DHBW
Duale Hochschule
Baden-Württemberg

Creating a quantum technology lab for interdisciplinary use

DHBW
QUANTUMLAB

An initiative of the Steuerkreis Quantum Technology Stuttgart

Idea and Motivation

Empowering tomorrow's engineers with Quantum Technology
Quantum technology is ready to influence engineering education. Our mission is to inspire young engineers through accessible, hands-on experimentation, fostering curiosity and confidence. We approach teaching with an operational and epistemological focus, recognizing the paradigm shift quantum computing brings, as outlined by Deutsch and Shor. Inspired by Wheeler's "It from bit" and Zeilinger's quantum information work, our lab emphasizes immediate, hands-on experiments to spark creativity and drive quantum innovation.

Bachelor's degree programs 5th and 6th semester

Electrical Engineering
- → **Praktische Anwendungen Produktion**
  Integrated Quantum Photonic Technologies
- → **Optoelectronics II**
  Supplementary lab lecture to Optoelectronics I

Embedded Systems
- → **Quantentechnologie** with focus on Quantum sensing

Computer Science
- → **Quantencomputer**

Interdisciplinary student research projects

Scientific Director Prof. Dr. Carmen Winter

Cooperation and support

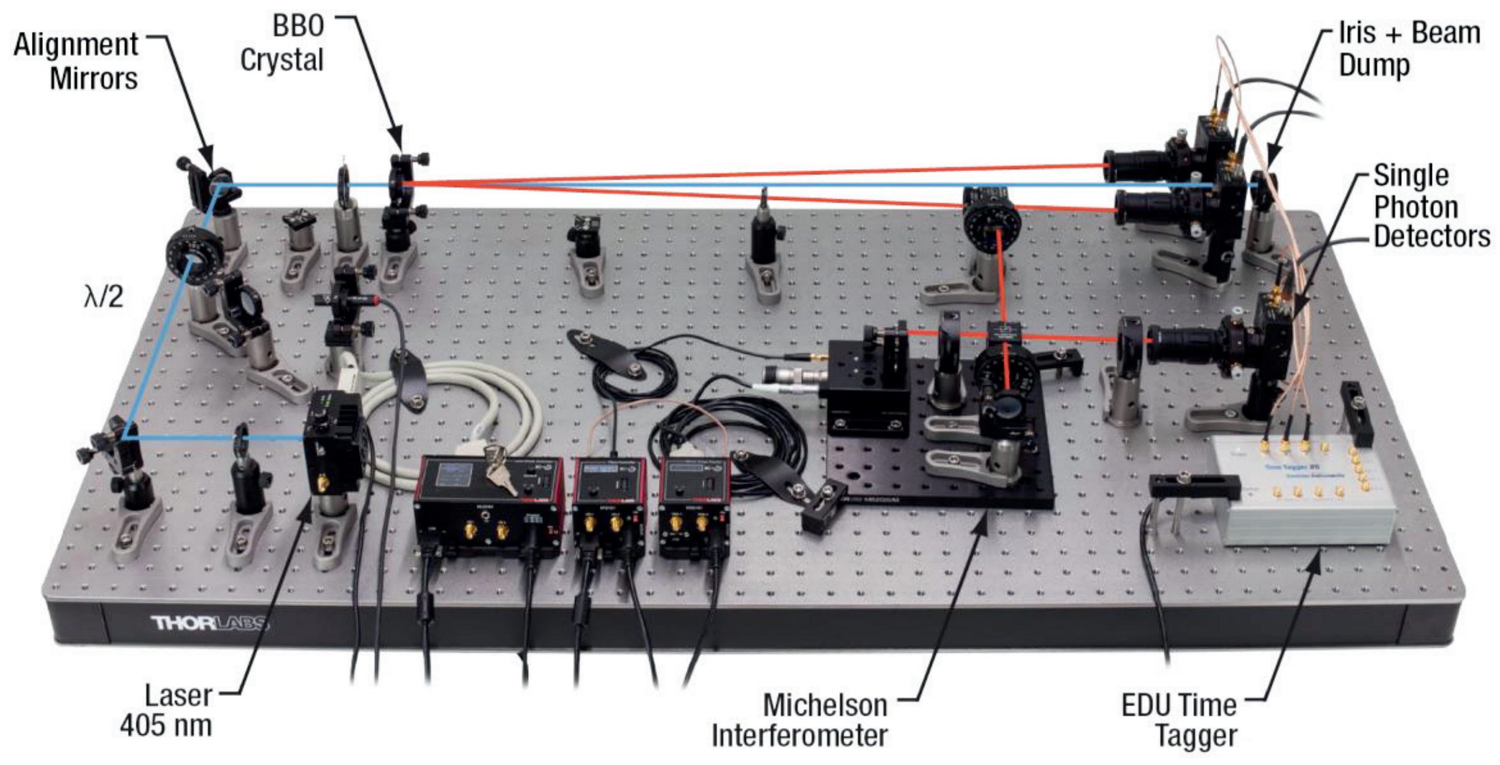
Our cooperation partners from the Quantum BW project:
- → **5th institute of Physics** University Stuttgart
- → **Institute of Quantum Technologies**
  German Aerospace Center (DLR), University Ulm

