machine learning. Through lectures and discussions, attendees will have the opportunity to explore the cross-fertilization of cybersecurity and quantum technologies, and to interact with internationally leading experts in both fields in order to foster knowledge sharing and research collaborations.



Quantum sensing

Quantum mechanics can be employed to implement innovative sensors, i.e. using quantum systems or phenomena (coherence and entanglement) as probes for the quantum or classical environment. Leveraging the intrinsic sensitivity of the quantum world to external perturbations, quantum-enhanced sensing can enable unprecedented performance in terms of accuracy, stability, sensitivity and precision. Quantum sensors have recently emerged as a promising technology for a variety of applications, ranging from imaging, detection of substances, up to autonomous navigation.

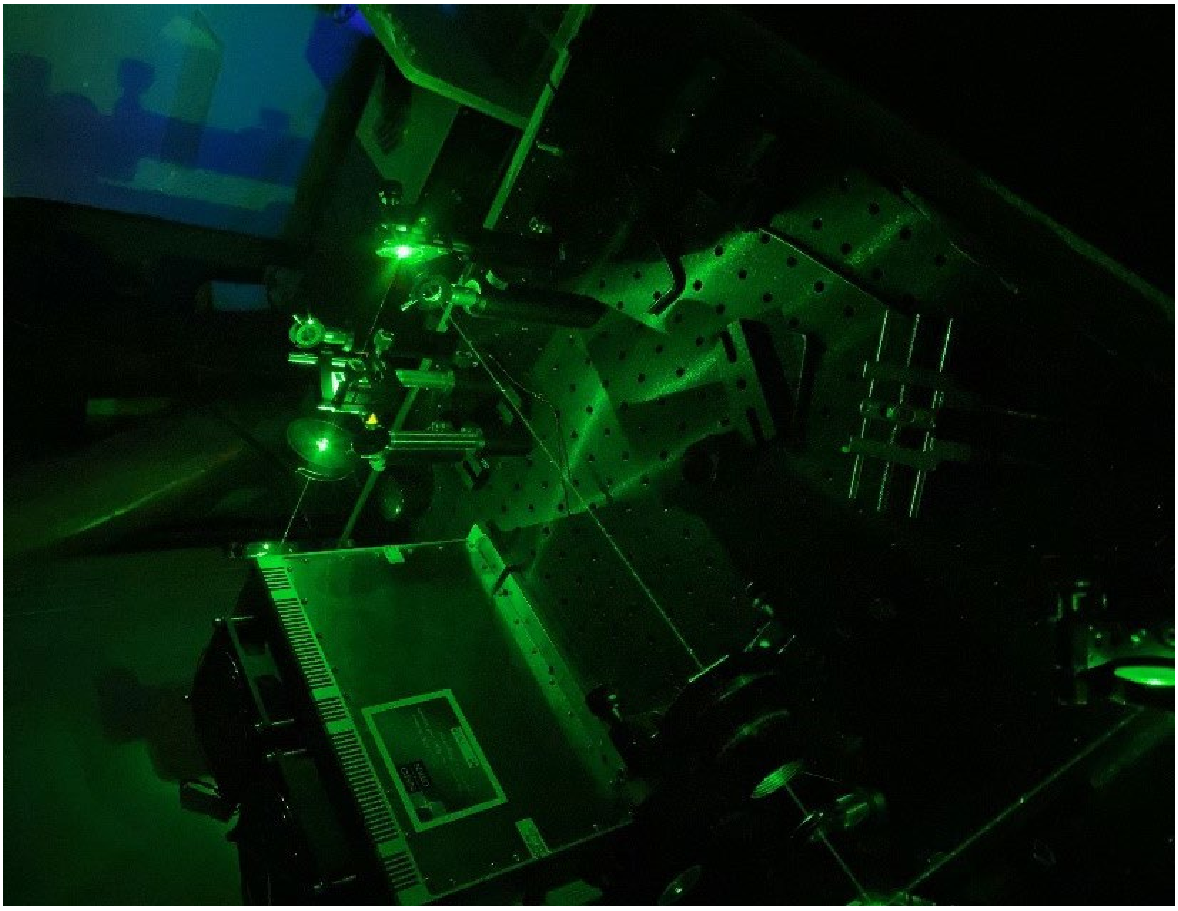
Laser-printed Early Warning Sensors: Quantum Detection of Chemical and Biological Agents (LiGAlert)

