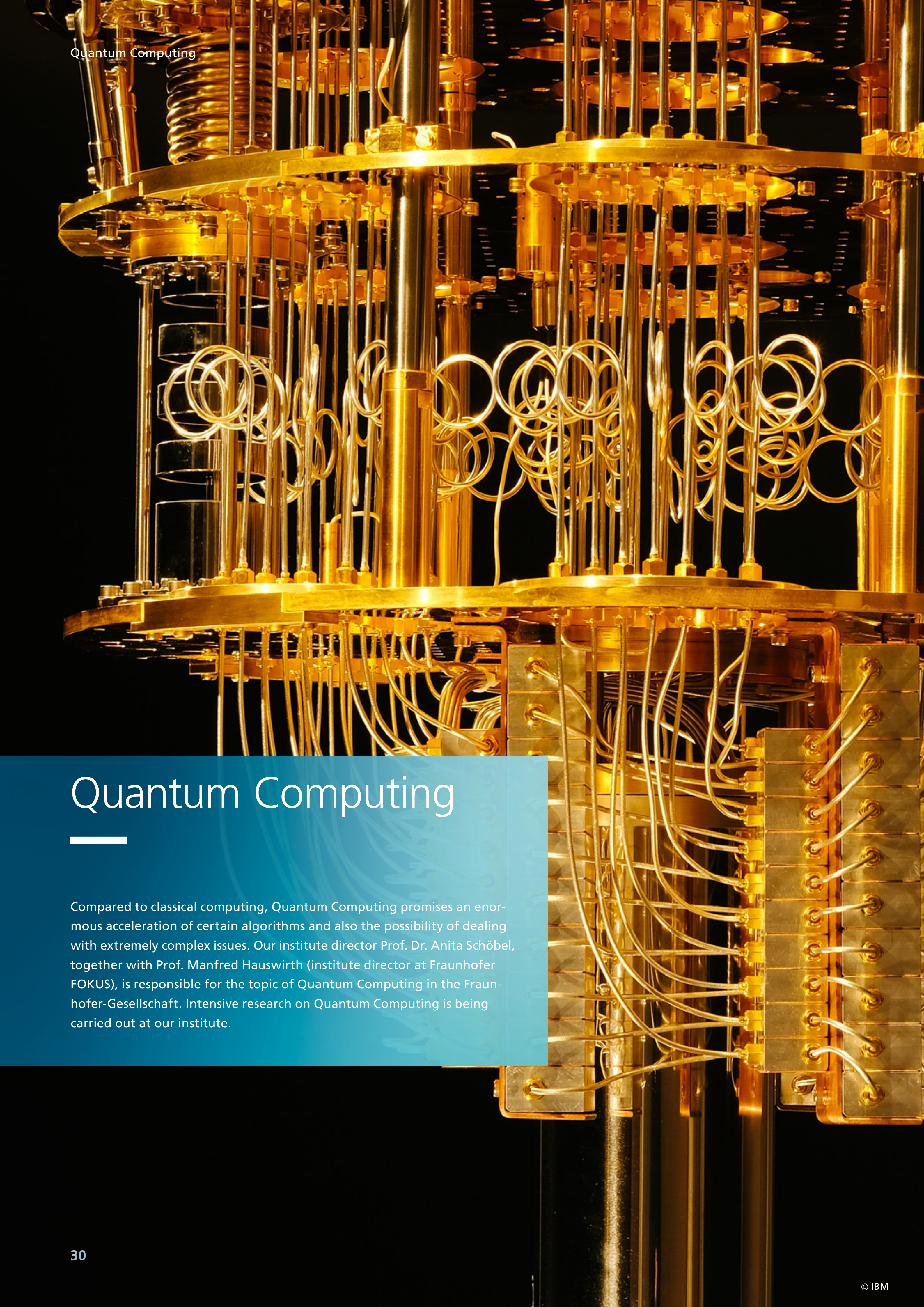


Quantum Computing

Compared to classical computing, Quantum Computing promises an enormous acceleration of certain algorithms and also the possibility of dealing with extremely complex issues. Our institute director Prof. Dr. Anita Schöbel, together with Prof. Manfred Hauswirth (institute director at Fraunhofer FOKUS), is responsible for the topic of Quantum Computing in the Fraunhofer-Gesellschaft. Intensive research on Quantum Computing is being carried out at our institute.

