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PHY FB Physikingenieurwesen
Department of Engineering Physics

Using NV Center in Diamond for Education in Quantum Technology

Prof. Markus Gregor

Laboratory for Quantumtechnology (Qute Lab)
Department of Engineering Physics
University of Applied Sciences - Münster

Overview

Using NV Centers in Education

Topics for the talk:

1) **Introduction to the Quantum Sensing Group activities**
2) Motivation – NV centers in education
3) Introduction to NV centers and magnetic field sensing
4) New! Coherent Control of Spin States

Quantumsensors Group @ FHM

The most important facts first!

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- Lab Director – HBL (Professor): Peter Glösekötter
- Lab Director – QuTe (Professor): Markus Gregor

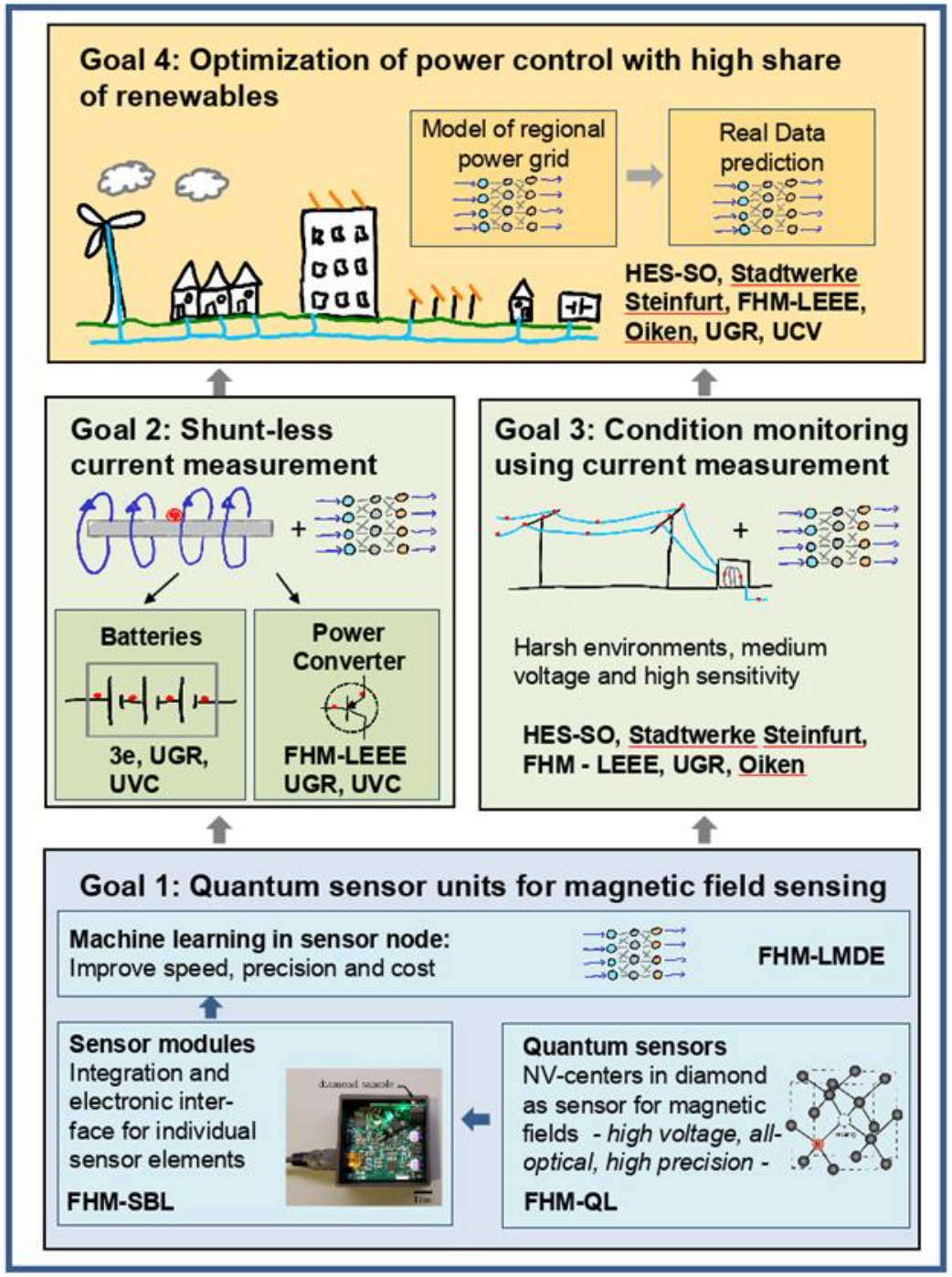
- PhD candidates: 6 (HBL) + 3 (QuTe) + 1 post-doc
- research assistants: Several + >3 MSci. cand.
- administrative assistant: Part-time + two lab engineers: Part-time

Quantum Current Sensors

Ongoing Projects

Project QuantumIRES in the context of reginal power grids:

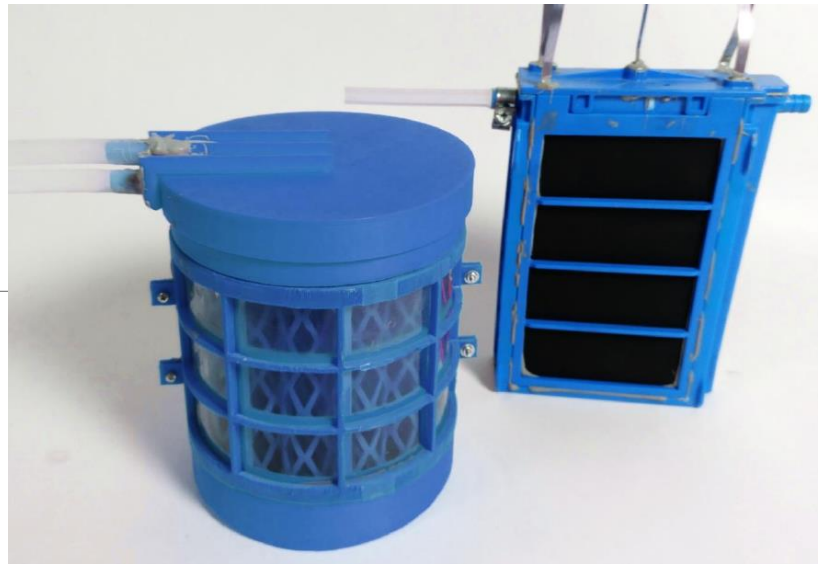
- Quantum sensor units for magnetic field sensing
- Shunt-less current measurement
- Condition monitoring using current measurement
- Optimization of power control with high share of renewables



The clean Energy Transition Partnership
Co-funded by the EU

Optimizing Batterie Designs

Ongoing Projects in Quantum Sensors

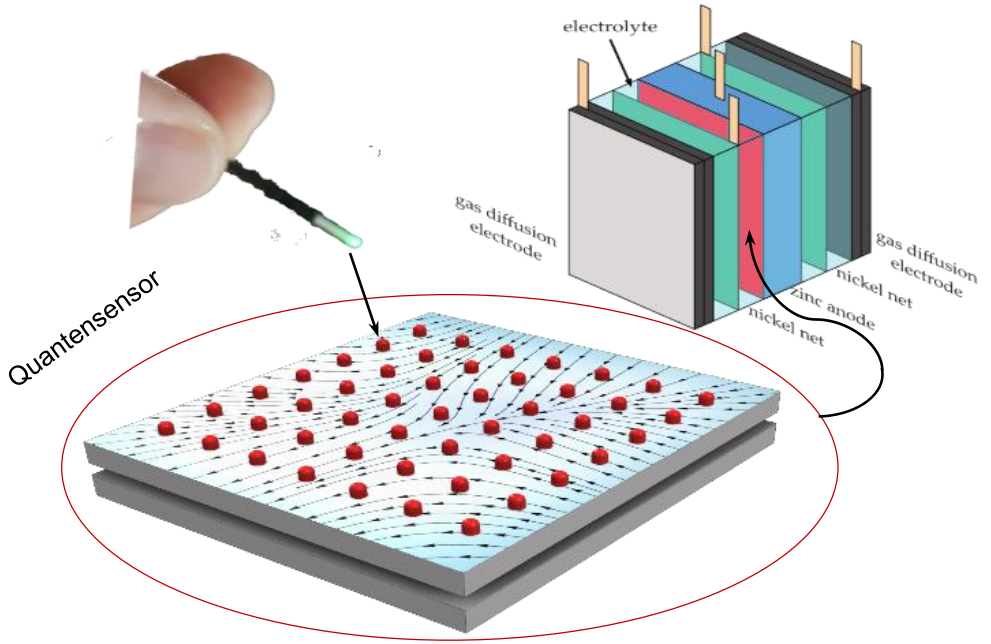


Project ZSLM2

Further development of zinc-air technology towards a marketable and safe stationary battery storage system, taking ecological and economic aspects into account

Objectives:

- Optimizing the battery management system
- **Quantum sensors for measuring current density**



Project partners:

Stadtwerke Steinfurt ... spürbar nah!

3e Batterie Systeme GmbH

LÜTTGENS Kunststoff-Technik

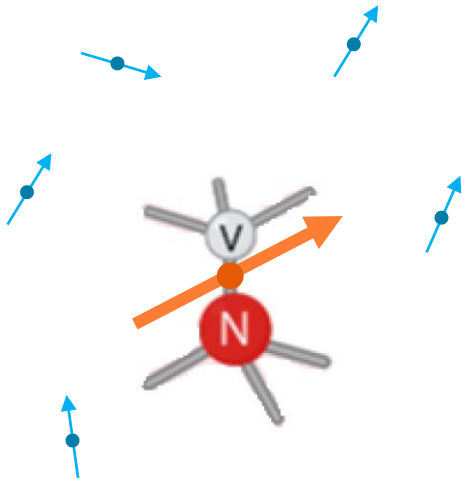
Funded by:

Kofinanziert von der Europäischen Union

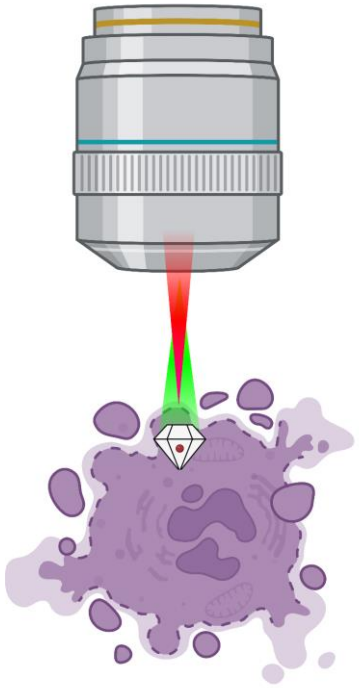
Die Landesregierung Nordrhein-Westfalen

Tumor Diagnostics with Nanodiamonds

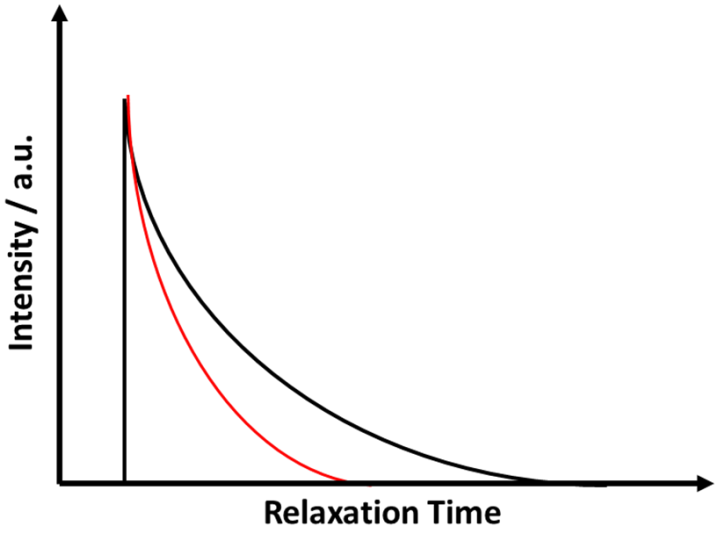
Ongoing Project in Quantum Sensors



electron spin in NV center interacts with the local spin environment



Nanodiamond in cell



Relaxometry – Spinstatelifetime T1 changes

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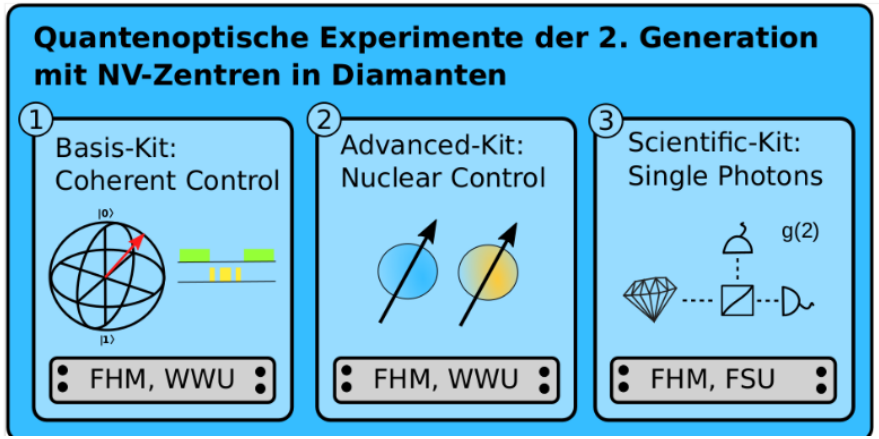
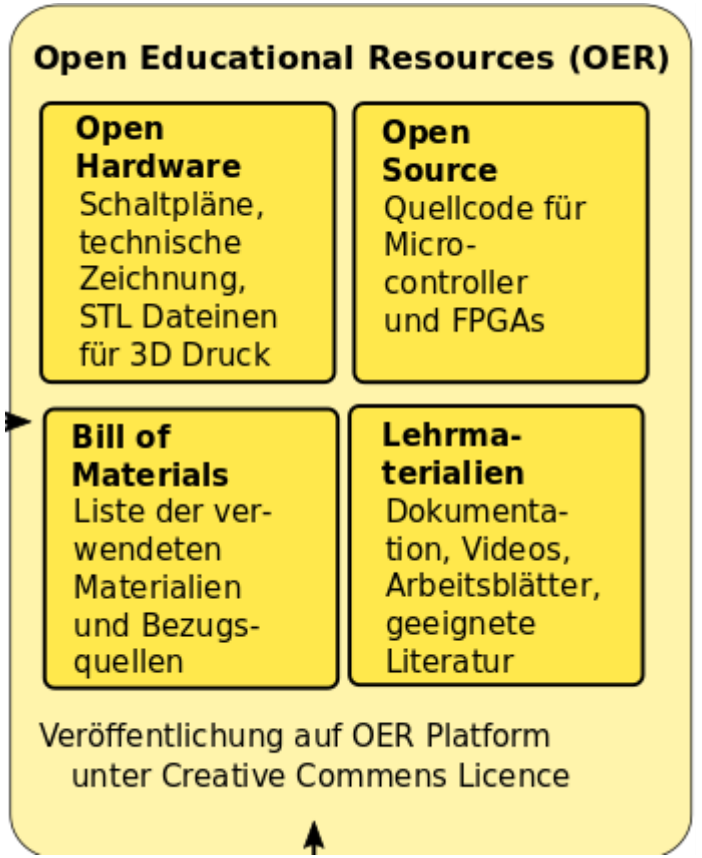
Motivation

Low-cost student experiments in quantum physics

- „Quantum physics” is a mandatory topic in the secondary school physics curriculum
- Demonstration experiments by teaching materials companies often beyond the financial means of schools (no student experiments)
- Focus on modern quantum physics (2nd gen.)





