Superconducting qubits in architectures for quantum computing

1 Overview

Course highlights:

- Advanced course with original and review articles as reading material
- Block 4: flexible meeting times but aim for schedule placement B
- 7.5 ECTS
- PhD or masters students
- Prerequisites: Lagrange/Hamilton formulation, Legendre transformation - e.g. Analytical Mechanics.
  Superconductivity, superconducting phase, Cooper pairs - e.g. CMP2 or CMT2.
  Programming (Python or similar, linear algebra, differential equations, basic functions, googling)
- Three hand-in problem sets during the course
- Course responsible: Karsten Flensberg

This course aims to bring masters and PhD students up to date with the foundational literature on superconducting qubits and to the forefront of research. There is a focus on reading contemporary articles and using computational resources to solve, analyze and engineer qubit systems. The course is relevant for interested theorists and experimentalists alike.

An example week could be: Students prepare by reading 2-3 articles. On Mondays, the 2 hour lecture will discuss the key points of the week. On Tuesdays, the students can solve problems together at the 4 hour session (peer-to-peer). On Fridays, the TA will help the students with the problems and go through the most important ones in a 2 hour session.

There are three hand-in problem sets comprised of selected exercises from the course that counts towards the final evaluation of the students.

Learning outcome:

- *Skills:* Solve, analyze and engineer qubit systems using analytical and numerical tools. Read and understand research in the field.
- *Knowledge:* Deep understanding of the field of superconducting qubits. Knowledge of the vast vocabulary used, the intrinsic trade-offs in qubit design and the numerous different qubit variations.
- *Competences:* The students will be able to design, control and analyze both existing and novel qubit systems. The students can compare different systems and assess the pros and cons of each, navigating in the complex space of trade-offs.

2 Curriculum

The curriculum is flexible and may be updated considering the students' preferences. In addition to the curriculum, a number of exercises will be given each week. The course is structured over the 9 weeks of block 4:

- **Week 1: Introduction to circuit quantization and the transmon**

  Keywords: Qubit basics, circuit quantization, transmon, anharmonicity.

  [1, Chapters: I, IIa-b, Fig. 14a] Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. A Quantum Engineer's Guide to Superconducting Qubits. *Applied Physics Reviews*, 6(2):021318, June 2019. arXiv: 1904.06560

  [2, Chapters: 1-2.1, 3.1.1-3.1.2] Uri Vool and Michel Devoret. Introduction to quantum electromagnetic circuits. *International Journal of Circuit Theory and Applications*, 45(7):897–934, jun 2017

  [3, Chapters: I-II, VI] Jens Koch, Terri M. Yu, Jay Gambetta, A. A. Houck, D. I. Schuster, J. Majer, Alexandre Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf. Charge-insensitive qubit design derived from the Cooper pair box. *Physical Review A*, 76(4):042319, October 2007

- **Week 2: Numerical experiments and decoherence**

  Keywords: Phase/charge basis, flux/charge decoherence, T_1, T_2, noise power spectral density.

  [4, Chapters: I-IIIA] Philipp Aumann, Tim Menke, William D. Oliver, and Wolfgang Lechner. CircuitQ: An open-source toolbox for superconducting circuits. *arXiv:2106.05342 [quant-ph]*, June 2021. arXiv: 2106.05342

  [1, Chapter: III] Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. A Quantum Engineer's Guide to Superconducting Qubits. *Applied Physics Reviews*, 6(2):021318, June 2019. arXiv: 1904.06560

  [5, Chapters: 4, App. A] Peter Groszkowski, A Di Paolo, A L Grimsmo, A Blais, D I Schuster, A A Houck, and Jens Koch. Coherence properties of the 0- π qubit. *New Journal of Physics*, 20(4):043053, April 2018

- **Week 3: Single qubit gates**

  Keywords: Microwave control, DRAG, universal gate set, fidelity.

  [1, Chapters: IVA-D] Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. A Quantum Engineer's Guide to Superconducting Qubits. *Applied Physics Reviews*, 6(2):021318, June 2019. arXiv: 1904.06560

  [6] F. Motzoi, J. M. Gambetta, P. Rebentrost, and F. K. Wilhelm. Simple pulses for elimination of leakage in weakly nonlinear qubits. *Phys. Rev. Lett.*, 103:110501, Sep 2009

- **Week 4: The fluxonium qubit**

  Keywords: Artificial atom, heavy fluxonium, Josephson array.

