Il Colle di Galileo

Fostering innovation through quantum technology transfer: Insights from the second Vasco Ronchi Colloquium

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Abstract. The article presents an in-depth analysis of the topics covered by this second Vasco Ronchi Colloquium (VRC), held on March 27th 2024 at the Arcetri headquarters of the National Institute of Optics of CNR, entitled "(QU)BITS OF TECHNOLOGY TRANSFER" and focusing on quantum technologies for sensing and security. The VR Colloquia are a format of brief targeted meetings, designed specifically by CNR-INO for boosting the interaction between researchers from the institute and businesses with an effective approach which could trigger the start of a collaboration aimed at the technology transfer of the research results. The two VRCs experienced at CNR-INO have proven effective in capturing corporate interest and initiating collaborations for the transfer of technologies to the market, both with lower and higher TRLs. The fields of application of quantum technologies developed at CNR-INO and presented here range from biomedical imaging to next-generation sensors, to new data encoding methods for secure applications and transmissions. The experience of a spin-off in the reference sector that participates in the VRC serves as an important example of successful technology transfer in this specific market. At the same time, the VRC provides a valuable opportunity for spin-offs, offering a boost for potential new trade connections and opportunities for collaboration with entrepreneurs.

Keywords: Vasco Ronchi, Technology Transfer, intellectual property, quantum technology, sensing, quantum security.

Introduction

The Istituto Nazionale di Ottica of the Consiglio Nazionale delle Ricerche (CNR-INO) is a preeminent Optics, Photonics, and Quantum Technologies research institution. Its research covers a wide range of subjects, from atomic, molecular and condensed matter physics to quantum optics, non-linear optics and advanced optical materials. The institute is dedicated to bridging fundamental science with practical applications, aiming to transfer cutting-edge technologies to society.

CNR-INO has a longstanding tradition of solving the unmet needs of society and companies, since 1927 – the year of its foundation, when expertise in Optics and the creation of optical instrumentation was a priority for the nation's security. Collaborating with industrial partners is often a key strategy to translate scientific expertise into practical applications, drive innovation, and contribute to economic growth.

Despite the critical importance of technological transfer, it presents significant challenges. Bridging the gap between advanced research and practical applications requires the navigation of complex regulatory landscapes, securing adequate funding, and fostering strong partnerships with industry. Additionally, aligning cutting-edge innovations with market needs and consumer demands is often a difficult task, requiring continuous dialogue and collaboration between researchers and companies.

To address these challenge, over the past two years CNR-INO has been promoting and organizing the *Vasco Ronchi Colloquium* (VRC) at its headquarter in Arcetri (Florence). This event facilitates connections between researchers and industrial companies through a series of short thematic talks focused on specific areas of interest. The goal is to enable researchers to effectively communicate their findings to address societal needs, while also helping companies engage with the research community to proactively tackle foreseeable industry challenges.

The Vasco Ronchi Colloquium experience

The primary goal of the VRC is to create a platform for meaningful and productive dialogue between researchers and entrepreneurs. This interaction is designed to initiate collaborative initiatives that drive technology transfer activities, bridging the gap between innovative research and practical industrial applications. The core of the initiative lies in meticulously planning the meeting around a specific research area that has potential business applications. This focused approach ensures that the discussions are relevant and valuable for both researchers and industry participants[1].

Key aspects of the VRC:

- concentration of the event into a half-day session, minimizing the time commitment for both researchers and entrepreneurs;
- presentation of 5-6 innovative enabling technologies, including a successful case of technology transfer, such as a spin-off, licensing patent or other success stories;
- invitation of a select group of targeted companies.

The VRC provides valuable insights for researchers and entrepreneurs through the participation of a recognized expert who shares their vision and experience in technological transfer. The event also highlights funding opportunities and collaboration methods with CNR-INO, presented by the Director. These topics are further explored during face-to-face interactions at the concluding networking session with a *coffee with entrepreneurs*.

The selection of companies to invite is based on their alignment with the technologies presented and their existing relationships with the researchers or CNR-INO, fostering mutual trust and collaboration.

