

# Quantum enhancement protocol report

## D3.2

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## List of Acronyms

Acronym	Full name
OPM	Optically pumped magnetometer
BBOPM	Bell-Bloom optically pumped magnetometer
QE	Quantum-enhanced
PICSq	Photonic Integrated Squeezer
PCB	Printed Circuit Board
MEMS	Micro Electro-Mechanical Systems
SWaP	Size Weight and Power
SotA	State of the art
WFG	Waveform generator
DBR	Distributed Bragg reflector
PBS	Polarizing beam splitter
PD	Photodetector
PSN	Photon Shot Noise
SPN	Spin Projection Noise
RF	Radio Frequency
MBA	Measurement Backaction
SERF	Spin Exchange Relaxation Free

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# 1. Introduction

## 1.1 Purpose of this document

The goal of the QUANTIFY project is to develop advanced sensors based on functionalized MEMS atomic vapor cell technology (MEMS cells) and photonic integrated light sources, including the development of a quantum-enhanced optically pumped magnetometer using a photonic squeezer (PICSq). The purpose of this document is to describe the quantum-enhanced protocol to be later used with PICSq and MEMS cells. The work reported here was performed by and at ICFO.

## 1.2 State of art and status of exploited technology

State-of-the-art optically pumped magnetometers (OPMs) based on coherent-light probing and macroscopic vapor cells have achieved sub-femtotesla sensitivities in low magnetic fields ( $<1$  nT) working in the spin exchange relaxation-free SERF regime [1,2]. In contrast, OPMs operating at the Earth's magnetic field are limited to sensitivities of approximately  $1$  pT/ $\sqrt{\text{Hz}}$  and rely on centimeter-scale, glass-blown vapor cells together with bulky drive and control electronics [3].

Quantum enhancement through squeezed-light probing has recently emerged as a powerful approach to surpass the standard quantum limit by reducing photon shot noise (PSN) in OPMs [4–6]. Using macroscopic squeezed-light sources, quantum-enhanced OPMs have demonstrated sensitivities down to approximately  $300$  fT/ $\sqrt{\text{Hz}}$  at intermediate magnetic fields ( $\sim 4$   $\mu\text{T}$ ), employing back-action-evading detection schemes [5], and have enabled enhanced multiparameter sensing [6]. However, quantum-enhanced operation has not yet been demonstrated in OPMs operating in the Earth-field regime.

To date, all squeezed-light-enhanced OPM demonstrations have relied on macroscopic optical squeezers and centimeter-scale vapor cells. No prior work has achieved quantum-enhanced sensitivity or bandwidth in OPMs employing millimeter-scale MEMS vapor cells.

The QUANTIFY project advances the state of the art by developing quantum-enhanced OPMs that are compatible with Earth-field operation and extreme miniaturization. Polarization-squeezed light will be generated using integrated photonic platforms, enabling ultra-compact sources of this key quantum resource. In parallel, MEMS vapor cells tailored for squeezed-light probing and optimized for Earth-field performance have been developed (Deliverable 3.1). Together, these developments pave the way toward miniaturized quantum-enhanced OPMs with size, weight, and power consumption (SWaP) substantially below the current state of the art.

# 2. Methodology

## 2.1 Magnetometer operation

The OPM described in this report can operate in two distinct modes: (i) as a scalar magnetometer, referred to as a Bell-Bloom (BB) OPM, and (ii) a hybrid OPM (hOPM), which combines scalar and radio-frequency (RF) magnetometry within a single measurement protocol. In both modes, the dc magnetic field  $B_{\text{dc}}$  is extracted from the spin precession frequency, while the hOPM additionally enables detection of one rf magnetic-field quadrature via the spin-precession amplitude. The present work focuses exclusively on the dc magnetometry functionality.