Our supporters
- → **Advanced Quantum** Stuttgart
- → **Swabian Instruments** Stuttgart

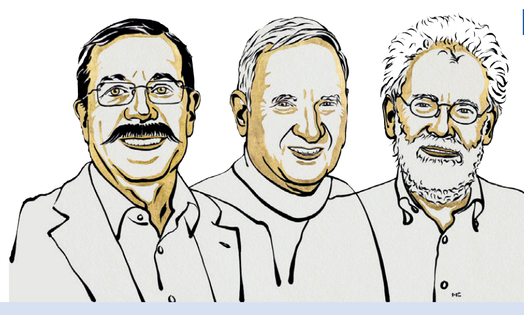
Our sparring partners
- → **Research group Clinical Neurotechnology** Charité , Berlin
- → **National Metrology Institute** PTB, Berlin

The experiments

Generating Single Photons

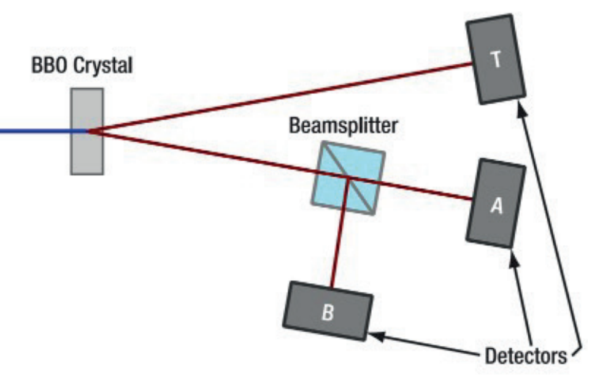


The basis of our quantum experiments
Our Thorlab EDU-QOP1 setup enables the generation of approximately 400,000 single photons per second via a spontaneous parametric down-conversion (SPDC) process using a BBO crystal. The crystal is pumped with a 405 nm laser, producing single photons at a wavelength of 810 nm. Spatially entangled photon pairs (signal and idler) are verified with second-order correlation measurements below 0.02, achieved using three SPAD detectors and a Time Tagger 20 from Swabian Instruments. The entangled photon pairs exhibit conical emissions, allowing us to isolate signal and idler photons at a 3° angle from the pump beam.
Between the single-photon source and detection area, a 400 cm^2 workspace supports quantum state preparation for experiments.
The platform, extended with the EDU-QOPA1(/M) Polarization Entanglement Add-on, also facilitates the generation of polarization-entangled photon pairs.



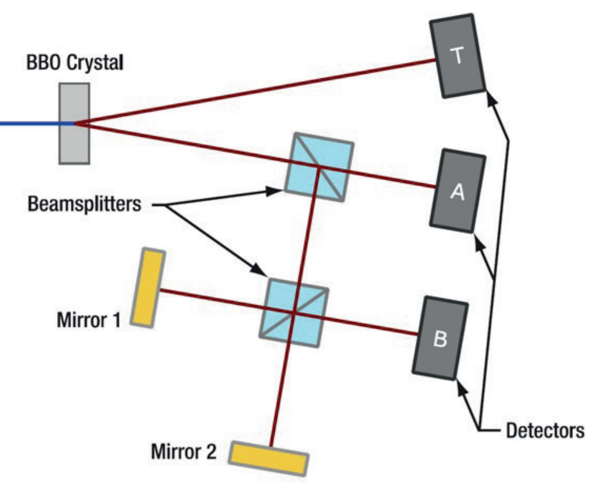
Inspired by Nobel Laureates
Our setup replicates key experiments of Alain Aspect, John Clauser and Anton Zeilinger. Their research on entangled particle pairs have proven the violation of the Bell's Theorem. The physicists were awarded the Nobel Prize in Physics in 2022 for this work.

