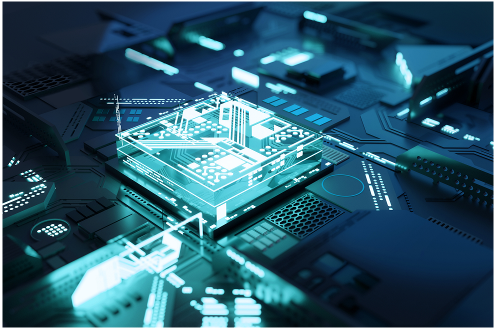
Center for Quantum Technology and Applications

A new IBM Quantum HUB

Karl Jansen

Hamburg, 14.6.2022

Overview



- > Center of Quantum Technologies and Applications (CQTA)
- > Applications
  - Classical optimization
  - Quantum machine learning
  - Theoretical models
  - Error mitigation and expressivity
- > Conclusion

Center for Quantum Technologies and Applications at DESY (Zeuthen place)

- Innovation funding from state of Brandenburg
- focus activities
  - DESY has become an IBM Quantum hub
  - provide access to quantum computer hardware
  - develop applications of uses case for industry and academia, e.g. particle physics
  - develop algorithms and methods
  - benchmark, test and verify emerging quantum computers
  - provide training in quantum computing
  - include quantum sensing

$\Rightarrow$ **DESY is becoming quantum ready**

DESY QUANTUM.

Quantum Technology Applications

Zeuthen

Quantum Simulations
Algorithms & Methods
Benchmarking

Access to Quantum Computers

Quantum Sensing

Knowledge & Technology Transfer

Training and Education

Outreach

Hamburg

Photon Science
for Quantum Materials and
for Quantum Devices

Quantum Machine Learning
Quantum Simulations

Quantum Sensing

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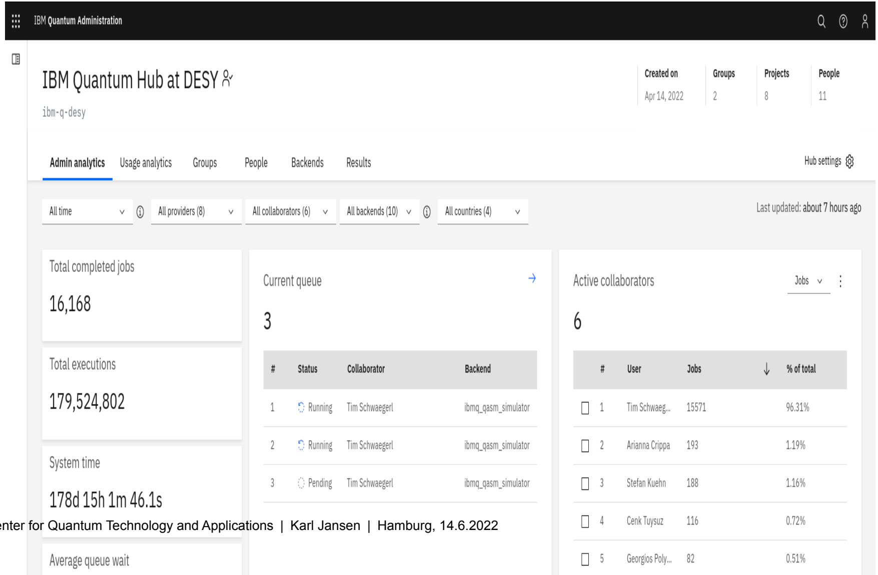
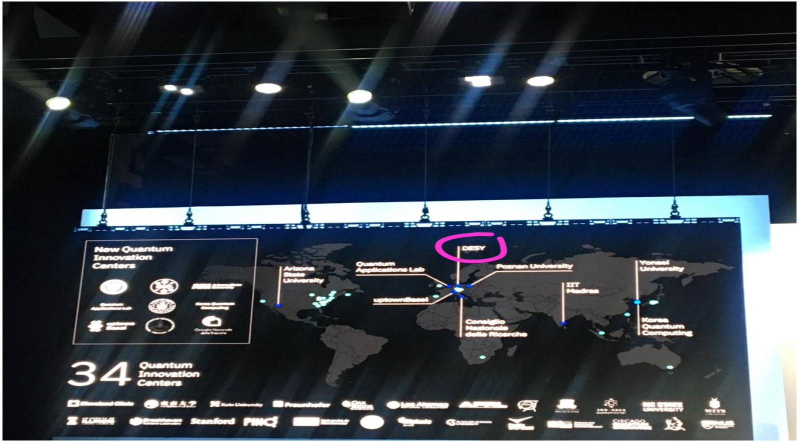
DESY IBM Hub


