Shot-noise-limited magnetometer with sub-pT sensitivity at room temperature

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We report a photon shot-noise-limited optical magnetometer based on amplitude-modulated optical rotation using a room-temperature $^{85}$Rb vapor in a cell with anti-relaxation coating. We describe the optimization of detuning, pump power and probe power and demonstrate a sensitivity of 70 fT/√Hz with operation from 5µT to 75µT, although with worsening sensitivity at high fields. We measure noise as a function of probe power, both with and without optical pumping, and from the observed noise scaling confirm the SNL performance of the magnetometer. The high sensitivity and large SNL range make the system attractive for sensitivity enhancement with squeezed light.

I. INTRODUCTION

Optical magnetometers [1–3] are currently the most sensitive devices for measuring low-frequency magnetic fields and have many applications, from medical diagnostics and biomagnetism [4,5] to the detection of fields in space [6,7] to tests of fundamental physics [8–11].

In this work we demonstrate a high-sensitivity shot-noise-limited magnetometer based on the process of nonlinear magneto-optical rotation (NMOR), also known as nonlinear Faraday rotation [12,13]. In this process, resonant or near-resonant light produces spin coherence by optical pumping, and the spin coherence in turn produces Faraday rotation, either of the optical pumping beam itself [13], or of a separate probe beam [14], leading to a detectable signal indicating the Larmor frequency and thus the magnitude of the field. Modulation of the pumping, either in frequency (FM NMOR) [13] or in amplitude (AMOR) [15], produces a resonant buildup of polarization with minimal disturbance to the spin coherence. The modulation strategy significantly increases the magnetic dynamic range, i.e., the ratio between the largest detectable signal, which in NMOR can reach the geophysical field range [16,17], and the lowest detectable signal. NMOR can give high sensitivity, due to the long ground-state coherence times, and hence narrow resonances, that arise when alkali vapours are confined with a buffer gas [18,19] or in anti-relaxation coated cells [20,21].

The sensitivity of optical magnetometers is ultimately limited by two quantum noise sources: the atomic projection noise and the optical shot-noise [22,23]. When atomic projection noise is limiting, quantum non-demolition measurement [22,25] and spin squeezing [26] can improve sensitivity for measurements within the atomic coherence time [24] and for non-exponential relaxation processes [27]. Similarly, optical squeezing can improve sensitivity [28,29] when photonic shot noise is limiting. The present sensitivity record for squeezed-light enhanced magnetometry is ~ 1 pT/√Hz, achieved with a CW single-beam nonlinear magneto-optic rotation (NMOR) technique [30]. Previous works on both AMOR [21] and FM NMOR [32] have shown experimental sensitivity about one order of magnitude above (i.e. worse than) the predicted fundamental sensitivity.

In this paper we study a two-beam pump-probe AMOR magnetometer operating in a considerable range around the earth field ~ 50µT, and show that it is capable of both high sensitivity, with detection noise as low as 70 fT/√Hz, and shot-noise-limited performance from 5µT to 75µT. The shot-noise limited performance makes this instrument an attractive test-bed for the study of squeezed-light sensitivity enhancement in comparison with the state-of-the-art scalar magnetometers with sub-pT sensitivity [14,31,32].

The paper is organized as follows: in Section II we describe the experimental setup; in Section III we explain the modulation strategy by showing representative AMOR signals and we define the magnetometer sensitivity. In Section IV we describe the optimization of the experimental parameters to maximize the sensitivity and we present its trend versus probe light power. In Section V we study the noise properties of the detection system and we experimentally demonstrate the shot-noise-limited (SNL) performance of the optimized magnetometer.

II. EXPERIMENTAL SETUP

The experimental scheme is shown in Fig. 1. A sample of isotopically-pure $^{85}$Rb is contained in a spherical vapor cell of 10 cm diameter, with no buffer gas. The cell is at room temperature (~25°C) corresponding to $^{85}$Rb atomic density of $n = 1.27 \times 10^{10}$ atoms/cm$^3$ [33]. The inner cell walls are coated with an antirelaxation (paraffin) layer that prevents atoms from depolarizing upon collision with the walls and prolongs the ground-state Zeeman coherence lifetime to ~100 ms. The cell is inside a “box solenoid,” a cubical box made of printed-circuit-board material, with three mutually per-
pendicular sets of printed wires, each in a solenoidal pattern. Together with an accompanying ferrite box, that extends the length of the solenoid based on the method of images for magneto-statics, we can generate a uniform field along the three directions. In this experiment we generate a constant magnetic field along the $z$-axis, which is also the probe beam direction, while the coils in the perpendicular directions are used to compensate the residual transverse magnetic field. Residual magnetic field gradients are compensated by a set of three mutually perpendicular anti-Helmoltz coils wound around the box. This setup was kept inside three nested layers of metal shields, giving a whole magnetic shielding of $\sim 10^6$ efficiency.