The principle of operation is as follows: dc magnetic field is applied along the  $x$ -axis in the BB-OPM mode, and along both the  $x$ - and  $z$ -axes in the hOPM mode. An optical pumping beam propagating along the  $z$ -axis drives the atomic spin polarization  $\mathbf{F}$  at a time-dependent pumping rate  $R_{OP}(t)$ , which is periodically modulated at a frequency  $\Omega_p$  following the Bell-Bloom scheme [5]. When the modulation frequency is tuned near the Larmor frequency, resonant enhancement of the spin polarization occurs, causing the longitudinal spin component  $F_z$  — and hence the polarization rotation angle  $\phi$  — to oscillate at  $\Omega_p$ . The resulting polarization-rotation signal is demodulated using a digital lock-in amplifier referenced to  $R_{OP}(t)$ , yielding in-phase and quadrature components. The quadrature component is subsequently used to infer the magnitude of the dc magnetic field. A schematic overview of the OPM configuration and operating principle is shown in Fig. 1.

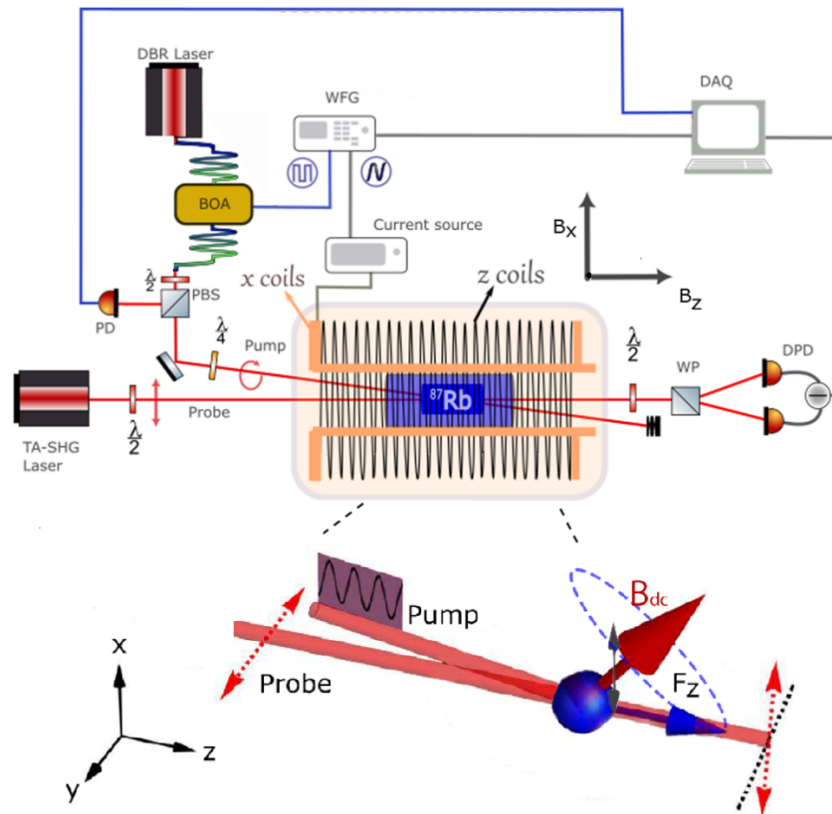


Figure 1. Bell-Bloom OPM experimental setup. The vapor cell, heater, and magnetic field coils are enclosed within a three-layer  $\mu$ -metal magnetic shield. BOA: booster optical amplifier; WP: Wollaston prism; DPD: differential photodetector; PD: photodetector; PBS: polarizing beam splitter; DAQ: data acquisition card; TA-SHG: tapered amplifier second-harmonic generator; WFG: waveform generator; DBR: distributed Bragg reflector laser. Inset: The combined dc magnetic field components  $B_x$  and  $B_z$  induce atomic spin precession at the Larmor frequency  $\omega_L$  in the transverse plane. Synchronously modulated optical pumping sustains the spin polarization, while a linearly polarized continuous-wave probe beam experiences Faraday rotation.

Isotopically enriched  $^{87}\text{Rb}$  together with 100 Torr of  $\text{N}_2$  buffer gas is contained in a vapor cell with a 3 cm internal optical path, housed inside a ceramic oven. The cell is maintained at  $105^\circ\text{C}$  using intermittent Joule heating, yielding an  $^{87}\text{Rb}$  vapor density of approximately  $8.2 \times 10^{12}$  atoms/cm<sup>3</sup>. Induction coils positioned along the  $x$  and  $z$  axes are driven by a low-noise current source (TwinLeaf CSUA300) to generate a dc bias field of  $B \approx 4.3 \mu\text{T}$  (up to  $70 \mu\text{T}$ ), corresponding to a Larmor frequency  $\omega_L \approx 33$  kHz (up to 500 kHz). Four layers of  $\mu$ -metal shielding provide isolation from ambient magnetic fields.

