Experimental and theoretical study of the phase response of M_x magnetometer to modulating transversal magnetic field

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Introduction

- The M_x magnetometers in the so-called M_x-geometry, in which the frequency of a weak oscillating magnetic field is actively kept in resonance with the atomic spin precession at the Larmor frequency.
- Investigation the phase response of a true scalar M_x magnetometer to the sudden changes of transversal magnetic field [1].
- Numerical and analytical modeling of a system.
- Obtaining set of simple equations describing detected signal for comparison with experimental results and tracking of the phase evolution.
- Presenting obtained results, and discussing which conditions lead to the signal abnormalities.
- Changes in the measured phase depending on the orientation of the applied modulating field.

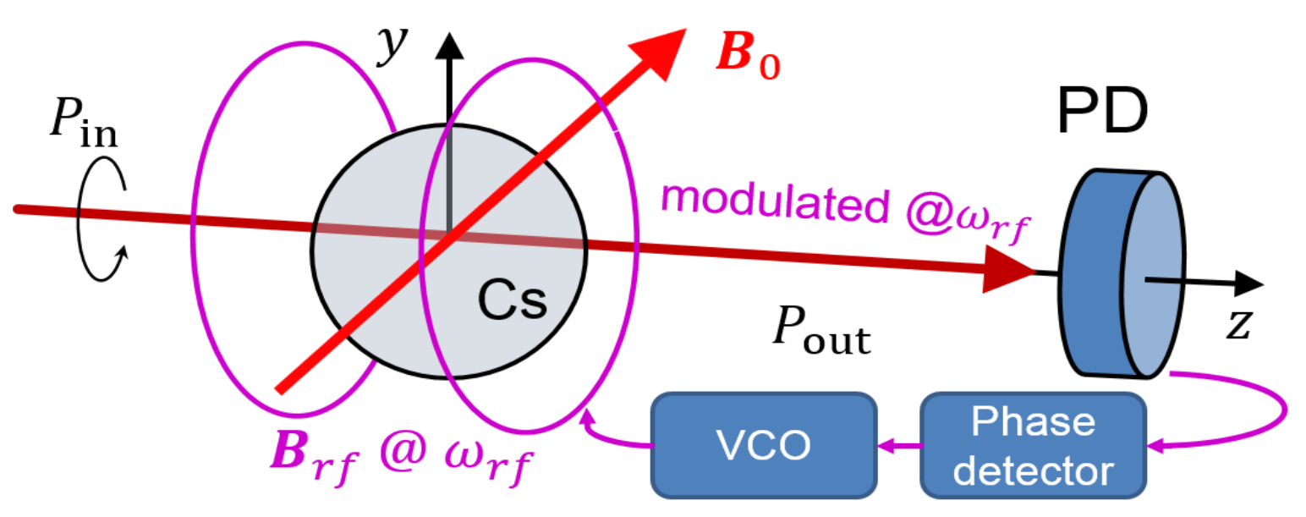


Figure 1: M_x magnetometer

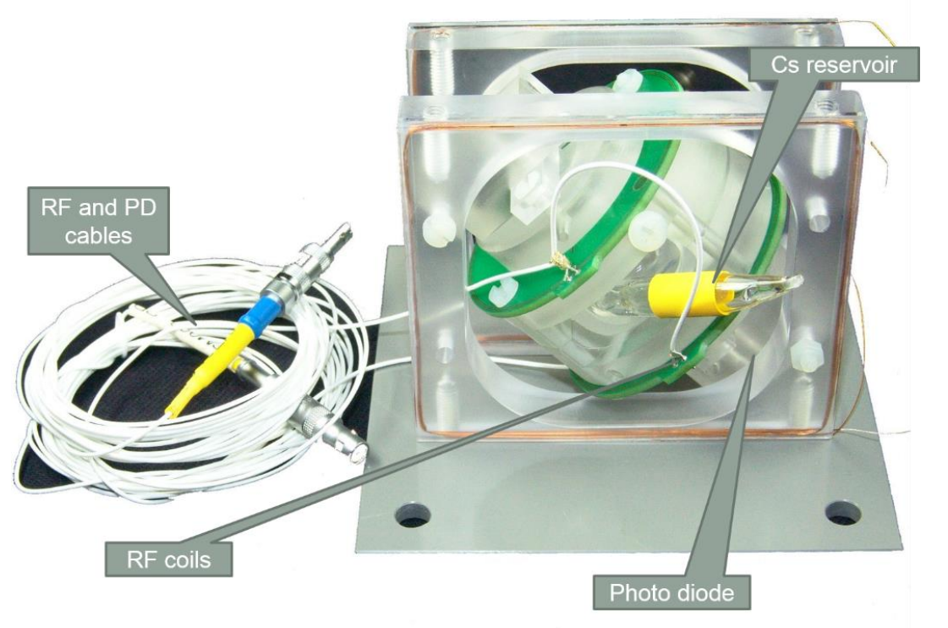


Figure 2: M_x magnetometer components

- With the main offset field in z-direction, and applied modulation in yz plane, phase of the signal shows an unexpected behavior for a scalar magnetometer.
- We analyze a specific case when modulus $|\vec{B}_0(t)| = const.$ remains constant while direction of the $\vec{B}_0(t)$ changes.
- In such case, phase Δθ, of a TSM magnetometer should not change, but, we show here might encounter unexpected transient until settling back to its steady state.
- If a rotation Rx,y(β) (around $\hat{x}$ or $\hat{y}$ axis) to $\vec{B}_0$ is applied at t = 0 moment in time we will actually obtain a new, equivalent true scalar magnetometer (TSM)

