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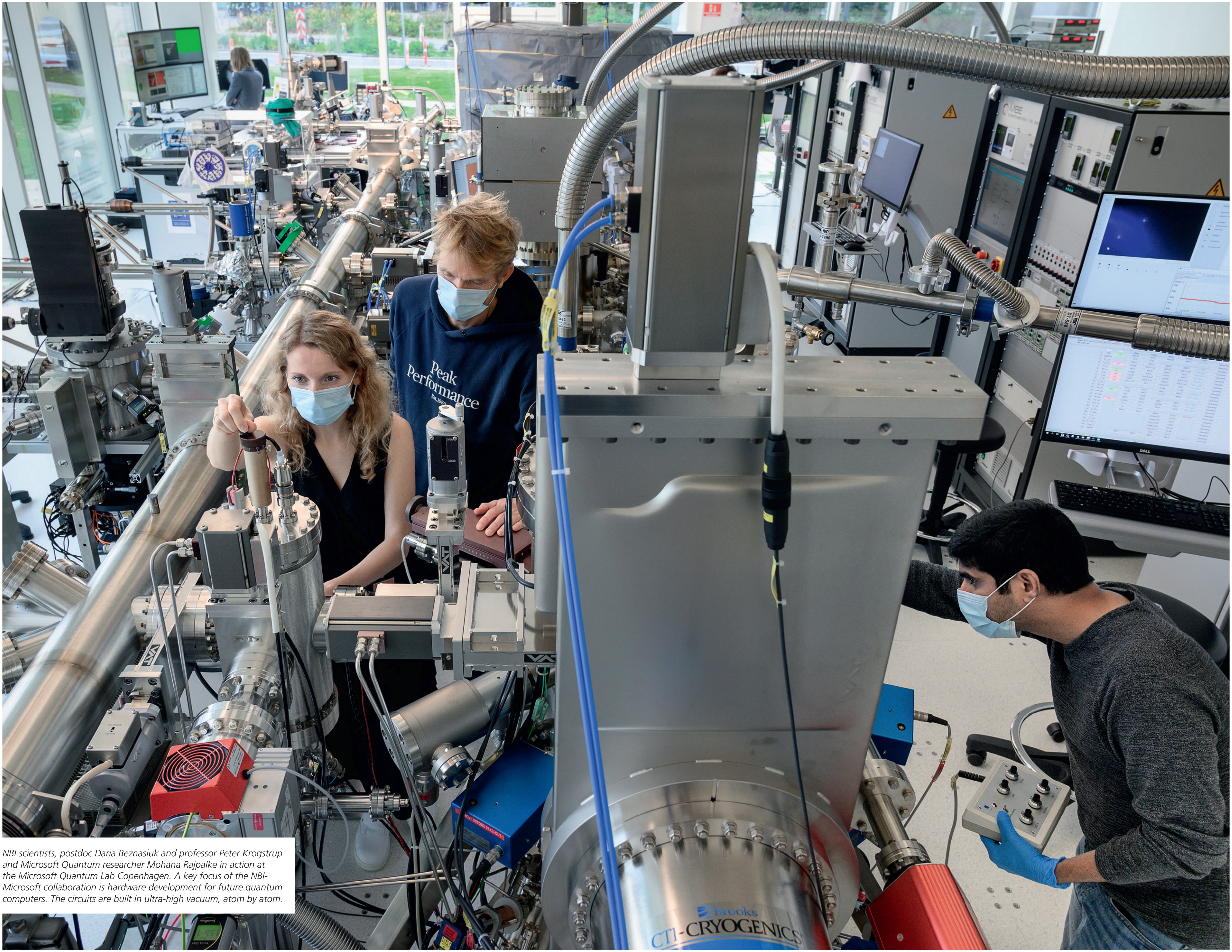
QUANTUM
from Science to Solutions

100 years after – the heritage of Niels Bohr



NBI scientists, postdoc Daria Beznasiuk and professor Peter Krogstrup and Microsoft Quantum researcher Mohana Rajpalke in action at the Microsoft Quantum Lab Copenhagen. A key focus of the NBI-Microsoft collaboration is hardware development for future quantum computers. The circuits are built in ultra-high vacuum, atom by atom.

INTRODUCING QUANTUM 2.0

Niels Bohr opened the door to our understanding of nature at the atomic level. Today, the institute named after him is at the forefront of a technological revolution based on the foundation laid by Bohr and his colleagues a little more than a century ago.

Based on quantum technology, we will see a truly digitized, "smart" society enabling sustainable use of energy and natural resources. Similarly, the health care sector and development of new, personalized medicine will be revolutionized.

Following the initial breakthroughs in quantum theory, a first wave of applications soon emerged. Nuclear medicine, radiology for the health care sector, the transistor and the laser laying the foundation for the information society. Now a second wave of applications are underway. Notably, this time the impact could be even greater.

Quantum simulators and computers will outperform today's computers to a mind-blowing degree. Eventually a present-day high-performance computer will seem like an abacus in comparison.

