ML4Q CLUSTER OF EXCELLENCE

ANNUAL REPORT 2019

ML4Q

MATTER AND LIGHT FOR QUANTUM COMPUTING

University of Cologne

RWTH AACHEN UNIVERSITY

UNIVERSITÄT BONN

JÜLICH Forschungszentrum


ANNUAL REPORT 2019

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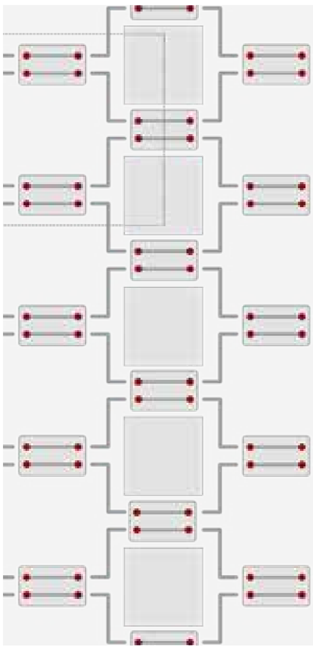

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ML4Q
ANNUAL REPORT 2019

The Cluster of Excellence "Matter and Light for Quantum Computing" (ML4Q) was newly founded in 2019 in the context of the Excellence Strategy of the German Federal Government with generous financial support from the German Research Foundation (DFG). ML4Q is based on the partnership between the universities of Cologne, Bonn and Aachen as well as the Research Center Jülich to foster synergistic research on quantum information technologies. Our vision is to develop the key technologies to realize scalable quantum computers and to network them, which will open the door to the quantum information age. Just as the internet has changed our lives in a fundamental way, the "quantum internet" is expected to bring about another fundamental change to the society for the better, although we don't know its full potential yet.

There are five Clusters of Excellence founded in the field of quantum science and technologies in Germany. Those five clusters have formed a cooperation framework named "Quantum Alliance", so that we can better respond to the political and societal developments when it comes to anything "Quantum". Among the five clusters, ML4Q is unique in that it has a strong focus on quantum computing. In recent years, societal expectations for quantum computers are significantly heightened, which was a tailwind to the launch of ML4Q. Nevertheless, there is a lot of hypes around quantum computing, and we, as an academic consortium, are determined to make solid and long-lasting contributions to quantum computing by performing fundamental research based on matter and light.

When one looks back into the past, there are certain events that are perceived to have happened as a matter of course. For many people, the installation of ML4Q may be one of such cases: It's a natural outcome of the recent accumulation of expertise in Cologne, Aachen, Bonn, and Jülich in physics due to new hires; the strengths of the four institutions are very much complementary to each other; the research field of quantum computing & communication is booming and there are strong reasons, both scientific and political, to join forces. However, the actual birth of ML4Q was far from a matter of course, and it took a lot of brainstorming and detours before we arrived at our defining concept. I am very pleased that we are fortunate enough to be given the opportunity to contribute to the exciting field of quantum information technologies and to bring you this first annual report showing how ML4Q is progressing towards its goals.

As you will see in the following pages, ML4Q is currently involving 151 members and associated members in our research programs and this number will grow further, since we plan to hire 7 new professors.

We pay particular attention to promoting young scientists and equal opportunities. To foster collaborations between different sites to create synergy, we have introduced various mechanisms such as the Focus Area structure, shared research facilities, and the ML4Q Research School. Also, efficient use of the online-meeting format greatly facilitates the communications within ML4Q. I hope that this annual report will give you a glimpse of how ML4Q makes use of the resources made available to us to set the foundation of future quantum information technologies through excellent fundamental research.

ML4Q
AT A GLANCE

01

ML4Q
AT A GLANCE

ML4Q stands for Matter and Light for Quantum Computing. The Cluster of Excellence set off in 2019 for a long collaborative journey in order to develop new computing and networking architectures using new findings in the fundamental research in solid-state physics, quantum optics and quantum information.

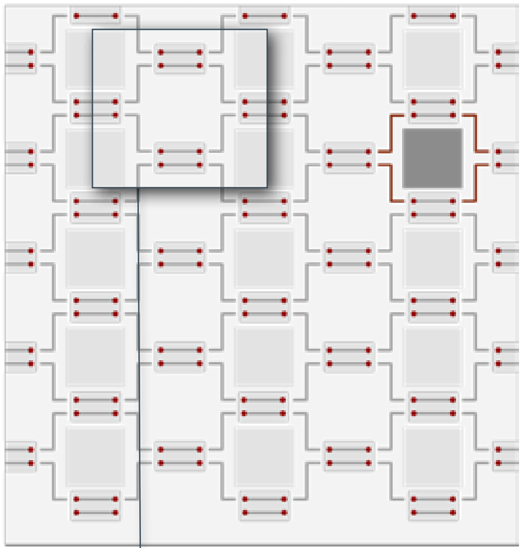
THE CLUSTER'S MISSION

Using the principles of quantum mechanics, it is the long-term goal of ML4Q to develop new computing and networking architectures with a power beyond anything classically imaginable. Quantum computers could be powerful tools in key areas such as materials design, pharmaceutics, or artificial intelligence. Quantum communication could be made effectively secure. ML4Q builds on the complementary expertise in the three key research fields of solid-state physics, quantum optics, and quantum information science to develop the best hardware platform for quantum information technology, and provide comprehensive blueprints for a functional quantum information network.

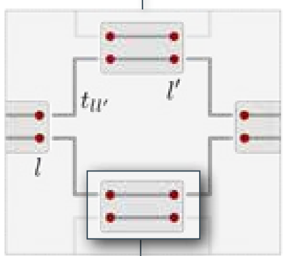
The long-term goal of the cluster is to realize network and processing architectures protected by error-correction protocols and eventually connected to a quantum version of the internet.
This goal defines a hierarchy of challenges, both in fundamental science and in technology, which must be overcome at early and intermediate stages.

qubits	processing	connectivity
for information storage	quantum information	through quantum links

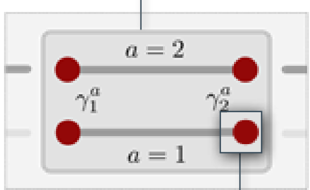
THE VISION



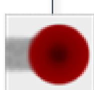
The processor units of a network comprise arrays of qubits whose implementation requires scalable designs. We envision to realize these units by the end of the second funding period.



The ML4Q core projects are dedicated to the development of both spin qubit platforms as well as topologically protected Majorana qubits as an alternative platform with the prospect of superior performance in the long term.



As Majorana-based quantum information hardware is still in its infancy, major intermediate challenges need to be overcome. These include the actual engineering of Majorana qubits.



On an even more fundamental level, the realization and optimization of quantum materials harboring Majorana states are goals for the first two years of the running period.

THE SCIENTIFIC APPROACH

The scientific structure of ML4Q spans four Focus Areas, each addressing a specific set of problems relevant to the cluster's mission. All Focus Areas include theoretical as well as experimental components and transcend the boundaries of disciplines and institutions.

- **Focus Area 1** aims to identify and explore novel topological hardware platforms for quantum information processing, including hybrid structures of topological insulators and superconductors as well as the ways to realize parafermions.
- **Focus Area 2** aims to realize Majorana qubits as a promising alternative to superconducting qubits or spin qubits. In parallel, protocols for readout, manipulation, and error correction are designed.
- **Focus Area 3** designs novel schemes of quantum control, error correction and mitigation. It investigates the operation of quantum devices under realistic noisy environmental conditions and explores topological and computational quantum matter subject to external driving.
- **Focus Area 4** focuses on the linkage of quantum processing units. Specifically, it will take steps towards realizing integrated atomic/optical and solid-state platforms and implementing quantum links between heterogeneous qubit setups.

OPPORTUNITIES FOR YOUNG SCIENTISTS

Attracting and retaining the best young talents in the field by offering competitive career opportunities is a top priority for ML4Q. Current offers include:

- Undergraduate grants
- Independence grants for postdoctoral researchers
- New tenure-track professorships
- ML4Q Research School with cluster-specific courses, e.g. "Platforms for Quantum Technologies" for Master students
- Master program for Quantum Technology in Aachen as well as specialized lectures on quantum technologies in Bonn and Cologne

PARTICIPATING INSTITUTIONS

ML4Q is a cooperation by the University of Cologne, University of Bonn, RWTH Aachen University as well as the Research Center Jülich. Partner institutions are the Heinrich Heine University Düsseldorf, the Fraunhofer Institute for Laser Technology ILT and the Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR.

FUNDING

ML4Q is funded within the Excellence Strategy by the German Research Foundation (DFG) since January 2019. The first funding period ends in 2025.

ML4Q **IN NUMBERS**

151

MEMBERS AND ASSOCIATES

39

PROFESSORS

52

INTERNATIONAL SCIENTISTS

58

PHD STUDENTS

25

FEMALE SCIENTISTS

9

ADMINISTRATIVE & TECHNICAL STAFF

4

UNIVERSITIES

22

PUBLICATIONS IN 2019

35

POSTDOCS

3

NON-UNIVERSITY RESEARCH INSTITUTIONS

10

PUBLICATIONS IN 2019

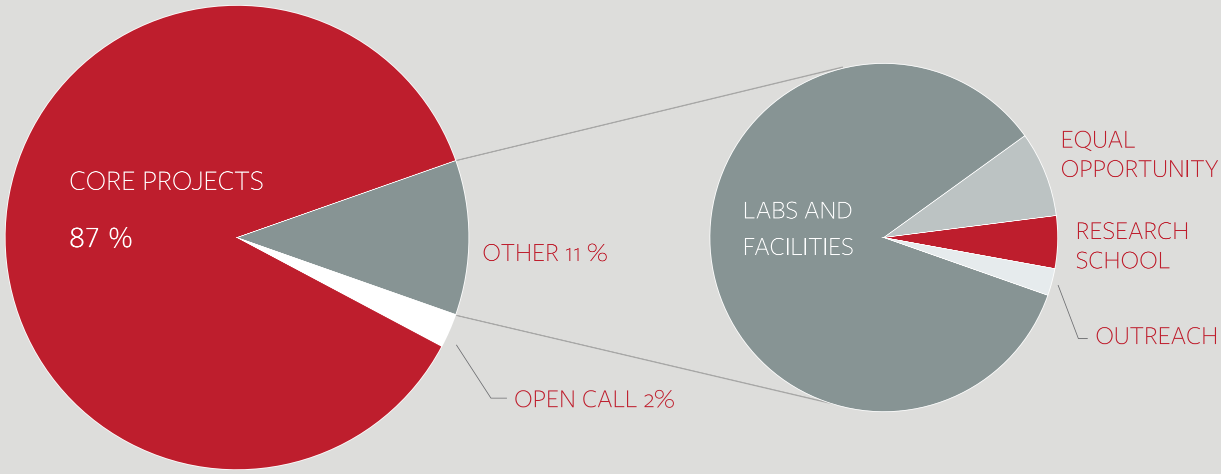
WITH TWO OR MORE ML4Q GROUPS INVOLVED (3 CROSS-SITE PUBLICATIONS)

> “We want to contribute to accelerating the promising developments this field has seen in the recent years.

YOICHI ANDO

ML4Q **IN NUMBERS**

CORE PROJECTS & CENTRAL MEASURES



In 2019, 87% of the expenses were dedicated to personnel, instrumentation and consumables in the core projects. 2% were allocated to Open Call projects. Expenses for supporting measures (equal opportunity, ML4Q Research School, outreach), labs and facilities (Fiber Lab, ML4Q Devices and central office) made up about one-tenth of the annual budget.

All Focus Areas include theoretical as well as experimental components bringing different needs for personnel, consumables and instrumentation. Here is an overview of the allocation of core project funds in 2019 broken down by Focus Area and type of fund.

INTERNATIONALISATION

Postdoctoral scientists have shown in 2019 the highest level of internationalization. Almost 35% of ML4Q members and associated members are international scientists coming from over 20 countries (see map below). For 2020/21, ML4Q aims at attracting top international researchers to faculty positions offered in Cologne, Bonn and Aachen in both theoretical as well as experimental physics.

AUSTRIA	GREECE	ROMANIA
BELGIUM	INDIA	RUSSIA
BRAZIL	IRAN	SWEDEN
CANADA	ITALY	SWITZERLAND
CHINA	JAPAN	UKRAINE
FRANCE	NETHERLANDS	UNITED KINGDOM
GEORGIA	POLAND	USA

FIRST DEVELOPMENTS IN 2019

Recognizing the fast-moving research field of quantum science and technologies, it was one of the most vital measures envisioned by ML4Q to implement an Open Call funding line, complementing the core projects. The first call for proposals was opened very early on (March 2019) in order to respond quickly to new developments, be ready to pick up ideas, and implement new collaborations. A second call was launched by the end of 2019. In total, about a dozen proposals were accepted, both strengthening existing core projects and enabling new collaborations. The most noteworthy benefit of the Open Call strategy is the low-bureaucracy process that brings new groups and institutions into the cluster in an agile manner. This way ML4Q was able to extend its collaborative network with the Fraunhofer Society to include the Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR at Wachtberg as well as the Fraunhofer Institut for Laser Technology (ILT).

Workshops organized in the first year aimed at kick-starting ML4Q-internal collaboration, in particular across the different cluster sites. The first kick-off workshop was held in January 2019 and brought together all principal investigators and cooperation partners. Focus Area meetings were introduced in order to insure successful cross-site project coordination. On the individual core project level, mini-workshops included further staff from the participating groups and enabled a regular assessment of project progress, identification of potential threats and discussion of future strategies.

As for the hiring status, the majority of approved scientific positions has been filled throughout 2019. The recruitment of the seven new professorships to be established in Cologne, Bonn and Aachen is planned to start in 2020. On the administration level, the ML4Q office was almost fully staffed by the end of the first funding year, leaving the position for public outreach to be advertised in the beginning of 2020.

Finally, exciting new opportunities for students emerged as existing and new Master programs became accessible for students at all cluster sites. For the first time, cluster groups in Aachen were involved in the Master student recruiting rounds of the Bonn-Cologne Graduate School of Physics and Astronomy. In turn, Master students in Cologne and Bonn can benefit from a novel Master study-track on Quantum Technology, starting from the winter semester 2019/20 at RWTH Aachen.

ML4Q
RESEARCH

02

FOCUS AREA 1: Fundamentals and technology for topological interfaces

P1.1: Optimizing interfaces between topological insulators and superconductors

P1.2: Topological-insulator nanowires for Majorana states

P1.3: Controlling and probing of ultraclean interfaces

P1.4: Majorana states and parafermions in ultracold-atom systems

FOCUS AREA 2: Majorana qubits

P2.1: Majorana qubits based on topological-insulator nanowires

P2.2: Alternative platforms for Majorana qubits

P2.3: Advanced Majorana-qubit designs

FOCUS AREA 3: Decoherence, measurements, and error correction

P3.1: Topology in and out of equilibrium

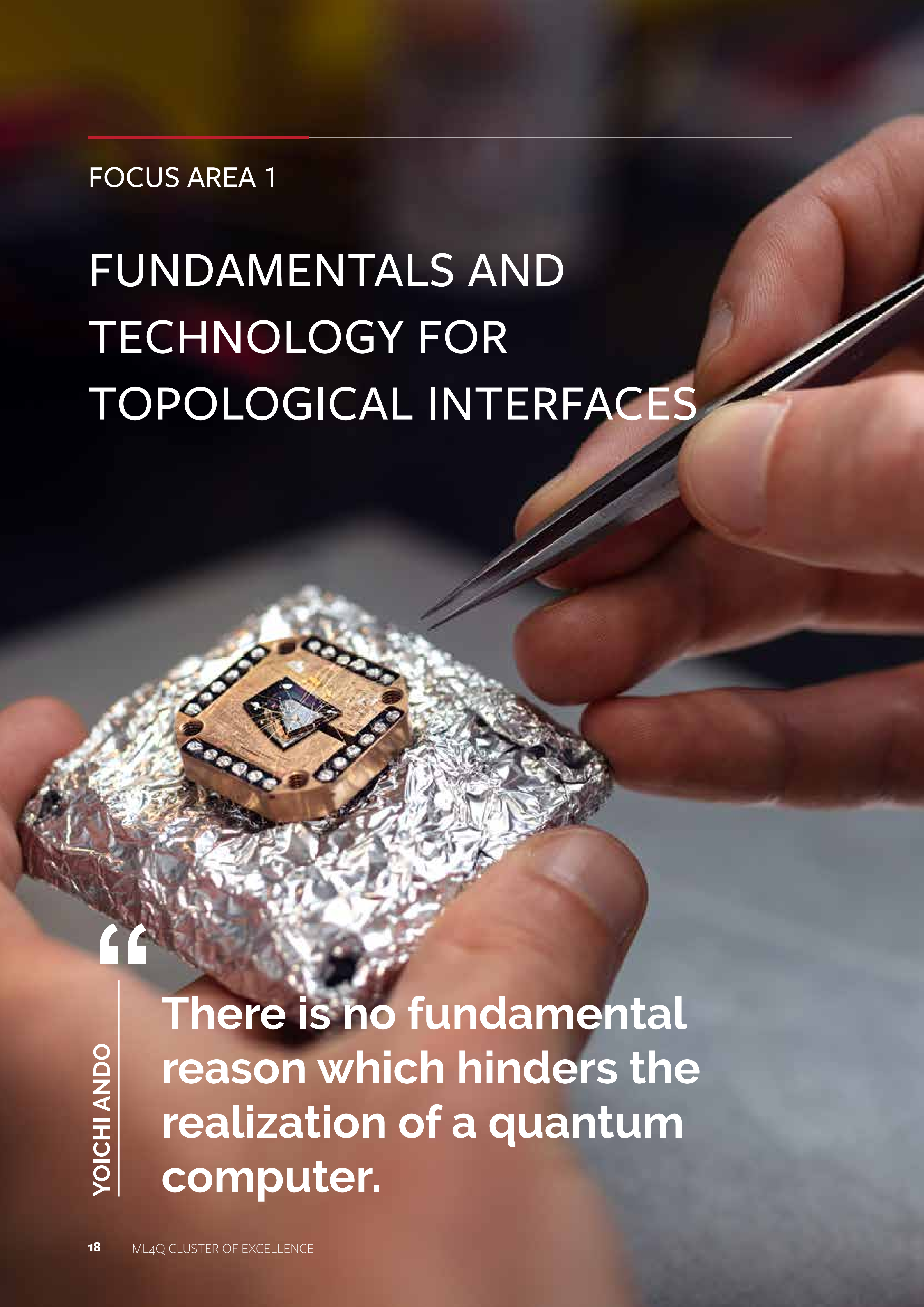
P3.2: Theory of error characterization, mitigation, and correction

