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Quantum sensing and metrology for market uptake (IA)

PROMISE

PROtotypes of Magnetic Imaging Systems for Europe

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= Deliverable D1.2 =

System specifications

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Reviewer name	Reviewer organisation	Reviewer role	Validation date
Enrico Manuzzato	FBK	WP1 leader	04.06.2025
Hans Bartling	TNO	T1.2 leader	11.06.2025
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Roman Pasek	ABIMI	Project Manager (PM)	19.06.2025

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11.06.2025	v0.1	WP, Task leaders, PC and PM for internal review
20.06.2025	v2.0	Submission at EC portal

Executive Summary

This document lists all instrument requirements to ensure measurements and enable the successful execution of the use cases. It is the second technical step to reach TRL7 at the end of PROMISE. For each use case, we list the requirements for the sample, image and measurement sensitivity, as well as additional requirements particular to that use case. From those use-case requirements, we then draw conclusions for the specifications of the instrument, which will be directing the system design in the next phase of the PROMISE.

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1. Introduction

The details of this deliverable have been discussed partially or in its totality by the following participants:

Name	Surname	Organisation
Abdellatif	Bachar	MF
Hans	Bartling	TNO
René	Böttcher	Airbus CRT
Lola	Boyano	UPV/EHU
Milan	Calic	MF
Estibaliz	Garrote	TEC
Johannes	Lang	DIA
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Enrico	Manuzzato	FBK
Rafael	Morales	UPV/EHU
Amaia	Rebollo	GSEMI
Xavier	Vidal	TEC
Amaia	Zurutuza	GSEMI
Alba	Centeno	GSEMI

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2. Requirements per use case

This section defines the requirements for the instrument in order to enable successful execution of each use case. In a later section, we will discuss the instrument specifications that follow from the individual use case requirements.

2.1. Graphene chips

Graphene chips are provided by GSEMI. The measurements will be compared with GSEMI's electrical quality control measurements, which gives average mobility of charge carriers information. These samples are related to T5.1.

		Comments
Magnetic requirements		
Magnetic resolution	10 µA → 60 nT	Based on 10 µA through infinite sheet
Total measurement time	1 hr	
Sensitivity	3 µT / $\sqrt{\text{Hz}}$	
Max. magnetic field	100 µA → 0.6 µT	
Dynamic range	4.0 GHz	
External magnetic field	~ 10 mT	To split NV transitions
Imaging requirements		
Spatial resolution	1 µm	
Field of view	200 µm x 200 µm	
Sample requirements		
Sample size graphene (length x width)	90 µm x 90 µm	Size of interest to image
Sample size full chip (length x width x height)	3 mm x 3 mm x 1 mm	
Other requirements		
Laser power	< 1 mW / µm^2	
DC current	< 100 µA, better < 25 µA	

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2.2. Al alloys and conductive samples

Aluminium alloys and conductive samples are provided by Airbus CRT. These samples are related to T5.2. The samples will be compared with data obtained by the scanning vibrating electrode technique (SVET), which is one of the main techniques employed by Airbus CRT for R&D-related characterization of localised corrosion. This technique requires long duration measurements, and the sample position is typically 200 μm away.

For the requirements, we focus on samples 1-3 (see D1.1).

		Comments
Magnetic requirements		
Magnetic resolution	100 pT	Rough estimate based on 100 μA / cm^2 at 200 μm above surface, so > 100 μA / cm^2 at 20 μm. The signal may be stronger.
Total measurement time	~ 1 hr	
Sensitivity	~ 10 nT / $\sqrt{Hz}$	
Max. magnetic field	~ 100 nT	
Dynamic range	4.0 GHz	
External magnetic field	~ 10 mT	To split NV transitions
Imaging requirements		
Spatial resolution	1 μm	Cu particles 1-20 μm
Field of view	200 μm x 200 μm	Minimal value
Sample requirements		
Sample size region of interest (length x width)	200 μm x 200 μm	Size of interest to image, minimal value. Optionally 1000 μm x 1000 μm.
Sample size Al alloy (length x width x height)	2 cm x 2 cm x 1 mm	
Other requirements		
Electrolyte incorporation	20 μm to 100 μm of electrolyte on sample	To generate a corrosion current

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2.3. Micromagnets

Arrays of micromagnets are provided by MF. These samples are related to T5.3. The aim is to reach a spatial resolution of the magnetic field below 15 µm, which is the current resolution obtained with CMOS camera.

