Accuracy before sensitivity: Magnetically-silent vector magnetometer a new tool for nEDM search

Z. D. Grujić, P. Knowles, and A. Weis

Department of Physics, University of Fribourg, Switzerland

Scope

The study of magneto-optics, the interactions of resonant light with atoms in magnetic fields, has long served as the basis of optical magnetometers [1, 2]. The resulting magnetometers fall into two broad classes; driven magnetometers, where some form of feedback maintains a resonance condition, and free induction decay (FID) magnetometers, where an initial spin polarization is prepared and subsequently monitored during the natural decay of the system's transient response. One advantage of FID magnetometers when compared to driven magnetometers such as the optically detected magnetic resonance M_x-method [3, 4], is that FID magnetometers are self-calibrating. The free nature of the precession makes it possible to measure the absolute value of the magnetic field.

For many applications it is preferable that the magnetometer operation does not disturb the environment being measured, as occurs, i.e., by the rf magnetic drive field of the M_x magnetometer, or by the spin-manipulation ($\pi/2$) pulses used for FID magnetometers.

In this contribution, we detail our progress toward a magnetically silent (all-optical) magnetometer based on Bell-Bloom pumping. Pumping with strong laser beam creates a magnetization of the Cs atoms contained in an antirelaxation coated vacuum cell. Following the creation of spin polarization, a weak probe beam measures the resulting FID. The direction and amplitude of the magnetic field are reconstructed by monitoring the transmitted light intensity of three nonparallel beams traversing the vapor cell.

Resonant optical pumping

The spin orientation $\vec{S}$ of the Cs vapor is produced by circularly polarised light resonant with the $F = 4 \rightarrow F = 3$ transition of the D_1 line. The light power is modulated by a square wave with a frequency approximately equal to the Larmor frequency ω_L. An orientation S_z^{max} is created by this Bell-Bloom pumping scheme. The absorption coefficient of the polarised medium is given by

$$\kappa_0 \rightarrow \kappa_0 (1 - S_z),$$

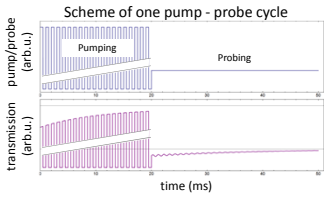
so that the transmitted light power (in the optically thin medium) becomes

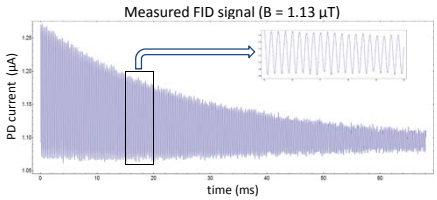
$$P(t) \approx (1 - \kappa_0 L) P_0(t)$$
$$= (1 - \kappa_0 L) \frac{P_S}{\gamma} \Gamma_p(t) + \kappa_0 L \frac{P_S}{\gamma} \Gamma_p(t) S_z(t),$$

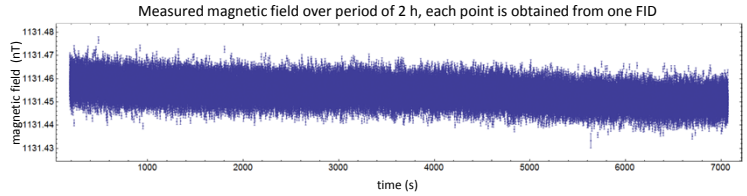
where $\gamma (=\gamma_1 = \gamma_2)$: polarization relaxation rate
$\Gamma_p(t) = \gamma P_0(t)/P_S$: optical pumping rate
P_s : optical pumping saturation parameter

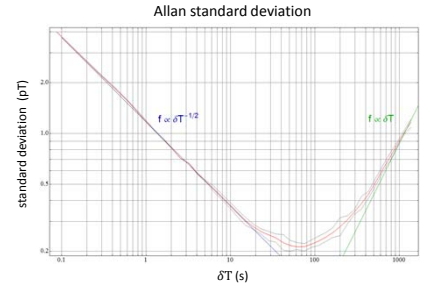
After pumping, the light power is attenuated to a probe level Pp, and the transmitted power P(t) is given by

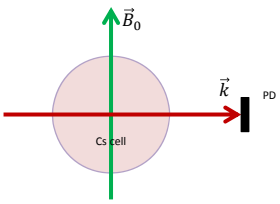
$$P(t) = (1 - \kappa_0 L) P_p + \kappa_0 L P_p S_z^{max} e^{-\gamma t} \sin \omega t$$











Three-beam vector magnetometer

We record FID signals using a 16 bit vertical resolution digital oscilloscope. We then remove the low frequency background and high frequency noise from the raw FID data using a finite response (FIR) band pass filter, similar to the method described in [5]. The frequency and phase of the individual FID signals are inferred fitting the time dependent part of Eq. (1) to the data, while the orientation (θ, φ) of the magnetic field is determined by the relative phases of the three signals.

We estimate that the fundamental Cramér-Rao lower bound (CRLB) for the frequency determination (at B=4 μT) is 2 pT. The fits yield typical standard errors of 3 pT for a single FID measurement, and a 1.6 mrad (preliminary) error for the field direction. One measurement cycle is 50 ms. With 20 cycles per second this yields a statistical (absolute) accuracy of ±700 fT for $|B|$ (2×10^{-7} relative uncertainity) and ±400 μrad for $\vec{B}$.

