Technical Note

Qnami ProteusQ™ Imaging Modalities

Related products: Qnami ProteusQ™ , MicrowaveQ™ , Quantilever™MX

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At one glance

The Qnami ProteusQ™ measurement software LabQ is equipped with the quenching, full-B, iso-B and dual-isoB imaging modality. We first discuss the quenching mode and then the other modes which are based on optically detected magnetic resonance (ODMR). While the quenching mode is best suited to image samples with large magnetic stray fields, the ODMR based modes are ideal to resolve µT-mT fields. The full-B mode records detailed quantitative data while the iso-B mode is used to gain a quick overview. The dual-isoB mode provides an excellent compromise between acquisition speed and information content.

Imaging modalities and their strengths

	Measurement time*	B-field range	B-field information
Full-B mode	3h	‹1mT	quantitative
Iso-B mode	2min	‹3mT	qualitative
Dual iso-B mode	4min	‹1mT	semi-quantitative**
Quenching mode	2min	›3mT	qualitative

*100x100 pixel with standard integration time
**Quantitative between 1-3mT

1 Quenching mode

The quenching mode, Fig. 1, provides the most basic contrasting mechanism of NV magnetometry. A prototypical measurement situation is depicted in Fig.1a, where a Quantilever™MX tip is scanning a surface that contains a magnet. The turquoise dashed line depicts the topography that the tip senses, whereas sample magnetic field lines are represented in grey. While scanning the topography, the NV center is excited by a green laser (515 nm) and fluorescently decays by emitting red light ($600 - 850$ nm). The amount of (fluorescent) photons that are counted while scanning depends on the local magnetic structure of the sample.

The sample in Fig. 1b shows regions with more (red) and less (blue) counts. This is owed to the fact that strong surface magnetic fields (∼mT), which are aligned perpendicular to the NV center quantization axis (black arrow), reduce - or quench - the NV fluorescence. Such a situation is marked at position (1) in Fig. 1. If the perpendicular component of the surface magnetic field is reduced, position (2), the fluorescence count value recovers. More details are found in the Qnami technical note [1]. The sensitivity to perpendicular magnetic field components is used to image pronounced magnetic features where the magnetization vector of the sample is rotating, e.g. domain walls. An overview for which samples the quenching mode is ideal is discussed in the Qnami white paper [2].

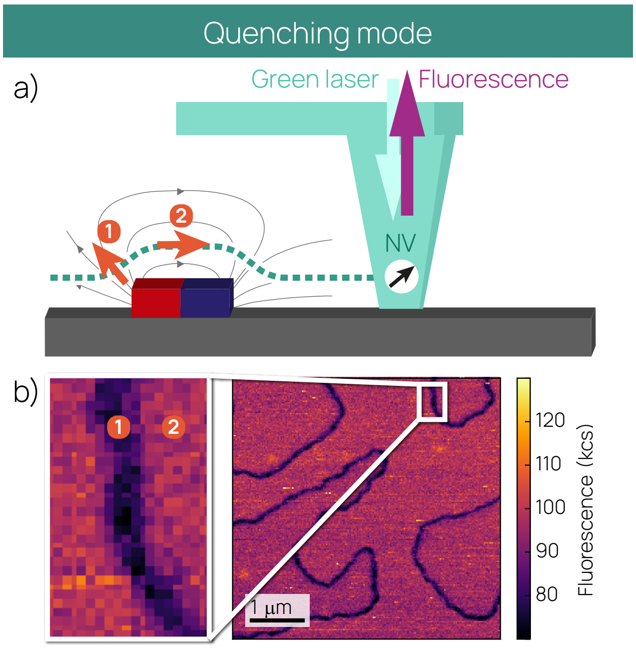

Fig. 1: a) The fluorescence of the NV center is recorded while the Quantilever™MX scans over a sample surface. At position (1), the NV center is exposed to a strong magnetic field perpendicular to its quantization axis. This reduces (or quenches) the fluorescence, an effect that is not pronounced if the perpendicular component of the field is weaker, position (2).