Quantum Computing: Gold-Rush Fever in Research

Quantum Computers are currently expected to bring nothing less than a paradigm shift: the significantly increased amount of information that can be processed is raising high expectations. Researchers see the opportunity to carry out completely new computing operations to solve mathematical problems that have so far prevented conventional computers from working. Eva Fröhlich from our "Communication" team talks to our Institute Director Prof. Dr. Anita Schöbel and Dr. Pascal Halffmann, Research Coordinator Quantum Computing at the Fraunhofer ITWM, about the current state of research.

"We have found our niche."

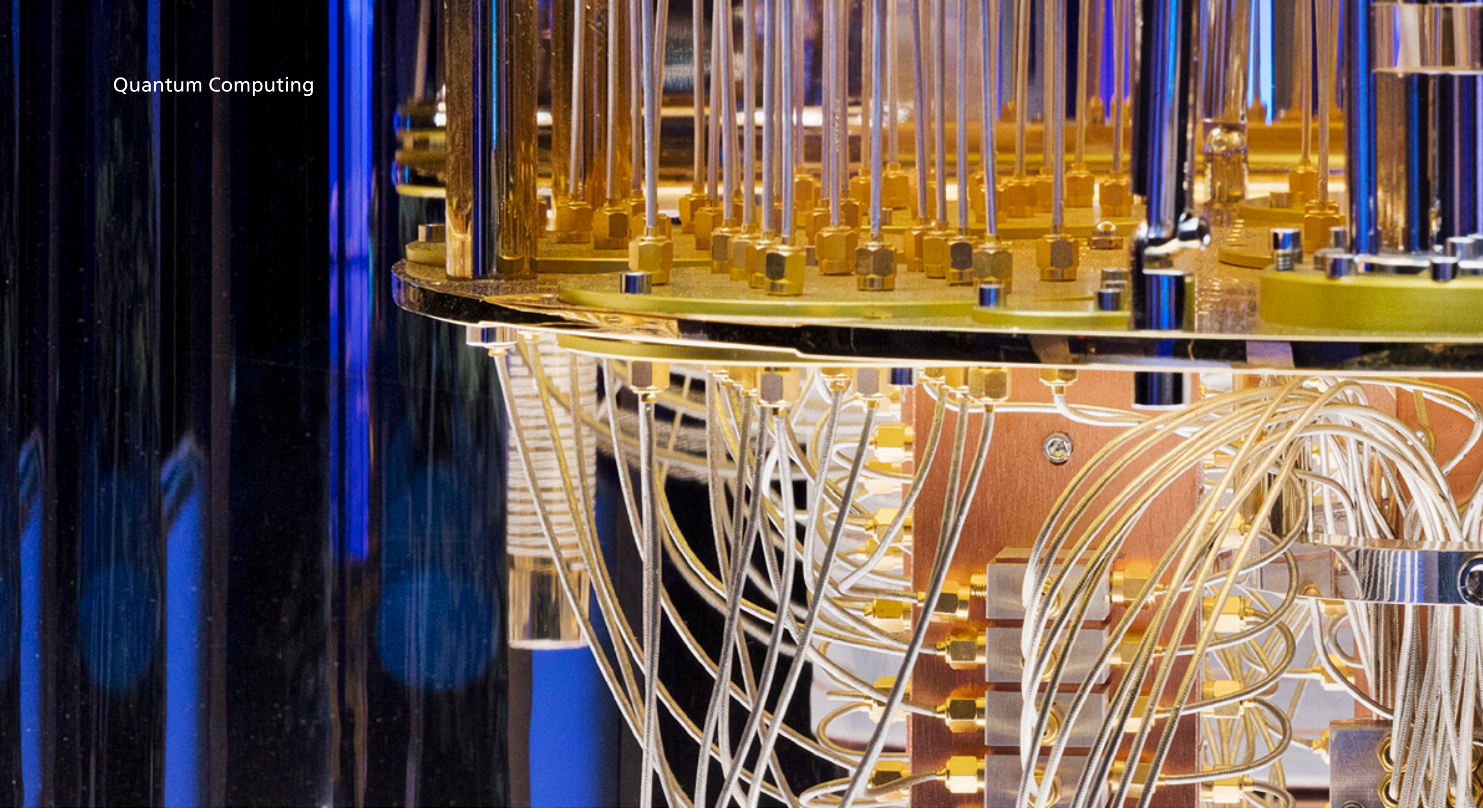
The Fraunhofer-Gesellschaft has defined quantum technology as a strategic field of research and is thus pooling the expertise of the various Fraunhofer Institutes. What are the most important findings from Fraunhofer series so far?