IBM Quantum Administration
IBM Quantum Hub at DESY
ibm-q-desy
Created on
Apr 14, 2022
Groups
2
Projects
8
People
11
Admin analytics
Usage analytics
Groups
People
Backends
Results
Hub settings
All time
All providers (8)
All collaborators (6)
All backends (10)
All countries (4)
Last updated: about 7 hours ago
Total completed jobs
16,168
Total executions
179,524,802
System time
178d 15h 1m 46.1s
Average queue wait
Current queue
3
Status Collaborator Backend
1 Running Tim Schwaegerl ibmq_qasm_simulator
2 Running Tim Schwaegerl ibmq_qasm_simulator
3 Pending Tim Schwaegerl ibmq_qasm_simulator
Active collaborators
Jobs
6
User Jobs % of total
1 Tim Schwaeg... 15571 96.31%
2 Arianna Crippa 193 1.19%
3 Stefan Kuehn 188 1.16%
4 Cenk Tuysuz 116 0.72%
5 Georgios Poly... 82 0.51%

Highlighting DESY Quantum Hub

> DESY highlight at IBM Quantum summit in New York



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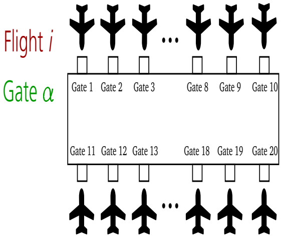
Quantum computing the flight gate assignment problem

- A classical optimization problem: flight gate assignment
  (Y. Chai, L. Funcke, T. Hartung, S. Kühn, T. Stollenwerk, P. Stornati, K. Jansen)
- Find shortest path between connecting flights
- Different incoming and outgoing flights need to be assigned to gates
  → find optimal assignment
- Classical optimization problem
  → quantum advantage?



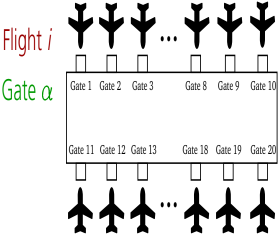
Quantum computing the flight gate assignment problem

- binary variables encoding gates and flights

$$x_{i\alpha} = \begin{cases} 1, & \text{if flight } i \in F \text{ is assigned to gate } \alpha \in G \\ 0, & \text{otherwise} \end{cases}$$

$x \in \{0,1\}^{F \otimes G} \rightarrow x$ binary variable $\rightarrow x \in \{-1, 1\}$

eigenstate of third Pauli matrix σ_z



- leads to mathematical description of Hamiltonian

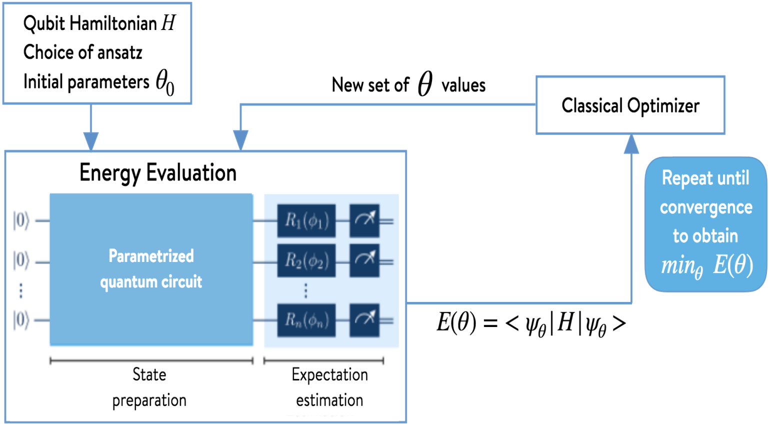
$$H = \sum_{j=1}^{n} Q_{jj}\sigma_j^z + \sum_{\substack{j,k=1 \\ j<k}}^{n} Q_{jk}\sigma_j^z \otimes \sigma_k^z$$