P3.3: Electron shuttling for spin-qubit surface code

FOCUS AREA 4: Quantum connectivity

P4.1: Multipartite quantum networks

P4.2: Quantum links

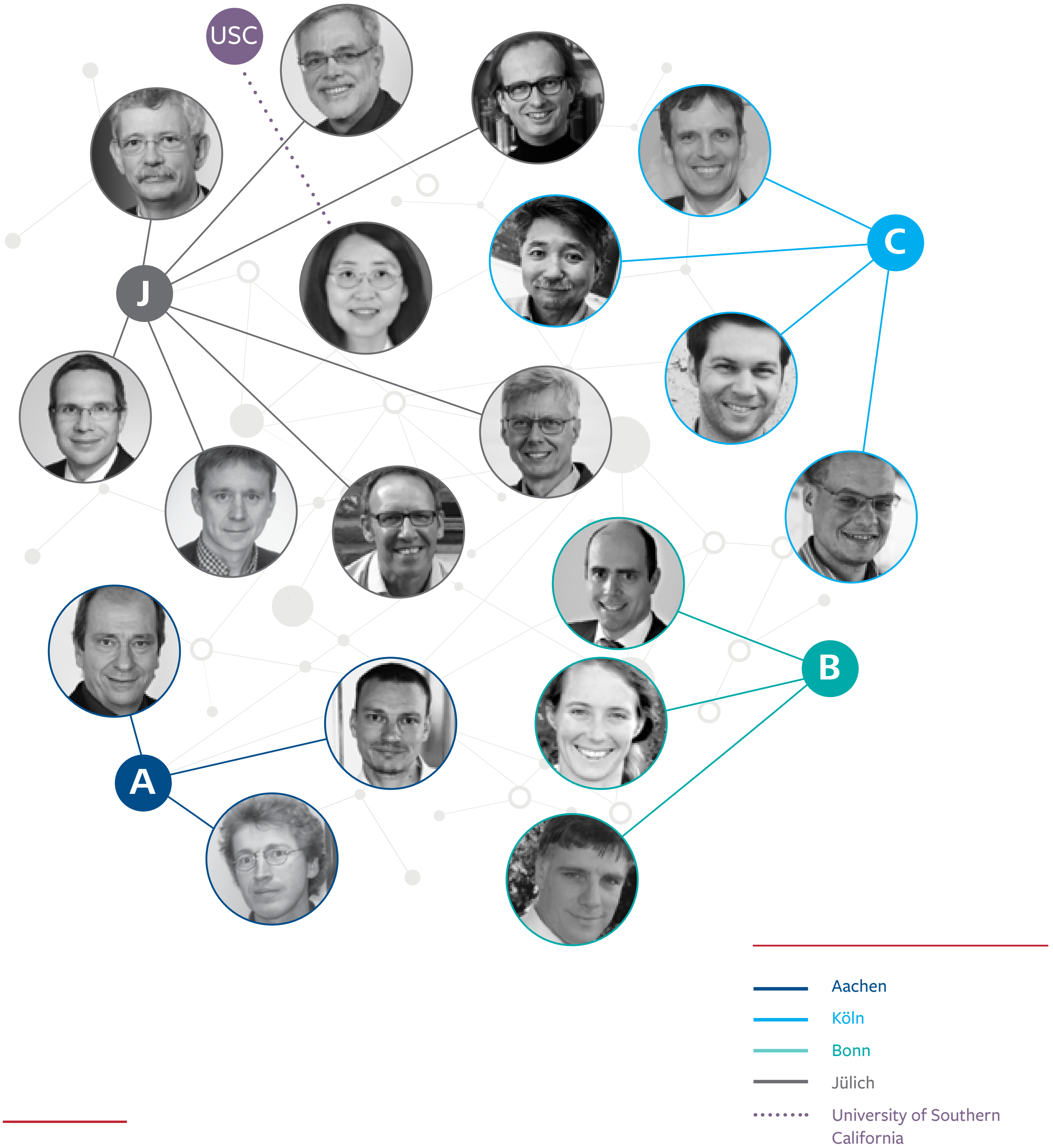


FOCUS AREA 1

FUNDAMENTALS AND TECHNOLOGY FOR TOPOLOGICAL INTERFACES

"There is no fundamental reason which hinders the realization of a quantum computer.

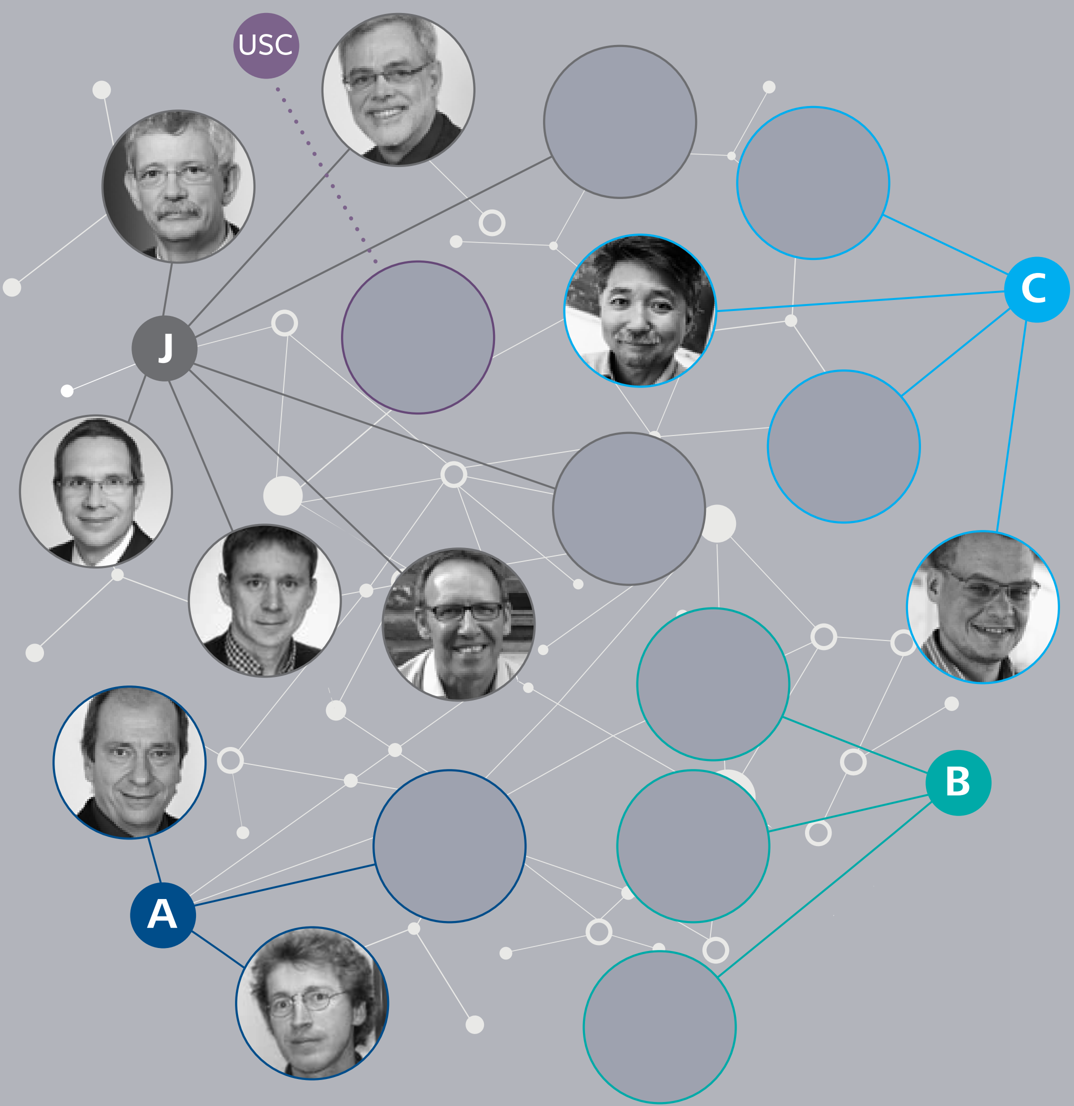
YOICHI ANDO



Focus Area 1 comprises four projects on materials and hybrid structures hosting topological edge modes such as Majorana states and explores how such edge states can be optimized for their use as building blocks of quantum information technologies. More than 15 research groups are collaborating in order to investigate hybrid structures based on topological insulators and superconductors and use ultracold atoms to realize Majorana states and parafermions controlled by light.

A central goal of *Focus Area 1* is to explore the stability of topological edge states determined by their interaction with thermal quasiparticles and impurity states in all these systems. In order to prepare ultraclean interfaces and devices, new fabrication methods in ultra-high vacuum are being developed. This is complemented by novel ab-initio approaches able to predict quantitatively how superconductors can penetrate into spin-orbit coupled matter via the proximity effect.

P1.1 OPTIMIZING INTERFACES BETWEEN TOPOLOGICAL INSULATORS AND SUPERCONDUCTORS



1
FOCUS AREA

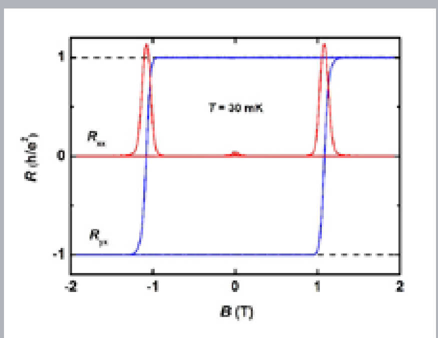


Figure 1: Experimental data to show the realization of the quantum anomalous Hall effect achieved recently in Cologne. The Hall resistance R^{yx} shows the exact quantization to h/e^2, while the longitudinal resistance Rx^x becomes zero.

ACHIEVEMENTS

The Ando group worked on finding viable ex-situ recipes for inducing robust superconductivity in the surface states of bulk-insulating topological insulators (TIs), where it turned out to be much more difficult to induce superconductivity compared to the surface of bulk-conducting TIs. While the group has reported in 2018 that using thin Pt as a buffer layer between aluminum and bulk-insulating $BiSbTeSe_2$ flakes gives a high-quality interface with the transparency of about 0.8, it turned out that this recipe is not very reproducible, depending heavily on the deposition condition of the aluminum layer. Finally, new recipes could be established in order to induce superconductivity with sputtered Nb in bulk-insulating $BiSbTeSe_2$ flakes and in bulk-insulating $Bi_{2-x}Sb_xTe_3$ thin films with ex-situ processes, obtaining the transparency of up to 0.8.

Besides the above-mentioned efforts for SC/TI interface improvements, the Ando group has serendipitously discovered that simple sputter deposition of Pd layer on $Bi_{2-x}Sb_xTe_3$ thin films leads to spontaneous formation of epitaxial PdTe2 superconducting layer through diffusion of Pd into $Bi_{2-x}Sb_xTe_3$ [1]. By making Josephson-junction and SQUID devices, we have demonstrated that this self-epitaxy gives a highly transparent SC/TI interface [1]. The close collaboration between the Ando group and the Mayer group on the TEM analysis of this Pd/$Bi_{2-x}Sb_xTe_3$ system greatly helped the understanding of its structure, and further analysis to understand the mechanism of this self-epitaxy is going on.

The core project P2.2 in the FA2 aims at using chiral Majorana states generated in proximitized quantum anomalous Hall insulator (QAHI) for Majorana qubits, and P1.1 is responsible for growing the necessary QAHI samples. In 2019, the MBE growth of V-doped $Bi_{2-x}Sb_xTe_3$ ferromagnetic TI thin films was greatly advanced in Cologne thanks to the installation of a new MBE machine manufactured by MBE Komponenten, and the R_{yx} value close to the expected 25.8 kOhm has been observed. (In March 2020, the full quantization of R_{yx} with vanishing R_{xx} has finally been achieved, see below the figure on page 18, putting Cologne among the few groups worldwide to realize the QAHI sample.)

In Jülich, a second MBE system was successfully mounted to grow TI material. This new MBE system is connected to the Helmholtz Nanocluster which connects a total of 8 deposition chambers. This allows growing TI/SC structures fully in-situ via the Jülich process without the use of the vacuum suitcase, which yields to a substantially higher throughput of samples (i.e. 4 samples per day compared to 2 samples per week). In this way, structured TI/SC samples were grown by the Jülich process and capped with amorphous Se. Such samples were ex-situ transferred to the Morgenstern group at RWTH Aachen to carry out STM experiments. We could successfully remove the Se by heating in order to obtain a pristine surface with atomic resolution. Unfortunately, the substrate's doping level was not high enough to carry out the STM analysis at very low temperatures where superconductivity is induced. New TI/SC samples grown on substrates with sufficiently high doping levels (rho < 0.005 Ohm.cm) are being grown.

Coordinator:

Detlev Grützmacher

Participants:

Yoichi Ando

Stefan Blügel

Alexander Grüneis

Joachim Mayer

Markus Morgenstern

Gregor Mussler

Lukasz Plucinski

Thomas Schäpers

PUBLICATIONS

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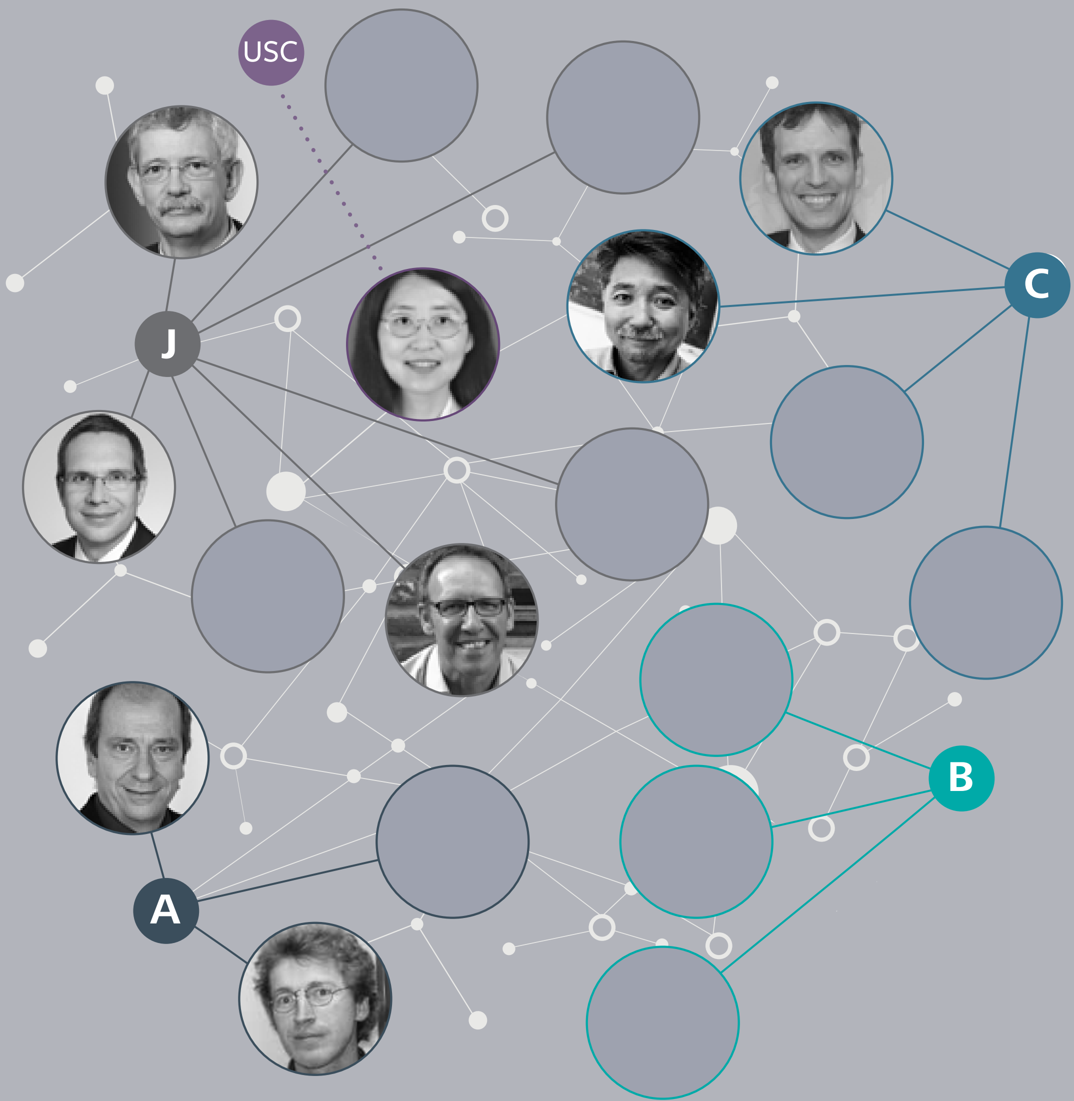
[3] Felix Jekat, Benjamin Pestka, Diana Car, Saša Gazibegović, Kilian Flöhr, Sebastian Heedt, Jürgen Schubert, Marcus Liebmann, Erik P. A. M. Bakkers, Thomas Schäpers, and Markus Morgenstern, Exfoliated hexagonal BN as gate dielectric for InSb nanowire quantum dots with improved gate hysteresis and charge noise, arXiv:2001.08461 (2020)

P1.2 TOPOLOGICAL-INSULATOR NANOWIRES FOR MAJORANA STATES



1 FOCUS AREA

ACHIEVEMENTS

Topological-insulator (TI) nanowire growths have been successfully performed using various techniques and for various compounds in Cologne and Jülich. The Jülich team focuses on selective-are-growth (SAG) method, while the Cologne team pushes three methods in parallel: vapor-liquid-solid (VLS) method, top-down etching method, and the SAG method. We have already achieved an important milestone, growth of bulk-insulating TI nanowires and realization of a few 1D modes in such wires. This was done in Cologne through successful tuning of the composition of $Bi_{2-x}Sb_xTe_3$ nanowires grown via the VLS method, in which the nanowire diameter was reduced down to about 30 nm [1]. In such nanowires, we were able to directly observe the peculiar subband formation of the Dirac surface states via resistance oscillations upon sweeping the chemical potential across the Dirac point by gating [1].