Experiment

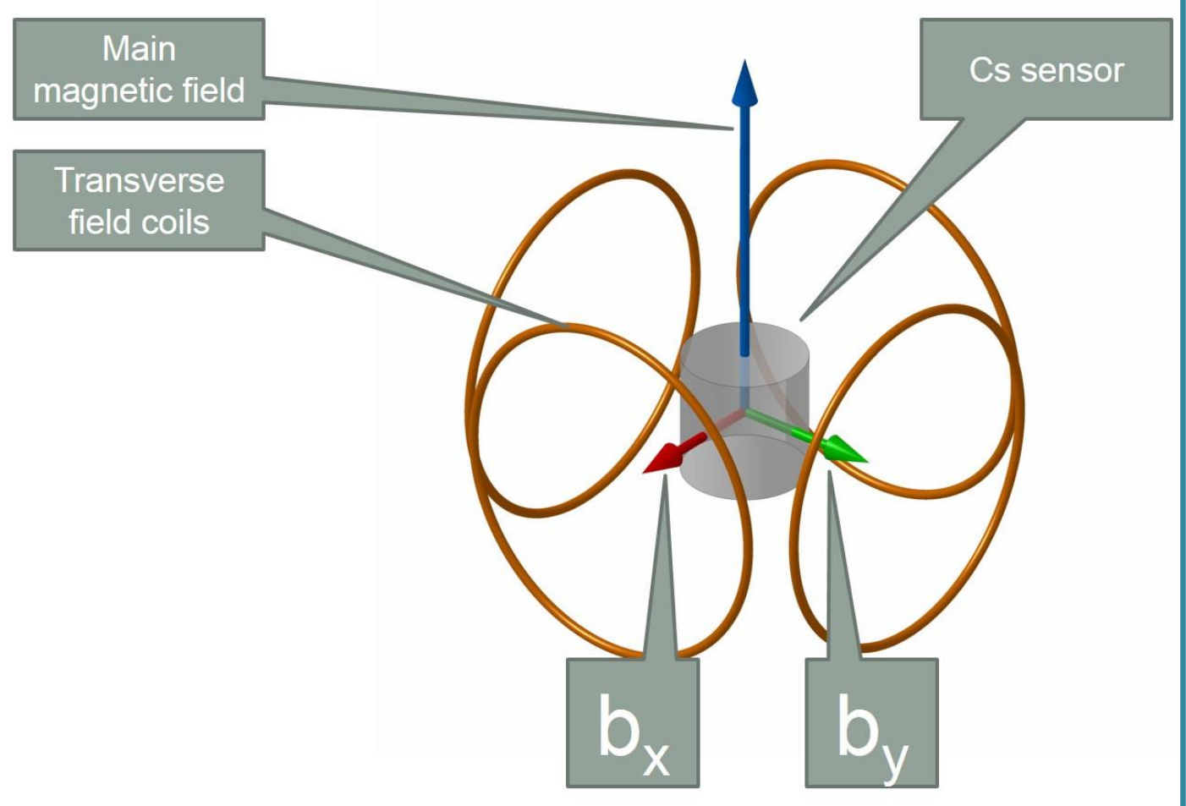


Figure 3: Experiment scheme.

- As a sensing element we employ paraffin coated cell filled with Cs.
- A single light source is used for both pumping the medium and probing.
- Pump light is circularly polarized.
- The wave vector and RF magnetic field that drives the spin precession are at 45° with the respect to the main static magnetic field B_0 as presented on Fig. 1.
- The sensor head is placed inside a three layer mu-metal shielding.
- Changes of the magnetometer response are detected with a lock-in amplifier, which enables us to obtain in-phase and quadrature components of the transmitted probe signal.

Theoretical and analytical study

- Theoretical study is based on the transient Bloch equation.

$$\dot{\vec{S}}(t) = \vec{S}(t) \times \vec{\Omega}(t) - \gamma \vec{S}(t) + \gamma_p(\vec{k} - \vec{S}(t))$$

- Analytically, the equation is solved in rotating frame after applying a rotating wave approximation (RWA), as it is simplest way to solve it.
- The spin orientation will precess around z axis thus this will be our rotation axis at frequency ω_{rf} and in the same clockwise direction.
- The essence of the RWA approximation is to disregard components rotating in opposite direction of the spin, as they have lower impact than co-rotating one.
- In rotating frame, static magnetic field and and k vector are:

$$\vec{\Omega}^{R} = \vec{\Omega}^{R}_{rf} = \Omega_{rf}\begin{pmatrix} 0 \\ \sin\alpha \\ 0 \end{pmatrix}, \quad \text{and} \quad \vec{k}^{R} = \begin{pmatrix} 0 \\ 0 \\ \sin\alpha \end{pmatrix}.$$

- Obtained equation is free from time dependent coefficients so it can be solved analytically. We will split the solution into stationary and transient part.

$$\vec{S}^{R}(t) = \vec{S}^{RS} + \vec{S}^{RT}$$

- The spin orientation in laboratory frame $\vec{S}^{L}(t)$ is obtained after multiplying solution in rotating frame by rotation matrix.
- And for phase calculation we obtain:

$$\Delta\theta'_x(t) = -\frac{\pi}{2} - \arctan\left(\frac{-e^{-(\gamma+\gamma_p)t}(\gamma+\gamma_p)\sin(\beta)}{\Omega_{rf}\sin(\alpha) + 2e^{-(\gamma+\gamma_p)t}(\gamma+\gamma_p)\sin^2(\beta)\sin(\Omega_{rf}\sin(\alpha)\,t)}\right)$$

