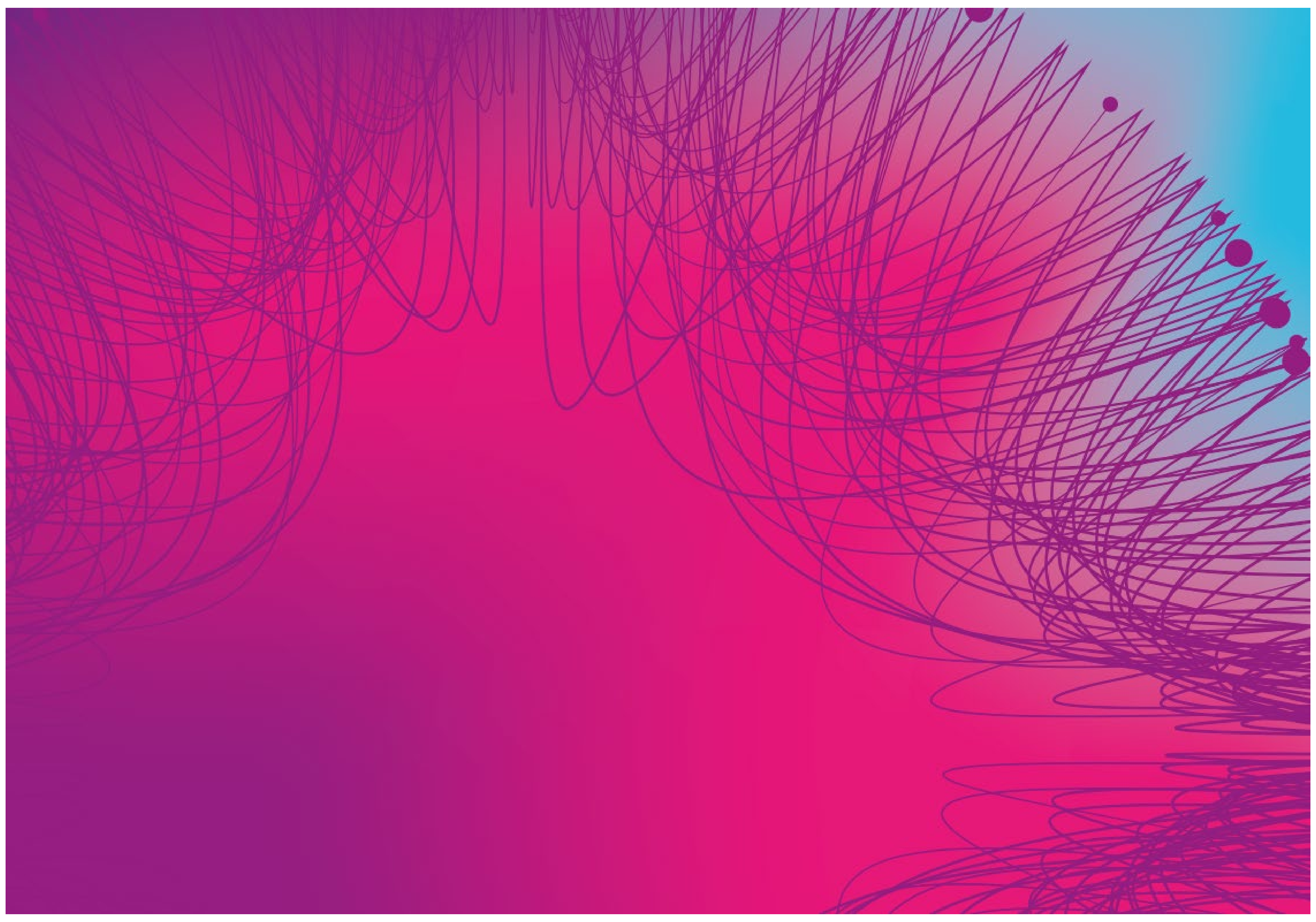
IQDA
Ion trap-based quantum computers with co-design elements

We adapt and test two technological paradigms, Digitized Adiabatic Quantum Computing with Non-Stoquastic Terms (DAQCNS) and Digital-Analog Quantum Computing (DAQC), for the ion-trap-based quantum computers of the DLR QCI. Our main goal: to test applications across analog and digital quantum computers to reduce noise.