The magnetometer is optically pumped by a circularly polarized beam from a distributed Bragg reflector laser with an average power between 2 and  $15 \mu\text{W}$ . The pump amplitude (frequency) is

modulated at frequency  $\Omega_p$  in a BB-OPM (hOPM) configuration to produce the periodic pumping rate  $R_{OP}(t)$ . A separate extended-cavity diode laser at 795 nm is stabilized 20 GHz to the blue of the  $^{87}\text{Rb}$   $D_1$  transition using a fiber interferometer [7]. A 500  $\mu\text{W}$  probe beam (unless stated otherwise) is analyzed with a shot-noise-limited balanced polarimeter located after the vapor cell (Thorlabs PDB450A). Pump parameters (power, detuning, duty cycle) and probe parameters (power, detuning) are tuned following the optimization strategy described in [13] to maximize sensitivity. A data acquisition system records the balanced polarimeter output and the pump modulation signal.

## 2.2 Optical pumping at Earth's fields

In contrast to the BB-OPM configuration reported in [5], the present BB-OPM system is engineered to operate at geomagnetic field strengths in the range of 30-70  $\mu\text{T}$ . Operation in this regime necessitates optical pumping at proportionally higher frequencies, between 350 and 500 kHz. To accommodate these requirements, an amplitude-modulated pumping architecture has been implemented using a booster optical amplifier (BOA, Thorlabs).

The BOA is housed within a butterfly-package module. Injection current is delivered by a Koheron (DRV200-A-400) current driver, and thermal stabilization is provided by a Meerstetter Engineering (TEC-1091) temperature controller. The current driver permits external modulation bandwidths up to 6 MHz, which are supplied by a Keysight (33600A) waveform generator. The waveform generator produces 1 V pulses with a duty cycle of 10 percent, which drive the BOA into the amplification regime. The waveform generator is operated under computer control, and additionally provides the reference signal for subsequent demodulation.

Figure 2 shows representative BOA-generated pulse trains at modulation frequencies of 42 kHz, 350 kHz, and 500 kHz, demonstrating the capability of the system to generate short, well-defined pulses suitable for high-frequency Bell-Bloom optical pumping. Measurements of the polarization noise show quantum-noise-limited performance for the amplitude-modulation schemes (AM1 and AM2), comparable to that obtained using the frequency-modulation (FM, as in [5,6]), apart from the technical noise spikes at the harmonics of the 50 Hz power line and probe light present but - line frequency and  $1/f$  noise below 20 Hz. Spin-noise spectroscopy, measured without optical pumping, reveals that the noise spectrum in the 20–200 Hz band is dominated by spin-projection noise (SPN), which exceeds the photon shot noise (PSN) in this frequency range. Comparable noise levels are observed for AM1, AM2, and FM in this band, confirming that the low-frequency noise is SPN-limited. At intermediate frequencies, the noise arises from a combination of SPN and PSN, while at higher frequencies the noise is dominated by PSN, proving that the use of BOA does not contribute any additional technical noise to the OPM operation.

As a final stage in evaluating the BOA-based pumping scheme, we investigated the achievable polarization contrast by increasing the average pump power from 2  $\mu\text{W}$  up to 120  $\mu\text{W}$ . At elevated pump powers, additional low-frequency noise attributable to the optical-pumping process was observed. Under these conditions, the measured sensitivity of the BB-OPM was approximately 200  $\text{ft}/\sqrt{\text{Hz}}$ .