$$\Delta\theta'_y(t) = -\frac{\pi}{2} - 0$$

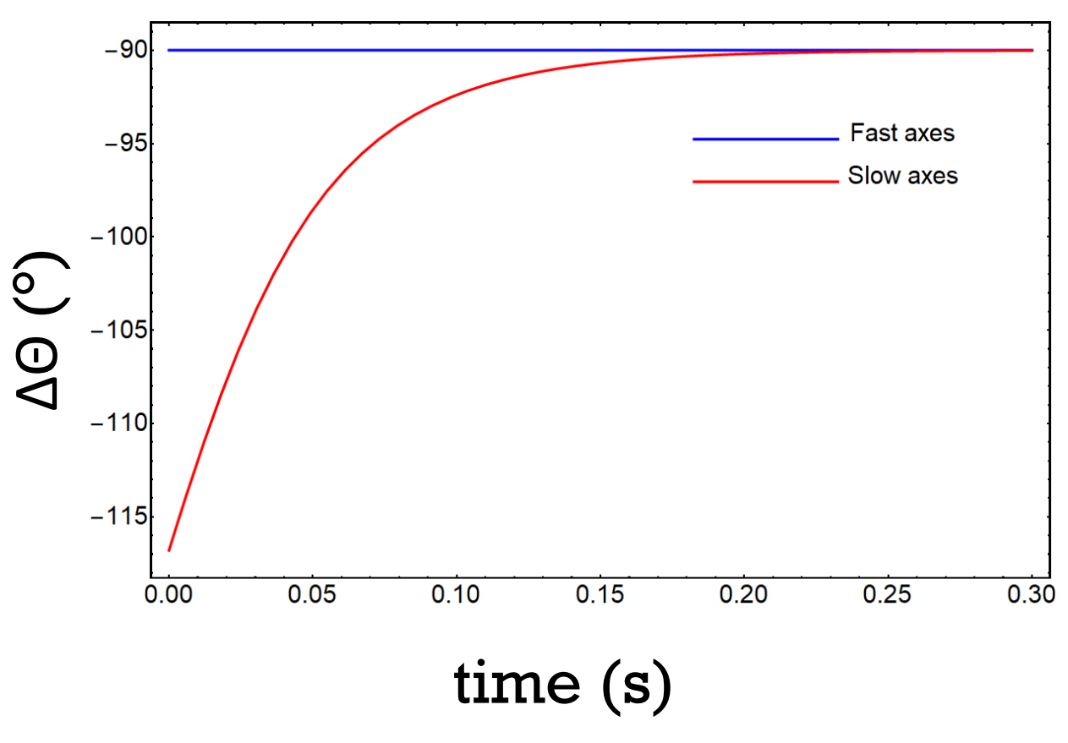


Figure 4: Phase evolution in case of "fast" and "slow" axis.

In a new coordinate system we obtain that rotation of the $\vec{B}_0$ around $\hat{y}$ doesn't cause any phase shift in TSM magnetometer (fast axis), while rotation around $\hat{x}$ cause transient (Fig.4).

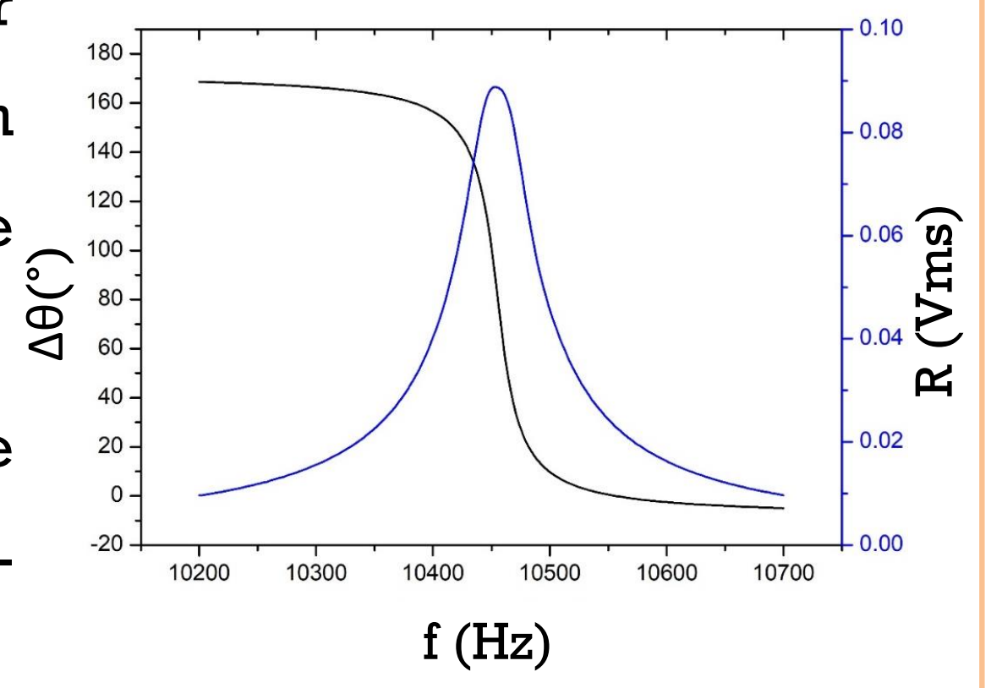
References

[1] A. Weis, G. Bison, Z.D. Grujic, High Sensitivity Magnetometers – Magnetic Resonance Based, Atomic Magnetometers, Springer, pp 361-424 (2016).