Revealing the Photon's Particle Nature



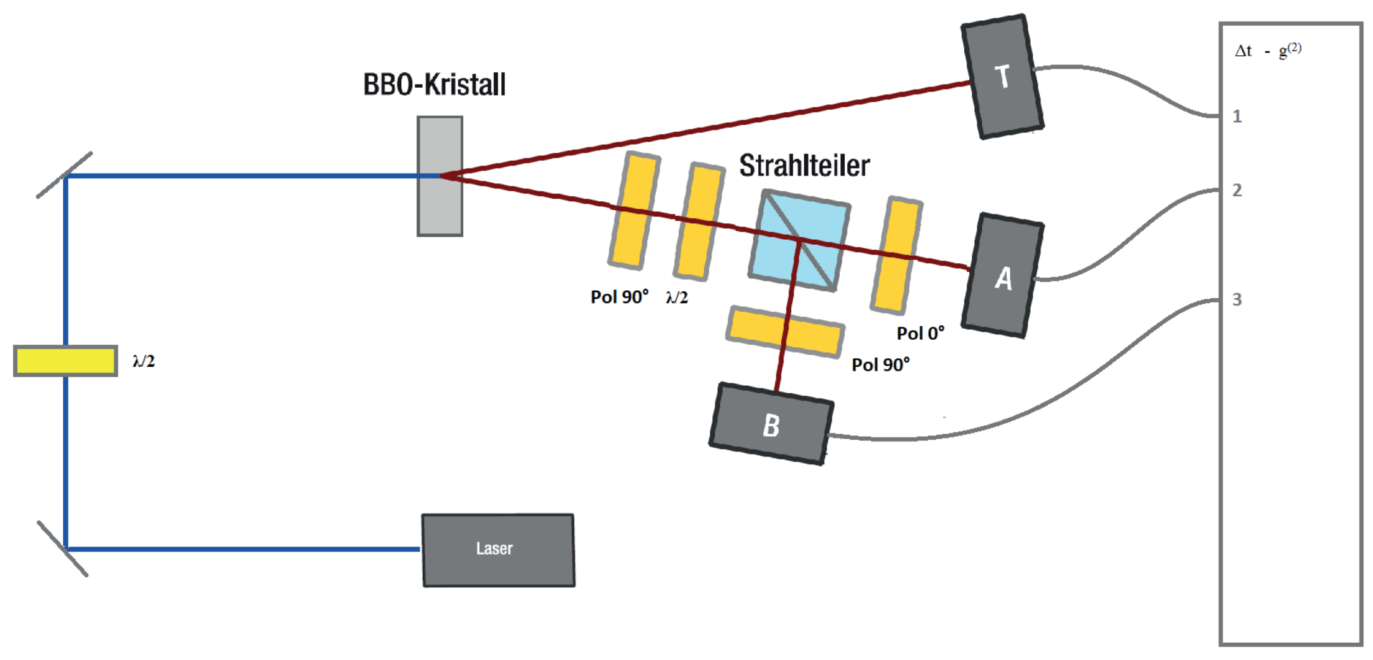
The Grangier-Roger-Aspect Experiment
The GRA-experiment in our lab demonstrates the particle nature of photons as quantum objects in the Fock state.
Using this setup, we distinguish between single-photon states and strongly attenuated laser signals, which are averaging near the single-photon level, but remain Poisson-distributed and exhibit bosonic bunching tendencies. This distinction can be further investigated through a Hanbury-Brown-Twiss (HBT) experiment. These experiments allow us to address the quantization of the electromagnetic field in relevant lectures, providing students with basic insights into quantum optics. By conclusively demonstrating the particle-like behavior of photons, the GRA experiment serves as a core element of our laboratory and builds a bridge between theory and experiment to enable a deeper understanding of quantum phenomena.

Unveiling Wave-Particle Duality



Photon Self-Interference
Building on the Grangier-Roger-Aspect (GRA) experiment, we can illustrate the duality of photons by demonstrating self-interference in a Michelson interferometer. The interference of a single photon with itself is both, astonishing and revealing, offering a profound glimpse into the challenges and beauty of the quantum world. While textbooks describe such phenomena, seeing it firsthand leaves an undeniable impact. This experiment not only showcases the experimental power of quantum mechanics but also introduces students to the complementary nature of quantum mechanics. By exploring the wave-particle duality of photons, we provide a tangible and unforgettable foundation for understanding one of the most fundamental concepts in quantum physics.