- Task: find lowest energy $\Leftrightarrow$ shortest path

- Same mathematical description for problems in **traffic, logistics, particle tracking, ...**

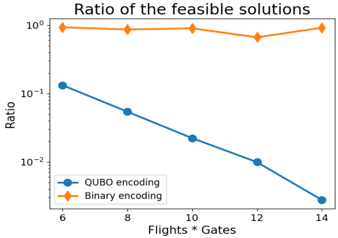
Variational Quantum Eigensolver (VQE)

> a hybrid quantum/classical variational approach

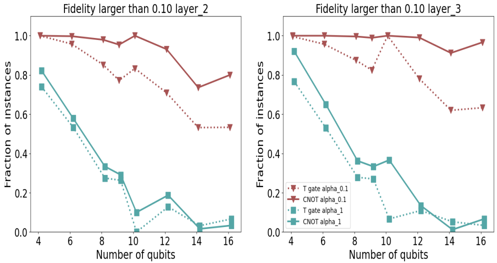


Quantum computing the flight gate assignment problem

- Started with QUBO implementation
- Implementation of various improvements
  - using binary encoding
  - reformulation of Hamiltonian through projectors
  - Using Conditional Value at Risk (CVaR)
- see indications of improvement through entanglement



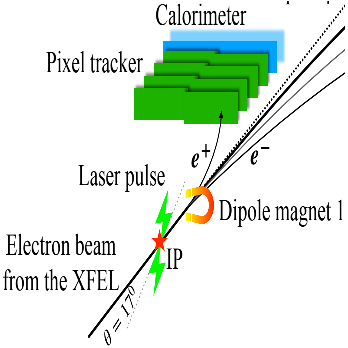
Feasible ratio



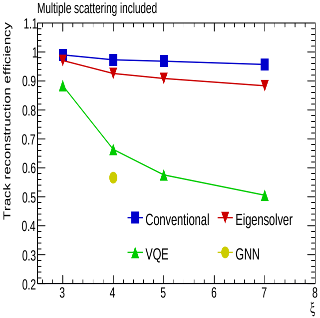
role of entanglement

Particle tracking at LASER und XFEL Experiment (LuXE)

- using Ising Hamiltonian for particle tracking
  (L. Funcke, T. Hartung, B. Heinemann, K. Jansen, A. Kropf, S. Kühn, F. Meloni, D. Spataro, C. Tüysüz, Y. Yap, arxiv:2202.06874)



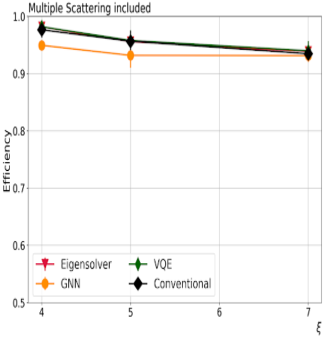
experiment layout



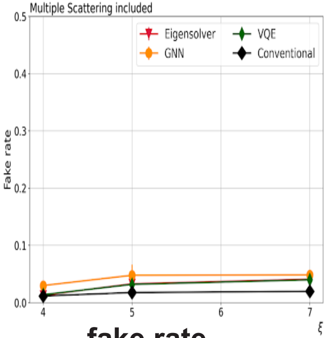
track finding effciency

Particle tracking at LASER und XFEL Experiment (LuXE)

