

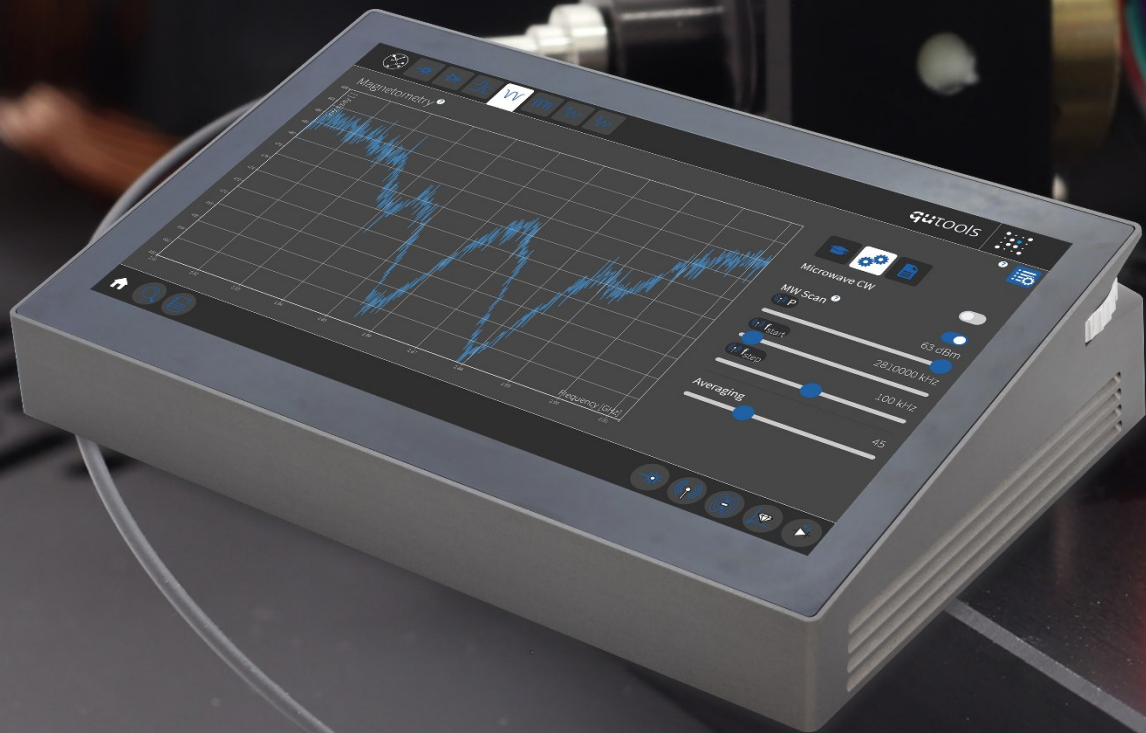


quEDU Education Kit



quADD-NV Experiment Board

Manual V1.2



MMMB

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## 1. Introduction to quEDU-NV Kit

The quEDU is a platform for various quantum physics experiments. It contains fast photodetectors and time tagging electronics for data acquisition and analysis as well as digital interfaces to control different experiment boards. The quEDU and its experiment boards combine the latest achievements in quantum optics technology into an easy-to-use system for academic, research and applied purposes with high precision. Advanced models for scientific purposes are also available, with high performance to meet the requirements of state-of-the-art physics experiments.

The quEDU is the central unit to control connected experiments and measure their photon output. All experiment boards are connected via data cable and multiple optical fibers to the temperature controlled photodetectors.

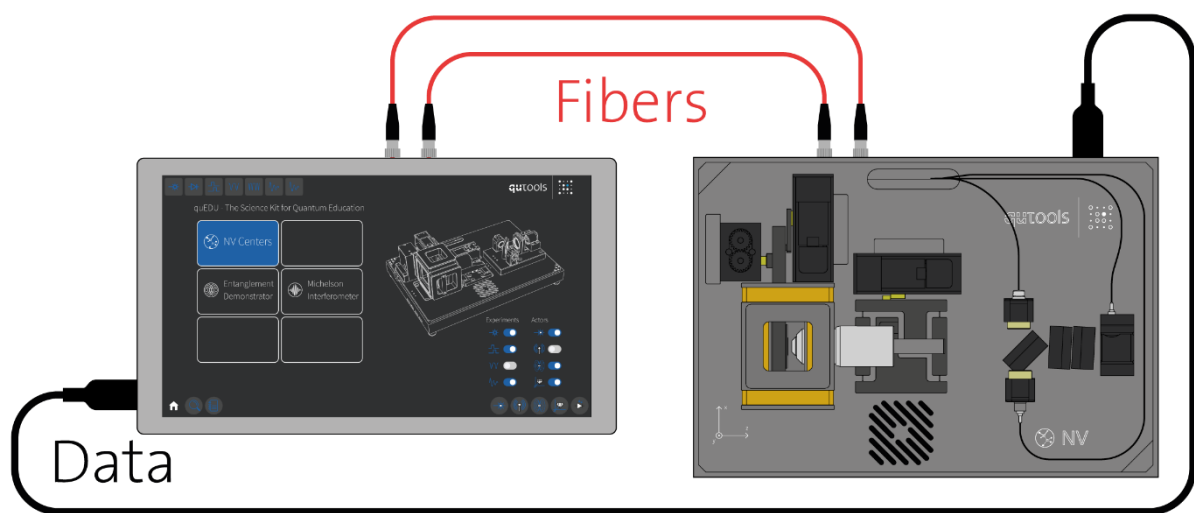


Figure 1 - quEDU control unit on the left connected with a quADD-NV board via data cable and two optical fibers.

The quADD-NV is one of the experiment boards, which can be controlled by quEDU. The quEDU-NV set allows you to experience the properties of nitrogen vacancy centers in diamond, such as NV center fluorescence, electron spin manipulation, optically detected magnetic resonance, and magnetic field sensing of samples.

At the heart of quADD-NV is a green laser that is focused on the nitrogen-doped diamond through a microscope objective. The diamond begins to fluoresce in the red wavelength range. This light is collected by the objective and, after some filtering, is coupled into a fiber. The fiber is connected to the quEDU and the fluorescence can be analyzed by its fast photodiodes.

The diamond sample itself is in close proximity to a microwave antenna and is surrounded by coils that generate a user-defined homogeneous magnetic field. In addition, the quEDUs built-in pattern generator precisely controls the pulse sequences for laser, microwave and readout, enabling a variety of spin control experiments.

## 2. Safety and Maintenance

### 2.1. Legend



**Caution**

General risk of danger.



**Warning**

An instruction which draws attention to the risk of injury or death.



**Warning**

Risk of electric shock. High voltages present.

### 2.2. General Instructions



The equipment, as described herein, is designed for use by personnel properly trained in the use and handling of mains powered electrical equipment. Only personnel trained in the servicing and maintenance of this equipment should remove its covers or attempt any repairs or adjustments. If malfunction is suspected, immediately return the part to the vendor for repair or replacement. There are no user-serviceable parts inside the electronics. Modified or opened electronics cannot be covered by the warranty anymore. Take special care if connecting products from other manufacturers. Follow the General Accident Prevention Rules.



If this equipment is used in a manner not specified by the manufacturer, the protection provided by the equipment may be impaired. Do not operate the instrument outside its rated supply voltages or environmental range. In particular, excessive moisture may impair safety.



For laboratory use only. This unit is intended for operation from a normal, single phase supply, in the temperature range 5° to 25°C, 20% to 80% RH.

### 2.3. Environmental Conditions

Warning. Operation outside the following environmental limits may adversely affect operator safety:



- Indoor use only
- Maximum altitude 2000 m
- Temperature range 5°C to 25°C
- Maximum humidity less than 80% RH (non-condensing) at 25°C
- To ensure reliable operation the unit should not be exposed to corrosive agents or excessive moisture, heat or dust. If the unit has been stored

at low temperature or in an environment of high humidity, it must be allowed to reach ambient conditions before being powered up.

## 2.4. Electrical Installation

The unit must be connected only to an earthed fused supply of 100 to 240V (Japan, USA and Europe).



Use only power supply cables supplied by the manufacturer, other cables may not be rated to the same current. The unit is shipped with appropriate power cables for use in Europe. When shipped to other territories the appropriate power plug might have to be fitted by the user.



**Never connect any cabling to the electronics when contacts are exposed!**  
Avoid short-cuts.



**Prevent electrical shock from electronic.** To prevent electrical shock do not remove the covers. Unplug power cord and all other electrical connections and consult qualified service personnel when servicing or cleaning. Operate only under dry conditions and at room temperature conditions.

## 2.5. Preventive Maintenance



The equipment contains no user serviceable parts. There is a risk of severe electrical shock if the equipment is operated with the covers removed. Only personnel authorized by the vendor and trained in the maintenance of this equipment should remove its covers or attempt any repairs or adjustments. Maintenance is limited to safety testing and cleaning as described in the following sections.

### 2.5.1. Safety Testing



Safety testing in accordance with local regulations, should be performed on a regular basis, (typically once per year for an instrument in daily use).  
Caution. The instrument contains a power supply filter. Insulation testing of the power supply connector should be performed using a DC voltage.

### 2.5.2. Cleaning



Disconnect the power supply before cleaning the unit. Never attempt to clean the device by immersion into any liquid. Never allow water to get inside the case. The device contains parts sensitive to any kind of liquid. Do not use any type of abrasive pad, scouring powder, or solvent, e.g. alcohol or benzene. Please note that all parts of the unit are cleaned in our production facility.

## 2.6. Laser Safety

This product contains Class 3B laser according to IEC 60825-1 (or EN 60825-1) Safety Standards.

Class 3B lasers are hazardous to the eye from direct beam viewing, and from specular reflections even for short and unintentional exposures! Therefore, it is absolutely necessary to take overall safety measures when operating the source.



The quADD-NV should be operated in a restricted area equipped with post warning signs to alert those present. To ensure adequate warning of hazards associated with the accessible laser radiation, relevant warning signs and labels are conspicuously affixed to the quADD-NV. When removing the protective laser enclosure, always wear suitable safety glasses to prevent exposure to laser light. For additional information users should refer to appropriate documents specifying the safety standards such as IEC 60825-1 “Safety of laser products – Part 1: Equipment classification and requirements”.