Magnetic resonance

By sweeping the frequency of the rf magnetic field over Larmor frequency we observe Lorentzian resonance in amplitude R signal with maximum at $\Omega_L = \Omega_{rf}$, and a signal's phase swing from 180° to 0°, where phase of 90° corresponds to resonant conditions.

The dispersive shape of the phase curve is used to directly determine value of $|B|$ in free running magnetometers and to actively tune Ω_{rf} in so-called PLL loop.



Experimental and numerical results

The phase evolution obtained from experiment, when excitation by magnetic field is in the transverse direction, is presented in the following figures, around slow axis (Fig. 5) and fast axis (Fig. 6).

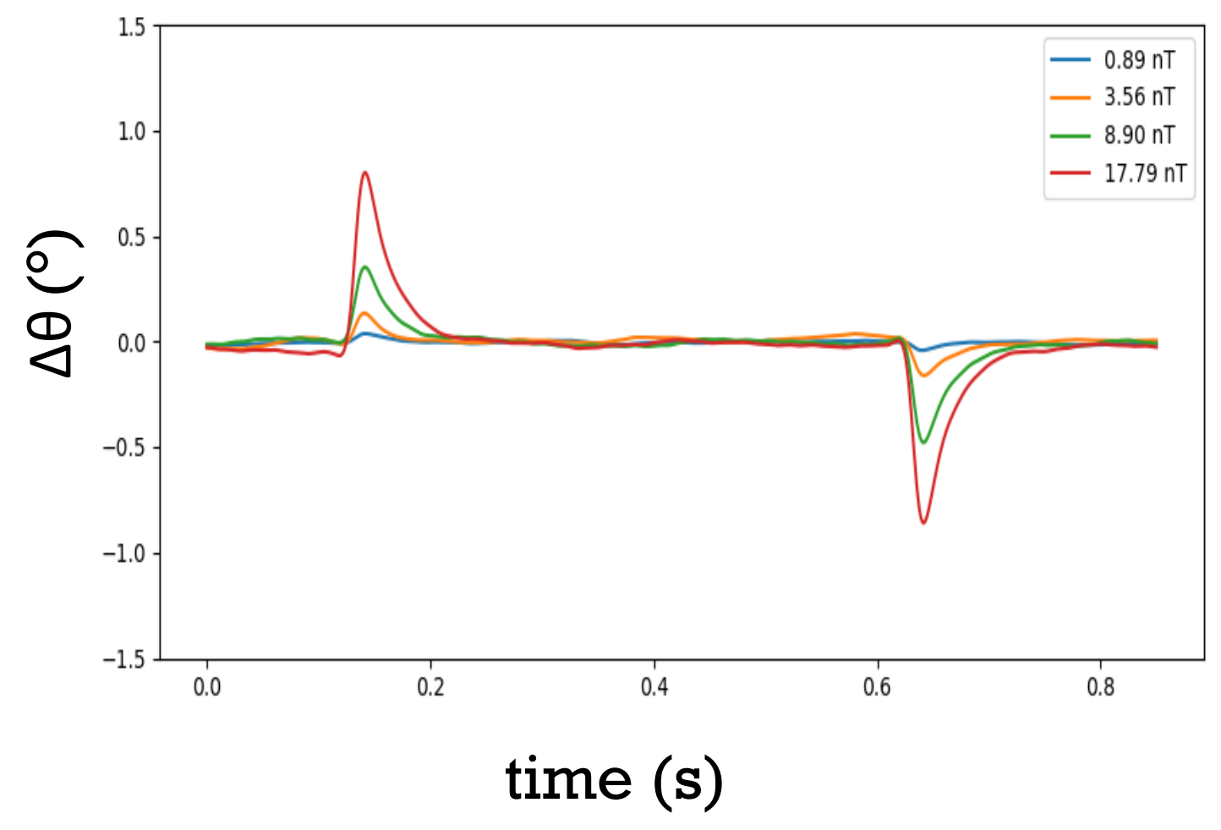


Figure 5: Phase evolution around slow axis.

