Measurement of Magnetic Field Stability Using $^{40}Ca^{+}$ ion

Tuan Minh Pham, Adam Lesundak, Martin Cizek, Simon Rerucha, Petr Jedlicka Josef Lazar, Ondrej Cip.
Department of Coherence Optics, Institute of Scientific Instruments of the CAS, Brno, Czech Republic,
Email: tuan@isibrno.cz

Lukas Podhora, Lukas Slodicka
Department of Optics,
Palacky University, Olomouc, Czech Republic

***Abstract*— in this paper, we present the preliminary results of a local magnetic field measurement at the position of $^{40}Ca^{+}$ ion. We employ the simultaneous locking of the frequency of clock laser onto two transitions of Zeeman sublevels on transition 4s $^2S_{1/2}$ (m=-1/2) − 3d $^2D_{5/2}$ (m=-1/2 and -5/2). The frequency deviation from the spectral line center of both selected Zeeman transitions determines the magnetic field value on basis of the linear Zeeman shift thus one can estimate the clock frequency of the unperturbed 4s $^2S_{1/2}$ − 3d $^2D_{5/2}$ transition.**

Keywords—magnetic field stability; Zeeman sublevels; frequency stability.

I. INTRODUCTION

The enhancement of the accuracy and stability of the absolute frequency measurement of a 4s $^2S_{1/2}$ − 3d $^2D_{5/2}$ clock transition of an ultra-cold $^{40}Ca^{+}$ ion trapped in a radiofrequency trap would greatly increase the reliability of an optical clock as an ultraprecise frequency standard. Among these fundamental interests, optical frequency standards based on $^{40}Ca^{+}$ isotope would benefit for a broad usability and convenience of this isotope for laser cooling and efficient readout, which alleviates the need for the overall infrastructure and for the quantum logic spectroscopy. Generally one of the main limitations in the realizations of measurements of optical stability of optical clocks corresponded to the magnetic field fluctuations and Zeeman shifts, [1], [2]. The time-varying fluctuations of an external magnetic field of lead to frequency shifts of Zeeman splitting components and thus reduce the frequency stability of the optical clock over time, [3] and [4]. In addition to the spatial stability of the magnetic field, the homogeneity of the magnetic field within the linear Paul trap is especially important when working with Coulomb crystals as ions are stretched over a large area. One can significantly reduce the excessive magnetic perturbation by covering the setup with the magnetic shield or use permanent magnets instead of conventionally used magnetic coils, [5]. Another method is by averaging over transition to multiple hyperfine levels, [6]. This paper covers a simple method to measure the stability of the magnetic field in the position of the ion.

II. METHODS/RESULTS

Our setup consists of an ultra-high vacuum chamber with a linear Paul trap, where we can hold up to thousands of trapped $^{40}Ca^{+}$ ions. A set of a frequency stabilized lasers are used for laser cooling, quantum state control, and electron shelving. The detection of ion fluorescence at 397 nm is realized by single-photon avalanche photodetector. Using an optical frequency comb and transfer oscillator technique we have locked a spectroscopy laser working at 729 nm to a sub-Hertz reference laser (1540 nm), which is stabilized by a high-finesse cavity resonator with a finesse over 400000. The long term stability of the comb is ensured with an active H-maser. The method of measuring the magnetic field stability in the position of the ion is realized as a measurement of the frequency drift of the clock laser while it is locked onto several Zeeman components. An AOM is used to tune the frequency of the clock laser onto two selected Zeeman transitions, namely $S_{1/2}$ (m=-1/2) to $D_{5/2}$ (m=-1/2) and $S_{1/2}$ (m=-1/2) to $D_{5/2}$ (m=-5/2) (see Fig. 1). Each transition has its independent digital servo loop controller. The AOM is then multiplexing between the two targeted frequencies that include a corrective action for the clock laser.

Fig. 1. Detailed view of Zeeman components of the clock transition for $^{40}Ca^{+}$ ion.