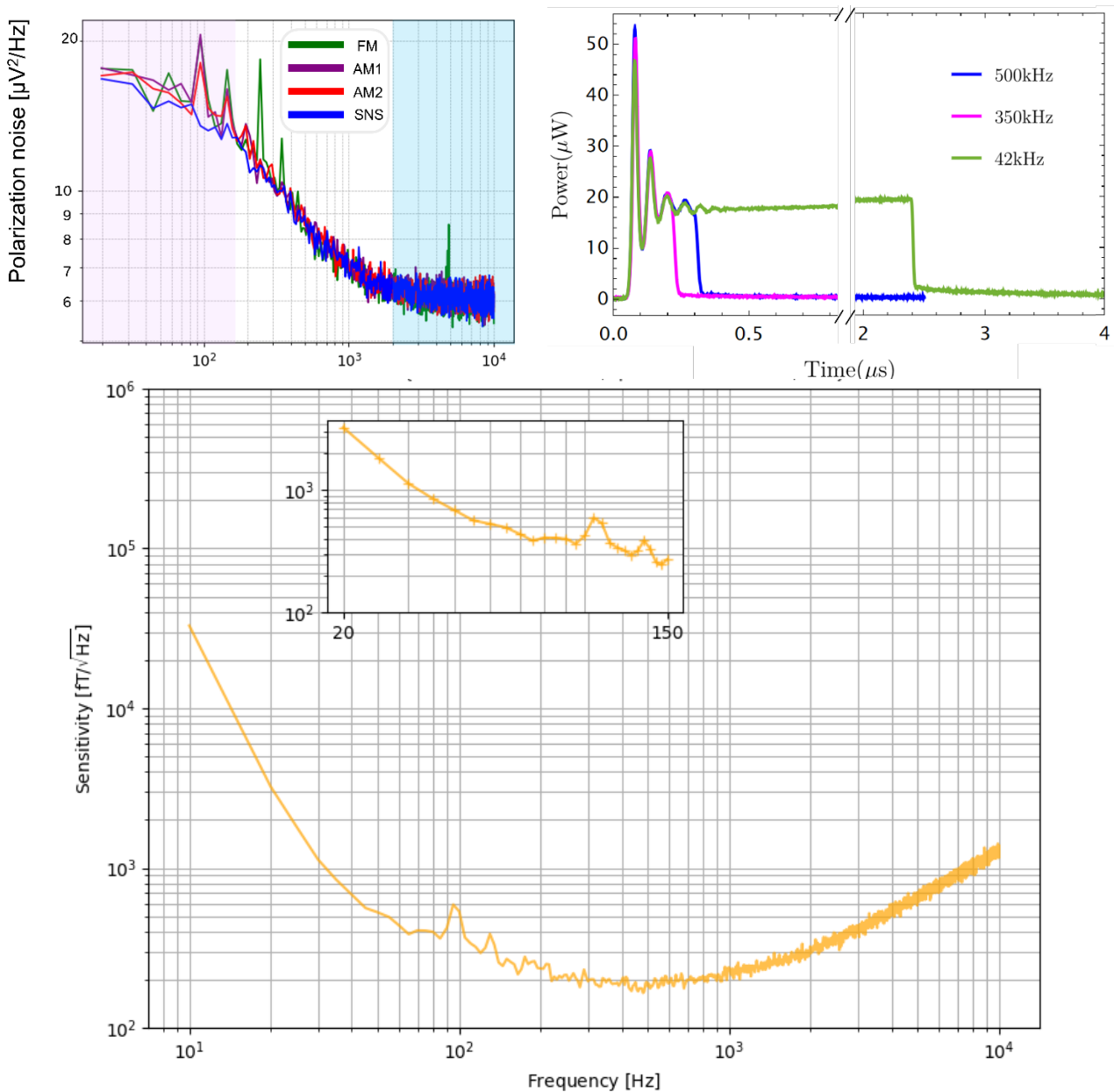


Figure 2. Left: Noise spectra measured for BB-OPM. Blue: unpolarized atomic ensemble (spin-noise spectroscopy, SNS). Green: frequency modulation (FM) as used in Ref. [5,6]. Purple: BOA amplitude modulation resonant with the  $F = 1$  hyperfine state (AM1). Red: BOA amplitude modulation resonant with the  $F = 2$  hyperfine state (AM2). The pink shaded region indicates the frequency range where the magnetometer is limited by spin-projection noise, while the baby blue shaded region denotes the photon shot-noise-limited regime. Right: Optical pulse trains generated by the BOA at modulation frequencies of 500 kHz (blue), 350 kHz (orange), and 42 kHz (pink), averaged over 64 acquisitions. Bottom: BBOPM sensitivity at high pumping with BOA.

