Microwave frequency standard based on $^{25}\text{Mg}^+$ ions

I Zalivako$^{1, 2, 3}$, I Semerikov$^{1, 2}$, A Borisenko$^{1, 2, 3}$, K Khabarova$^{1, 2, 4}$, V Sorokin$^1$ and N Kolachevsky$^{1, 2, 4, 5}$

$^1$P. N. Lebedev Physical Institute of the Russian Academy of Sciences, 119991, 53 Leninsky prospekt, Moscow, Russia
$^2$Russian Quantum Center, Business-Center Ural, 143025, 100A Novaya st., Skolkovo, Moscow, Russia
$^3$ Moscow Institute of Physics and Technology (State University), 141700, 9 Institutskiy per., Dolgoprudny, Moscow region, Russia
$^4$All-Russian Scientific Research Institute of Physical-Technical and Radiotechnical Measurements, 141570, Mendeleev, Moscow region, Russia
$^5$National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409, 31 Kashirskoe sh., Moscow, Russia

E-mail: zalivako.ilya@yandex.ru

Abstract. Development of compact transportable frequency standards is an important goal of the modern applied physics. Despite of the great progress in the field of optical frequency standards with their ultimate accuracy and stability, they remain bulky, complex and sensitive systems. At the other hand, the best microwave frequency standards like cesium fountains are also bulky and sensitive to adjustments. Combination of techniques developed for optical and microwave standards can result in compact and robust transportable frequency standard. Here we suggest the microwave transition in $^{25}\text{Mg}^+$ laser cooled ion cloud for realization of highly accurate microwave frequency reference. We describe its design and experimental sequence, estimate its expected accuracy and stability.

1. Introduction
The progress in the field of frequency standards impacted wide range of technologies and opened new possibilities for modern fundamental research. Highly stable frequency standards are used for global navigation satellite systems (GNSS) [1] and fast data transfer using telecommunication links [2]. They are applied in radioastronomy and tests of fundamental theories like Einstein equivalence principle [3], searching for exoplanets and gravitational waves detection.

Most of today’s ultimately accurate and stable clocks utilize optical transitions in neutral atoms confined in optical lattices or transitions in single ions confined in radio-frequency traps. Such clocks show short-term relative instability on the level of $2 \times 10^{-18}$ and fractional inaccuracy reaching $2.1 \times 10^{-18}$ [4, 5]. However these systems are still very complex, sensitive to misalignments and vibrations, heavy and bulky. Also optical frequency standards require femtosecond frequency combs for frequency conversion from optical to radio-frequency domain. All these factors restrict their applications in many applied fields. There are several groups working on development of compact and transportable optical
clocks [6, 7] but the volume and mass still appear to be inappropriate for e.g. practical usage on the
GNSS satellites.

Another approach relies solely on highly stable Fabry-Perot cavity as a frequency reference. The
laser stabilized to e.g. a cavity made from Ultra-Low Expansion (ULE) glass or crystalline silicone
provides prominent short-term frequency instability of order 10^{-16} [8, 9]. However, for the long
integration time (more than 10^3 s) the frequency stability is insufficient for most of today’s
applications due to long-term drifts coming from temperature fluctuations and recrystallization of
cavity’s material.

At the moment the best tradeoff between frequency stability, mass and robustness is achieved for
radio-frequency clocks based on clouds of neutral atoms or ions. Today all GNSSs use such standards
as on-board timekeepers. The most widespread spaceborn atomic clocks (installed on GPS,
GLONASS, GALILEO, BEIDOU, IRNSS and QZSS satellites) are based on Rb gas cells and Cs
atomic beams. These Rb clocks have mass of around 3 kg and their relative instability reaches 10^{-14}
level after 8 hours of averaging [10]. Another promising on-board frequency standard which is
currently being installed on GALILEO satellites is a passive hydrogen maser. While having higher
mass, close to 12 kg, H-maser exhibit higher both short- and long-term stability [10]. Corresponding
Allan deviation reaches 2×10^{-15} in relative units. Along with better stability, passive hydrogen masers
show lower frequency sensitivity to temperature fluctuations. However they are subjected to rare but
significant frequency jumps caused by degradation of a hydrogen cell.

Ion radio-frequency clocks are also of great interest for space applications. In contrast to clocks
discussed in previous paragraph, which are based on neutral atoms in gas cells or atomic beams, ions
are stored in radio-frequency Paul traps. This ensures long interaction time between ions and
interrogation field, absence of collisions between ions and cell walls which provides better frequency
stability and accuracy. At the same time Paul traps are very robust and have trap depth on the order of
several eV. At the moment several groups worldwide are developing atomic clocks where microwave
transitions between hyperfine components of ground state in ions are used as a frequency reference.
^{199}Hg^{+} [11], ^{137}Ba^{+} [12], ^{9}Be^{+} [13], ^{171}Yb^{+} [14] and ^{113}Cd^{+} [15] ions are under investigation. The Deep
Space Atomic Clock developed in JPL [16] and based on ^{199}Hg^{+} ions trapped in combined quadrupole
and 16-pole Paul trap worth special attention. It was designed for spacecraft navigation in deep space
and exhibit stability by the order of magnitude better than clocks currently used in GNSSs, however
they are still more heavy (17.5 kg). Relative instability of this clock after 24 hours of averaging is on
the level of 2×10^{-15}. Space tests of this clock are scheduled to be carried out this year.

Here we consider design and estimate characteristics of a new transportable radio-frequency atomic
clock based on a laser cooled cloud of ^{25}Mg^{+} ions trapped in a linear quadrupole Paul trap. Magnetic
dipole transition at 1.789 GHz between hyperfine components of ground state serves as the clock
transition. The clock will need only one diode laser system for cooling, ions state preparation and
detection which makes this clock quite compact and robust.