To engage entrepreneurs, it's crucial to present technologies in *layman's terms* while clearly outlining the competitive advantages for companies adopting them. To assist researchers in this task and provide clear, concise documentation, we have created a leaflet for the technologies showcased at each VRC edition. The leaflet summarizes the value proposition, underlying physical principles or key technologies, potential market applications, and relevant intellectual property background.

Technological leaflets created for VRC editions are accessible on a dedicated CNR-INO webpage (see Figure 1). This page also provides the option to download a double-sided PDF of the leaflets.

During the inaugural edition of the Vasco Ronchi Colloquia, a range of photonic technologies were showcased, highlighting their applications across the biomedical sector, telecommunications, and various industrial fields. The success story was based on the case study of the start-up Regensight[2].

Organized within the framework of the National Quantum Science and Technology Institute (NQSTI) project (PE000023 PNRR Next Generation EU), the

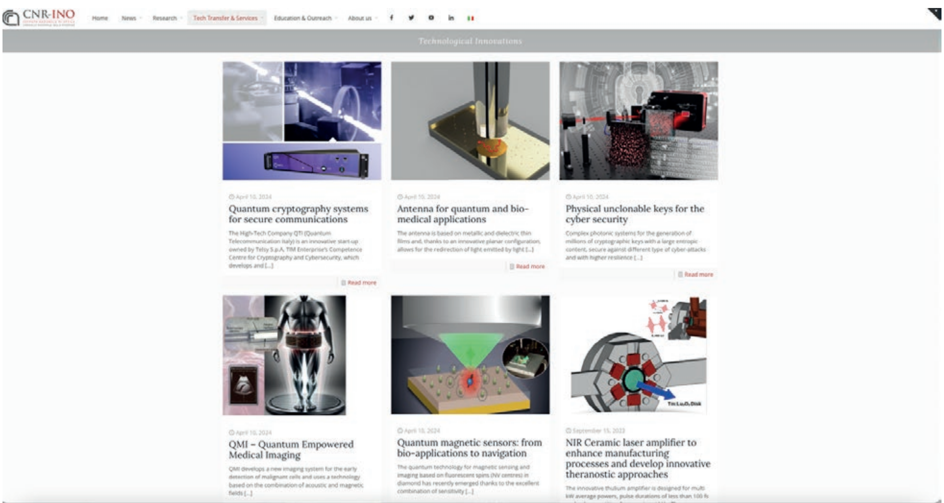

Figure 1. CNR-INO webpage dedicated to Technological Innovations portfolio accessible from Tech Transfer & Services website menu (https://www.ino.cnr.it/?page_id=21418).

second VCR showcased cutting-edge advancements in quantum technology and smart photonic materials, highlighting their applications in security and biomedical fields. A successful user case, in quantum technologies, was presented by Dr. Alessandro Zavatta, co-founder of Quantum Telecommunications Italy (QTI). QTI aims to revolutionize communication security using Quantum Key Distribution (QKD)[3](see Figure 2), as stated by Dr. Zavatta:

> Our idea was to use individual photons to make communications intrinsically secure, meaning they are unbreakable by any hacker, even the powerful computers of the future, such as quantum computers. Today, we can generate, manipulate, and detect single light quanta with unprecedented reliability to achieve communications systems guaranteeing the so-called unconditional security.

QTI[4] was founded in October 2020 as a spin-off of CNR-INO. The initial challenges were numerous, including pragmatic issues typical of spin-offs originating in public research sectors, such as interactions between different entities (CNR-INO, Technical University of Denmark and University of Florence), Intellectual Property management and, most importantly, finding the funds to develop the first industrial device. The question of whether to merge with an already established company arose, as simple seed funds were insufficient. Millions of euros were needed to start bridging the technological gap with competitors and to penetrate a young but already highly competitive market.

