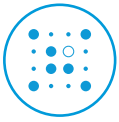




# Quantum Physics Education

## Education & Science Kits Portfolio





# Education Portfolio

## Quantum Concepts

The Second Quantum Revolution is advancing rapidly, driven by the ability to manipulate single quantum objects. Qtools focuses on quantum education by creating hands-on, easy-to-use devices that offer practical experience with real quantum systems, not simulations. To meet future research and workforce needs, it's essential to train students using these genuine quantum tools.

### Spin

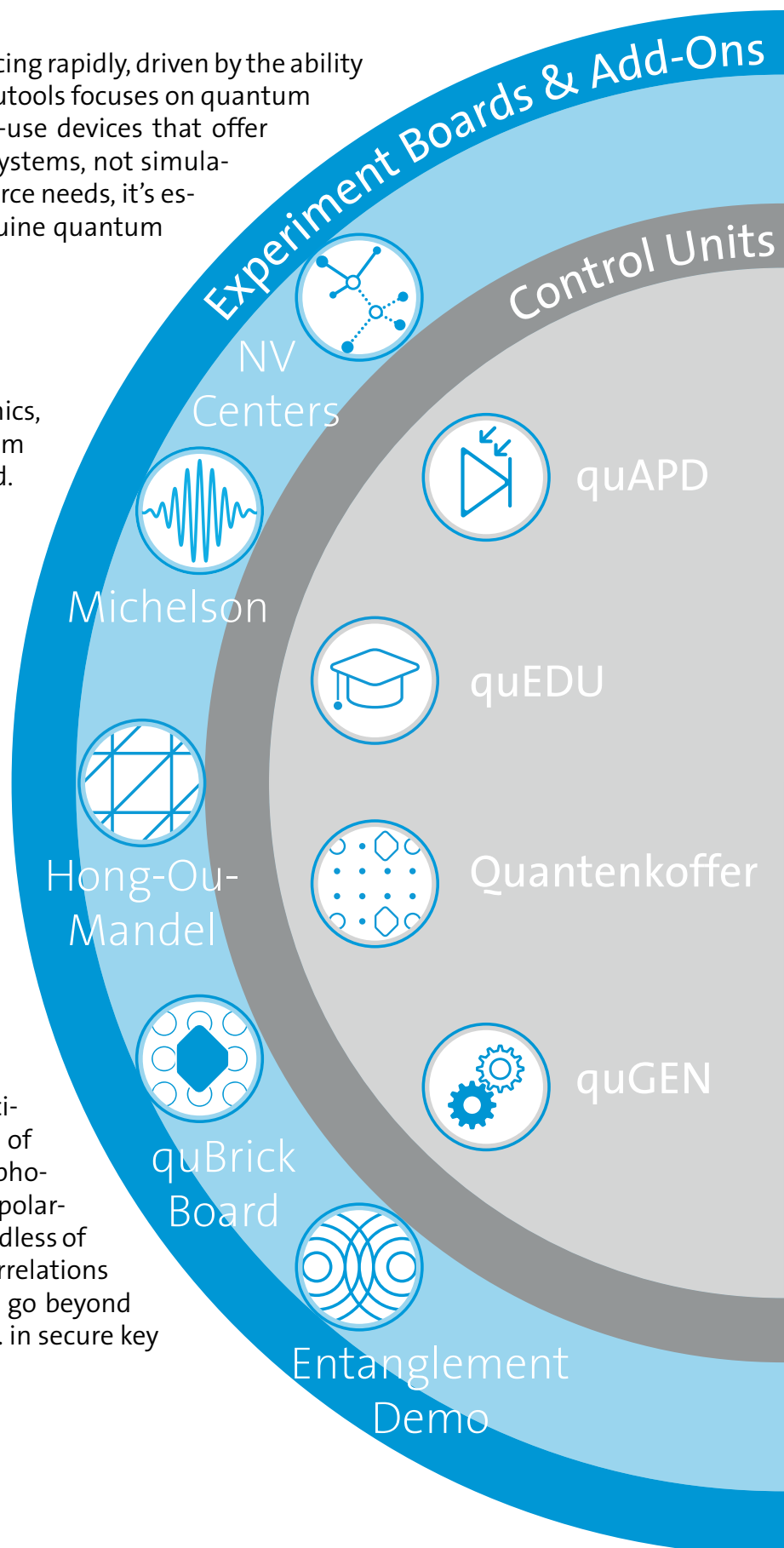
Spin is a key aspect of quantum mechanics, and its properties are accessible at room temperature in NV centers in diamond. The NV-system allows direct insights into crucial quantum technologies, including sensing and qubit applications.

