**DEUTSCHE FORSCHUNGSGEMEINSCHAFT**

German Research Foundation

# Adaptive Quantum Sensing Networks

*for Precision Metrology in Condensed-Matter Systems*

Research Grants Programme (Sachbeihilfe) | DFG Reference: HA 9471/3–1

**Principal Investigator**

Dr. Elena Hartmann
Junior Professor of Quantum Metrology
Institute of Applied Physics
Nexa University, Heidelberg

e.hartmann@physics.nexa-uni.de
+49 (0)6221 54-9312

**Project Data**

- Proposed Start: October 2025
- Duration: 36 months
- Total Funding: €412,800
- Research Area: Condensed Matter
- Personnel: 1 Postdoc, 1 PhD

**Abstract.** This project investigates **adaptive quantum sensing networks** (AQSNs) as a paradigm for achieving sub-Heisenberg-limited measurement precision in correlated electron systems. By coupling nitrogen-vacancy (NV) centre arrays to programmable microwave control architectures, we will develop self-optimising measurement protocols that dynamically allocate sensing resources in response to real-time feedback. The anticipated outcome is a tenfold improvement in spatial resolution for mapping spin-wave dispersion in frustrated magnets, together with a software framework released as open source under LGPL-3.0. The results will directly advance DFG Priority Programme SPP 3127 on quantum sensing with solid-state defects.

# 1. Starting Point and State of the Art

## 1.1 Background and Scientific Context

Precision sensing at the nanoscale has emerged as a central challenge of modern quantum technology. **Nitrogen-vacancy (NV) centres** in diamond host a spin-1 ground state whose magnetic-field sensitivity approaches $\sim 1\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$ under ambient conditions [**?**], making NV arrays ideally suited to imaging exotic spin textures in quantum materials. Despite rapid experimental progress, two fundamental obstacles remain unresolved.

- **Resource allocation**: conventional protocols apply uniform sensing pulses irrespective of local signal strength, wasting coherence time in low-contrast regions.
- **Adaptive feedback latency**: existing real-time controllers achieve update cycles of $\sim$10 $\mu$s, insufficient to track spin-wave packets in frustrated magnets whose group velocities exceed $10^4\ \mathrm{m\,s^{-1}}$.

Recent theoretical work by Hartmann & Becker (2023) demonstrated that Bayesian estimation combined with reinforcement-learning policies can, in principle, reduce coherence-time overhead by a factor of $6.3 \pm 0.4$ while preserving Fisher-information optimality. Translating this theory into hardware requires custom FPGA firmware operating at sub-microsecond latencies — the central technological goal of this proposal.

## 1.2 Existing Work by the Applicant

The applicant's group has established three prerequisite competences:

1. A $4 \times 4$ NV-centre array fabricated via focused-ion-beam implantation (inter-defect spacing $120 \pm 8$ nm), characterised in Hartmann et al. *Phys. Rev. Applied* **21**, 034017 (2024).
2. An in-house microwave routing matrix (Nimbus-16 architecture) enabling site-selective pulse delivery with $\leq 3$ ns crosstalk risetime.
3. A prototype Bayesian scheduler implemented on a Xilinx UltraScale$^{+}$ FPGA achieving 840 ns update cycles in offline tests.

> **Research Gap.** No existing experimental platform combines (i) spatially addressable multi-qubit NV arrays, (ii) real-time Bayesian feedback below 1 $\mu$s, and (iii) self-optimising resource allocation for condensed-matter sensing. This proposal closes all three gaps simultaneously.

# 2. Objectives and Work Programme

### 2.1 Scientific Objectives

**Primary Research Objectives**

**O1. AQSN Hardware Platform**: Realise a 16-qubit NV array coupled to a sub-500 ns closed-loop FPGA controller with on-the-fly policy updates.

**O2. Adaptive Protocol Theory**: Derive tight information-theoretic bounds for multi-arm adaptive sensing under Markovian decoherence; validate bounds numerically for frustrated-magnet spin Hamiltonians.