## 2.7. Additional Warnings

The following precautions should be thoroughly reviewed and followed to avoid the risk of any damage or failure.

- Use the provided fiber optic cables. Be careful when connecting fiber optic cables, quEDU and quADD-NV use FC/PC connectors. When storing the fibers, always protect both the fiber tips and the connectors from dust by using the included caps.
- The lifetime of the laser diode can be significantly shortened by applying driving currents above 90%. Please use higher powers only when necessary and for short amounts of time.

### 3. Device and technical data

#### 3.1. quEDU-NV

quEDU-NV consists of the detection-and-control unit quEDU and the experimental board quADD-NV. The quantum probe is composed of three small diamonds placed in an area of 1 mm diameter on top of the MW-Antenna . The user can choose on which of the diamonds to carry out a given experiment by adjusting the sample alignment in the x-y plane and the distance between diamond and objective along the z-axis . For excitation and detection of the NV centers we use a confocal optical setup with a green laser source, an objective, a dichroic mirror, bandpass filters, and an off-axis parabolic mirror that couples the NV-fluorescence light into a fiber. For the spin-state manipulation in each direction, in addition to the broadband MW antenna, there are three pairs of magnetic field coils .

The quEDU controls all parts of the quADD-NV-board and displays the user interface on a touchscreen.

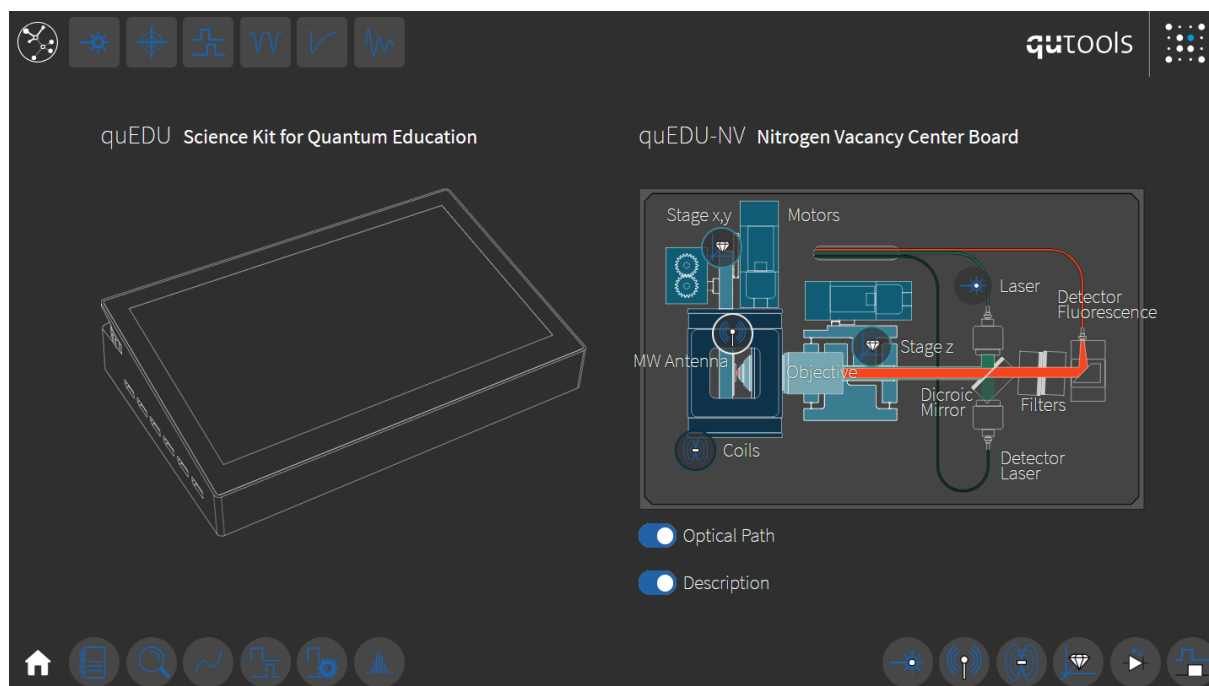



Figure 2: User interface of quEDU-NV. This start screen appears when the quADD-NV is connected to the quEDU. The icons of the actuators are recurring in the menus, parameter settings, and views for better orientation.

### 3.2. Actuators and Sensors


The settings of all available actuators and sensors can be accessed at any time through the actuator icons on the bottom right of the quEDU GUI. The user can run their own experiments using these settings and the general views.

Laser  :

- P: The laser current can be increased until the maximum power is reached – please note that operation at lower powers is preferable in order to prolong the lifetime of the laser diode. At 100% laser current the power of the green laser reaching the probe is about 15mW.
- CW: If activated, the laser pulsing will be overwritten so that the laser is always on.
- Pulse sequence options, see the subchapter about pulse generator.

Microwave antenna  :


- P: The power of the microwave signal source can be adjusted in percentage, where steps of 10% decrease the microwave power by 1dBm from the maximum of 100%.
- CW: If activated, the pulsing is overwritten and the microwave is always on.
- f: The frequency of the microwave source and also the starting frequency of a scan.
- $f_{\text{step}}$ : Frequency increment used to scan over a wide range of frequencies.
- Pulse sequence options, see the subchapter about pulse generator.

Magnetic coils  :


- The current through the coil pairs for x,y, and z direction can be adjusted from -1.5A to +1.5A. The orientation of the coils is indicated by the coordinate systems on the quADD-NV board.

Diamond positioning  :

- There are three stepper motors controlling 3 flexure stages to position the diamonds at the focal point of the objective: X and Y move the microwave antenna circuit board with the diamonds mounted to it, Z moves the objective towards the circuit board to shift the focus into the correct plane. The positions are given in  $\mu\text{m}$  with an origin at the edge of the possible movement range. The motors check their position with internal sensors.
- The z-position stepper changes the distance between objective and diamond. This is the only possible optical alignment of the otherwise prealigned confocal setup.
- There are 3 diamond positions that can be loaded as starting points or saved for future sessions.
- You can also make steps of various sizes in either direction if you want to optimize the current position for a stronger fluorescence signal.
- Here are also the settings of the quADD-NV fans, which might be necessary for prolonged use of the device at high laser or coil current or if the ambient temperature is higher than 24°C. Fan 1 is the inlet fan under the coils and Fan 2 is the outlet through the electronics of the quADD-NV board. The fans start running above 70% speed.

Photodiodes  :


- Delay is a crucial parameter for pulsing experiments to ensure that a laser pulse beginning at 0 ns is also detected at 0 ns. See the subchapter about pulse generator for more information.
- Gain is a very important parameter for the photodiode: this allows to choose how fast the reaction of the photodiode should be, but too much gain can lead to an overshooting and oscillating signal. As the fluorescence signal is proportional to the intensity of the green excitation, you should also consider the laser power when optimizing the photodiode gain.
- Averaging:  $Avg_{Seq}$  and  $Avg_{Param}$  are in the detector settings because the averaging happens in the FPGA and the single shot data is not being transmitted (see the subchapter about pulse generator).

Sequence  :


- see the subchapter about pulse generator.

### 3.3. Views and Displays

The general views can be accessed at any time through the view icons on the bottom left of the quEDU GUI. They can be used to run user-defined experiments. Even if you prefer to use the guided experiments, these views give insights into the system.

Manual  :


- This is a short manual always accessible during quEDU-NV operation

Status  :

- Check this view from time to time to learn how well the device copes with the ambient temperature. quEDU and quADD-NV have multiple temperature sensors that constantly monitor the state of temperature-sensitive parts. If a certain temperature approaches a critical value, the user will see a red warning sign at the top right corner and eventually the device will turn off this part completely to prevent overheating.
- The status of the firmware and software is important for updates or service.

Time Plot  :

- This is a time plot of the fiber input 4 of quEDU. It is like the view of the experiment “Laser & NV Alignment”, but it is constantly running without the need to press a “play” button.

Sequence Plot  :

- The plot shows a high temporal resolution on x axis versus the intensity of fiber input 4 of quEDU in arbitrary units on the y axis. It is like the view of the experiments “Pulsing & Timing” and “Nutation”, but it is constantly running without the need to press a “play” button.
- Shows exactly 1024 data points from a pulse sequence with a minimal time resolution of 5ns. Hence the lowest possible limit of the x-axis is 5120ns.
- To observe longer sequence times increase the parameter Res resolution.

Sequence Pattern  :

- This display visualizes the sequence pattern and is extremely helpful to understand the pulsing sequences and the parameter scans. Note that this view is not a measurement in contrast to the sequence plot.
- The length of the x-axis is the sequence duration.
- The green bars show the time settings of the laser pulses. The laser power is not visualized, and you will see these green bars even at zero laser power.
- The orange window shows the time settings of the microwave pulse. The power of the microwave is not visualized, and you will see this orange window even at zero microwave power. The frequency of the microwave is also not visualized.

- The violet window shows which part of the sequence is plotted in the sequence plot.
- The blue window describes the detection width chosen for a parameter plot.
- The play button simulates a parameter run and its effect is best observable with the presets of the experiment “Rabi Oscillation”.