- (no complicated math, no vacuum setups, no low temperatures)
- Enable research-based experimentation

Open-Hardware Student Experiments
from quantum optics

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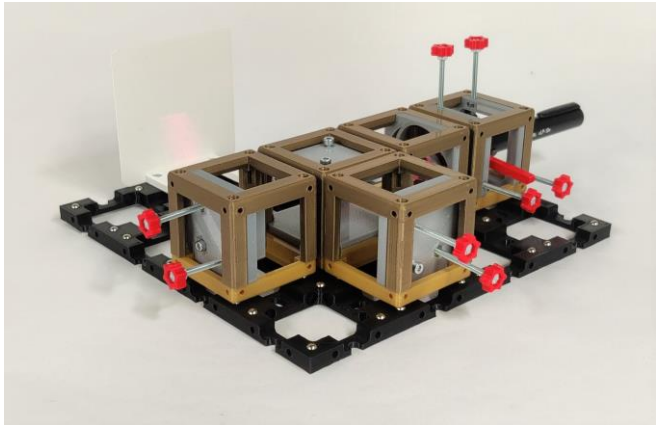
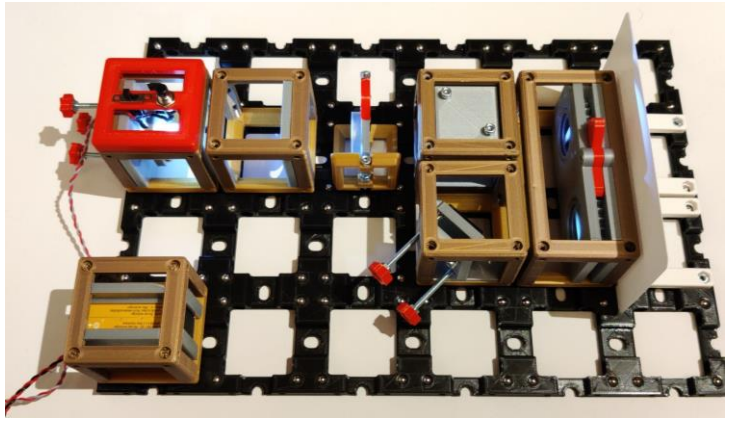
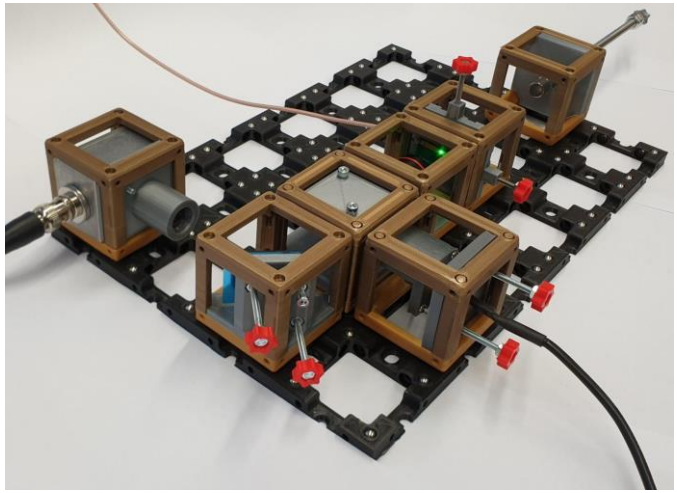
Interferometer



BB84 – Modellexperiment zur Quantenkryptographie



Quantensensorik mit NV-Zentren in Diamanten



A simple modular kit for various wave optic experiments using 3D printed cubes for education.
Nils Haverkamp, Alexander Pusch, Stefan Heusler, Markus Gregor. Physics Education, 57: 1–13. doi:10.1088/1361-6552/ac4106.

Outreach for Quantentechnology

Experiment kits for schools and universities

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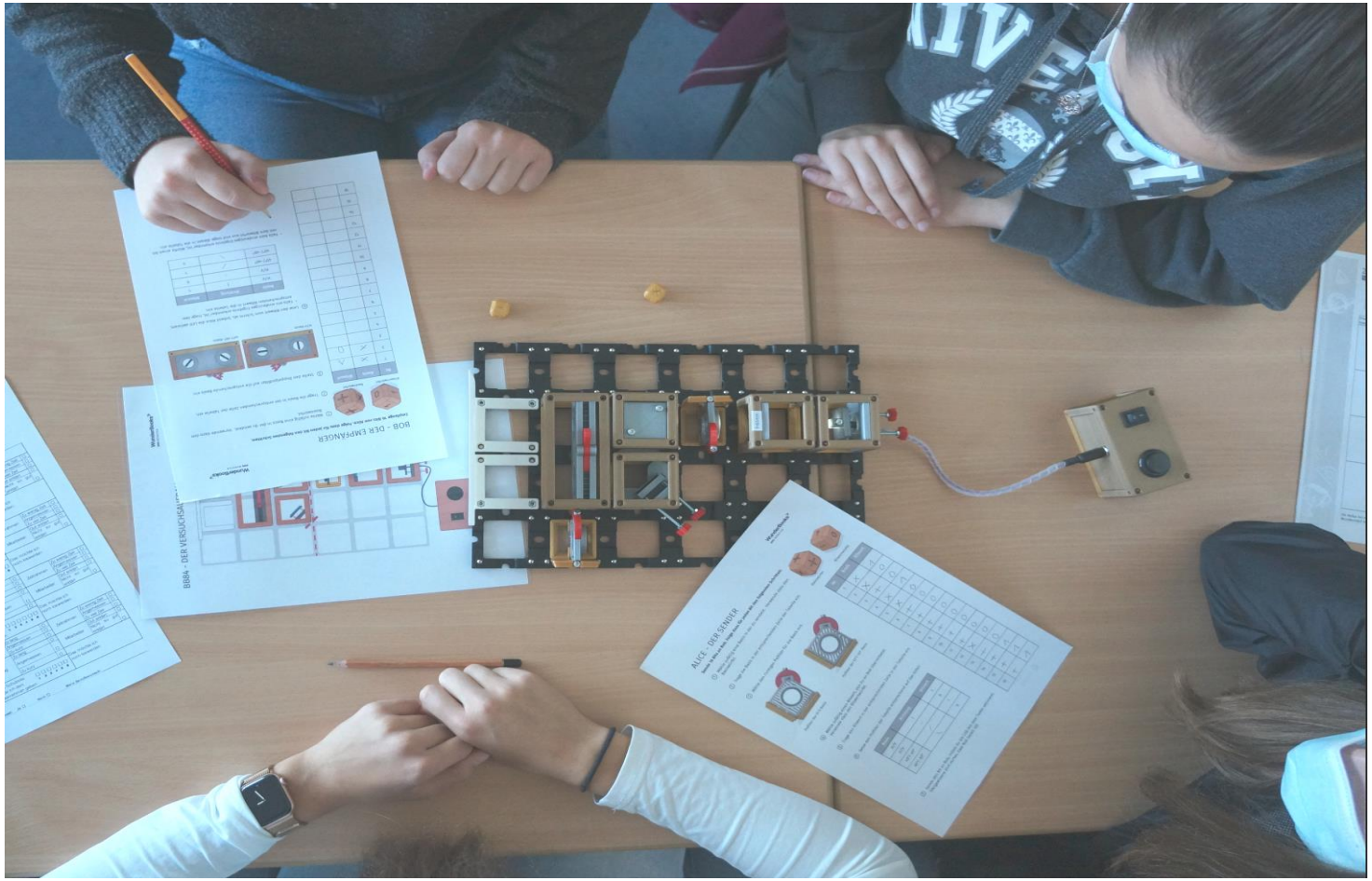

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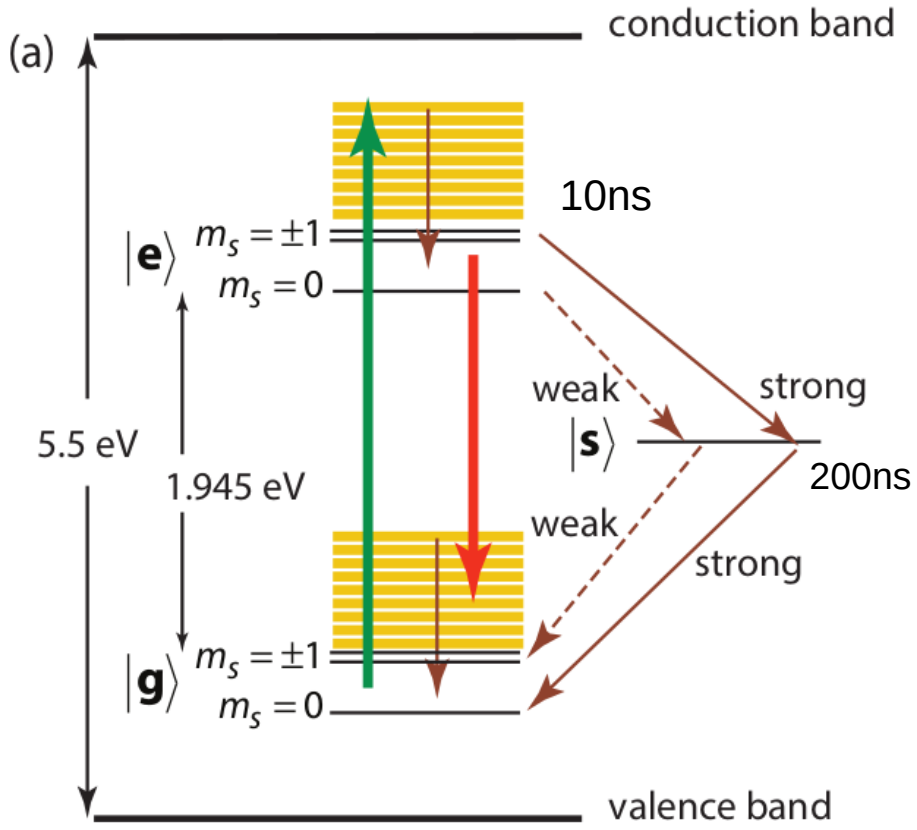
Concept of ODMR for Sensing

Optically Detected Magnetic Resonance



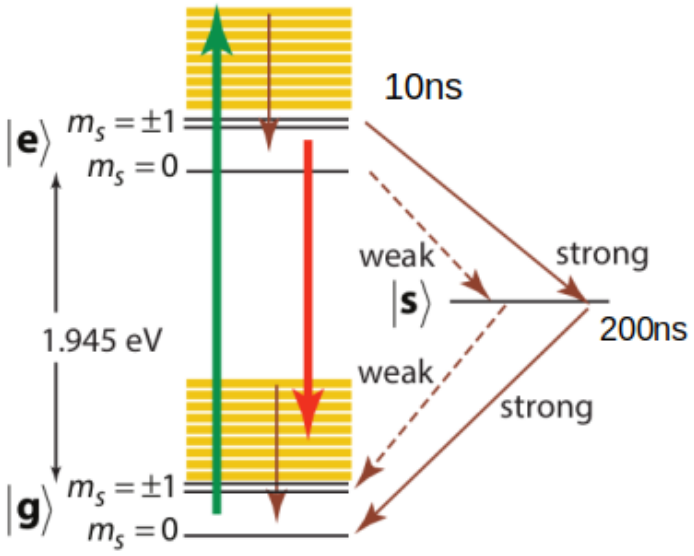
Zhang,H. ,Am. J. Phys. 86, 225–236. (2018)
[Adv. Sci. 2022, 9, 2200059]

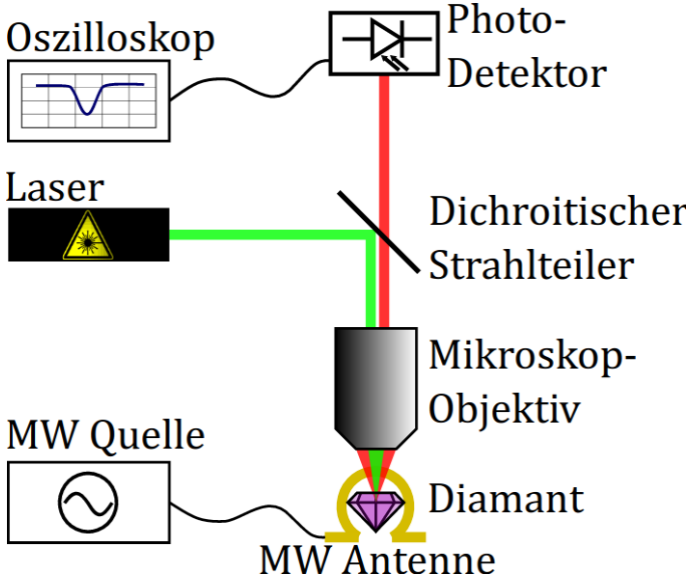
magnetic sensing: m_s=+/-1 split due to external magnetic field $B_{||}$ (Zeeman-Splitting)

Spinstate can be detected by the fluorescence intensity.