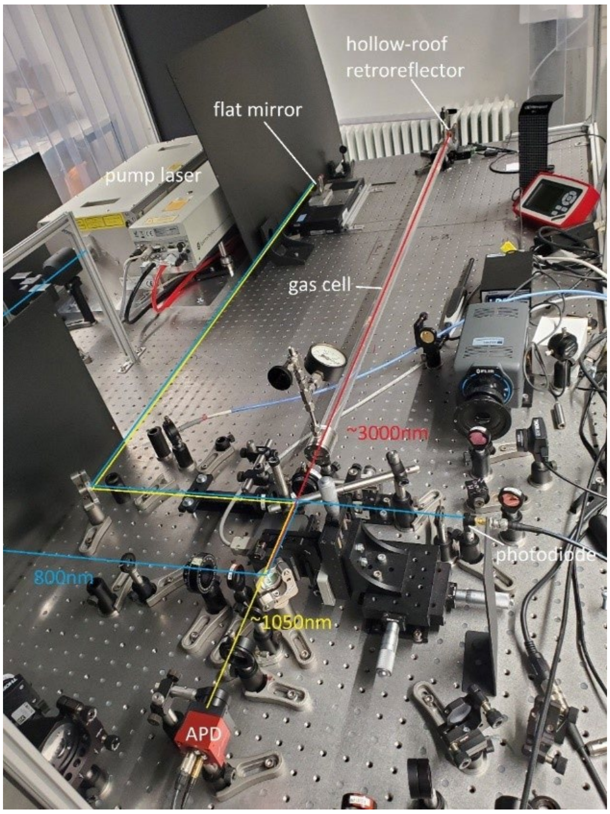
(G6112 MYP – Gdańsk University of Technology, Poland; Johannes Kepler Universität Linz, Austria; Military University of Technology, Poland; Ohio State University, USA; California Institute of Technology, USA; University of South Bohemia in Ceske Budejovice, Czechia – 2023-2026)

The 2023 multi-year project 'Laser-printed Early Warning Sensors: Quantum Detection of Chemical and Biological Agents (LiGAlert)' aims to develop a flexible, cost-effective electrochemical sensor based on voltammetry analysis to detect explosive and chemical warfare substances. The new sensor will be designed to detect specific groups of substances including primary and secondary explosives, solid propellants, and chemical warfare agents, and will have the potential to improve the effectiveness of crisis management in preventing terrorist attacks. The project is a collaboration between research institutes in Poland, Austria, the USA and Czechia that will incorporate AI algorithms for data analysis, using neural networks and genetic algorithms to recognize chemical compounds based on their impedance characteristics. Work will also focus on designing and implementing dedicated readout systems for the LIG electrical characterization results.

HADES: HAzards DEtection with quantum Sensors

(G5839 MYP – Italian National Agency for New Technologies, Energy and Sustainable Economic Development; University of Geneva, Switzerland; University of Roma Tre, Italy – 2021-2024)