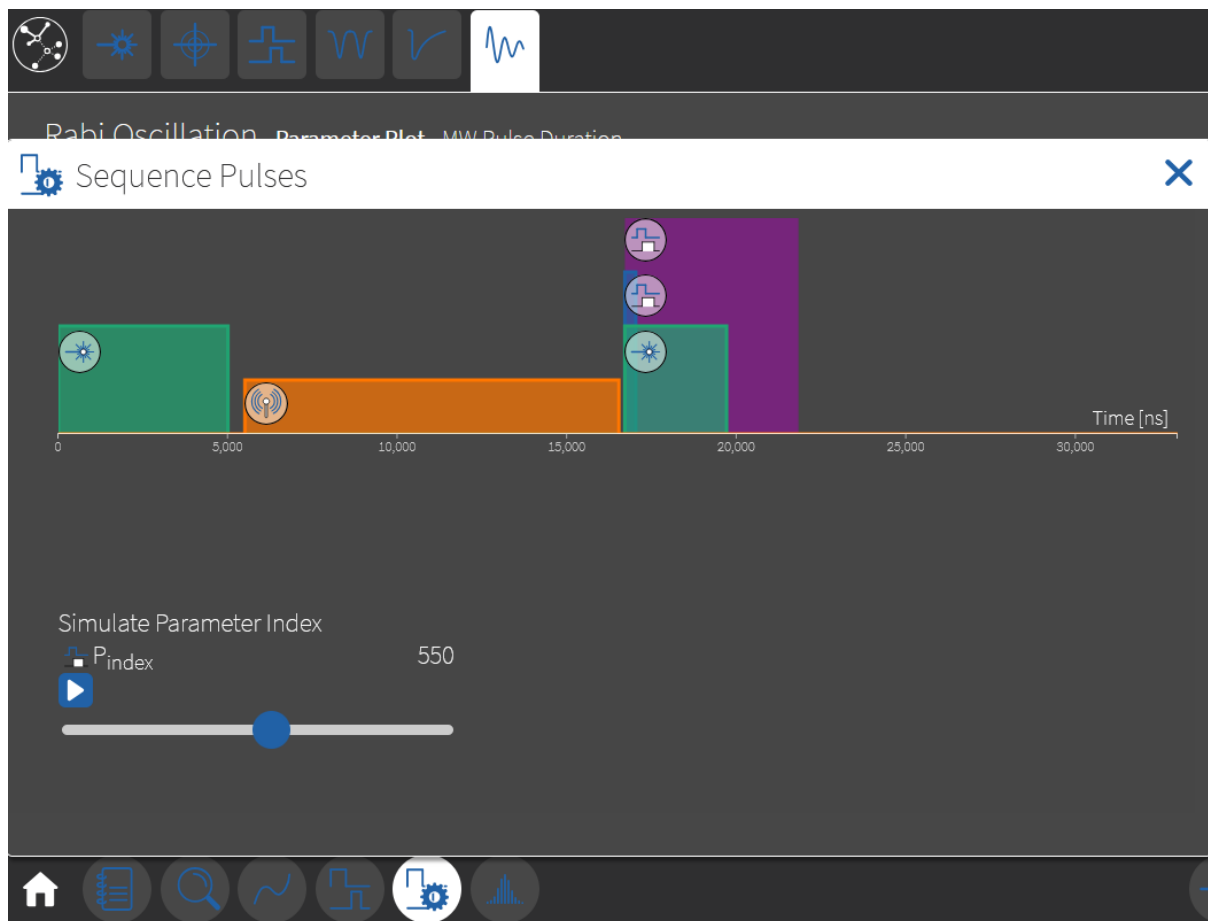


Figure 3: Sequence Pattern View that visualizes the different pulses of a sequence or a parameter scan

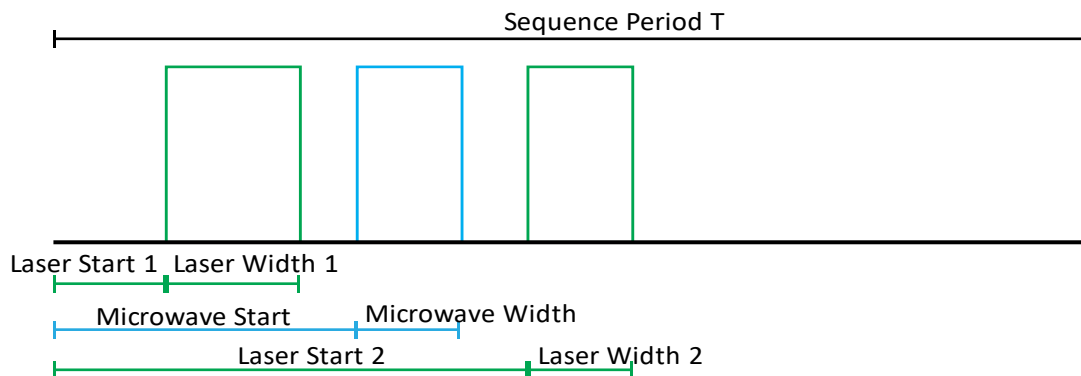
#### Parameter Plot :

- This view shows the effect of a parameter sweep. It is like the view of the experiments “Magnetometry” and “Rabi Oscillations”, but it is constantly running without the need to press a play button and the x axis is always from 0 to 1023 parameter values.
- The value on the y-axis depends on the detection window and the averaging settings.
- See the subchapter about pulse generator for details.

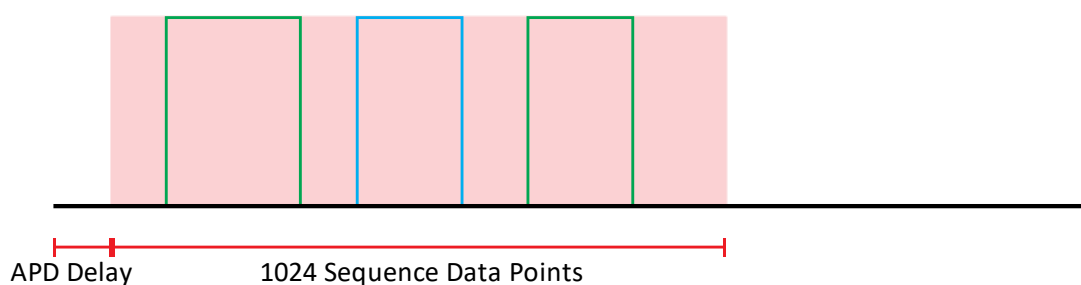
### 3.4. Pulse generator

For all the advanced functions of the quEDU-NV, a fast FPGA is controlling pulse sequences and measuring and analyzing the detected signal. You can either observe a single sequence in the “Sequence Plot” or you can observe the effect of sweeping a parameter through consecutive sequences in the “Parameter Plot”. Pulsed operation can be set in the following way:

1. A single pulse sequence is characterized by these parameters:

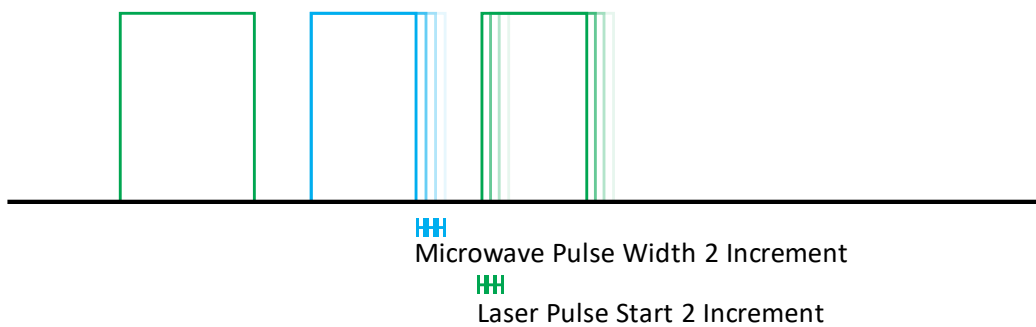


- Sequence Period T: Length of one individual pulse sequence before it is repeated
  - Laser Pulse Start 1: Time of activation of first laser pulse
  - Laser Pulse Start 2: Time of activation of first laser pulse
  - Laser Pulse Width 1: Length of first laser pulse
  - Laser Pulse Width 2: Length of second laser pulse
  - Microwave Pulse Start: Time of activation of microwave pulse
  - Microwave Pulse Width 2: Length of microwave pulse
2. Concerning the measurement, one can observe exactly 1024 data points from a pulse sequence in a “Sequence Plot”, with a minimal time resolution of 5ns. This means that usually only a small portion of the sequence is actually observed. The available parameters are:

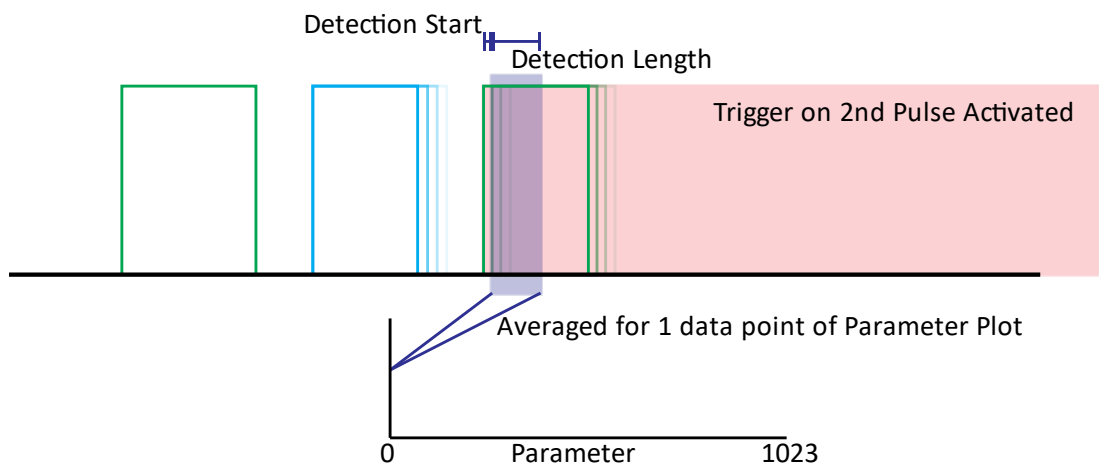


- Delay PD ( $\Delta t_{red}$ ): There is an inevitable delay in the electronic and optical paths from giving the command to activate the laser until one measures a change in the signal. The parameter PD delay is used to compensate for this effect.
- Resolution Res: Increases the resolution in potentials of 2 in order to observe longer sequence times in the Sequence Plot.