  [7] Vladimir E. Manucharyan, Jens Koch, Leonid I. Glazman, and Michel H. Devoret. Fluxonium: Single Cooper-Pair Circuit Free of Charge Offsets. *Science*, 326(5949):113–116, October 2009

  [8, Chapters: II, IV] Long B. Nguyen, Gerwin Koolstra, Yosep Kim, Alexis Morvan, Trevor Chistolini, Shraddha Singh, Konstantin N. Nesterov, Christian Jünger, Larry Chen, Zahra Pedramrazi, Bradley K. Mitchell, John Mark Kreikebaum, Shruti Puri, David I. Santiago, and Irfan Siddiqi. Blueprint for a high-performance fluxonium quantum processor. *PRX Quantum*, 3:037001, Aug 2022

[9, Chapters: I-II, V-VI] Helin Zhang, Srivatsan Chakram, Tanay Roy, Nathan Earnest, Yao Lu, Ziwen Huang, D. K. Weiss, Jens Koch, and David I. Schuster. Universal fast-flux control of a coherent, low-frequency qubit. *Phys. Rev. X*, 11:011010, Jan 2021

- **Week 5: Two-qubit gates (transmon)**

  Keywords: iSWAP, CPHASE, tunable coupler.

  [1, Chapters: IIC, IVE-H] Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. A Quantum Engineer's Guide to Superconducting Qubits. *Applied Physics Reviews*, 6(2):021318, June 2019. arXiv: 1904.06560

  [10] Fei Yan, Philip Krantz, Youngkyu Sung, Morten Kjaergaard, Daniel L. Campbell, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. Tunable coupling scheme for implementing high-fidelity two-qubit gates. *Phys. Rev. Applied*, 10:054062, Nov 2018

  [11] Youngkyu Sung, Leon Ding, Jochen Braumüller, Antti Vepsäläinen, Bharath Kannan, Morten Kjaergaard, Ami Greene, Gabriel O. Samach, Chris McNally, David Kim, Alexander Melville, Bethany M. Niedzielski, Mollie E. Schwartz, Jonilyn L. Yoder, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. Realization of High-Fidelity CZ and Z Z -Free iSWAP Gates with a Tunable Coupler. *Physical Review X*, 11(2):021058, June 2021

- **Week 6: Two-qubit gates (fluxonium)**

  Keywords: Multi-tone drive, entanglement entropy, low-frequency gates.

  [12] Paolo Zanardi, Christof Zalka, and Lara Faoro. Entangling power of quantum evolutions. *Phys. Rev. A*, 62:030301, Aug 2000

  [8, Chapters: V-VI] Long B. Nguyen, Gerwin Koolstra, Yosep Kim, Alexis Morvan, Trevor Chistolini, Shraddha Singh, Konstantin N. Nesterov, Christian Jünger, Larry Chen, Zahra Pedramrazi, Bradley K. Mitchell, John Mark Kreikebaum, Shruti Puri, David I. Santiago, and Irfan Siddiqi. Blueprint for a high-performance fluxonium quantum processor. *PRX Quantum*, 3:037001, Aug 2022

  [13] Quentin Ficheux, Long B. Nguyen, Aaron Somoroff, Haonan Xiong, Konstantin N. Nesterov, Maxim G. Vavilov, and Vladimir E. Manucharyan. Fast Logic with Slow Qubits: Microwave-Activated Controlled-Z Gate on Low-Frequency Fluxoniums. *Physical Review X*, 11(2):021026, May 2021

- **Week 7: Readout and the C-shunted flux qubit**

  Keywords: Dispersive shift, C-shunted flux qubit, Wigner functions.

  [1, Chapter: V] Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. A Quantum Engineer's Guide to Superconducting Qubits. *Applied Physics Reviews*, 6(2):021318, June 2019. arXiv: 1904.06560

  [3, Chapters: III] Jens Koch, Terri M. Yu, Jay Gambetta, A. A. Houck, D. I. Schuster, J. Majer, Alexandre Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf. Charge-insensitive qubit design derived from the Cooper pair box. *Physical Review A*, 76(4):042319, October 2007

[14] Fei Yan, Simon Gustavsson, Archana Kamal, Jeffrey Birenbaum, Adam P Sears, David Hover, Ted J. Gudmundsen, Danna Rosenberg, Gabriel Samach, S Weber, Jonilyn L. Yoder, Terry P. Orlando, John Clarke, Andrew J. Kerman, and William D. Oliver. The flux qubit revisited to enhance coherence and reproducibility. *Nature Communications*, 7(1):12964, December 2016

- **Week 8: The generalized flux qubit framework and beyond transmon qubit**

  Keywords: Multi-mode qubits, the 0-π qubit, bifluxon, protection.