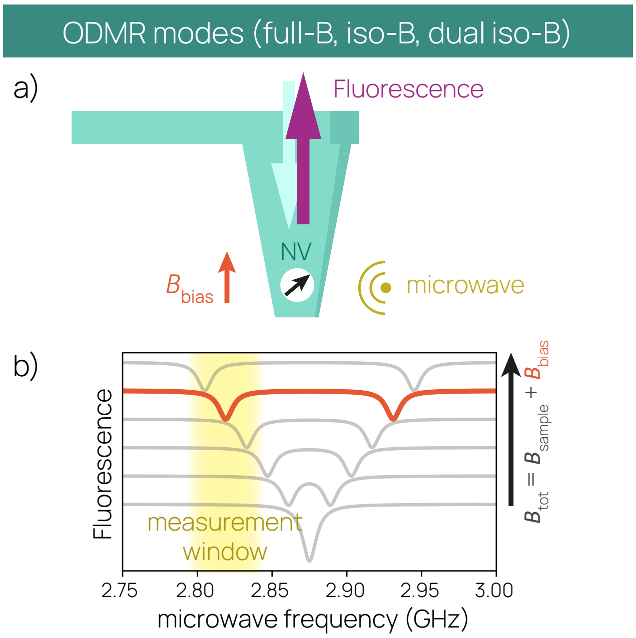

Fig. 2: a) The ODMR-based imaging modalities (full-B, iso-B, dual iso-B) require the application of a microwave frequency and are most commonly operated under a bias magnetic field B_{bias}. b) The ODMR spectra (fluorescence versus microwave frequency) exhibits a dip at about 2.87 GHz which splits linearly as a function of $B_{\text{tot}} = B_{\text{bias}} + B_{\text{sample}}$. ODMR spectra are typically recorded in a restricted measurement window (yellow shaded). The window is chosen according to the B_{sample} range, i.e. the expected variation of the dip position within the sample area.

2 ODMR based modes

We now discuss ODMR-based imaging modalities where a GHz microwave field is applied to the NV center, Fig. 2a. The microwave is used to probe states of the NV center which are sensitive to external magnetic fields. Specifically, the energy of those states varies linearly with the component of the external magnetic field along the NV center quantization axis. In the ODMR spectrum, Fig. 2b, the states are seen as a dip in the fluorescence which linearly splits with increasing component of the external total magnetic field B_{tot} along the NV center axis, Fig. 2b.

The Qnami ProteusQ™ is equipped with a bias magnet which produces a field of a few $\sim$ mT and provides an initial splitting of the resonance. In the LabQ software, the user defines a measurement window (yellow shaded region in Fig. 2b) corresponding to the expected magnetic field fluctuations at the sample surface. For example, a measurement window of $\Delta\nu = 50\,\text{MHz}$ allows the detection of magnetic field fluctuations $< 1\,\text{mT}$. This allows the user to measure local magnetic field variations, discriminate between positive and negative field values, and minimize acquisition time. In addition, it is possible for the user to choose between three different ODMR measurement modes, depending on whether the user looks for high-quality quantitative data, for fast acquisition time or for a good compromise. Those three measurement modes, the full-B mode, the iso-B mode and dual iso-B mode, and their respective advantages are described in more details in the following section.

ODMR measurement example

The full-B mode provides an unambiguous measurement of the exact value of the magnetic field at the NV center location. At each pixel, a full ODMR spectrum is recorded and the value of the resonance frequency is automatically extracted. The resulting map directly shows the value of magnetic field for each coordinate. In Fig. 3a we expose such a full-B measurement. The bottom panel shows a magnetic field pattern with a typical size of $\sim 100\,\text{nm}$ and surface magnetic fields B_{sample} of a few hundred µT. In the top left panel, we zoom into a region