### Photons

Single photons are the fundamental particles of light and have played a central role in the development of quantum theory. As the fastest quantum objects, photons excel at exchanging quantum information between systems, enabling breakthroughs in various fields of quantum technology.

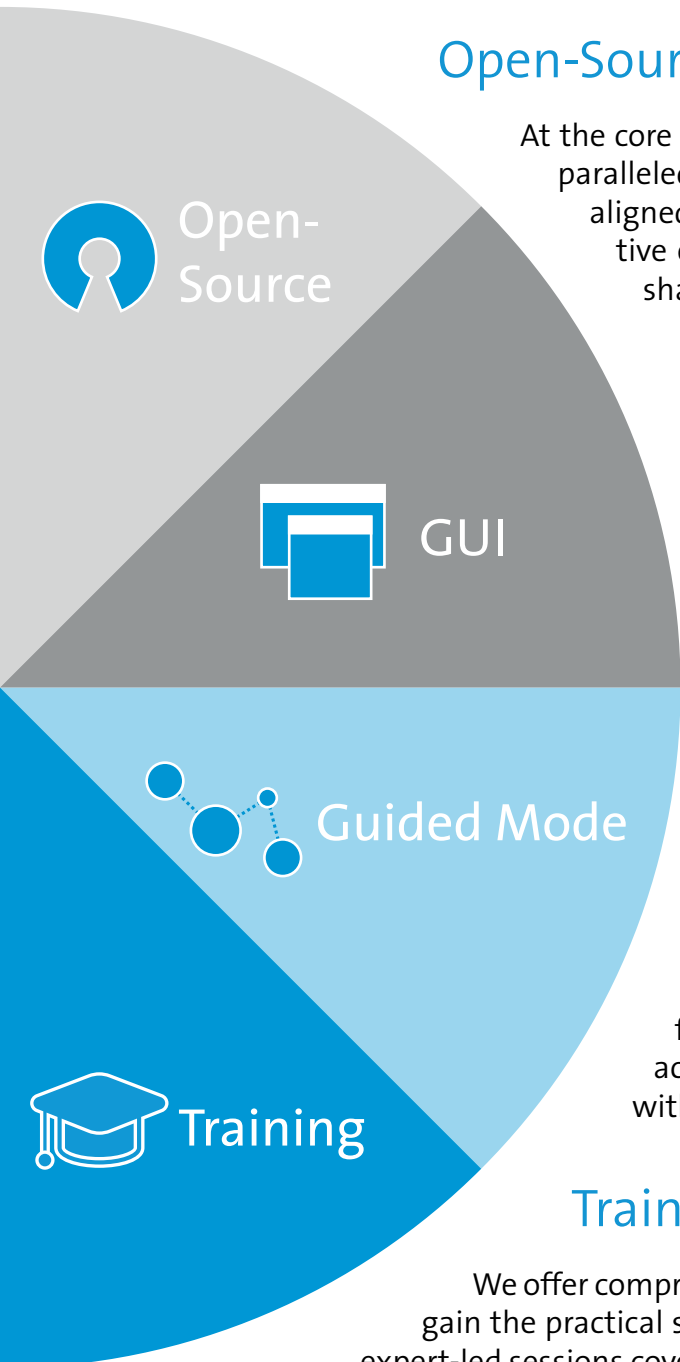
### Entanglement

Polarization entanglement, another fascinating concept, involves the correlation of the polarization states of two or more photons. When photons are entangled, their polarization states are intrinsically linked, regardless of their spatial separation. This non-local correlations can be used as a resource allowing us to go beyond the limits of classical communication, e.g. in secure key generation for encrypting information.



## Usability & Operation

The qutools portfolio for the education sector offers a wide range of operating concepts to optimally support your application and training. Possibilities range from customizing our open-source examples and software to develop your own unique applications, over using the intuitive GUI and comprehensive didactic materials to letting our guided mode lead you through the experiments.



### Open-Source Software

At the core of our offering is the power of open source, giving you unparalleled flexibility to create software solutions that are perfectly aligned with your unique requirements. We foster a collaborative environment, where new concepts and improvements are shared across the community, accelerating development.

### GUI

Our intuitive GUI is designed to help you get up and running in no time, making it easy to navigate and start working the units immediately. Alongside this, we provide concise, well-organized didactic materials that focus on the essentials, enabling you to quickly grasp key concepts. With these tools, you'll be ready to dive into teaching quantum physics without unnecessary delays.

### Guided Mode

Our guided mode is specifically designed to walk you through the most important experiments in quantum physics. Whether you're new to the field or looking to refine your knowledge, this feature makes complex concepts accessible and helps you confidently execute experiments with precision.