At the unpublished level, the Cologne team has achieved the top-down fabrication of bulk-insulating nanowires of $Bi_{2-x}Sb_xTe_3$ by etching MBE-grown thin films, and successfully observed the Aharonov-Bohm-like oscillations as well as its ϖ phase shift as a function of gate voltage; the data analysis is going on in collaboration with the Rosch group. In Jülich, various quantum transport signatures have been successfully observed in SAG nanowires of $Bi_{2-x}Sb_xTe_3$ and Bi_2Te_3 (although bulk-conducting) and they are used for quantitative characterizations of the nanowires. In particular, their magnetotransport measurements found interesting anisotropy of the phase coherence length with respect to the orientation of the applied magnetic fields. In addition, the Jülich team is growing thin films of Bi_xTe_y phases such as Bi_1Te_1, Bi_4Te_3 and Bi_7Te_8, which were characterized by TEM, ARPES, and transport. The choice of substrate for the SAG nanowires at Jülich is being extended beyond Si(111).

To realize Majorana states, these TI nanowires must be proximitized by an s-wave superconductor. In this regard, the Jülich team has developed a lithography process to fabricate Nb Josephson junctions in-situ in the MBE chamber on the SAG-patterned TI films and observed a Shapiro-step anomaly in a wide junction, which is a possible signature of Majorana states [4]. The Jülich team is trying this technique also for SAG nanowires, but so far no Shapiro-step anomaly has been observed. The Cologne team has succeeded in establishing an interface cleaning protocol to induce robust superconductivity in VLS and top-down etched nanowires using Nb. The interface between TI and a superconductor (Nb, Al, or Pt/Al) has been analyzed by TEM, which gave useful insight about inter-diffusion.

Coordinator:
Yoichi Ando

Participants:
Detlev Grützmacher
Grace Lu
Joachim Mayer
Markus Morgenstern
Gregor Mussler
Achim Rosch
Thomas Schäpers

PUBLICATIONS

[1] Felix Münning, Oliver Breunig, Henry F. Legg, Stefan Roitsch, Dingxun Fan, Matthias Rößler, Achim Rosch, and Yoichi Ando, Quantum confinement of the Dirac surface states in topological-insulator nanowires, arXiv:1910.07863 (2019)

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[3] Lionel Andersen, Aline Ramires, Zhiwei Wang, Thomas Lorenz, and Yoichi Ando, Generalized Anderson's theorem for superconductors derived from topological insulators, Science Advances 6, eaay6502 (2020, made public in 2019 as arXiv:1908.08766)

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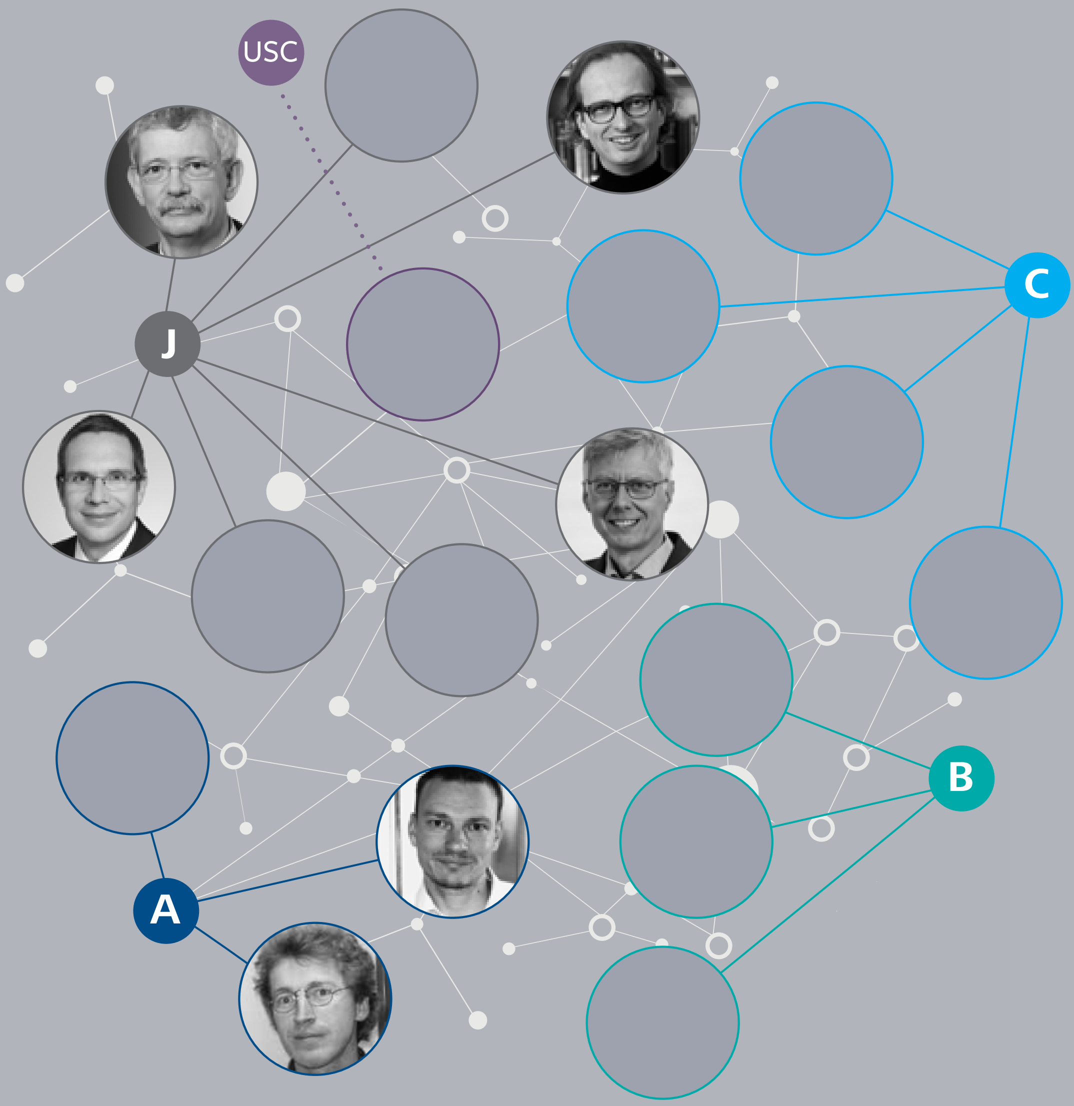
P1.3 CONTROLLING AND PROBING OF ULTRACLEAN INTERFACES



1
FOCUS AREA

ACHIEVEMENTS

The Grützmacher and Mussler Groups further developed the combination of in-situ selected area growth of topological insulators (TIs) and in-situ shadow mask evaporation employing SiN masks patterns produced on the chip. They obtained quasi 1D Josephson junctions of a ternary TI with 100 nm long and 200 nm wide proximitized areas of TI between superconducting Nb contacts. Transport characterization of these structures is ongoing. Moreover, a method to remove the mask by HF dip after Te capping has been shown to provide STM clean interfaces between TI and superconductor in cooperation with the Morgenstern group.
The Stampfer group has finalized the planning of an ultrahigh vacuum (UHV) stamping apparatus using a Ar-glovebox for exfoliation of various 2D materials and a directly connected UHV system for stamping compatible with all sample holders used by the groups in Jülich and Aachen. A load-lock to a UHV suitcase is additionally implemented. Purchasing of components has been started and commissioning of the whole apparatus is planned for the end of 2020. The group has, moreover, produced graphene based Josephson junctions with MoRe superconductors as edge contacts. They exhibit Fraunhofer patterns that indicate transport via the edge regions of the graphene, Fabry-Perot oscillations of critical current across the charge neutrality point and the possibility of gating two independent areas in order to tune p-n interfaces. Quantum Hall effect as required for Majorana zero modes is observed at ~0.3 T and degeneracy lifting at ~1 T.
The groups Morgenstern, Voigtländer and Tautz have developed a cryostat concept for the 4-tip-STM enabling sub-100 mK operation in UHV. The 91b proposal for delivery of the corresponding cryostat is submitted and waiting for approval. Time-resolution of 100 ps, respectively, operation up to 30 GHz is achieved for the 4-tip STM by adequate modification of tip holders for impedance matching. Voigtländer and Tautz have realized spin-transport measurements of topological insulators via magnetic tips and have refined their analysis to disentangle different transport channels via distance dependent 4-tip measurements.

Coordinator:
Markus Morgenstern
Participants:
Detlev Grützmacher
Gregor Mussler
Christoph Stampfer
Stefan Tautz
Bert Voigtländer

PUBLICATIONS

[1] Shaham Jafarpisheh, An Ju, Kevin Janßen, Takashi Taniguchi, Kenji Watanabe, Christoph Stampfer, and Bernd Beschoten, Reducing the impact of bulk doping on transport properties of Bi-based 3D topological insulators, arXiv:2001.04368 (2020)

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[5] Shaham Jafarpisheh, Frank Volmer, Zhiwei Wang, Bárbara Canto, Yoichi Ando, Christoph Stampfer, and Bernd Beschoten, Non-local electrical detection of spin-momentum-locked surface currents in the 3D topological insulator BiSbTeSe2, arXiv:1907.10347 (2019)

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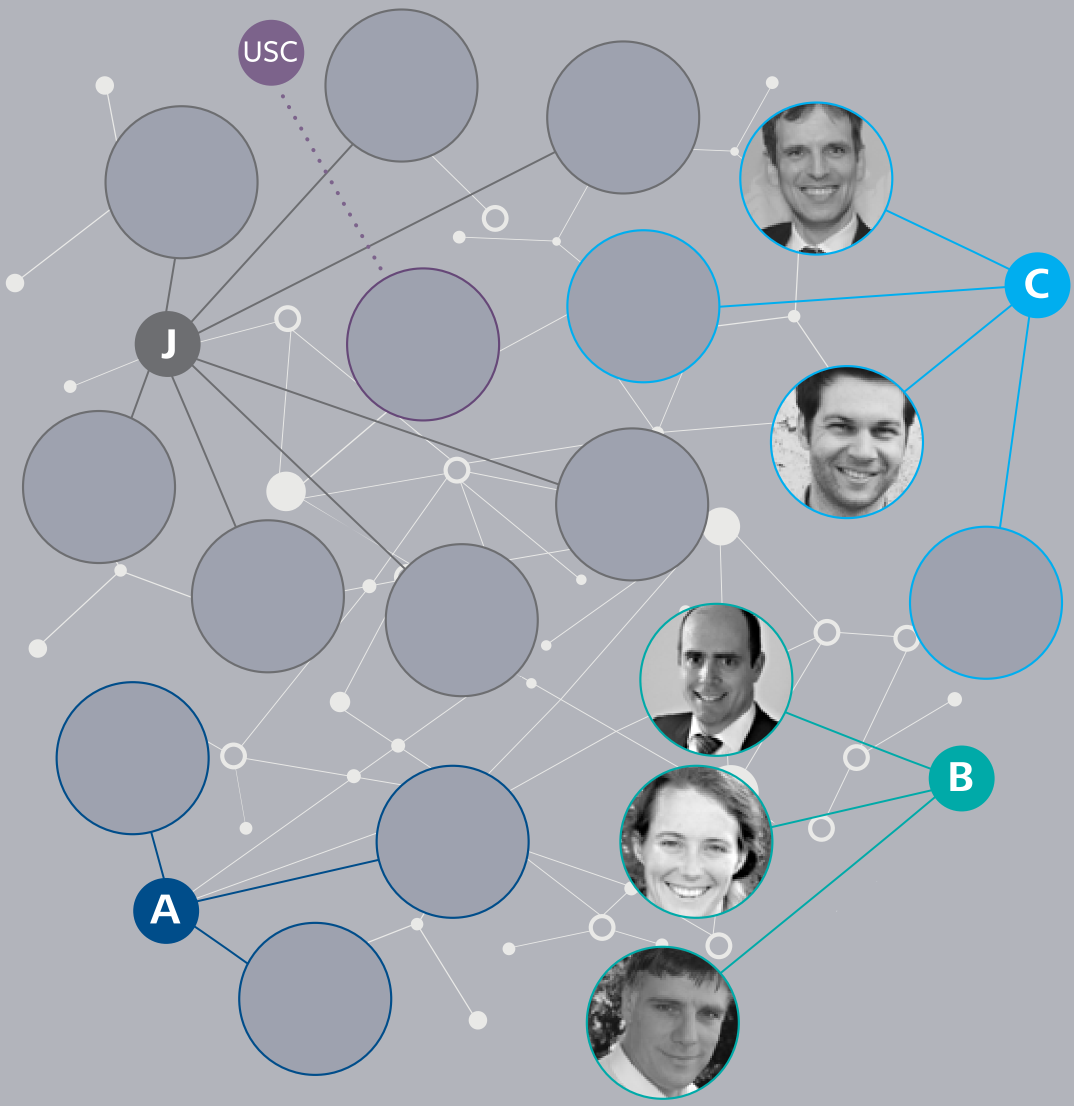
P1.4 MAJORANA STATES AND PARAFERMIONS IN ULTRACOLD-ATOM SYSTEMS



1
FOCUS AREA

ACHIEVEMENTS

The aim of this core project is to realize Majorana and parafermion (i.e. fractional Majorana) states in cold atomic gas systems. This experimental environment is a well-controlled dilute AMO physics system, providing a counterpart to solid-state system platforms.

In this first year of the project, we have experimentally realized and studied attractively interacting Hubbard models with ultracold Fermi gases in optical lattices. This has provided us with means of building novel quantum simulator in which quantum phases can be mapped to very different regimes and may become more easily detectable. Furthermore, we have detected non-local pairing correlations in the attractive Hubbard model above the critical temperature for superfluidity and investigated theoretically pair correlations in a driven Hubbard ladder.

In the part of the core project aiming at para-fermions, we have been working to realize a fractional quantum Hall system with ultra-cold erbium atoms, as a first important step to our goal. In the report period, Bragg scattering of ultra-cold erbium atoms off an optical standing wave using radiation tuned to near the same narrow-line transition as will be used for the imprinting of synthetic fields has been experimentally demonstrated. We are presently working to implement synthetic magnetic fields for the electrically neutral erbium atoms.

On the theory side, we have investigated the effects of dissipative edges in quantum wires of ultracold fermionic atoms. We have elaborated on the existence of a many-body variant of the quantum Zeno effect, which is induced by strong collective quantum fluctuations and leads to either complete blocking of transport for repulsive interactions, or full transparency in the case of attractive ones. An analytical study is complemented by a numerical approach. In other work, we initiated a project that investigates enabling Majorana edge modes in number conserving systems of ultracold fermionic two-leg ladders based on many-body interference, where the crucial parity symmetry in each leg is protected by translation symmetry.

Coordinator:
Martin Weitz
Participants:
Sebastian Diehl
Michael Köhl
Corinna Kollath
Achim Rosch

PUBLICATIONS

[1] Marcell Gall, Chun Fai Chan, Nicola Wurz, and Michael Köhl, Simulating a Mott Insulator Using Attractive Interaction, Phys. Rev. Lett. 124, 010403 (2020)

[2] Stefan Wolff, Ameneh Sheikhan, Sebastian Diehl, and Corinna Kollath, Nonequilibrium metastable state in a chain of interacting spinless fermions with localized loss, Phys. Rev. B 101, 075139 (2020)

[3] Chun Fai Chan, Marcell Gall, Nicola Wurz, and Michael Köhl, Pair correlations in the attractive Hubbard model, Phys. Rev. Research 2, 023210 (2020)

[4] Heinrich Fröml, Christopher Muckel, Corinna Kollath, Alessio Chiocchetta, and Sebastian Diehl, Ultracold quantum wires with localized losses: many-body quantum Zeno effect, arXiv:1910.10741 (2019)

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[5] Daniel Babik, Roberto Röll, David Helten, Michael Fleischhauer, and Martin Weitz, Synthetic magnetic fields for cold erbium atoms, arXiv:1911.09583 (2019)

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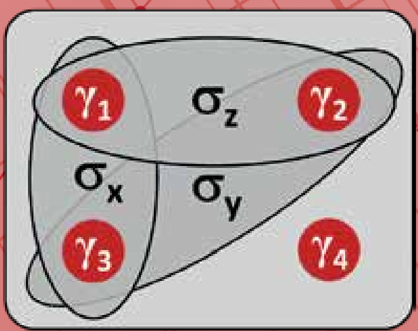
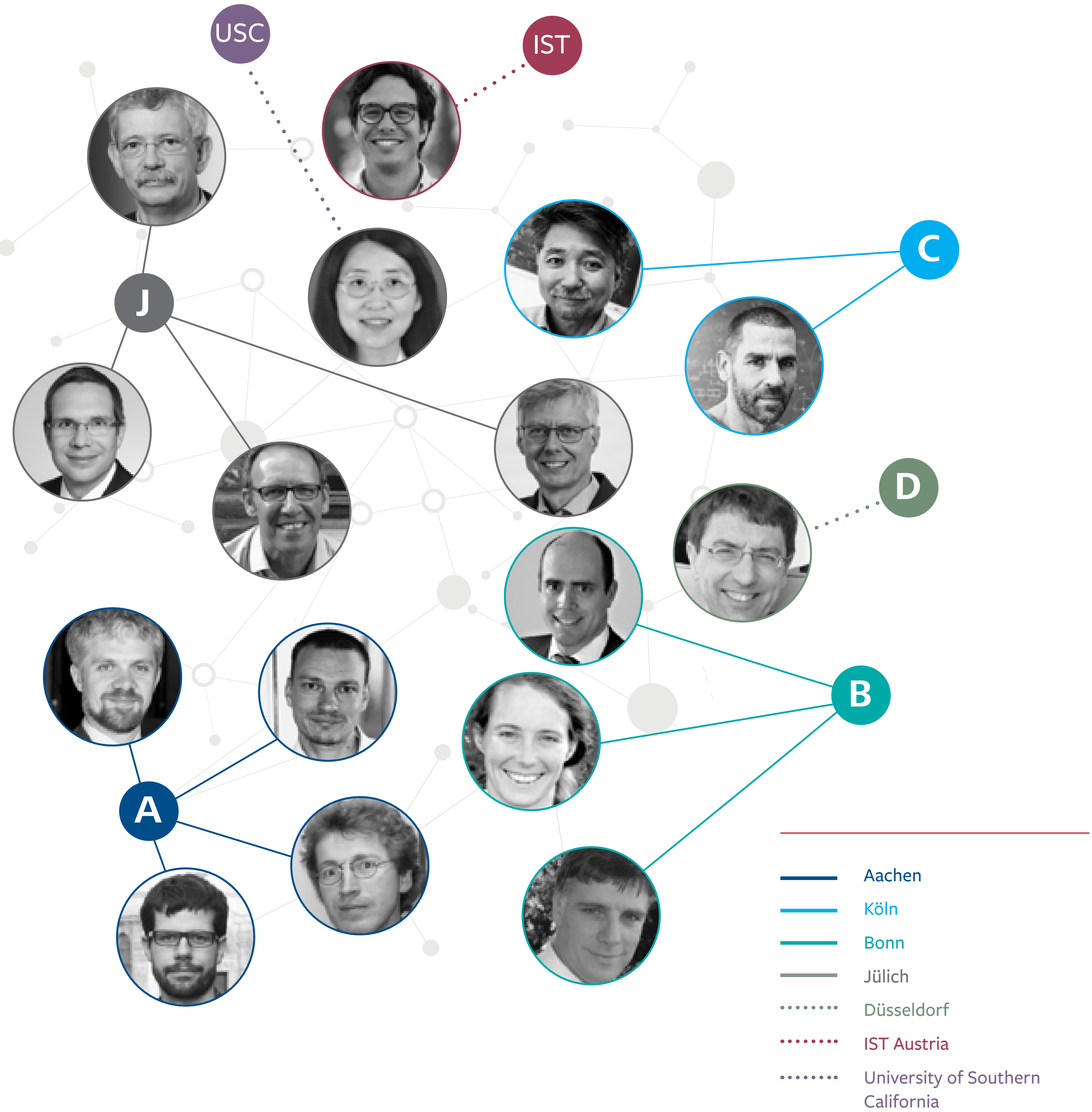
FOCUS AREA 2