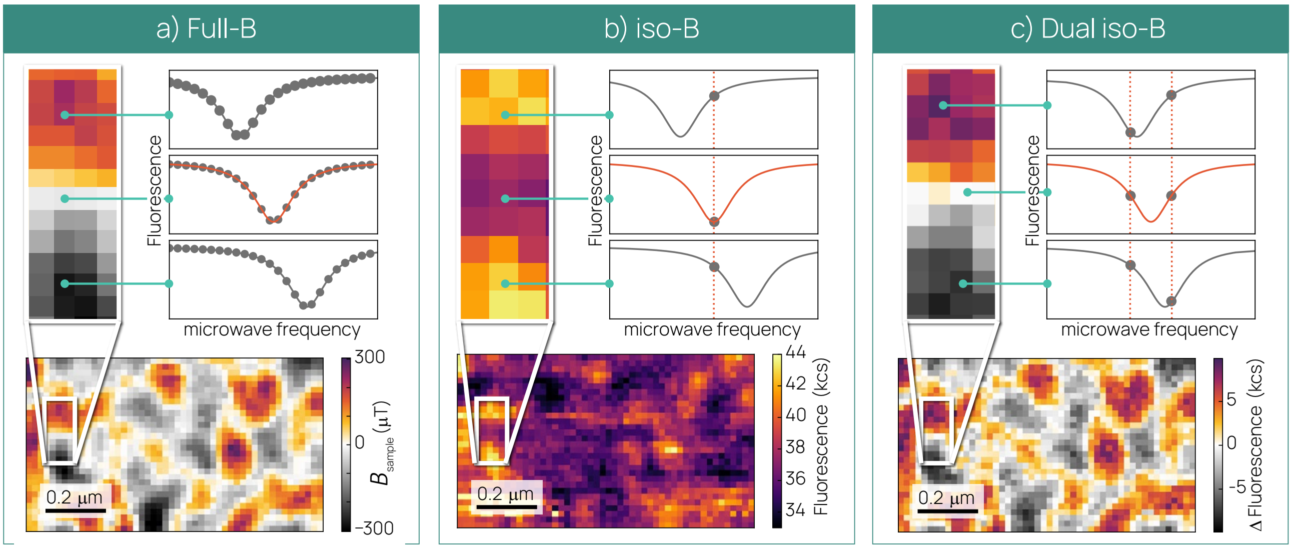

Fig. 3: ODMR spectra, measurements and a zoomed image (in the region marked with a white square in the measurement) are shown for the different imaging modalities. a) In the full-B mode, an ODMR spectrum is recorded in a restricted measurement window (top right panels). A negative shift of the ODMR dip (top panel) corresponds to positive B_{sample} (orange contrast), while a shift in the opposite direction (bottom panel) is caused by negative B_{sample} (black contrast). The middle panel (white contrast) corresponds to the bias magnetic field.b) In the iso-B mode, the fluorescence is recorded at one fixed microwave frequency (orange dashed line). A dark contrast is obtained for a resonance frequency (and thus magnetic field) that coincides with the chosen frequency (middle panel), while positive B_{sample} (top panel) and negative B_{sample} (bottom panel) give a brighter fluorescence signal. c) The fluorescence count at two predefined frequencies is subtracted from each other in the dual iso-B mode. This leads to a positive signal for positive fields (orange, top panel) and vice versa (black, bottom panel).

where B_{sample} changes from positive (red) to negative (black) values. The middle of the three spectra illustrates the information contained in one white pixel. It shows one dip in the restricted measurement window (yellow shaded region in Fig. 2b). Here, $B_{\text{sample}} = 0$ since $B_{\text{tot}} = B_{\text{bias}}$. For positive sample magnetic fields (top panel, red contrast), the spectrum is shifted to lower microwave frequencies due to a larger splitting. For negative B_{sample} (bottom panel, black contrast), a positive shift is recorded. For each pixel, the recorded spectra are fitted with a Lorentzian in order to extract the shift in frequency $\Delta\nu$ and to calculate B_{sample} from the Zeeman splitting: $\Delta\nu = \overline{\gamma}_{\text{NV}} B_{\text{sample}}$, where $\overline{\gamma}_{\text{NV}} = 28\,\text{MHz/mT}$.

The iso-B mode, Fig. 3b, reduces the measurement window to a single frequency, allowing to reduce measurement time by a factor of up to a hundred. The resulting map highlights regions of equal (i.e. iso) fluorescence value (corresponding to a target magnetic field value) and is used for rapid sample investigation. Similar to the quenching mode, the measured quantity is the fluorescence count value, but in contrast to the quenching mode the counts are recorded at a finite microwave frequency. The frequency is typically chosen such that the fluorescence is reduced (blue contrast) at $B_{\text{sample}} = 0$ (middle spectrum). Both positive (top spectrum) and negative (bottom spectrum) sample magnetic fields lead to larger fluorescence count values (yellow contrast). The main advantage of the iso-B mode is the drastically enhanced measurement speed. While it gives a quick overview, it may exhibit artifacts. Specifically, it is not possible to distinguish quenching effects (which lower the baseline of the fluorescence counts) from the ODMR effect. This can be problematic if the sample has a pronounced topography.

