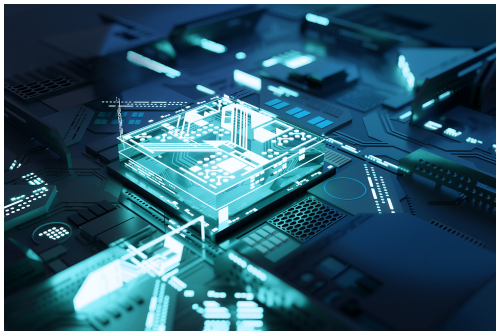
Quanten Computing

Liebenberg meeting

Karl Jansen

Liebenberg, 13.9.2022

Overview



- Center of Quantum Technologies and Applications (CQTA)
- Selected applications at DESY
- Answers to the questions

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

⇒ **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

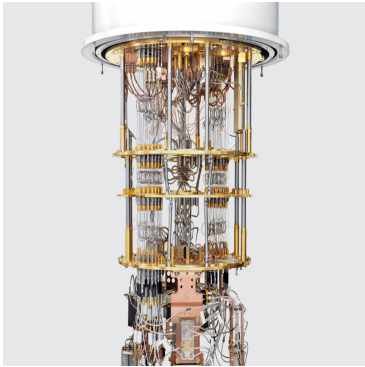
Photon Science
for Quantum Materials and
for Quantum Devices

Quantum Machine Learning
Quantum Simulations

Quantum Sensing

Quantum computer: from the outside

Quantum computer: from the inside

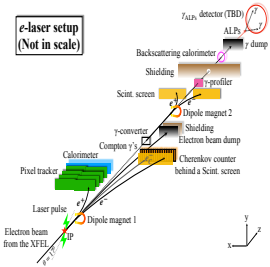


- Shielded to 50,000 times less than Earth's magnetic field
- In a high vacuum: pressure is 10 billion times lower than atmospheric pressure
- Cooled 180 times colder than interstellar space (0.015 Kelvin)
  → prevent quantum noise

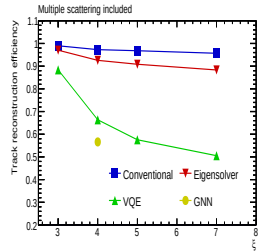
- IBMQ: 433 qubits 2022, >1000 qubits 2023, >4000 qubits 2024
→ 10K to 100K error corrected, parallelized
- Google promise: 1.000.000 qubits 2030, 1000 qubits error corrected

Particle tracking at LASER und XFEL Experiment (LuXE)

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



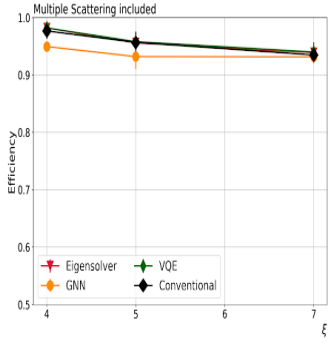
experiment layout



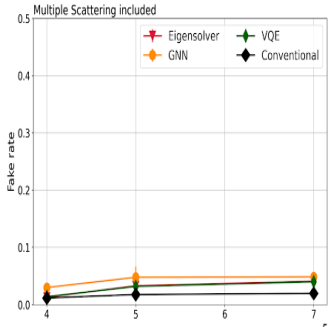
track finding effciency

Particle tracking at LASER und XFEL Experiment (LuXE)

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



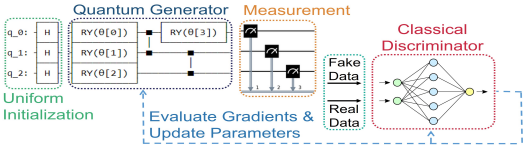
efficiency



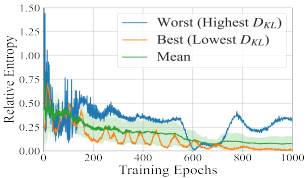
fake rate

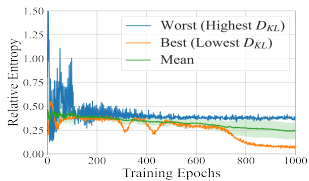
Quantum machine learning

> 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





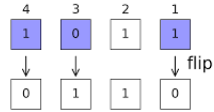
role of noise

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

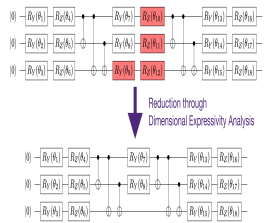
BMBF project **”Noise in Quantum Simulations (NiQ)”**, PI G. Morigi

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)
  → remove superfluous gates
- both methods scale polynomially
  ⇒ they are efficient
- methods are developed from applications in
  fundamental research