MAJORANA QUBITS

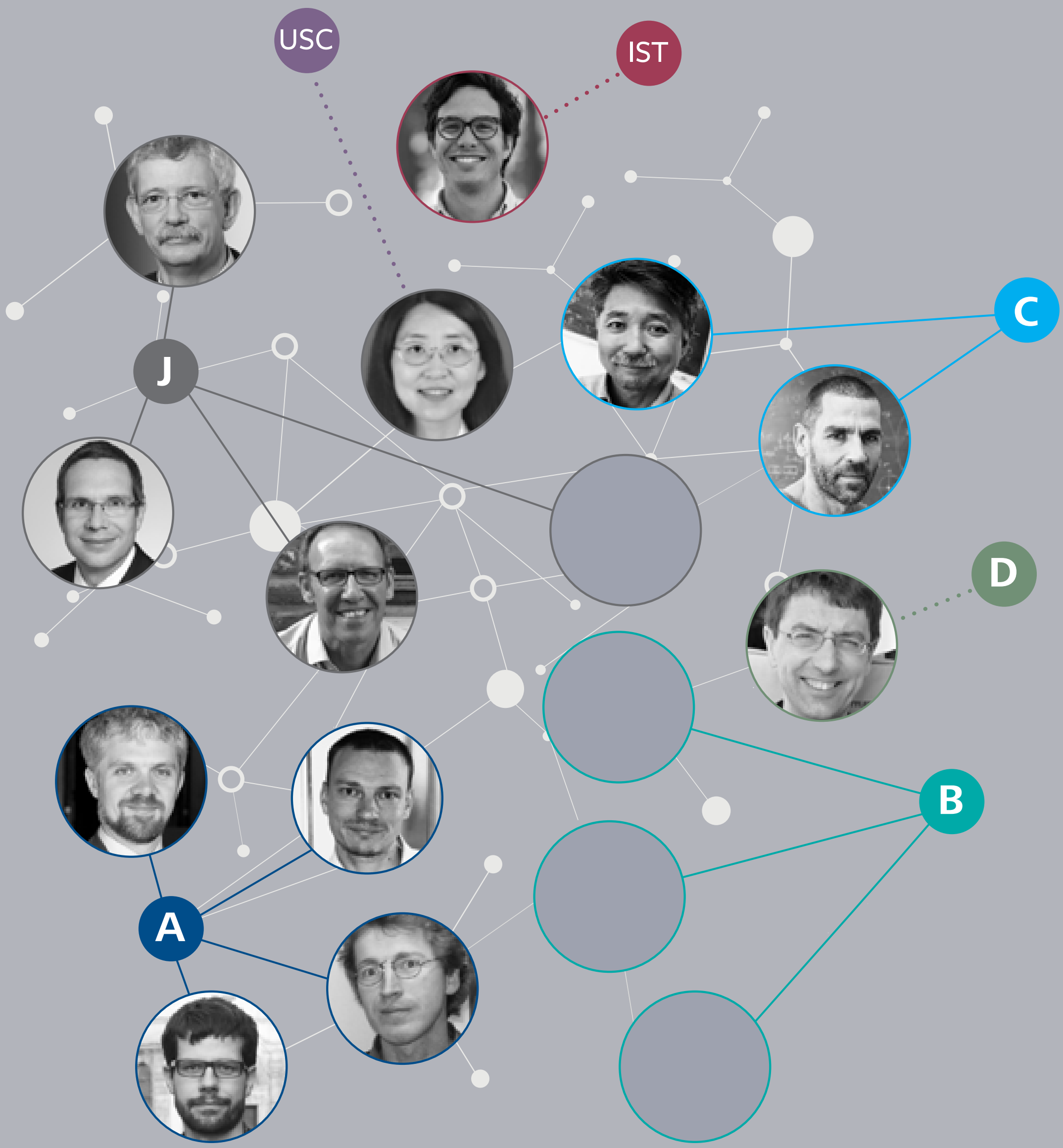




In *Focus Area 2*, 15 groups including collaborating teams at HHU Düsseldorf, IST Austria and University of Southern California are joining efforts to explore viable ways to utilize majorana states as carriers of quantum information. Employing the materials basis developed in *Focus Area 1*, this area aims at building Majorana qubits and devising concepts for implementing error-correcting codes, mainly using topological insulators. Prime objectives include the development of the necessary hardware for Majorana qubits, the initialization and readout of the fermion parity, and the verification of the qubit functionality.

Advanced error-correcting designs on a specific Majorana qubit setting will be theoretically explored and experimentally tested, which bridges topological qubits to *Focus Area 3*. The developed Majorana qubits will later be used in *Focus Area 4* for establishing strong coupling to microwave photons, which can be subsequently used for various quantum connections.

P2.1 & P2.2



2
FOCUS AREA

P2.1 MAJORANA QUBITS BASED ON TOPOLOGICAL-INSULATOR NANOWIRES

ACHIEVEMENTS

Although no publication has been generated, the capability to perform superconducting qubit experiments has been successfully installed in Cologne, where there was no expertise in qubit experiments. It is now possible to fabricate transmon qubits and perform their characterizations as well as one-bit operations. So far, two dry dilutions fridges have been set up for qubit experiments with all the necessary microwave wirings and low-temperature components. All necessary control instruments are set up and the qubit control software is written in-house. Since our fridge has a vector superconducting magnet, we have measured how T_1 and T_2 of an aluminum transmon qubit changes with the orientation and strength of the applied magnetic field, the result of which is analyzed in collaboration with Gianluigi Catelani at Jülich. Currently, as a first step towards making a qubit involving a topological insulator (TI), experiments to incorporate TI-based Josephson junction in the 3D transmon is going on in Cologne.

The Jülich team performed transport measurements of TI nanoribbon networks and ring structures, both fabricated by the selective-aregrowth (SAG) method, as a basic step towards future quantum circuits.

Coordinator:
Yoichi Ando
Participants:
Alexander Altland
Hendrik Bluhm
Reinhold Egger
Johannes Fink
Detlev Grützmacher
Fabian Hassler
Grace Lu
Markus Morgenstern
Gregor Mussler
Thomas Schäpers
Christoph Stampfer

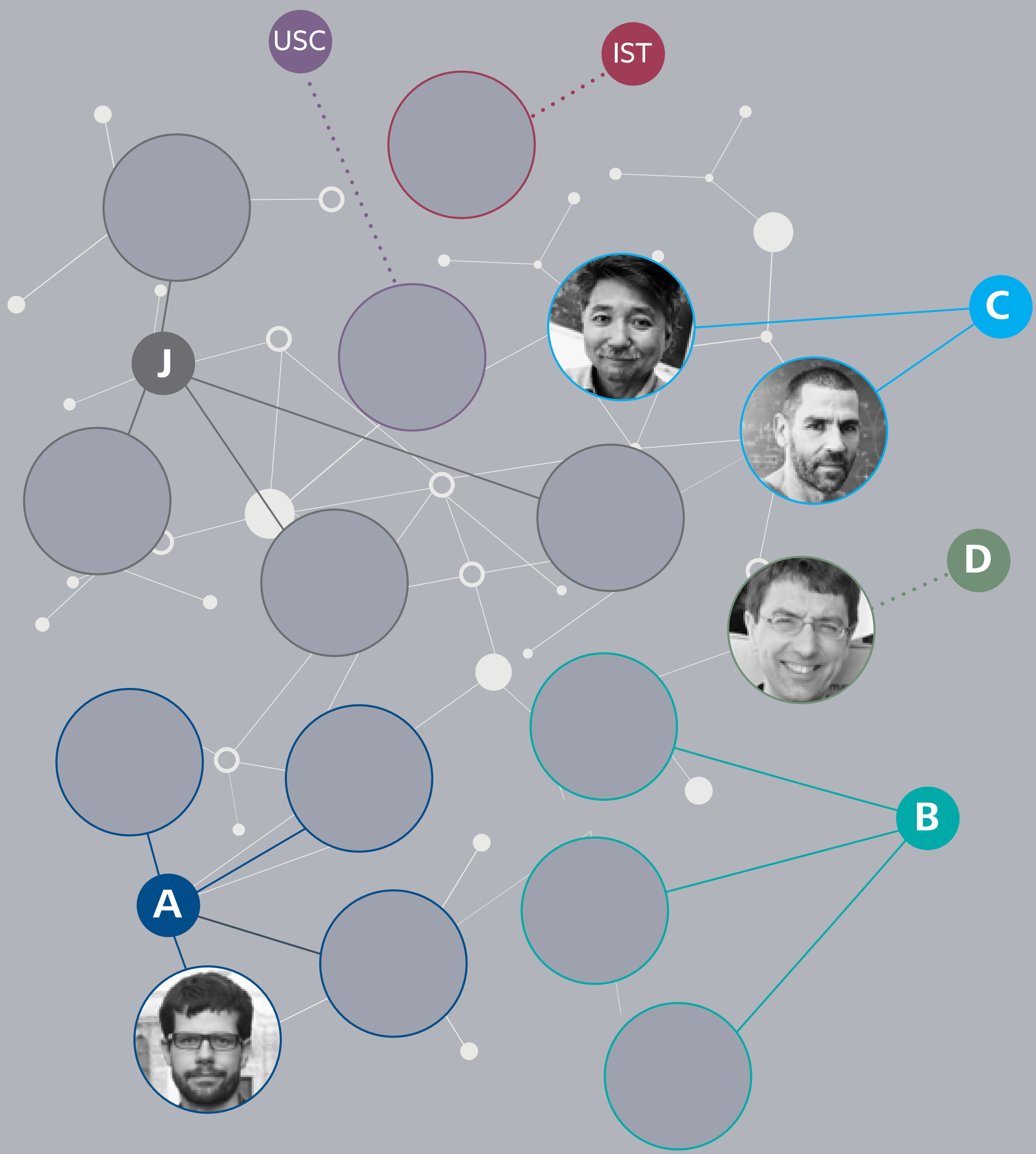
P2.2 ALTERNATIVE PLATFORMS FOR MAJORANA QUBITS

ACHIEVEMENTS

Whereas P2.1 pursues to build qubits using topological insulator (TI) nanowires, P2.2 explores qubits using other possible realizations of Majorana states. In concrete terms, P2.2 is conceived to investigate Majorana states in vortices in proximitized TI surface, in proximitized quantum anomalous Hall insulator (QAHI), and in proximitized graphene. The Cologne team has been making devices to proximitize the surface of bulk-insulating TI thin film with Nb with small holes (about 100 nm diameter), and make a tunnel junction on the hole to perform conductance spectroscopy for the proximity-induced superconducting state within the hole; upon field cooling, these holes trap vortices and should harbor Majorana states. In our preliminary experiments, an interesting set of subgap peaks were observed, and the data analysis is going on in collaboration with the Hassler group.

To utilize the Majorana states generated in QAHI, the availability of QAHI samples is a prerequisite. In 2019, the MBE growth of V-doped $Bi_{2-x}Sb_xTe_3$ ferromagnetic TI thin films was greatly advanced in Cologne thanks to the installation of a new MBE machine, and the R_{yx} value close to the expected 25.8 kOhm has been observed. (In March 2020, the full quantization of R_{yx} with vanishing R_{xx} has finally been achieved, putting Cologne among the few groups worldwide to realize the QAHI sample.)

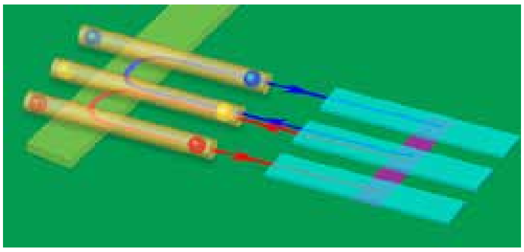
P2.3 ADVANCED MAJORANA-QUBIT DESIGNS



2
FOCUS AREA

ACHIEVEMENTS

The aim of project P2.3 is to investigate the potential of advanced Majorana qubit designs. In this respect, we would like to highlight several insights that we have obtained in the last year. In total, three papers were published and another three have been put on the arXiv preprint server. Note that all the results so far have been of theoretical nature.



Experimental setup to distinguish MZMs from conventional Andreev bound states: the red and blue arrow denote the current that is injected form the middle lead and drained in the two side leads. MZMs manifest themselves in an extra large cross-correlation between the two currents. [Figure is taken from H.-Z. Lu, Physics 13, 30 (2020)]

The progress has been achieved on a variety of platforms. In the publication by Dorn et al. (2020), we have analyzed the effect electron phonon interactions on the stability of Majorana zero modes (MZMs) in topological insulator nanowires. Most importantly, we have found that the MZMs are stable when the nanowire is pierced by a half-integer flux quantum. This result increases our confidence in the topological nanowire platform as it shows that inelastic processes do not destroy the topological protection in the right parameter regime. Moreover, we have found indications that the topological insulator surface state exhibits an instability toward superconducting pairing.

The central problem that hinders future progress in the quest to determine the most promising experimental platform for topological quantum computation is the fact that it is quite difficult to distinguish MZMs from standard Andreev states that are ubiquitous in semiconductors that are in proximity to superconductors. In the manuscript Manousakis et al. (2020), we have tackled this problem and proposed a way to test for MZMs by rather elementary transport experiments. Due to the importance of this insight for further progress of the field, the manuscript has been selected as an Editors' suggestion by Physical Review Letters and featured as a Viewpoint in Physics.

Addressing problems which are further along the road to realize a topological quantum computer, in the publication Ziesen et al. (2019), we have analyzed the stability of quantum information that is encoded in the Majorana toric code, that is a network of superconducting islands with MZMs, that serves to correct the quantum information. In particular, we have found that the quantum information is rather insensitive to Cooper pairs that are inadvertently moving around the network giving us confidence in viability of the platform in order to implement quantum error correction.

Coordinator:
Fabian Hassler
Participants:
Alexander Altland
Yoichi Ando
Reinhold Egger

PUBLICATIONS

[1] Alexander Ziesen, Fabian Hassler, and Ananda Roy, Topological ordering in the Majorana toric code, Phys. Rev. B 100, 104508 (2019)