Leveraging its scientific and entrepreneurial expertise, in Trieste, in August 2020, QTI participated in the Euro Science Open Forum (ESOF), the most sig-

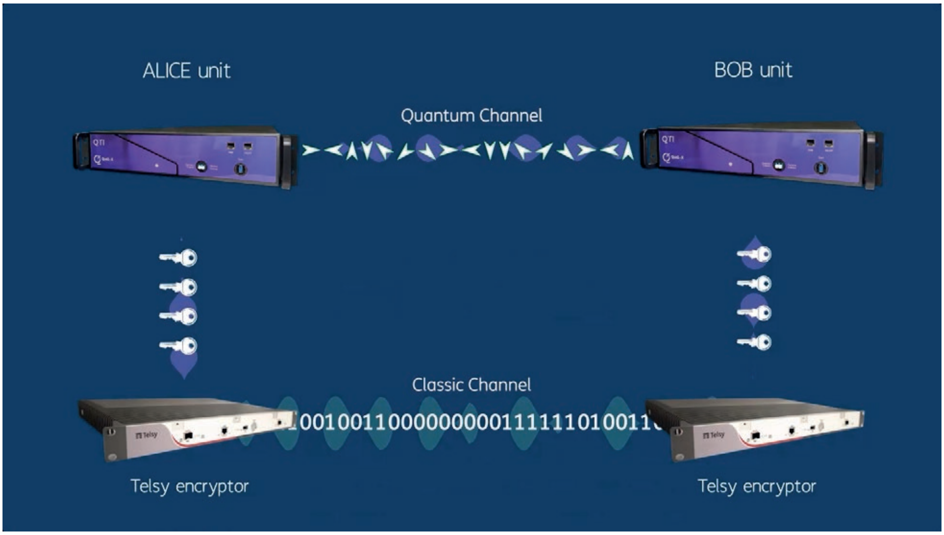

Figure 2. Quantum Key Distribution (QKD): devices that generate, encrypt and decrypt quantum cryptographic keys. Difference between classical and quantum channel systems.

nificant European event dedicated to dialogue among science, technology, society, and politics. During this event, QTI presented its first *proof-of-concept*, which was used for the first demonstration in Italy of quantum encryption communication.

This demonstration facilitated a secure video call between the Rector of the University of Trieste and the then Italian Prime Minister Giuseppe Conte, connecting the port of Trieste with the Rectorate of the University of Trieste. The event received significant media coverage, sparking interest in QTI's activities and leading to involvement in new research initiatives both in Italy and abroad. Following this success, QTI was invited to organize another public demonstration of quantum communication during the G20 ministerial meeting on digitalization in Trieste in 2021[5]. This event marked the first encrypted quantum communication link between three European countries, with a real-time video call transmitting a live concert between Trieste, Rijeka and Ljubljana, and demonstrated that QKD technology ensured unconditionally secure live communications and accurate reporting, marking a real-world use of quantum technology.

Today, QTI operates within the TIM Group and markets turn-key QKD systems that are compatible with existing telecom infrastructure. QTI is also a QKD provider of the EuroQCI network, the European Union's initiative aimed at building a secure quantum communication infrastructure that will span the whole EU territory.

Alongside the successful use case, other CNR-INO researchers also presented their work within the quantum and smart materials field, using simple and direct language to showcase the technological potential of their studies to the business audience. The next section discusses the main concept of their activities and potential applications.

Quantum and Smart material applications illustrated during 2nd VRC edition

1st Technology - Antenna for quantum and bio-medical applications

By Mario Agio, Costanza Toninelli

A planar antenna configuration aims to achieve the efficient collection and detection of the extremely faint signals emitted by microscopic light sources, such as single fluorescent molecules, thanks to the efficient redirection of their radiation pattern.

The operating principle of this technology is very similar to that of a Yagi–Uda antenna, where dipole elements are arranged to obtain the desired radiation characteristics, that may not be achievable by a single element. The antenna configuration can be optimized so that the contribution of the elements adds up to give maximum radiation in a particular direction or directions, minimum radiation in others, or otherwise as desired. In this way, the radiation pattern of interest can be designed according to the needs for the specific applications.