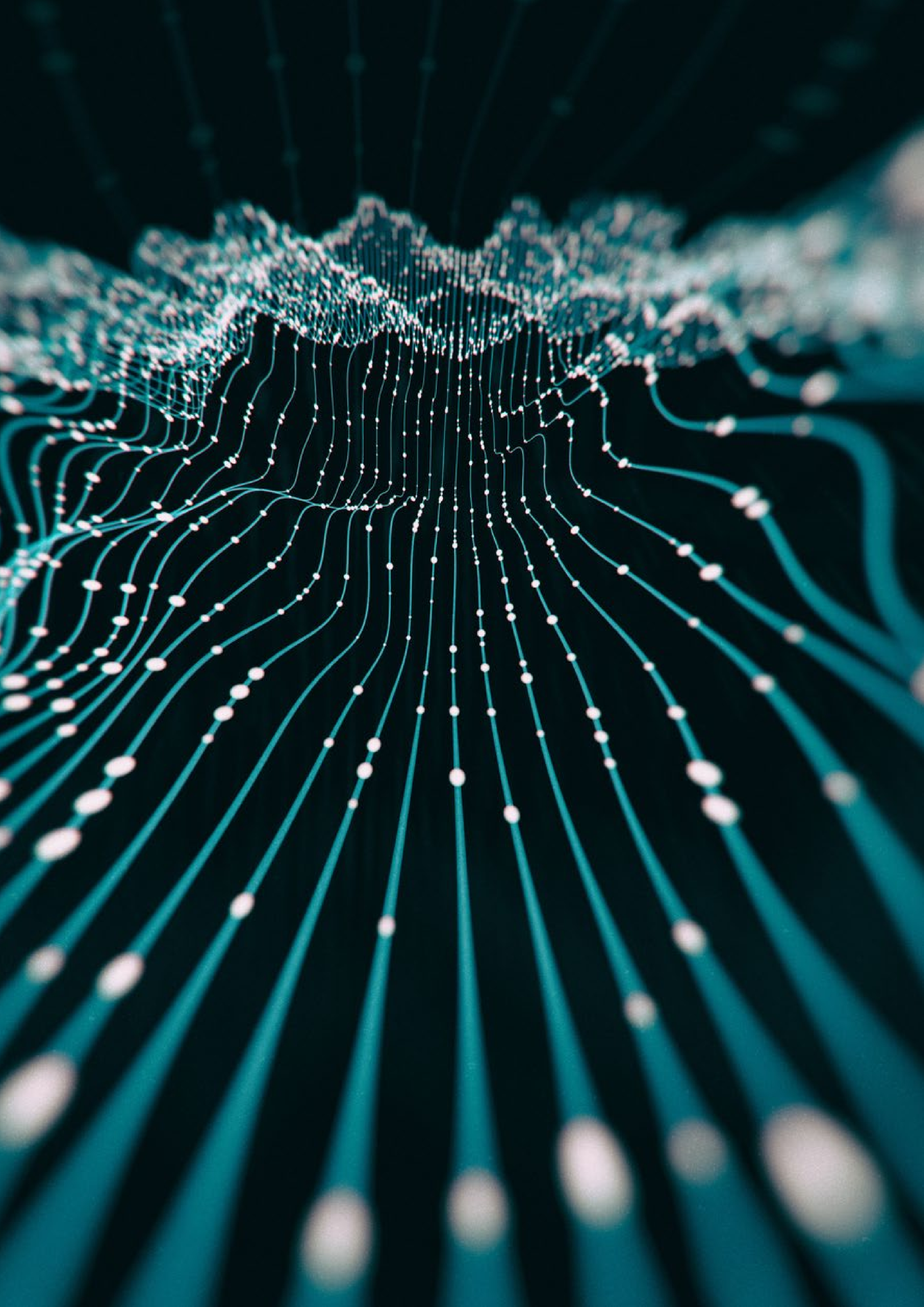


The "HADES: HAzards DEtection with quantum Sensors" multi-year project, launched in 2021 by researchers at a number of research institutes in Italy and Switzerland, is using novel quantum-sensing technologies for the detection of chemical, biological, radiological and nuclear (CBRN) threats such as the presence of undetected harmful gases, hydrocarbons, post-explosion residues and nuclear waste. In particular, the project is exploring Quantum Ghost Spectroscopy and Quantum Fourier-Transform Infra-Red Spectroscopy, two techniques that generate photons at a desired wavelength, and will develop a final prototype that will be tested in field conditions. The project will advance state-of-the-art technology in the field of CBRN detection, providing improved capabilities of security assessment in a wide array of potentially hazardous environments.