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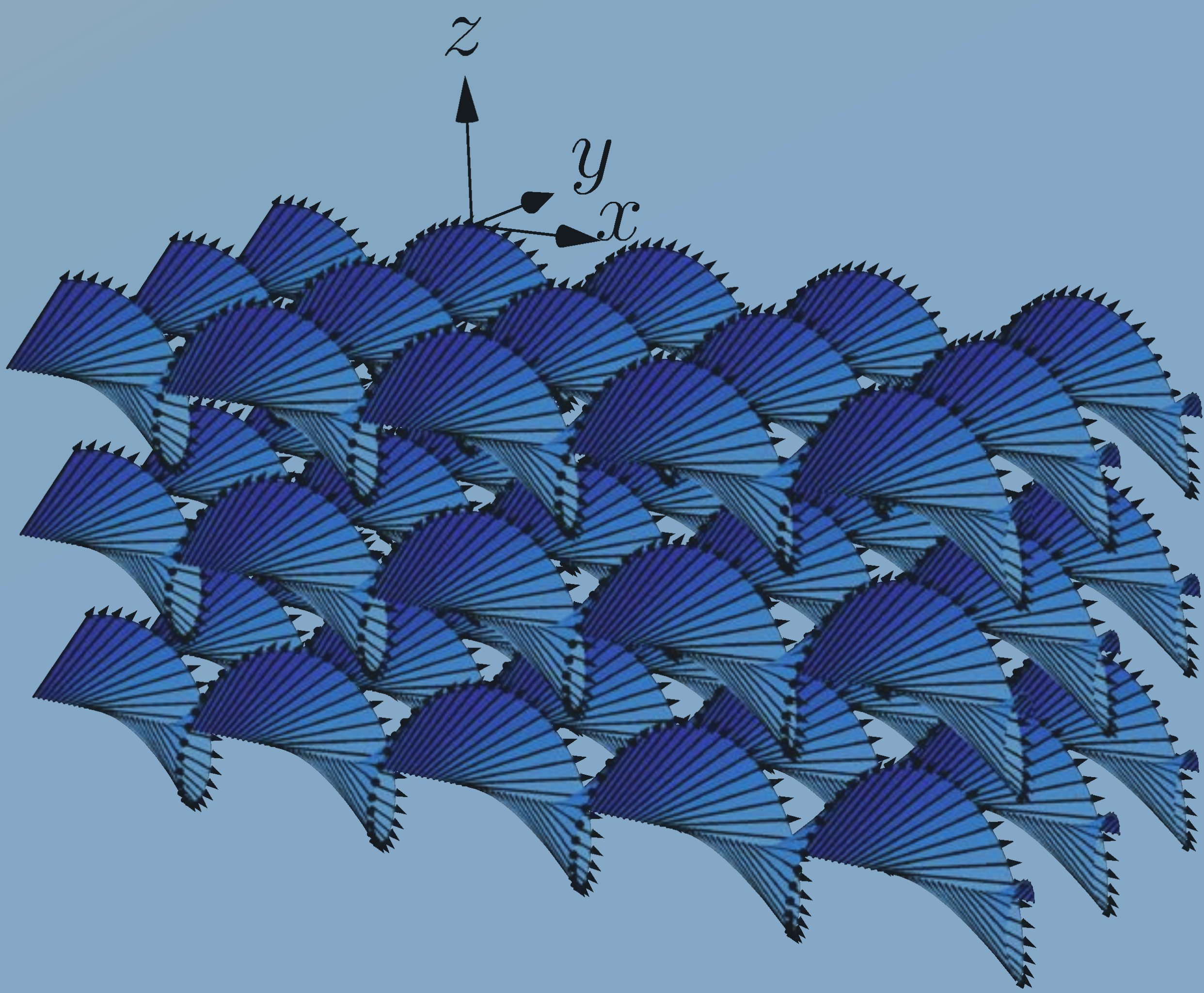
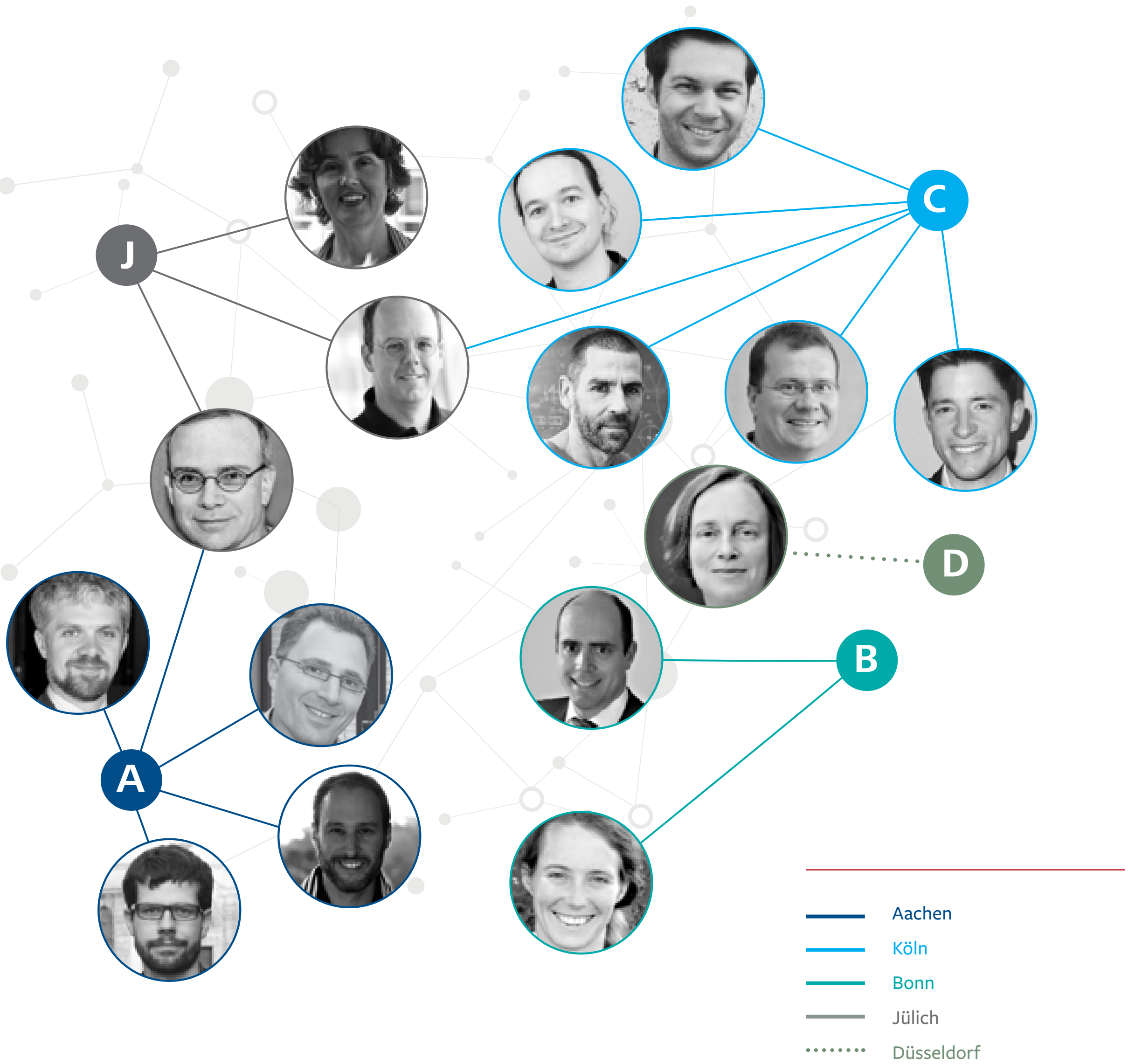
FOCUS AREA 3

DECOHERENCE, MEASUREMENTS, AND ERROR CORRECTION

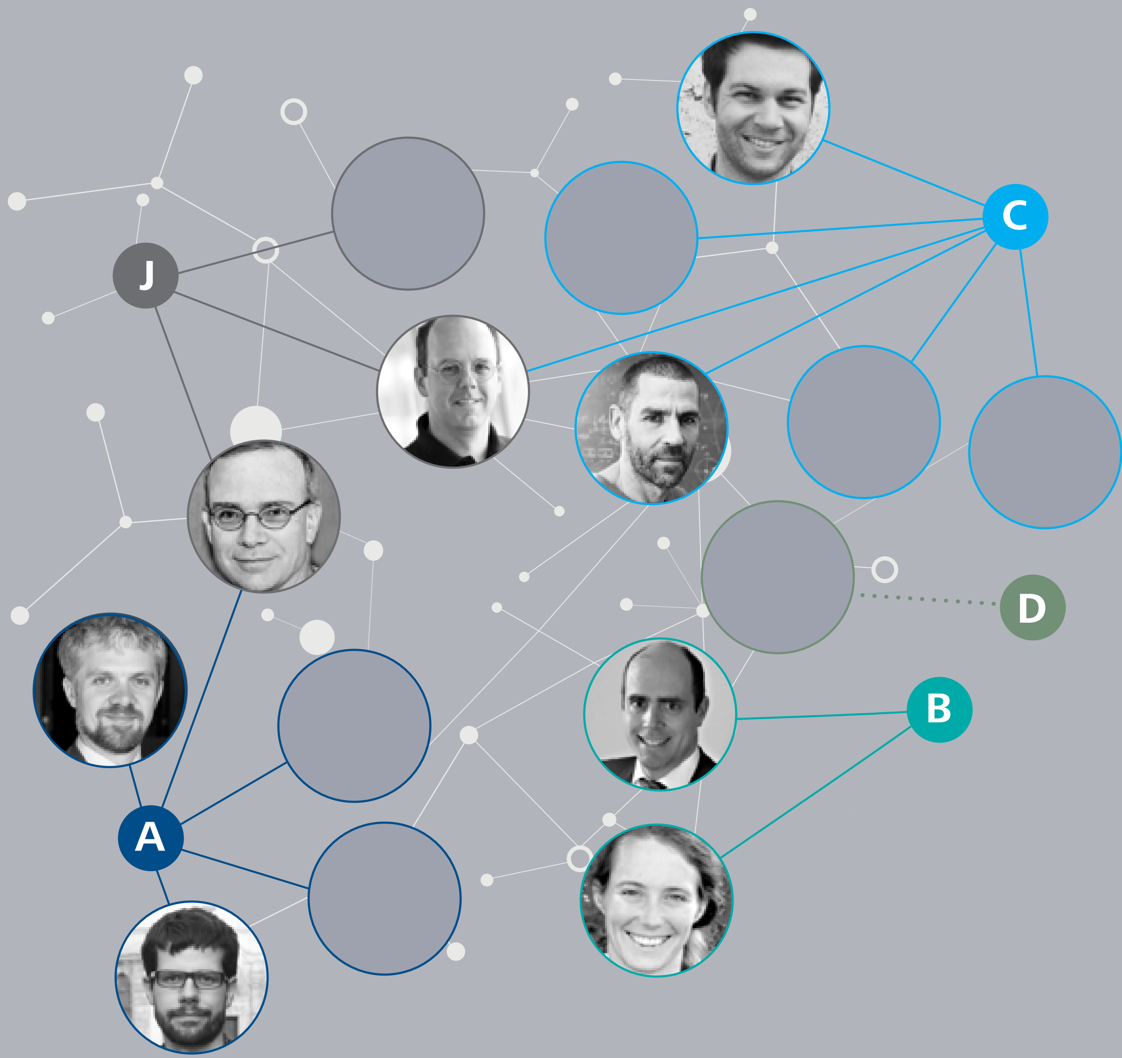




Fully characterizing quantum decoherence, and combatting it with the techniques of quantum error correction are essential for quantum technologies and for constructing a quantum computer.
In *Focus Area 3* 15 groups are teaming up in three different projects to tackle these partially understood phenomena by harnessing topological matter and quantum devices under real-world noise conditions and using suitably engineered dissipative processes and extended error-correction schemes to control them.

Carefully chosen experiments will put the theories developed here to the test. In particular, the Focus Area explores the dissipative preparation of topological states of ultracold atomic fermions and implements electron shuttling in spin-qubit arrays to ultimately construct a minimal realization of a topological surface code. Developed theories shall also be applied to the physical platforms designed in the other Focus Areas.

P3.1 TOPOLOGY IN AND OUT OF EQUILIBRIUM



3 FOCUS AREA

ACHIEVEMENTS

The aim of this core project is to develop a comprehensive understanding – theoretically and experimentally – of the implications of topology beyond ground states, i.e. in mixed quantum states and/or under non-equilibrium conditions.

In the first year of the project, our investigation has opened up the challenging field of topological properties in open and interacting quantum many body systems.

In [1] we focus on observable consequences of topology out of equilibrium, and we have shown that the physical response of a purely dissipative system can be topologically quantized. To this end, we have extended the concept of topological field theory to driven open quantum systems far from thermodynamic equilibrium, and sharpened the conditions for its presence. As a corollary, we predict chiral edge modes stabilized by a dissipative bulk. These findings are currently extended to include additional Hamiltonian dynamics, to connect them to the current stream of research on non-hermitean quantum systems.

In [2] we have developed a protocol to dissipatively stabilize topologically interesting states, helical states, in interacting spin chains, using a boundary dissipation. We show how the intriguing interplay of interactions and a tailored dissipative coupling gives access to novel topologically interesting properties at sweet spots of the interaction.

In [3] the melting of critical behavior under the influence of dissipative processes has been studied at the example of a Tomonaga-Luttinger liquid subject to dephasing noise.

In [4] we have developed a method in order to treat dissipative systems consisting of photons coupled to atoms. This will be of great help in order to investigate whether in such systems topologically non-trivial states can be stabilized in a dissipative fashion in the future.

On the experimental side, we have set up the laser system for creating the superlattice and are currently working on the implementation of the topological Su-Schrieffer-Heeger model. We have used the superlattice to create bilayer Hubbard models and have identified novel magnetically ordered phases.

Coordinator:
Sebastian Diehl
Participants:
Alexander Altland
David DiVincenzo
Fabian Hassler
Michael Köhl
Corinna Kollath

PUBLICATIONS

[1] Federico Tonielli, Jan Carl Budich, Alexander Altland, and Sebastian Diehl, Topological Field Theory far from Equilibrium, arXiv:1911.07834 (2019)

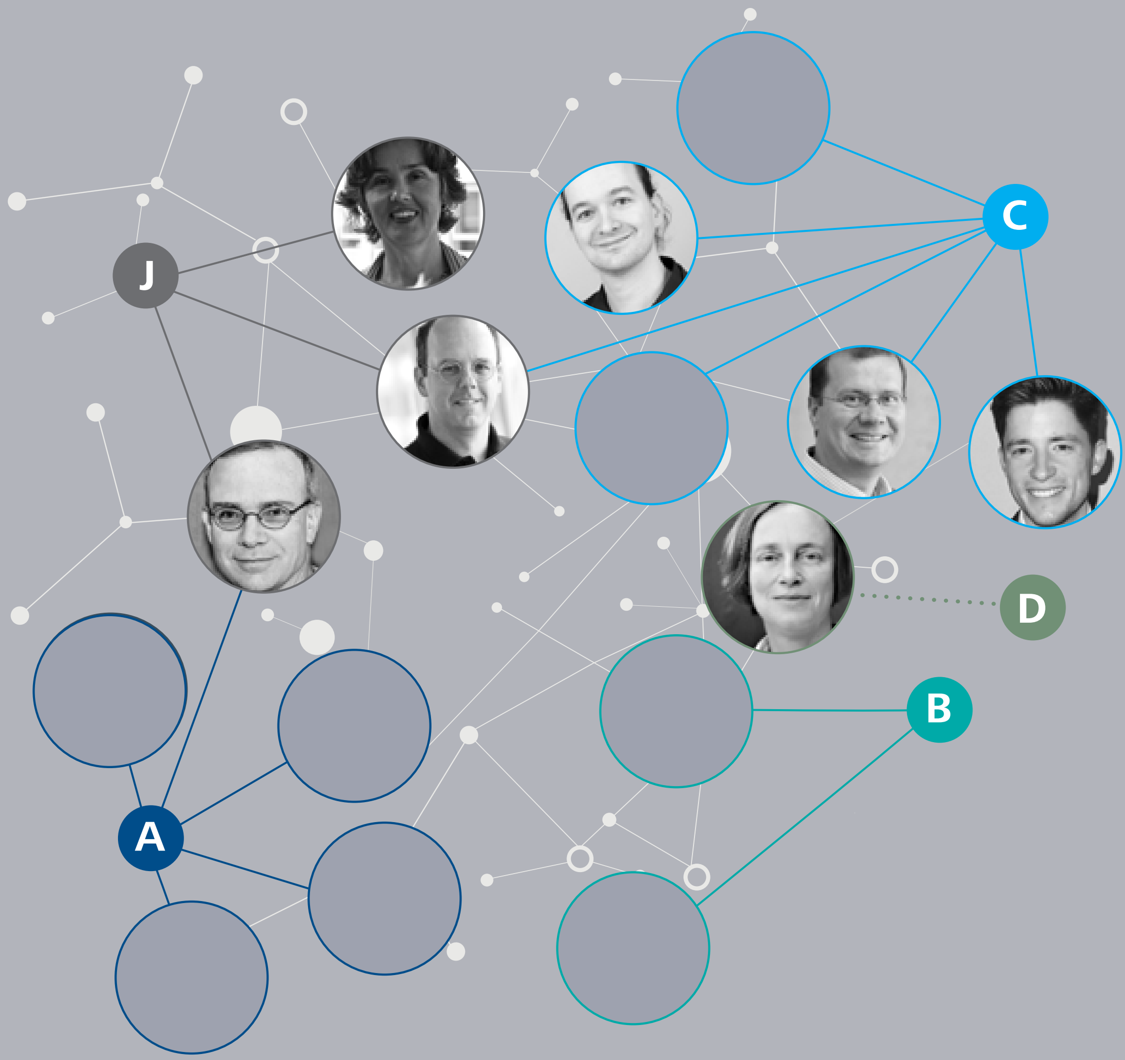
[2] Simon Essink, Stefan Wolff, Gunter M. Schütz, Corinna Kollath, and Vladislav Popkov, Transition between dissipatively stabilized helical states, arXiv:1910.04501 (2019)

[3] Jean-Sebastien Bernier, Ryan Tan, Chu Guo, Corinna Kollath, and Dario Poletti, Melting of the critical behavior of a Tomonaga-Luttinger liquid under dephasing, arXiv:2003.13809 (2020)

OTHER REFERENCES

[4] Catalin-Mihai Halati, Ameneh Sheikhan, Helmut Ritsch, and Corinna Kollath, Dissipative generation of highly entangled states of light and matter, arXiv:1909.07335 (2019)

P3.2 THEORY OF ERROR CHARACTERIZATION, MITIGATION, AND CORRECTION



3
FOCUS AREA

ACHIEVEMENTS

The project unites the efforts to characterize, mitigate, and correct errors. The Bruss group has shown that employing symmetries helps to improve the performance of machine learning techniques for decoding of the toric code [1].

The Trebst group has devised a neural decoder for quantum stabilizer codes (such as the toric code) that has proved to be scalable up to 1,000 qubits in numerical simulations (well beyond the current state-of-the-art, e.g. reported in an influential paper by Melko and Torlai).

In Cologne, a student supervised by Kastoryano, Gogolin, and Gross has conducted a study of optimization strategies that are hoped to be useful for finding ground state energies of quantum chemistry systems on NISQ computers. Positive findings include new methods for improving convergence times. On the negative side, we can now explicit examples where a larger variational gate set significantly worsens convergence. A pre-print is about to be published. In a different development, the group has constructed new efficient randomization procedures [2], that might improve characterization protocols such as Randomized Benchmarking.

DiVincenzo and Terhal report achievements on two projects. First: A superconducting electric circuit, with the novelty of non-reciprocal elements, can be designed so that its ground space is doubly degenerate and is spanned by the two code states of the GKP code. Noise-protected quantum logic gates are proposed [3]. A second project addresses the question, whether the classical dynamics of the canonical multi-transmon Hamiltonian are chaotic. Does this imply that the quantum eigenstates of this model are close to the desired tensor product of Fock states? First findings show that chaos does seem to be an issue; the details are being discussed with the Altland group.

The Calarco group has finished a draft on a measurement protocol for dispersively measured systems. The protocol will be tested in the experiment of Pavel Bushev (PGI-11) to enable circa 10x improvement in measurement error and speed. There is also a plan to use it for Ando's topological qubit experiment to measure quasiparticle states which can be short-lived and benefit especially from fast measurement.