### Training

We offer comprehensive training programs for all our devices, ensuring you gain the practical skills needed to operate and optimize them effectively. Our expert-led sessions cover everything from basic operation to advanced techniques, helping you fully harness the potential of our technology. Whether you're a beginner or an experienced user, our training is tailored to meet your needs and enhance your proficiency.



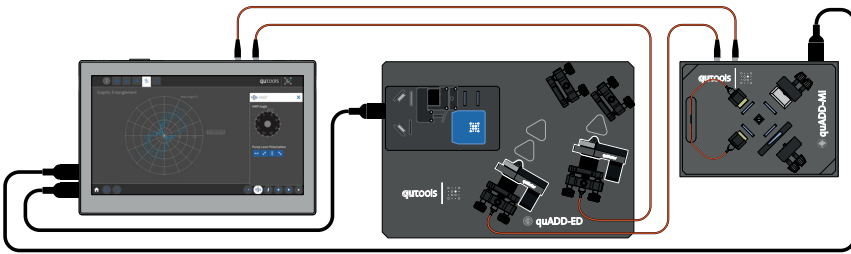
# Control Units

## Units to control the Experiment Boards

The **quEDU**, the **quAPD** and the **quGEN** are the central units to control experiment boards. All boards are connected to these units via a data cable. Lasers, motors, switches, and pulsing sequences can only be controlled through one of the control units.

The **quEDU** and the **quAPD** also include fiber-coupled avalanche photodiodes or fast photodiodes to measure the photon output of the experiment boards and create timetags and intensity data.

A touch display and the two rotary wheels make the **quEDU** to an easy to use stand-alone system. The **quAPD** and the **quGEN** are controlled via USB. All three devices can be remote controlled by individual programming in C or Python, including open source examples.



*The new educational concept of qutools includes a control unit with photodetectors. Experiment boards with the individual quantum physics experiments and their actuators are connected to the control unit. Additional optical boards can be connected between the experiment board and the photodetectors.*

## Photodetector Variants

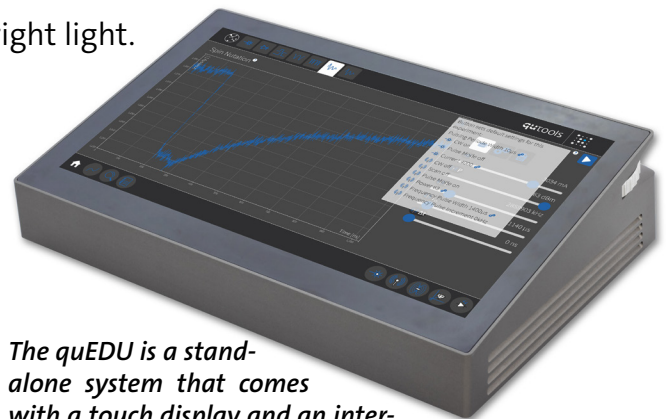
The **quEDU** and the **quAPD** offer different variants in number of photodetectors and modes. The modes differ in the electronics for

- APD avalanche photodiodes: detecting single photons
- PD fast photodiodes: detecting fast edges with bright light.



	APD	PD
<b>quEDU - 4 switch</b>	4*	4*
<b>quEDU - 2 PD</b>	0	2
<b>quEDU - 4 APD</b>	4	0
<b>quEDU - 0 switch</b>	0	0
<b>+ switch APD/PD</b>	2-4*	2-4*