A quantum internet will interconnect quantum computers. Not only will the quantity of information exchange surpass the current standards greatly, we will also see entirely new possibilities.

In this pamphlet we have tried to give a few examples to illustrate the fantastic possibilities offered by emerging quantum technologies. However, we need to grasp this chance now. Standing still in the quantum race equals moving backwards!

Internationally recognized as a leading research institution in quantum physics, the Niels Bohr Institute is well positioned to spearhead the development of second generation of quantum technologies in collaboration with partner institutions world-wide and innovative industrial corporations and startups.

Jan W. Thomsen
Professor, head of the Niels Bohr Institute.

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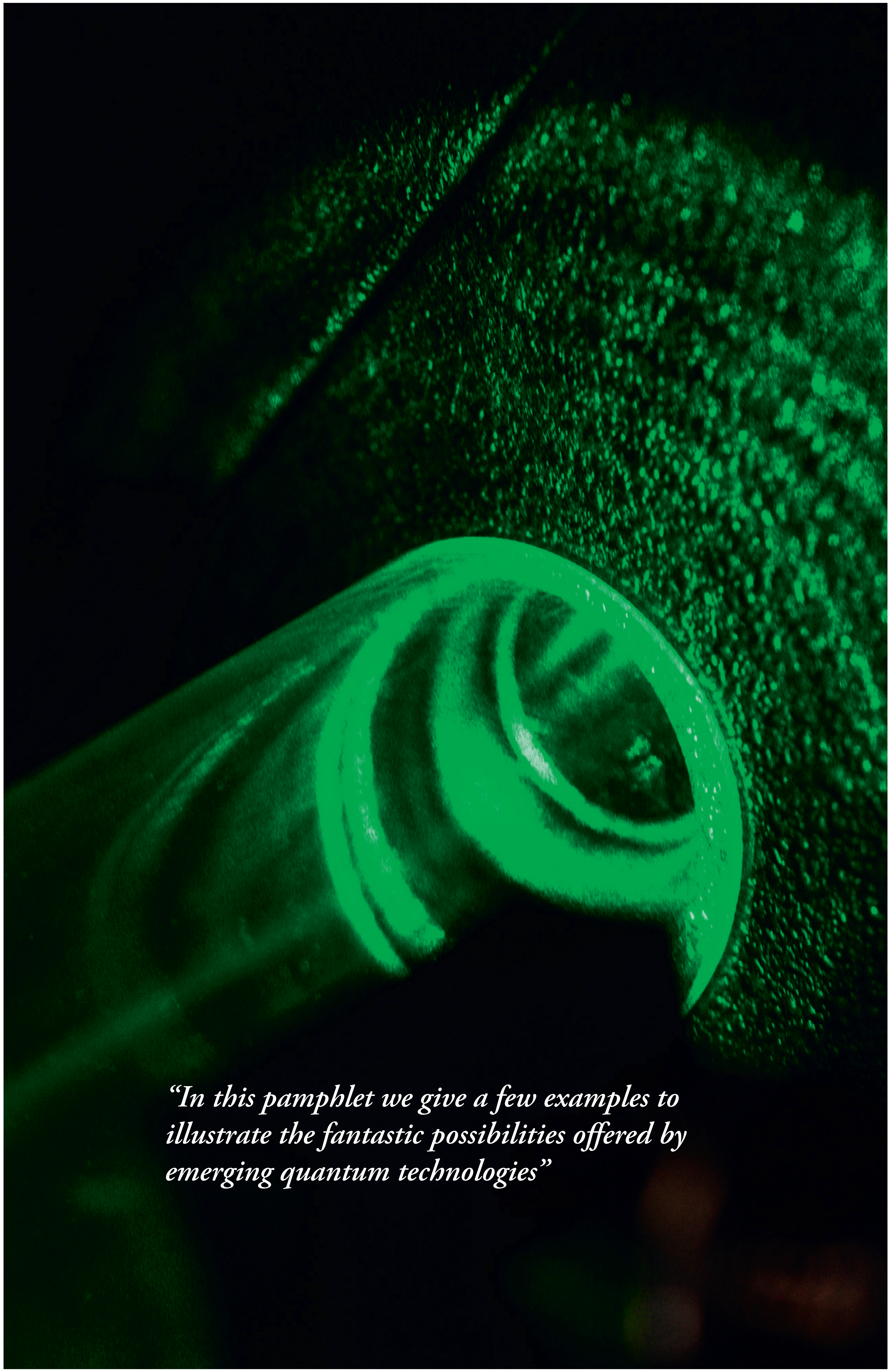
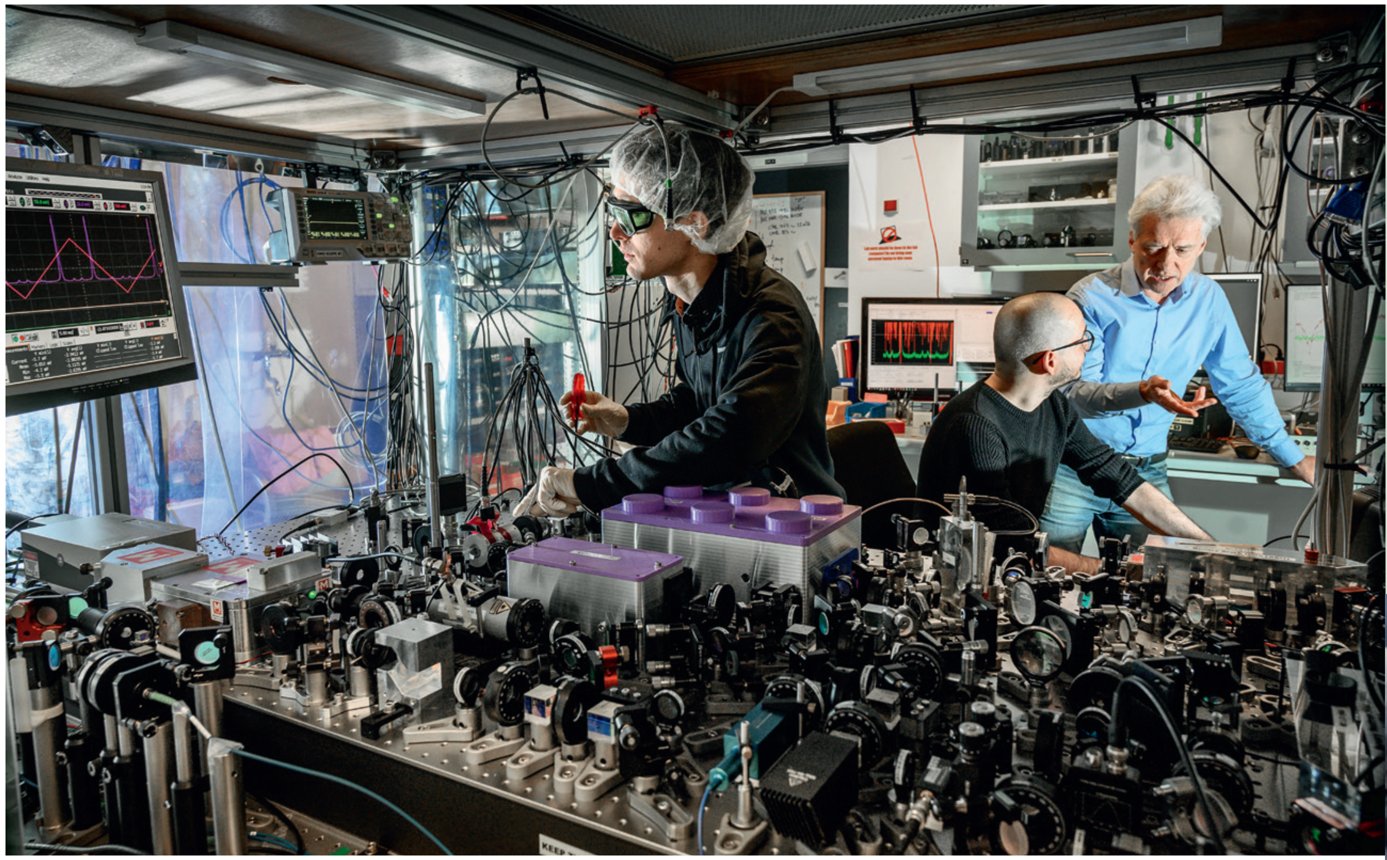
Front page: NBI postdoc Hanna le Jeannic aligning complex optics for quantum experiments.