Coordinator:
David Gross
Participants:
Dagmar Bruss
Tommaso Calarco
David DiVincenzo
Michael Kastoryano
Barbara Terhal
Simon Trebst

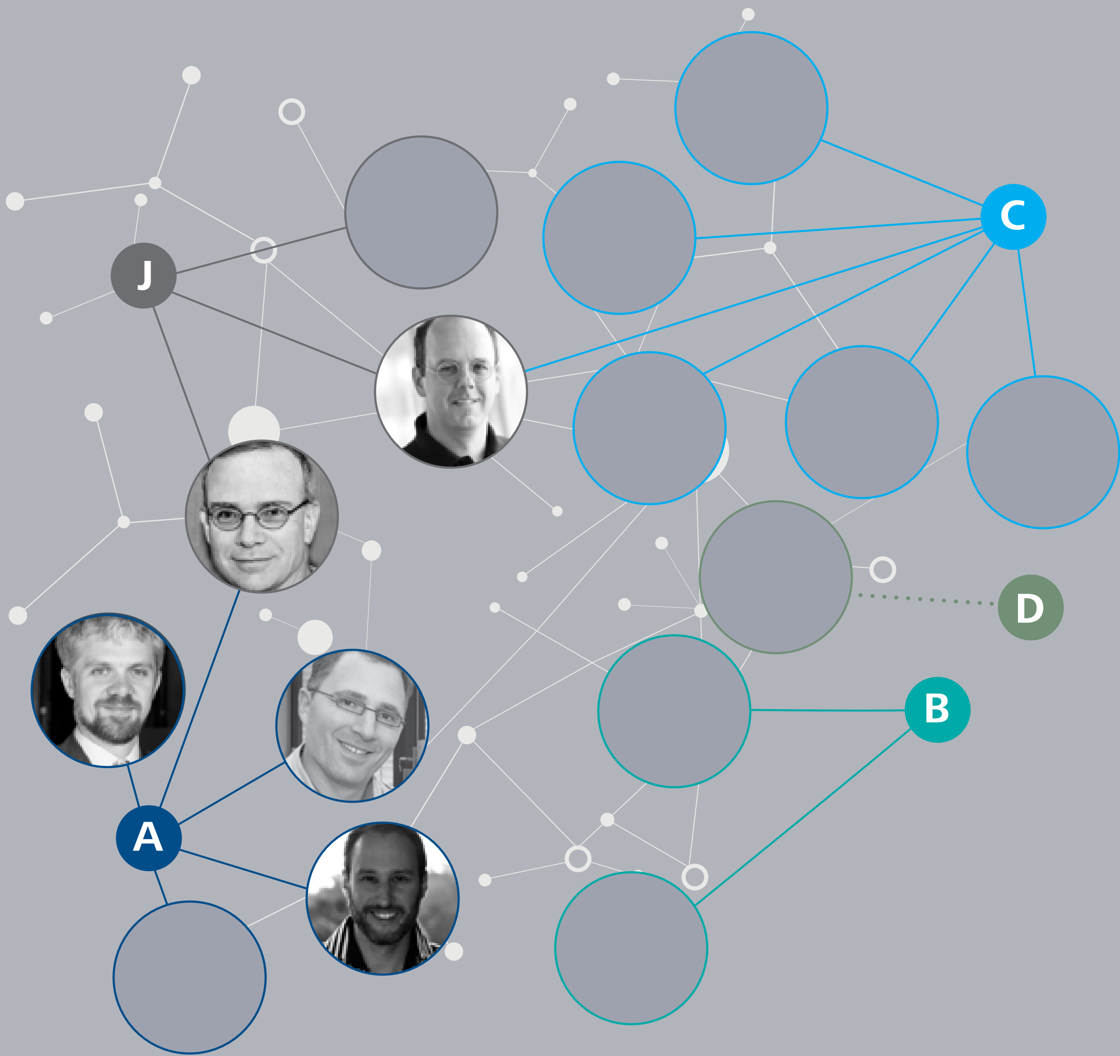
PUBLICATIONS

[1] Thomas Wagner, Hermann Kampermann, and Dagmar Bruß, Symmetries for a High Level Neural Decoder on the Toric Code, arXiv:1910.01662 (2019)

[2] Jonas Haferkamp, Felipe Montealegre-Mora, Markus Heinrich, Jens Eisert, David Gross, and Ingo Roth, Efficient unitary designs with a system-size independent number of non-Clifford gates, arXiv:2002.09524 (2020)

[3] Martin Rymarz, Stefano Bosco, Alessandro Ciani, and David P. DiVincenzo, Passive Quantum Error Correction with Grid States in a Non-Reciprocal and Superconducting Circuit, arXiv:2002.07718, submitted to Phys. Rev. X. (2020)

P3.3 ELECTRON SHUTTLING FOR SPIN-QUBIT SURFACE CODE



3
FOCUS AREA

ACHIEVEMENTS

This project aims to realize a spin-qubit based architecture for surface code error correction based on electron shuttling.

The main activity at this point is the fabrication of appropriate devices, pursued in two different ways. For standard lift-off processing, conveyor devices have been fabricated in a high-resolution 3 layer electron beam lithography process. Some batches did not function properly, likely due to charge trapping at interfaces or in material defects. The latest batch looks promising in the pre-characterization. A 10 µm long quantum bus sample with 300 gates shows no gate leakage and looks good with respect to SEM inspection. SET sensors at both ends operate with 50% yield. A current path can be accumulated through the conveyor channel and pinched-off by the gates. We are now trying to capture single electrons at 100 mK. The valley 200 µeV splitting found in one of our MBE grown Si/SiGe single-dot samples [2] is among the largest reported to date.

More advanced fabrication based on an industry-style spaced process is progressing well, but has not reached the stage of complete devices yet. With the work packages for lithography and deposition running, the next step is to establish the required CMP process.

Experiments in GaAs (independent of ML4Q-funding) have shown evidence for quantized charge transport when a conveyor device is driven as intended.

Looking further ahead, we have conceived a complete 2D architecture based on the approach considered here. Interestingly, qubit operations can be expected to be simpler than in conventional devices if shuttling works, as they can be spatially separated. Simulations of the individual elements (Junction, manipulation zones) to provide guidance for the implementation have started. Theory work focusing on understanding the shuttling process as well as architectural considerations complements the experimental program and is achieved by the participating groups independent of ML4Q funding.

Coordinator:
Hendrik Bluhm
Participants:
David DiVincenzo
Joachim Knoch
Lars Schreiber
OpenCall PIs:
Tommaso Calarco

PUBLICATIONS

[1] Tom Struck, Arne Hollmann, Floyd Schauer, Olexiy Fedorets, Andreas Schmidbauer, Kentarou Sawano, Helge Riemann, Nikolay V. Abrosimov, Łukasz Cywiński, Dominique Bougeard, and Lars R. Schreiber, Low-frequency spin qubit detuning noise in highly purified 28Si/SiGe, arXiv:1909.11397 (2019)

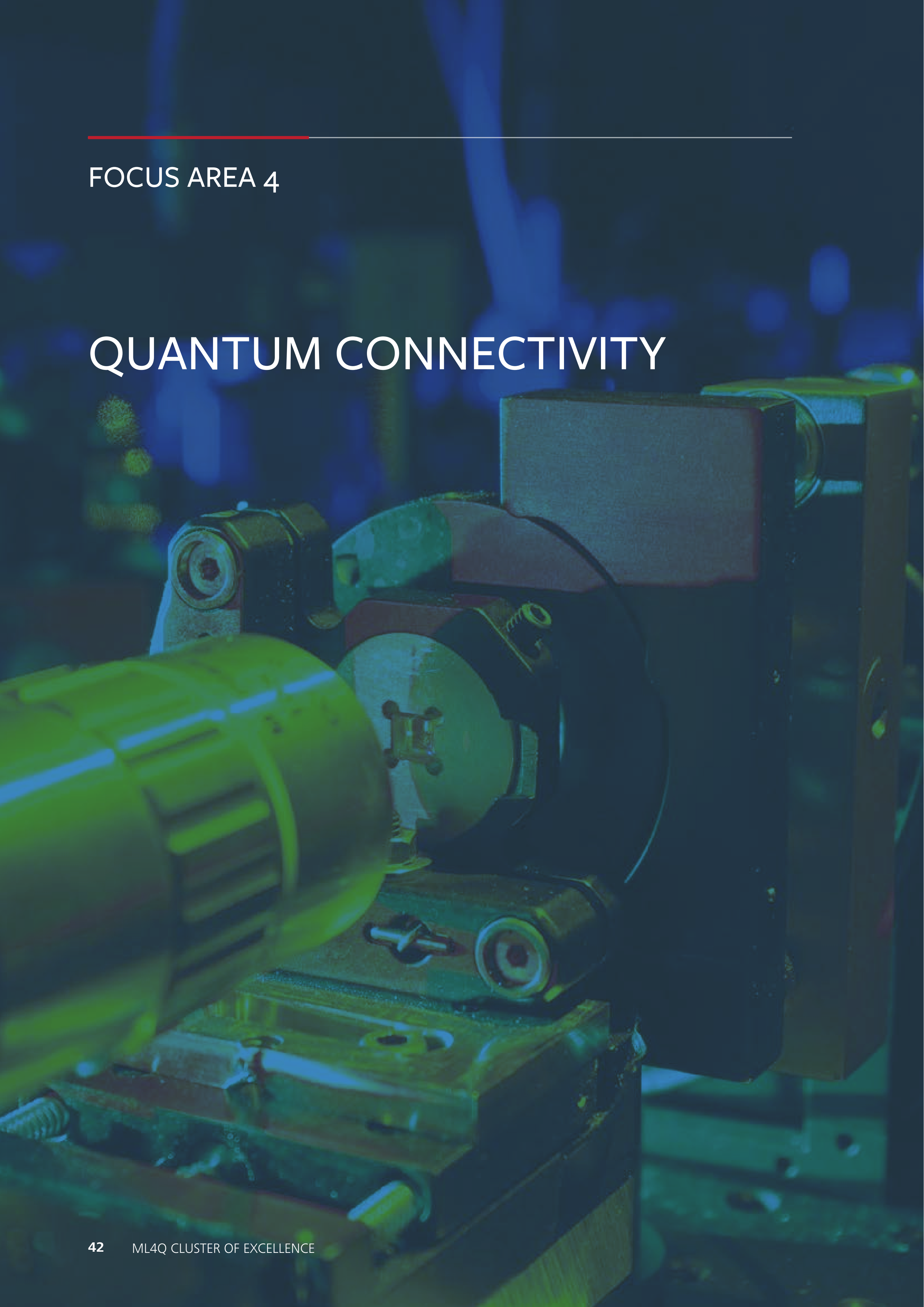
[2] Arne Hollmann, Tom Struck, Veit Langrock, Andreas Schmidbauer, Floyd Schauer, Kentarou Sawano, Helge Riemann, Nikolay V. Abrosimov, Dominique Bougeard, and Lars R. Schreiber, Large, Tunable Valley Splitting and Single-Spin Relaxation Mechanisms in a Si/SixGe1−x Quantum Dot, Phys. Rev. Appl. 13, 034068 (2020)

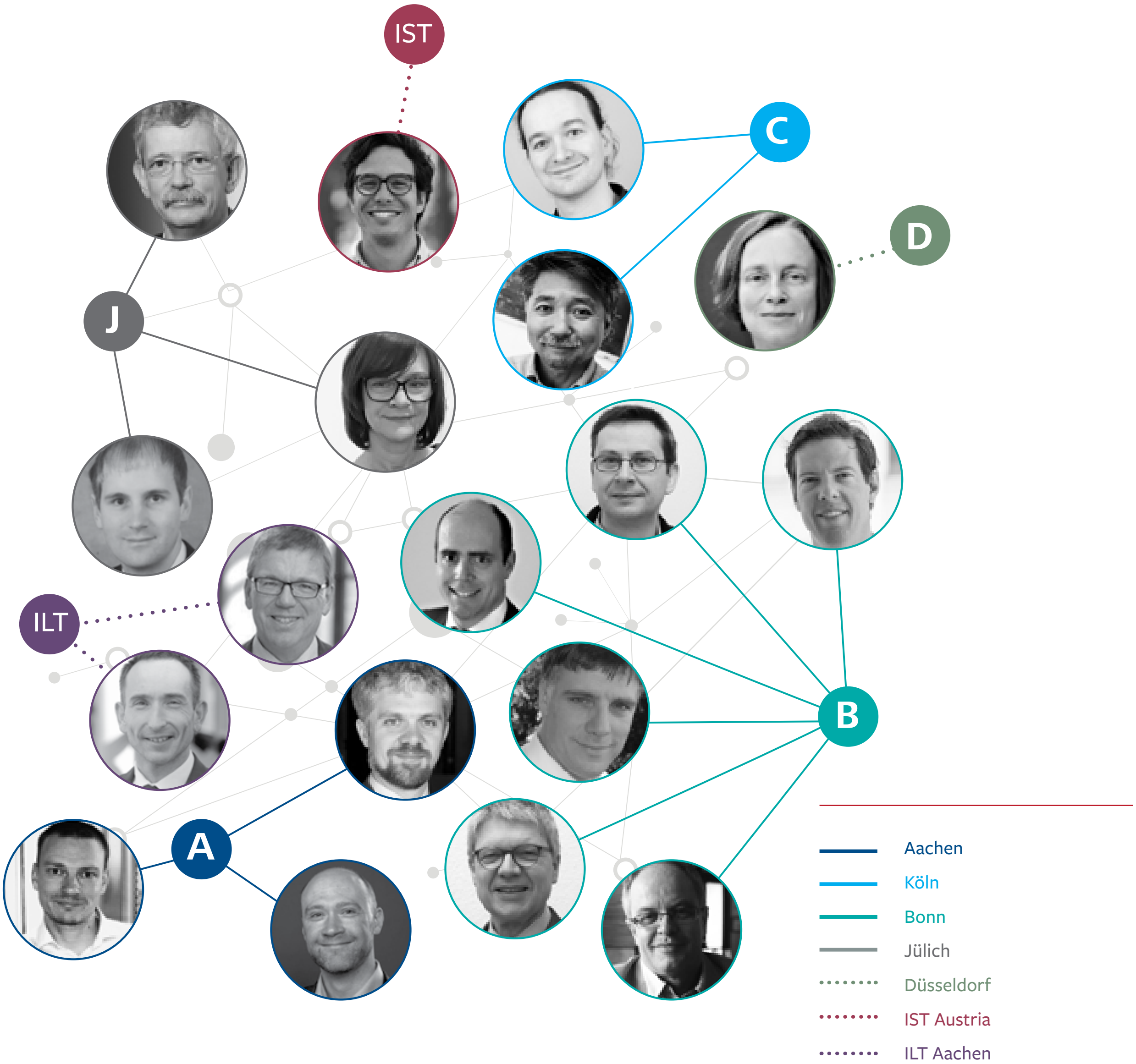
[3] Jan Klos, Bin Sun, Jacob Beyer, Sebastian Kindel, Lena Hellmich, Joachim Knoch, and Lars R. Schreiber, Spin qubits confined in a silicon nano-ridge, Appl. Sci. 9(18), 3823 (2019)

Two provisional patent applications for shuttling concept and architecture submitted, resulting in RWTH Innovation award 2020.

FOCUS AREA 4

QUANTUM CONNECTIVITY



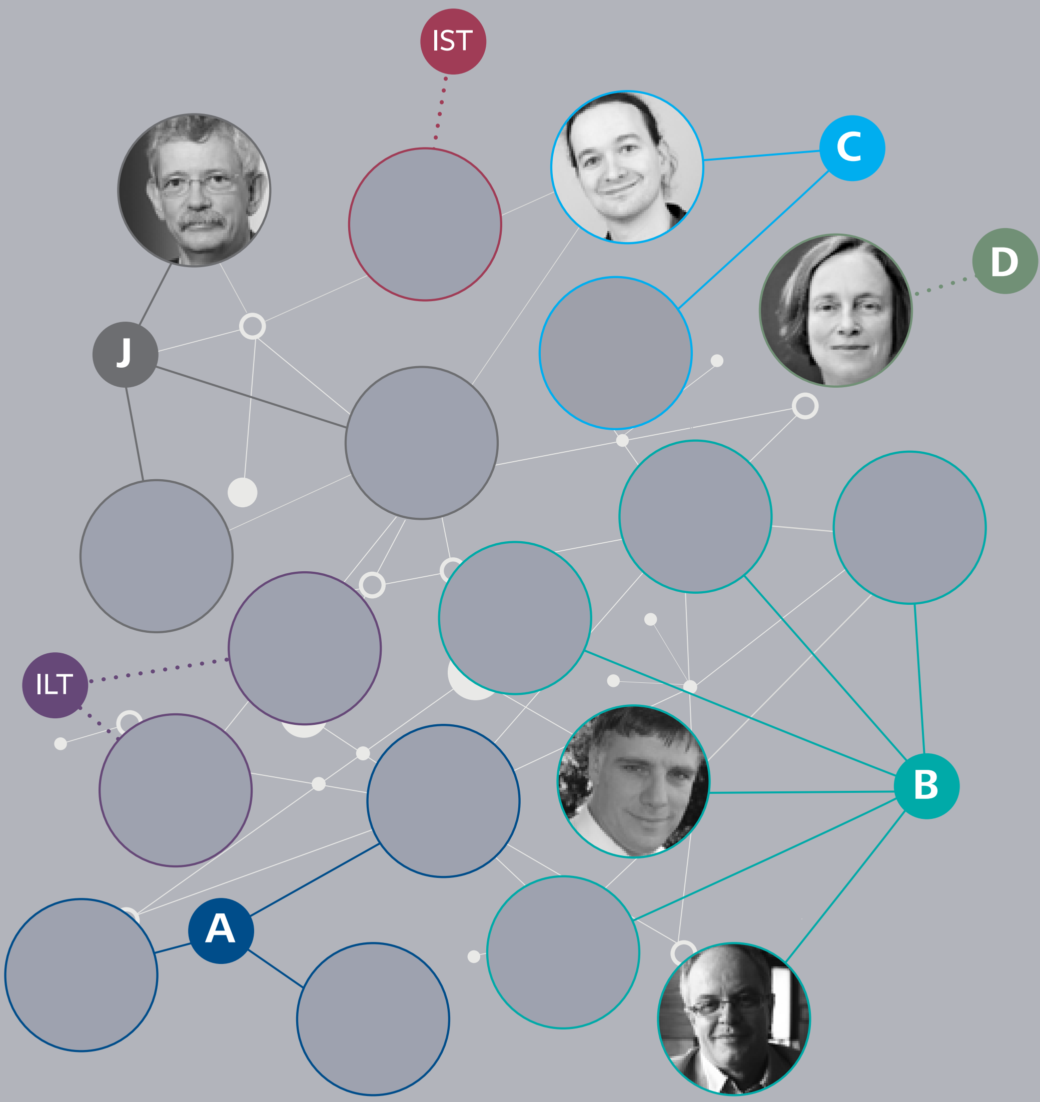


Connectivity between quantum processing units arises at many layers of an envisaged quantum computing infrastructure. Small ensembles of qubits should connect with each other in quantum networks. Such quantum networks will not only provide information transfer between nodes but, by realizing (generalized) quantum repeaters, these networks can also be used to reduce error rates in transmission over large distances. These architectures are addressed both theoretically and experimentally in *Focus Area 4*.