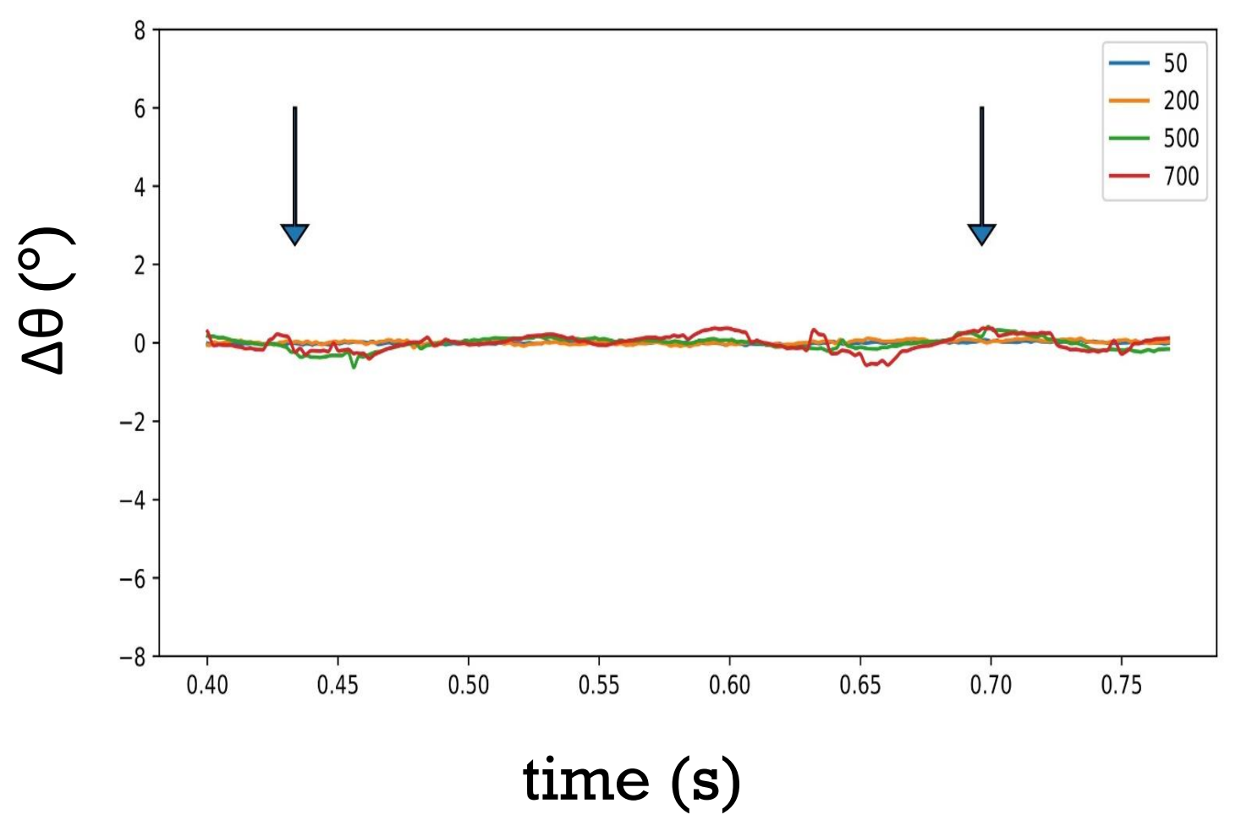


Figure 6: Phase evolution around fast axis.

The phase response from numerical results, when M_x magnetometer is in the free running mode, is presented in the following figures, Fig. 7 for slow axis and Fig. 8 fast axis.