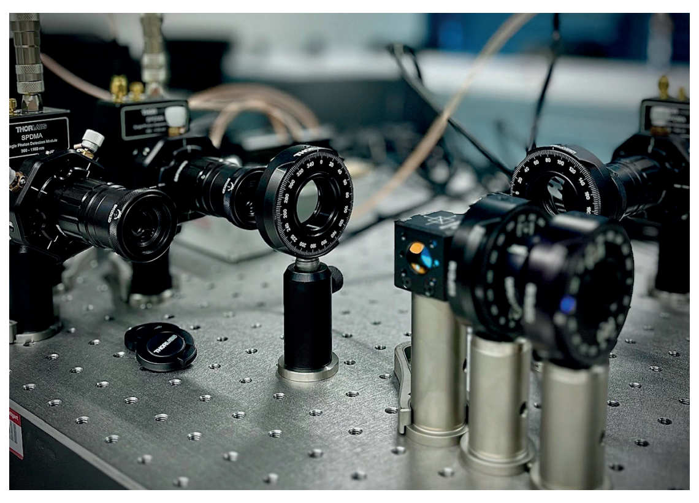
Bridging the Quantum Divide



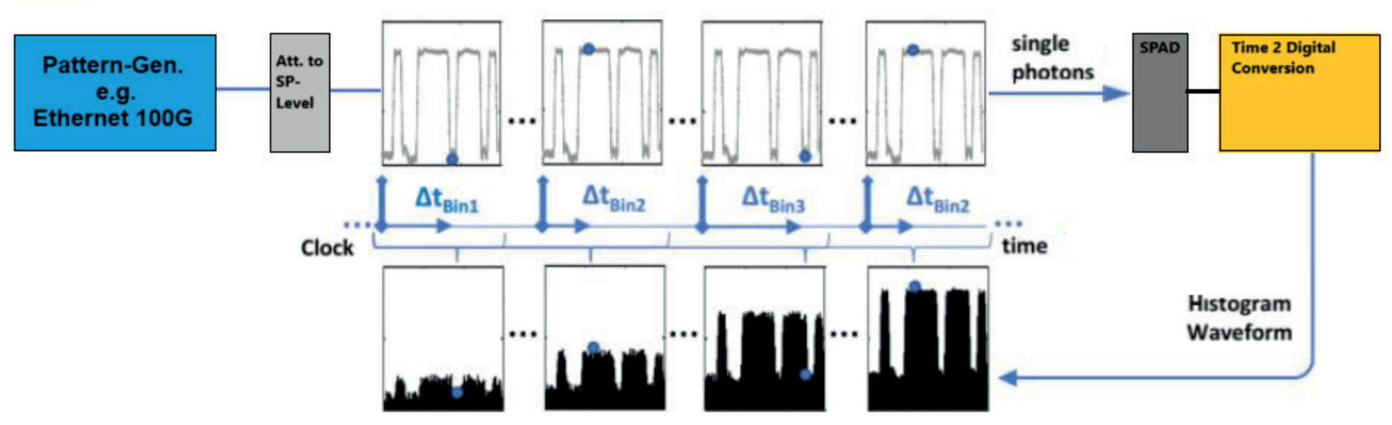
From Light Pulses to Photonic Qubits
Building on the Grangier-Roger-Aspect (GRA) experiment, we move on to create a polarization-encoded photonic qubit using single photons. This transition allows students to explore quantum information beyond classical light pulses.

Our journey started with the EDU-QCRY1 experiment on quantum cryptography, implemented in our optoelectronics lab. This setup introduces students to qubit encoding in polarization using short light pulses. While not a native quantum experiment, it provides an intuitive understanding of qubit encoding, allowing students to visualize how polarization translates into information. Transitioning from light pulses to single photons helps students grasp quantum states and forms the basis for understanding the BB84 protocol in quantum cryptography.