  [15] Fei Yan, Youngkyu Sung, Philip Krantz, Archana Kamal, David K. Kim, Jonilyn L. Yoder, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. Engineering Framework for Optimizing Superconducting Qubit Designs. *arXiv:2006.04130 [quant-ph]*, June 2020. arXiv: 2006.04130

  [16] András Gyenis, Agustin Di Paolo, Jens Koch, Alexandre Blais, Andrew A. Houck, and David I. Schuster. Moving beyond the Transmon: Noise-Protected Superconducting Quantum Circuits. *PRX Quantum*, 2(3):030101, September 2021

- **Week 9: Scalable architectures and error correction**

  Keywords: Surface code, multi-qubit processors, logical qubits.

  [17] Eric Dennis, Alexei Kitaev, Andrew Landahl, and John Preskill. Topological quantum memory. *Journal of Mathematical Physics*, 43(9):4452–4505, sep 2002

  [18] Sebastian Krinner, Nathan Lacroix, Ants Remm, Agustin Di Paolo, Elie Genois, Catherine Leroux, Christoph Hellings, Stefania Lazar, Francois Swiadek, Johannes Herrmann, Graham J. Norris, Christian Kraglund Andersen, Markus Müller, Alexandre Blais, Christopher Eichler, and Andreas Wallraff. Realizing repeated quantum error correction in a distance-three surface code. *Nature*, 605(7911):669–674, may 2022

3 Workload

- **Lectures:** 2 hours a week $\times$ 9 weeks = 18 hours
- **Problem solving sessions:** 6 hours a week $\times$ 9 weeks = 54 hours
- **Preparation:** 80 hours
- **Hand-in problems (exam):** 6 hours a week $\times$ 9 weeks = 54 hours
- **Total:** 206 hours

References

[1] Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. A Quantum Engineer's Guide to Superconducting Qubits. *Applied Physics Reviews*, 6(2):021318, June 2019. arXiv: 1904.06560.

[2] Uri Vool and Michel Devoret. Introduction to quantum electromagnetic circuits. *International Journal of Circuit Theory and Applications*, 45(7):897–934, jun 2017.

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[6] F. Motzoi, J. M. Gambetta, P. Rebentrost, and F. K. Wilhelm. Simple pulses for elimination of leakage in weakly nonlinear qubits. *Phys. Rev. Lett.*, 103:110501, Sep 2009.

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[8] Long B. Nguyen, Gerwin Koolstra, Yosep Kim, Alexis Morvan, Trevor Chistolini, Shraddha Singh, Konstantin N. Nesterov, Christian Jünger, Larry Chen, Zahra Pedramrazi, Bradley K. Mitchell, John Mark Kreikebaum, Shruti Puri, David I. Santiago, and Irfan Siddiqi. Blueprint for a high-performance fluxonium quantum processor. *PRX Quantum*, 3:037001, Aug 2022.

[9] Helin Zhang, Srivatsan Chakram, Tanay Roy, Nathan Earnest, Yao Lu, Ziwen Huang, D. K. Weiss, Jens Koch, and David I. Schuster. Universal fast-flux control of a coherent, low-frequency qubit. *Phys. Rev. X*, 11:011010, Jan 2021.

[10] Fei Yan, Philip Krantz, Youngkyu Sung, Morten Kjaergaard, Daniel L. Campbell, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. Tunable coupling scheme for implementing high-fidelity two-qubit gates. *Phys. Rev. Applied*, 10:054062, Nov 2018.

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[12] Paolo Zanardi, Christof Zalka, and Lara Faoro. Entangling power of quantum evolutions. *Phys. Rev. A*, 62:030301, Aug 2000.

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[18] Sebastian Krinner, Nathan Lacroix, Ants Remm, Agustin Di Paolo, Elie Genois, Catherine Leroux, Christoph Hellings, Stefania Lazar, Francois Swiadek, Johannes Herrmann, Graham J. Norris, Christian Kraglund Andersen, Markus Müller, Alexandre Blais, Christopher Eichler, and Andreas Wallraff. Realizing repeated quantum error correction in a distance-three surface code. *Nature*, 605(7911):669–674, may 2022.