Experimental setup for quantum sensing by the group of professor Eugene Polzik (right). Here with PhD student Valerii Novikov (left) and postdoc Tulio Brito Brasil (center).

WHAT IS QUANTUM?

Quantum mechanics describe the behavior of very tiny particles, e.g. atoms, electrons, and photons. In this tiny world, the classical laws of nature are not sufficient to describe what is happening. We need to use the laws of quantum mechanics instead. Sometimes this can lead to quite counterintuitive phenomena. For instance, the theory of quantum mechanics describes that a particle can be in so-called superposition – meaning it can be present at more than one position at a given time. Similarly, an atom can be in two different energy states at the same time.

Another cornerstone of quantum mechanics is the fact that elementary particles are not only described in terms of a mass and a charge, they also have a spin – the latter being unexplainable according to classical physics. And finally, a key phenomenon in quantum mechanics is entanglement. Here, two or more quantum particles interact in such a way that the quantum state of a single particle cannot be described independently of the state of the other(s) – even when the particles are distant from each other.

Based on the above phenomena, quantum sensors and clocks with extreme precision have already been developed, and more are underway. A simple version of quantum communications based on so-called quantum key distribution is also commercially available today, offering greatly improved security for communications links.

Spin, superposition and entanglement also form the basis for quantum computing. While no winning quantum computing technology has yet emerged, it remains clear that once quantum computers become available, they will initiate an exponential growth in the capability of computing. Further, these novel computers will become interconnected by means of a quantum internet with much improved cyber security. In the quantum internet, it will not be possible to tamper with information unnoticed.