The light source for both probing and pumping is an extended-cavity diode laser which frequency is stabilized by saturated absorption spectroscopy at 20 MHz below the $F = 3 \rightarrow F' = 2$ transition of the $^{85}$Rb D$_1$ line (see Section IV). The laser beam is split into pump and probe beams which pass through acousto-optic modulators independently driven by two 80 MHz RF signals so that, before reaching the atoms, the frequency is additionally red-detuned 80 MHz away from the $F = 3 \rightarrow F' = 2$ transition. Additionally, the intensity of the pump beam is sinusoidally modulated with frequency $\Omega_m/2\pi$. [30]

Both beams are vertically polarized ($x$-direction) with high-quality crystal polarizers to ensure pure linear polarization and the light intensity that interacts with the atoms can be adjusted with half-wave plates situated in front of the polarizers. The pump beam passes through the cell in the $y$ direction, perpendicular to the $z$-axis bias field. When the pumping modulation frequency coincides with twice the Larmor precession frequency, a large precessing alignment accumulates in the $x-y$ plane (see Section IV). The probe beam propagates through the atomic vapor cell along the $z$-axis, i.e. parallel to the field, and experiences Faraday rotation (NMOR) of the polarization plane due to the precessing alignment.

Polarization rotation is detected with a balanced polarization polarimeter consisting of a Wollastion prism set at an angle of 45° (with respect to the vertical polarization) and a fiber-coupled variable gain balanced photo-detector (PDB) (Thorlabs PDB150A DC). The differential output is analyzed with a radio-frequency (RF) spectrum analyzer (SA) (RIGOL DSA1030A) or demodulated at $\Omega_m/2\pi$ with a Lock-in Amplifier (Stanford Research Systems model SR844). The in-phase and quadrature output signals are then stored on a computer for later analysis. As explained in section IV both SA and lock-in signals are used to determine the magnetometer sensitivity. Throughout this work we used SA resolution bandwidth RBW= 30Hz and video bandwidth VBW= 30Hz.

III. FARADAY ROTATION SIGNAL

The AMOR signal is generated by means of amplitude modulated pumping and unmodulated CW probing in a right-angle geometry. Optical pumping with linearly polarized light generates spin alignment, i.e. ground state coherences between Zeeman sub-levels with $\Delta m_F = 2$ [34, 35]. The alignment describes a preferred axis, but not a preferred direction along this axis. Due to this additional twofold symmetry, the signal associated with alignment, precessing at the Larmor frequency, oscillates at two times bigger frequency. In other words, the recurrence of alignment during the Larmor precession occurs at twice the Larmor frequency, $2\Omega_L = 2g_F\mu_0B/h$ where $g_F$ is the Landé factor and $\mu_0$ is the Bohr magneton. Amplitude modulated optical pumping at $2\Omega_L$ produces a resonant build-up of spin alignment, as already performed in several earlier works [14, 17]. The alignment behaves as a damped driven oscillator, and in steady state responds at frequency $\Omega_m$ with an amplitude and phase relative to the drive that depend on the detuning $\Omega_m - 2\Omega_L$ [30]. The weak probe is sensitive to alignment through linear dichroism, i.e., linearly polarized light parallel to the alignment experiences less absorption [3]. When the alignment is neither parallel nor perpendicular to the probe polarization, this dichroism rotates the probe polarization. This rotation signal also oscillates at $2\Omega_L$, and we demodulate it with the lock-in amplifier to extract the in-phase and quadrature components, shown in Fig. 2 for a representative magnetic field intensity of $B = 10 \mu T$.