- Trigger on 2nd pulse: Changes the observation start time to the beginning of the second laser pulse, instead of the beginning of the pulse sequence. This setting is important for the detection window.
  - Averaging  $Avg_{Seq}$ : A potential of 2 of these sequence measurements can be averaged together in order to decrease noise and data rate. This setting only influences the sequence plot, it is not relevant for a parameter sweep.
3. After a pulse sequence has concluded, the next one will start immediately. However, you can change a certain parameter by a small amount each time. This parameter will be increased exactly 1023 times before the starting value will be assumed again. You have access to the following parameters:



- Laser Pulse Start 2 Increment: Time of activation of second laser pulse will be increased each sequence.
  - Microwave Frequency Step: Microwave frequency will be increased each sequence.
  - Microwave Pulse Width 2 Increment: Length of microwave pulse will be increased each sequence.
4. To observe the effect of a parameter sweep, you can use the “Parameter plot”. It has 1024 data points, one for each value of the changed parameters. For detection width > 0, each data point is an average of multiple points from the sequence data:



- Detection Start: Start index of the sequence data points to use

- Detection Width: Number of sequence data points to average together for one parameter data point. Has to be a potential of 2. Please note that the actual timings of Detection Start and Width depend on the resolution of the sequence data “Res” as well as on “Trigger on Second Pulse”.
- Averaging Avg\_P: A potential of 2 of these parameter measurements can be averaged together in order to decrease noise and data rate.

## 4. Installation and Operation

### 4.1. Installation



Before installing the system, make sure that you are familiar with and have obeyed all necessary laser safety precautions. Please refer to paragraph 2 for this purpose.

Do not operate the device with the orange cover removed under any circumstances!

quEDU is capable of hot-plug connections, but for the initial installation you can follow these steps:

- Unpack the devices from the delivery boxes and place them close together.
- Follow the unpacking steps described on the flyer in the delivery box of quADD-NV.
- Handle the provided optical fibers with care! The two fibers are identical, but the connection from the quNV outputs to the quEDU optical inputs must be as following:
  - quADD-NV board (1) to quEDU (4)
  - quADD-NV board (2) to quEDU (3)
- Connect quEDU and quADD-NV with the provided data cable. You can use any of the display ports on both devices.
- Connect the quEDU control unit to a power socket and turn it on.

### 4.2. Operation

You can control the quADD-NV through the touchscreen and UI of the quEDU. Or you can connect an external PC via network cable and use the quEDU-NV UI from a different device. Therefore, the quEDU has to be in the same network and the GUI can be called via a browser and the quEDUs IP address with the port 8082, e.g. 192.168.178.20:8082. You can have two clients connected to the same device and both will be active, the final command is decisive.

In the quEDU GUI the control of the device is organized as follows:

- In the top and bottom left corners are buttons which bring you to the home screen with the overview of which device is connected to the quEDU.
- On the left of the top line is a list of icons with “guided” experiments. The user can go step-by-step from left to right from initial alignment through ODMR to pulsed coherence measurements of the NV-ensemble. Within a given experiment there is a main view on the left and three submenus with useful settings on the right.
- On the right of the bottom line are the settings of the adjustable actuators and sensors. Those settings directly change the value of a given actuator, no matter if an experiment is running or not.
- On the left of the bottom line are the general views, which are independent of specific experimental settings, manual and device settings.

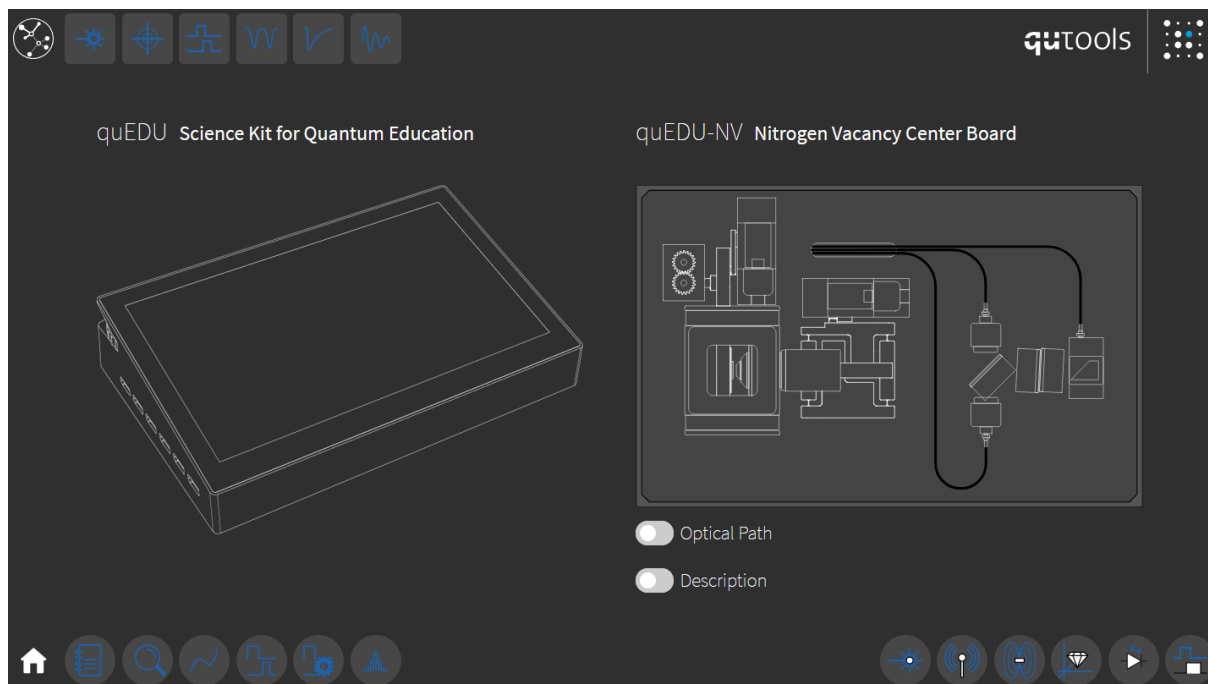


Figure 4 - GUI home screen of the quEDU with a quADD-NV board connected. Three general areas with buttons for experiments with the connected board on the top left, all connected actuators and sensors at the bottom right, and with general views at the bottom left.

### 4.3. Experiments

The icons on the top left corner open the “guided” experiments. The user can go step-by-step from left to right from initial alignment through ODMR to pulsed coherence measurements of the NV-ensemble. In each case, the experiment has to be started using the “Play” button in the top right corner. Default starting settings for the pulse generator will be loaded, and the data acquisition will start. You can see the default settings by tapping the question mark next to the play button.

#### 4.3.1. Laser & NV Alignment

Before running any of the following experiments, the laser needs to be turned on. After that, one diamond with NV centers must be positioned into the focal area of the objective. Then the NV centers get excited by the green laser radiation and the responding red fluorescence is collected by the objective since both share the same optical path.

The procedure would be:

- Tap on the blue “Play” button to start the experiment.
- Figure 5.
- Switch to displaying the red fluorescence signal with the switch to the top left of the plot and set the Gain of  $PD_{red}$  to 90%.
- Load one of the saved diamond positions. You can use the 3 diamond positions determined at the qutools factory, or you can load one of 3 previously saved user positions.
- You should see the red signal changing. This can take a few seconds to take effect.
- In the settings tab, you can improve the position using steps of various sizes while looking at the signal (Figure 6). Please note that in this “stepping mode”, there is no correction for hysteresis.

You should aim to settle on maximum possible intensity. Please note that it can help to repeat this procedure from time to time during later experiments in order to ensure good alignment because ambient conditions (like temperature) might have changed.