Photons will disrupt development of medicine

Since biological systems are highly complex, it is currently considered impossible to calculate how proteins and other key target molecules will respond to new pharmaceuticals. Therefore, drug development depends heavily on large-scale testing of libraries of often 10,000-100,000 similar molecules.

Researchers at NBI have invented a new technology, which may disrupt the way pharmaceuticals are developed. Known as single-photon quantum technology, the invention can pave the way for quantum simulators that are up for the job.

Photons are the fundamental constituent of light, and Niels Bohr explained how a photon is born when an electron undergoes a quantum jump between two states in an atom. Massive information can be encoded in single photons, and advanced photonic circuit technology allows to reliably process it. This is a unique advantage of photonics compared to competing quantum computing approaches where the technology to scale up is still a major challenge.

Just about 50 photons are necessary to reach the threshold of Quantum Advantage, i.e. this modest number of photons may process more information than the World's largest existing classical computer can handle. The NBI researchers have demonstrated and patented a scalable single-photon source with the potential to demonstrate Quantum Advantage.

Notably, more efficient and environmentally benign development of pharmaceuticals is just one of several target applications for this unique invention.

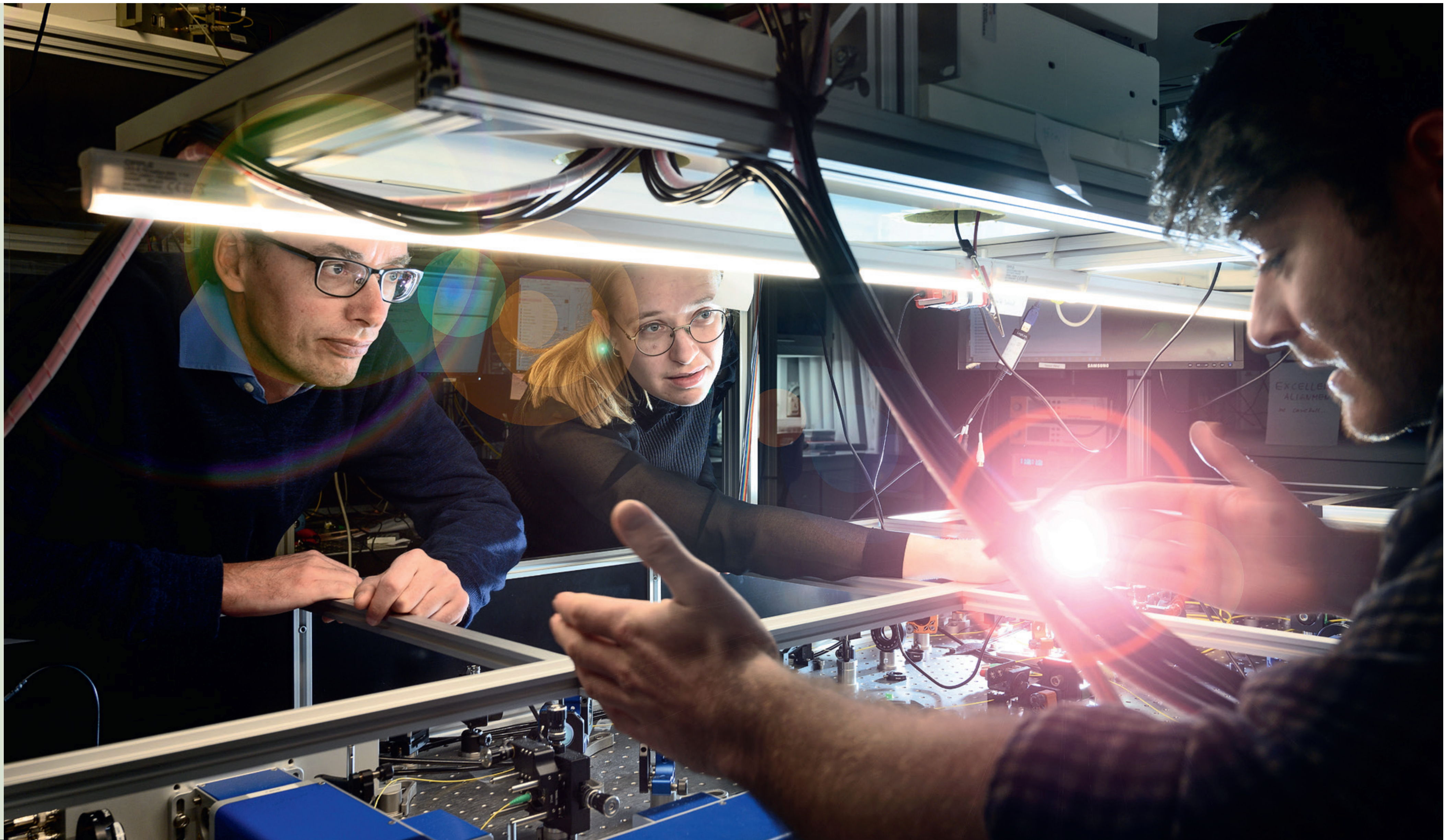
> *"50 photons may process more information than the World's largest existing classical computer can handle"*