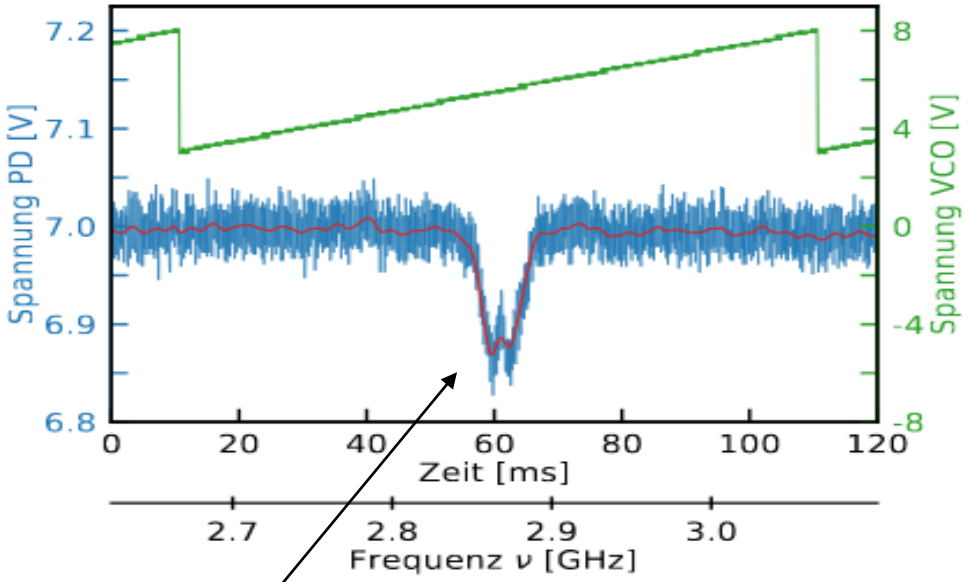
Concept of ODMR

Optical Setup and Resonance Signal





Typical ODMR signal with ZFS
(zero field splitting)



Spinstate is optically detected.

Optically Magnetic Resonance mit NVs

Optic cubes based setup for schools and student labs

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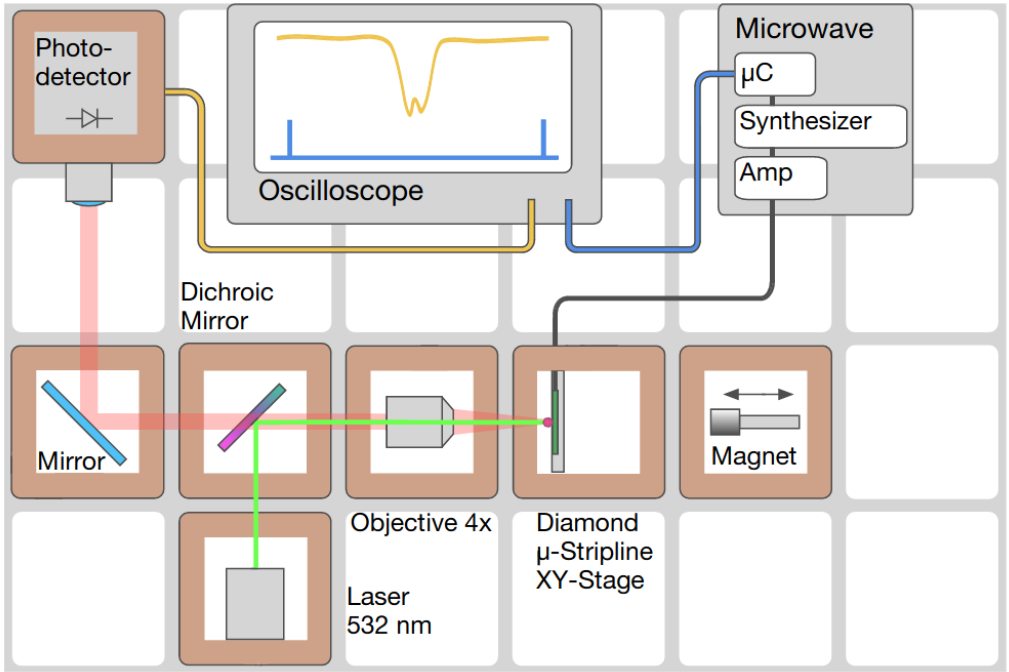
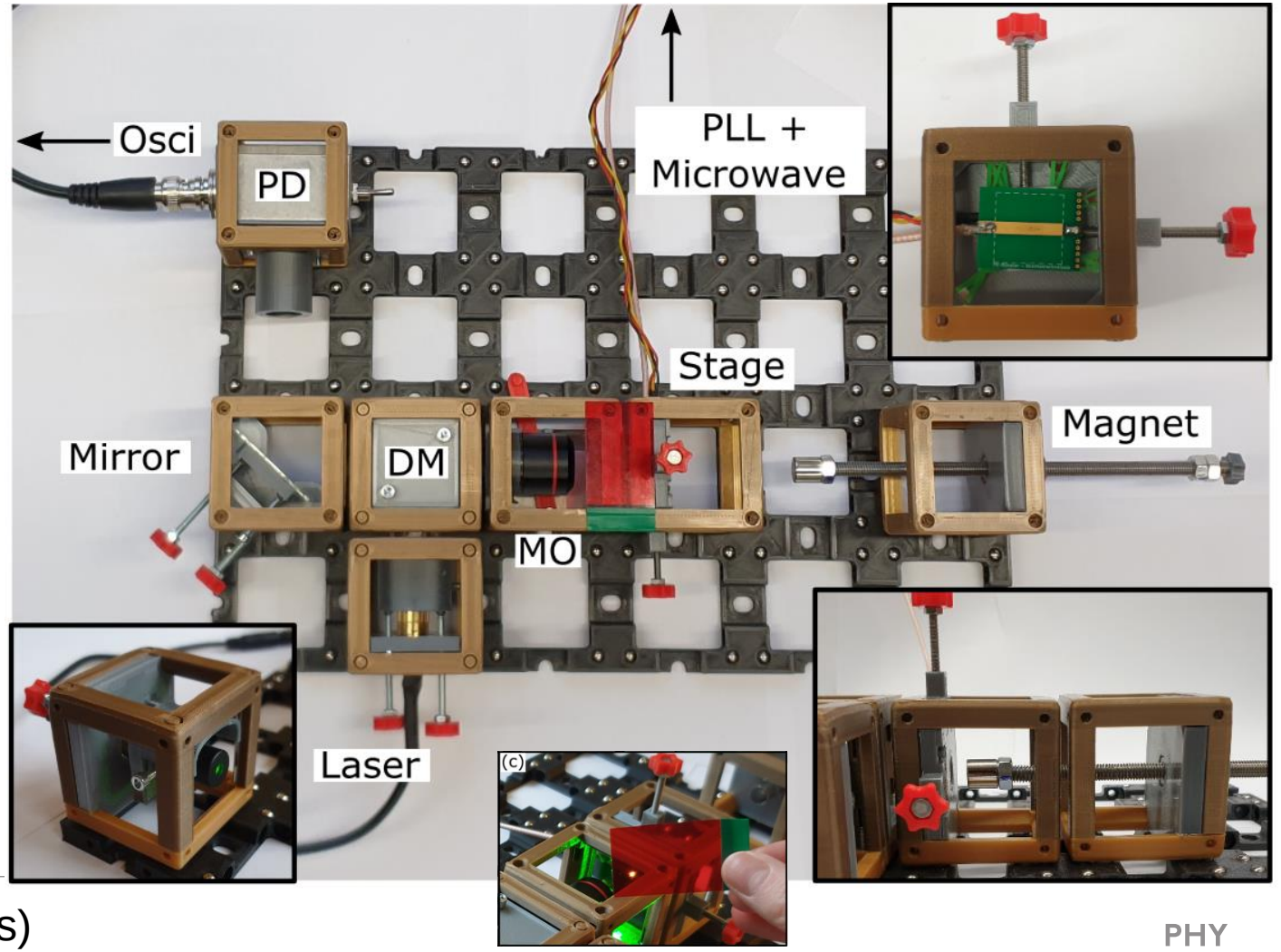
Modular low-cost 3D printed setup for experiments with NV centers in diamond, Jan Stegemann, Marina Peters, Ludwig Horsthemke, Nicole Langels, Peter Glösekötter, Stefan Heusler and Markus Gregor. Eur. J. Phys. 44 035402 (2023). doi.org/10.1088/1361-6404/acbe7c



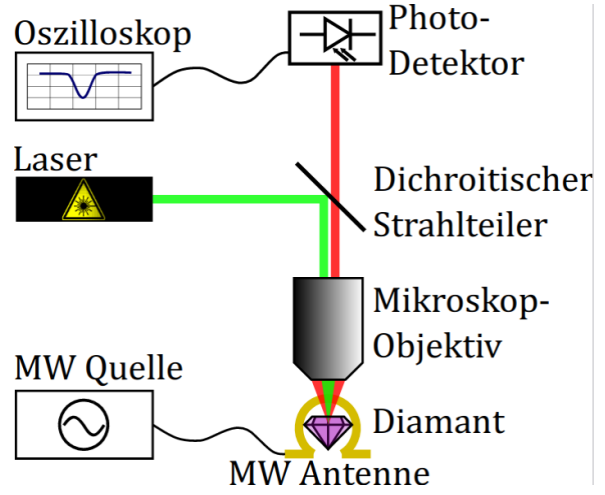


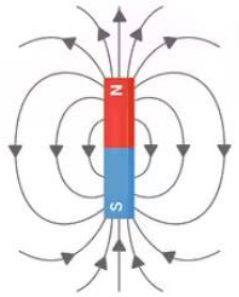
Costs less than 400 Euros (without oscilloscopes)

PHY

Sensing

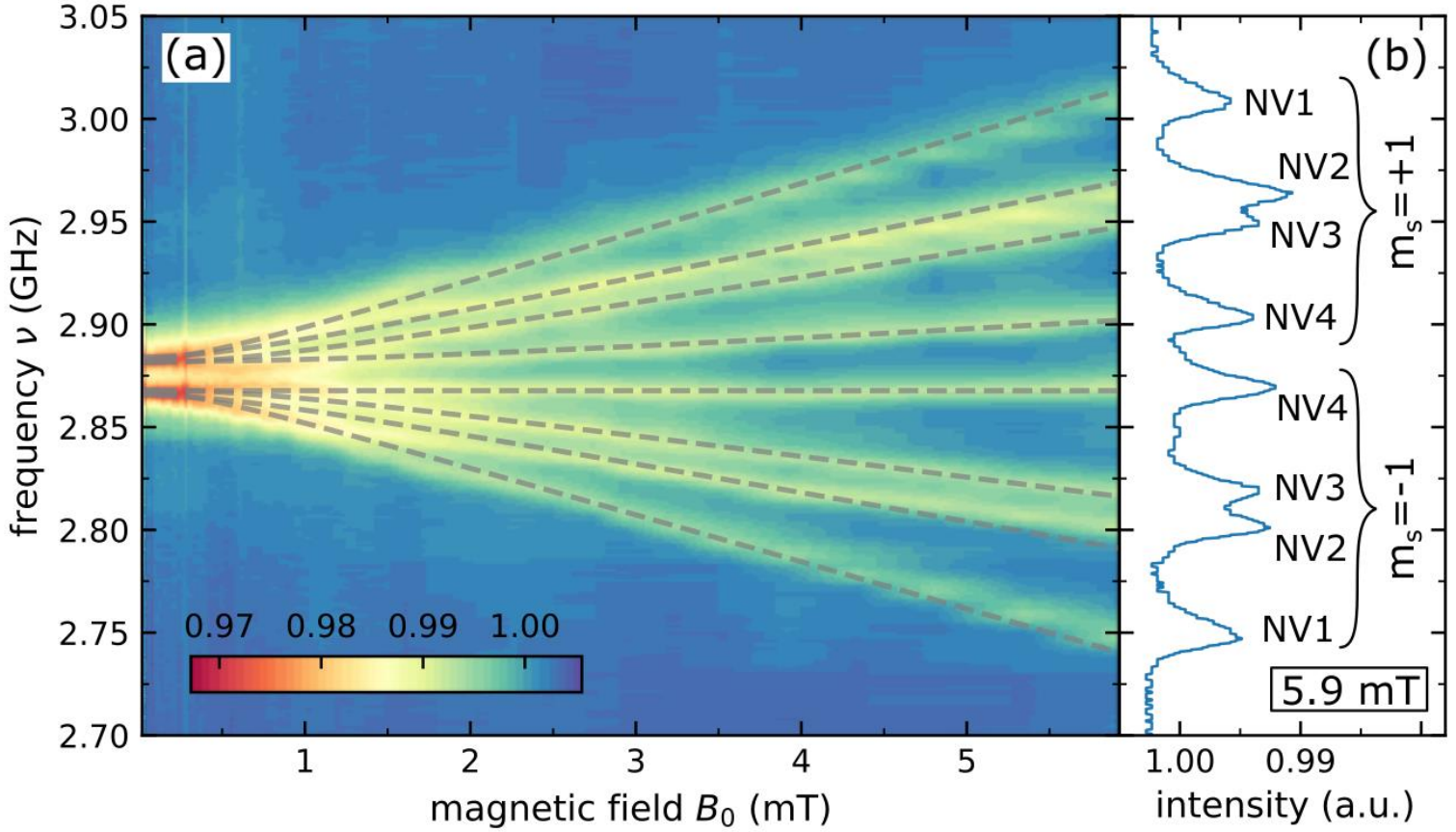
External Magnetic Fields shift Energy levels