The optical extraction angle is an oscillating function at the modulation frequency $\Omega_m$ with the amplitude dependence well described by a Lorentzian

$$\phi(t) = \phi_0 \text{Re} \left[ \frac{i\Gamma/2}{\Delta + i\Gamma/2} e^{i\Omega_m t} \right] + \delta \phi(t)$$

$$\phi(t) = \phi_0 \cos (\Omega_m t) + \phi_Q \sin (\Omega_m t) + \delta \phi(t) \quad (1)$$
where $\phi_0$ is the maximum rotation angle, which depends on the optical detuning, cell dimension, and pump power. The detuning between the modulation frequency and $2\Omega_L$ is $\Delta \equiv \Omega_m - 2\Omega_L$ while $\Gamma$ is the FWHM line width due to relaxation, pumping, and non-linear Zeeman shifts. The symbols $\phi_F$ and $\phi_Q$ are the in-phase and quadrature components, respectively, directly observable by demodulation at $\Omega_m$. The photon shot-noise contribution, $\delta\phi(t)$, is a white noise with a power spectral density $S_{\phi}(\omega) = 1/(2\Phi_{\text{ph}})$, where $\Phi_{\text{ph}}$ is the flux of photons arriving to the detector.

We note that on resonance, i.e. with $\Delta = 0$, the signal consists of a cosine wave at frequency $\Omega_m$ with amplitude $\phi_0$, plus a white-noise background due to $\delta\phi(t)$. In the balanced condition, and with $\phi_0 \ll \pi$, the polarimeter signal is $\propto \phi(t)$. When recorded on a spectrum analyzer with resolution bandwidth RBW, the signal shows a peak power spectral density $S_{\text{sig}} = g_{\text{det}}^2\phi_0^2/(2\text{RBW})$, where $g_{\text{det}}$ is the gain relating rotation angle to RF amplitude at the SA (the factor of one half represents a mean value of $(\cos^2) = 1/2$). A typical RF spectrum of the AMOR resonance recorded in our measurements is shown in Figure 3. The signal peak rises above a flat background $S_{\text{bg}} = g_{\text{det}}^2\overline{\delta\phi^2}/2$, where $\overline{\delta\phi^2} = S_{\phi}$ is the spectral noise density of the phase, so that $\overline{\delta\phi}$ has units rad/$\sqrt{\text{Hz}}$. The photon shot-noise contribution to the noise of the demodulated signal, while both are recorded by the SA). The signal-to-noise ratio SNR is given by $\text{SNR} = S_{\text{sig}}/S_{\text{bg}} = \phi_0^2/\overline{\delta\phi}$, which is independent of $g_{\text{det}}$ and RBW and can be directly measured.

![FIG. 2: AMOR Signals versus Modulation Frequency. In-Phase $\phi_F$ (blue) and quadrature $\phi_Q$ (red) output signals of the lock-in amplifier for $B = 10\mu$T, $P_{\text{probe}} = 80\mu$W and $P_{\text{pump}} = 60\mu$W. The modulation/demodulation frequency $\Omega_m/2\pi$ is scanned around the resonance condition $\Omega_m = 2\Omega_L$ ($\Delta = 0$). Experimental data are fitted by dispersive (red) and absorptive (blue) Lorentzian curves. From the fit we obtain resonance frequency and FWHM width $\gamma = \Gamma/2\pi$.](image1)

![FIG. 3: AMOR Magnetometer Resonance Spectrum. Spectrum of the rotation signal acquired on SA at the resonance condition $\Omega_m = 2\Omega_L$ with RBW = 30Hz and VBW = 30Hz. The red curve shows the signal spectrum $S(\Omega) \equiv S_{\text{sig}}$ is the magnetic field of $B = 10\mu$T and 40kHz span frequency around $\Omega_m$, while the blue dashed line indicates the background noise level, i.e. $S(\Omega) \equiv S_{\text{bg}}$ acquired with $B = 0$ and averaged over a 4kHz range around $\Omega_m$.](image2)

The magnetic sensitivity can be related with SNR by noting that the slope of the quadrature component on resonance is

$$\frac{d\phi_Q}{dB} = \frac{g_F \mu_0 \phi_0}{\pi \hbar} \gamma.$$  

(2)

where the width $\gamma = \Gamma/2\pi$ has unit of Hz. Considering that on resonance $\Omega_m = 2\Omega_L = 4g_F \mu_0 B/\hbar$, we find the noise in magnetic units, i.e., the sensitivity

$$\delta B = \left| \frac{d\phi_Q}{dB} \right|^{-1} \overline{\phi^2} = \frac{\pi \hbar}{g_F \mu_0} \frac{\gamma}{\text{SNR}},$$  

(3)

with units T/$\sqrt{\text{Hz}}$.

