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The Center for Quantum Technology and Applications

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Summary: We describe the Center for Quantum Technology and Applications (CQTA) at DESY in Zeuthen which is a science-led center, enabling researchers from universities, industry, governmental agencies and other research institutions to develop new applications for complex quantum systems, or optimization algorithms for current and future quantum computers. The broad portfolio in quantum computing of the center is summarized, ranging from basic quantum field theories to logistics problems, health care and life sciences, quantum sensing and even quantum art.

Keywords: quantum computing, quantum machine learning, classical optimization, quantum health, quantum art

Introduction to the Center for Quantum Technology and Applications (CQTA)

Quantum computing and quantum sensing are novel and extremely rapidly developing fields which have the potential to change our way of computing, of performing precision measurements and even our way of performing science as a whole. It can be used to carry out unprecedented accurate simulations, to explore parameter regions in physical models inaccessible for classical methods and to lead to more efficient and fast solutions for problems in combinatorial optimization, health care and life science chemistry, drug design, finances, quantitative biology and beyond.

The Center for Quantum Technology and Applications (CQTA) is sketched as a house in fig. 1. It has as overarching activities networking, scientific exchange and training in quantum computing and sensing. As an IBM Quantum Innovation Center, it has access to IBM quantum hardware on a license fee basis. The center is mainly financed through a financial support of the MWfK of the state of Brandenburg but, of course, has also in house support from DESY and a large number of third party grants through which it receives funds.

An essential role of CQTA is the support of universities, industry, governmental agencies and research institutes to make their applications and use cases ready for an eventual quantum computation on real hardware. In fact, CQTA can give access to IBM hardware to third parties with a possible income for the CQTA based on negotiations.

Important additions to CQTA are detector development, quantum sensing and, in particular training for scientists and engineers in quantum computing and quantum sensing for which a dedicated effort is made. Another important activity of CQTA is to provide, through the center's applications and use cases, benchmarks and tests and for emerging novel quantum hardware developed by different research groups from industry and academia.

Applications in High Energy Physics

The portfolio of CQTA in quantum computing, on which we concentrate here, is very broad and in the following we want to provide some examples, not claiming to be comprehensive. For the author of this article quantum computing started to become a reality with a first quantum computation on Rigetti hardware, [1], [2], using up to three qubits. These quantum computations were very important to gain experience in the performance of real quantum hardware and it became clear very fast that a naive approach would not lead to successful computations.

A lot of effort was therefore put in the development of algorithms, in particular focusing on error mitigation, [3], [4], and expressivity analysis of quantum circuits, [5], [4], which recently led also to use the expressivity algorithm developed by us to a theoretical analysis of the controllability of quantum devices [6]. In addition, noise models, [7], [8], the role of noise in equivariant quantum neural networks, [9] and methods such as the Bayesian approach, [10], or classical splitting of quantum circuits, [11], were investigated for their use in practical quantum computing applications. Attempts to find ground states of simpler quantum systems using imaginary time evolution and making use of symmetries were carried out in, [12], [13], with promising results also for an eventual application to more complex models.

Coming from theoretical particle physics, this author was particularly interested in porting high energy physics models on a quantum computer. To this end, the sheer formulation, the encod-

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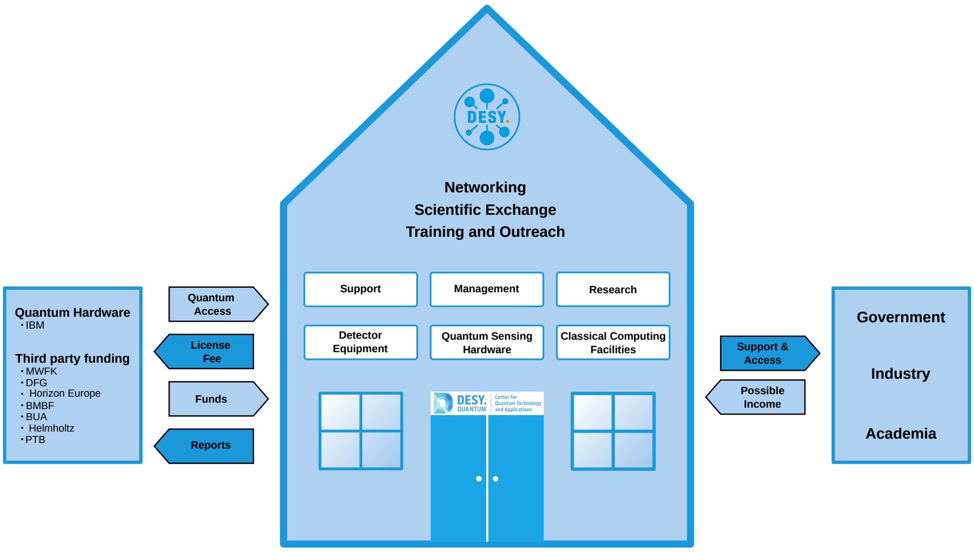

