WHITE PAPER

Use cases for Qnami ProteusQ™ Imaging Modalities

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Scanning NV magnetometry has been successfully deployed to image a vast variety of magnetic materials. However, when approaching a novel compound with a scanning NV system it can be challenging to pick the appropriate methodology. In this note, we discuss how to use the Qnami ProteusQ™ imaging modalities for different types of magnetic samples. A summary is given in Fig.1, where we relate expected surface field strengths to the Qnami ProteusQ™ imaging modalities. In Fig.2 we show contemporary device architectures and sought-for physical phenomena therein, and explicitly refer to scientific work created with scanning NV and Qnami ProteusQ™ technology. Finally, in Fig.3, we provide representative measurement examples for the available modalities.

The strength of the magnetic field that a sample generates in the vicinity of its surface is the key parameter for choosing the appropriate measurement modality. This parameter is given by the magnetic field strength $|\mathbf{B}|$ that the NV center experiences in its spin quantization axis[1]. A typical distance between the NV center and the sample surface is $\sim 10\,\text{nm}$.

If the sample of interest has ferromagnetic order, one may expect strong magnetic fields at its surface. For example, a ferromagnet of 1 nm thickness and saturation magnetisation of 1 MA/m will exhibit stray field strengths up to 40 mT 10 nm above a domain wall. Such large fields quench the fluorescence of the NV center. Especially in the vicinity of domain boundaries, the magnetic field direction quickly changes, thus $\mathbf{B}$ projected on the NV axis can take large values. This will lead to

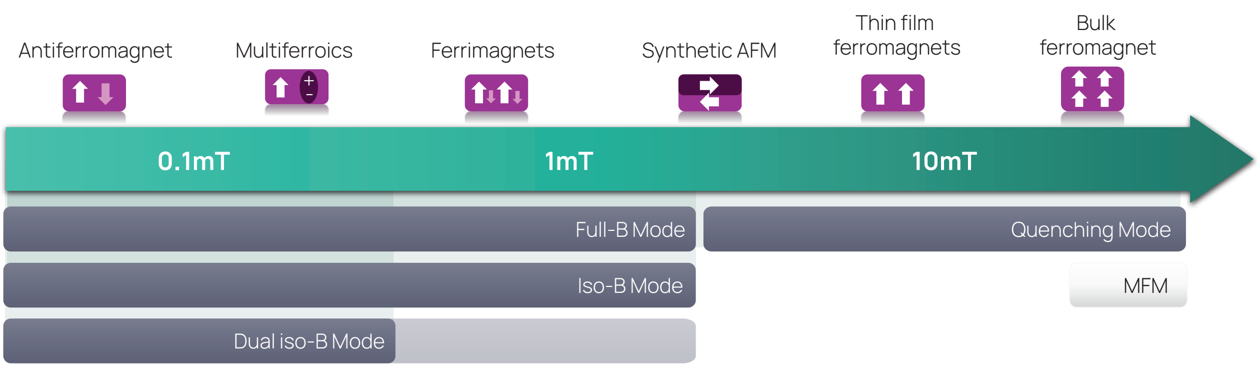

Fig. 1: Surface Magnetic fields and Qnami ProteusQ™ imaging modalities. The graphic illustrates typical magnetic fields at the NV-center height ($\sim 10\,\text{nm}$ from the sample surface) that are expected for distinct magnetic phases. The magnetic field range of the imaging modalities serves as a guide. Magnetic force microscopy (MFM) serves as a reference point for the reader, which becomes a sample invasive technique below 10mT.

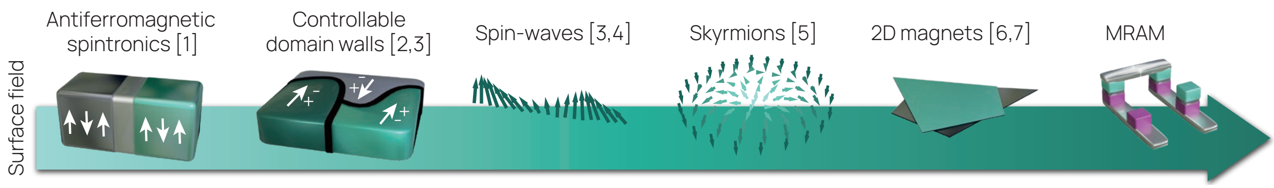

Fig. 2: Examples of physical phenomena and emerging spin technologies. The publications we refer to are based on measurements recorded with scanning NV technology (mostly using Qnami ProteusQ™): Antiferromagnetic spintronics[2], controllable domain walls[3, 4], spin-waves[4, 5], skyrmions[6], 2D crystals[7, 8] and thin films for MRAM

a quenching of the fluorescence (for details see [1]). This contrasting mechanism is encoded in the Qnami ProteusQ™ acquisition software, LabQ, through the quenching mode. Thus, to characterize samples with significant surface magnetic fields such as ferromagnets, 2D ferromagnets or synthetic antiferromagnets it is advisable to preform quenching mode measurements. They provide fast insights into the domain structure (200 × 200 pixels recorded in 7 min). An example is shown in Fig.3a.