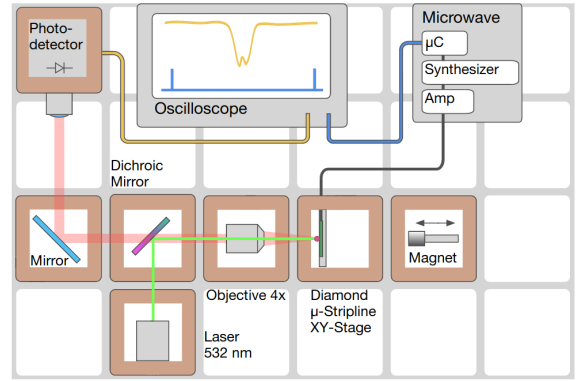




Magnetic field sensor

Magnetic field sensor - Zeeman effect





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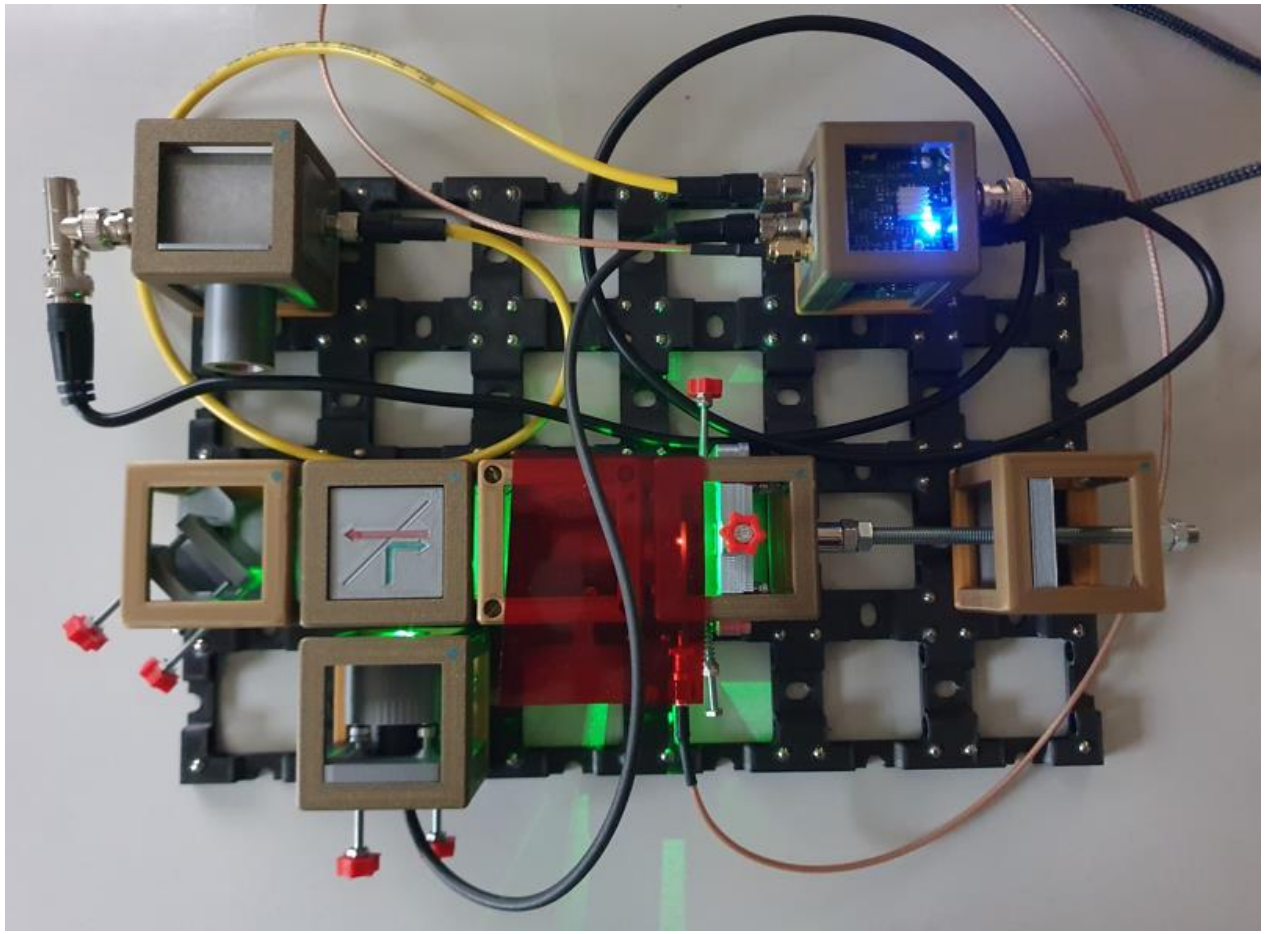
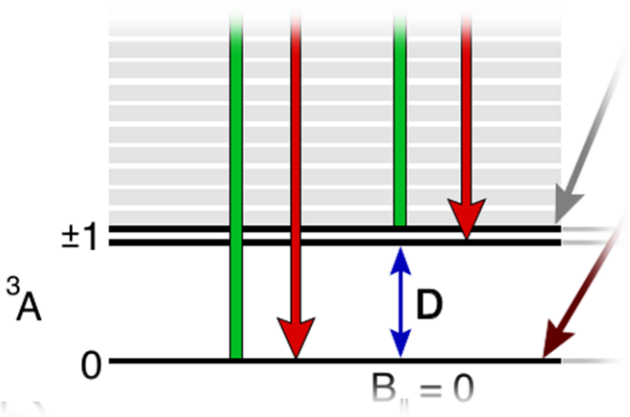
New Setup for Coherent Control

So, what is new?



Controlling the Spin State

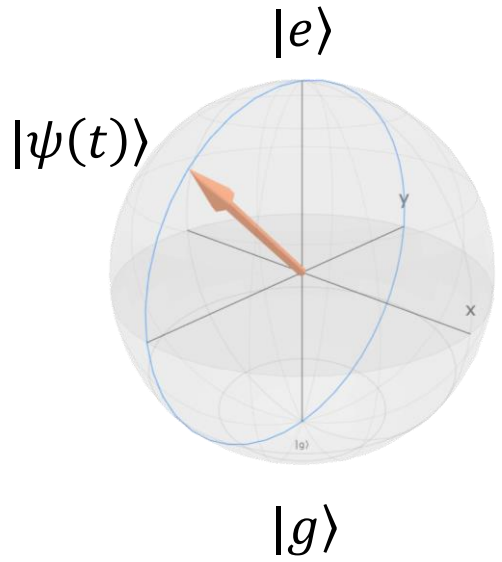
NV Centers as two level systems



$m_s = -1$ —— $|e\rangle$

$\Omega \cdot t$

$m_s = 0$ —— $|g\rangle$



- external MW magnetic field connects the ground and excited spin states represented by off-diagonal elements in the Hamiltonian.
- The interaction strength is given by γ.
- An oscillation between the $|g\rangle$ and $|e\rangle$ is driven by the frequency Ω. **(Rabi Oscillation)**

$$H_{total} = H + H_{int} = \begin{pmatrix} E_g & \gamma^* \\ \gamma & E_g \end{pmatrix}$$

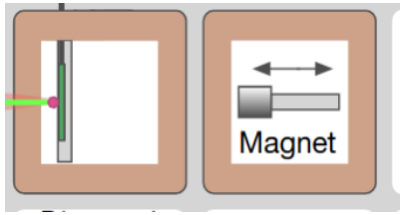
$$|\psi(t)\rangle = \cos(\Omega t)|g\rangle - i\sin(\Omega t)|e\rangle$$