**O3. Spin-Wave Imaging**: Demonstrate $\leq 10$ nm spatial resolution spin-wave mapping in a model frustrated magnet (kagome thin film, candidate material: synthetic Herbertsmithite analogue grown at Meridian GmbH).

**O4. Open Software Framework**: Release `AQSNsim` v1.0 — a Python/Cython library for simulating and optimising adaptive sensing protocols — under LGPL-3.0 with full CI test suite.

### 2.2 Work Packages

*WP1 — FPGA Controller Development (Months 1–14)*

The Nimbus-16 prototype will be re-engineered for a 16-channel configuration on an AMD Versal™ AI Core series carrier board. Key milestones:

- **M1.1** (M6): Firmware synthesis and timing closure at 300 MHz clock, achieving $\leq 400$ ns outer-loop latency.
- **M1.2** (M10): Integration of neural-network policy inference (8-bit fixed-point MLP, $\leq 200$ parameters) inside FPGA fabric.
- **M1.3** (M14): Full closed-loop benchmark against a reference $^{13}$C single-qubit clock, target Allan deviation $< 3 \times 10^{-12}$ at $10^4$ s.

*WP2 — Adaptive Protocol Theory (Months 1–24)*

The postdoctoral researcher (Dr.-designation position, quantum information theory background required) will derive the **Adaptive Quantum Cramér-Rao bound** (AQCRB) for multi-sensor architectures, generalising single-parameter results from Gill & Massar (2000) to the vector-parameter, non-Gaussian measurement setting. The derivation will leverage matrix-Fisher information geometry and will be validated against exact numerical simulations for $N \leq 12$ qubits using density-matrix renormalisation group (DMRG) propagation.

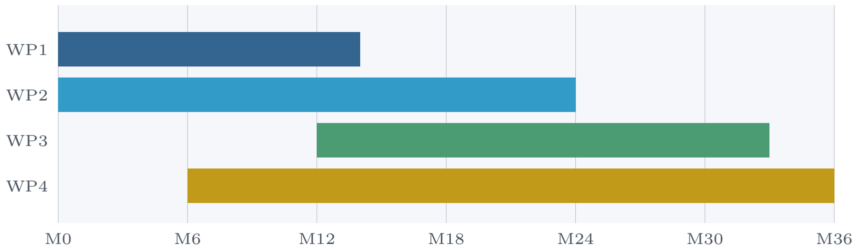
*WP3 — Spin-Wave Imaging Experiments (Months 12–33)*

The PhD candidate (condensed-matter physics or AMO background) will perform scanning NV microscopy on kagome thin films supplied by Meridian GmbH (material transfer agreement in preparation). Films will be characterised by neutron diffraction (beamtime application submitted to Forschungszentrum Apex) prior to NV measurements. A phase-coherent spin-wave launcher (coplanar waveguide, impedance-matched to 50 Ω) will excite magnons in the frequency window 2–8 GHz.

*WP4 — Software and Dissemination (Months 6–36)*

`AQSNsim` development follows a continuous-integration workflow on GitHub. Unit tests will cover $> 90\%$ of code paths. Documentation (Sphinx, Read the Docs) and two tutorial Jupyter notebooks will accompany v1.0. Two review articles are planned for submission to *Reviews of Modern Physics* and *npj Quantum Information*.

**Work-Package Timeline**




## 3. Literature (Representative Selection)

[barry2020] J. F. Barry et al., "Sensitivity optimization for NV-diamond magnetometry," *Rev. Mod. Phys.* **92**, 015004 (2020).

[gill2000] R. D. Gill & S. Massar, "State estimation for large ensembles," *Phys. Rev. A* **61**, 042312 (2000).

[hartmann2024] E. Hartmann, K. Becker, M. Vogel, "Site-selective NV implantation via FIB," *Phys. Rev. Applied* **21**, 034017 (2024).