\* up to 4 switchable APD/PD in 1 device



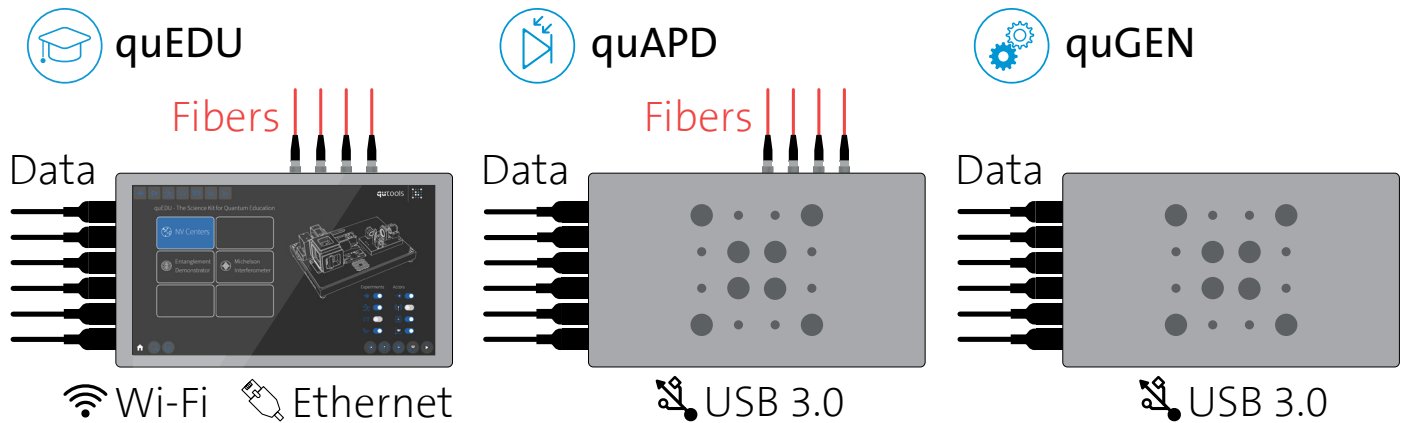
*The quEDU is a stand-alone system that comes with a touch display and an internal computer. The quAPD includes six data ports and up to four fiber inputs, but it also requires a control computer via USB.*



	APD	PD
<b>quAPD - 1 PD</b>	0	1
<b>quAPD - 3 APD</b>	3	0



## Included Features



	quEDU	quAPD	quGEN
<b>Firmware</b>			
Pattern Generator	✓	✓	✓
Time Tagger	✓	✓	X
<b>Software</b>			
DLL / Python	✓	✓	✓
GUI	✓	✓	✓
VNC (via NUC)	✓	X	X
<b>Optics</b>			
Fiber Coupled (A)PDs	2-4	1-4	X
Detection Modes	APD / PD	APD / PD	X
<b>Control</b>			
Touch Display & Raspi	✓	X	X
Rotary wheels	✓	X	X
Wifi / Ethernet	✓	X	X
USB 3.0	X	✓	✓
<b>Add-On Control</b>			
Display Port	6	6	6
Supported quADDs	All	All	Only with detectors

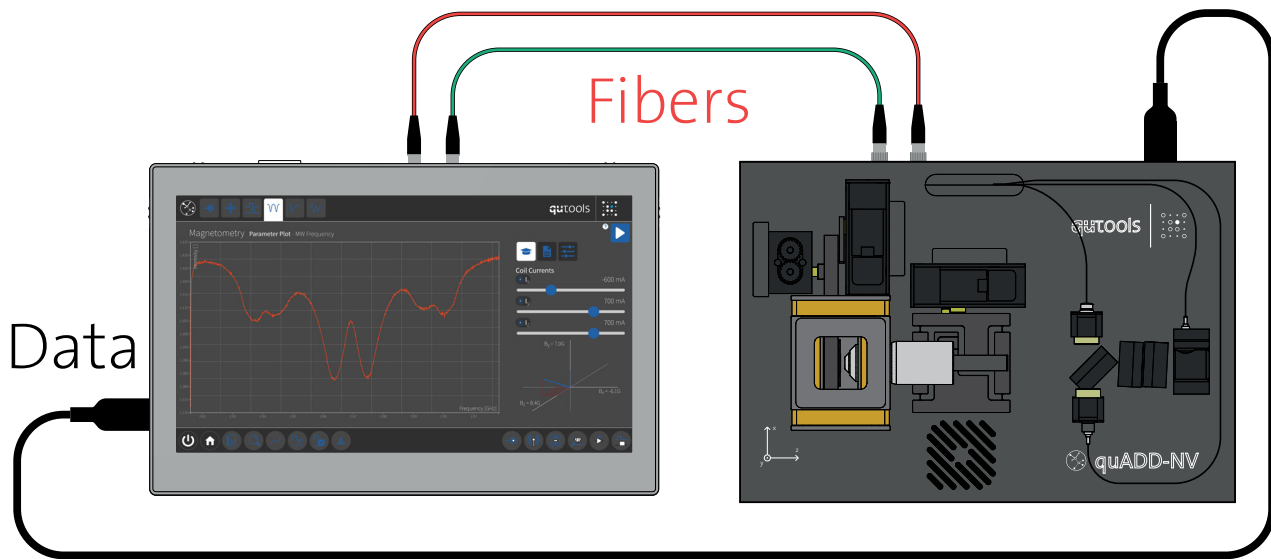
List of features for the different control units of the education portfolio. quEDU and quAPD include photodetectors. quGEN has no photodetectors and only controls the experiment boards and addons.