Schöbel: First of all, I realized that it is incredibly exciting to talk about and research Quantum Computing. Since I have immersed myself in this field, I have found many open research questions and that is fun. But I've also noticed that: Quantum Computing is very collaborative, especially in the Fraunhofer context – I don't know of any other area where Fraunhofer collaborates so intensively. It's not just our departments or the institutes themselves, we even work with universities and the Leibniz and Max Planck Institutes across research institutions. I think it's remarkable that Quantum Computing brings so many people together.

Halffmann: Quantum Computing is a very broad, interdisciplinary field, which means we need different skills. In the beginning, we had a very broad approach here at the Fraunhofer ITWM. I think that we have now found our niche in which we can best transfer the strengths that we already have in the departments to the quantum world. And that is in the field of applied Quantum Computing. Improving classical algorithms and hybrid algorithms is where we are strong and where we have achieved good results in recent times. Be it in financial mathematics, image processing or high performance computing – we are seeing progress. Our investment in these areas in the last three to four years are paying off scientifically.

Since 2021, Fraunhofer has been able to test application-related quantum software and expand its expertise on the "IBM Quantum System One" in Ehningen, the most powerful quantum computer in Europe to date. It is now known that this cooperation will not be continued in its current form. What will happen with practical research?

Schöbel: The experience from Ehningen really helped us to take the first steps. We calculated a lot in the IBM Cloud and we saw a lot: To be honest, most of all what is not yet possible, but definitely progress. The collaboration will continue in a different form, Fraunhofer will continue to have computing time at IBM. But this also offers us the opportunity to look at other hardware platforms. There are very different types of hardware that are perhaps better or less suitable for certain algorithms. It is therefore important that we also explore other platforms.



"Expectations are becoming more realistic."

Halffmann: At IBM in particular, we have been able to see very clearly how hardware has developed. This is very important for us because we are partly involved in building hardware ourselves. And I agree that we are clearly hardware agnostic, because we can't predict at this point in time which hardware technology will develop and how, and which will really become established. We are testing a broad selection. But it's definitely important for us to have some form of access to hardware so that we can see: How is the progress? Do the algorithms we are developing work? We want practice, we want application-oriented research and so we also have to look at: how well do our methods work in application? And this is particularly important for our young scientists, so that they get a feeling for how to work with a quantum computer.

Almost all departments at the Fraunhofer ITWM have gained initial experience with Quantum Computing. Where do you see the greatest potential? Are there any projects that stand out?

Schöbel: With image processing, you can literally see how the recognition of images is getting better and better. For the simulation, we put a lot of work into the fast Fourier transformation, so we can assess both the potential and the pitfalls. And in the Rymax project, I find it impressive that we are involved in the construction of a real quantum computer in Kaiserslautern. Not in the construction itself, but we are trying to contribute the algorithms and also those that mediate between software and hardware. That is exciting to experience.

Halffmann: In financial mathematics and optimization, we focus on algorithms, in particular algorithms from Quantum Machine Learning and quantum optimization, which we really – and this is the exciting thing here – try out with specific use cases. In the energy sector, for example, we have solved a power plant scheduling problem. This has definitely brought significant improvements in the performance of Quantum Machine Learning.

The public has high expectations of quantum technologies and there is a great deal of interest. What do you think is realistic in the near future?