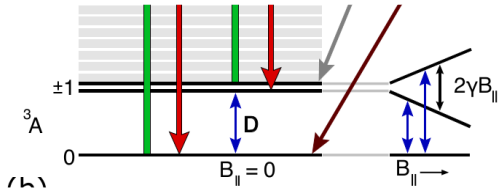
with $\Omega = \gamma / \hbar$

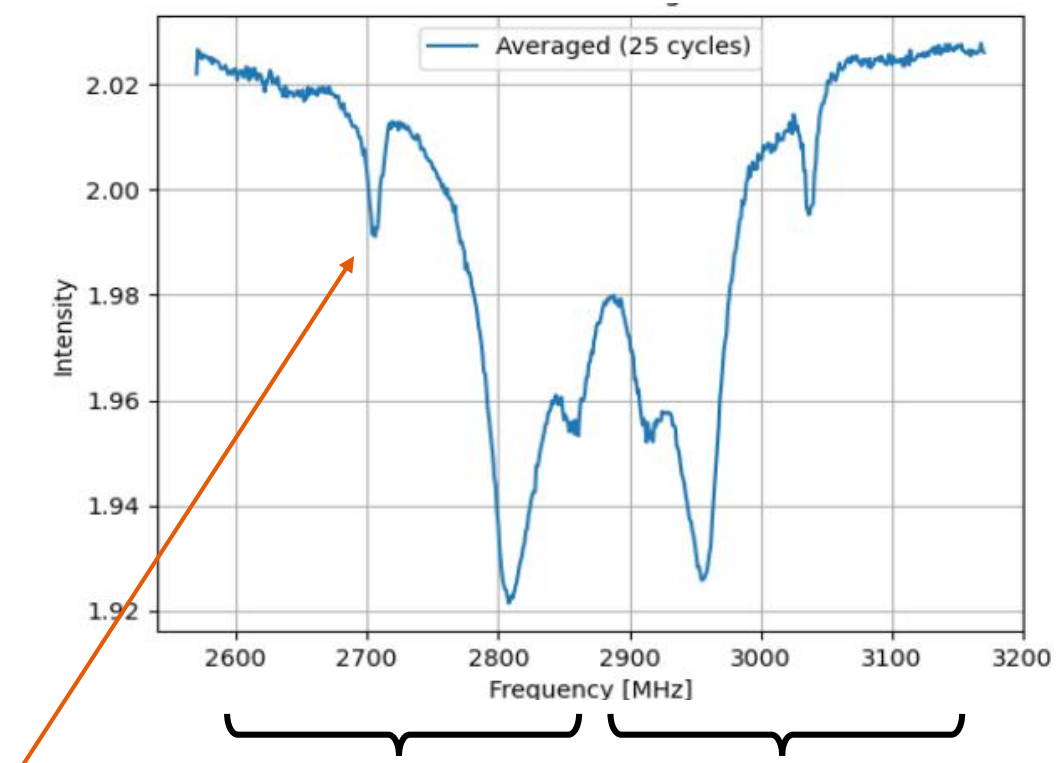
NV centers as two level system

Spitting the energy levels using an external magnetic field

permanent magnet splits energy level $m_s = \pm 1$

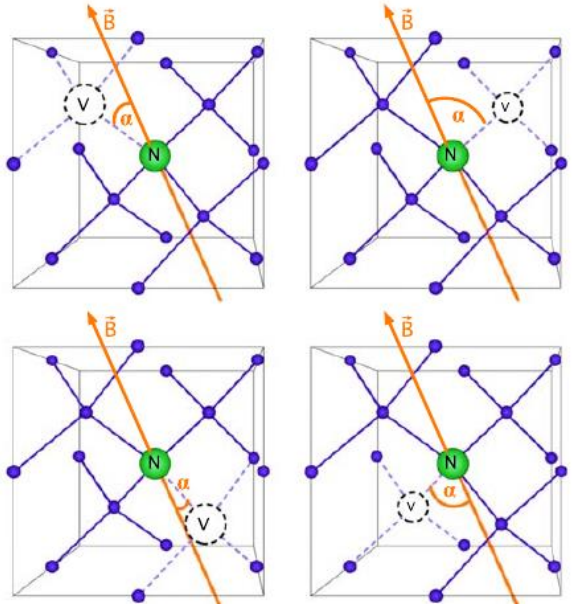






$m_s = -1$ $m_s = +1$

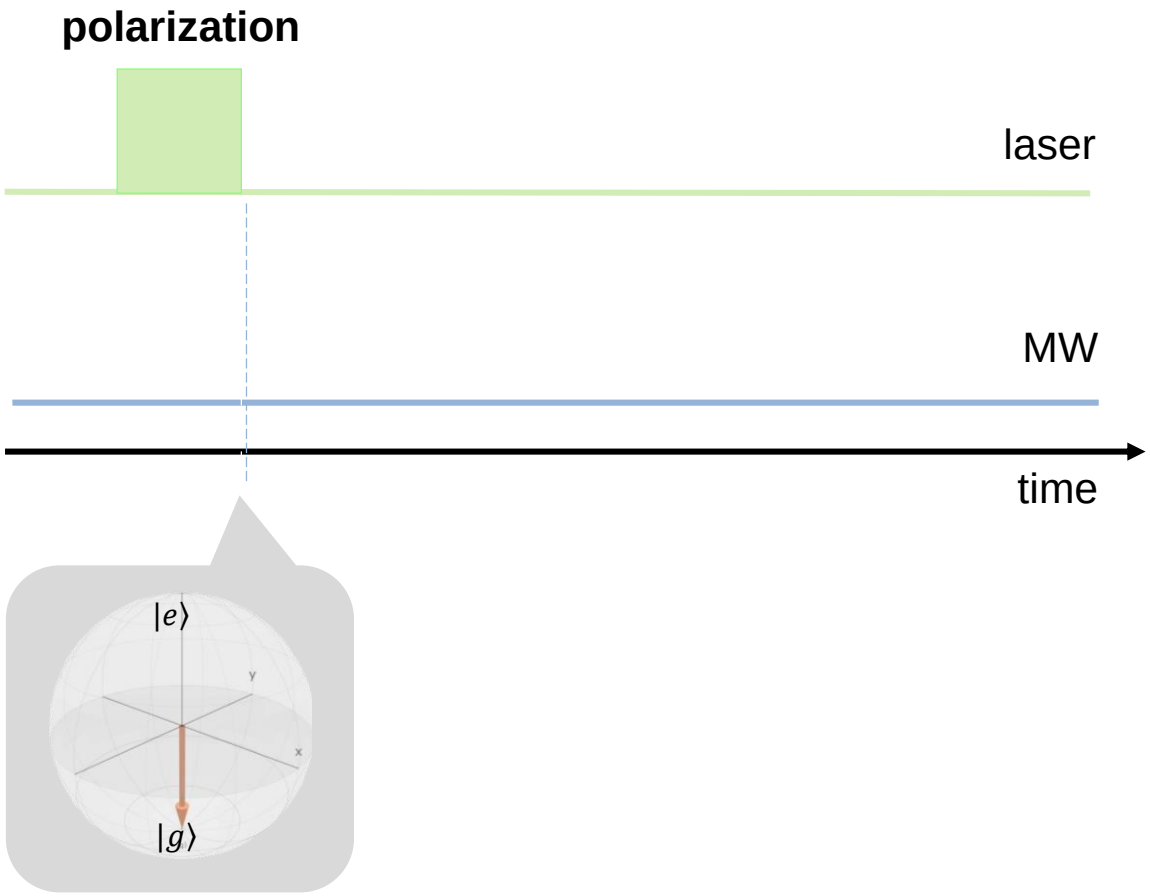
up to four resonances visible

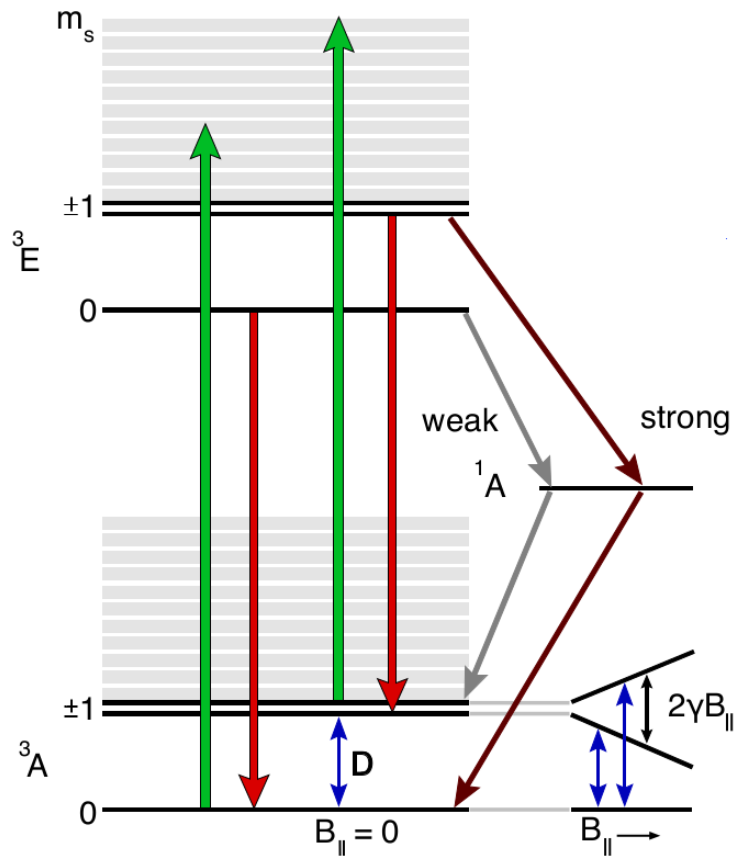


possible suitable resonance for coherent control

Pulse Sequences

Detecting Rabi oscillation





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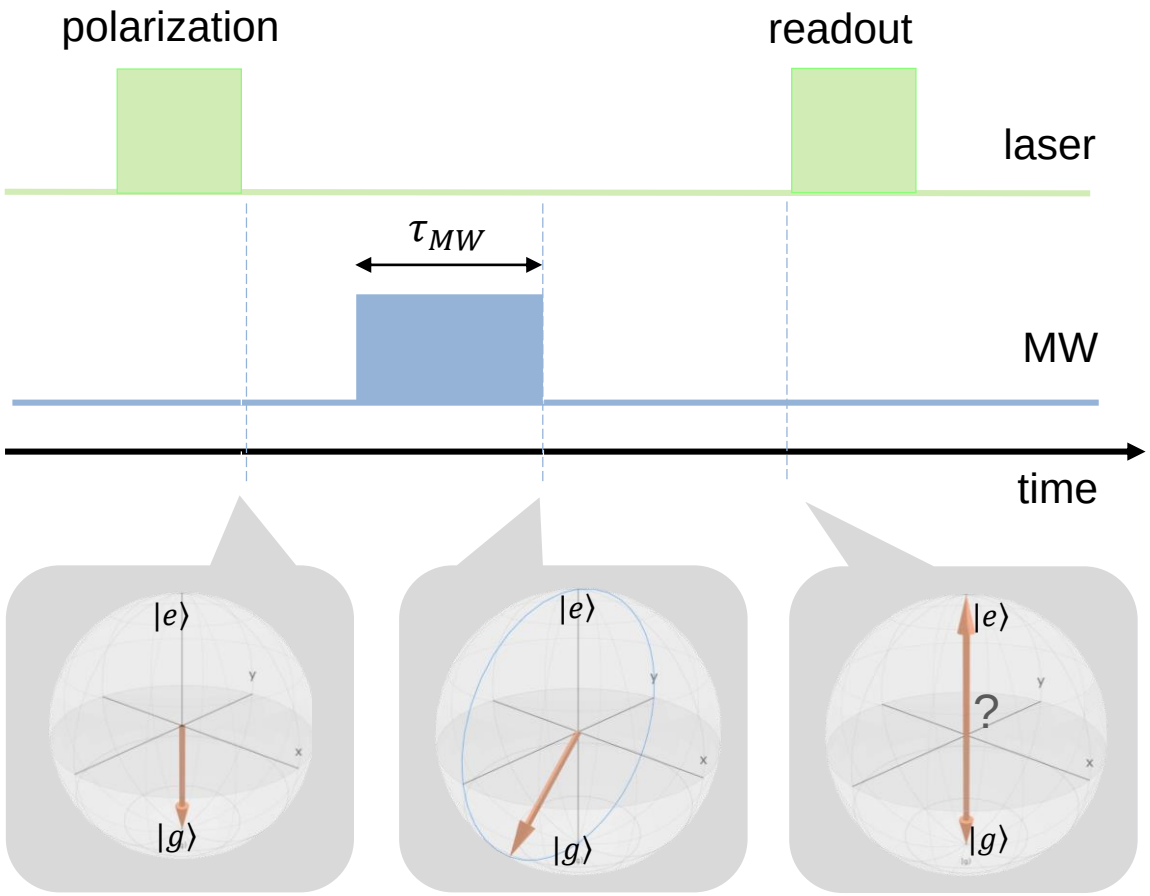
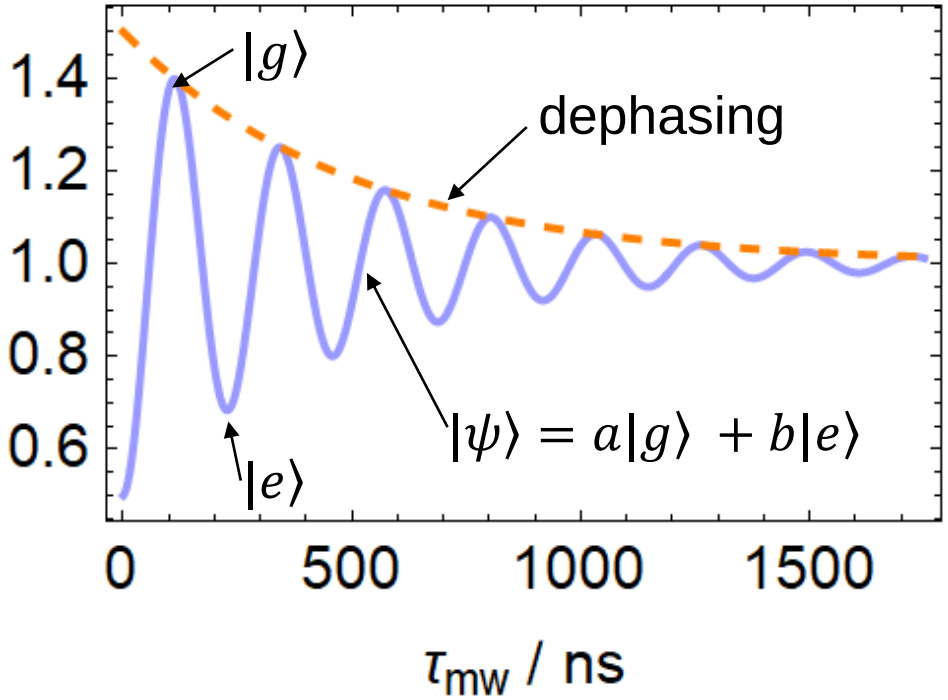
Detecting Rabi oscillation

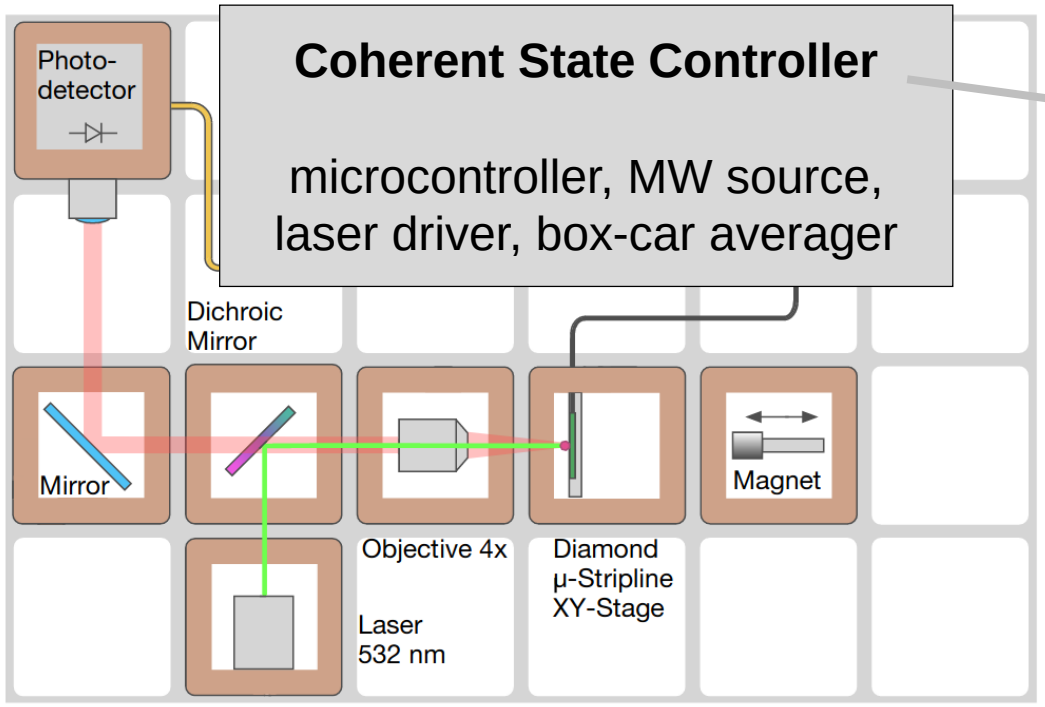


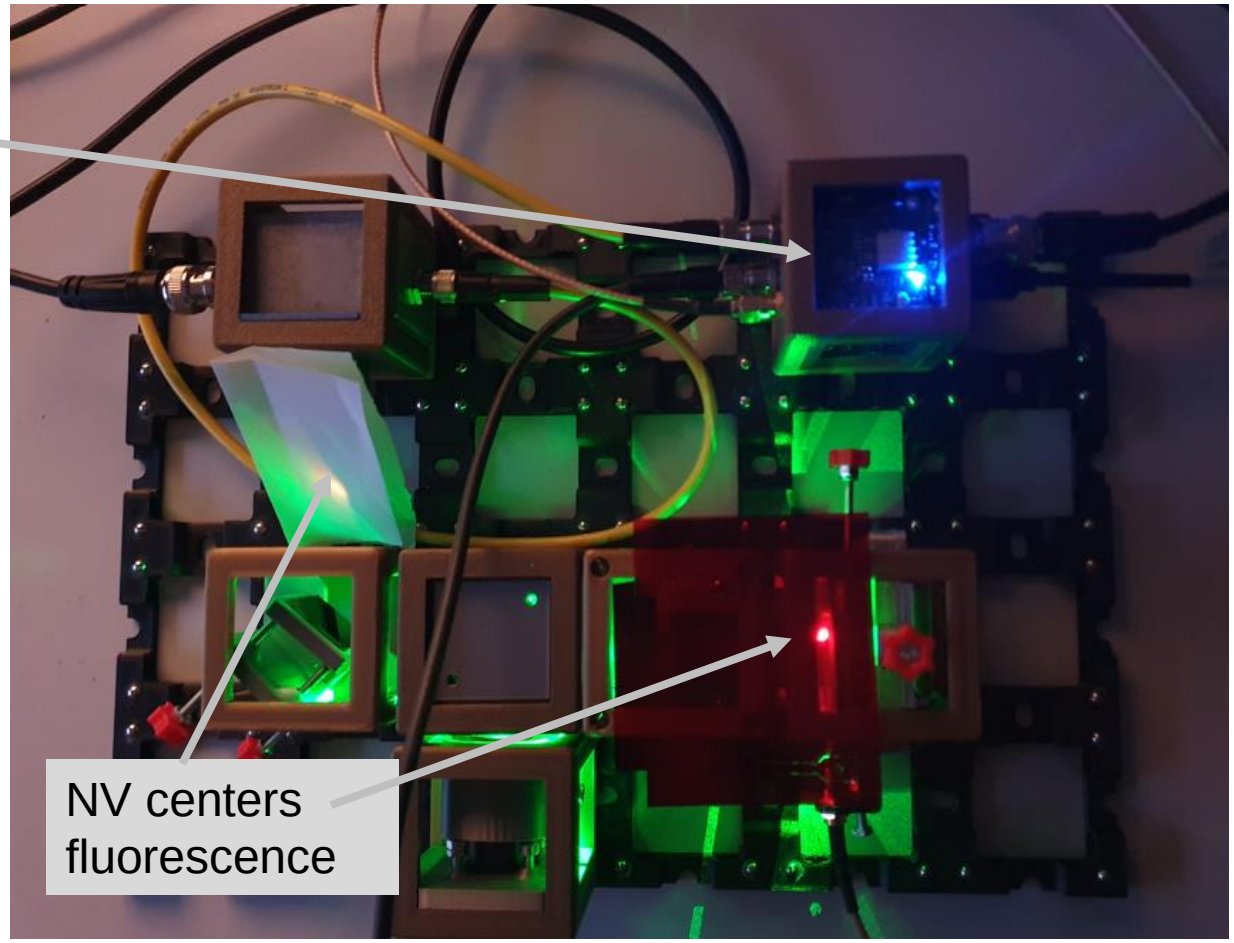


Varying length of MW pulse to drive the NV centers from a $|g\rangle$ into $|e\rangle$ and back.