The setup begins with defining the photon's polarization state and using a quarter-wave plate to achieve superposition. The GRA beam splitter is modified into a polarizing beam splitter (PBS), where detection rates at the SPAD detectors correspond to the quantum states $|0\rangle$ and $|1\rangle$. The qubit's superposition state is expressed as $|\psi\rangle=a|0\rangle+b|1\rangle$, with complex amplitudes a and b satisfying $|a|^2+|b|^2=1$. To enhance robustness, polarizers filter stray light, and light-tight housing minimizes interference, addressing typical engineering challenges like improving system reliability. This hands-on experiment demonstrates how polarization-encoded qubits are prepared and measured, while revealing a key limitation: a superposition state cannot be fully determined from a single measurement unless aligned with a basis state.
By exploring the probabilistic nature of quantum measurements, students gain insights into why quantum computers require multiple runs for reliable results. Realizing a physical qubit bridges theoretical and practical quantum information, preparing students for advancements in quantum technology.



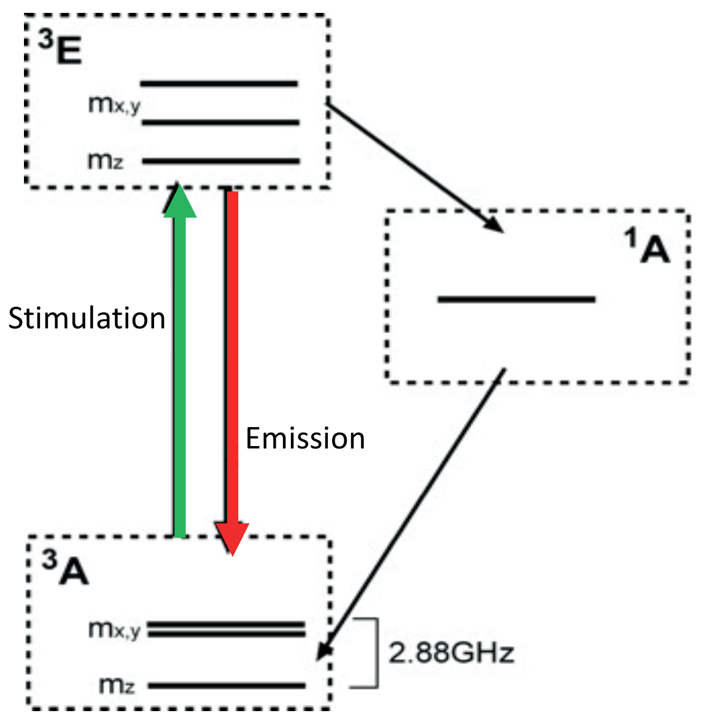
Measuring at Quantum Level



Single Photon Random Sampling
A key application of our quantum lab is the "Single Photon Random Sampling" experiment, generously donated by Swabian Instruments, a Stuttgart-based company with whom we have collaborated since 2022. While our Thorlabs EDU-QOP1 experiments focused on generating and handling single photons, this experiment emphasizes their detection and precise temporal analysis at the picosecond level using a time-to-digital converter.
The setup demonstrates an optical sampling oscilloscope capable of capturing digital signals from optical transmitters, such as high-speed Ethernet transceivers. It records single-photon avalanche diode (SPAD) detector events as histograms over time relative to a trigger signal, directly analyzing optical signals without electrical conversion. The measurement precision is limited only by detector jitter.
This experiment introduces students to single-photon detection technologies like SPADs and superconducting nanowire single-photon detectors (SNSPDs) and familiarizes them with the Time Tagger, a key quantum measurement tool. Based on the research by Helmut Fedder and Steffen Oesterwind in 2018, we demonstrated its capability in a 2022 student project, detecting signals from highly attenuated sources, such as distant space probes.