Schöbel: Unfortunately, it's still a bit of a guess as to what will be ready for industrial use and when. We have identified a few areas where we believe progress is realistic. What I find interesting is that the areas where we can prove mathematically that it really is better than anything we've seen before still seem to be further away from application than other

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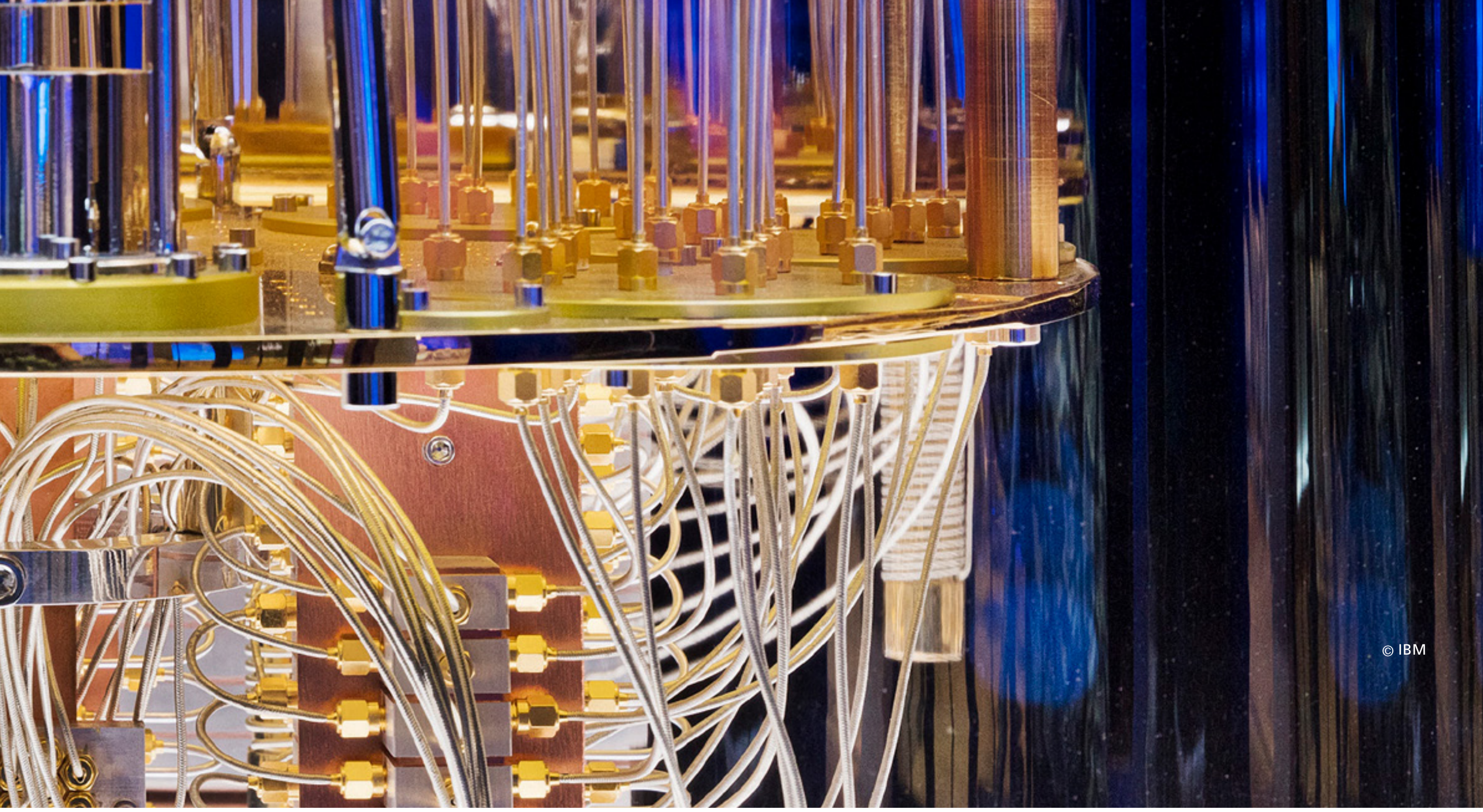
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areas, such as optimization, where quantum annealing technology, for example, is already working quite well. Quantum annealing is not an exact procedure that leads to a provably good solution, but a heuristic. However, it is becoming apparent that this may be better than other methods that are currently available.

Halffmann: In my view, public expectations have changed over the past year and a half. People have become a little more realistic after the first two years of quantum hype – we surfed along on this wave. We have taken advantage of this, but we have always remained realistic.