- Algortihms
- Hardware
- Hardware/Software Co-Design



Introduction to the project
In the coming years, the DLR will acquire various quantum computers. These will be attributed to digital quantum computing. Since purely digital quantum computers have demonstrably high error rates, making it difficult to run algorithms with high precision in the near future, bridge technologies must be developed. Digital-Analog Quantum Computing is exactly such a bridge technology between the purely analog adiabatic quantum computer and the purely digital quantum computer.
The project IQDA is a central component of the quantum computing initiative and is led by the Institute for Software Technology. This ambitious endeavor aims to further develop and optimize the promising ion-trap technology for digital-analog quantum computing. Ion traps are one of the leading platforms in quantum computing because they allow for precise control of individual ions, which can be used as quantum bits (qubits). These qubits, due to their stability and reliability, are particularly well-suited for complex quantum computations.

Main focus of the project
As part of the IQDA project, a special focus is placed on the research and implementation of technologies for Digitized Adiabatic Quantum Computing and Digital-Analog Quantum Computing. In Digitized Adiabatic Quantum Computing, the adiabatic computing process, where the system is gradually transitioned from an initial state to a final state, is converted into a sequential digital form. This approach allows the benefits of adiabatic processes to be utilized while maintaining the flexibility and precision of digital control.

Digital-Analog Quantum Computing (DAQ), on the other hand, combines digital and analog computation steps in a hybrid approach. This approach leverages the advantages of both worlds: the high precision and fault tolerance of digital controls are combined with the natural dynamics and efficiency of analog systems. Especially in the use of ion traps, these hybrid approaches can yield promising results, as the ions in the traps can be used both for digital logic gates and for analog interactions.

The IQDA project aims to specifically adapt these advanced computing methods to the properties and challenges of ion traps. Co-design elements are also integrated, enabling a close integration of hardware and software development. By combining digital and analog quantum computing, more efficient and scalable quantum computers could be developed in the future, fully exploiting the advantages of both computing approaches. Research within the IQDA project thus plays a crucial role in laying the foundation for the next generation of quantum computers.

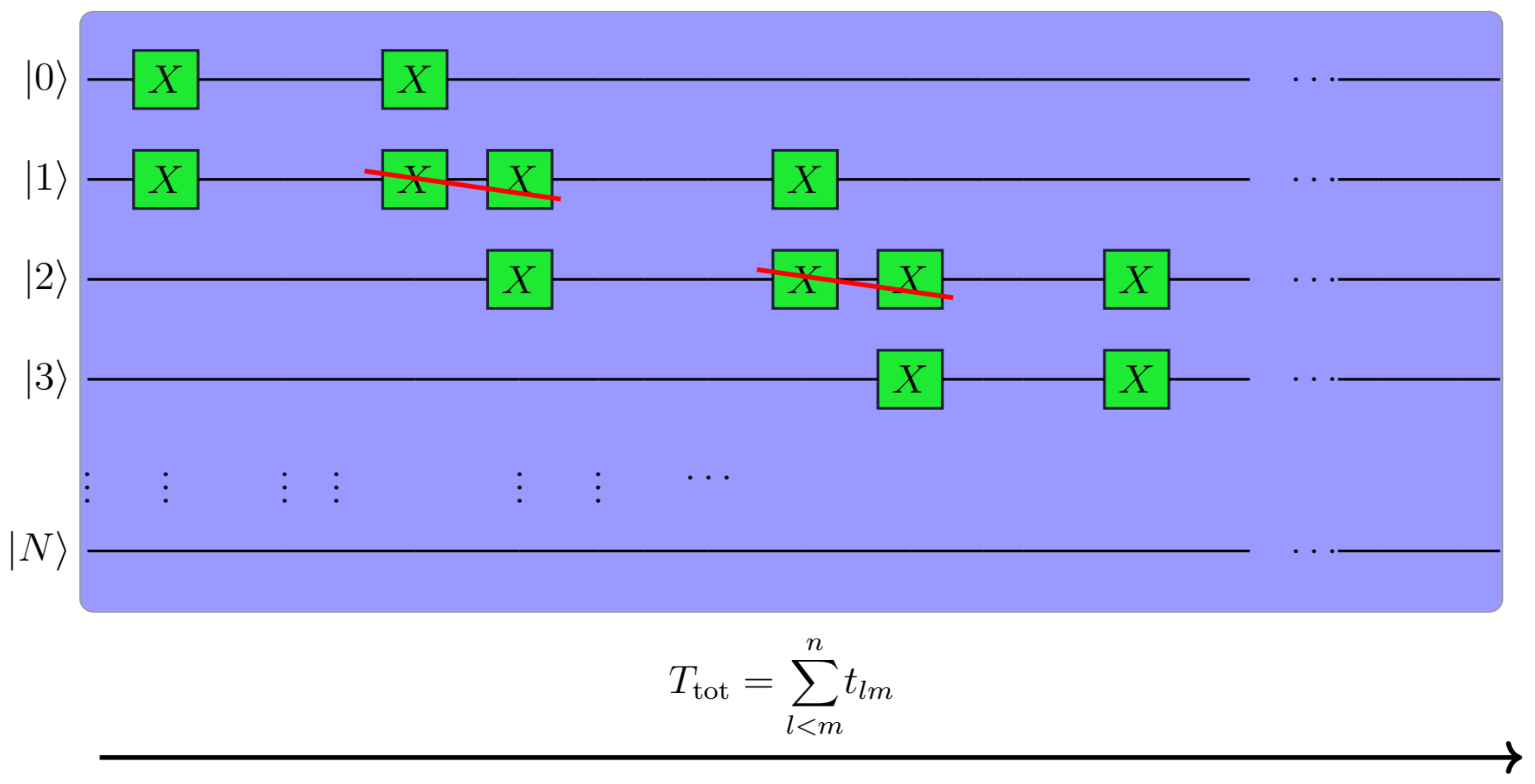
The motivation for the project
The goal of this project is to highlight the advantages of Digital-Analog Quantum Computing (DAQC) technology using ion traps, especially in comparison to the currently available digital quantum machines, which are still prone to errors and limitations. By leveraging the hybrid capabilities of digital and analog approaches, this technology aims to overcome some of the challenges faced by traditional digital quantum systems. The project will explore and generate new insights into the transition between analog and digital principles, aiming to optimize their interplay for more efficient quantum computations.