# quADD-NV

## Nitrogen-Vacancy Center Board

The **quADD-NV** and its variants are experiment boards for NV centers and their quantum effects. The board contains an on-board laser, a microscope objective, coils, a microwave antenna and diamonds with NV centers. These **quADD** boards are controlled by **quEDU**, **quAPD** and **quGEN**.



*quEDU with touchscreen, pulsing logic and photodetectors with the NV center board quADD-NV for experiments of NV centers in a diamond.*

## Variants & Features

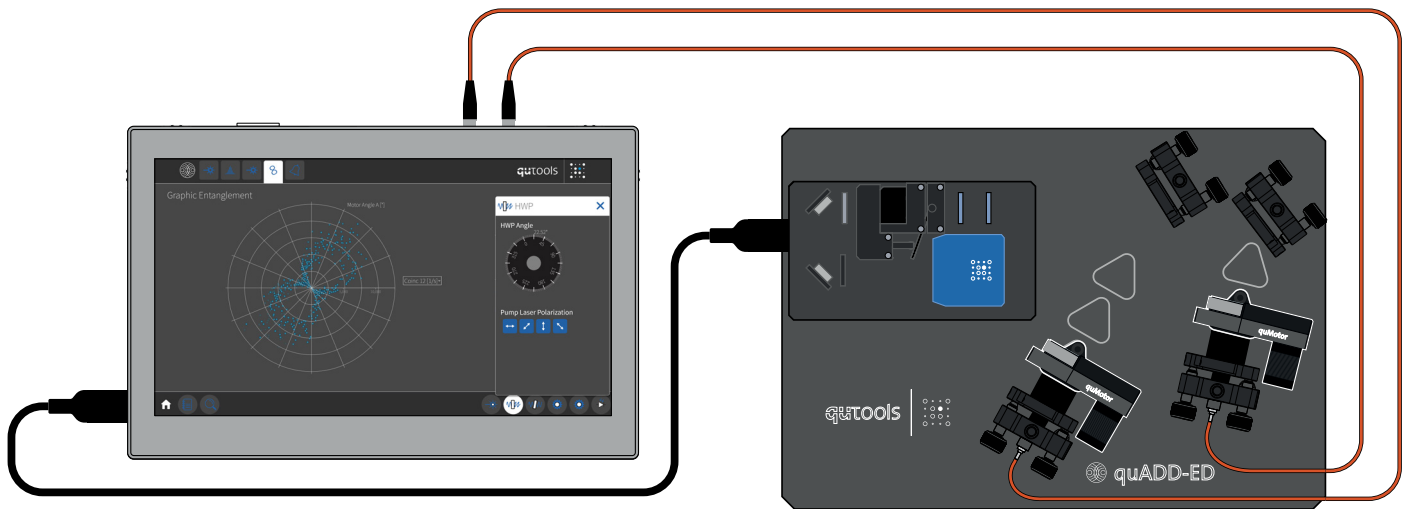
	quADD-NV	quADD-NV bas	quADD-NV cav
<b>Optics</b>			
Laser 520 nm	20 mW	20 mW	20 mW
Fluorescence Output	✓	✓	✗
Laser Output	✓	✗	✗
<b>Hardware &amp; Electronics</b>			
Diamond Samples	3	1	3
3 Coil Pairs	✓	✓	✓
xyz-Stages	✓	✗	✓
Pulse Mode	✓	✗	✓
MW Analyzer	✗	✗	✓
<b>Control</b>			
Unit via Display Port	quEDU, quAPD	quEDU, quAPD	quEDU, quAPD, quGEN



# quADD-ED

## Entangled Photon Board

The **quADD-ED** and its variants are boards for single photon pairs or polarization entanglement. It can be extended either by additional boards, connected by fibers and a data cable, or by Add-Ons. All **quADD** boards are controlled by **quEDU**, **quAPD** and **quGEN**.

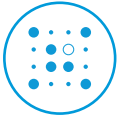


*quEDU with touchscreen, pulsing logic and photodetectors with the photon entanglement board quADD-ED for the generation of polarization entangled photon pairs.*

## Variants & Features

	quADD-ED	quADD-ED bas	quED*	Quantenkoffer**
<b>Optics</b>				
Laser 405 nm	80 mW	30 mW	80 mW	50 mW
Photon Pair Source	✓	✓	✓	✓
HWP	motorized	fixed	2 states	motorized
YVO	motorized	fixed	fixed	motorized
BBO	fixed	fixed	fixed	motorized
Entanglement	✓	X	✓	✓
Polarizers Add-On	upgradeable	X	✓	≥2 integrated
<b>Control</b>				
Unit via Display Port	quEDU, quAPD	quEDU, quAPD	quADD-ED-Adapter & quEDU, quAPD	stand-alone
Add-Ons	4 slots	X	5 slots	90 quBrick slots
Motor Driver	4	X	2-4 by qu3MD	≥10