Anita Schöbel: I agree with you! My very first application for AnQuC already states that we are starting with the aim of seeing what works and what doesn't work. And I also agree with you that expectations are becoming more realistic.

Halffmann: We can't promise that we will have quantum superiority in five years' time. Even if some people postulate this, we have not yet seen any reliable arguments for this. Nevertheless, we are optimistic that the use of (hybrid) quantum algorithms will provide advantages in certain areas, some of which include our areas of application. Until then, however, there is still plenty of work to be done, especially in order to achieve sustainable practical benefits from these algorithms.

In conclusion: From a scientific point of view, what fascinates you about the topic of quantum?

Halffmann: I jumped in at the deep end when I joined the Fraunhofer ITWM. I had no background in Quantum Computing when I came here and started straight away with my first project. For me, the exciting thing is simply that we have to completely rethink things, a big difference to classical methods. It's fascinating to be involved in a young topic at an early stage. There's a kind of gold-rush fever in research.

Schöbel: I feel the same way. New paradigms are emerging. There are many things that are turning around a bit and that makes it particularly exciting from a scientific point of view. Quantum Computers offer potential and maybe we need another spark, a brilliant idea, and then something completely new could emerge. The whole time you have the feeling that the last word has not yet been spoken.

www.itwm.fraunhofer.de/quantum-computing

"The last word has not yet been spoken."

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Quantum Technology: Our Experience

Almost all of our departments and divisions have already carried out projects with the support of quantum technologies. An overview of the research activities in the "Application-oriented Quantum Computing" (AnQuC-3) project funded by the state of Rhineland-Palatinate.

Image Processing

In the field of Machine Learning (ML) with Quantum Computers (QC), researchers have developed their own algorithm for recognizing edges in images using QC. The algorithm delivers very robust results – not only on a quantum simulator, but also on a currently still error-prone superconducting QC. Our team has thus developed what is probably the first quantum edge detection algorithm that can also be used for larger image sizes. Compared to existing methods, the method developed at the Fraunhofer ITWM requires only a few measurements of the quantum states.

Financial Mathematics

The department's research activities focus on identifying use cases in financial mathematics, transferring classical financial mathematics methods to QC applications and further developing QC algorithms. The researchers investigate and evaluate the use of quantum algorithms and computers for financial mathematics issues.

In addition, quantum algorithms are further developed, for example by automatically finding QC circuits, e.g. for the simulation of financial mathematical processes. Artificial Intelligence methods are used to enable the most efficient possible calculation of a wide range of simulation problems. Existing, so-called variational QC algorithms are adapted accordingly to the department's use cases.

High Performance Computing

Our "High Performance Computing" (HPC) division focuses on the interplay between HPC and QC. In the AnQuC project, researchers are looking at the benchmarking of Quantum Computers and other quantum chemistry simulations.

Comparing different systems with each other is important in order to quantify the advantages of Quantum Computing. Various parameters are considered. The focus is on the runtime of quantum circuits. In addition to specific measurements, the department is also working on the German industry standard (DIN) SPEC 91480 "Benchmarking of Quantum Computers" in order to identify suitable metrics and methods.

Materials Characterization and Testing

Optical technology is playing an increasingly important role in production. Quantum technology is revolutionizing the way we deal with light and can be used in many industries in the future. The department conducts research into quantum measurement technology, spectroscopy and tomography in particular.

Mathematics for Vehicle Engineering

The "Mathematics for Vehicle Engineering" division looks at various ways of using QC for traffic control. In particular, the researchers are investigating whether the use of hybrid quantum algorithms, such as the "Quantum Approximate Optimization Algorithm" (QAOA) or "Quantum Annealing", can already achieve performance gains compared to classic optimization methods.

Optimization

The "Optimization" division sees the potential of QC mainly in specialized optimization algorithms and for quantum-based Machine Learning (ML) methods. Hybrid quantum algorithms are methods in which both conventional digital computers and Quantum Computers are used. They can be used, for example, to solve combinatorial optimization tasks.