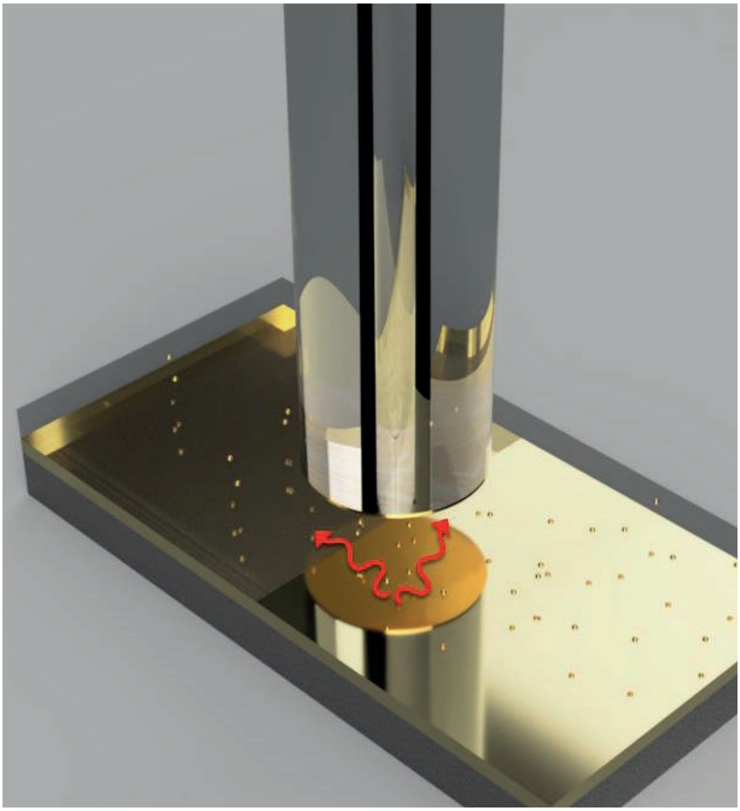

Figure 3. A schematic realization of the planar antenna made up of dipole elements arranged in order to obtain a specific radiation patterns.

The planar antenna configuration presented here is inspired by this concept and adapts it to the case of microscopic light sources, such as single-photon emitters, for which having an efficient interface for photon extraction is key to process the weak signals for the desired applications. In this scenario, the researchers replaced the array of resonant elements of the Yagi-Uda antenna with a multilayer of thin metallic and dielectric films. The dielectric films are placed in the middle of the multilayer structure to embed the microscopic light sources while preserving their photo-physical characteristics. The metallic outer layers act as reflector and director of the light emitted, and, thanks to an interference effect, allow the redirection of the radiation pattern, making it possible to efficiently collect/detect even very weak light signals down to 100 fW and below by simply approaching the fibre with an optical fibre. This innovative planar configuration overcomes the technological challenges of more complex nanostructures involving 3D elements, which require high-resolution micromachining techniques to pattern and etch thin films or depositing materials. Indeed, the planar antenna presented can be implemented via standard thin-film deposition methods, like spin-coating and sputter-coating. Thanks to the simplicity and efficiency of the configuration, this technological offer can be incorporated into optical systems, directly coupling the redirected emission to an optical fibre without the need for any additional optical element, thereby minimizing costs and complexity compared to standard instruments, which typically involve expensive lenses and optical objectives. These advantages make the technology extremely convenient in terms of cost, simplicity of production and use, beyond spectral flexibility, as it can be employed for a wide range of optical wavelengths.

The technology can be used as key element for quantum photonic technologies, for fast and efficient single-photon collection from sources (fluorescent molecules, quantum dots, colour centres in diamond, defects in 2D materials). The possibility of efficiently coupling single photons to single-mode optical fibres is key for fibre-based optical networks and systems, typically used in applications ranging from quantum computation and simulations to quantum communications.