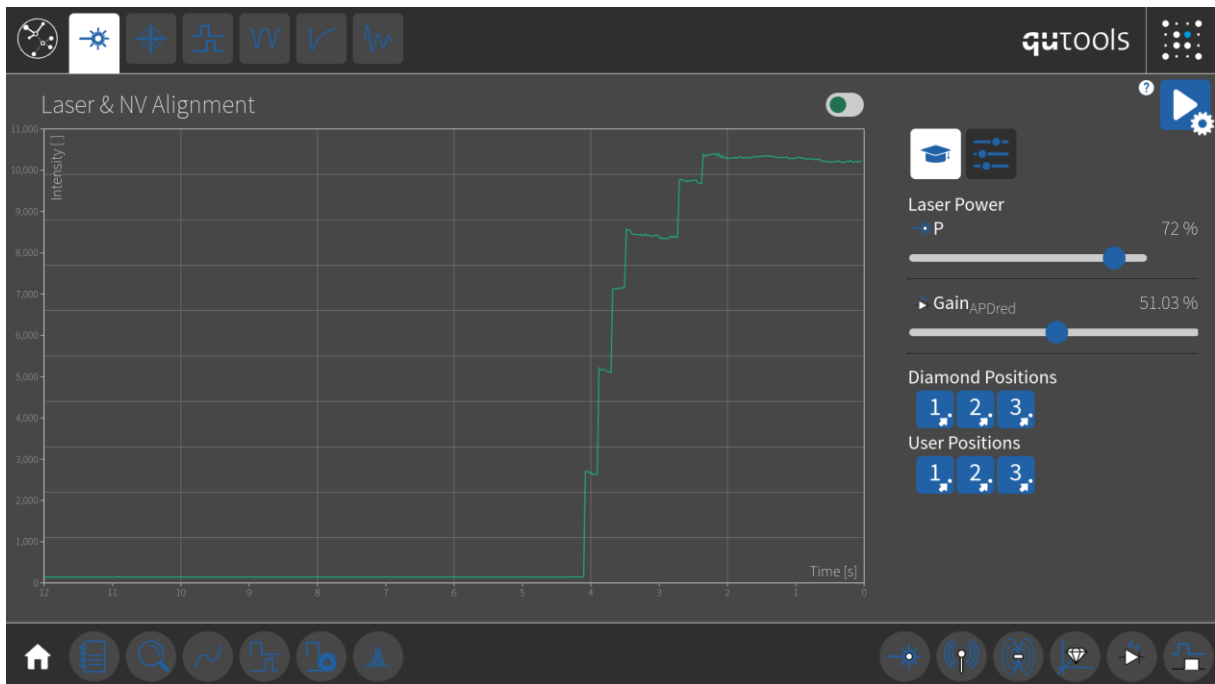


Figure 5 - Starting up the green pump laser

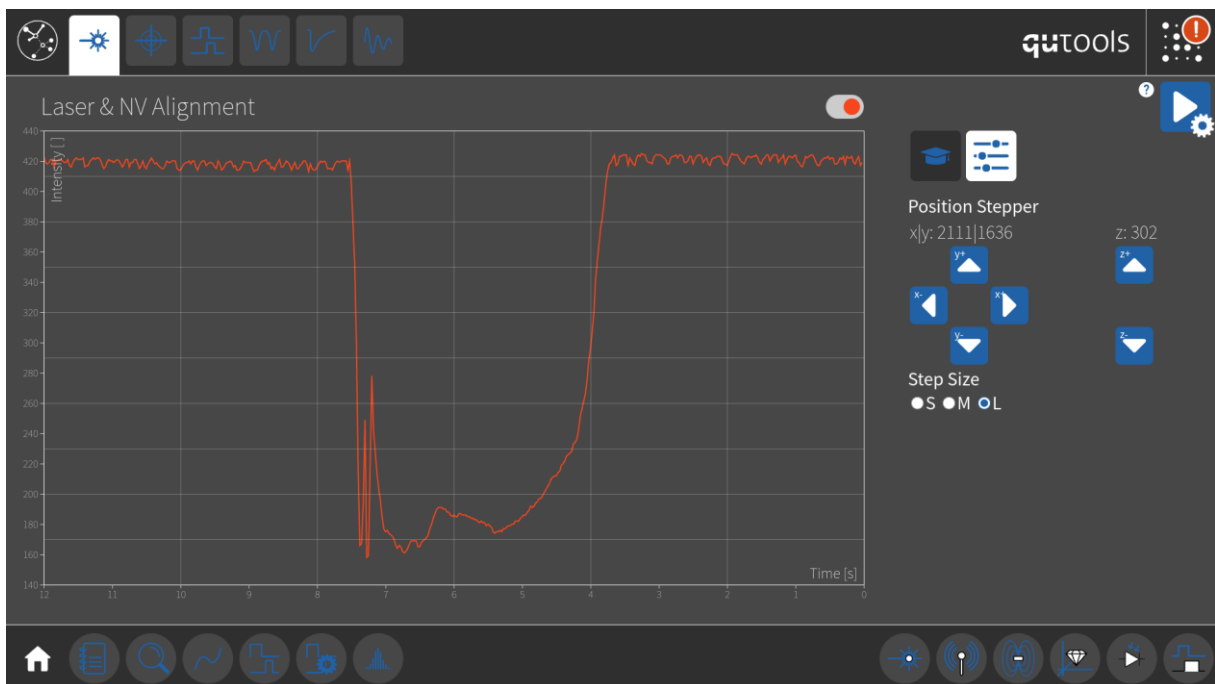


Figure 6 - The alignment can be manually improved by using small steps of the alignment motors. A medium step size is optimal for a quick check of the best spot.

### 4.3.2. Confocal Alignment

You can use this experiment to visualize the different diamonds on the circuit board of the MW antenna. A crucial parameter is the Z position which moves the objective towards or away from the diamonds. Since the diamond chunks are in various forms, their images are not homogeneous.

- Tap on the blue “Play” button to start a pre-defined scan of X and Y.
- A scan will start and slowly fill out measurement data in the scan plot area (leftmost plot). You can zoom in or out of the scanned area by pressing the zoom toggle button. You can stop the scan by tapping on the “Stop” button.
- You will see lighter areas in the scan plot and a histogram of intensity values to the right of it. By adjusting the two control circles on the histogram plot, you can change the color coding for the scan plot to resolve intensities better, see Figure 7.
- You can use the control circles on the x and y axes to change the scan area in order to scan a diamond in more detail. Note that the upper limit will be automatically adjusted to account for impossibilities with range and resolution.
- The resolution of the scan can be adjusted in the settings tab.
- You will always see the current intensity in the line plot on the top right.
- Increase that intensity by adjusting the z position, and x and y again iteratively, by using the step buttons in the first control menu.
- You can also select and go to a specific point in the scan using crosshairs. Select the brightest point and tap on the “Go To” Button, see Figure 8. Beware that the crosshairs define only x and y, but the “Go To” button assumes also the z value that is set in the slider. To ensure that you keep your z-Position, you can use the “Swap live” button first.
- The “Swap Live” button transfers the current position of all motors to the sliders of the “Go To position”.

You should aim to settle on maximum possible intensity. Please note that it can help to repeat this procedure from time to time during later experiments in order to ensure good alignment because ambient conditions (like temperature) might have changed.

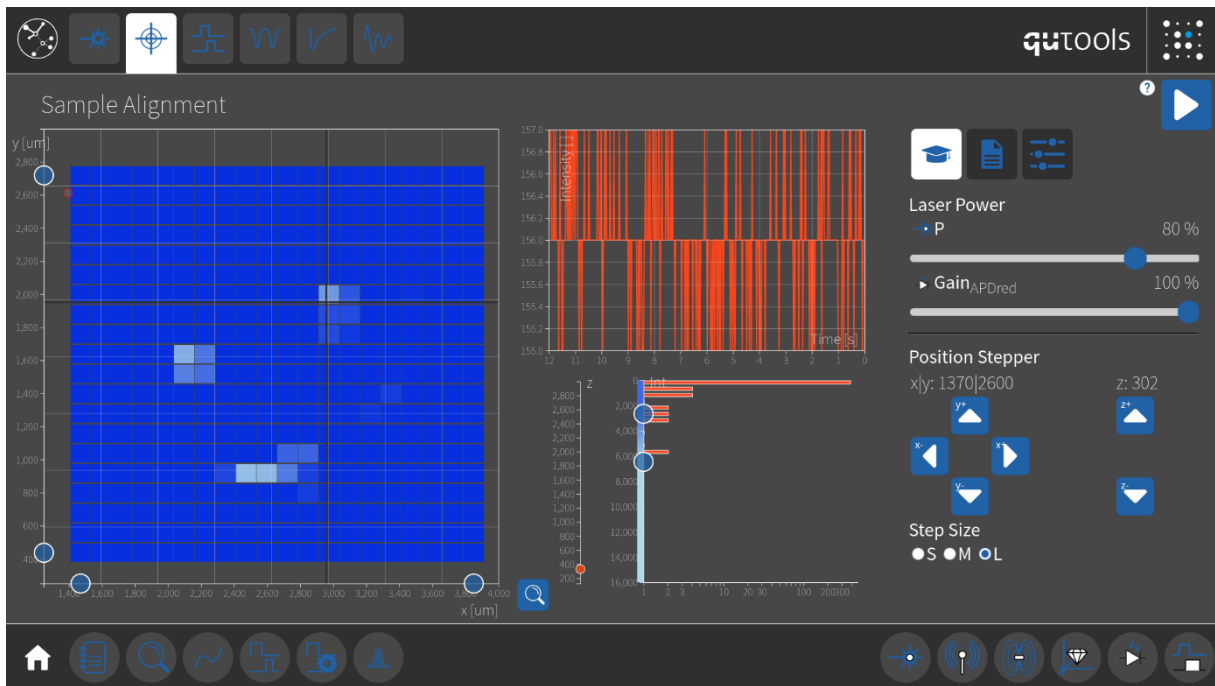


Figure 7 – A wide area scan shows the position of the three diamonds.

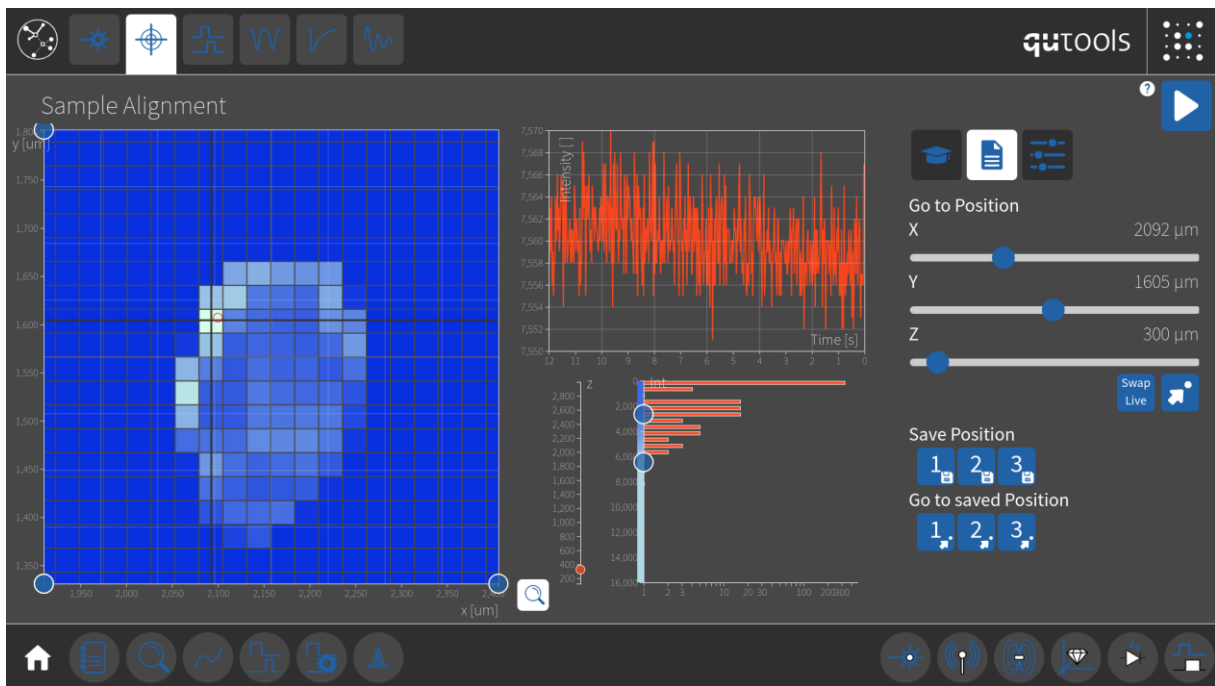


Figure 8 - When zoomed into a detail scan, you can select the best spot using crosshairs, and save a position for the next session.