Pursuing Quantum Sensing for Reliable Roadmaps

(G6067 ARW – Italian National Agency for New Technologies, Energy and Sustainable Economic Development; Griffith University, Australia – December 2023)

The "Pursuing Quantum Sensing for Reliable Roadmaps" Advanced Research Workshop, which will be held in Frascati, Italy, in December 2023, will mark a significant step forward in bringing innovative hardware from the lab to the field and in developing a promising roadmap for future quantum sensing technology. It will bring together experts from 19 NATO Allies and Partner countries, who will develop methodologies for assessing practical applications of quantum sensing capabilities. They will also identify potential practical opportunities for quantum sensing for detection and evaluate field applications of a wide range of quantum sensing technology, creating proto-types and transitioning to operational use.



Quantum Computing and Enabling Technologies

Quantum computing is a multidisciplinary field comprising aspects of computer science, physics, and mathematics that utilizes quantum mechanics to solve complex problems faster than classical computers. Research activities around quantum magnonics, spintronics, transparent electronics, quantum optics and quantum information science contribute to the advancements in this field and can represent a breakthrough for novel applications in quantum computing.

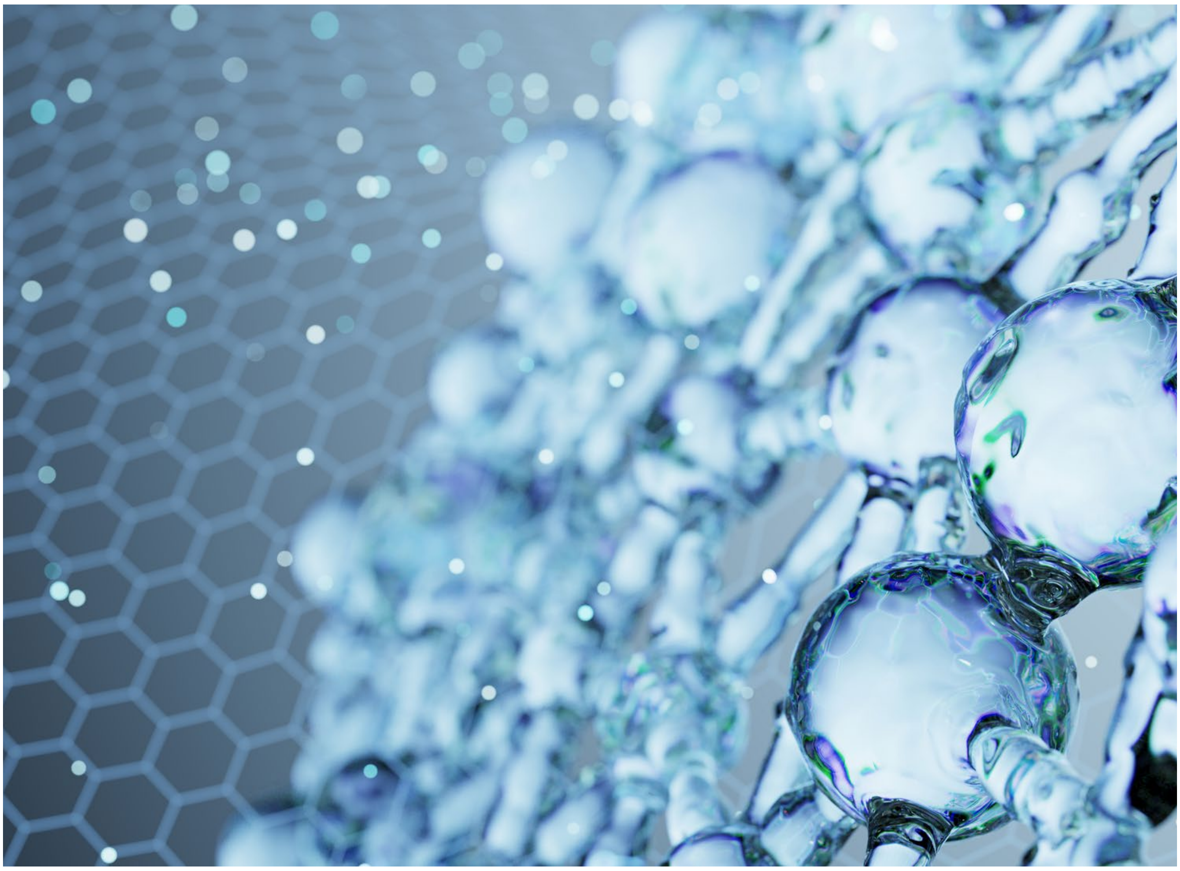
Spintronics

Spintronic Devices for Microwave Detection and Energy Harvesting Applications

(G5792 MYP – Institute of Nanoscience and Nanotechnology, Greece; Igor Sikorsky Kyiv Polytechnic Institute, Ukraine; Helmholtz-Zentrum Dresden-Rossendorf, Germany; Taras Shevchenko National University of Kyiv, Ukraine; CNRS - Laboratoire de Physique des Solides, France; Consejo Superior de Investigaciones Científicas-Instituto de Micro y Nanotecnología, Spain; University of Debrecen, Hungary – 2021-2024)

Spin-based electronics, or spintronics, is a branch of quantum physics that addresses the storage and transmission of information based on the spin of electrons and their charge. This technology can be used to develop novel devices that overcome the limitations of conventional electronics, e.g. chip size, power consumption, frequency stability, sensitivity, etc., enabling a number of potential practical applications, including non-volatile memories, radar systems, magnetic field sensing, microwave generation and detection, and microwave energy harvesting.