\*former unit, \*\* for comparison

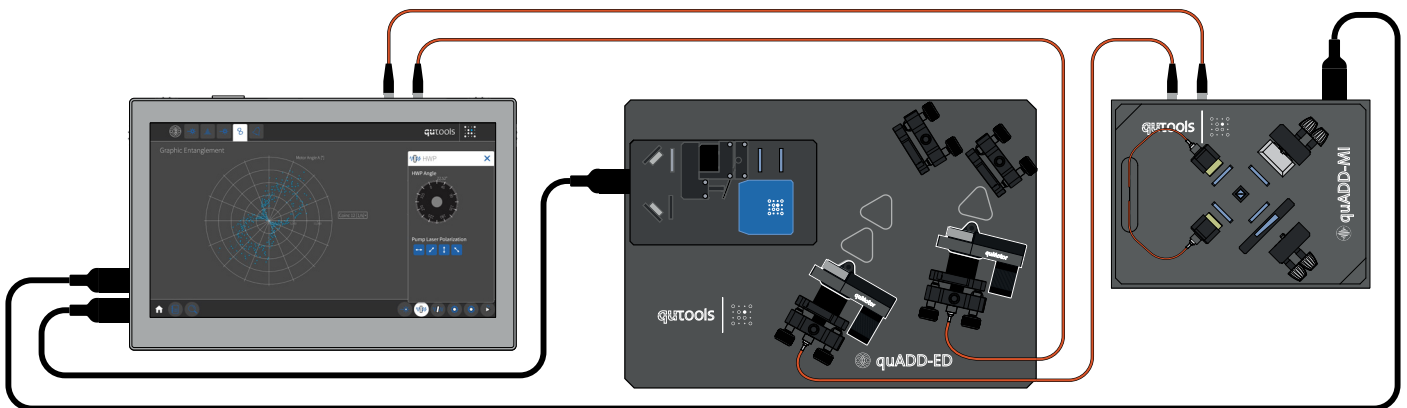


# Experiment Boards

Boards for optical combination with a source board and a control unit.

All of the following **quADD** experimental boards are fiber coupled and require a photon source like the **quADD-ED**. Almost all **quADD** are motorized or piezo driven and can be connected to a controller like **quEDU**, **quAPD** or **quGEN**. The **quADDs** have a fiber coupled photon output that can be detected by **quEDU** or **quAPD**.

<b>quADD-MI</b>	Michelson Interferometer	This fiber based single photon interferometer consists of a beam splitter, 2 mirrors, 1 motorized glass wedge and a piezo. The piezo can quickly change the optical length of an interferometer arm in very small steps for further experiments. 3 additional polarizers before and after the BS are included for experiments like the quantum eraser.
<b>quADD-QKD</b>	Quantum Key Distribution	This is a fiber coupled quantum key distribution experiment board. It is controlled by <b>quEDU</b> or <b>quAPD</b> .
<b>quADD-BS</b>	Beam Splitter	The central optical element is a beam splitter with 4 add-on slots, each before or after the BS. Input and output of this <b>quADD</b> are fiber based.
<b>quADD-PSI</b>	Phase Shifter	Two prisms on a motorized stage, including a piezo, change the optical path length and also shift the phase. Input and output of this <b>quADD</b> are fiber based.
<b>quADD-POL</b>	Polarization Analyzer	After the fiber input of this board, a half-wave plate (HWP) and a quarter-wave plate (QWP) change the polarization of the incoming photons in front of a PBS. Both exits of the PBS are then coupled into fiber outputs for measurement with <b>quEDU</b> or <b>quAPD</b> .



*quEDU with the entanglement board quADD-ED and a connected Michelson interferometer board quADD-MI. The motors of the boards can be controlled by the quEDU and the measurements of the photodetectors is correlated to this movement.*

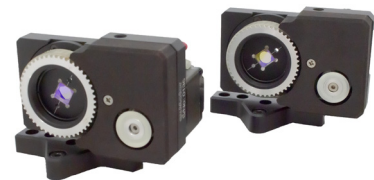


# Experiment Add-Ons

Elements for optical and mechanical combination with a source board.

The experiment add-ons are optical tokens or boards extending the functionality of the **quADD** systems. Some include software and educational material for experiments.

