# Levitated magnetic particles as ac magnetic  ield sensors

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Exploiting the precession of a levitated magnetic particle in ultra-high vacuum, it is shown that ac magnetic fields smaller than a picotesla can be detected. It is also argued that this new AC magnetometer will have a large dynamic range of more than a millitesla and can be continuously tuned over several GHz. Such a magnetometer can be used as a receiver for electromagnetic waves.

## I. INTRODUCTION

Detecting weak electromagnetic (EM) fields has applications in radar, communications and fundamental science [1, 2]. Traditionally, EM fields are detected using antennas which once made cannot be changed and hence are not tunable and have a relatively narrow frequency range. In principle, EM fields can be detected using either an electric or a magnetic field sensor. Examples of tunable electric field sensors include Rydberg atoms [3, 4]. Such sensors can only detect discrete frequencies where they are most sensitive. Existing magnetic field sensors such as atomic vapours [5] and the nitrogen-vacancy centre (NVC) in diamond based sensors [6] are predominantly used as dc field sensors, although some progress has been made towards the detection of EM fields using NVCs in diamond [7]. Such magnetic field sensors have a relatively small dynamic range e.g., $\leq \mu T$ . Atomic vapour-based sensors also require magnetic shields. Superconducting quantum interference devices-based magnetometers are excellent magnetic field sensors but require cryogenic temperatures [8].

Levitation in vacuum provides a contactless and a near-frictionless environment. This makes levitated particles very susceptible to external stimuli making them extremely good sensors. For example, using the center-of-mass motions of such particles zeptonewton scale force sensitivity has been achieved [9]. Likewise, exploiting the rotational motion of a levitated particle, torque as small as $4.7 \times 0^{-28}$ N m has been measured [10]. Among levitated particles, magnetic particles are unique in the sense that they contain an extra degree of freedom e.g., the spin which makes them even more versatile. The coupling between the spin and the other degrees of freedom of a levitated magnetic particle has not been explored yet but is promising for developing new technologies and exploring fundamental physics [11].

In this article, using the precessional motion of a levitated magnetic particle in ultra-high vacuum, it is shown that extremely weak electromagnetic waves can be detected. Such a magnetometer has a dynamic range over a millitesla and can be continuously tuned for several GHz.

## II. THEORETICAL MODEL

Consider a magnetic sphere of magnetic moment $\mu$ is levitated in vacuum. A homogeneous dc magnetic field $B_0$ is applied along the $z$ direction which ensures $\mu$ aligns with $B_0$ (Fig. 1). Given that in a ferromagnetic or ferrimagnetic material spins and thus magnetization are attached to the crystal lattice via the magnetocrystalline anisotropy [12] and levitated particles are free to move, such objects spontaneously align with $B_0$ like magnetization. In addition to ensuring the alignment of the magnetization along a chosen direction, $B_0$ also determines the frequency at which spins or magnetization can be manipulated. In particular, when spins are exposed to rotating electromagnetic waves in the $x - y$ plane e.g., $\mathbf{b_s} = b_x \cos \Omega_0 t \, \hat{x} + b_y \sin \Omega_0 t \, \hat{y}$,

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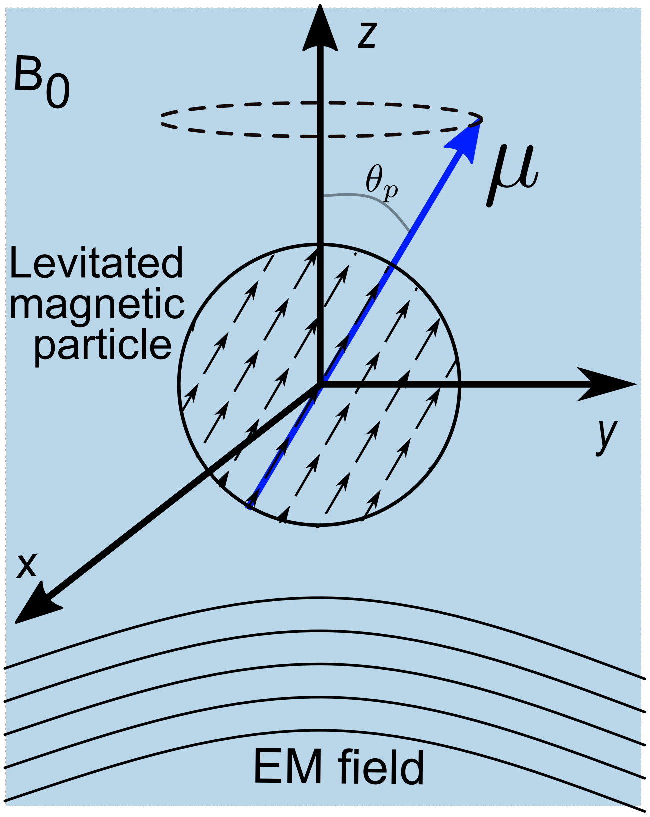