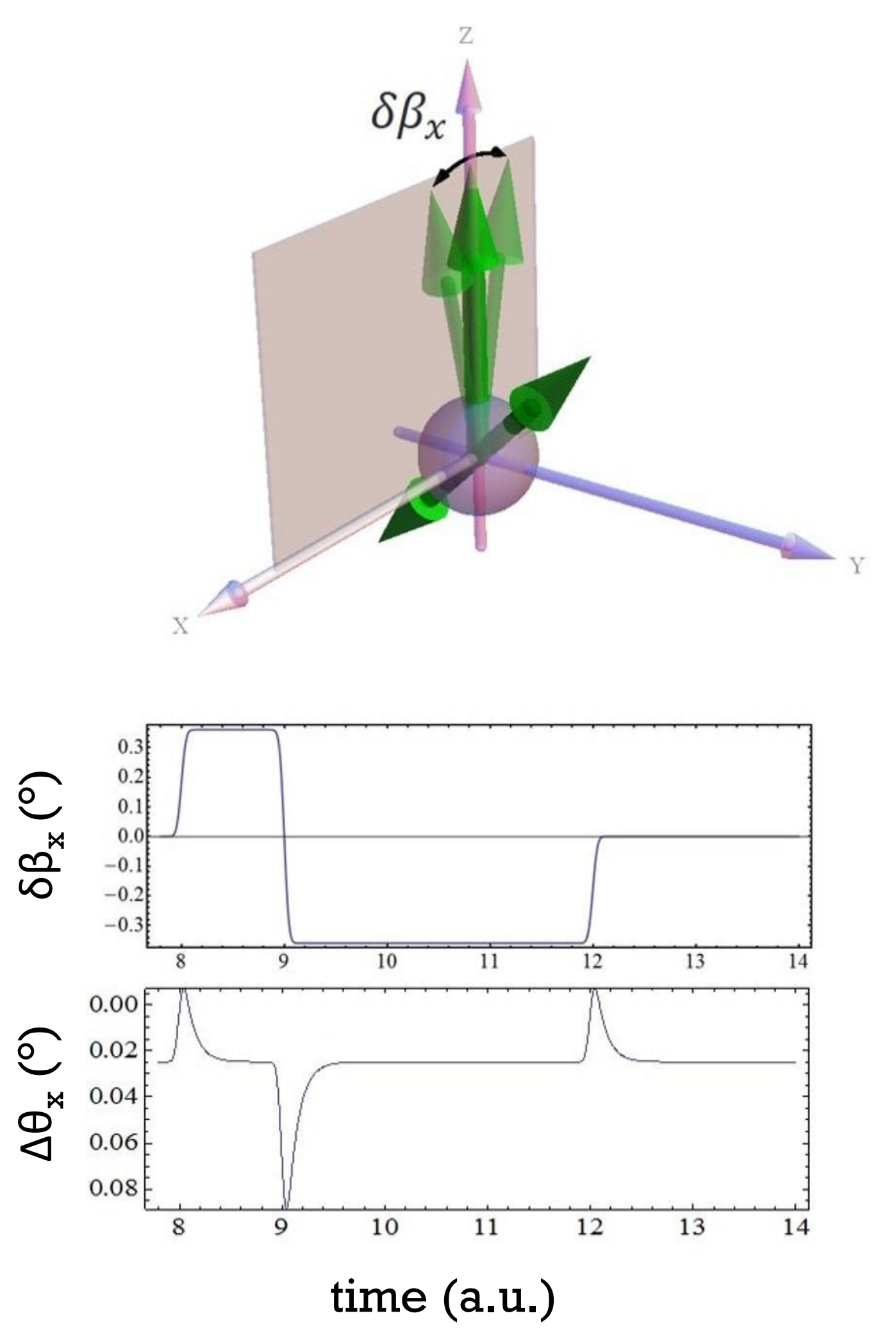


Figure 7: Phase evolution around slow axis.