The randomness of measurement results is an intrinsic property of quantum systems. Random numbers are also an essential component of numerous Machine Learning methods, especially in the field of deep learning. It therefore makes sense to combine these two topics. An empirical study by the research team refutes earlier hypotheses that predicted a clear quantum advantage.

Flow and Material Simulation

Numerical simulation is an important tool for characterizing composite materials. The researchers are focusing on the potential of Quantum Computers to resolve complex material models quickly and efficiently. To this end, they are investigating both methods that promise a long-term advantage – such as the Quantum Fourier Transform (QFT) – and heuristic methods that could be used in the short to medium term – such as variational hybrid methods.

The QFT makes it possible to accelerate the classical Fourier transform exponentially. The latter is the bottleneck in the creation of replacement models for the multiscale simulations of composites. It has been possible to carry out small material simulations on IBM Quantum Computers.

www.itwm.fraunhofer.de/anquc-3-en

Quantum Technology: We Train the Next Generation

The Quantum Initiative Rhineland-Palatinate (QUIP) focuses on young scientists: young researchers are given the opportunity to familiarize themselves with the topics of Quantum Computing (QC) or quantum technologies (QT) at the Fraunhofer ITWM or at our project partners in Rhineland-Palatinate. The Rhineland-Palatinate Ministry of Science and Health is funding the project.

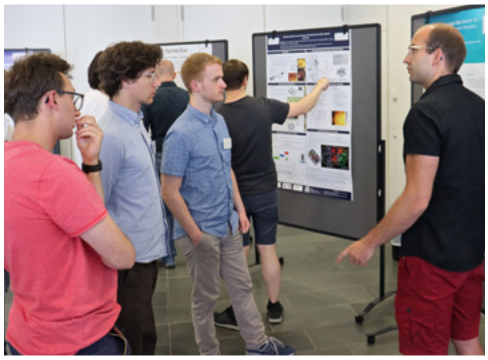
At "QUIP", young quantum scientists receive a detailed, broad research program for training, further education and networking. "It's really great that the ferderal state is supporting us in this way, both in terms of funding and networking," emphasizes Institute Director Prof. Dr. Anita Schöbel. Quantum technologies and QC research are well established in Rhineland-Palatinate, both in projects at universities and institutions as well as in companies.

QUIP is already successfully training and developing experts, bringing them to Rhineland-Palatinate and networking them in a targeted manner. The first "Summer Schools" and "Winter Schools" have already taken place. "The skills are still rare, there are few offers but a high demand for experienced researchers," says Quantum Research Coordinator Dr. Pascal Halffmann.

"It is important that we have established our own program. For the 'Winter School' in February, we were able to attract speakers from the major Quantum Computing players. This event led to internships with people from the USA and Europe, which was the only way we could get them to come to Rhineland-Palatinate."

Structured Qualification Concept at the Quantum Graduate Center

The Quantum Graduate Center (QGC) is another central element of QUIP. All doctoral students with topics in the field of "Quantum Computing and Quantum Technologies" can apply for the QGC and thus benefit from a wide range of scientific programs and individual training courses.



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Dr. Alexander Geng, Image Processing

In my doctoral thesis, I investigated the potential of Quantum Computers in the field of image processing. The focus was not only on the theoretical advantages, but especially on the practical benefits and limitations of Quantum Computers in the current NISQ era, where the hardware still has comparatively large errors.

In addition to loading an image onto a quantum computer and improving the algorithm, I developed a robust algorithm for detecting object edges after recognizing the limitations of current Quantum Computers. Finally, I combined the topics of Quantum Computing and Machine Learning to develop a hybrid algorithm to solve a classification problem in an industrial setting.

Tom Ewen, Financial Mathematics

Since the EU introduced the Solvency II Directive in 2016, insurers in Europe have had to calculate their solvency capital requirements. The Monte Carlo simulations required for this – even if highly parallelizable – are particularly time-consuming, so that they are usually only carried out once a year.

In my PhD, I am investigating how methods from Quantum Computing, such as Quantum Machine Learning or the Quantum Fourier Transform, can help to accelerate these calculations. In particular, I am looking at the problem of pricing options as an important building block in the calculation of the solvency capital requirement.

Thomas Cheng, High Performance Computing

My thesis covers different aspects of state-of-the-art quantum algorithms in order to improve the performance in the simulation of fermionic systems, e. g., those found quantum chemistry.