Moreover, the technique proposed can be a fundamental element for improving light collection in fluorescence-based in-vitro diagnosis, bio-sensing applications and bio-imaging techniques based on the redirection of emission of biological markers. It has been investigated in this sense within a European ERANET project, under the Photonic Sensing call, for the development of a fluorescence diagnostic prototype for biomedical applications. The device consists of a planar antenna, an optical fiber, a 3D motorized stage for mechanical control of the fiber position, a commercial fluorescence detection system, and a computer for remote control. The prototype enables the automatic reading of biomedical assays for in-vitro diagnosis of diseases through the study of fluorescence biomarkers. In particular, it has been validated in the laboratory for reading IgG and IgG* tests (capture antibody and detection antibody), for a CRP assay, an analyte connected to SEPSIS, and promising results have also been obtained for reading in serum.

Planar antenna technology is currently protected by two patents, with protection specifically concerning the design aspects for directing and collecting light signals. The current level of technological maturity is TRL 4, as the technology has been tested and validated in the laboratory.

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2nd Technology - QMI Quantum Empowered Medical Imaging

By Augusto Smerzi

QMI develops an innovative imaging system for the early detection of malignant cells based on a technology which makes use of the combination of acoustic and magnetic fields to measure the electrical conductivity of human organs.

Current nuclear and radiological medical imaging technique have high costs and specialized infrastructure requirements. They also rely on potentially harmful methods such as ionizing radiation (CT scans), radioactive tracers (PET, SPECT), or high magnetic fields (MRI). Additionally, these standard imaging techniques typically do not provide specific tissue characterization; instead, they measure factors like water content (MRI), bone density (CT), or the decay of radioactive materials (PET, SPECT), from which relevant tissue information is inferred.

QMI proposes to actively & non-invasively probe and spatially map the organ tissues which present anomalies, by using weak magnetic fields and a new generation of state-of-the-art quantum sensors. This will not only allow an altogether novel structural medical imaging platform, but also the interrogation of the healthiness of tissues at sub-cellular level.

The novel medical imaging proposed is a novel atomic interferometry based on quantum enhanced sensors, which is extremely sensitive to environmental fields. The idea of QMI is exploiting this sensitivity to distinguish between healthy human body tissues and those affected by cancer cells, which exhibit anomalous values of electrical conductivity. The core of the technology lies in the development and optimization of compact and ready-to-use new-generation atomic magnetic sensors, to allow non-invasive probing which can be applied externally to the human body part under diagnostic investigation, without the need to restrict the technique to in-vitro samples. The technique could therefore enable the in-vivo mapping of local electrical conductivity values, allowing the detection of alterations and monitoring the progression and healing of the patient’s condition over time. In general, the technology can be promising for the early detection of various types of cancer. In practice, the technique relies on the creation of ultrasound waves at a specific point within the body, with a resolution of 1 mm. In the presence of an applied static magnetic field, positive and negative ions within the human body tissues are separated, creating a secondary electric or magnetic field that can be detected outside the body. The detectable output values depend

Figure 4. A scheme of innovative and non-invasive acoustic and magnetic probes enabling the early detection of various types of cancer.

on the permeability and local conductivity of the tissue investigated. To implement a map of the cancerous tissues, both high sensitivity and spatial precision are needed. An array of magnetometers must be placed accurately around the body, while standard coils are too large to achieve the required spatial probing precision. A major clinical advantage is that this technology does not require the use of radioactive dyes or ionizing radiation. A second key point addressed by the technology proposed concerns a theoretical aspect, specifically the challenge of image reconstruction. This involves managing large datasets, differentiating signals from background noise, and minimizing error rates that lead to false positive or false negative diagnoses. To tackle these challenges, QMI has developed an artificial intelligence algorithm based on machine learning techniques. This algorithm facilitates high-resolution reconstruction of images of biological tissues from experimental measurements of various parameters and properties associated with the biological sample. Notably, the algorithm enhances the efficient mapping of the presence of cancer cells and their development by analyzing tissue response to electromagnetic fields.