Optical Setup

Optic cubes based setup for student labs – new setup





Costs below 500 Euros (80 000 ¥) for entire setup

Coherent State Controller

Electronics controlling pulse sequences and data acquisition

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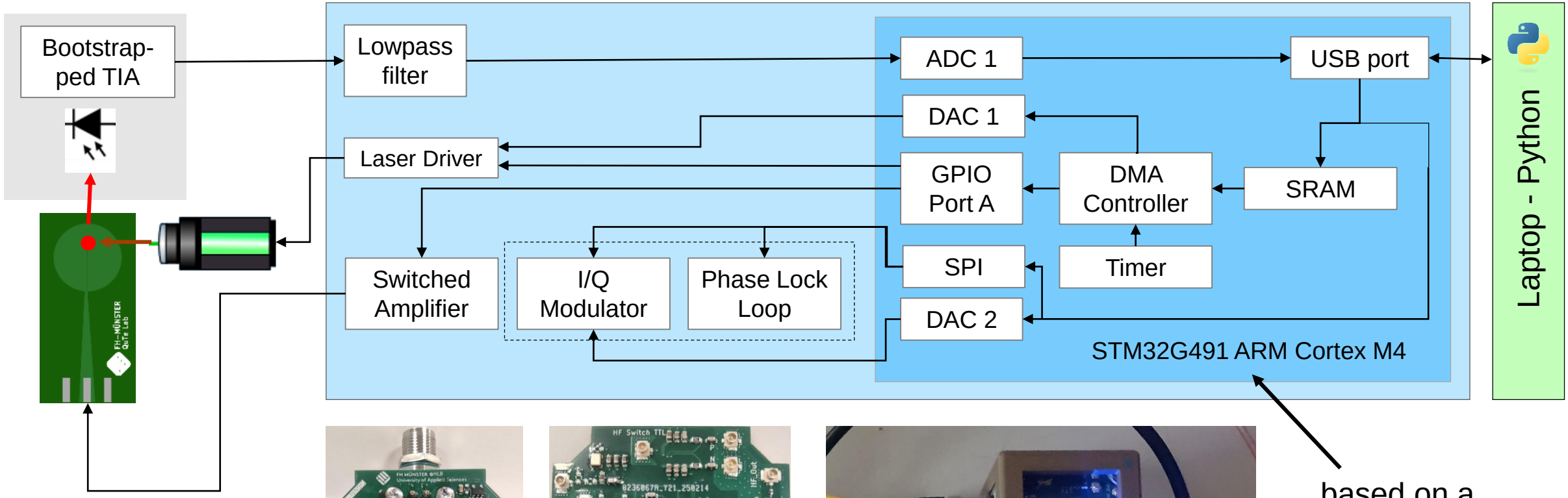
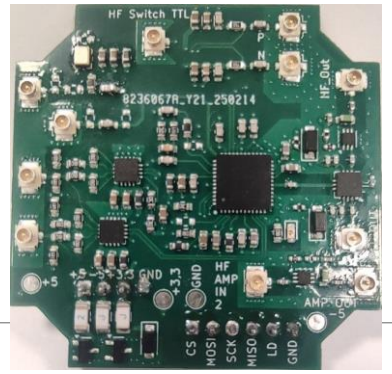
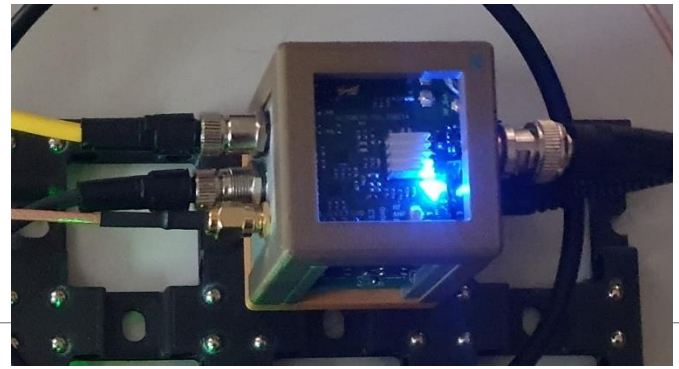




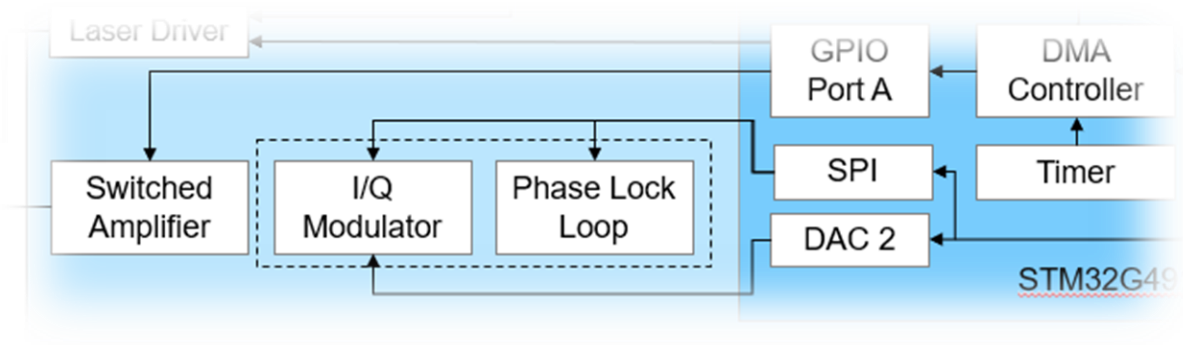


based on a microcontroller only!

(no FPGAs, no DSSs)

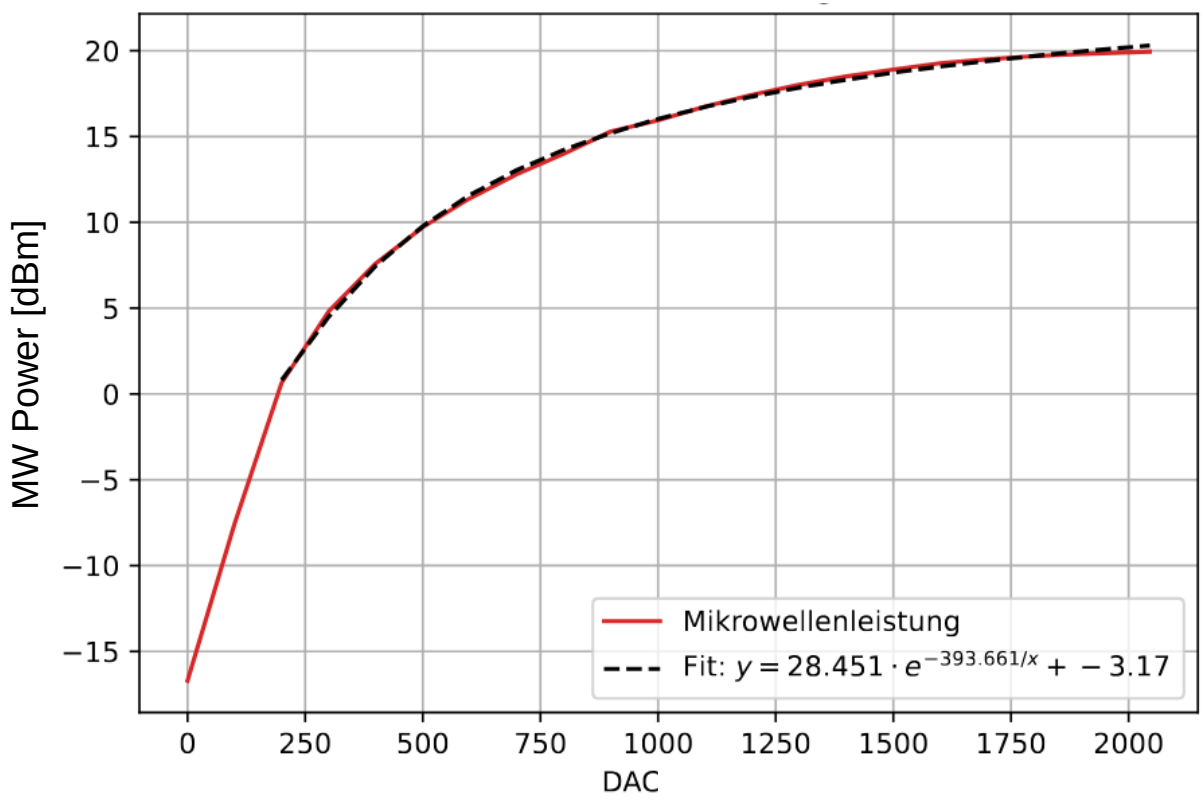
Microwave Source

Limits of microwave pulse width



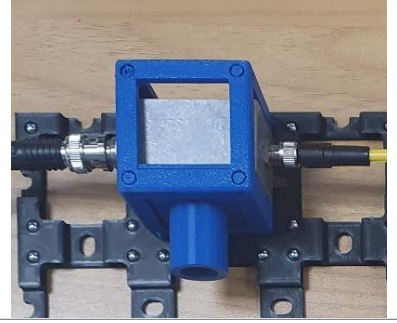
MW Pulse length limited to 53ns due the cycle speed of the microcontroller

→ no problem: changing the MW power to adjust the Rabi oscillation frequency



Fluorescence Detector

A simple boot strapping TIA circuit



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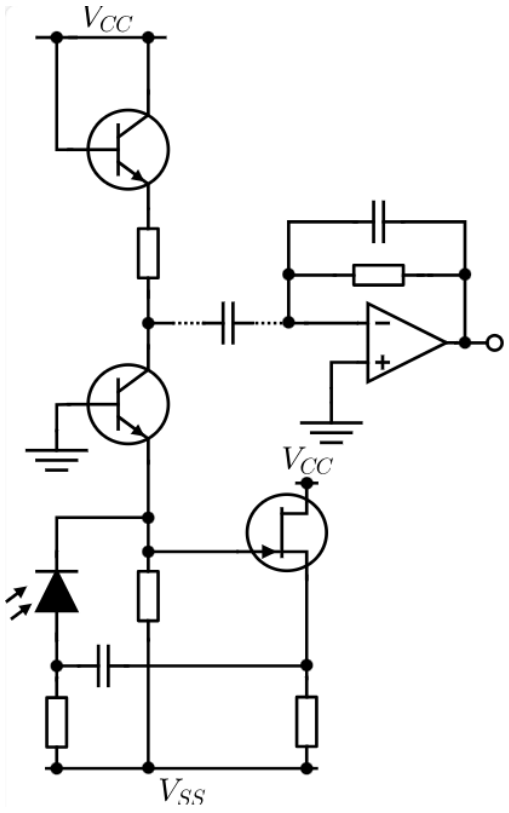