## 3. Results obtained

### 3.1 Quantum noise limited sensitivity

The sensitivity of the BB-OPM was evaluated following the methodology described in Refs. [5,6]. The magnetometer operates in the Earth-field range of 30–70  $\mu\text{T}$ , with optical pumping implemented using the BOA at averaged power of 2  $\mu\text{W}$ , as described in the previous section. Details of the sensitivity measurement procedure and data analysis are provided in Ref. [5]. Figure 3 presents the measured sensitivities across the 30–70  $\mu\text{T}$  field range, with values in the few-pT/ $\sqrt{\text{Hz}}$  regime. Apart from discrete noise features, such as peaks at harmonics of the 50 Hz power-line frequency and excess  $1/f$  noise below 20 Hz, the sensitivity reaches sub-pT/ $\sqrt{\text{Hz}}$  levels in the 10–200 Hz frequency band of interest and is limited by quantum noise.

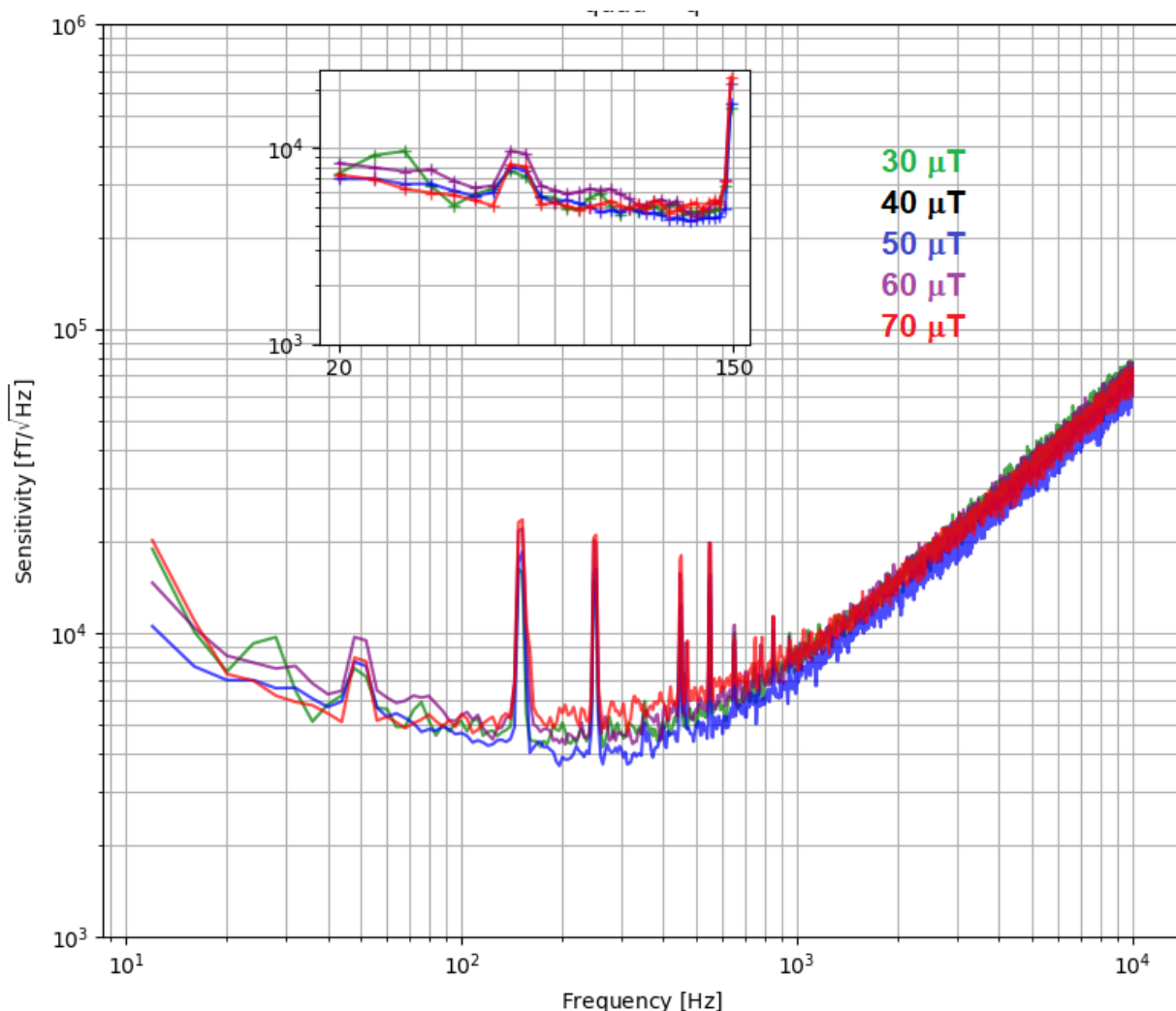


Figure 3. Sensitivity of the BB-OPM to a small harmonic perturbation at frequency  $f$ , measured for a range of Earth's magnetic fields, with amplitude modulation implemented with BOA. Averaged pump power: 2  $\mu\text{W}$ .

### 3.2 Quantum-enhanced protocol

To evaluate the quantum-enhancement protocol, a macroscopic squeezer was incorporated to generate polarization-squeezed light. The 795 nm probe beam was frequency doubled to 397.4 nm using a Toptica TA-SHG 110 module. This violet beam was transmitted through a polarization-