Ferrimagnets and multiferroic materials typically generate smaller surface magnetic fields, below 2 mT. In this range, different qualitative and quantitative imaging modalities can be used.When measuring such samples, a first overview image is obtained in the iso-B mode. This mode provides contours at a chosen magnetic field and will give a first impression on the magnetic structure of the sample (100 × 100 pixels recorded in 2 min). In order to obtain quantitative data, measurements are performed in the full-B mode which, however, is much slower (100 × 100 pixel recorded in 3 h). An interesting alternative is the dual iso-B mode that can provide quantitative information if the sample fields are sufficiently small (~ 0.2 mT) and qualitative information for larger fields. Data is recorded in only 4 min for the above scan area.

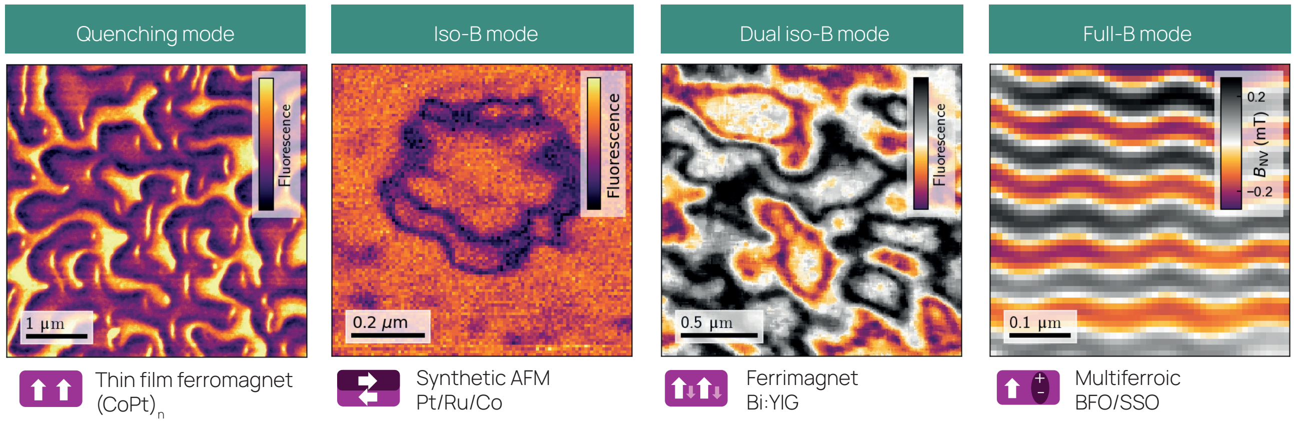

Fig. 3: Data gallery recorded with Qnami ProteusQ™ . The examples range from domain walls in thin-film ferromagnets to spin-waves in multiferroic materials.

Antiferromagnetic materials also give measurable signals for NV magnetometry. This may be unexpected since their magnetic moments alternate on an atomic scale, an order of magnitude below the spatial resolution of scanning NV microscopes. However, the presence of uncompensated magnetic moments is not uncommon in antiferromagnets, they lead to weak stray magnetic fields on their surface. In fact, all antiferromagnetic samples measured in Qnami's AppLab exhibited measurable stray magnetic fields so far. Their typical amplitudes are $|\mathbf{B}| < 0.3$ mT, thus in a well suited range to employ the full-B , iso-B and dual iso-B modes.

- For ferromagnets, the quenching mode is suited to measure domain walls.
- For ferrimagnets and antiferromagnets, a quick overview can be obtained with the iso-B mode. Quantitative data is recorded in the full-B and in the dual iso-B mode.

Further reading

- Qnami technote on measuring magnetic field with NV centers [1]
- Qnami white-paper explaining the SNVM data [9]
- Qnami introduction to NV magnetometry [10]

References

1. Qnami AG, *Fundamentals of magnetic field measurement with NV centers in diamond*, (2020) https://qnami.ch/wp-content/uploads/2020/12/2020-12-07-Qnami-TN1-The-NV-center-1.pdf.

2. T. Kosub, M. Kopte, et al., "Purely antiferromagnetic magnetoelectric random access memory", Nature Communications **8**, 1–7 (2017).

3. A. Finco, A. Haykal, et al., "Imaging non-collinear antiferromagnetic textures via single spin relaxometry", Nature Communications **12**, 1–6 (2021).

4. J. Y. Chauleau, T. Chirac, et al., "Electric and antiferromagnetic chiral textures at multiferroic domain walls", Nature Materials **19**, 386–390 (2020).

5. A. Haykal, J. Fischer, et al., "Antiferromagnetic textures in BiFeO3 controlled by strain and electric field", Nature Communications **11**, 1–7 (2020).

6. K. G. Rana, A. Finco, et al., "Room-Temperature Skyrmions at Zero Field in Exchange-Biased Ultrathin Films", Phys. Rev. Applied **13**, 44079 (2020).

7. F. Fabre, A. Finco, et al., "Characterization of room-temperature in-plane magnetization in thin flakes of $CrTe_2$ with a single-spin magnetometer", Phys. Rev. Materials **5**, 034008 (2021).

8. Q. C. Sun, T. Song, et al., "Magnetic domains and domain wall pinning in atomically thin CrBr3 revealed by nanoscale imaging", Nature Communications **12**, 1–7 (2021).

9. Qnami AG, *Qnami ProteusQ™ imaging modalities*, (2021) https://qnami.ch/wp-content/uploads/2021/08/Qnami_TN_Imaging_Modalities.pdf.

10. Qnami AG, *NV Magnetometry*, (2020) https://qnami.ch/wp-content/uploads/2020/07/Qnami_WhitePaper1_NV_magnetometry-5.pdf.

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