Quantum algorithms will be executed on ion-trap-based systems to solve complex problems that are particularly difficult for classical computers to address. These problems may span various industries, ranging from optimization tasks to simulations of quantum systems, which are often intractable for classical computing methods. By focusing on real-world applications, the project seeks to provide solutions to critical industrial challenges, demonstrating the potential of quantum computing in addressing practical and significant issues in fields such as manufacturing, logistics, and materials science.

Furthermore, this project offers a unique opportunity to open up new industrial sectors within Germany, specifically in areas of quantum technology that have so far seen limited development in the national quantum computing industry. By advancing the understanding and application of Digital-Analog Quantum Computing, the initiative aims to foster innovation and establish Germany as a key player in the emerging global quantum technology landscape. This could lead to significant advancements in both the academic and industrial domains, driving economic growth and technological leadership.

Challenges
A major challenge in the development of powerful quantum computers is currently improving gate fidelity and managing noisy gates. This is because current multi-qubit gates, such as the Controlled-NOT gate, introduce significant noise. Typical values for gate fidelity range from 90% to 99.9%. Single-qubit gates are generally at least one to two orders of magnitude better. Digital-Analog Quantum Computing (DAQC) could potentially offer a solution to this problem, as it does not rely on multi-qubit gates. However, this method is still very new and much less researched compared to purely digital quantum computing. Therefore, further research is needed to fully exploit its advantages.