> using FGA Ising Hamiltonian for particle tracking
(L. Funcke, T. Hartung, B. Heinemann, K. Jansen, A. Kropf, S. Kühn, F. Meloni, D. Spataro, C. Tüysüz, Y. Yap, arxiv:2202.06874)



efficiency

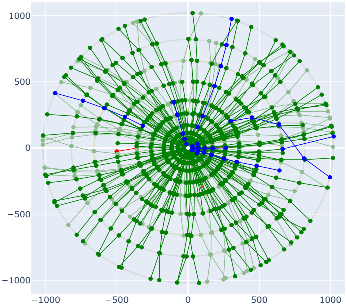


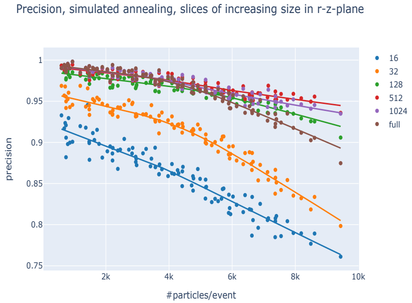
fake rate

Particle Track Reconstruction in an ATLAS-like Detector

(Cigdem Issever, Karl Jansen, Teng Jian Khoo, Stefan Kühn,
Tim Schwägerl, Cenk Tüysüz, Hannsjörg Weber, in preparartion)

> using again Ising Hamiltonian for particle tracking





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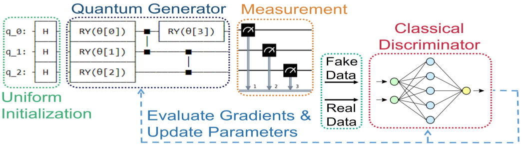
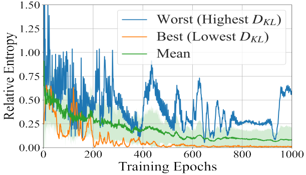
event **precision success probability**

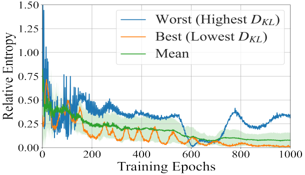
Quantum machine learning

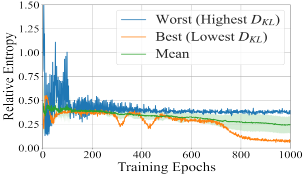
- using **Quantum** Generative Adversarial Networks
  (K. Borras, S.Y. Chang, L. Funcke, M. Grossi, T. Hartung, K.J., D. Kruecker, S. Kühn, F. Rehm, C. Tüysüz, S. Vallecorsa, arxiv:2203.01007)



qgan model







bit-flip probability p=0.01 **p=0.05** **p=0.1**

BMBF project "**Noise in Quantum Algorithms (NiQ)**" → cooperation with IBM Zürich

2+1-dimensional quantum electrodynamics

- lattice Hamiltonian, lattice spacing a, periodic boundary conditions

$$\hat{H}_{\text{gauge}} = \hat{H}_E + \hat{H}_B$$

$$\hat{H}_E = \frac{g^2}{2}\sum_{\boldsymbol{n}}\left(\hat{E}^2_{\boldsymbol{n},\boldsymbol{e}_x} + \hat{E}^2_{\boldsymbol{n},\boldsymbol{e}_y}\right)\ , \hat{H}_B = -\frac{1}{2g^2a^2}\sum_{\boldsymbol{n}}\left(\hat{P}_{\boldsymbol{n}} + \hat{P}^\dagger_{\boldsymbol{n}}\right)$$

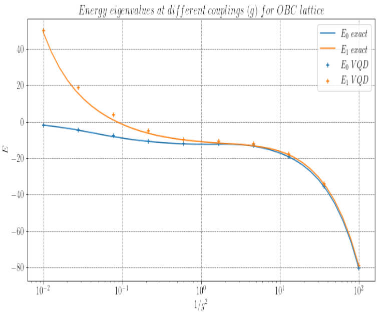
- electric field operator: $\hat{E}_{\boldsymbol{n},\boldsymbol{e}_\mu}\left|E_{\boldsymbol{n},\boldsymbol{e}_\mu}\right\rangle = E_{\boldsymbol{n},\boldsymbol{e}_\mu}\left|E_{\boldsymbol{n},\boldsymbol{e}_\mu}\right\rangle, \quad E_{\boldsymbol{n},\boldsymbol{e}_\mu} \in \mathbb{Z}$
- plaquette operator: $\hat{U}_{ij} = \hat{U}_{ij,e_x}\hat{U}_{ij+e_x,e_y}\hat{U}^\dagger_{ij+e_y,e_x}\hat{U}^\dagger_{ij,e_y}$