The goal of the "Spintronic Devices for Microwave Detection and Energy Harvesting Applications" multi-year project, launched in 2020, is to investigate novel materials for fabricating spintronics-based devices for microwave detection and energy harvesting. The project brings together scientists from research institutes in Greece, Ukraine, Germany, France, Spain and Hungary in order to develop a high performance Spin-Torque Microwave Detector (STMD) device for microwave generation, detection, and energy harvesting, using a novel materials (ferromagnetic manganese-based chemically ordered alloys). Additionally, the project aims to install such materials and devices on commercial silicon wafers, ensuring compatibility with standard microelectronics processes and allowing the development of a low-cost, commercially viable sensor technology.



Functional Spintronic Nanomaterials for Radiation Detection and Energy Harvesting

(G6027 ARW – TU Kaiserslautern, Germany; Igor Sikorsky Kyiv Polytechnic Institute, Ukraine – May 2023)

The "Functional Spintronic Nanomaterials for Radiation Detection and Energy Harvesting" Advanced Research Workshop, which was held in May 2023, brought together scientists from 12 NATO allies and partner countries and focused on the scientific foundations of spintronic radar detectors and energy harvesters along with potential applications for armoured vehicle threat detection. These devices incorporate spintronic-based oscillators, called Spin-Torque Nano Oscillators (STNOs), which are compact, easy to fabricate and compatible with conventional silicon technology. In addition, their minimal power consumption makes spintronic radar systems particularly attractive in communications devices and radar systems when compared with conventional electronic systems.

In addition, this workshop was held in conjunction with the celebration for the 125th anniversary of the Igor Sikorsky Kyiv Polytechnic Institute, marking a significant milestone of the oldest and most prestigious Ukrainian institutions and strengthening cooperation with Ukraine on a particularly relevant field of research.

Quantum enabling technologies

Single Microwave Photon Counter based on Tunable Flux Qubit

(G5796 MYP – Université Savoie Mont Blanc, France; G. V. Kurdyumov Institute for Metal Physics of the National Academy of Science, Ukraine – 2020-2024)

The current state-of-the-art approach to measuring qubits involves low-noise cryogenic amplifiers and substantial hardware and electronics, which are difficult to scale up for increased qubit arrays. The "Single Microwave Photon Counter based on Tunable Flux Qubit" multi-year project, which got underway in 2020, aims at developing an advanced microwave single-photon counter based on a superconducting flux qubit with a widely tunable reception frequency, a significantly reduced dark counting rate, and elevated speed. The project has brought together experts from research institutes in France, Ukraine, Slovakia and Sweden, and its results will further the understanding of superconducting qubit operations in single-photon counting.