Such a distinction is possible by employing the dual iso-B measurement mode, at the cost of slightly larger acquisition time. As seen in the bottom panel of Fig. 3c, the measurement resembles the full-B result. The dual iso-B mode records the difference in fluorescence measured at two frequencies that the user can choose. By this, it is insensitive to changes of the fluorescence base line. Ideally, the frequencies are chosen to be symmetric around the frequency corresponding to $B_{\text{sample}} = 0$. In such configuration, the fluorescence difference

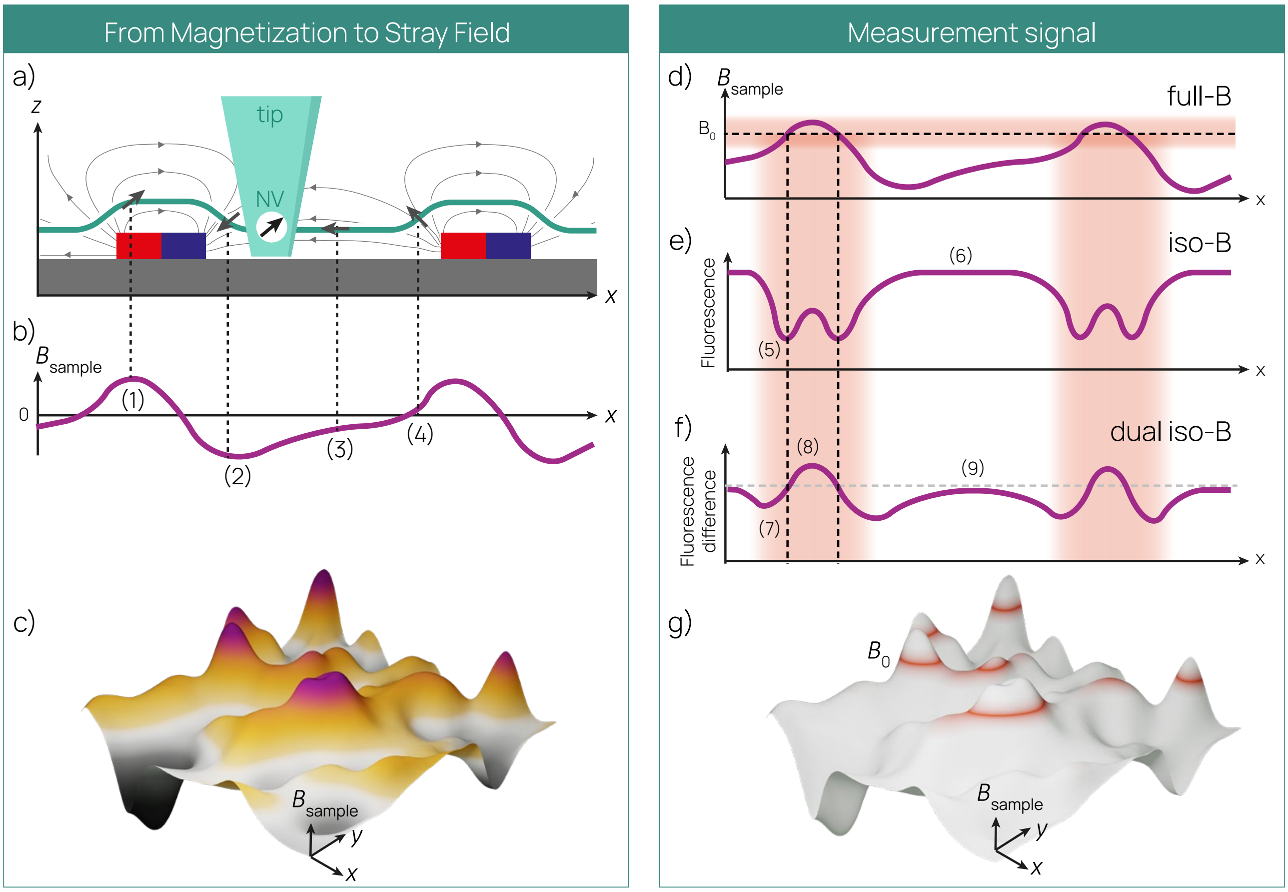

Fig. 4: Qnami ProteusQ™ imaging modalities. a) The sketch depicts a scanning NV tip, measuring the topography $z(x)$ of a (magnetic) surface. b) Full-B trace $B_{\text{sample}}(x)$. Maxima are measured if the surface magnetic field is strong and parallel to the NV quantization axis. By taking several full-B traces, the magnetic landscape $B_{\text{sample}}(x, y)$ is recorded. An example is given in c). d) $B_{\text{sample}}(x)$ of the sample in a). To understand the contrast obtained in the iso-B and dual iso-B modes, consider a chosen magnetic field B_0 (horizontal dashed line). e) Whenever the NV center is exposed to B_0 (vertical dashed lines), the fluorescence drops in the iso-B mode. f) In the dual iso-B mode under the same condition, the signal (fluorescence difference) becomes zero, but the mode is able to capture the shape of the $B_{\text{sample}}(x)$ trace within a limited B-field range (yellow shaded). g) The measurement outcome of the iso-B mode can be viewed as an iso-contour (orange) at B_0 in the magnetic landscape $B_{\text{sample}}(x, y)$. The dual iso-B mode maps $B_{\text{sample}}(x, y)$ in the vicinity of this contour. Note that the sample in Fig.3 exhibits small B-field variations, very close to the iso-contour.