Imaging down to the molecular level

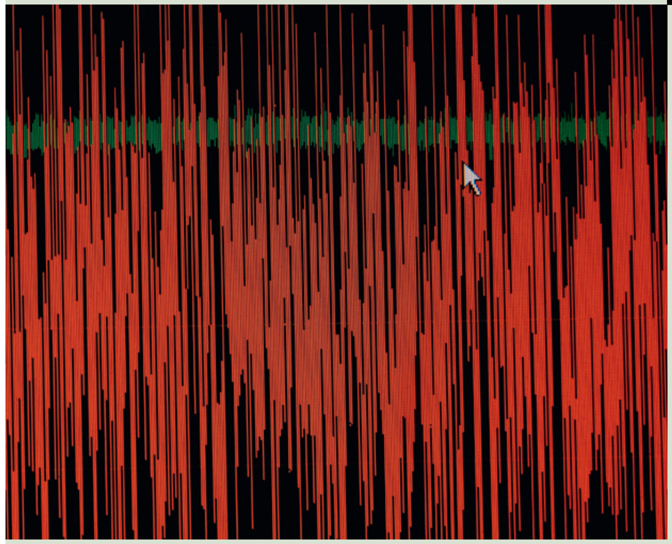
Magnetic Resonance Imaging (MRI) and similar methods for seeing conditions inside the human body have been standard in health care for decades. However, second generation quantum technology may take imaging to an entirely different level of detailing.

Researchers at NBI take part in creating the foundation for this upcoming revolution. Unnoticed by the average consumer, several of our everyday devices such as smartphones and computer-assisted safety systems in cars already have microscopic mechanical sensors built in. The NBI researchers develop quantum-engineered mechanical sensors able to detect magnetic forces at the quantum limit.

The function of a quantum-sensor is similar to that of a microscope, only will the sensitivity be many orders of magnitude larger. In principle, a quantum microscope can photograph individual molecular complexes even in 3D.



Professor Peter Lodahl (left) with colleagues PhD student Freja Thilde Pedersen and MSc student Mikkel Thorbjørn Mikkelsen at the NBI single photon facility.



Sensing the beating of an unborn heart

For obvious reasons, medical examination of a human fetus is a delicate matter. Even in cases where heart anomaly or another serious condition is feared, avoiding the use of any intrusive disturbance is highly desirable. Here, quantum technology comes to the rescue.

All life processes involve tiny variations in magnetic fields and tissue conductivity. Researchers at NBI develop quantum sensors able to detect these extremely small variations. Besides heart anomaly, several other possible fetal abnormalities may be surveyed. All, while the fetus rests undisturbed inside the womb.

Similar types of quantum sensors may be used for entirely different purposes. One example is detection of gravitational waves, one of the key sources of information about the Universe.

> *"Several possible fetal abnormalities may be surveyed. All, while the fetus rests undisturbed inside the womb"*