OPTIcal liMIting and SwiTching with nanoscale photonic structures (OPTIMIST)

(G5850 MYP – National Research Council – National Institute of Optics, Italy; Australian National University – 2021-2024)

The proliferation of commercial lasers is an emerging security threat, with lack of regulation exacerbating risks and current laser protection systems limited in their effectiveness. To meet this challenge, scientists from the Italian National Institute of Optics and the Australian National University have been collaborating on the "OPTIcal liMIting and SwiTching with nanoscale photonic structures (OPTIMIST)" multi-year project since 2021. They are designing a novel class of self-activating optical limiting and switching devices, with large angular acceptance and bandwidth, fast response and reset times and high laser damage threshold. To create such devices, the project is assessing the property of metallic and dielectric photonic resonators (thin-film multilayers) and incorporating phase-change-materials (PCMs), namely vanadium oxide. The project opening new avenues of research in the field of linear and nonlinear reconfigurable and tunable nano-photonics.

Conversion Technologies for Quantum Sensing and Secure Communications

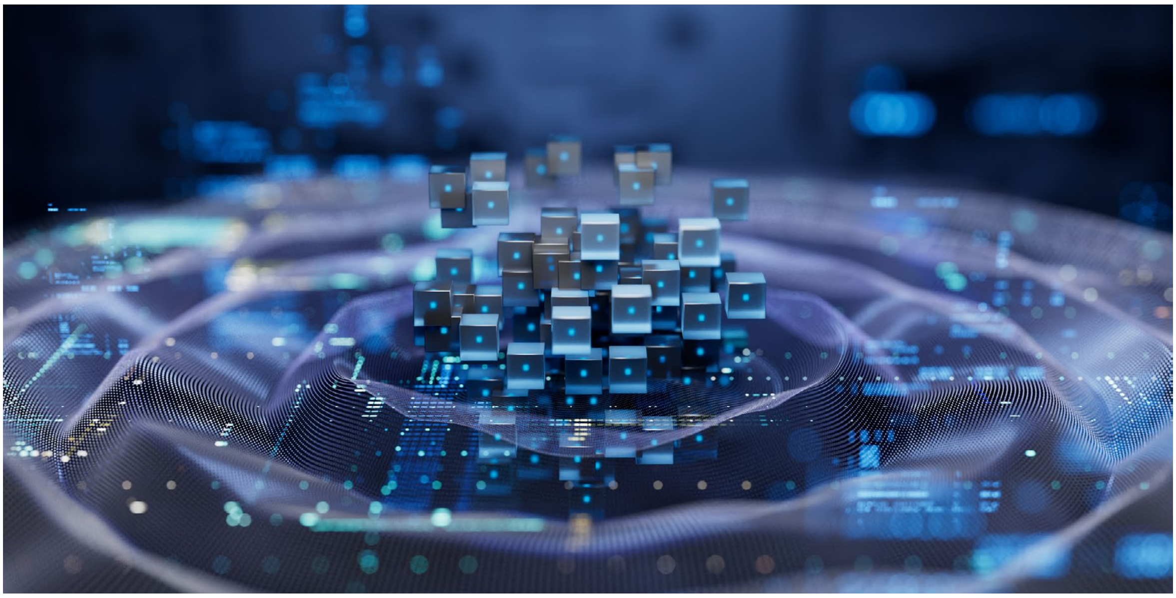
(G5859 MYP – Gebze Technical University, Türkiye; National Academy of Sciences of Ukraine – 2021-2024)

The basic concepts of quantum mechanics are fundamental to many of the Emerging and Disruptive Technologies that are changing the security landscape around the globe, and coherent quantum networks are necessary for the proper functioning of many of these technologies. The aim of the "Conversion Technologies for Quantum Sensing and Secure Communications" multi-year project, which was launched in 2021, is to gain an understanding of novel concepts of hybrid spin-photonic systems with potential applications in up/down quantum frequency-converter technologies.