is zero (white contrast) for $B_{\text{sample}} = 0$ (middle spectrum). The highest sensitivity is obtained if the frequencies are positioned at the maximal positive and negative slope of the $B_{\text{sample}} = 0$ ODMR dip. Positive sample magnetic fields (top spectrum) shift the peak to the left and result in a positive signal (red contrast), while negative fields (bottom spectrum) give a negative signal (black contrast). Such contrasting mechanism provides semi-quantitative data as long as the shifts are small enough (corresponding to fields below a few hundred µT). That is, the fluorescence difference can be calculated back to B_{sample} if the shape of the ODMR dip has been measured before.

Measurement Interpretation

The signal recorded in an ODMR measurement is directly linked to the stray field produced by the sample. It only depends on the NV orientation (a fixed quantity) and the scan distance and requires no calibration. As an illustration, we derive the expected measurement signal for a sample consisting of two permanent magnets in all three different ODMR-based modes. We start describing a sample consisting of two permanent magnets, Fig.4a, and construct a measurement result in the full-B, iso-B and dual iso-B mode.

As described above, an atomic force microscopy (AFM) signal (turquoise line in Fig.4a) is recorded while scanning the sample. At position (1), Fig.

4b, the magnetic field that the NV center senses, B_{sample}, is maximal. Here, the tip is on top of the magnet and the field vectors of the sample (denoted by the grey magnetic field lines) are aligned with the quantization axis of the NV center (indicated by a black arrow). The minimum of B_{sample} at position (2) is reached for strong field vectors that are anti-parallel to the NV axis. With increasing distance from the magnets, position (3), the field strength decreases. It reaches zero at position (4), where the B field components are perpendicular to the NV axis. Several line-cuts form a magnetic landscape map, $B_{\text{sample}}(x, y)$, see Fig. 4c.

The full-B mode, Fig. 4d, directly scans $B_{\text{sample}}(x)$, the measurement thus corresponds to the sample magnetic field component at the NV position ($\sim 10\,\text{nm}$ distance from the surface), in the direction of the NV axis.

In the iso-B mode, the user chooses a measurement frequency. This corresponds to a magnetic field B_0, which we indicate with a horizontal dashed line in Fig. 4e. Whenever $B_{\text{sample}} = B_0$, the iso-B fluorescence is minimal, e.g. at position (5). Relevant in the iso-B modes is the width of the ODMR dip. This width corresponds to a magnetic field range (red shaded) within which the iso-B signal changes. For magnetic fields that are out of this range, position (6), the fluorescence signal recovers its baseline value and becomes insensitive to variations of the magnetic field.

The dual iso-B measurement, Fig. 4f, maps the magnetic landscape within the same range around B_0 (here, B_0 corresponds to the middle frequency between the two chosen frequencies). The fluorescence difference is negative for negative B_{sample}, position (7), and positive for positive B_{sample}, position (8), as long as the magnetic fields are small enough (red shaded area). The dual iso-B measurement exhibits zero fluoresence difference, both if $B_0 = B_{\text{sample}}$ and if B_{sample} is out of range.

Given a magnetic landscape, $B_{\text{sample}}(x, y)$, the iso-B mode measures magnetic field contours at B_0, see Fig. 4g. Within a width around B_0 (red shaded), the dual-isoB mode maps the local magnetic landscape. For samples that exhibit small variations of B_{sample}, e.g. where the entire magnetic landscape is within the red shaded band, dual iso-B images provide quantitative data.

To conclude, for rapid overview of magnetic materials presenting strong stray fields (e.g thin film ferromagnets [2]), quenching mode measurements are ideal. For detailed analysis of samples presenting weak fields such as antiferromagnets or ferrimagnets, a combination of iso-B, dual iso-B and full-B provides fast overview and complete data information.

Further reading

- Qnami technical note on SNVM [1]
- Qnami white-paper on imaging mode use-cases [2]
- Qnami introduction to NV magnetometry [3]

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] Qnami AG, *Use cases for Qnami ProteusQ™ imaging modalities*, (2021) https://qnami.ch/wp-content/uploads/2021/08/Qnami_WP_ _Imaging_Modalities_for_distinct_samples.pdf.

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

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