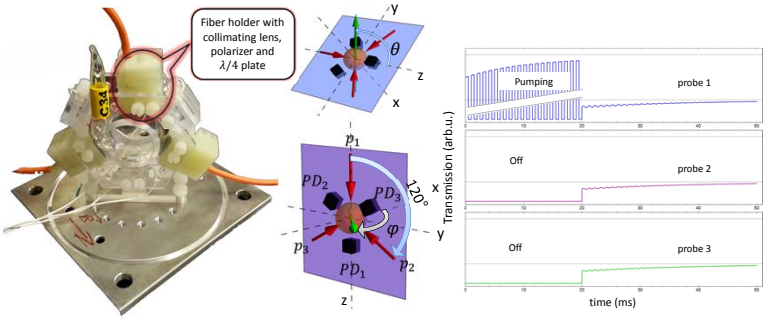
References

[1] D. Budker and M. Romalis, Nat. Phys. 3, 227 (2007)
[2] D. Budker, W. Gawlik, D. F. Kimball, S. M. Rochester, V. V. Yashchuk, and A. Weis, Rev. Mod. Phys. 74, 1153 (2002).
[3] E. Alexandrov, M. Balabas, A. Pazgalev, A. Vershovskii, and N. Yakobson, Laser Phys. 6, 244 (1996).
[4] S. Groeger, G. Bison, P. Knowles, R. Wynands, and A. Weis, Sensors and Actuators A 129, 1 (2006).
[5] E. Breschi, Z. Grujic, A. Weis, submitted to Appl. Phys. B, 2013.
[6] N. Castagna, G. Bison, G. Domenico, A. Hofer, P. Knowles, C. Macchione, H. Saudan, and A. Weis, Appl. Phys. B 96, 763 (2009).

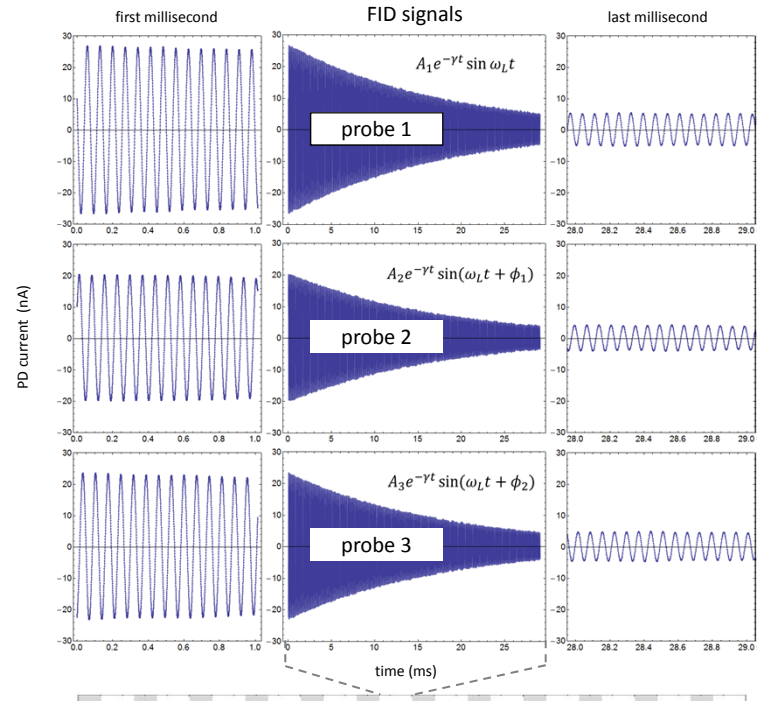
work supported by FNSNF

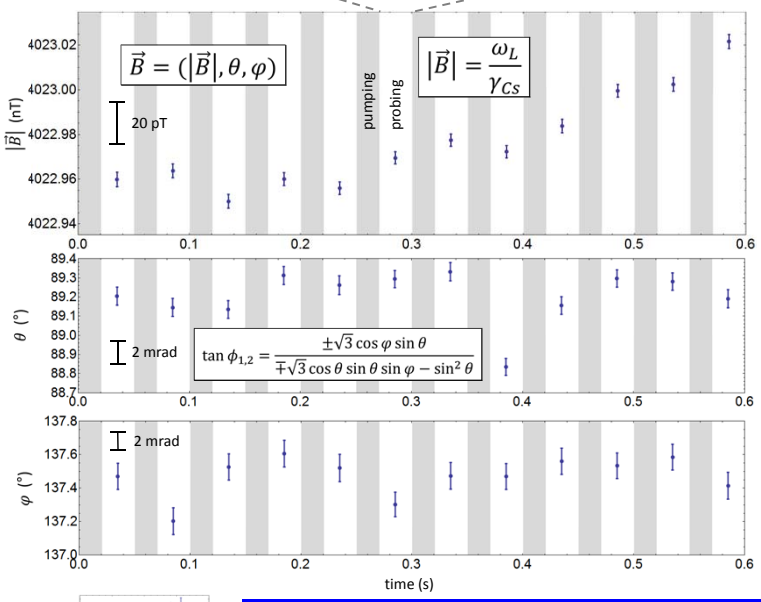
Experiment

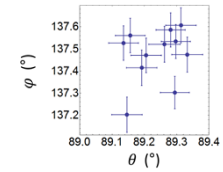
Our sensor consists of a Cs vapor cell with antirelaxation coating [6], three fiber couplers and three photodiodes. The power of the pump beam is controlled by a fiber-coupled electrooptical modulator. The two additional probe beams are turned off by two AOMs during pumping. All materials used for construction are nonmagnetic and vacuum compatible.



Results







Conclusion

We demonstrate an atomic vector magnetometer in a proof-of-principle experiment. Our design targets absolute accuracy rather than sensitivity. Future development will be devoted to offline data analysis. We intend to make modules with highly accurate geometry since this currently sets limit on the precision of the measured magnetic field direction $\vec{B}/|\vec{B}|$.