FIG. 1. Levitated magnet precessing around a dc magnetic field $B_0$ when exposed to an electromagnetic wave. The blue background represents the homogeneous dc magnetic field $B_0$ while the curved lines indicate electromagnetic waves.

they are subjected to torques and attempt to precess around $B_0$ [13]. In ultra high vacuum where the damping due to gas molecules can be neglected, the levitated magnetic particle precesses at the frequency of the incoming electromagnetic waves. By measuring the precession rate, the frequency of the unknown EM wave can be determined. The linewidth of such a driven precessional motion can be mHz or smaller [14] implying a highly accurate frequency measurement. Most importantly, the precession frequency of the levitated magnet and thus the frequency of the field to be detected can be continuously tuned by changing $B_0$. The lowest frequency that can be detected using such a magnetometer is determined by the saturation magnetization of the levitated particle while the highest frequency is determined by the potential shearing of the levitated particle due to precession.

The strength of the unknown magnetic field is proportional to the angle of precession of a levitated magnetic particle. The angle of precession ($\theta_p$) is maximum when the frequency of the incoming electromagnetic wave is equal to the ferromagnetic resonance (FMR) of levitated particle i.e. $\Omega = \gamma B_0$ [13]. $\theta_p$ can be measured using the rotational Doppler effect. That is the rotational Doppler shift that a circularly polarized light beam or light with orbital angular momentum propagating parallel to $B_0$ encounters while interacting with a precessing magnetic particle is a function of the precession angle [15] -

$$\Omega_D = 2\Omega_0 \cos\theta_p, \tag{1}$$

where $\Omega_D$ is the Doppler shift suffered by the scattered light. On FRM, $\theta_p$ can be found from the geometrical consideration i.e., $\sin\theta_p = b_s/\sqrt{b_s^2 + B_0^2}$. Given that $b_s$ is expected to be significantly smaller than $B_0$, one can approximate $\theta_p \approx b_s/B_0$. From the difference $\Delta\Omega$ between the measured ($\Omega_D$) and the expected ($2\gamma B_0$) Doppler shifts, the strength of the AC magnetic field can be found. That is

$$\begin{aligned} \Omega_D &= 2\Omega_0 \cos\theta_p \\ &\approx 2\Omega_0(1-\theta_p) \\ \theta_p &= \frac{2\Omega_0 - \Omega_D}{2\Omega_0} \\ b_s &= \frac{B_0\Delta\Omega}{2\Omega_0} \\ &= \frac{B_0\Delta\Omega}{2\gamma B_0} \\ &= \frac{\Delta\Omega}{2\gamma}, \end{aligned} \tag{2}$$

where we have used $\Delta\Omega = 2\Omega_0 - \Omega_d$ and $\Omega_0 = \gamma B_0$. From Eq. (2), it is obvious that the smallest field that can be measured is determined by how accurately one can measure the rotation frequency e.g., $\Delta\Omega$. Importantly, due to the driven nature of the precessional motion we are considering here, such frequencies can be measured with a resolution better than a mHz [14]. As a result, the measurement of frequency is very accurate. Assuming $\Delta\Omega = 10^{-3}$ Hz, the minimum detectable field is $1.78 \times 10^{-14}$ T. When converted to electric fields, we have $E = cb_s = 5.5 \times 10^{-6}$ v m$^{-1}$, where $c$ is the speed of light in vacuum. This is comparable to the best electric field sensor [3]. However, the new magnetometer does not require any tunable lasers and a microwave source which are generally very costly.

The dynamic range of the magnetometer in regards to the amplitude of $b_s$ can be understood from Eq. (1). That is as the strength of the field to be detected increases so does the precession angle thus the the Doppler shift. Measuring a larger Doppler shift is easier than a small shift. As a result, the sensitivity of the new magnetometer does not degrade with the increasing magnetic field. This is in contrast with other magnetometers [5, 6, 8]. However, the strength of the unknown magnetic field must be $\ll B_0$. Otherwise, the approximation made in deriving (2) breaks down. Generally, the $B_0$ is in tens of millitesla implying a large dynamic range e.g., picotesla to millitesla for a levitated magnet-based magnetometer.

## III. CONCLUSIONS

In conclusion, it has been shown that levitated magnetic particles can be used as AC magnetic field sensors. Such a magnetometer can be tuned over several GHz and remains sensitive even when fields to be detected vary by a millitesla.

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