The principle behind Digital-Analog Quantum Computing



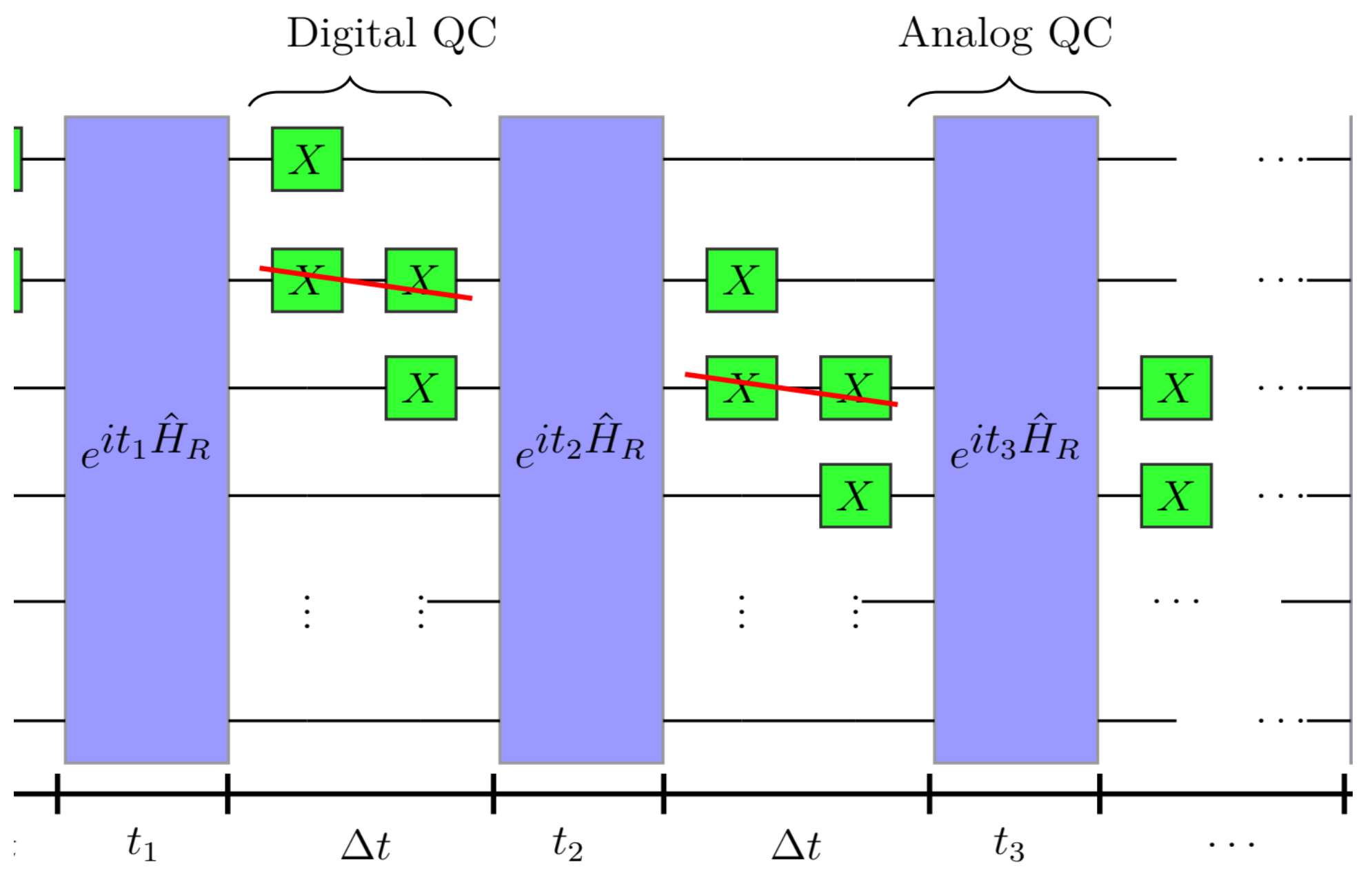
$$T_{\text{tot}} = \sum_{l<m}^{n} t_{lm}$$

Generalized Banged Digital-Analog Quantum Computing (bDAQC)
In Generalized Banged Digital-Analog Quantum Computing (bDAQC), the system employs a hybrid approach that integrates both digital and analog computing techniques. The core component of this method involves the resource Hamiltonian, represented by the blue gate, which functions as an analog device. This resource Hamiltonian is activated over a specified total duration, effectively driving the quantum system in an analog fashion.

Simultaneously, single-qubit X rotations are applied at predetermined time points during the operation of the system. These rotations are executed digitally, acting as discrete operations that complement the continuous analog evolution induced by the resource Hamiltonian. The timing and coordination of these digital rotations are critical, as they ensure that the desired quantum state evolution is achieved while maintaining the benefits of both digital precision and analog efficiency.

The combination of continuous analog operations with discrete digital steps in this "banged" approach allows for a more flexible and powerful quantum computing model. This method enables more efficient state transitions and can potentially reduce the impact of noise and errors, offering a promising route towards achieving more scalable and reliable quantum computing solutions.

In the stepwise Digital Analog Quantum Computing (sDAQC) framework, the quantum computation is divided into two main components: analog and digital operations. The general process involves alternating between these components, leveraging both continuous and discrete quantum dynamics to achieve efficient computation.



More information about the project on our website

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