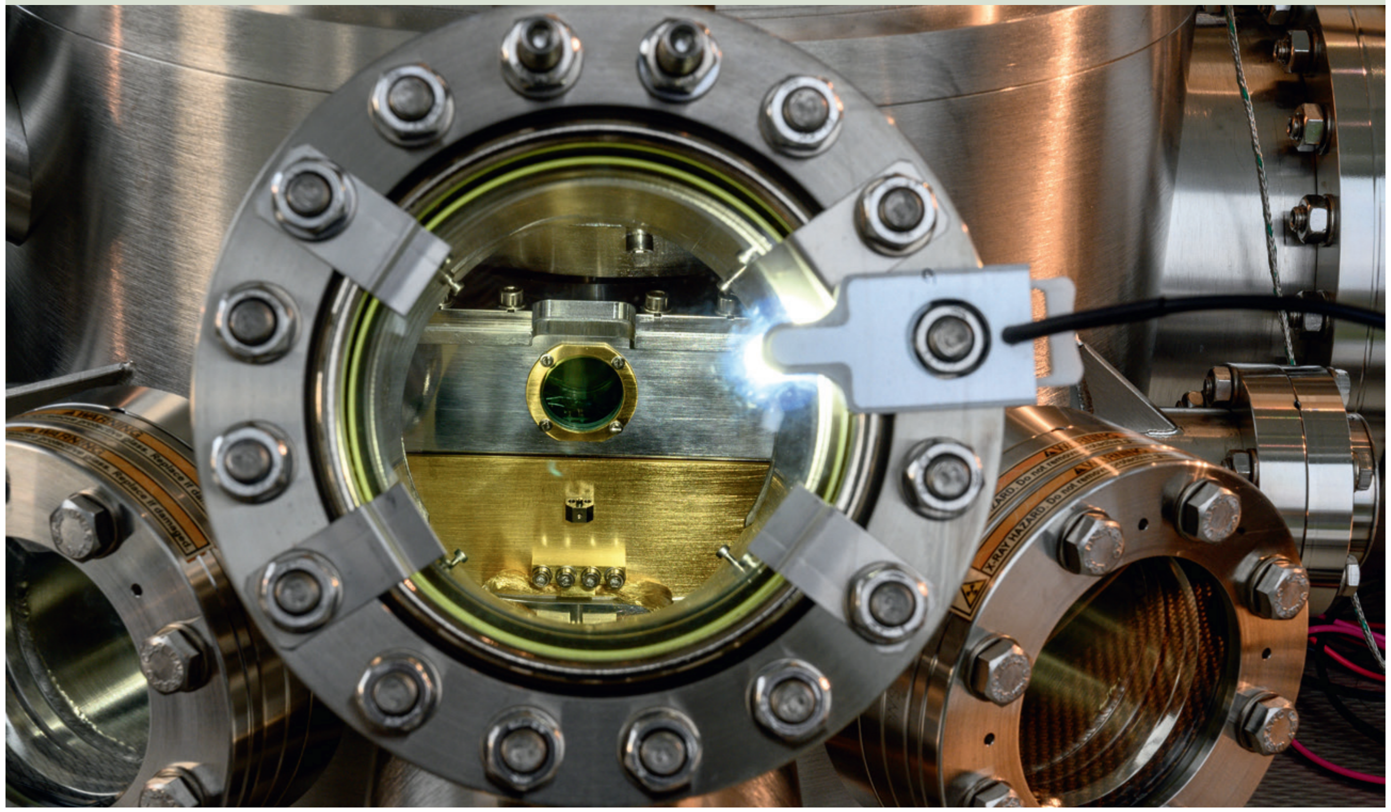
Mind-blowingly powerful quantum computers

For several decades, the power of computers has shown exponential growth, i.e. a doubling every 2 years. In the computing industry, this phenomenon is known as "Moore's Law". However, with existing technology this law is running out of steam. Current computing is based on transistors, which are the physical devices suppling the basic units of information – the bits. Over time, the transistors have become ever tinier. By now, they have gotten so small, and are packed so tightly, that quantum physics play in, causing chaotic behavior and thus prohibiting further shrinking. Ironically, it is exactly quantum technology that may provide a solution. By managing the quantum physics involved, industry will not only be able to keep Moore's Law going, but could even accelerate things further.

In traditional computers, the bit can have two values only, one or zero. The corresponding quantum unit of information – known as the qubit – will be able to assume more than two values. The exact number will depend on how many quantum properties you manage to control.

Researchers at NBI are active on many fronts when it comes to managing quantum properties with possible quantum computing applications. One example is controlled quantum entanglement - a powerful resource for computation, communication and sensing. The targeted applications, which emerge naturally as they always have at the frontier of knowledge, are currently limited by the development of quantum hardware. In fact, the major challenge is the fragile nature of quantum objects leading to the loss of information through interactions with the environment.

The NBI group has over the recent year taken the lead in developing quantum materials through intense programs at the frontiers of physics, nano science, materials science, and engineering. However, moving capabilities of a quantum technology, such as quantum computing forward to serve simulations of e.g. complex molecular systems, chemical reactions, etc. the hardware needs to support fault free operations of 1,000's of logic qubits which will require advanced hardware engineering including the processing of quantum materials with precision down to the single atom.



A view into a quantum fabrication-characterization system that characterize the material properties while being built atomic layer by layer.

ENTERING THE QUANTUM SOCIETY

An individual quantum computer will be impressive. Still, the real revolution comes when these new computers become connected, forming a quantum internet. This will greatly increase the capacity and quality of information exchange, leading to a truly digitized society.

In the near future, claiming to be able to make better judgements in traffic than the built-in safety system of your vehicle will just seem ridiculous. Not only will this type of Artificial Intelligence improve safety, it will also allow much more energy efficient transport – especially when control systems of the individual vehicles are able to exchange information and find the optimal route and speed in any given scenario.

The same logic will apply to all other aspects of society's consumption of energy and natural resources. For instance, it is highly challenging for energy suppliers today to integrate fluctuating renewable energy sources like solar power and wind energy into the energy system in an optimal manner. Interconnected quantum computers will be able to handle the necessary optimizations easily.

In other words: quantum tech will be just the missing piece we needed to make a green society become a reality.

Also, we will see entirely new possibilities. A clear example is in cyber security. While we have become used to the constant arms race between hackers and defenders, quantum technology will introduce a novel dynamic: it will not be possible to tamper with information transmitted over the quantum internet unnoticed.