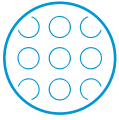
<b>quADDON-POL</b>	Polarizer	The quADDON-POL is a motorized polarizer. It is an important add-on for the quADD-ED source board.
<b>quADDON-QWP</b>	Quarter-Waveplate	This add-on is a motorized quarter-wave plate (QWP).
<b>quADDON-HWP</b>	Half-Waveplate	This add-on is a motorized half-wave plate (HWP).
<b>quADDON-HBT</b>	Hanbury Brown-Twiss	Fiber beam splitter and software for Hanbury Brown-Twiss HBT experiments, requires at least 3 APDs in the controller.
<b>quADDON-HOM</b>	Hong-Ou-Mandel	This fiber based two photon interferometer includes a beam splitter and software for HOM experiments.
<b>quADDON-MI</b>	Michelson Interferometer	This fiber based single photon interferometer consists of a beam splitter, 2 mirrors and 2 glass wedges. One wedge is motorized to change the length in an interferometer arm.
<b>quADDON-TOM</b>	Quantum State Tomography	This add-on contains two motorized quarter-wave plates (QWP), software and firmware to perform quantum state tomography.
<b>quADDON-QKD</b>	Quantum Key Distribution	The add-on contains a motorized half-wave plate (HWP), software and firmware to demonstrate the BB84 protocol.



*quEDU with the entanglement board quADD-ED with blue marked sockets for add-ons. The quADDONS, like these quarter waveplates, can be placed in the beam path and are electronically connected to the board for motor control.*

# Adapters for quEDU

<b>quADD-ED-Adapter</b>	Adapter for quED to quEDU	The <b>quADD-ED-Adapter</b> kit allows the use of the former <b>quED</b> optic board with the <b>quEDU</b> or <b>quAPD</b> . This adapter connects to the <b>quEDU</b> via the display port and provides a laser port and 4 motor ports for the <b>quED</b> optical board.
<b>quADD-Metric</b>	Adapters Add-On & quBricks	The <b>quADD-Metric</b> allows the qutools optical tokens to be integrated into open optical setups with common mounting.



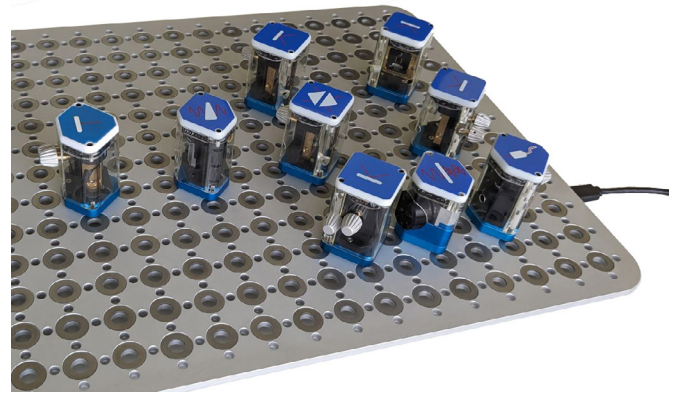
# quADD-BB - Brick Board for quBricks

## Experiment Board for quEDU & quAPD

The brick board is an experiment platform on which optical tokens, the **quBricks** of the **Quantenkoffer®**, can be assembled to individual optical setups. The board and all bricks can be controlled by the **quEDU**.

### Control

- 1 Data Port for quEDU & quAPD Control
- 13x18 Ports for quBrick of Quantenkoffer



# quBrick - Optical Bricks for Quantenkoffer®

## Experiment Bricks for Quantenkoffer® and quADD-BB

Multiple optical tokens – the quBricks – can be freely combined on the board of the **Quantenkoffer®** or **quADD-BB** and combined into various experiments. In addition to optical elements, the tokens contain sensors and microprocessors through which the **Quantenkoffer®** can recognize, readout and digitally control them.

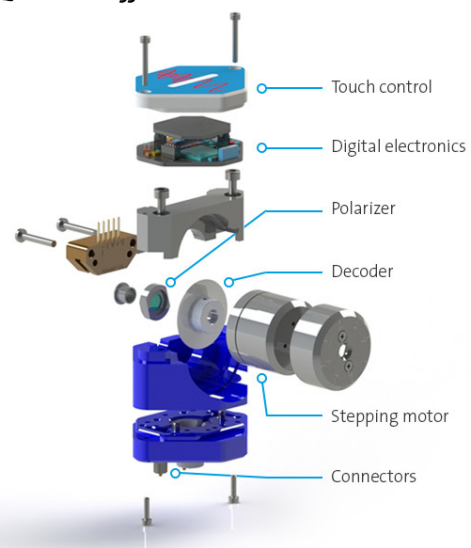
### Variants

#### quBrick

Periscope	In- & Output
Polarizer	Manual and motorized
Beam Splitter	Manual alignment
PBS	Polarizing beam splitter
Mirror 45°	Manual alignment
Mirror 90°	Manual alignment
Mirror 90°	Piezo Driven
Lambda/4	Waveplate, motorized
Lambda/2	Waveplate, motorized
Glas Wedge	Adjustment of optical path
Camera	For Digital Alignment
Fiber Coupler	Fiber Connector PC