As described in the next section, using this method to measure the sensitivity we find $\delta B \geq 70 \text{ fT}/\sqrt{\text{Hz}}$. For comparison, the atomic projection noise contribution to the overall measurement is: $\text{[1, 2]}$:

$$\delta B_{\text{at}} \simeq \frac{h \pi}{g_F \mu_0} \sqrt{\frac{\gamma}{N_{\text{at}} \Delta \tau}}$$  

(4)

where $N_{\text{at}}$ is the number of atoms involved in the measurement. With our cell volume of $4\pi R^3/3$, $R \approx 5 \text{ cm}$, atomic density $n = 1.27 \times 10^{10} \text{ atoms/cm}^3$, measured relaxation rate $\gamma \approx 10 \text{ Hz}$ and $\Delta \tau = 1 \text{ s}$ time of measurement we find $\delta B_{\text{at}} \simeq 0.134 \text{ fT}/\sqrt{\text{Hz}}$. This value is two orders of magnitude lower than the observed sensitivity, justifying our earlier step of ignoring this contribution. If all other noise sources have lower amplitude than the shot noise, then the magnetometer can be expected to be photon shot-noise-limited. In Section ![we demonstrate that, in the experimental conditions that optimize the sensitivity, this is indeed the case.](image3)
IV. OPTIMIZATION OF THE MAGNETOMETER SENSITIVITY

In this section we examine different setup parameters in order to find the optimal conditions maximising the magnetometric sensitivity.

In our configuration, with a pump and probe of the same frequency, laser tuning affects the pumping efficiency, the rotation signal corresponding to a given degree of atomic alignment, and the probe absorption. In addition, the pump power increases both the amplitude and the width of the rotation signal. To optimize these parameters, we first adjust the gradient fields to minimize the broadening due to magnetic field inhomogeneities \[37\], and then optimize the laser frequency and pump power to maximize the slope of the AMOR signal. The optimum conditions which we use throughout this work occur at the detuning of 100 MHz to the red of the \(F = 3 \rightarrow F' = 2\) transition and 60 \(\mu W\) of pump power.

To measure the magnetometric sensitivity for a given probe power and field strength, we first set the detuning and pump power to the optimal values discussed above. We then set a constant current in the solenoidal coil along the \(z\)-axis, and minimize the width of the AMOR resonance with the help of the gradient coils. Demodulation of the signal yields the in-phase and quadrature components of the resonance versus \(\Omega_m\), as depicted in Fig. 2. By fitting a Lorentzian to these curves, the central resonance modulation frequency \(\Omega_m = 2\Omega_L\) (\(\Delta = 0\)) and width \(\gamma\) are obtained. Keeping then \(\Omega_m\) fixed and maximizing the in-phase component allows one to measure the spectrum as in Fig. 3 and to extract \(S_{\text{sig}}(\Omega_m) = S_{\text{sig}}/\text{RBW}\). A second spectrum is taken with the B-field set near zero. This moves the resonance peak far away from \(\Omega_m\), so that \(S(\Omega_m)\) now gives the background noise \(\delta B_{\text{RMS}}\). In analogy with previous works \[31, 38\] the experimental sensitivity, defined by equation \[3\], can be calculated in terms of the width (FWHM) and signal-to-noise ratio. The magnetometric sensitivity of the instrument was measured in the range from 5 \(\mu T\) to 75 \(\mu T\). We employ two detector bandwidths, 300 kHz and 5 MHz, corresponding respectively to transimpedance gains of \(10^6\) V/A and \(10^5\) V/A.

Typical results, taken at a field of 7.6 \(\mu T\) (modulation frequency of 71 kHz, detector gain setting \(10^6\) V/A) are shown in Figs. 4 and 5. In Fig. 4 we present signal \(S_{\text{sig}}\) and noise \(S_{\text{bg}}\) power spectral densities with the resulting signal-to-noise ratio (SNR) as a function of the probe power. Signal grows with the probe power until saturation occurs. In contrast, noise grows monotonically, so that the SNR has an optimal value before the signal saturates. Fig. 5 depicts the slope \(\phi_B/\gamma\) and the sensitivity \(\delta B\), calculated using equation \[3\] as a function of probe power, also acquired with \(B = 7.6 \mu T\). An optimum sensitivity of 70 \(\mu T/\sqrt{\text{Hz}}\) is observed at a probe power of 80.5 \(\mu W\) \[52\] and it doesn’t get worse than 10% between 50 \(\mu W\) and 100 \(\mu W\) \[53\].