A particularly relevant problem is that of the encoding to the qubit space. The standard here is the Jordan-Wigner transformation, which requires M qubits for M fermionic states, however, this can be reduced to Nlog M qubits for an N electron system. Using techniques from error correction, we have developed a classical scalable quantum data compression method with optimal qubit count and measuring costs. This scheme can be encoded and decoded in polynomial time and reduces the number of qubits required as well as noise. This scheme can be generalized to address quantum error correction and theoretic bounds for quantum information in physical systems.

Higher, Faster and Further

Computers are expected to be able to do more and more – which increases the performance requirements for hardware and software. Conventional computer technologies are reaching their limits. "Next generation computing" is a strategic field of research at the Fraunhofer-Gesellschaft. Our researchers are looking for new solutions to significantly increase the efficiency of data processing. Three streams are particularly promising: specialized energy-efficient supercomputing, neuromorphic computing and Quantum Computing.

Newly Founded: UNEEC Systems GmbH

August 2023 saw the launch of the latest Fraunhofer ITWM spin-off to date – UNEEC Systems GmbH. Its goal: to market energy-efficient supercomputers based on European technologies. At the heart of the spin-off is the stencil and tensor accelerator (STX), which is being developed using a consistent hardware-software co-design approach. The team of researchers at the Fraunhofer ITWM led by Dr. Jens Krüger is working on optimizing the hardware.

Simulate Instead of Destroy

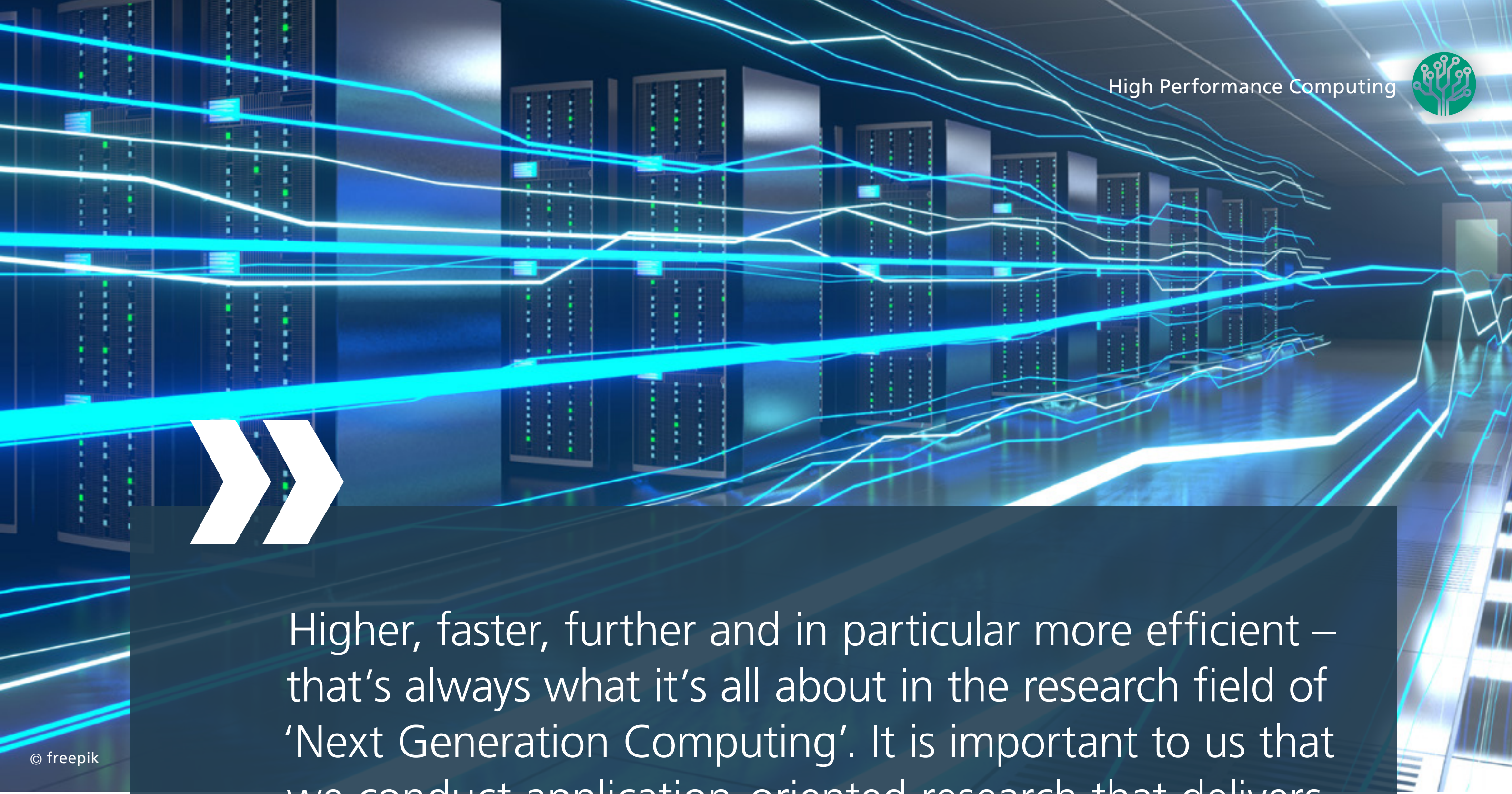
The aim is to create optimal conditions for improved simulations in particular. "Simulations are now an integral part of science and industry, but they also consume energy. Model-based simulation is now replacing many experiments, such as crash tests in the automotive industry," explains Dr. Jens Krüger. "Digitalization is therefore the key to increasing efficiency, but ever larger amounts of data and more complex algorithms mean that IT is expected to account for around ten percent of total energy requirements. It is important for us to use our research to help ensure that high-performance, energy-efficient systems are part of the solution and not the problem."