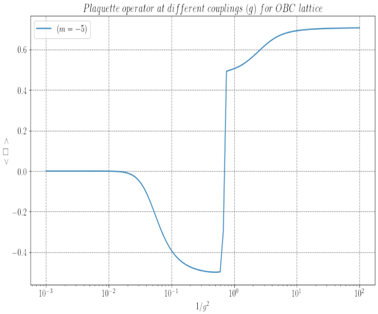
  $\rightarrow$ represented as lowering and raising operators, i.e. $\hat{U}_{ij}|e_{ij}\rangle = |e_{ij} - 1\rangle$
- Gauss law

$$\left[\sum_{\mu=x,y}\left(\hat{E}_{n,e_\mu} - \hat{E}_{n-e_\mu,e_\mu}\right) - \hat{q}_n\right]|\Phi\rangle = 0\forall n \quad \Longleftrightarrow |\Phi\rangle \in \{\ \text{physical states}\ \}$$

Quantum computing 2+1-dimensional quantum electrodynamics

> Variational Quantum Computer Simulations (VQCS) of QED
(G. Clemente, A. Crippa, K. Jansen, arxiv:2206.12454)





Particle mass $\Delta = E_1 - E_0$
$\rightarrow$ physical quantity

detecting a phase transition at negative mass
$\rightarrow$ not possible with Monte Carlo methods

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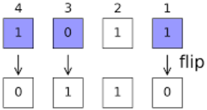
Error mitigation and expressivity of quantum circuits

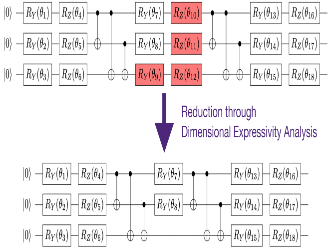
- Quantum computers are noisy: bit-flips in readout process

- analytically correct for readout errors
  (L. Funcke, T. Hartung, S. Kühn, P. Stornati,
  X. Wang, K.J., arxiv:2007.03663, to appear in PRA)



- dimensional expressivity analysis of quantum circuits
  (L. Funcke, T. Hartung, S. Kühn, P. Stornati,
  K.J, Quantum 5 (2021) 422)
  $\rightarrow$ remove superfluous gates
- both methods scale polynomially
  $\Rightarrow$ they are efficient

- methods are developed from applications in
  fundamental research



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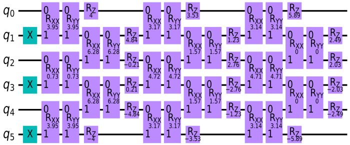
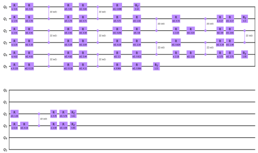
HEQS

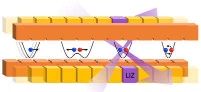
J. Hilder, K. Jansen, M. Lozano, C. Melzer, U. Poschinger, F. Schmidt-Kaler, S. Schuster, J. von Zanthier



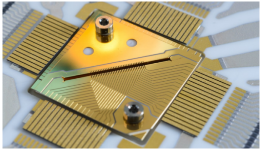
Circuit Compilation



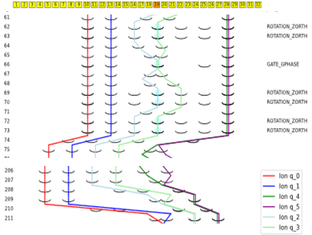
Transfer to Trap



Shuttling Compilation



Execution



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A block course in Aachen

Introduction to Quantum Computing - Open Block Course of the RTG-2497 RWTH Aachen University

11–13 Aug 2021
Zoom
Europe/Berlin timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- Registration
- Participant List

Contact

kerstin.borras@desy.de

Introduction to Quantum Computing

Open Block Course of the RTG-2497 RWTH Aachen University

This open block course of the

Research Training Group (RTG-2497)
"Physics of the Heaviest Particles at the LHC"
at the RWTH Aachen University
http://www.rwth-aachen.de/rtg2497/

provides a comprehensive introduction to quantum computing with a special emphasis on expressivity, error mitigation and machine learning. Please see below for the detailed description.