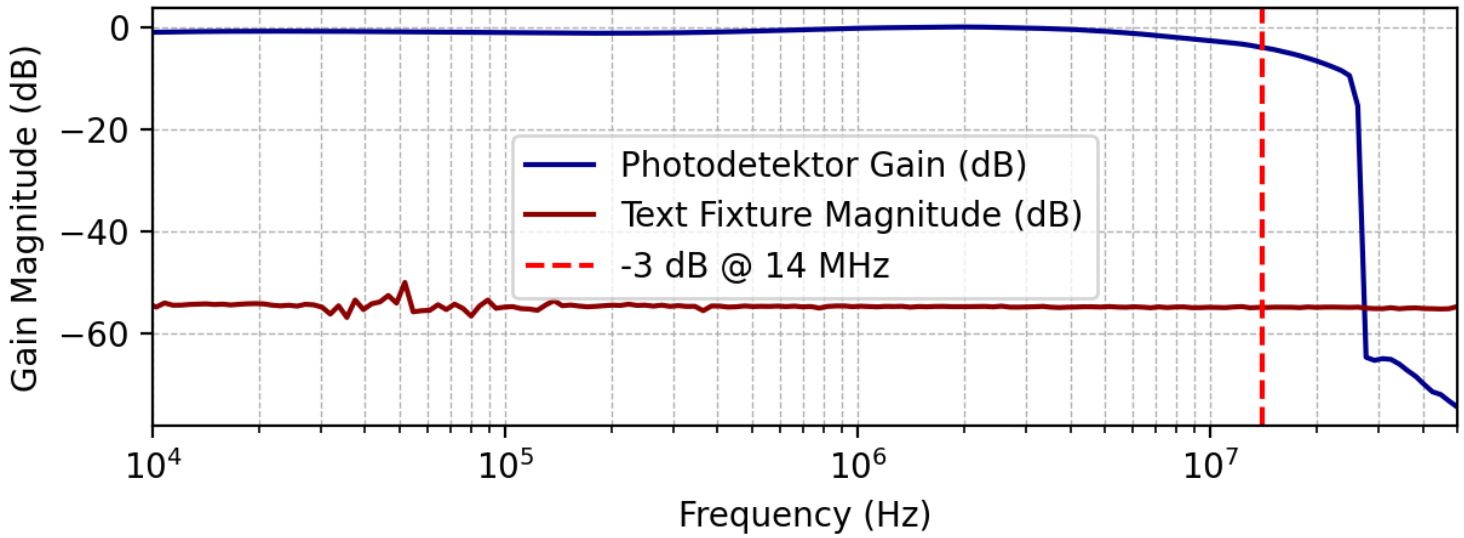

- Bootstrapping allows large photodiode (BPW43) while maintaining high frequency response
- 3dB cut-off frequency at 13 MHz - sufficient for coherent control

Green Diode Laser

Simple Laser driver circuit

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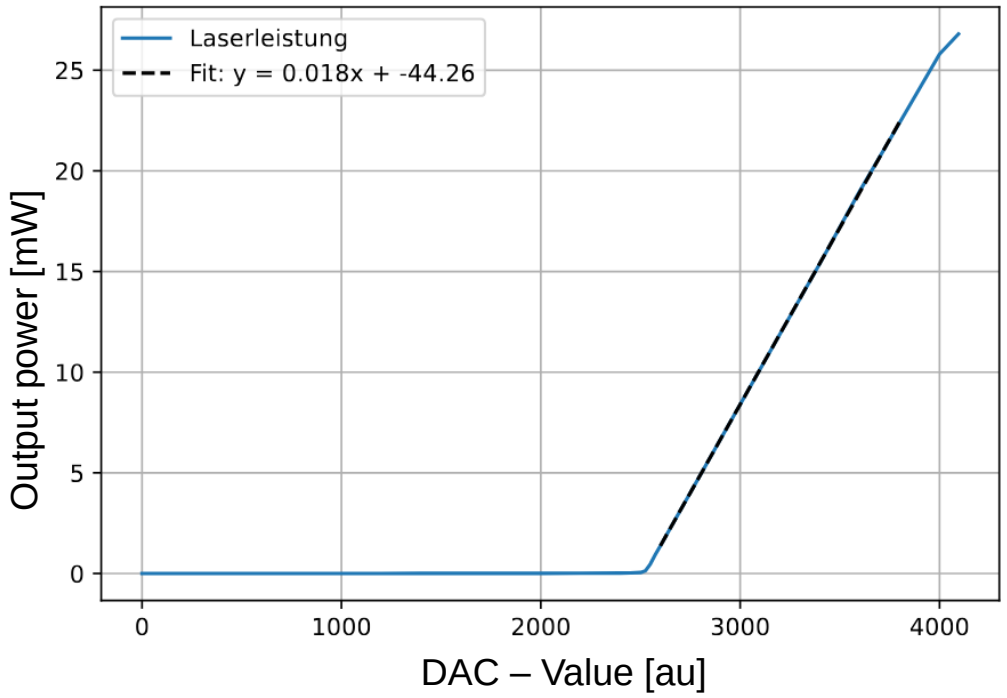
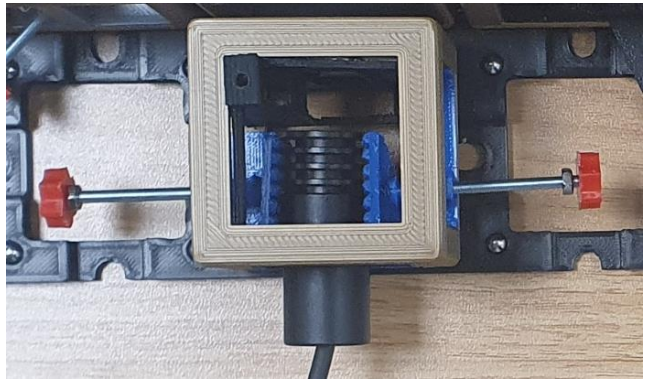
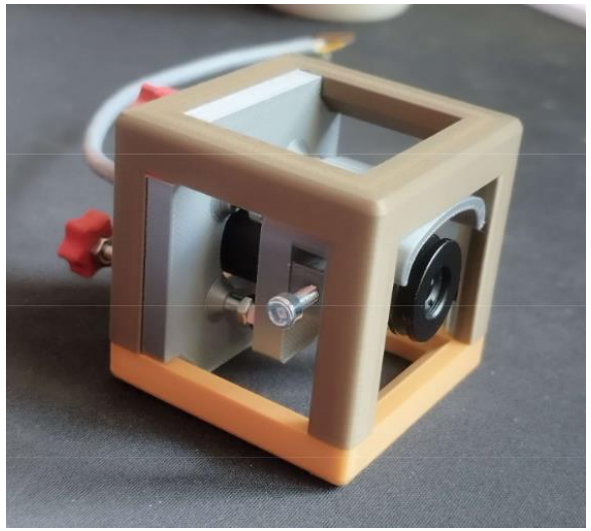
Laserdiode at 520 nm:

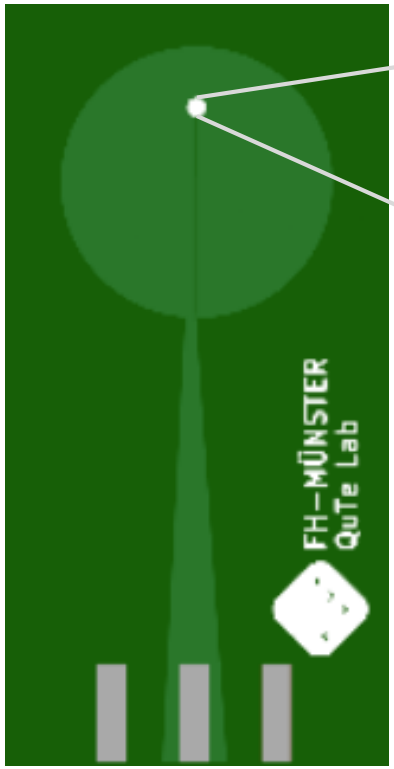
- PLT5 520
- ~ 20mW output power

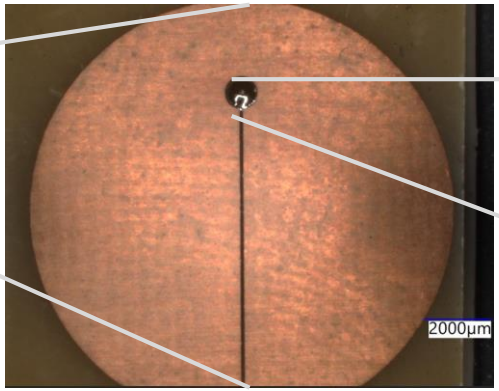


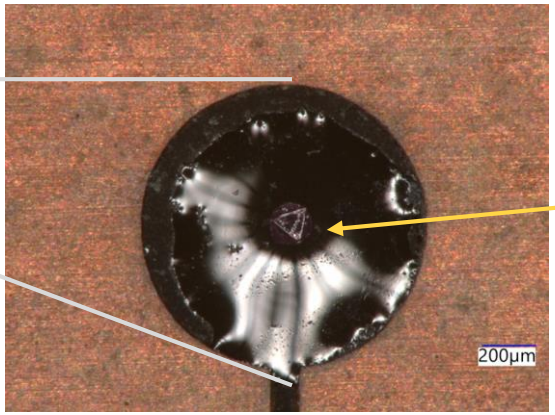




Antenna for Microdiamonds







LN3 Microdiamonds
(Adamas Nanodiamonds)
$\sim 150 \mu m$

Sasaki, et. al, Rev. Sci. Instrum. 87 (5), 053904

Measured Rabi - Oscillation

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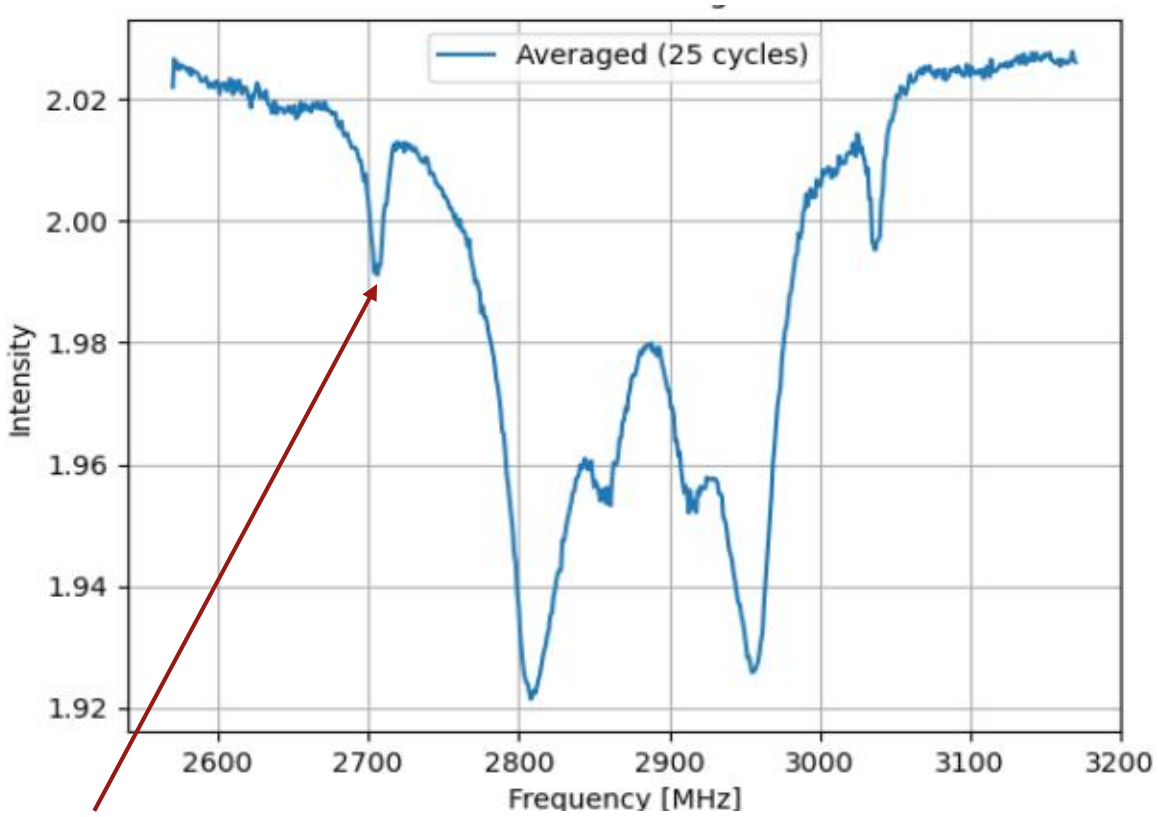
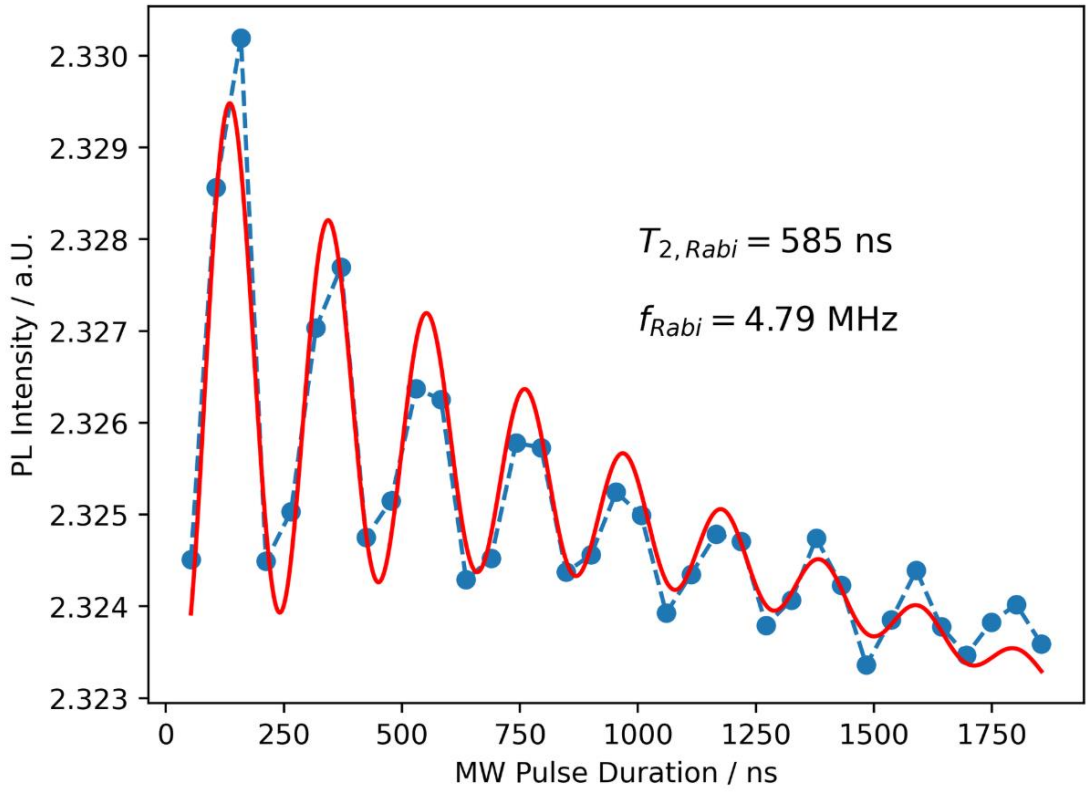
Results of the setup presented later in the workshop