Furthermore, scalable quantum computers will benefit from interfaces that can distribute entangled states over macroscopic distances of meters or even kilometers and link to quantum memories. We will demonstrate such interfaces and develop a small hybrid quantum network. We will also take a first step to networking Majorana qubits by coherently coupling them to single microwave photons.

Collaborating groups in this Focus Area combine solid-state qubits available in Aachen and Jülich with atomic qubits in Bonn, and Majoranas developed in Cologne, in order to demonstrate quantum connectivity. This endeavor is only possible through the extensive experience with electrically controlled state preparation and readout available at Aachen and Jülich as well as the expertise of the Bonn groups in light-matter interfaces and the Cologne and Düsseldorf groups in quantum network theory.

P4.1 MULTIPARTITE QUANTUM NETWORKS



4
FOCUS AREA

ACHIEVEMENTS

The experimental part of the core project aims at the generation of entangled N-photon quantum states in material-filled optical microcavities. In a collaboration of the Weitz and Rosch group, Bose-Einstein condensation of photons into a coherently split ground state has been demonstrated [1,2]. The experiment took place in a substructed dye microcavity inducing a potential for cavity photons with two minima. Repeated absorption and re-emission processes thermalize photons, leading to macroscopic population of a coherently spatially bifurcated low-energy state. The work is a precursor for the production of entangled many-body states by cooling.

The Open Call project of the Kroha group is designed to provide a bridge between the experimental and the theoretical endeavors [2,3]. The aim is the theoretical analysis of the coupled few-photon resonator structures, coupled to a dye reservoir, for use as a platform for the physical realization of GHZ states. A slave boson non-equilibrium technique for systematic calculation of reservoir-photon dynamics has been implemented. The calculation of the reservoir-induced photon-photon interaction vertex showed that in the dye alone it is too small to be relevant for inducing multi-photon entangled states. Therefore, the next step will be to consider 2nd/half harmonic photon interaction vertex as known in semiconductor materials, as to model the experimental group approach.

In the theoretical part of the core project, the Gross group has developed new methods for bounding the classical and quantum correlations that are compatible with certain network structures [4,5]. This is an important step towards the goal of finding applications of gaps between the classical and the quantum value for novel multi-partite quantum communication protocols. The Bruss group has designed a protocol for verifiable secret sharing within a quantum network [6], combining the benefits of quantum and classical schemes. An analysis of rates for quantum key distribution with asymmetric noise [7] has given hints for protocol designs in real-world scenarios. Furthermore, a new family of multipartite Bell inequalities has been particularly designed for device-independent conference key agreement [8,9].

Coordinator:
Dagmar Bruss
Participants:
David Gross
Detlev Grützmacher
Johann Kroha
Martin Weitz

PUBLICATIONS

[1] Christian Kurtscheid, David Dung, Erik Busley, Frank Vewinger, Achim Rosch, and and Martin Weitz, Thermally condensing photons into a coherently split state of light, Science 366, 894 (2019)

[2] Fahri Emre Ozturk, Tim Lappe, Göran Hellmann, Julian Schmitt, Jan Klaers, Frank Vewinger, Johann Kroha, and Martin Weitz, Fluctuation dynamics of an open photon Bose-Einstein condensate, Phys. Rev. A 100, 043803 (2019), Editors' Suggestion

[3] Zlata Fedorova (Cherpakova), Haixin Qiu, Stefan Linden, and Johann Kroha, Observation of topological transport quantization by dissipation in fast Thouless pumps, Nature Communications, in print, arXiv:1911.03770 (2019)

[4] Aditya Kela, Kai Von Prillwitz, Johan Åberg, Rafael Chaves, and David Gross, Semidefinite tests for latent causal structures, IEEE Transactions on Information Theory 66(1), 339 (2020)

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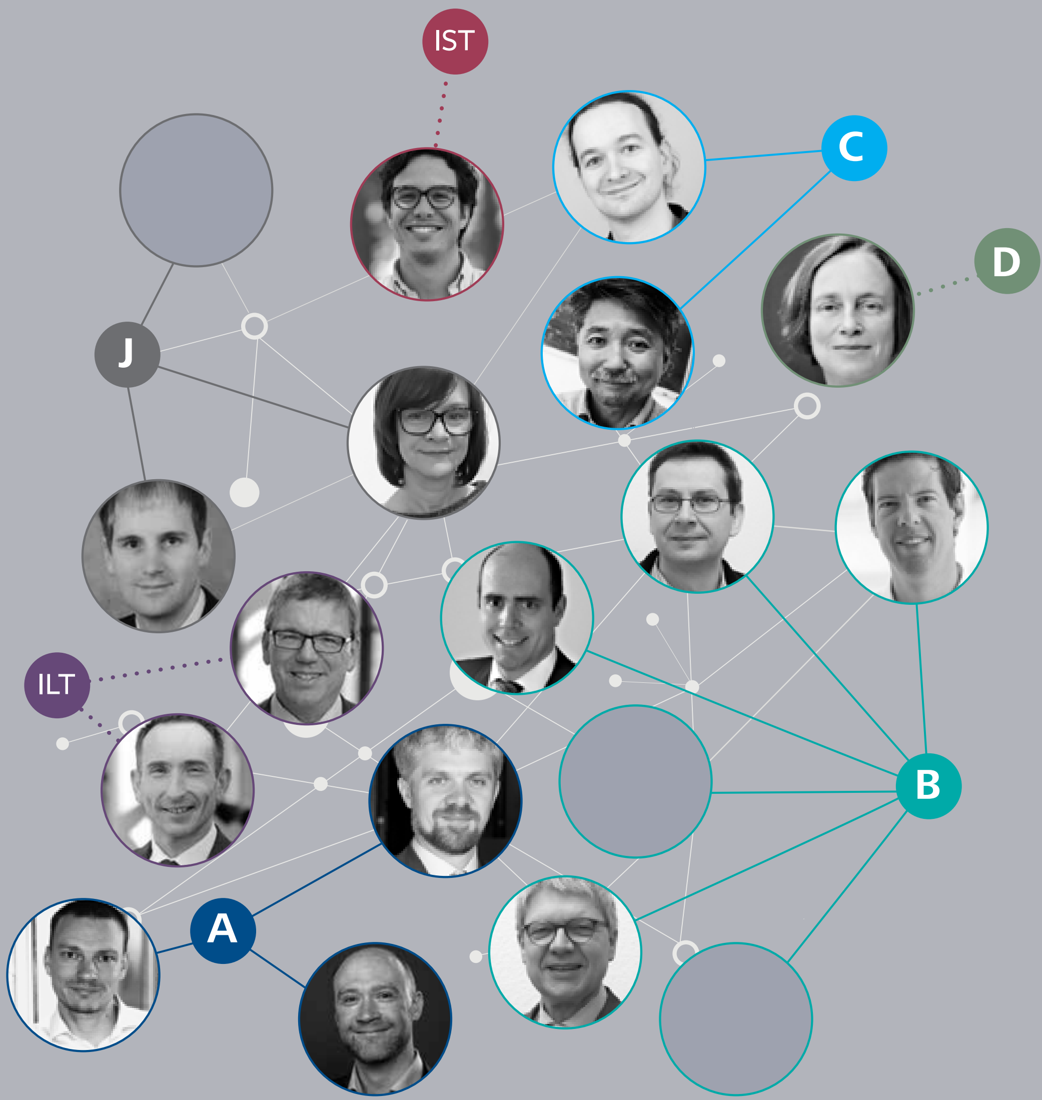
P4.2 QUANTUM LINKS



4
FOCUS AREA

ACHIEVEMENTS

The Bluhm group has established the fabrication of electrostatic exciton traps and verified that a trapping potential can be generated using a challenging membrane process. The observed photoluminescence effect shows a peak structure tentatively attributed to interaction between excitons, which would indicate the suitability as single photon source. The Kardynal group has established the parameter space for the growth of quantum dots of desired wavelength and areal density. In collaboration with the Linden group, parameter ranges for near-field photon extraction were established by numerical simulation. Furthermore, the Linden group has demonstrated direct laser-writing of lenses on top of single-mode optical fibers. The Köhl group has achieved spin-photon entanglement of the 171 Yb+ ion with a fidelity > 90% and has developed a route for photon conversion from 860 nm to 370 nm together with the Stellmer and Kardynal groups. The Pawlis group has grown first ZnMgSe/ZnSe:Cl/ZnMgSe QW structures that are delta-doped with chlorine and has performed basic photoluminescence (PL) investigations of this new system.

Within the Open Call project QUEST, ILT (Fraunhofer Institute for Laser Technology) has demonstrated wavelength conversion from 855 to 1550 nm with an an internal efficiency of 87 %. For the fundamental mode, modelling is in good agreement with the results. In another Open Call project, the group of Jeremy Witzens has simulated photonic crystal cavity solutions to improve the extraction efficiency from quantum dots in membranes, predicting that values in excess of 50 % are possible. The concept is being extended to geometries that can accommodate several dots and specifically considers the impact and possible adaptations of the gate geometrys. First fabrication steps were made by the Bluhm group.

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OpenCall PIs:
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Peter Loosen
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PUBLICATIONS

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DISCOVER

03

ML4Q
LIFE

ML4Q RESEARCH SCHOOL AND EARLY-CAREER SUPPORT

A wide collaborative network brings along a multifaceted and rich training environment for early career scientists. It is therefore the aim of the ML4Q Research School to implement an attractive training program for Master and PhD students as well as for postdocs, making use of bundled expertise in various subdisciplines of physics that are relevant to quantum science and technology. In addition to a deepened understanding of this exciting interdisciplinary field of quantum technologies, young scientists can acquire skills that are useful for further scientific and personal development. At the same time the school activities serve as a platform to enhance interactions between the cluster sites and between young researchers at different career stages.

As a cluster-wide program, it brings together expertise and training infrastructure already existing at all sites and profits from well-established successful inter-site arrangements such as the Bonn-Cologne Graduate School of Physics and Astronomy (BCGS). For the first time, cluster groups at RWTH Aachen were involved in the Master student recruiting rounds of the BCGS. In turn, Master students in Cologne and Bonn can benefit from a novel Master study-track on Quantum Technology, starting from the winter semester 2019/20 at RWTH Aachen.

In December 2019, Magda Baer Radermacher joined the ML4Q office and took over the coordination duties of the Research School. Therefore, new activities and training offers beyond existing ones are still in planning.

One exciting offer is a new Master course on Platforms for Quantum Technologies that is planned for spring 2020 and covers all major topics represented in the cluster research program and its Focus Areas. It is taught by lecturers from all cluster sites and open to students at all three partner universities. In addition, students from all locations gained access to and made use of available cross-site courses in quantum technology.

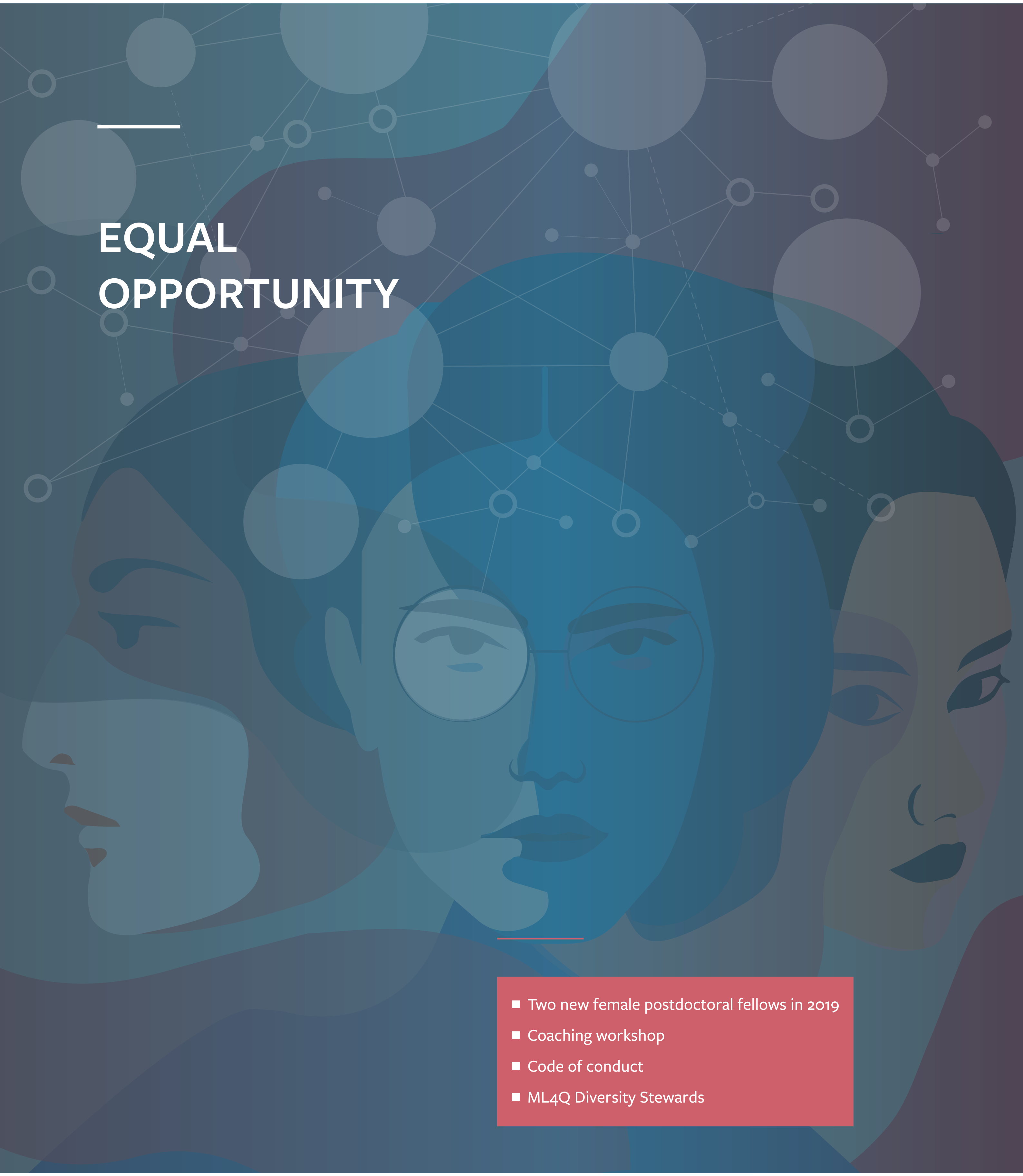
For 2020, we plan several courses on transferable skills, including good scientific practice training, as well as networking events such as Alumni Career Talks and a Students' & Postdocs' Retreat. We also plan to complement the Platforms for Quantum Technologies Lecture with intensive weeks on various topics related to quantum science and technologies including lab trainings and more practical insight into the research work of local groups.

- Wide collaborative network
- Bonn-Cologne Graduate School
- Master study-track on Quantum Technology at RWTH
- New Master course on Platforms for Quantum Technologies

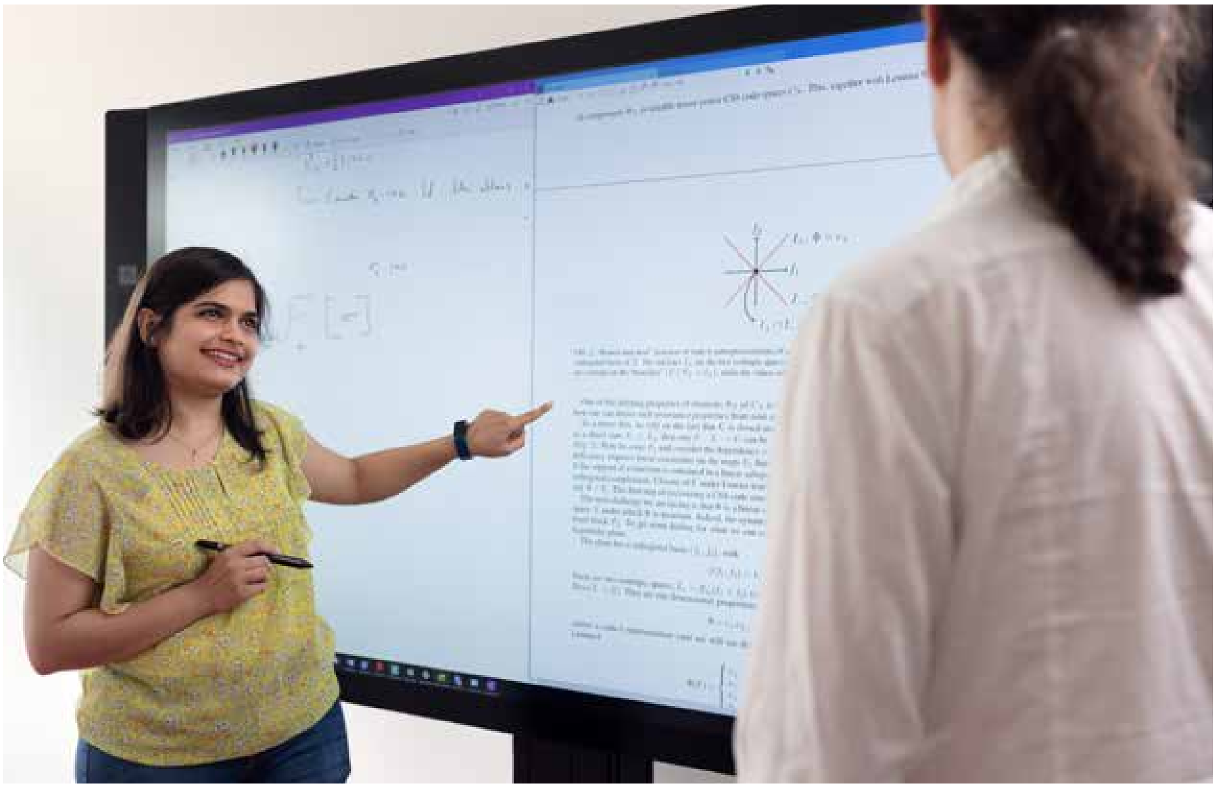
03
ML4Q LIFE

03

EQUAL OPPORTUNITY



- Two new female postdoctoral fellows in 2019
- Coaching workshop
- Code of conduct
- ML4Q Diversity Stewards



Convinced that the lack of diversity in physics is not only an issue of inequality and that it rather affects how research is conducted and applied, ML4Q is dedicated to enhance diversity within the cluster by different measures addressing aspects of gender, work-life-balance, internationalization as well as disabilities.