The technology is currently in the early development stage, with a patent application in progress. A dedicated core team of researchers has already been assembled, bringing together expertise in both experimental and theoretical domains. The team is actively seeking seed investment to facilitate the spin-off process.

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3rd Technology – Physical unclonable keys for cyber security

By Francesco Riboli, Sara Nocentini

Complex photonic materials which exploit the interaction with light for the generation of non-cloneable physical keys for the generation of high-security passwords and for the information security in general.

Besides a secure communication and data sharing protocol, this digital age calls for secure and reliable authentication methods to protect private information and to safeguard access to personal devices and services. To date, the most effective method for ensuring an authentication source involves the permanent storage of digital keys in electronic devices, for example in smartphones, car keys, bank cards or computers, and then relies on hardware cryptographic operations such as digital signatures or classical encryption algorithms. Besides the cost in terms of both design and power consumption, this approach is often susceptible to invasive attacks. Protecting against such attacks requires active tamper detection and prevention circuitry, which must be powered constantly, creating an inconvenient limitation, especially for portable electronic device.

Researchers at CNR-INO propose a new technology which offers physical generators of cryptographic keys secure against different types of cyber-attack and with higher resilience against machine learning attacks. Unlike non-volatile memories in which traditional keys are recorded, the technology is based on Physical Unclonable Functions (PUF) which can encode many cryptographic keys in the structural complexity which specific materials can exhibit at microscopic level. This technology belongs to the context of non-digital key generation

Figure 5. Experimental optical setup for generating and collecting millions of cryptographic keys generated by complex photonic materials.

processes, also called primitives, which can derive a secret key by relying on the unique complexity of a physical system, thereby eliminating the need for continuously powered tamper-detection mechanisms. The key generation process in this case is based on PUFs, which rely on randomly structured physical systems that exhibit a complex input–output behavior unique to each PUF. Their uncontrollable individual disorder on small length scales makes them practically unclonable, even for their original manufacturer, and prevents any remote purely digital data connection.

In this context, disordered photonic structures are the perfect choice for creating optical PUFs to be used for authentication or anticounterfeiting. These photonic systems are characterized by many degrees of freedom which, under illumination with coherent light, produce a complex intensity pattern in transmission and/or reflection. This pattern, known as speckle, is the result of the interference of numerous independent transmission channels and is extremely sensitive to microscopic changes in the physical structure of the materials, thereby serving as a unique fingerprint PUF of the scattering volume.

The novel technology proposed here uses smart disordered photonic materials made of dye-doped Polymer-Dispersed and Polymer-Stabilized Liquid Crystals (PD&PS-LCs). These materials can be reversibly reconfigured to achieve a spatial-temporal control of the scattering potential that can be made hysteresis-free by customizing their chemical composition. Furthermore, the optical PUFs made of PD&PS-LCs possess an extremely large internal degree of freedoms that translate into a net entropy increase of the key generated. This new technology enables the integration of multiple cryptographic functions in a single device, facilitating the creation of a multilevel optical PUF, referred to as Hyper-PUF (HPUF). Each level of the HPUF is defined by a distinct configuration of the scattering potential, significantly enhancing its cryptographic versatility and security. These results allow the generation of more complex photonic cryptographic keys and are promising for a variety of applications, ranging from anticounterfeiting labels for goods with multi-factor identification to authentication and secure transmission of classical and quantum data.

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4th Technology – Quantum magnetic sensors: from bio-applications to navigation

By Nicole Fabbri

A quantum magneto-microscope, utilizing fluorescent defects in diamond, is designed to map magnetic signals with exceptional sensitivity and spatial resolution.

Magnetometry is a sensing technology with wide applications ranging from material science, chemistry and biomedicine, through to earth monitoring, navigation and even space exploration. In all these applications, significant limitations of current devices in spatial resolution and sensitivity often limit the information that one is able to acquire.

Quantum magnetometers based on fluorescent defects in diamond have the potential to lead an enhancement capable of beating the limits of conventional techniques for sensing and imaging, thanks to their excellent combination of sensitivity and space resolution, operability over large temperature ranges, biocompatibility, and possibility of miniaturization.