*The quBricks mirror 90°, mirror 45° and the motorized polarizer can be freely mounted into the slots of quADD-BB and Quantenkoffer.*





# Quantenkoffer® - Quantum Education Kit

## Control Unit and Photo Detectors for quBricks

The **Quantenkoffer®** is a quantum physics science kit for a variety of quantum optics experiments. The key feature is its flexibility in generating and detecting visible laser light, single photons, and even entangled pairs.

### Features

- SPDC source with motorized BBOs and YVO
- 9x10 Ports for **quBrick**
- Touch display & rotary knobs
- 8 motorized mirrors for alignment
- 2 included polarizers in sub-beam path
- 4 avalanche photodiodes

A set of lasers and optical crystals form the core of the photon source, which the user can view by rotating the optical setup board. Individual photon pairs are generated by nonlinear processes within the optical crystals. Each element of the precision source can be adjusted by the user or automatically optimized by the Quantenkoffer. Additional red laser light follows the path of the single photons for proper adjustment of the optical setups.

Four avalanche photodiodes with improved electronics allow the detection of single photon pairs with high time resolution and the measurement of bright light sources. The four detectors allow more complex experiments.

The ultra-fast processing of the measured events, enabled by powerful digital technology, allows the detection of time differences in the picosecond range, e.g. to measure the speed of light on the board with few tokens.

The boards on the top includes 9x10 slots for the **quBricks**, optical and mostly motorized optical tokens to put together individual experiment setups.



*On the high-precision board with 86 slots various setups can be individually created by placing the optical tokens into the electromechanical slots.*



*The sensitive optics and electronics are mounted safely and shockproof in the interior of the robust case, which makes it a mobile lab. Flexible, precise and quickly ready to use - explore playfully the world of quanta!*



# Experiments

Summary of prepared experiments with boards and add-ons

## NV Center Experiments

NV Center Fluorescence	NV	Spin Initialization and Readout*	NV
ODMR	NV	Spin Nutations*	NV
Zeeman Effect	NV	Rabi Oscillations*	NV
Orientation of NV-Centers in Lattice	NV	Pulse Sequence Development*	NV
Magnetic Field Sensing	NV	Qubit Control, Hadamard Gate*	NV
Microwave Absorption Readout**	NV	Hahn Echo*	NV

*quEDU/quAPD and quADD-NV needed, \*not with quADD-NV bas, \*\*only with quADD-NV cav*

## ED Experiments

Wave Nature of Photons: Single Photon Michelson Interferometer	ED & MI	Particle Nature of Photons	<sup>3</sup> ED & HBT
Quantum Eraser	ED & MI	Second order correlation function	<sup>3</sup> ED* & HBT
Wave-Particle Dualism: Interference & Indivisibility	ED & MI & HBT	Quantum Cryptography / QKD: BB84 Protocol	ED* (& HWP) & POL
Double Michelson Interferometer	ED & 2x MI	QKD: E91/B92 Protocol	ED* & POL
Measurement of Properties of Single Photons	ED & MI	Tomographic Single Photon State Reconstruction	ED* & QWP & POL
Interaction-Free Measurement (Bomb Test)	ED* & MI	Quantum Random Number Generation	ED & HBT
Violation of Bell's Inequality (CHSH)	ED* & POL	Hong-Ou-Mandel 2-Photon Interference	ED & PSI & HOM or BS
Graphic Entanglement	ED* & POL	Hong-Ou-Mandel Interference + Hanbury Brown & Twiss	<sup>3</sup> ED&PSI&HOM or BS & HBT
Tomographic State Reconstruction of an Entangled Photon State	ED* & POL & 2x QWP	N00N-State Interferometer	<sup>4</sup> ED & 2x PSI 2x HOM/BS
Franson Interference	ED & 2x MI	Entanglement Creation at BS	<sup>4</sup> ED & PSI & BS 2x HWP
		Bell State Measurement	<sup>4</sup> ED*&PSI&BS 2xHWP & 2xQWP & SM Fiber

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*Either quEDU/quAPD or Quantenkoffer needed, \*not with ED-bas, <sup>3-4</sup> 3-4 APDs needed*