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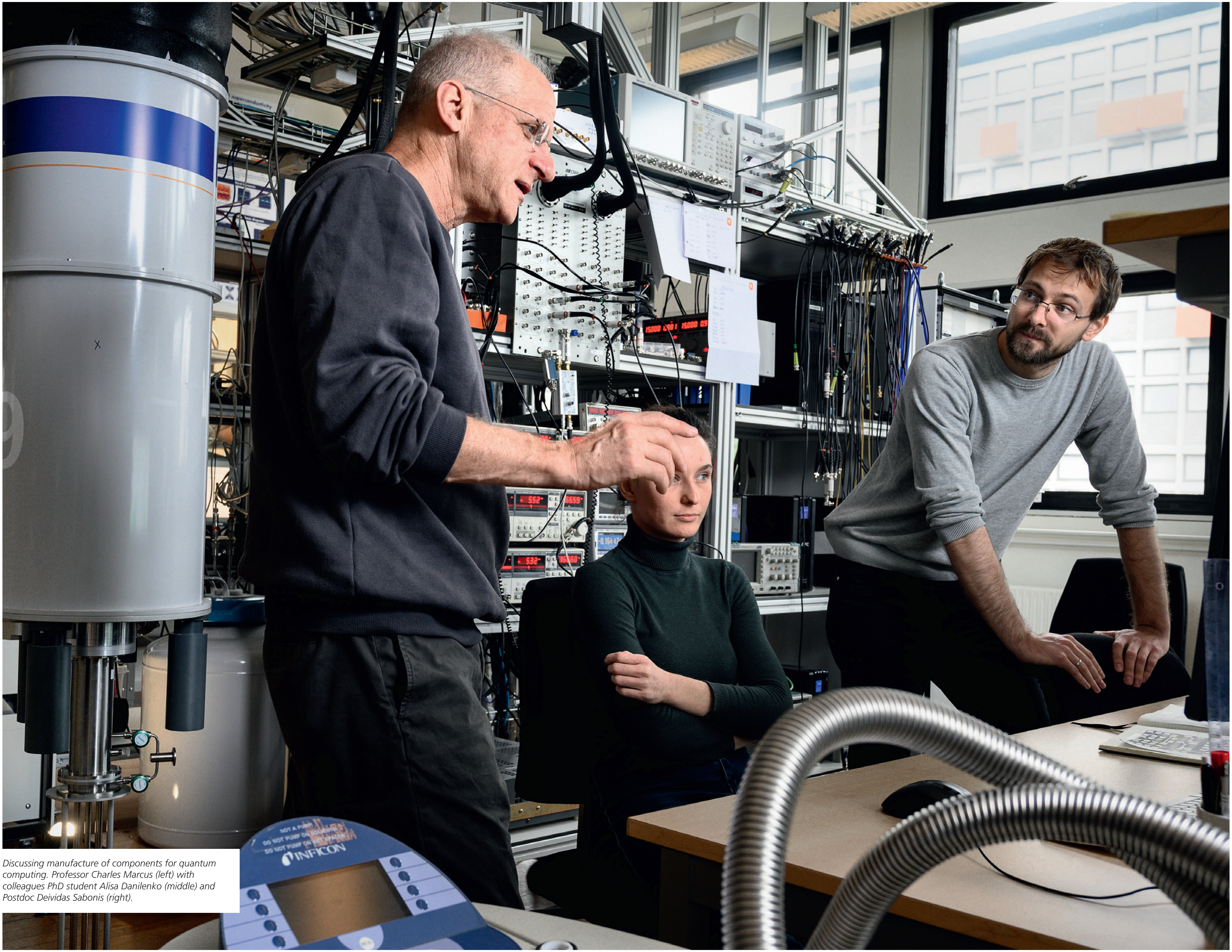


Discussing manufacture of components for quantum computing. Professor Charles Marcus (left) with colleagues PhD student Alisa Danilenko (middle) and Postdoc Deividas Sabonis (right).

Reflection. Albert Schliesser, quantum optics professor at NBI.

A GOLDEN OPPORTUNITY FOR DENMARK

Denmark is the top country in the world on number of candidates trained in quantum technology relative to population size. Also, Denmark is among the world's top countries when it comes to higher education in general, and blessed with a rich high-tech startup scene and a strong digital infrastructure.

Further, Danish industry has matching strengths. For instance, Denmark holds a very strong position on photonics technology, including industrial engagement and advanced infrastructure, which will be essential embedding of a large-scale photonic quantum initiative.

Several Danish industry sectors will potentially benefit significantly from using quantum technologies. Examples are transport and logistics (Mærsk, DSV Panalpina), pharma (Novo Nordisk, Lundbeck, LEO Pharma), wind energy (Vestas, Siemens-Gamesa), and medtech (GN Resound, Oticon, Radiometer, Widex).

Adding to the optimism is the fact that Danish researchers and innovative industrial partners are able to compete for funding provided by a major European Union scheme on quantum technology. Launched in 2018, the EU "Quantum Flagship" program has allocated 1 billion euro to "consolidate and expand European scientific leadership and excellence in quantum research" while also kick-starting a European industry in the field.