![Graph of Magnetometer SNR](image)

**FIG. 4:** Magnetometer SNR. Signal-to-Noise ratio versus optical probe power. The modulation frequency was 71kHz \((B = 7.6\mu T)\). The green dashed line indicates the probe power value of 80.5\(\mu W\) that maximizes the sensitivity. This condition does not correspond to the best SNR because of the trade-off with the width trend (see Eq. 3).

![Graph of Magnetometer Sensitivity](image)

**FIG. 5:** Magnetometer Sensitivity. Signal slope \(\phi_B/\gamma\) and magnetometer sensitivity versus optical probe power. The sensitivity is computed as in Eq. 3 using the width from the demodulated signal, as in Fig. 4, and the measured SNR, as in Fig. 4. The green dashed line indicates the probe power that gives the best sensitivity of 70 \(\mu T/\sqrt{\text{Hz}}\) for a modulation frequency of 71 kHz \((B = 7.6\mu T)\).

V. SHOT-NOISE-LIMITED PERFORMANCE

Here we report the results of two noise analyses: the first characterises the probing and detection system, without an atomic contribution. This was performed by probing at the optimal laser detuning but with the pump beam off. The second analysis characterizes the magne-
tometer under the experimental conditions that optimize the sensitivity, as described in section IV.

\[ N = Ap + Bp^2 + Cp^3, \]  
where \( A, B \) and \( C \) are constants. The three terms of this polynomial are the “electronic noise” (stemming, e.g. from the detector electronics), the shot noise, and the “technical noise” contributions, respectively [39].

The laser source can contribute to technical noise, e.g. through power fluctuations if the detection is imbalanced or if its optical elements are unstable. By determining the noise scaling as the function of light intensity, we can identify the dominating noise source. When \( BP^1 > AP^0 \) and \( BP^1 > CP^2 \), we say the system is shot-noise limited. These two inequalities define the range of powers \( B/C > P > A/B \) in which the system is SNL. If \( B/C < A/B \), the system is not SNL for any power.

For a given field \( B \), and thus the Larmor precession or modulation frequency, the noise of interest is \( N = S(\theta_m) \), the noise spectral density at the demodulation frequency \( \theta_m \). Using the SA we collect output noise spectra for several probe intensities. The data shown in Figs. 6 and 7 reveal the resulting scaling of the noise level. In the next step we examine the scaling of this growth.

For any given detection frequency \( \theta_m \) (that will be the modulation/demodulation frequency in the magnetometer operation mode), we can then fit the polynomial of Eq. (5), and find the range of powers and frequencies in which the detection system is SNL.

In Figure 8 we show an example of such analysis for a detection frequency of 48.5kHz. We can see that scaling of the noise amplitude is different for different intensity ranges. The red area represents the SNL range. This is the only power range in which quantum noise reduction via probe squeezing could significantly enhance the magnetometer sensitivity. Data in Fig. 8 show that at 48.5kHz detection frequency, for light power below 30\( \mu \)W the electronic contribution of Eq. (5) dominates the noise budget (blue area); on the other hand, above the SNL range, the noise power increases quadratically due to technical noise (green area).

After performing the same analysis over all detection
Optical Power $@mW$:  

$D$: 1000, 100, 10

$10^6$V/A, $A/B$ and $B/C$ were found by fitting the spectra of Fig. 6 as illustrated in Fig. 8. To reduce scatter, spectra were first averaged in 3kHz bins. See text for details.

**FIG. 9:** SNL Power Range for low frequencies. Blue and red curves show $A/B$ and $B/C$, the lower- and upper-limits, respectively, of the SNL range (shaded region) with PDB gain $10^5$V/A. $A/B$ and $B/C$ were found by fitting the spectra of Fig. 7 as illustrated in Fig. 8. To reduce scatter, spectra were first averaged in 3kHz bins. See text for details.

**FIG. 10:** SNL Power Range for high frequencies. Blue and red curves show $A/B$ and $B/C$, the lower- and upper-limits, respectively, of the SNL range (shaded region) with PDB gain $10^5$V/A. $A/B$ and $B/C$ were found by fitting the spectra of Fig. 7 as illustrated in Fig. 8. To reduce scatter, spectra were first averaged in 10kHz bins. See text for details.

fig.