maintaining fiber to seed a subthreshold optical parametric oscillator, which produced vertically polarized squeezed vacuum at the fundamental wavelength, following the procedures described in [5,6]. The squeezed vacuum was subsequently overlapped with a mode-matched, horizontally polarized local-oscillator (LO) beam at 795 nm on a polarizing beam splitter to realize the polarization-squeezed probe field. The relative LO-squeezed-vacuum phase was actively stabilized using a piezoelectric actuator with feedback derived from the broadband noise amplitude.

To demonstrate quantum-enhanced magnetometry, continuous-wave squeezed-light probing was applied to the quantum-noise-limited hOPM. Measurements were conducted with 2 dB of polarization squeezing (measured after the atomic cell) at the optimal atomic number density for enhanced operation,  $8.2 \times 10^{12}$  atoms/cm<sup>3</sup>, following [15]. Results were compared in Figure 3 against coherent-state probing and anti-squeezed-quadrature probing. Quantum enhancement is clearly visible at high frequencies, where the magnetometer noise floor is dominated by photon shot noise; in this regime, the squeezed-light probe yields a measurable reduction in noise relative to both coherent and anti-squeezed operation.

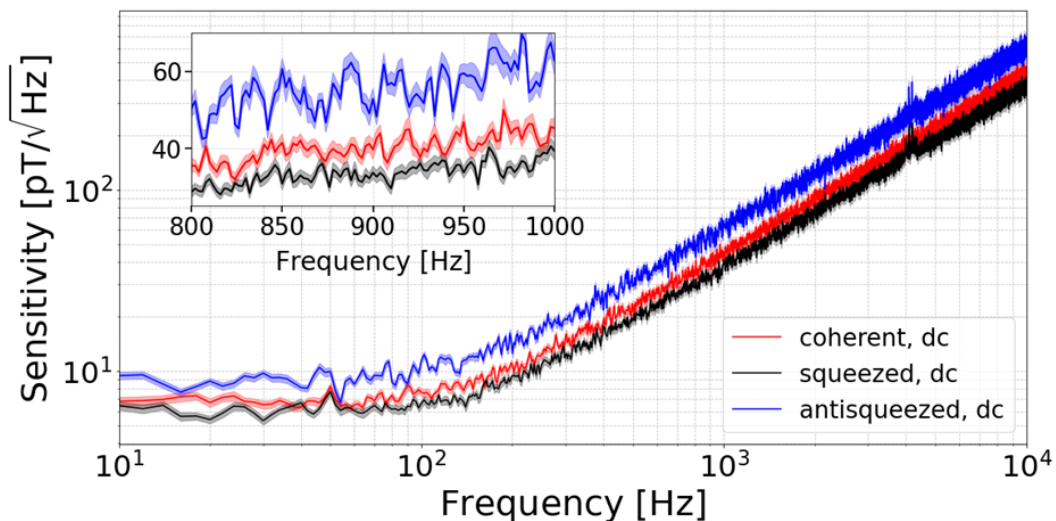


Figure 4 Magnetic sensitivity for quantum-enhanced hOPM. Sensitivity spectra for hOPM magnetometer probed with coherent, squeezed, and anti-squeezed. Polarization squeezing: 2dB after the atomic cell, measured at the balanced detector.