Fig. 1: A sketch of CQTA, see text for details.

ing and the development of suitable quantum circuits needed to be performed on the theoretical level before a quantum simulation on real hardware could be aimed at. This theoretical work is documented in a number of publications, [14], [15], [16], [17], [18], [19], [20], [21], [22]. [21] [22] These works layed the ground for a recently carried out run on the IBM quantum hardware employing up to 12 qubits, [23], for the investigation of high energy physics model and, [24], for a scattering experiment in the Thirring model. There is also a work computing causal loops employing a VQE approach in Feynman graphs, [25], which showed some advantages over Grover searches. Works for quantum computing within theoretical particle physics, in particular lattice gauge theories, can be found summarized in the reviews, [26], [27], [28]. It is also worth mentioning that besides the works listed above which use the circuit approach, there are also efforts to look at measurement based quantum computations for theoretical high energy physics models, see [29], [30].

The application of quantum computing is not restricted to theory but also on the experimental high energy physics side there is a high demand for quantum computing. The amount of data expected in the future, e.g. at the LHC at CERN or the Luxe experiment at DESY is becoming so large that classical methods might not be efficient enough to analyze them. It is therefore very worthwhile to explore, whether quantum computing can help here in finding solutions more efficiently and more accurate. At CQTA, together with researchers from CERN and DESY, we have therefore tried to use quantum computing algorithms for particle track reconstruction, see [31], [32], [33], [34], [35]. At the moment our results using O(10) qubits matches the classical algorithms in their performance and it will be very interesting to see how the quantum algorithms will scale when a larger number of qubits is employed.

Both, the theoretical and the experimental efforts in high energy physics and the prospect to use quantum computers in the future is summarized in a white paper, led by CERN, DESY and IBM, [36]. There, also the applications and use cases that can be explored already now on quantum computers are provided with a prospect to run them on about O(100) qubits.

Applications outside High Energy Physics

It is important to emphasize that at CQTA also applications are followed which are not connected to high energy physics. A prominent example is the so-called flight gate assignment (FGA) problem. Here, an optimal path for the passengers in an airport between connecting flights is looked for. Clearly, finding a very good way to connect flights and gates will allow for more starts and landings in an airport, making the airport hence more efficient.

In [37] we studied the FGA problem employing data from a real airport and found through a binary encoding and the conditional value at risk method very good results up to O(20) qubits in a quantum simulation including shot noise. A very important information here is that the same mathematical formulation that is used in the FGA problem can be used for many other problems in logistics, traffic, distributing energy or electricity networks and beyond. The good results we found for the FGA problem are therefore very promising to be transferred also to such problems, a path we are following presently at CQTA. Even more promising is that a hardware computation at Ionq, [38], gave very could results outperforming in some cases even exact classical methods.

Further applications within CQTA are in quantum chemistry, [39], looking at boson sampling on a photonic quantum device, [40], and even quantum music, [41], [42]. The latter application attracted quite some attention and led to the organization of quantum music symposium in Berlin in October 2023 through CQTA. Ideas outlined in the quantum music papers were also played live in a concert in February of 2024 by some of the authors.

Conclusions

CQTA started in 2021 with two PhD students and now the group has grown to 20 scientists consisting of 50% female and 50% male representatives in the quantum computing team. This shows the rapid development of CQTA and quantum computing in general. The large group with its many connections and collaborations in Europe and beyond allows for a very broad portfolio of applications, uses case and algorithms in high energy and condensed matter physics, classical optimization problems, chemistry and even quantum art.

It can therefore be expected that quantum computing becomes a new and general way of computing as such. The rapid development both on the hardware and the algorithm side makes quantum computing therefore a most promising choice for solving classically very hard of even impossible to tackle problems, overcoming thus barriers and opening completely novel paths to solutions. In this respect, CQTA is determined to contribute to this avenue with its expertise, knowledge and experience.

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