The lectures take place in the morning and early afternoon and are accompanied by consultation hours in the late afternoon, please note the shifted times in the afternoon of the 12th of August:

- 11 August 2021:
  Stefan Kühn: Introduction to quantum computing I 10:00 - 11:30 a.m.
  Stefan Kühn: Introduction to quantum computing II 1:00 - 2:30 p.m.
- Consultation: 4 - 5 p.m.

- 12 August 2021: ***please note the adjustment of the afternoon lecture and consultation to the usual time slots***
  Stefan Kühn: Introduction to Quantum Computing III 10:00 - 11:30 a.m.
  Lena Funcke: Introduction to Error Mitigation 1:00 - 14:30 p.m.
  Consultation: 4 - 5 p.m.

- 13 August 2021:
  Tobias Hartung: Dimensional Expressivity Analysis 10:00 - 11:30 a.m.
  Pan Kessel: A Lightning Introduction to
  Machine Learning for Quantum Physicists 1:00 - 2:30 p.m.
  Consultation: 4 - 5 p.m.

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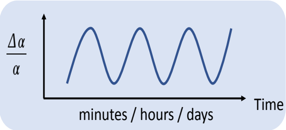
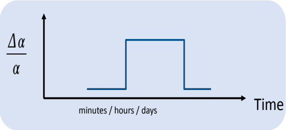
Quantum Sensing & QSNET

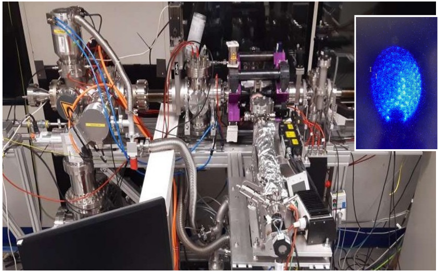
- Clock-based search for variations in alpha — optical atomic clock based on trapped, highly charged ion
- QS essential for ultra-light Dark Matter (eg axion/ALPs)
- Physics beyond colliders: fantastic new tools lead to new, innovative table-top experiments (QSNET)
- Strong links to quantum computing, AP, FS…



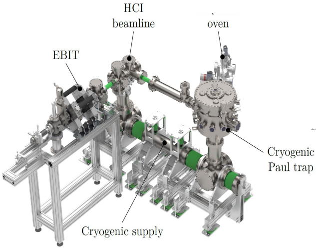
Ultra-light dark matter

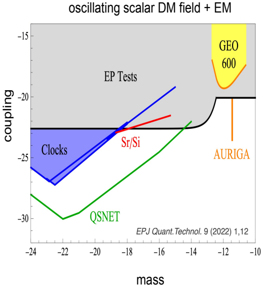


Dark matter, topological defects



EBIT test stand for QSNET (MPIK)





Summary and outlook

- It took 40 years to start realizing Feynman's vision of using quantum computers
- Quantum computing offers the fascinating possibility
  - to address applications very hard or not accessible to classical computers
  - to show a quantum advantage to solve problems
- Presently: we research the second quantum revolution
- For quantum computing
  - identify and evaluate applications for quantum computers
  - develop quantum algorithms and methods
- Midterm: employ quantum computations for solving problems
  → most probably through hybrid quantum/classical algorithms
- Long term: routinely use quantum computers in daily life

Thank you!

Special thanks to IBM Zurich Research Lab for all the support, discussions and cooperation
In particular:
Sieglinde Pfändler, Heike Riel, Ivano Tavernelli, James Wootton and Walter Riess

Thanks also to **Voica Radescu** (IBM Deutschland Research & Development GmbH) for the administrative and technical support for the DESY IBM Hub

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

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