UNEEC Systems GmbH's approach includes its own system-on-chip architecture – from a plug-in card to a complete HPC rack. The company is thus picking up on the trend of offering application class-specific solutions: If you know what the user expects, you design the hardware accordingly. Thanks to the co-design approach, the STX system concept combines an innovative architecture, maximum energy efficiency and simple programmability for highly parallel simulation applications.

Neuromorphic Computing: NASE Extended

A bird's brain is small, but extremely powerful: The organ manages to navigate the bird, enables communication with conspecifics and all other functions that ensure its survival – to put it simply: a small brain with enormous output. Neuromorphic chips aim to mimic this efficiency. The AI product NASE (Neural Architecture Search Engine) has now been developed on the basis of an energy-efficient AI chip, for which researchers at Fraunhofer ITWM received the 2021 Pilot Innovation Award from the German Federal Ministry of Education and Research.

With NASE, a team from the "High Performance Computing" department is helping companies to design neural networks tailored to their needs



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> Higher, faster, further and in particular more efficient – that’s always what it’s all about in the research field of ‘Next Generation Computing’. It is important to us that we conduct application-oriented research that delivers real added value for our clients. But we also see it as our responsibility to develop energy-efficient solutions.”

Dr. Jens Krüger
Team Lead “Next Generation Computing – New Architectures”

and integrate them into their own networks. NASE brings together several technologies for this purpose. “We at Fraunhofer ITWM are developing a hardware-aware neural architecture search with NASE,” explains project manager Dominik Loroch. “This type of search also takes into account the limitations of the hardware platform, and we find solutions that run optimally. Anyone who wants to use NASE only provides the data and needs little to no knowledge of DNN (Deep Neural Networks). Since both the search and the training are automatic, this is a very scalable method for quickly obtaining solutions for the hardware.” NASE acts as a productivity booster that identifies complex DNNs very quickly and thus significantly reduces development costs.

Quantum Computing

The researchers from the “Next Generation Computing” department are naturally also looking very closely at the topic of “Quantum Computing”. “It’s exciting for us to see how two worlds – the classical and the quantum world – are developing,” says Krüger. “We see a lot of potential, especially for using quanta in a hybrid system as an accelerator unit. An exciting question for us is how to optimally distribute parts of applications in a system consisting of classical and Quantum Computers. We are researching this in an application-oriented way with realistic applications from industry, while many others focus primarily on the hardware.”

www.itwm.fraunhofer.de/nextgenerationcomputing-en

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