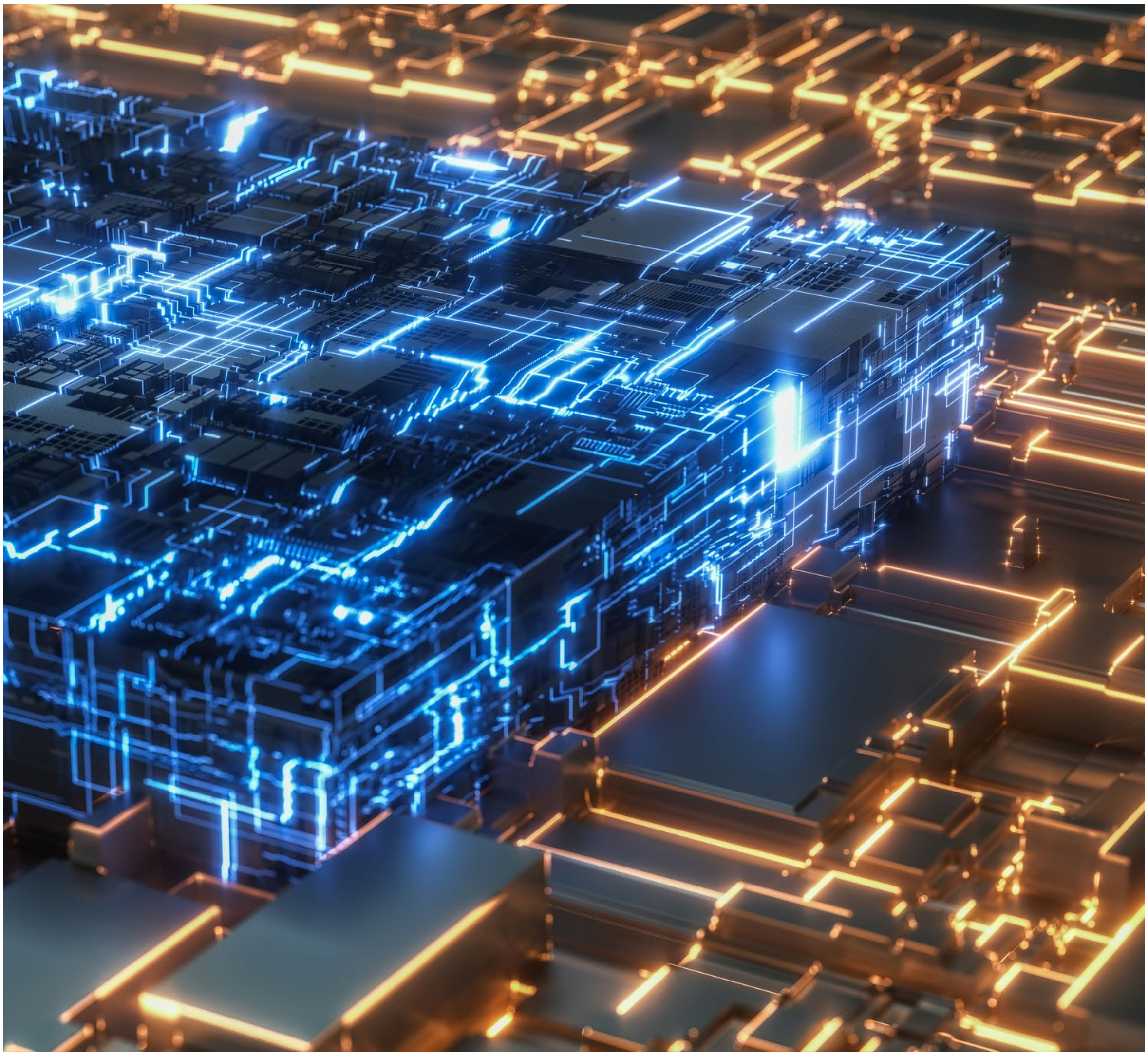
Researchers from Gebze Technical University in Türkiye and National Academy of Sciences of Ukraine are investigating the use of ferromagnetic (magnonic) material as an effective medium to transfer quantum information from one quantum system to another. They are also looking to develop hybrid quantum structures for efficient conversion of microwave photons to optical photons and assessing meta-material patterns and magnonics implementation in quantum converters.