### 4.3.3. Laser Pulsing & Photodiode Timing

In the next tab “Laser Pulsing & Photodiode Timing” the pulsing behavior, time delays and the PD gain can be observed and adjusted. The plot shows a high temporal resolution on x axis versus the intensity in arbitrary units on the y axis.

- Tap on the blue “Play” button in the top right corner to start experimenting.
- Adjust the “red” gain such that the edge is steep, the peaks are not in saturation and the overshoot is not too high. The pulse shape should look like in Figure 9.
- With too much gain, the peak at the start of the pulse will be overshooting more and even oscillate, with too little gain the rising flank of the photodiode will not be steep enough. Experiment with this setting and note the influence of laser power. The gain parameter will affect the measurement results of the later experiments and must be set correctly at the beginning of every session.

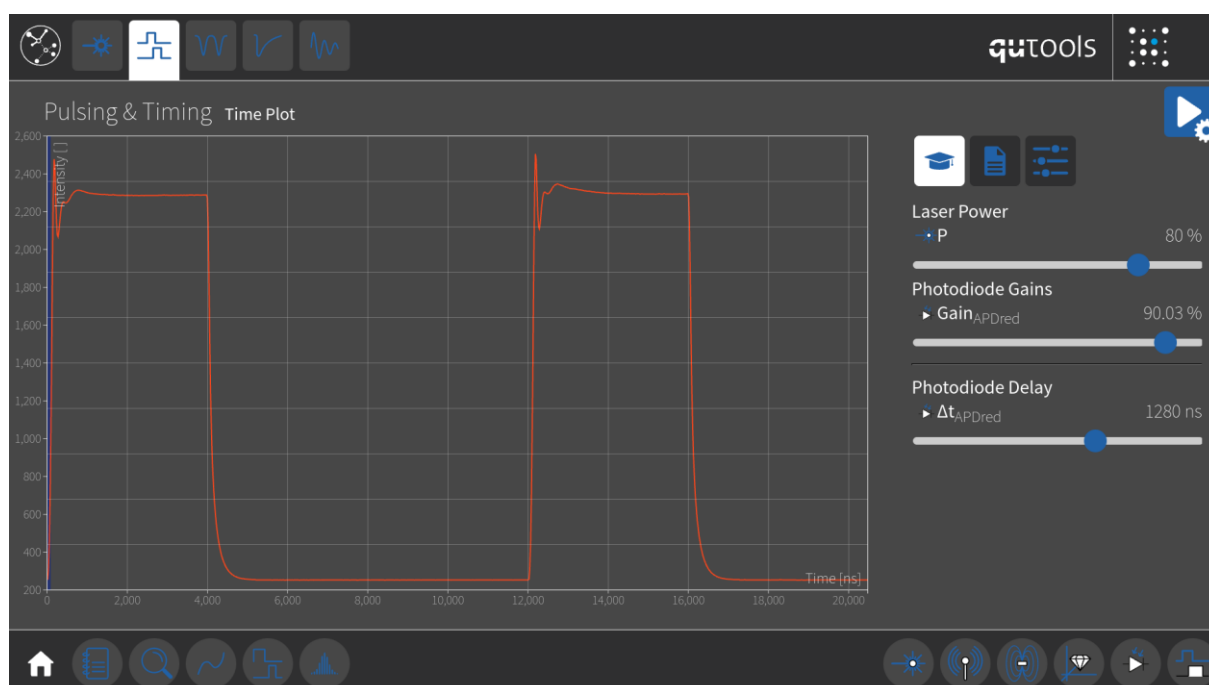


Figure 9 - Adjustments for the "red" PD measuring the fluorescence.

- The influence of the pulsing parameters can be seen in the measurement as well. Play around and get a feeling of the control of the pulse sequences.
- For later experiments, it is important to set the PD delay  $\Delta t_{red}$  such that a laser pulse beginning at 0 ns is also detected at 0 ns: Move the slider until the rising flank of the pulse is on the leftmost side of the diagram. This must be done in every session since the later experiments depend on a correct setting.

#### 4.3.4. Magnetometry (ODMR)

Go to the third tab of the top left corner to do the first measurements of the “Magnetometry” experiment. This view shows a parameter plot. That means that during a sequence, parameters can be changed in 1024 steps. In this case, the microwave frequency is the changing parameter, so the plot shows GHz on the x axis. On the y-axis, the fluorescence intensity is displayed.

- Tap on the blue “Play” button in the top right corner to start experimenting with the presets.

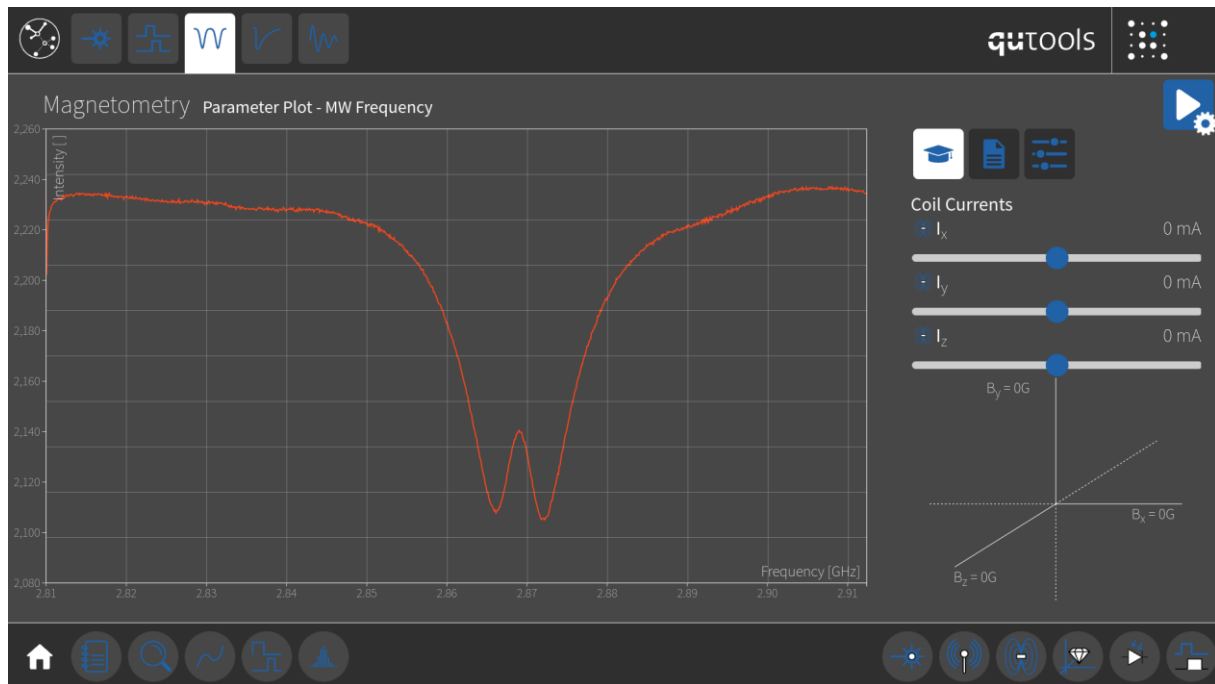


Figure 10 - Preset ODMR Scan

- If the signal is not clear, optimize the confocal alignment, laser power and photodiode gain. You can also adjust the detection window and the PD delay, since each data point in this parameter plot is an average of multiple points from the sequence data.
- You can change the sequence settings by adjusting the duration and timing of laser and microwave pulses.
- You can change the frequency range of the sweep by selecting a new range with the cursors or by defining start frequency and step size, both in the settings tabs on the right side.
- Play with the different averaging options and get a feeling of their effects. More averaging ( $Avg_{Param}$  or  $Avg_{Display}$ ) will make the system’s response to a change in magnetic fields slower, but you will get rid of noise and fluctuations, making your signal clearer.

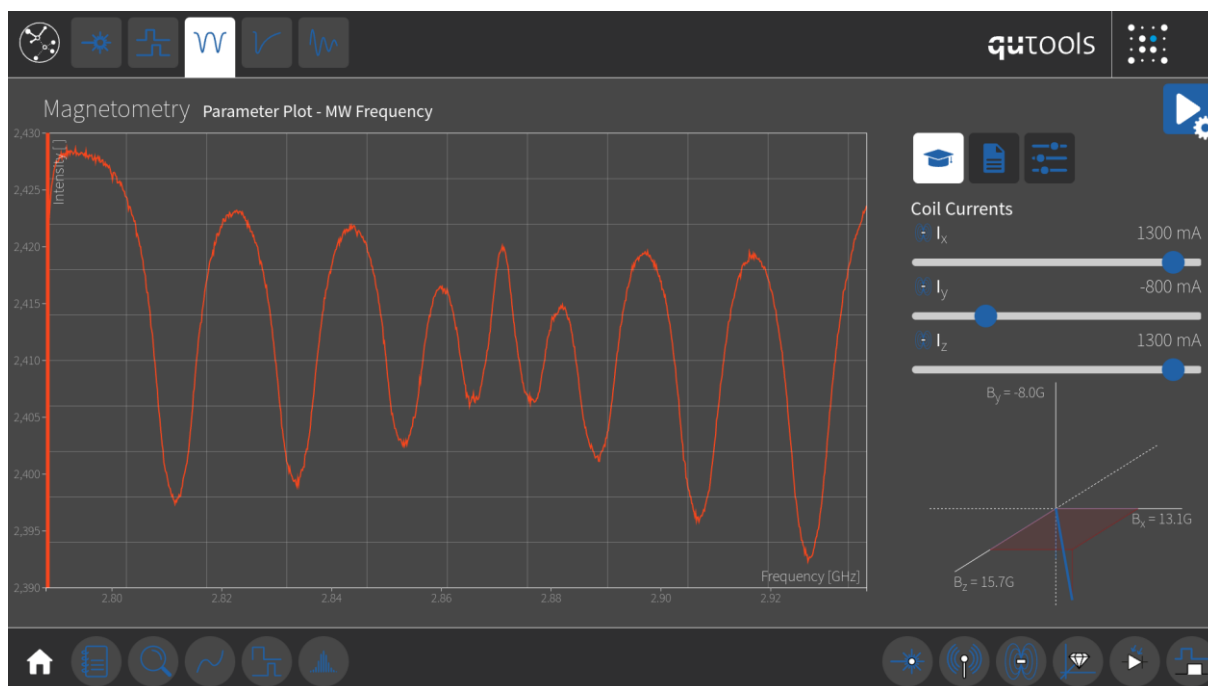


Figure 11 - Up to 8 distinct dips can be seen with the right settings for the magnetic field coils.