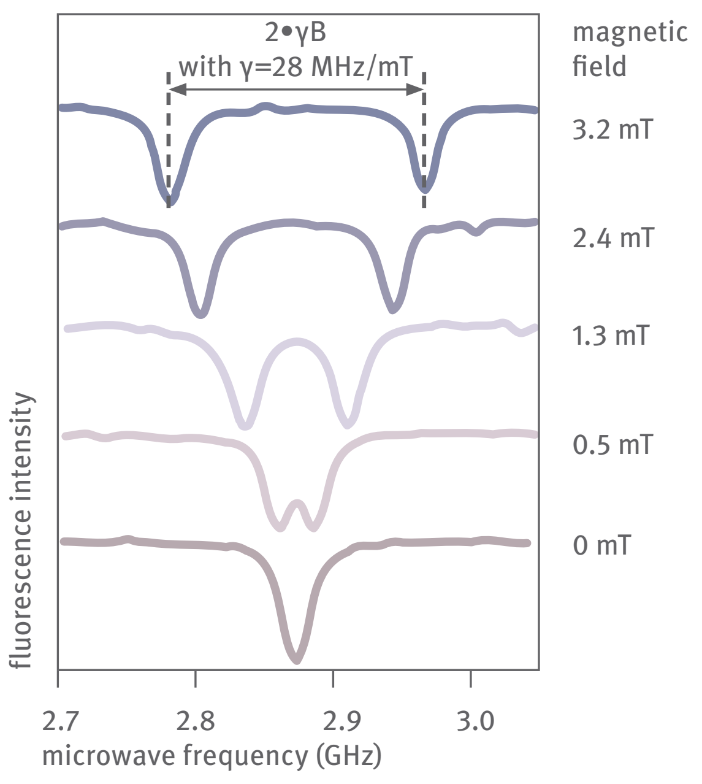
Quantum Sensing with NV-Diamonds

From Brain Waves to Battery Testing
Our quantum lab traditionally explores quantum technology using photons as quantum particles, an intuitive approach due to the mapping of quantum states onto geometric space. Our new experiment introduces another paradigm: quantum technology based on electron spins in solid-state systems, such as nitrogen-vacancy (NV) centers in diamond.

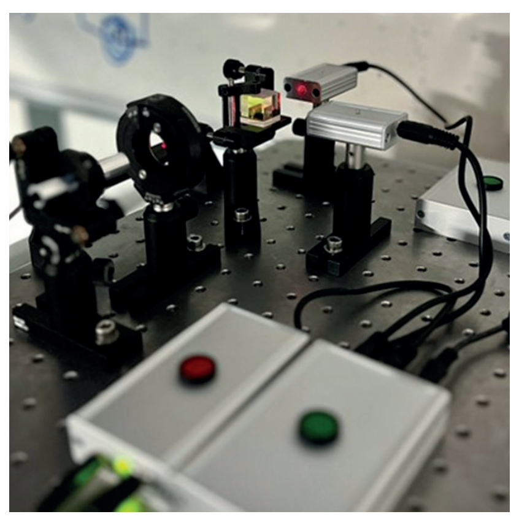
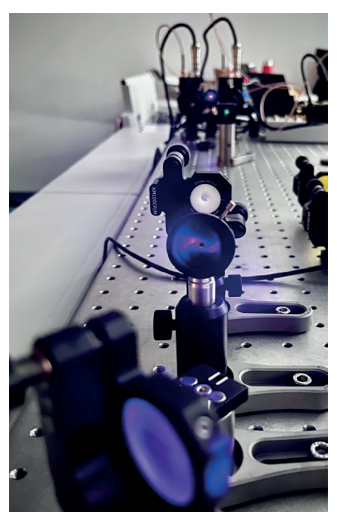
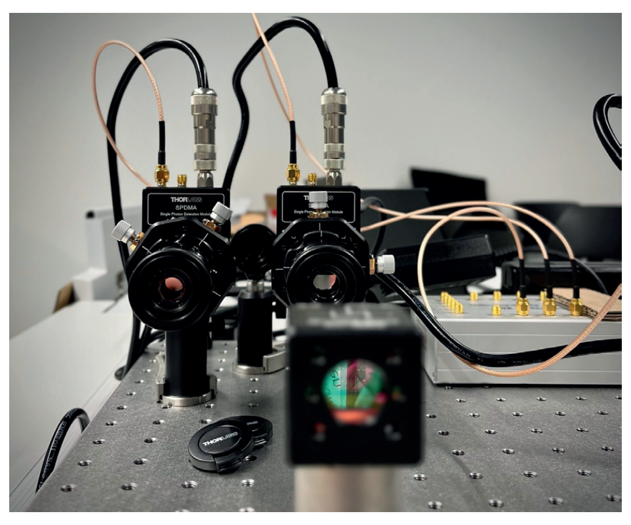
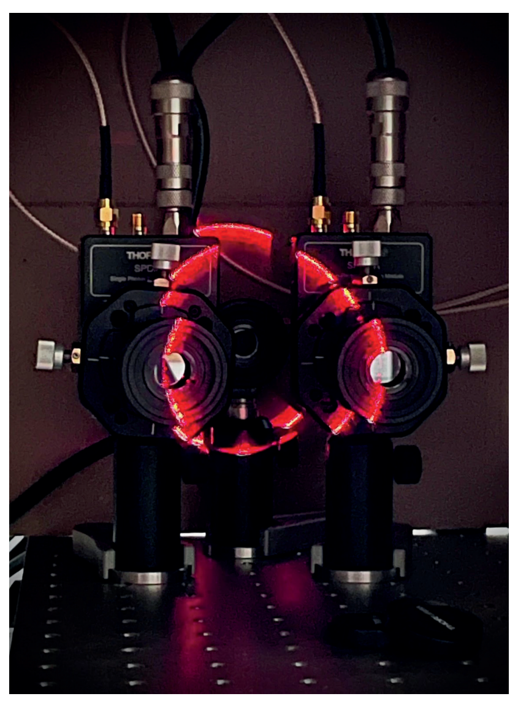
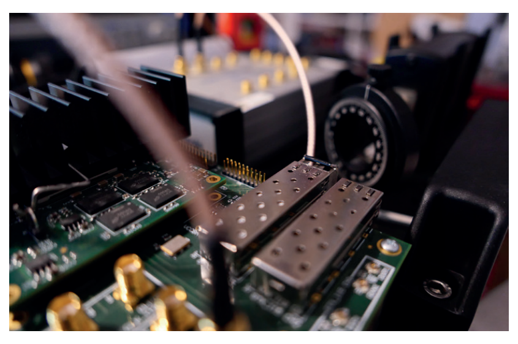
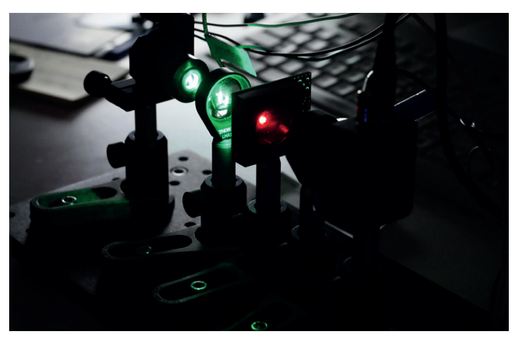