To confirm that the system operates in the quantum-noise-limited regime, we examine the dependence of photon shot noise (PSN) and spin-projection noise (SPN) on the probe power. As expected, the PSN exhibits linear scaling, while the SPN follows quadratic scaling, and neither noise contribution shows any dependence on the pump power. The corresponding measurements are presented in Figure 5.

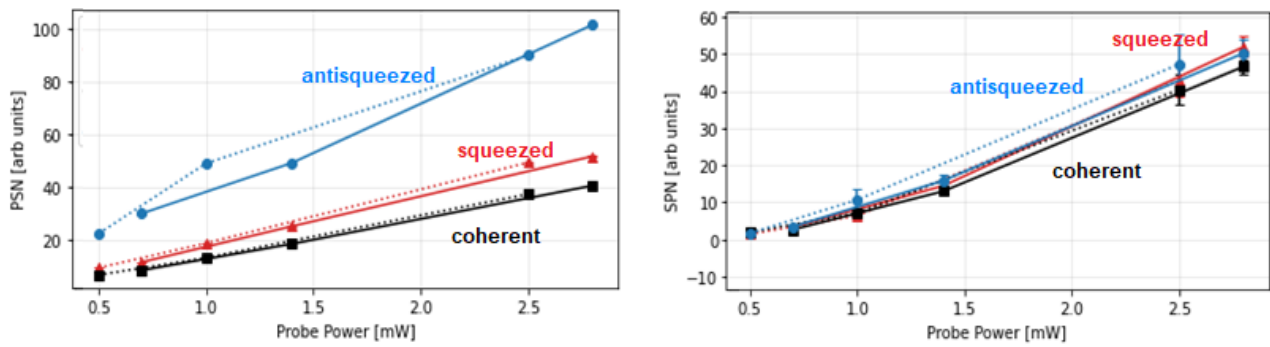


Figure 5. Photon shot noise (PSN, left) and spin-projection noise (SPN, right) as functions of probe and pump powers. Solid curves correspond to a pump power of  $5 \mu\text{W}$ , while dotted curves represent measurements taken at  $10 \mu\text{W}$  pump power. Results are shown for anti-squeezed, coherent, and squeezed probing, as indicated in the legend.

It is noted that the degree of quantum advantage achievable in the present configuration is limited primarily by the amount of squeezing generated by the optical parametric oscillator (determined by the available blue-pump power), as well as by transmission losses in the probe path. In principle, these optical losses can be reduced without altering other magnetometer parameters by increasing the probe detuning while proportionally increasing probe power to maintain constant power broadening.

