Quantum Technology (QT)

New track as of WS 2019!
What is Quantum Technology (QT)?

Quantum technology is a novel field of physics and engineering, which exploits quantum entanglement, quantum superposition and quantum coherence for practical applications such as:

- quantum communication (or cryptography),
- quantum computing, Major research focus at RWTH and FZJ
- quantum sensors (or metrology), and
- quantum simulation.
Quantum Computing

What is the difference between classical and quantum computers?

**Classical bits**
0 or 1

N bits => $2^N$ states 0, 1, ..., $2^N-1$

**Quantum bits**

$$\alpha |0\rangle + \beta |1\rangle$$

N qubits: $2^N$ dimensional Hilbert space

$|0\rangle, |1\rangle, ..., |2^N-1\rangle$

**Principles of quantum mechanics**

⇒ Built-in parallelism

⇒ **Exponential speedup** (for some problems)

Fundamentally different physical principles to boost computing power.
Quantum Computing

What is the difference between classical and quantum computer?

Classical arithmetic

Quantum logic

Principles of quantum mechanics
⇒ Built-in parallelism
⇒ Exponential speedup (for some problems)

Biggest change of paradigm since invention of the abacus!
Applications

… with practical relevance.

Prime factorization and decryption

Quantum Chemistry
• Quantum material design
• Catalyst design for CO$_2$ capture or fertilizer production
  => Societal and economic impact

Information security
  => Consumer application
Quantum bits (qubits)

Electron spin qubits

Majorana Qubits

Trapped Ions

Superconducting Qubits
Superconducting qubits

- Use zero-resistance electrical circuits to represent quantum states.

- A key circuit element are Josephson junctions (superconducting tunnel contacts).

- Charge, flux, current, phase, … have been explored to encode qubit state.

**Transmon**: A weakly anharmonic quantum oscillator

**Flux qubit**: State represented by current in loop

![Josephson junctions](image)

Equivalent circuit

![Microwave cavity for control, readout, coupling](image)

Low-loss capacitor

![2 µm](image)

100 µm
Spin qubits

Defining feature: Use spin of confined electrons (or holes)
Confinement via combination of material interfaces/band structure engineering and electrostatics

⇒ Fabrication with standard semiconductor technology

Record-setting lifetime of quantum states an control accuracy at RWTH.
Long-term goal

Dilution refrigerator

Temperature $= 0.1$ K

Quantum computer with millions of qubits and highly integrated control system.

1 $\mu$m
Research questions

• How do qubits loose their coherence? How can their lifetime be extended?

• How can they be controlled and coupled to each other?

• Multi-qubit circuits

• Spin-photon conversion

• How can errors be corrected (quantum error correction)

• Discover new applications
Local research groups (RWTH and FZJ)

**Experimental**
- Prof. Hendrik Bluhm
- Prof. Beata Kardynal
- Prof. Thomas Schäpers
- Prof. Markus Ternes
- PD Dr. Alexander Pawlis
- Dr. Lars Schreiber

**Theory**
- Prof. David DiVincenzo
- Prof. Fabian Hassler
- Prof. Kristel Michelson
- Prof. Markus Müller
- Prof. Barbara Terhal (FZJ*/ TU Delft)
- Dr. Gianluigi Catelani

+ New groups!
Cluster of Excellence

ML$^4$Q MATTER AND LIGHT FOR QUANTUM COMPUTING

Research mission
“Optically-linked, fault-tolerant quantum computing modules capable of both processing and networking”

Teaching aspects
• Integrated research school
• Courses at Bonn and Cologne also accessible

Participating universities:

(Managing)

Non-university partner:
Quantum Technology (QT) study track @RWTH

M.Sc. in Physics, new study track starting winter semester 2019/2020.

• Focus on quantum information and quantum technology topics

• Also provides strong condensed matter background

• Addresses both theory and experiment

Also offered
M.Sc. in Electrical Engineering, Information Technology and Computer Engineering, part of study track Micro- and Nanoelectronics (MINA).
## Curriculum – QT

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<thead>
<tr>
<th>Department of Physics</th>
<th>Faculty of Electrical Engineering and Information Technology</th>
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<tr>
<td><strong>Winter semester (Total 30 ECTS)</strong></td>
<td><strong>Winter semester (Total 32 ECTS)</strong></td>
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<tr>
<td>Condensed matter physics I or Quantum theory of condensed matter I or Theoretical solid state physics – 10 ECTS</td>
<td>Compound Semiconductors and Optical Components and High Frequency Electronics and Solid state technology and VLSI-Design for Digital Signal Processing - Fundamentals – 16 ECTS</td>
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<tr>
<td>Hardware platform for QT – 5 ECTS</td>
<td>Hardware platform for QT – 4 ECTS</td>
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<tr>
<td>Elective courses¹ – 15 ECTS</td>
<td>Elective courses² – 8 ECTS</td>
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<td><strong>Summer semester (Total 30 ECTS)</strong></td>
<td><strong>Summer semester (Total 32 ECTS)</strong></td>
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<tr>
<td>Quantum Information – 10 ECTS</td>
<td>Quantum Information – 8 ECTS</td>
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<tr>
<td>Lab course quantum technology – 5 ECTS</td>
<td>Lab course quantum technology – 4 ECTS</td>
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<td>Elective courses² – 20 ECTS</td>
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<tr>
<td><strong>Winter semester (Total 30 ECTS)</strong></td>
<td><strong>Winter semester (Total 26 ECTS)</strong></td>
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<tr>
<td>Master’s seminar and practical – 30 ECTS</td>
<td>Master’s internship – 22 ECTS</td>
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<tr>
<td></td>
<td>Elective courses² – 4 ECTS</td>
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<tr>
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¹ Physics and ² Electrical Engineering
Bold – Compulsory course