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

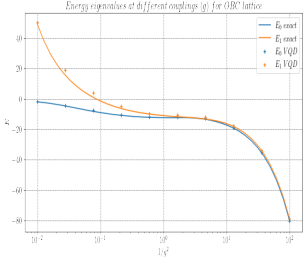
$$\left[\sum_{\mu=x,y} \left(\hat{E}_{n,e_\mu} - \hat{E}_{n-e_\mu,e_\mu} \right) - \hat{q}_n \right] |\Phi\rangle = 0 \forall n \iff |\Phi\rangle \in \{ \text{ physical states } \}$$

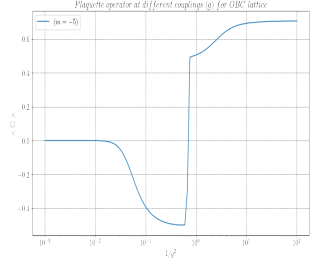
- New development: *Hardware efficient quantum simulation of non-abelian gauge theories with qudits on Rydberg platforms*

  D. Gonzalez-Cuadra, T. Zache, J. Carrasco, B. Kraus, P. Zoller

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

Where are our scientific and technological gold mines?

Citation from quantum task force fact sheet

Quantum computing enabler to solve presently unsolvable challenges in theory and experiment, big data analysis and industrial applications with novel tools beyond classical methods, reaching out to the expected quantum advantage

My own list

- Theory: solve non-abelian gauge theories with topological term, chemical potential, real time evolution
- Experiment: demonstrate quantum computing for real event
- November: common CERN, DESY, IBM workshop to identify potential quantum advantage problem

What are our future applications fields?

- Quantum computing has potential to become a new way of computing in general
  $\Rightarrow$ relevant for many fields
- DESY
  - theory (simulation, Feynman diagrams, PDFs, ...)
  - experiment (particle tracking, anomalies, jet clustering, ...)
  - other areas (optimization problems, ...)

What are our mission-critical research infrastructures?

- Quantum computing
  - Privileged access to quantum hardware
  - Compute clusters for preparation of quantum simulations
- Else see Walter's slide
  - Postdocs and PhD students
  - Travel
  - Space

What are DESY obligations in international collaborations?

- Funding from Brandenburg
- Contract with IBM
- Consortium agreements
  NiQ, T-Nisq, Engage, Stimulate, Era-chair, ...

How can we increase the societal impact of the lab?

Citation from quantum task force fact sheet

With QT, DESY will crucially contribute to disruptive changes in science, business and society. Quantum Computing:

- *Benchmarking, testing and verifying novel and different QC hardware*
- *Dedicated application in optimization problems: logistics, material/medical science, ...*
- *QC calculations for material science, chemistry, biology, medicine ...*
- *Counseling: which QC for which problem (in case of tailor-made QC hardware)*
- *Training and education of a new generation of scientists and engineers.*

Third party funding

Akronym	Projektname	Start	Finanzierungsquelle
Aptivate	Advanced computing, quantum algorithms, and data-driven approaches for science, technology and engineering	tbd	EU
CQTA (inhalt: Projekt)	Center für Quantum Technologie Anwendungen	01.11.2021	MWFK
CQTA (BAU)	Bau des Centers für Quantum Technologie Anwendungen	01.01.2022	MWFK
Engage	Enabling the Next-Generation of Computational Physicists and Engineers	01.01.2022	EU (MSCA)
Einstein Research Unit	Novel application areas from molecular and high-energy physics (Project PA)	01.01.2022	Berlin University Alliance
HEIBRIDS	Helmholtz Einstein International Berlin Research School in Data Science	01.04.2018	HGF / IVF
NiQ	Noise in quantum algorithms	01.02.2022	BMBF
PTB-Training	Quantum-computing Training for Scientists and Engineers	01.01.2023	PTB
Quantum Luxe	Quantum Luxe	01.01.2021	BMBF - Innopool
QUEST (ERA Chair)	Quantum computing for Excellence in Science and Technology	01.01.2023	EU
STIMULATE	Simulation in Multiscale physiCAl and biological sysTEms	01.06.2018	EU
TNiSQ	Tensornetzwerke in Simulationen von Quantenmaterie	tbd	DFG
VQCS	Variational Quantum Computer Simulations for complex quantum systems and optimization problems	01.01.2021	BMBF - Innopool

Thank you!

Special thanks to IBM Zurich Research Lab for all the support and discussions

In particular:
Sieglinde Pfändler, Heike Riel, Ivano Tavernelli, James Wootton and Walter Riess

Contact

DESY. Deutsches Elektronen-Synchrotron
www.desy.de

Karl Jansen
0000-0002-1574-7591
Center for Quantum Technologies and Applications
karl.jansen@desy.de
+49–33762–77XXX