- Manipulate the current through the coils to generate a magnetic field. Observe the effect this has on the spectrum of the NV centers. Move one slider after the other and see the differences between the directions. Because of the 4 possible directions of NV centers in the diamond lattice, one can observe up to 8 distinct dips in the spectrum (Figure 11).
- The graphics visualizing the direction of the magnetic field represents the calculated magnetic field from the values of the current in x,y,z direction and the geometry of the coils, it is not a measurement.
- Investigate the shape of the signal while adjusting the sliders of the coils and try to isolate single dips from the rest. Change the direction of the magnetic field: If the observed dip does not split up when changing multiple currents, it is a single dip.
- When changing the microwave power in the settings of the third tab, you'll be able to see the tip of each dip split into 3 smaller ones (Figure 12). This is due to the hyperfine splitting.
- The magnetic field you set up in this experiment will stay until you change it. The device does not change the current of the coils in any presets.
- If you leave the current of all three coils close to the maximum value for a long time, you will probably get a temperature warning and eventually the device will shut off the coils as precaution.

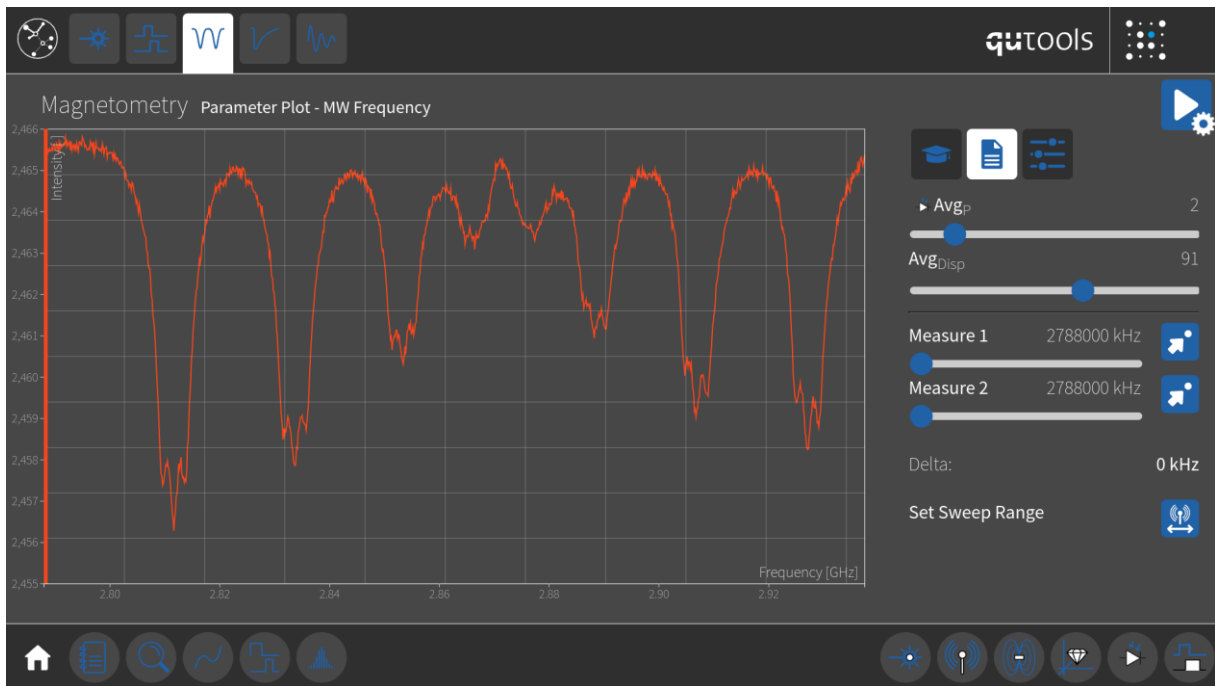


Figure 12 - With lower microwave powers, one can observe hyperfine splitting into three states in each of the dips.

Now one of the frequencies with a dip should be chosen for the next experiments. You can always come back to this experiment and choose another dip:

- The measure sliders and the associated go-to buttons help setting the desired frequency.

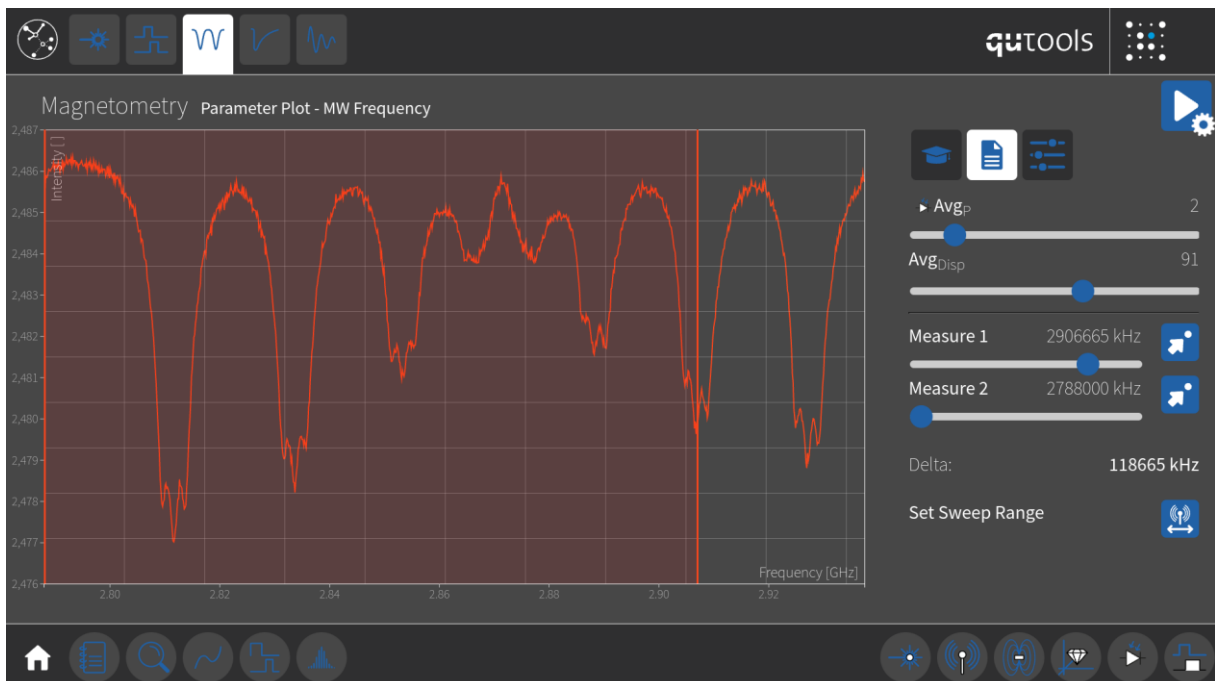


Figure 13 - Selecting a dip with the measurement feature.

- Move a measure slider to the selected dip, then press the “go to” button directly to the right from it.
- The Microwave frequency scan will change, since the selected frequency will now be the starting frequency. Therewith, the leftmost edge of the diagram should be in the dip.

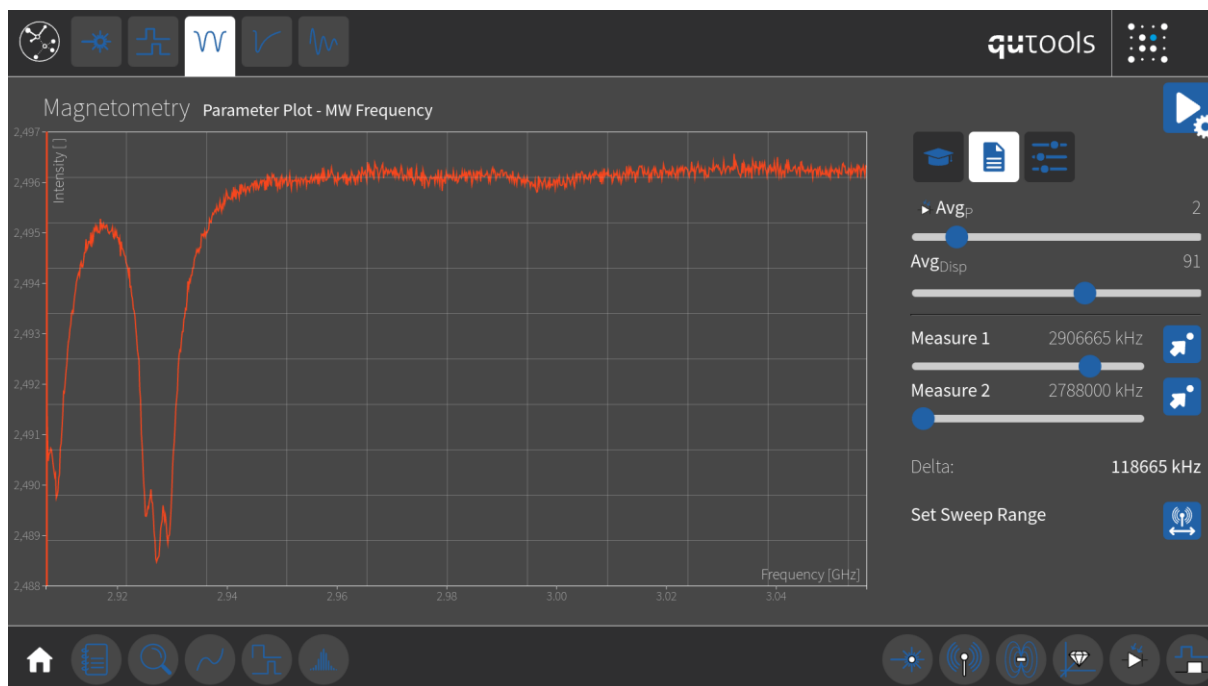


Figure 14 - Setting the dip frequency as starting frequency in order to use it for subsequent experiments.