In Fig. 11 we show the noise power at 71kHz ($B = 71\mu T$) and 700kHz ($B = 75\mu T$) as a function of probe power. Fitting both data with $N(P)$ of Eq. (5) and knowing the electronic noise coefficient $A$, we find the coefficients $B$ and $C$ and we can define the shot-noise-limited power range. The difference in power range and reference level between the two representative frequencies is due to the different employed BPD gain. In both cases the trend of the noise power is linear, i.e. shot-noise-limited, with good agreement in the power range of 30µW-500µW and 100µW-1mW for 71kHz and 700kHz respectively. The probe power intervals in which the magnetometer sensitivity is not worse than 10% of the reference level are shown in Fig. 11.

**FIG. 11:** SNL Magnetometer Performance. Background noise level (calculated as in Fig. 3) vs optical probe power at 71kHz (squares) and 700kHz (triangles). These are simultaneously AM frequencies of the optical pumping (kept on in the noise measurement) and SA detection frequencies. Electronic level (red), shot-noise (blue) and technical noise (purple) contributions are shown (dashed and dotted lines at 71kHz and 700kHz respectively). Optimal probe powers (green lines), i.e. maximum sensitivity, fall within the SNL power range.
maximum (reached at 80.5 $\mu$W and 620 $\mu$W respectively) are well inside the photon SNL region.

Indeed, the results of Fig. 11 show that the fundamental light shot-noise contribution dominates the magnetometer noise budget i.e. technical noise and atomic projection noise (Eq. 4) are negligible when the magnetometer noise sensitivity is optimized at room temperature. Similar SNL performance was observed between 5 $\mu$T and 75 $\mu$T, over all the investigated magnetic dynamic range.

VI. CONCLUSIONS

We have demonstrated a sensitive pump-probe optical magnetometer that is shot-noise limited over the field range 5 $\mu$T to 75 $\mu$T. We optimized the system for pump/probe detuning, pump and probe beam powers, and found sensitivity of 70 $\mu$T/$\sqrt{\text{Hz}}$ at a field of 7.6 $\mu$T. The shot-noise-limited performance of the system has been confirmed by the scaling of the magnetometer noise as a function of probe input power. This is the first experimental demonstration of a photon shot-noise-limited AMOR magnetometer.

This is a pre-requisite for any sensitivity improvements due to squeezing, which can only reduce the quantum noise of the light, not other noise sources. Although optical squeezing can be generated at low frequencies [40], in practice most squeezing experiments, and to date all atom-resonant squeezed light sources [41][45], have squeezed radio-frequency side-bands. Based on these observations, the described magnetometer is a good candidate for squeezed-light enhancement of sub-pT sensitivity over a broad dynamic range.

A number of improvements suggest themselves. The lower limit of 5 $\mu$T is set by the low-frequency electronic noise of the balanced detector. Electronics designed for lower frequency ranges [10] could make the system shot-noise-limited also for weaker fields. Recently-developed anti-relaxation coatings [40] could extend the ground-state coherence. Techniques to evade broadening due to the nonlinear Zeeman effect could improve the sensitivity at high fields [47][49].

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The AOM along the probe beam path makes the setup suitable also for single-beam NMOR but is not necessary in the strategy followed in this paper, where just the pump beam needs to be amplitude modulated.

The single-Lorentzian approximation should fail at large $B$, when the resonance splits into several lines due to the nonlinear Zeeman shift. This was not observed at the field strengths used in this work. Even at 75 $\mu$T, the response was well approximated as a single Lorentzian. This suggests a strong line-broadening accompanied the nonlinear Zeeman shift.

Although this probe power exceeded the pump power of 60 $\mu$W, the increased resonance broadening is compensated by higher signal amplitude and results in a better net sensitivity. Moreover, for the gain setting of $10^5$ V/A we find the optimal probe power to be as high as 620 $\mu$W.

While optimized sensitivity value of 70 fT/$\sqrt{\text{Hz}}$ is observed below 10 $\mu$T at higher fields this number rises significantly, roughly as $B^4$, reaching 250 pT/$\sqrt{\text{Hz}}$ at 75 $\mu$T ($\Omega_m = 700$ kHz). The observed reduction of the sensitivity for larger fields is related to the nonlinear Zeeman effect (NLZ) [3][16][17]. Saturation of the ferrite shielding cube at high fields and high-order magnetic field gradients that are not compensated in the current experimental setup could also contribute to the sensitivity worsening and need further investigation.