As for promoting gender equality, ML4Q could successfully recruit two outstanding international female scientists as postdoctoral fellows in 2019.

At the time of hiring, both had highly visible track record in quantum information, and ML4Q had to counter offers from other leading international institutions. In case of the more experienced researcher, this was done by using additional cluster funds to promote the position from a standard postdoc to a group leader role (the offer she accepted includes responsibility for hiring and advising a PhD student, as well as an independence grant for travel and consumables).

These examples show that our pro-active hiring strategy gives the cluster access to sought-after talent, increases our international visibility, and boosts leadership opportunities for top young female scientists.

On a further note, ML4Q welcomed and gladly co-funded a workshop initiative by the Department of Physics at UoC. The workshop, entitled "Bestehen als Frau in der Männerdomäne Physik", targeted advanced female Physics students and aimed at empowering and coaching them in confident self-presentation and professional interaction with their male colleagues. The workshop took place twice in May and August 2019 and was open to female students not only from Cologne, but also from Bonn and Aachen.

As for promoting a family-friendly work environment, ML4Q reserved places for children of cluster members at local day care providers - a service that might will become crucial in the negotiations for new professorships planned in 2020/21.

Finally, a code of conduct was adopted and published in 2019, documenting publicly that he cluster provides an attractive environment for researchers from diverse backgrounds. The code was implemented in agreement with the newly appointed ML4Q Diversity Stewards at all cluster's sites.

LAB FACILITIES

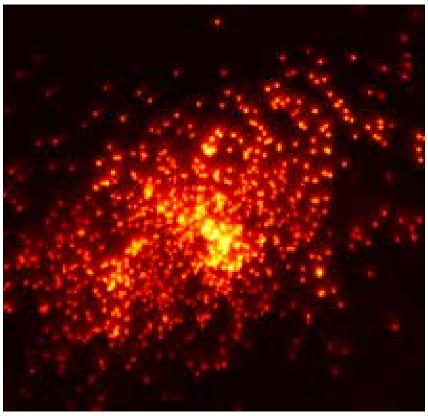
Research in quantum computing relies not only on theoretical efforts, but also on laboratory research requiring state-of-the-art equipment. Therefore, roughly one third of the expenditures in 2019 was dedicated in the crucial ramp-up phase of the ML4Q research to acquire additional equipment both in the labs of existing groups as well as in the central facilities, ML4Q Devices and ML4Q Fiber Lab.

- 1/3 of the expenditures dedicated to acquiring equipment
- 100 keV electorn-beam lithography tool at the Helmholtz Nano Facility in Jülich
- Manufacturing of miniaturized optical components
- Fabrication of micro-optical elements in the Fiber Lab in Bonn

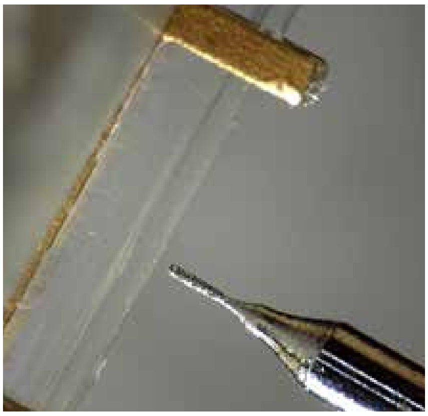
ML4Q DEVICES

ML4Q Devices is ML4Q's central technology platform. As a shared user facility, the platform makes use of the existing infrastructure of the Helmholtz Nano Facility (HNF) at FZJ. ML4Q researchers can now gain access and benefit from the high-level processing knowhow of state-of-the-art nanofabrication. In 2019, a new 100 keV electron-beam lithography tool was installed and put into operation, providing ML4Q groups with an additional valuable platform for device fabrication.

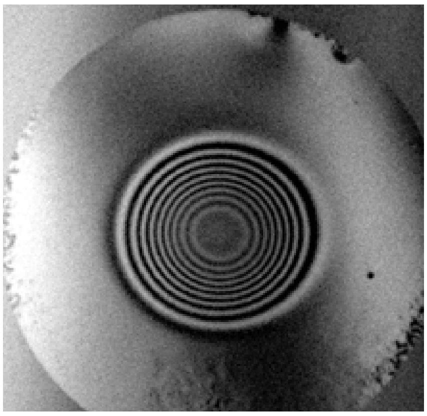
ML4Q FIBER LAB



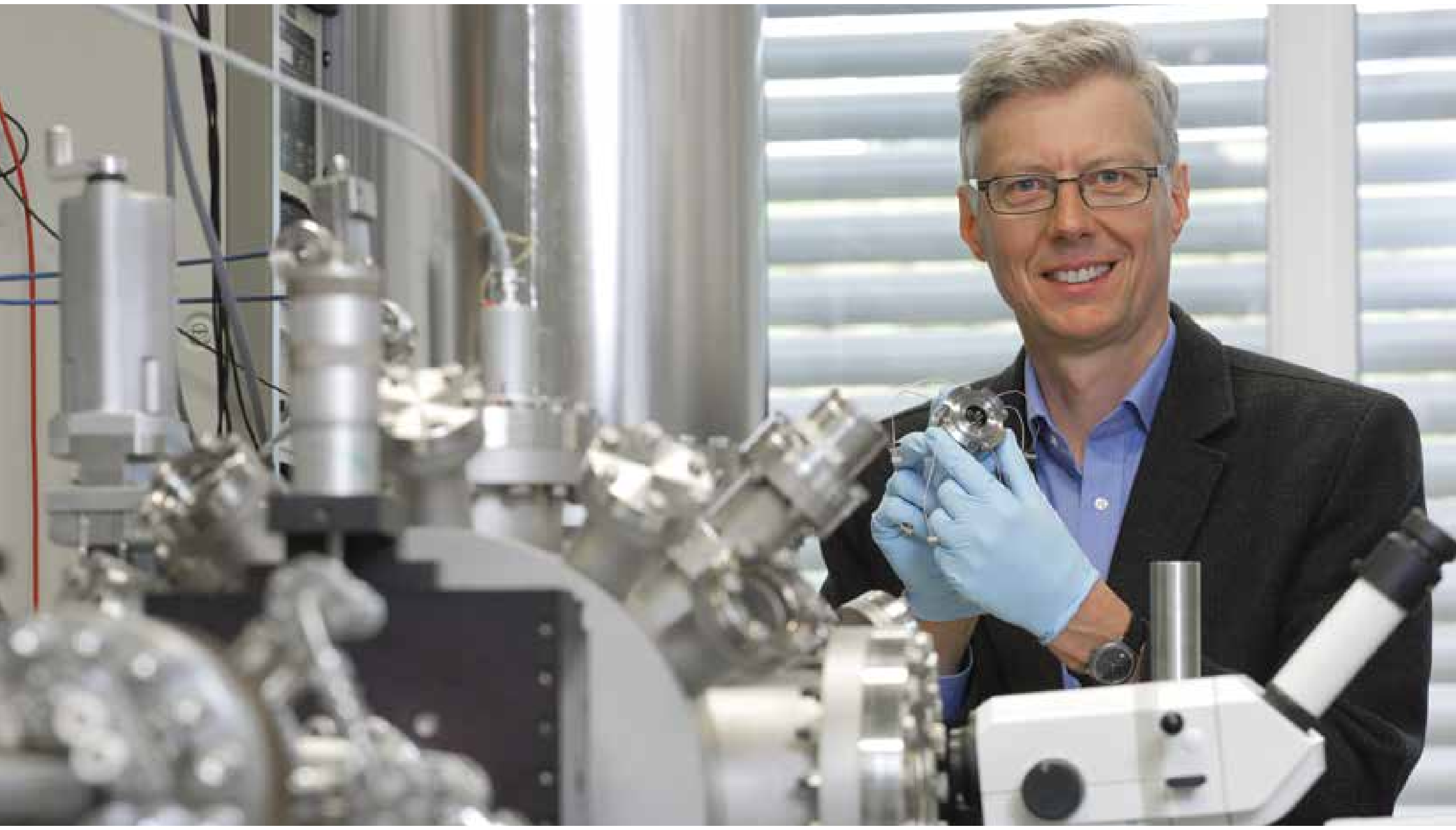
Several hundred ultra-cold Caesium atoms, trapped in an optical lattice



Drill for 0.2 mm optical fiber (waterdrop for size comparison)



Fiber end face



ML4Q Fiber Lab is an experimental facility dedicated to the manufacturing and integration of optical fibers which are the core of today's world-wide communication infrastructure. Fiber-optic components also form a key ingredient of quantum communication and are therefore required by ML4Q researchers.

The Fiber Lab in Bonn builds up on existing structures that have been funded by the Ministry of Education and Research in the past. It is equipped with a state-of-the-art apparatus for micro-machining of fiber end faces (2D) by laser ablation, a 3D lithography instrument, as well as a high-resolution interference microscope for in-line process control and fiber mirror surface analysis. The equipment allows for the manufacturing and characterization of miniaturized optical components and the fabrication of micro-optical elements that optimize the coupling of photons emitted by semiconductor quantum dots to optical fibers. In 2019, the Fiber Lab has been successfully integrated into ML4Q and is accessible to research groups at all sites.

ML4Q

MATTER AND LIGHT FOR QUANTUM COMPUTING

KNOWLEDGE TRANSFER

Quantum technologies are attracting substantial interest from industry and private capital. However, with many press releases overemphasizing success, ML4Q recognizes its competency to provide an unbiased expert opinion for decision makers in order to obtain a balanced picture of realistic future scenarios. The need for this competency became even clearer facing the media coverage of Google's quantum supremacy breakthrough in September 2019.

In a first step, ML4Q joined a growing network coordinated by QT.NMWP.NRW which is dedicated to bring quantum technology scientists and industry in NRW together and foster know-how transfer in the region. ML4Q aims to expand its collaboration network and encourage its junior scientists to present their projects at QT.NMWP.NRW networking events. A few collaborations with industrial partners exist already. Together with researchers from Covestro, we are working on quantum algorithms for chemistry problems, in particular with an eye on near-term „noisy intermediate-scale quantum computers“ (NISQ). This work is conducted as a joint PhD project within the core project 3.2. Another strategic partnership with Infineon Technologies was initiated in the core project 3.3. in order to conceive future fabrication of quantum devices. Additionally, Hendrik Bluhm was invited to give an overview of state of the art in quantum computing and related business aspects at the Infineon Innovation Week 2019. Similar seminars presented by ML4Q researchers are planned in order to outline application-relevant aspects of ML4Q research and explain how different industrial sectors can profit from advances in quantum technology.

ML4Q also participated in the 54th "Kölner Transfer-runde". This platform was established by the Chamber of Commerce and Industry in Cologne in order to foster entrepreneurial ideas as well as technology transfer in the city. Relevant issues for the emerging field of quantum computing and possible applications arising from ML4Q's research program were discussed.

On a further note, the Research Center Jülich and the RWTH Aachen joined in September 2019 a roundtable organized by the Metropolitan Region Rhineland e.V. at the representative quarters of NRW (Landesvertretung des Landes Nordrhein-Westfalen) in Berlin. The roundtable brought together politicians, entrepreneurs as well as experts involved in different projects developed in the Rhineland region. ML4Q's concept and mission were presented among other research activities of both the Research Center Jülich and the RWTH Aachen. Possibilities of technological transfer and scenarios for the technological development of the region were discussed.

OUTREACH

The German Research Foundation set a clear sign by funding six Clusters of Excellence within the field of quantum science technology (QST), thereby identifying quantum technologies as one of the most important key technologies for the future. Several programs launched by the German government and the Ministry of Education and Research complement the Excellence Strategy and dedicate high investments in research on QST. In order to strengthen the role of universities in this emerging and fast-growing field, ML4Q contributed significantly to the formation of the Quantum Alliance, the strategic consortium of German Clusters of Excellence and research centers working in QST. Joint participation in workshops and career fairs are planned in order to increase the visibility of German universities as an essential player in the innovation process and an attractive employer for highly-qualified, international quantum researchers.

On a further note, the German Physical Society (DPG) launched in 2019 a new meeting format dedicated to a research theme identified by its three sections. The first DPG Fall Meeting in September addressed Quantum Science and its relation to Information Technologies. ML4Q participated as part of the Quantum Alliance and Prof. Yoichi Ando gave an overview of successful research initiatives in the field during a lunch talk. Luckily, the International Conference of Physics Students ICPS 2019 was hosted by the junge Deutsche Physikalische Gesellschaft (jDPG) in the center of Cologne providing ML4Q with a great opportunity to present its scientific program to physics students coming from all over the world.

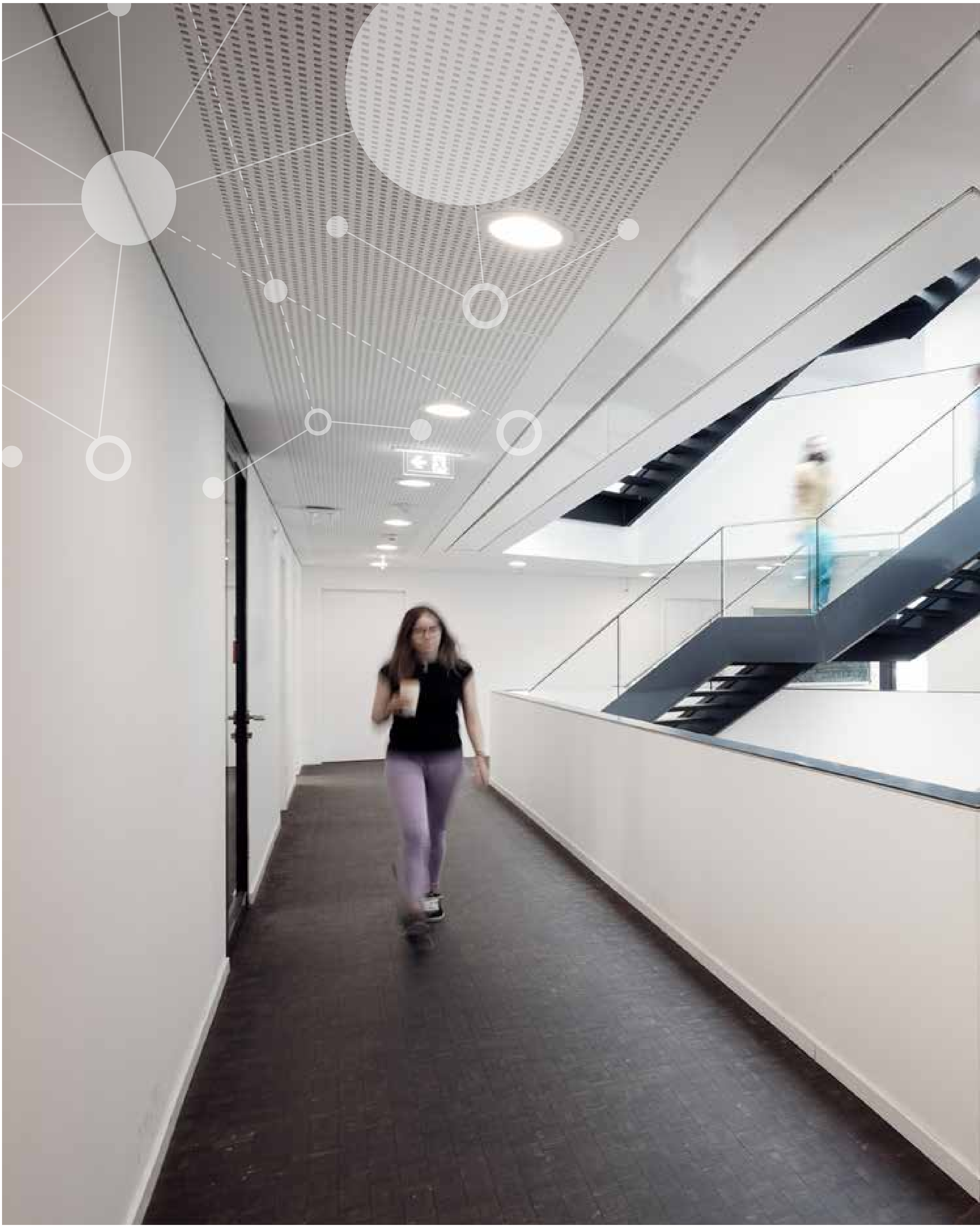
Complementing these networking and outreach activities within the scientific community, several events took place in order to introduce the basic and sometimes surprising concepts of modern physics to the general public. The RWTH Aachen opened its doors for the "Wissenschaftsnacht 2019" in the night of November 8 and welcomed about 6.000 visitors who participated in many science shows and demonstrations organized by different university institutes. ML4Q principal investigator, Hendrik Bluhm, held a lecture on quantum physics and explained how new developments and ongoing research in quantum information can change the future of computing. The biggest science festival in the field of physics "Highlights der Physik" which is organized by the German Physical Society (DPG) was hosted in 2019 by the city of Bonn and included "The quantum world" as one of its topics. ML4Q participated in the interactive exhibition and demonstrated the scientific approach of the cluster. Visitors could get a feel for the quantum computing world through exhibits from the cluster's laboratories including chips and ion traps.

2019 also witnessed a vigorous debate among quantum physicists as Google's research group led by John M.

Martinis published in Nature its proof of quantum supremacy using a 53-qubit processor to solve a problem in 200 seconds which would have needed thousands of years on a classical computer. Journalists approached ML4Q scientists in order to get an expert's opinion on the issue. In an interview with DER SPIEGEL, Prof. Tommaso Calarco pointed out how exciting this development is from a scientific point of view. However, he emphasized how huge the remaining challenges still are until useful quantum computing power can be achieved. Prof. David Groß explained to Kölncampus Radio how this development was possible and why it is still useless for relevant applications. He showed how ML4Q is using a different approach by testing new materials for better qubits that can contribute to useful calculation processes. Finally, ML4Q Advisory Board Member, Prof. Frank-Wilhelm Mauch, was invited by the #heiseshow to talk about the future of quantum computers.

Kölncampus Radio

- Quantum Alliance
- DPG Fall Meeting
- International Conference of Physics Students ICPS 2019
- Highlights der Physik 2019
- Wissenschaftsnacht 2019



IMPRINT

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DFG 2020 BECAUSE RESEARCH MATTERS