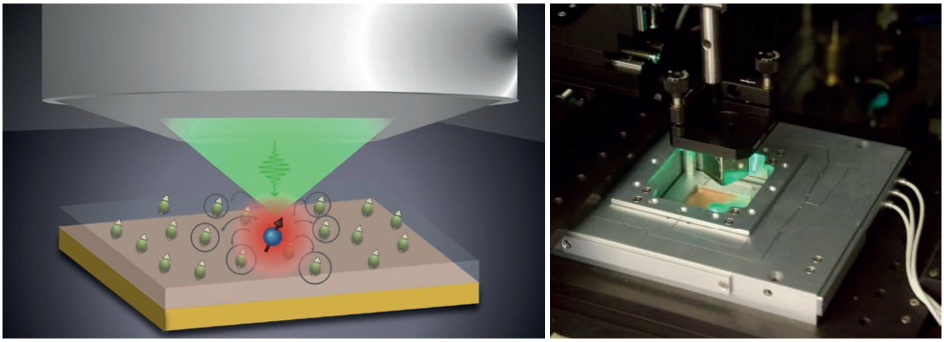

Figure 6. Left: A schematics of Quantum magnetic sensors based on optically readable spins (NV centres) in diamond. Right: a quantum magneto microscope optimized for bio-applications developed by the Research Team.

We have developed optimized diamond-based sensors, enhanced by quantum control techniques and deep learning algorithms for imaging heart disease.

Heart disease based on protein, metabolic and electrical disturbances represent one of the major causes of sudden death in young people worldwide. Understanding and controlling cardiac processes and dynamics is imperative to develop adequate tools for early diagnosis and personalized treatments of pathologies. Despite the huge progress achieved in the last decades, driven by laser-based classical microscopy and spectroscopy, current techniques still have significant limitations in spatial resolution and sensitivity, often leading to late diagnosis.

We have developed a bio-optimized quantum magneto microscope based on dense ensembles of Nitrogen Vacancy Centers in diamond. This magneto-microscope offers biology a distinctive host of powerful features – non-invasiveness, sensitivity, spatial and temporal resolutions, likely to conquer new frontiers in imaging, beyond the reach of their classical counterparts. Targeted sensitivity of nanoTesla on the microscales paves the way for the investigation of the magnetic signature of heart tissue activity. The diamond-to-tissue interface (involving thin layered materials) and the geometry of the excitation laser light are designed to avoid optical and thermal disturbances to the biosample. Exploiting the expertise of the group in quantum control and deep learning algorithms, we designed pulsed dynamical decoupling sensing protocols to enhance sensitivity.

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Conclusion

The second edition of the VRC serves as a compelling demonstration of the essential role that technological transfer plays in transforming groundbreaking laboratory research into practical applications that can profoundly benefit society. The event highlighted the significance of converting scientific discoveries into marketable technologies, emphasizing the impact such innovations can have on improving quality of life and driving economic growth.

Technological transfer bridges the gap between research and real-world applications, ensuring that advancements made in the lab do not remain confined to academic journals but are developed into solutions that address pressing societal challenges. This process is crucial for fostering innovation, creating new industries, and enhancing the competitiveness of existing ones.

The colloquium showcased a range of innovative technologies across various fields, including healthcare, cybersecurity, and quantum sensing. These technologies exemplify the potential of scientific research to bring about tangible benefits, from improving diagnostic tools and medical treatments to enhancing data security and developing advanced sensing capabilities.

By facilitating collaboration between researchers, industry partners, and policymakers, technological transfer initiatives like those highlighted at the VRC play a vital role in overcoming the challenges associated with bringing new technologies to market. Such collaborations ensure that innovations reach those who need them most, ultimately contributing to societal progress and economic development.

Looking to the future, continued investment in technological transfer will be essential for maintaining the momentum of innovation and addressing global challenges. The success of events like the VRC highlights the importance of these efforts and the transformative potential of converting research into real-world applications.

Acknowledgements

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