#### 4.3.5. Spin Nutation

The next tab shows the “Spin Nutation” experiment. The plot shows a part of the pulse sequence in high temporal resolution on x axis versus the intensity of the fluorescence light in arbitrary units.

This experiment is intended to show how a microwave pulse changes the population of the spin states while the green laser is on. You can observe the inevitable electronic delay of the microwave pulse, similar to PD delay. This experiment also shows the rate of optical pumping, which is needed for initialization in all pulsed experiments, and its dependence on the laser power.

Tap on the blue “Play” button in the top right corner to start experimenting.

- Adjust the averaging ( $Avg_{Seq}$  and  $Avg_{Display}$ ) in the second sub-tab in order to reduce noise and see the signal more clearly.
- Adjust the laser and the microwave power in the first sub-tab to observe how the shape of the curve changes.
- The frequency of the microwave was set in the previous experiment “magnetometry” but can also be varied here.
- If you do not see any oscillation in the fluorescence in the beginning of the MW pulse, maybe you haven’t chosen a single dip (NV orientation) from the ODMR spectrum.

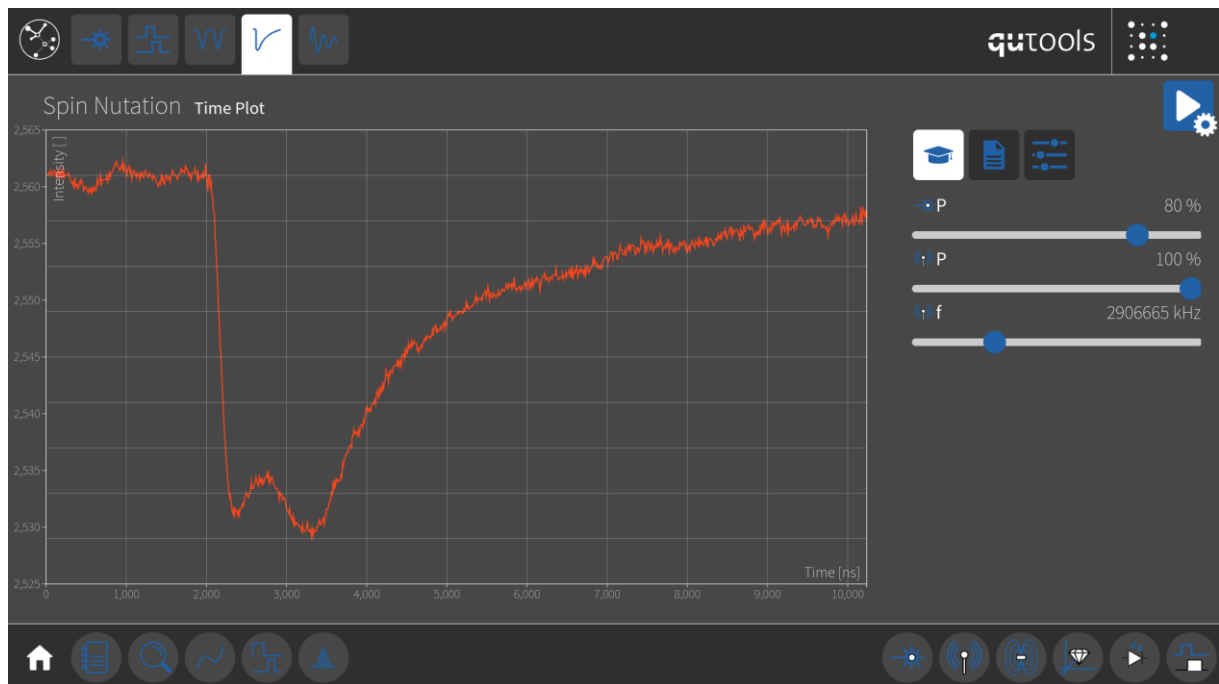


Figure 15 - In the Nutation Experiment, the microwave is pulsed while the laser is on the whole time. The state of the NV centers is starting to oscillate, and when the microwave turns off again, the system is optically pumped to the bright state.

### 4.3.6. Rabi Oscillation

The next tab shows the “Rabi Oscillation” experiment. The magnetic field and the microwave frequency have been chosen in the “Magnetometry” experiment. The length of the resonant microwave pulse determines in what superposition of both spin states the system is before the read-out laser pulse extracts the fluorescence. These coherent oscillations between the ground and excited spin states are crucial for understanding the notion of  $\pi$  and  $\pi/2$  pulses on a Bloch sphere.

The view in this experiment shows a parametric plot, where the changing parameter is the width of the microwave pulse, so the x axis shows tau[ns] in 1024 steps. In order to keep the time between end of MW pulse and beginning of read-out laser pulse fixed, the second laser pulse is also shifted with the same step size as the width of the microwave pulse.

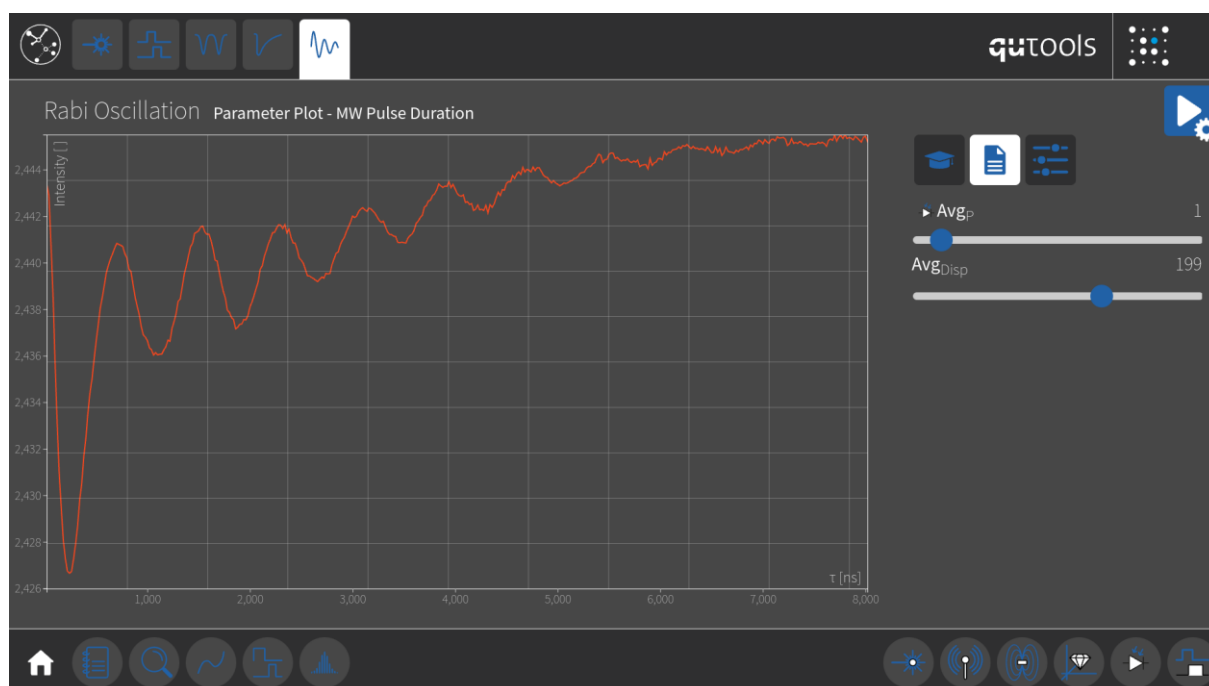


Figure 16 - A Rabi Oscillation experiment: A microwave pulse while the laser is off will drive the transition between bright and dark state with a certain frequency. This way, the state of the NV centers can be controlled and, e.g. a Hadamard Gate can be realized.

- Tap on the blue “Play” button in the top right corner to start experimenting.
- Adjust the averaging in the third sub-tab.
- Play around with the microwave power and frequency in order to see the change in the oscillation period. A typical Rabi frequency at maximum Mw power is about 1 MHz.
- You can also observe the effect the chosen measurement window timing can have on the measurement by changing the detection window start and width.

#### 4.4. Update

In case you want to update or restore the software of the control unit, please contact qutools GmbH: [info@qutools.com](mailto:info@qutools.com).

## 5. Troubleshooting

### 5.1. No signal

- Check if the optical fibers are connected correctly.
- Check if the laser is turned on. You can use the experiment “Laser & NV Alignment” or you can check the fiber output 2 of quADD-NV, which has less than 0,3 mW output power.
- Check if you are aiming at a diamond, as you can see the red glow through the protection cover of the quADD-NV.
- If the diamond glows, but you have no red signal in the “Time plot” of quEDU check the Photodiode gain and/or tweak the position of the objective.
- If you see fluorescence in the “Time plot”, but you have close to zero signal in the “Parameter plot”: adjust the Photodiode delay and/or the Detection window in the experiment “Pulsing and Timing”.

### 5.2. Noisy signal

- Optimize the confocal alignment, laser power and photodiode gain for better signal-to noise ratio.
- Optimize the detection window and the various averaging settings.
- Reduce vibrations. Since the diamond sample is placed on a flexure, the setup is sensitive to vibrations - not only to vibrations of the table, but also to vibrations in the air (noise, humming of an air conditioner). One source of vibrations can be the quEDU, so place the two devices on two separate tables. Another source of vibrations can be the internal fans of the quADD-NV, which are off in the presets, but might be necessary during long use or during hot summer days.
- Ambient light is not an issue thanks to the confocal alignment and the fiber coupling.

### 5.3. Temperature warnings

- Turn off the laser and the current through the coils, turn on the fans of quADD-NV and wait a couple of minutes. You can monitor the temperature of sensitive parts in the “Settings” view in the low left corner of quEDU.
- Reduce the ambient temperature.

### 5.4. Known bugs

- Shifted Sequence Plot: When increasing the Averaging of the Sequence plot, AvgSeq, it can happen that the x-axis of the plot is shifted by 100 points from then on. A restart of the device will fix this problem. We are working to fix this issue.