## 4. Conclusion

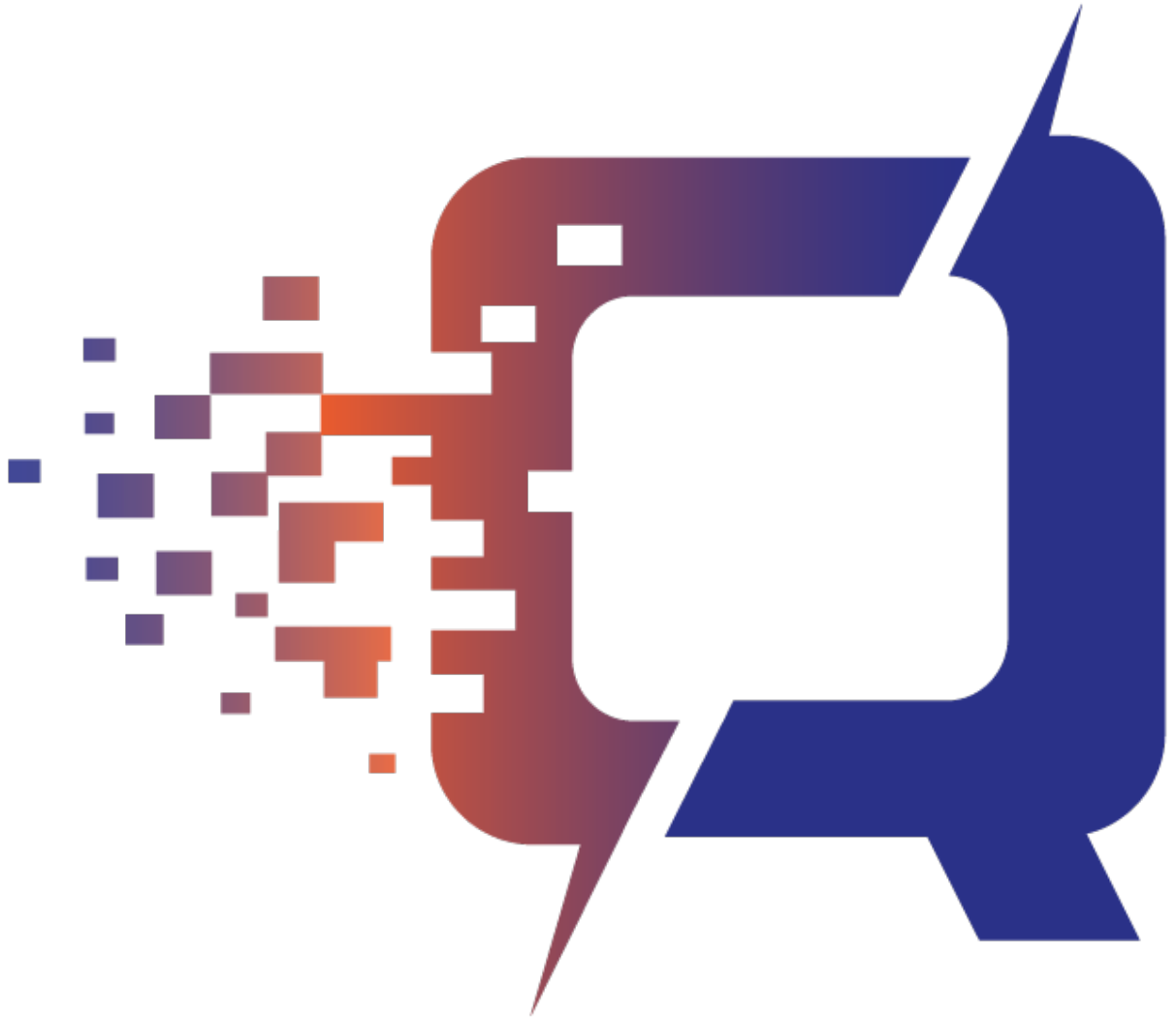
This work demonstrates the development of a quantum-enhancement protocol for an optically pumped magnetometer based on squeezed-light probing. By implementing high-frequency optical pumping using a Booster Optical Amplifier, we achieved stable and efficient Bell–Bloom operation at modulation frequencies up to 500 kHz without introducing additional technical noise. Noise spectroscopy confirms that the magnetometer performance is limited by fundamental quantum noise sources—spin-projection noise at low and intermediate frequencies, and photon shot noise at high frequencies—thereby establishing a suitable platform for quantum enhancement.

We implemented a macroscopic polarization squeezer to generate polarization-squeezed probe light and applied it to the quantum-noise-limited hybrid OPM. Using 2 dB of polarization squeezing measured after the atomic cell, we demonstrated clear quantum enhancement in the photon-shot-noise-dominated regime, with squeezed-light probing yielding a measurable reduction in magnetometer noise relative to both coherent and anti-squeezed operation.

These results constitute the demonstration of a quantum-enhancement protocol suited for eventual integration with MEMS vapor cells and photonic integrated squeezed-light sources. The techniques and validation presented here establish the operational framework upon which the PICSq and MEMS-cell-based quantum-enhanced OPM will be constructed. This represents a significant step toward the realization of compact, low-SWaP, quantum-enabled magnetometers envisioned in the QUANTIFY project.

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