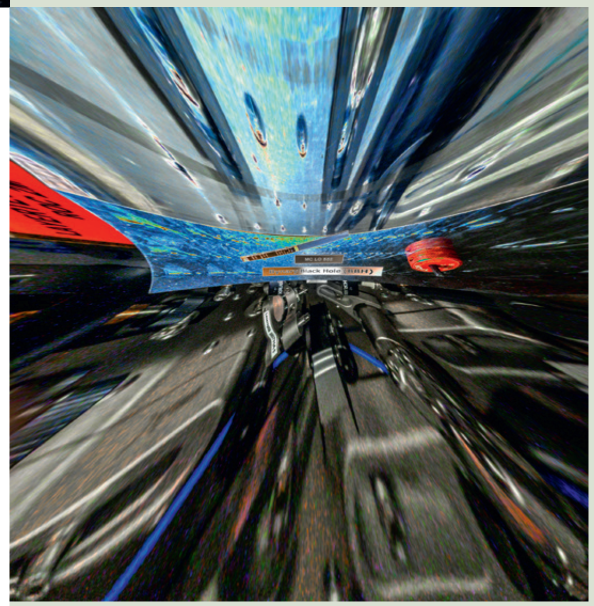
When adding these factors, it becomes clear that Denmark has a unique opportunity for embarking on a new high-tech adventure. Combining academic and industrial strongholds we will lay the foundation for a growth in quantum technology comparable to that of the Danish wind turbine sector.

"We will lay the foundation for a growth in quantum technology comparable to that of the Danish wind turbine sector"

New education:

THE NEXT BREED OF QUANTUM HEROES

As possibilities in quantum tech continue to open up, a new generation of scientists and engineers with quantum qualifications will be in high demand. Therefore, University of Copenhagen and the Technical University of Denmark (DTU), the two leading quantum tech institutions in Denmark, have teamed up. A new joint MSc education in Quantum Information Science is set to commence by summer 2022, contingent on the due approval from the Ministry of Higher Education.



The future candidates will be trained in fields such as quantum encryption, quantum-based communications, and applied quantum science. Internationally leading tech companies will provide input and collaboration in support of the Danish ambition of supplying training at the internationally highest level.

Denmark is the top country in the world on number of candidates trained in quantum technology relative to population size.

The University of Copenhagen ranks 7th in the world on quantum scientific impact measured by the number of unique first-author publications.

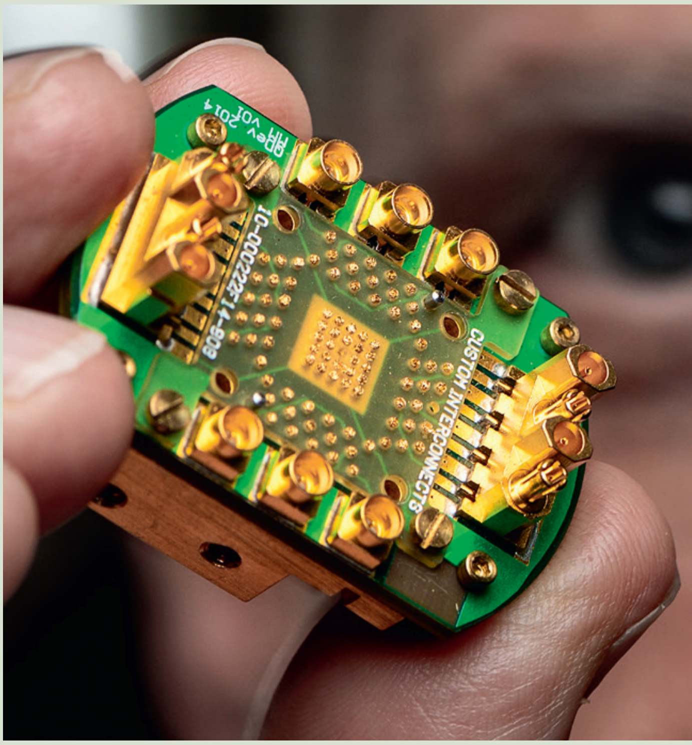
Source: "Economic impact of Quantum in The Netherlands" (Quantum Delta, 2020).

THE NIELS BOHR INSTITUTE – A QUANTUM POWERHOUSE

Awarded the Nobel Prize in physics in 1922 for his discoveries, Niels Bohr personified the early quantum theory revolution. Still, many other brilliant scientists accompanied him in what was known as the "Copenhagen School" of physics.

To this day, the Niels Bohr Institute (founded in 1921) remains among the most esteemed work places for both theoretical and experimental physicists. This fruitful environment has always enabled the institute to attract a large number of highly talented students and younger scientists from all over the world.

For Niels Bohr personally, the Nobel Prize undoubtedly marked the peak of his career. For the Niels Bohr Institute, an exciting journey is only just about to take off. We are well positioned to spearhead the academic side of the upcoming technological revolution and initiate the industrial collaborations which will make the quantum society a reality.



A golden opportunity for Denmark. The heart of a component for future quantum computing. Made at NBI.

"The Niels Bohr Institute remains among the most esteemed work places for both theoretical and experimental physicists"

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