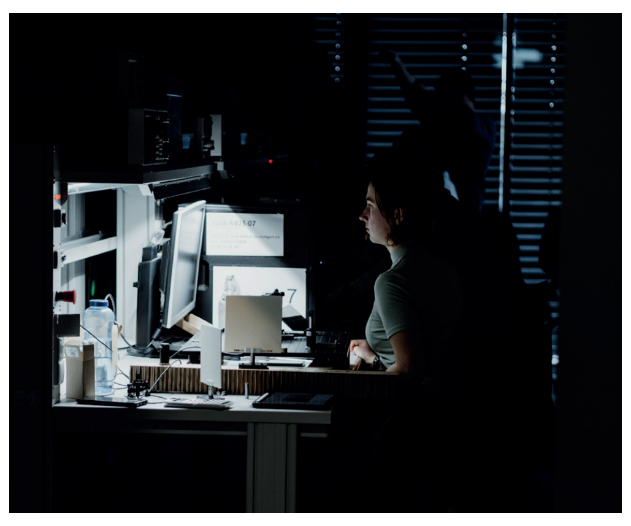
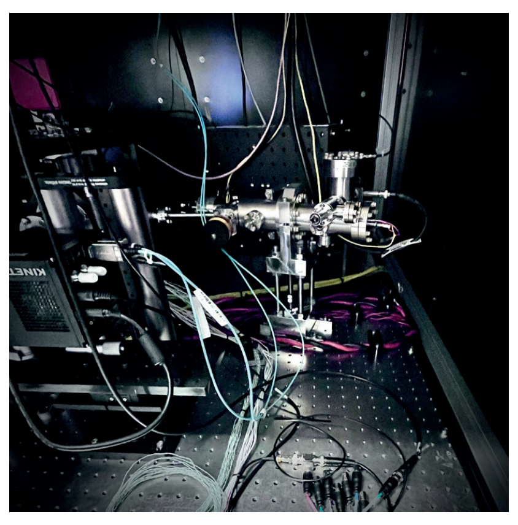
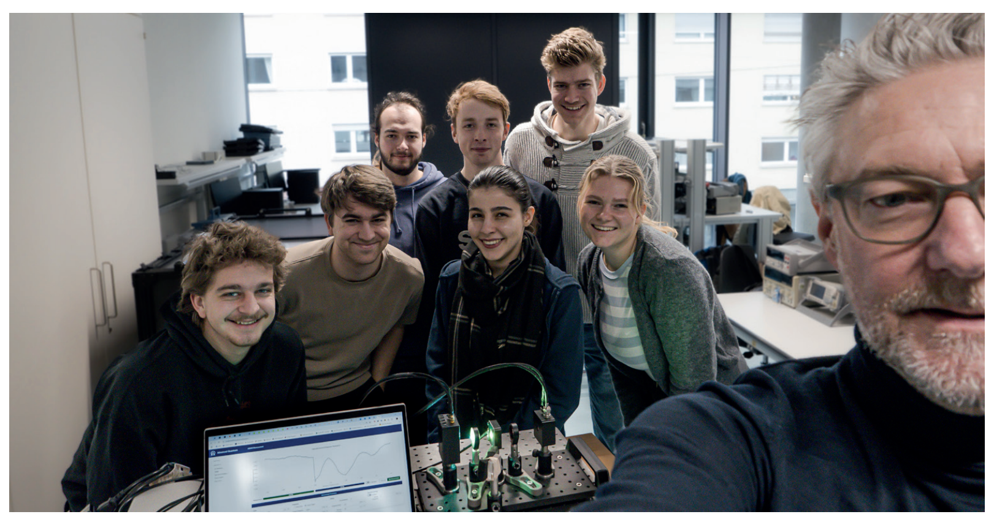
NV-diamond technology plays a pivotal role in quantum sensing, enabling ultra-precise magnetic field measurements. For instance, it is used in autonomous navigation without GPS and serves as a two-state system for illustrating qubits. The same NV-diamond EDU-kit is employed by the University of Ulm in their Master's program, Quantum Engineering.