		Comments
Magnetic requirements		
Magnetic resolution	0.1 mT	Expectation of signal to be measured
Total measurement time	1 s	
Sensitivity	100 µT / $\sqrt{\text{Hz}}$	
Max. magnetic field	~ 150 mT	At 10 µm above the surface, estimated from 100 mT at 50 µm above the surface
Dynamic range	10.0 GHz	
External magnetic field	~ 10 mT	To split NV transitions
Imaging requirements		
Spatial resolution	< 1 µm	
Field of view	500 µm x 500 µm	
Sample requirements		
Sample size region of interest (length x width x height)	300 µm x 300 µm x 50 µm	Size of interest to image
Sample size (length x width)	30 mm x 30 mm	Ideally up to 200 mm diameter wafer
Other requirements		
NV layer thickness	<= 100 nm	To avoid a magnetic field gradient over the NVs > 0.1 mT
NV-magnet distance should be known		To characterize the absolute magnetic field at a certain distance

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2.4. Microdisks and nanostructures

Microdisks and nanostructures are provided by UPV/EHU. These samples are related to T5.3. Measurements will be compared with simulations. Moreover, some sample will be benchmarked with vibrating sample magnetometer and magnetic hysteresis loop.

		Comments
Magnetic requirements		
Magnetic resolution	0.1 – 30 mT	At 0.5 – 1 µm from the microdisk
Total measurement time	~ 10 s	
Sensitivity	100 µT / $\sqrt{\text{Hz}}$	
Max. magnetic field	100 mT	
Dynamic range	6.0 GHz	
External magnetic field	100 mT	To reach saturation
Imaging requirements		
Spatial resolution	1 µm	Ideally < 500 nm
Field of view	500 µm x 500 µm	
Sample requirements		
Sample size microdisc (diameter)	200 nm – 4 µm	Single structures have sizes ranging from 200 nm x 800 nm to 4 µm x 4 µm
Sample size full chip	~ size of diamond	
Other requirements		
NV layer thickness	< 300 nm	
AC magnetic field	10 mT @ 1-20 Hz	Direction is perpendicular to the diamond. Only necessary for microdisks.

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2.5. Skin cancer and healthy cells

Skin cancer cells and healthy cells as control are provided by the Faculty of Medicine (SM) of the UPV/EHU. These samples are related to T5.4. Two of the three different groups of samples are combined with the above-mentioned nanostructures, which are part of T5.3. The measurements will be compared with their current approach using SQUID and confocal microscopes for the viability of the internalization of the nanostructures by the different cell types. Attention should be paid to whether changes in cell counts and cell viability come from growth conditions on the diamond surface compared to the surface used for SQUID and confocal measurements.

		Comments
Magnetic requirements		
Magnetic resolution	0.1 – 30 mT	
Total measurement time	~ 10 s	
Sensitivity	100 µT / $\sqrt{\text{Hz}}$	
Max. magnetic field	100 mT	
Dynamic range	6.0 GHz	
External magnetic field	10 mT	To reach saturation for microdisks. Can be as high as 100 mT, but we will focus on camples with M saturation below 10 mT external magnetic field.
Imaging requirements		
Spatial resolution	1 µm	
Field of view	500 µm x 500 µm	100 µm x 100 µm to analyse cell details
Sample requirements		
Sample size cell (diameter)	10 µm – 60 µm, most probably ~ 20 µm	
Sample size full chip	~ size of diamond	The diamond will later be integrated in chamber with dimensions of ~ few cm.
Other requirements		
NV layer thickness	< 300 nm	
AC magnetic field	10 mT @ 1-20 Hz	Direction is perpendicular to the diamond. Only necessary for microdisks.

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3. Instrument specifications

In this section, we distil the instrument specifications from the use-case requirements discussed in the previous sections. In making this translation, we assume that we want the same or very similar instruments for all the use cases. The instrument should therefore be able to fit all samples, cover all field-of-views, use the same camera, etc. An important requirement that may vary per use case is the diamond. For example, different NV layer thicknesses and concentrations might be appropriate depending on the requirements of each use case.

3.1. Sample requirements

Sample requirements		*Comments*
Sample size to inspect (length x width)	30 mm x 30 mm	Ideally up to 200 mm diameter wafer, but since that is only required for one use case, we do not consider that initially. Note that additionally we might need room for a chamber for biological cells.

3.2. Imaging requirements

Imaging requirements		*Comments*
Spatial resolution	1 µm	
Field of view	500 µm x 500 µm	

3.3. Magnetic requirements

Magnetic requirements		*Comments*
Sensitivity	Airbus CRT: 10 nT / $\sqrt{\text{Hz}}$ Other: 1 µT / $\sqrt{\text{Hz}}$	
Max. magnetic field	200 mT	
Dynamic range	10.0 GHz	Microwave frequencies
External magnetic field	~ 10 mT	To split NV transitions

3.4. Microwave requirements

Microwave requirements		*Comments*
MW amplitude (Rabi frequency, average over field-of-view)	20 MHz	
MW homogeneity in field-of-view	< 10%	

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3.5. Diamond requirements

Here, we present the diamond requirements per use case, as we may use different diamonds for different use cases. These are first indications. More detailed diamond specifications will be decided upon during the design phase in WP2.