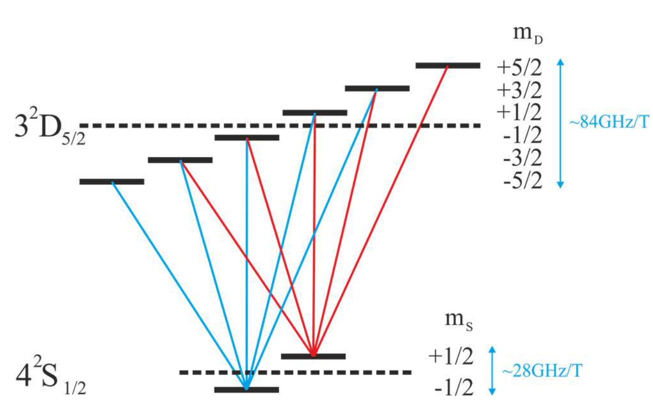
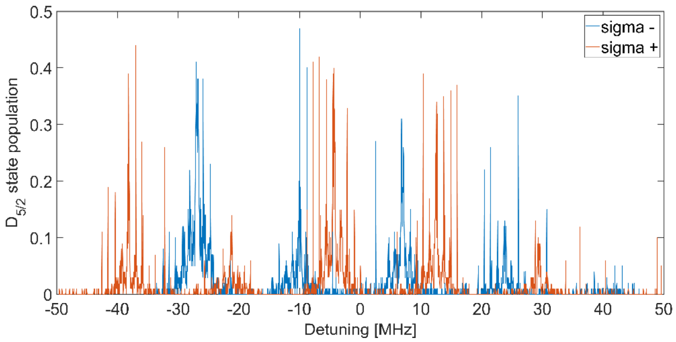
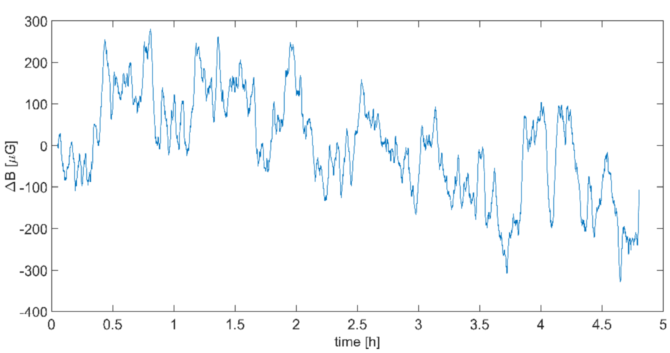


Fig. 2. Frequency scans over the Zeeman components for both $S_{1/2}$ ground states.



These two Zeeman sublevels are separated by 33.757 MHz (see Fig. 2). The $S_{1/2}$ (m=-1/2) to $D_{5/2}$ (m=-5/2) transition is five times more sensitive and has an opposite correlation to magnetic field than the other transition. The interrogation electron shelving sequence uses a Ramsey scheme with two short $\pi/2$ pulses separated by a non-interaction waiting time of τ ramsey $\approx$ 100 μs. The Ramsey time and the whole pulse sequence length are optimized to allow for fast bandwidths of the magnetic field sensing. The intensities of the 729 nm laser pulses for the individual Zeeman transitions were adjusted to get similar excitation times of $\tau \approx 20$ µs. To get a better signal-to-noise ratio, each measured point at both transitions is repeated 100 times. The frequency analysis of the ion state and tuning of the AOM to appropriate transitions are done sequentially with servo loop controllers. Fig. 3 shows the calculated magnetic field during 5 hours: the average value is 10.049 G with a standard deviation of 122 µG which corresponds to 71 Hz for less sensitive transition ($S_{1/2}$ (m=-1/2) to $D_{5/2}$ (m=-1/2).

Fig. 3. The measurement data of the magnetic field at the position of the ion.



III. Conclusions

Although the effect of such a fluctuation of the magnetic field measured by the ion can be significantly reduced thanks to the mentioned method of simultaneous control of the clock laser frequency on two Zeeman sub-levels, the installation of a magnetic shielding box around the ion trapping vacuum apparatus is currently undergoing. The assumed attenuation factor of the box is greater than 1000. However, even in these improved conditions, the presented method can be used to verify the achieved stability of the magnetic field and evaluate the field gradients relevant for the optical frequency metrology with large ion crystals.

Acknowledgment

The work has been performed within project 17FUN07 CC4C. This project 17FUN07 CC4C has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. The research was also supported by projects: 19-14988S (GA CR) and CZ.02.1.01/0.0/0.0/16_026/0008460 (MEYS CR).

References

[1] Benhelm, J., Kirchmair, G., Rapol, U., Körber, T., Roos, C. F., & Blatt, R. (2007). "Measurement of the hyperfine structure Of theS1/2−D5/2transition inCa+43,". Physical Review A, 75(3).

[2] Shapira, Y., Dallal, Y., Ozeri, R., & Stern, A. (2019). "Measuring magnetic fields with magnetic-field-insensitive transitions,". Physical Review Letters, 123(13).

[3] Aharon, N., Spethmann, N., Leroux, I. D., Schmidt, P. O., & Retzker, A. (2019). "Robust optical clock transitions in trapped ions using dynamical decoupling,". New Journal of Physics, 21(8), 083040.

[4] Itano, W. , Bergquist, J. , Bollinger, J. , Gilligan, J. , Heinzen, D. , Moore, F. , Raizen, M. and Wineland, D. (1993), "Quantum Projection Noise: Population Fluctuations in 2-Level Systems,", Physical Review A (Atomic, Molecular and Optical Physics).

[5] Ruster, T., Schmiegelow, C. T., Kaufmann, H., Warschburger, C., Schmidt-Kaler, F., & Poschinger, U. G. (2016). "A long-lived Zeeman trapped- ion qubit,". Applied Physics B, 122(10).

[6] Barrett, M. D. (2015). "Developing a field independent frequency reference,". New Journal of Physics, 17(5), 053024.