In preparation for our Quantum Technology lecture in the Embedded Systems program, we collaborated with Charité Berlin and PTB Berlin. Charité and PTB jointly presented applications like magnetoencephalography (MEG) and brain-computer interfaces (BCI). Additionally, PTB highlighted navigation in environments like the London Underground and testing leakage currents in e-mobility batteries. Advanced Quantum, our partner since 2022, facilitated these connections, and their EDU-kit has become an integral part of our lab. These diverse applications demonstrate NV-diamond technology's versatility in revolutionizing quantum sensing and engineering solutions, underscoring the real-world impact of quantum technology.

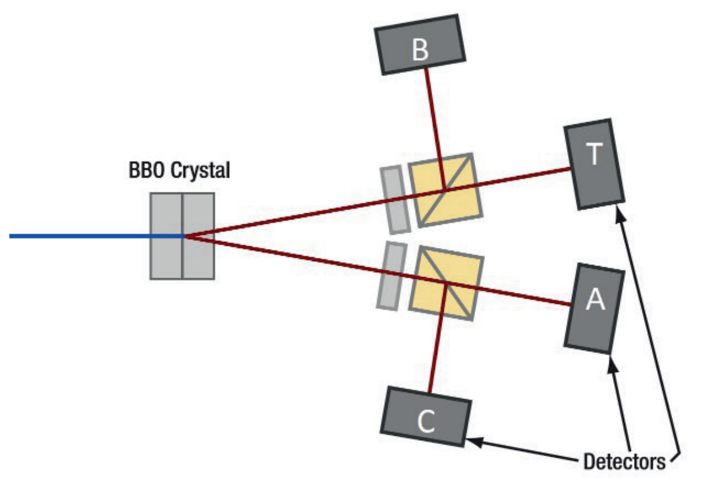


Impressions

Exploring the Core of Quantum Phenomena



Polarization-Entangled Photons
Our new add-on makes it possible to generate polarization-entangled photon pairs. This in turn enables us to demonstrate one of the most conceptually challenging phenomena in quantum physics directly through experiments, making it easy for students to understand.

The experiment allows us to showcase the violation of Bell's Theorem, disproving the local hidden variables proposed in the Einstein-Podolsky-Rosen paper. Technically speaking, this is the basis for advanced applications such as quantum cryptography (E91 protocol), quantum imaging (ghost imaging), Bell measurements and teleportation.

Although they are not yet suitable for rapid demonstration in lectures, we want to develop didactic concepts for these complex experiments through student projects in order to establish our laboratory at the leading edge of quantum experiments.

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