Development of New Quaternary Crystals for Security Applications

(G5912 MYP – Middle East Technical University, Türkiye; National Academy of Sciences of Ukraine – 2021-2024)



Another collaboration between the National Academy of Sciences of Ukraine and a Turkish university, in this instance the Middle East Technical University, aims to develop novel quaternary crystals to be used as sensing and detecting materials for a wide range of applications in the field of homeland security, radiation and nuclear safety and scanning systems. The primary goal of the "Development of New Quaternary Crystals for Security Applications" multi-year project is to explore the effectiveness of Cadmium Zinc Telluride Selenide and Cadmium Manganese Telluride Selenide as possible alternatives to currently used compounds, which are suboptimal. The project, launched in 2021, is developing a range of new methods to improve crystal properties, including synthesizing raw materials for crystal growth and addressing structural defects with special additives.



Electrochromic Metal Oxides for Transparent Superconducting Electronics

(G6082 MYP – University of Texas at Dallas, USA; Kyiv Academic University, Ukraine – 2023-2026)

Transparent electronics is an emerging technological field focused on producing invisible electronic circuitry and optoelectronic devices. The technology involves the replacement of normally opaque semiconductors, which have traditionally been used in electronic devices, with transparent conductors. The 'Electrochromic Metal Oxides for Transparent Superconducting Electronics' Multi-Year Project, a collaboration launched in 2023 by researchers at the University of Texas at Dallas and the Kyiv Academic University, aims to pave the way for an entirely new field of transparent electronics: the electronics of transparent superconductors. This collaboration between Ukrainian and American universities will identify materials appropriate the development of transparent electronics, perform detailed studies of their electrical and optical characteristics and develop optimized thin-film technologies for single-photon detectors and next generation integrated quantum electronics. The project will demonstrate the technology with a relevant prototype and explore the frontiers of knowledge concerning fundamental physical behaviour of transparent superconductors. It will also support the long-term innovation in cryogenic materials, which have the potential to make a significant impact on the field of security-related science.

Conclusion

In the coming years, quantum technologies will become further integrated into critical infrastructures around the world, and will certainly play a central role in shaping new paradigms in global security. Their potential to lead to revolutionary technological breakthroughs in defence and security contexts as well as in the civilian realm has created a fiercely competitive innovation environment and has attracted substantial investment from both public and private sources. The SPS Programme—with its decades-long history of supporting cutting-edge research and building extensive networks of scientists and experts from various backgrounds in a wide range of sectors in government, academia and industry—is ideally placed to play a leading role in the quantum era.

The SPS Programme has been funding quantum-focused research and innovation for more than five years. The Programme will continue to sharpen its focus on quantum technologies and is currently developing a plan to increase its presence in the field. One key aspect of its approach to our quantum future is to expand support for early stage researchers in order to connect with and encourage the next generation of quantum innovators. The SPS Programme is committed to promoting the work of these young scientists and to raising awareness among the broader scientific community of their vital contributions. A series of Advanced Training Courses, which will highlight their innovations and place them in a global context, is currently in its planning stages.

In parallel to its efforts to showcase the research of early stage researchers, the SPS Programme is also broadening its network of expertise geographically. Given the increase of strategic competition in regions around the globe and the growing complexity of an ever-changing international security landscape—and the risks they pose to the rules-based international order—NATO is working closely with partners in the Indo-Pacific and the South to ensure that they have the capabilities to counter rising threats. Quantum technologies are at the forefront of this effort. They also play a role in Ukraine's, where despite Russia's aggression, Ukrainian scientists are currently coleading six quantum-focused SPS activities—more than any other NATO partner country—and there are plans to initiate several more in the coming months. The SPS Programme continues to explore possibilities for connecting with new counterparts from across NATO's partnership frameworks.

The future is full of uncertainty, and NATO continues to prepare to face tomorrow's challenges. Due to the unique qualities and potential of quantum technologies, NATO has a strategic approach to ensure a coherent, innovative approach to staying ahead in the quantum race and to becoming quantum-ready by 2030. The quantum-focused activities of the SPS Programme are designed to be in line with this overarching strategy, and SPS engagement with partners will continue to serve as an example of scientific cooperation at its best.

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