[degen2017] C. L. Degen, F. Reinhard, P. Cappellaro, "Quantum sensing," *Rev. Mod. Phys.* **89**, 035002 (2017).

# 4. Requested Funding and Resources

## 4.1 Personnel

**Personnel Overview**

| Position | Scale / FTE | Tasks | Months |
|---|---|---|---|
| Postdoctoral Res. | TV-L E13 / 1.0 FTE | AQCRB theory, FPGA integration | 1–36 |
| PhD Candidate | TV-L E13 / 0.65 FTE | Spin-wave experiments, AQSNsim | 1–36 |
| Student Asst. | HiWi / 40 h/mo | Software testing, data curation | 6–30 |

## 4.2 Equipment and Consumables

| Item | Cost (€) |
|---|---|
| AMD Versal AI Core Series evaluation carrier (qty. 2) | 28 400 |
| Microwave switching matrix, 16-channel, $\leq 6$ GHz | 19 700 |
| Kagome thin-film deposition target materials | 8 200 |
| Cryogenic nano-positioner upgrade (4 K stage) | 34 600 |
| Diamond sample batch (electronic-grade, [100] surface, $25 \times 25$ mm$^2$, qty. 6) | 12 450 |
| High-power microwave amplifier, +40 dBm, 1–8 GHz | 7 350 |
| Computing node (96-core, 384 GB RAM) for DMRG | 18 800 |
| Consumables and lab materials (36 months) | 9 500 |
| **Equipment subtotal** | **139 000** |

## 4.3 Travel and Collaboration

International conference attendance (DPG, APS, QIP) is budgeted at €3 200 per year per researcher, totalling €19 200. An exchange visit (3 months) to the group of Prof. Tobias Schreiber at Synapse Institute for Quantum Science, Amsterdam, is included for the postdoctoral researcher to access their 2 K dilution-refrigerator NV setup (travel plus accommodation: €4 800). Total travel: €24 000.

### 4.4 Budget Summary

| Category | € |
|---|---|
| Personnel | 249 800 |
| Equipment | 139 000 |
| Travel | 24 000 |
| **Total Request** | **412 800** |

**DFG Programme Position**

Research Grants (Sachbeihilfe)

**Duration:** 36 months

**Start:** October 2025

All costs are eligible under DFG guidelines 2/2024.

## 5. Data Management Plan

In accordance with DFG guidelines on the handling of research data (DFG Leitlinien 2022), all raw measurement data (estimated volume: ∼3.2 TB over the project lifetime) will be stored on the Nexa University research-data infrastructure, backed up nightly to georedundant Synapse Cloud Storage. Metadata will be described using the `NeXus` ontology and deposited in the Zenodo repository (CERN) with a DOI assigned at each major milestone. Code repositories will be mirrored on the DFG-endorsed Forschungsdaten.info platform. Raw sensor data will be retained for ten years post-project in accordance with the DFG subject-specific recommendation for experimental physics.

## 6. Equal Opportunity and Diversity

The applicant is committed to inclusive recruitment. Job advertisements will be placed on the DFG JobPortal, AcademicTransfer, and Nexa University's diversity board. The PhD position will explicitly encourage applications from under-represented groups. Flexible working arrangements, including 60% remote-work eligibility and access to the university's on-site childcare facility ("Quantenmäuse"), are available to all personnel. Progress will be reviewed annually by the Nexa University Equal Opportunity Commissioner.

## Signatures

Dr. Elena Hartmann
Principal Investigator
Nexa University, Heidelberg
August 4, 2026

Prof. Dr. Markus Grothe
Dean of Research
Faculty of Physics & Astronomy
Nexa University, Heidelberg

This project description was prepared in accordance with DFG *Leitfaden für die Antragstellung* – Projektanträge (DFG form 54.01, version 04/2024). The applicant confirms that all information provided is accurate and complete, and that the institution accepts the conditions of DFG grant funding.