choose a suitable resonance



Measured Rabi - Oscillation

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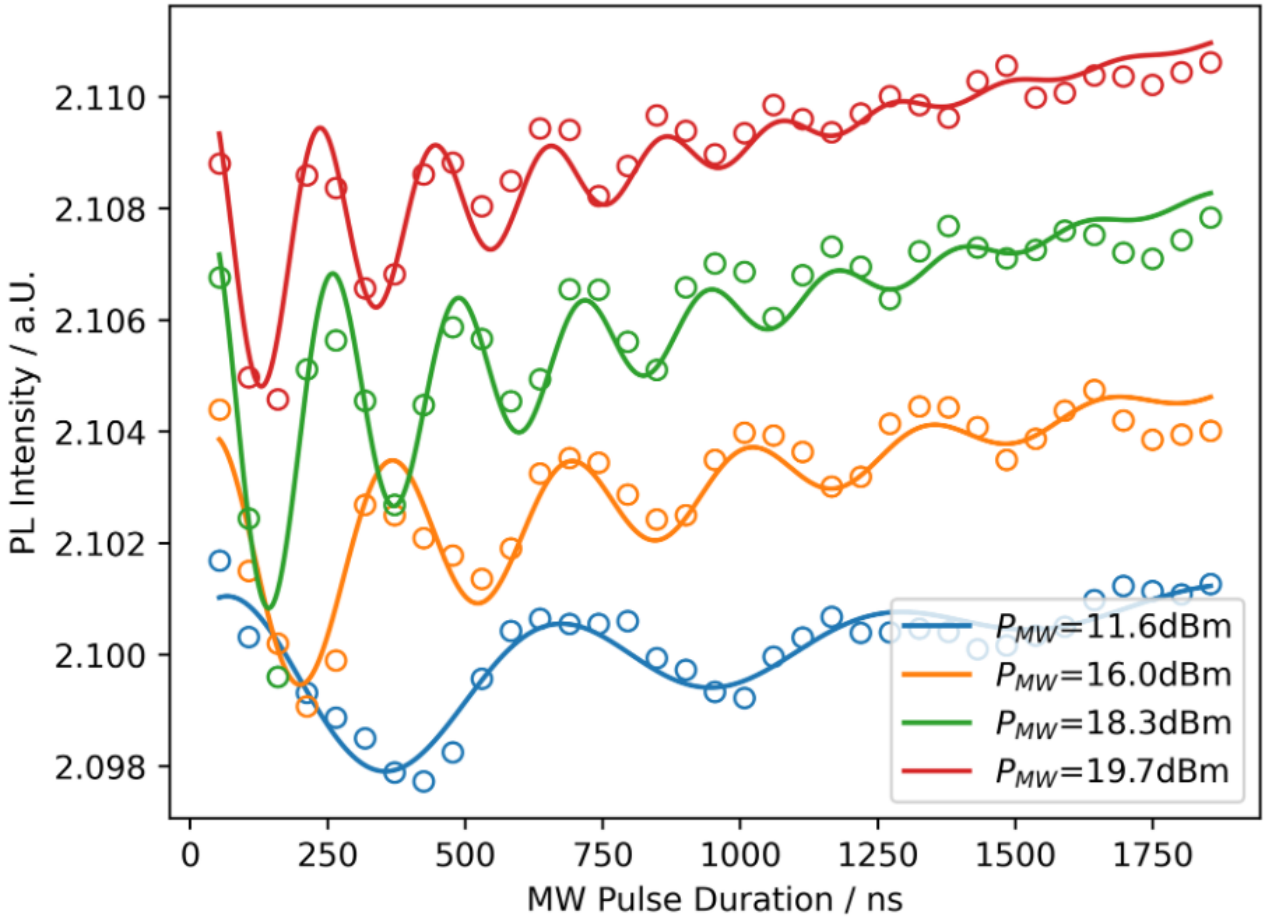
Results of the setup presented later in the workshop

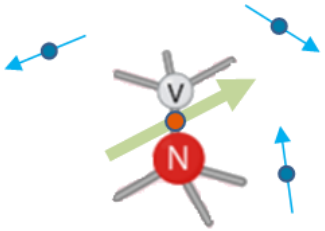


Reminder:

The Rabi oscillation frequency can be tuned by adjusting the MW power.

The limited minimal 53nm pulse length can be overcome to from π and $\frac{\pi}{2}$ pulses for application in quantum sensing and computing algorithm.

Longitudinal Spin Relaxation



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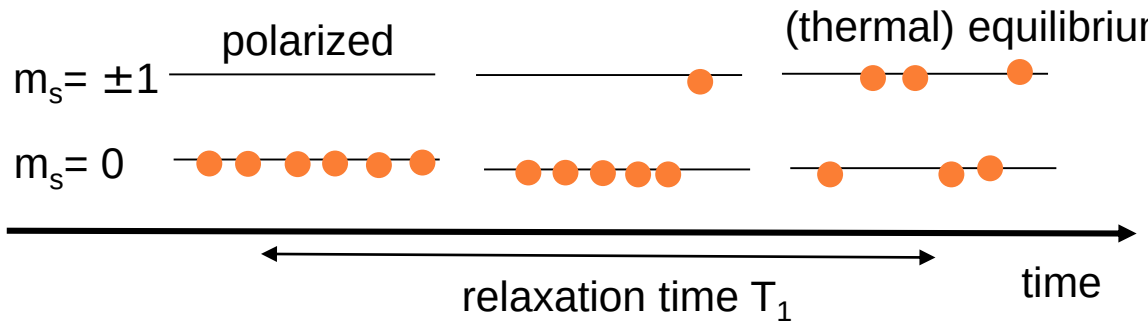
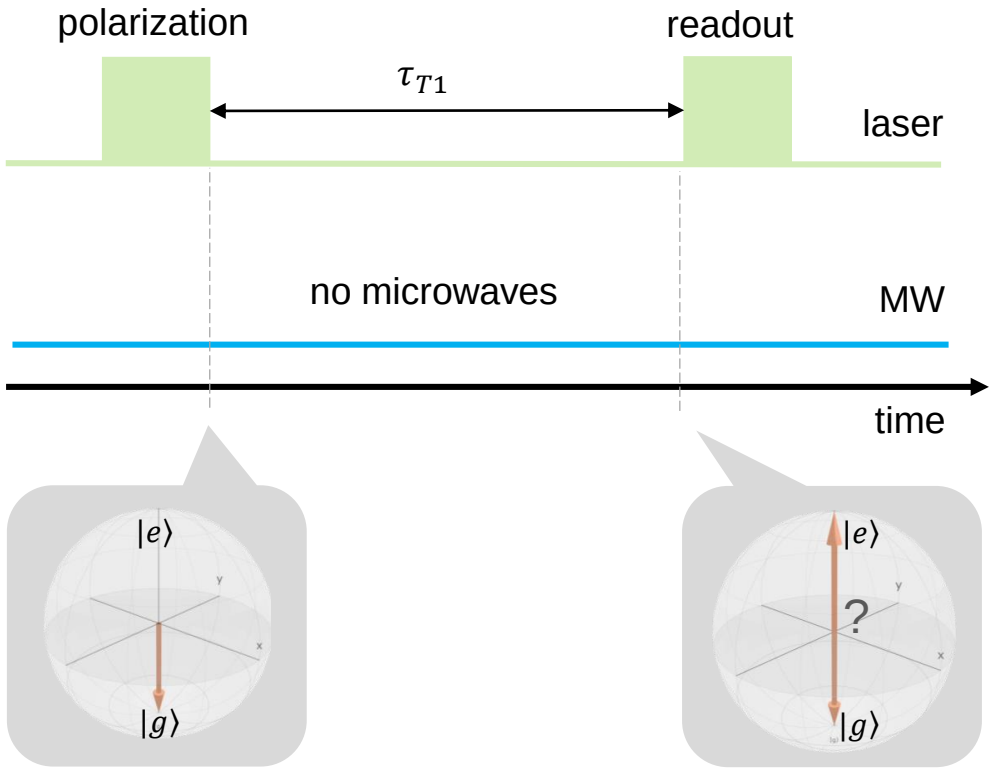
Detect spin-spin interaction



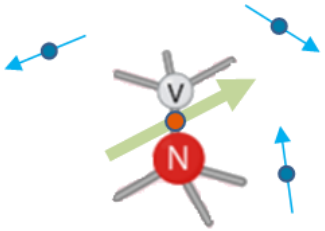
Surrounding spin bath interacts with the NV center spins and influences the relaxation time.

The exponential decay time can be measured.

Pulse Sequence



Longitudinal Spin Relaxation



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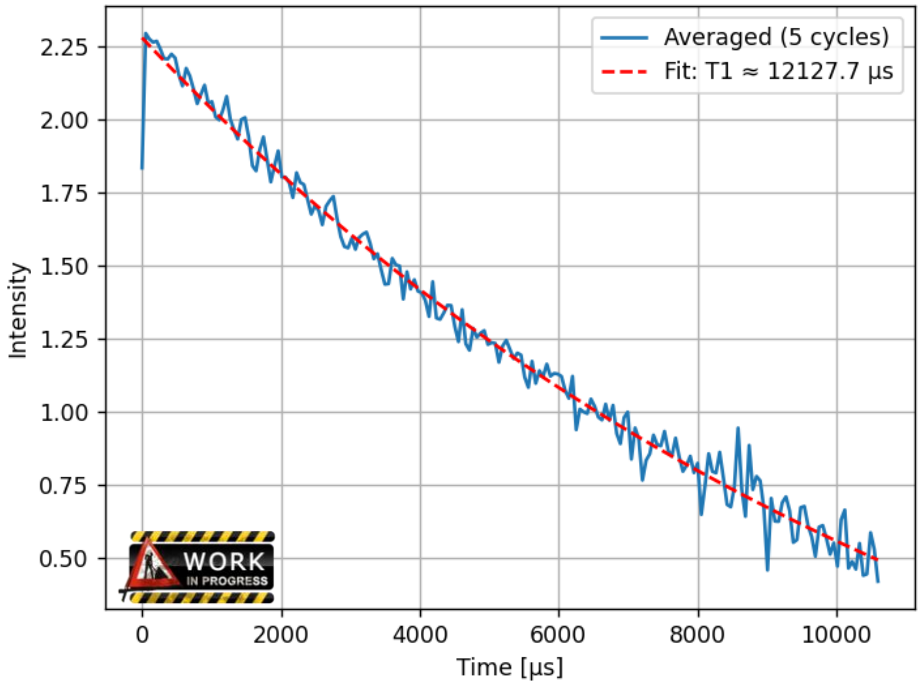
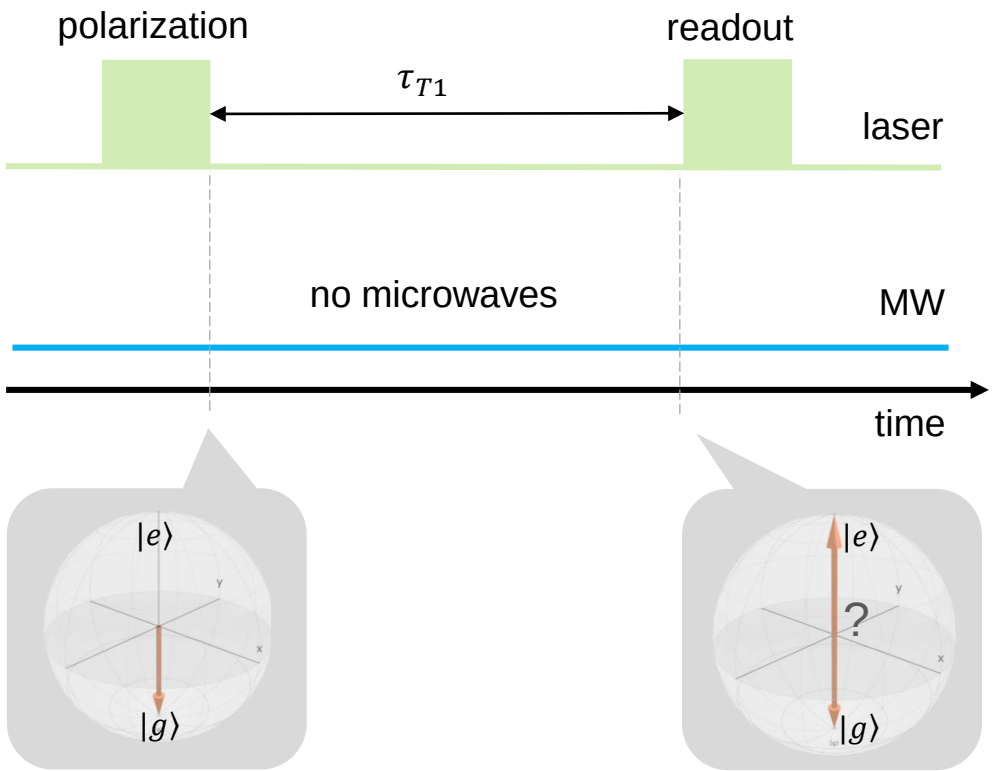
Detect Spin-Spin Interaction



Relaxation time for a microdiamond, with a small surface to volume ratio, is nearly constant.

However, nano diamonds are potential biomedical sensor.

Pulse Sequence



Quantumsensors Group @ FHM

The most important facts last, as well!

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Thank you for your Attention!!!

Enjoy the Workshop!