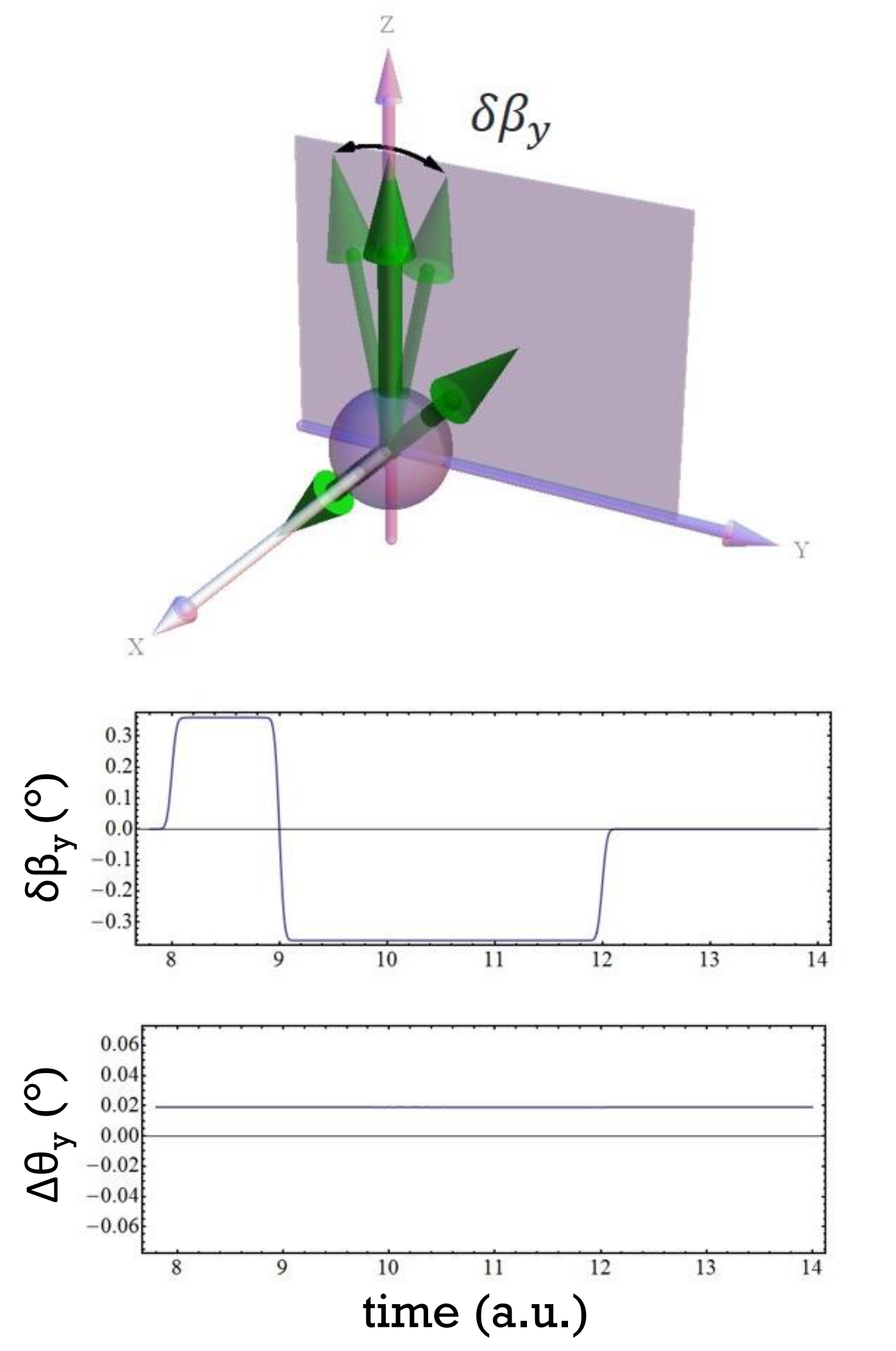


Figure 8: Phase evolution around fast axis.

Conclusion

Being a true scalar magnetometer, our sensor should not experience any changes in the measured phase depending on the orientation of the applied modulating field. However, both experimental measurements and model predictions have demonstrated this is not the case.

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