General diamond requirements		*Comments*
^{15}N enriched?	Yes, ideally	
^{12}C enriched?	Yes, ideally	For good sensitivity
Diamond thickness	100 µm	We aim for membranes to minimize spherical aberrations and get a high-quality image. A thickness below 100 µm would be a first goal but ideally, we will need 10 µm. The handling of the membrane can pose an issue. Note that this may not be necessary for all use cases, but particularly for those that require good spatial resolution.

GSEMI		*Comments*
NV layer concentration	As high as possible without deteriorating T_2^*	
NV layer thickness	~ 1 µm	For good sensitivity

Airbus CRT		*Comments*
NV layer concentration	As high as possible without deteriorating T_2^*	
NV layer thickness	~ 1 µm	Ideally thicker, to increase sensitivity

MF		*Comments*
NV layer concentration	As high as possible without deteriorating T_2^*	
NV layer thickness	<= 100 nm	To avoid a magnetic field gradient over the NVs > 0.1 mT

UPV/EHU: magnetic materials		*Comments*
NV layer concentration	As high as possible without deteriorating T_2^*	
NV layer thickness	< 300 nm	For good spatial resolution

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UPV/EHU: cells		
NV layer concentration	As high as possible without deteriorating T_2^*	
NV layer thickness	< 300 nm	For good spatial resolution

3.6. Camera requirements

We now discuss the requirements for the camera. First, we consider the expected photon flux at the camera. Assuming a laser power of 5 W, a 500 µm field-of-view, a 2% collection efficiency, a 5% quantum efficiency for the camera, 10^6 µm^{-2} NV area density, 40 µm pixel size, magnification 50x, we would get a per-pixel photon count rate of ~ 160 MHz. If instead the magnification is 20x (10x), we would get a per-pixel photon count rate of ~ 1 GHz (~ 4 GHz). Therefore, in 1 µs, one would expect to observe some hundred(s) photons. This does not serve as a strict requirement for the camera, but as an indication of what can be expected.

In order to combine a 500 µm field-of-view with 1 µm spatial resolution, the camera would need at least 500 x 500 pixels. If that is not possible, it is necessary to either reduce the field-of-view, which is possible for the *GSEMI*, *Airbus CRT* and *UPV/EHU* use case or reduce the spatial resolution, which may be the better way to go for the *MF* use case.

For pulsed operation, typical time scales of an experimental repetition (laser + MWs) are ~ 100-200 µs (except for relaxation, in which case it is ~ ms). Given that timescale, the readout time of the camera should ideally be comparable to or smaller than that. If that is not possible, the camera readout time should be as small as possible. In order to optimise the NV readout time, the camera exposure should be able to be chosen with ~ 50 ns accuracy. Typical exposure times will be in the ~ 300 ns to few µs regime.

For continuous operation, during which the laser and MWs are on simultaneously, typical time scales of an experimental repetition should be much larger than or comparable to the camera readout time of ~ 200 µs, which gives 10^4 - 10^5 photons, requiring > 14 bits-per-pixel.

Camera requirements		
Number of pixels	>= 200 x 200	
Readout time camera	200 µs	Ideally shorter
Pixel size	40 x 40 – 50 x 50 µm^2	This is set
Per-pixel photon count rate	~ 100s of MHz	Estimate of the per-pixel photon count rate for a relatively high-density NV sample
Sensor exposure time	Continuous: > 200 µs Pulsed: ~ 300 ns – 10 µs	
Sensor exposure setting accuracy	~ 50 ns	
Bits-per-pixel	Continuous: > 14 bbp Pulsed: 8-10 bbp	
Number of readout bins	> 3	
Readout bin time	> 100 ns	

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3.7. Other requirements

Other requirements	*Comments*
Computer-controllable stages	To allow for automation and larger field-of-views
Pulsed and continuous-wave operation	Mainly CW-ODMR and T1 relaxation
Compatibility with multiple cameras	
Allow simple exchange of objectives or a rotator stage	To exchange field-of-view for spatial resolution
Temperature stability	< 2 °C
Interlock on the instrument for laser safety	
Other potential requirements	
Non-magnetic objective	
Flat-top illumination	As opposed to Gaussian illumination

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4. Conclusions

In conclusion, we have discussed the requirements for PROMISE per specific use case and have deduced the requirements for the instrument to address each use case. This serves as important input for the system design, which follows in the next work packages.

5. Degree of progress

This deliverable is a 100% complete. The specification and requirements of WP1 to define prototypes are completed.

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