2. The level scheme and the experimental sequence
Since ^{25}Mg^{+} has nuclear spin of I = 5/2, each energy level possesses the hyperfine structure. The
hyperfine splitting of the ^{25}Mg^{+} ion ground state equals to 1.7 GHz and can be chosen as a clock
transition for the frequency standard (Fig. 1). Due to relatively simple energy level structure one could
use single laser system for both cooling and state preparation. Experimental cycle consists of 4 main
stages: (i) laser cooling, (ii) state preparation, (iii) interrogation with RF field, (iv) state detection.

(i) The laser cooling on a broadband 280 nm ^{2}S_{1/2} (F = 3, m_{F} = 3) → ^{2}P_{3/2} (F = 4, m_{F} = 4) transition
with natural linewidth Γ = 2π×41.4 MHz and saturation intensity I_{sat} = 250 mW/cm² can be performed.
Since the hyperfine splitting of the ^{2}P_{3/2} state has the same order of magnitude as line width of cooling
transition, the transition ^{2}S_{1/2} (F = 3, m_{F} = 3) → ^{2}P_{3/2} (F = 3, m_{F} = 3) will be also excited, such that after
some time all population will be transferred to the ^{2}S_{1/2} (F = 2, m_{F} = 2) metastable state. To prevent
ions loss from the cooling cycle a repumping beam exciting ^{2}S_{1/2} (F = 2, m_{F} = 2) → ^{2}P_{3/2} (F = 3, m_{F} = 3) transition is required (Fig. 2).
Figure 1. $^{25}\text{Mg}^+$ ion levels involved.

Figure 2. Cooling scheme. $\Delta$ – detuning of the laser frequency from the transition.

Figure 3. Pumping to the $^2S_{1/2} (F = 2, m_F = 0)$ state.

(ii) For the $^2S_{1/2} (F = 2, m_F = 0) \rightarrow ^2S_{1/2} (F = 3, m_F = 0)$ transition with the frequency of $\nu_0 = 1.789 \text{ GHz}$ the linear Zeeman shift is suppressed, and measured transition frequency can be expressed as $\nu_{\text{clock}} = \nu_0 + \eta B^2$, where $\eta = 2.199 \text{ kHz/G}^2$ and $B$ – magnetic induction. Thus pumping to the $^2S_{1/2} (F = 2, m_F = 0)$ state before clock transition excitation is necessary. For this purpose a $\pi$-polarized beam exciting $^2S_{1/2} (F = 2) \rightarrow ^2P_{3/2} (F = 2)$ transition and a beam for $^2S_{1/2} (F = 3) \rightarrow ^2P_{3/2} (F = 3)$ transition excitation with polarization changing periodically between $\pi$ and $\sigma^+$ should be used. Since transitions between $\Delta F = 0$ and $\Delta m_F = 0$ are forbidden, the $^2S_{1/2} (F = 2, m_F = 0)$ becomes a dark state (Fig. 3).

(iii) To probe the clock transition the Ramsey spectroscopy with two $\pi/2$ microwave pulses with $T_{\text{rams}} \approx 1 \text{ s}$ pause is suggested. Duration of the pulses should be defined experimentally.

(iv) To detect the part of excited ions the fluorescence rate of the ion cloud can be measured.

3. The setup
Basic scheme of setup is presented at the Fig. 4 and consists of 4 main parts: (i) the laser system, (ii) the ion trapping system, (iii) the microwave interrogation system, (iv) the detection system.

(i) Scheme of the laser setup is shown at the Fig. 5. Commercial Toptica TA pro laser provides 0.8 W power at 1120 nm. It is frequency stabilized with several MHz accuracy to a wavemeter (WS-U, Angstrom). The fourth harmonic of the laser irradiation is obtained by two consequent frequency
**Figure 4.** Sketch of the setup for trapping $^{25}\text{Mg}^+$ ions, laser cooling, clock transition excitation and fluorescence detection. 1 – cooling beam, 2 – pumping beam, PMT – photomultiplier, B – magnetic field. RF and GND electrodes provide radial confinement of ions and ring DC electrodes provide axial confinement.

**Figure 5.** Laser system scheme. WS-U – wavelength meter, SHG 1 and 2 – home-built second harmonic generators based on LBO and BBO crystals respectively, AOM – acoustooptical modulators, PC – Pockels cells, 1 and 2 – cooling and pumping beams going into the trap.  

Doublings in two home-built second harmonic generators based on LBO and BBO crystals respectively. The crystals are housed in bow-tie cavities. The output power of about 5 mW at 280 nm is provided. Two double-pass acousto-optical modulators (AOM) allow for fast frequency tuning of laser irradiation. For polarization switching we suggest Pockels cells.

(ii) The linear Paul trap with four cylindrical rods is suitable for storage up to $10^6$ ions. The trap is described in details in [17]. Secular frequencies for $^{25}\text{Mg}^+$ ions in the trap are $\omega_{\text{rad}} = 2\pi \times 500$ kHz for radial movement and $\omega_{\text{ax}} = 2\pi \times 100$ kHz for axial. Trap depth corresponds to $D = 3$ eV. Ions are generated by electron impact ionization of magnesium atomic beam in the center of the trap. Ion trap, electron gun and atomic oven are situated inside the vacuum chamber under pressure less than $10^{-10}$.
mbar. To separate $^{25}\text{Mg}^+$ isotope of magnesium from other particles the mass-selective properties of the trap can be used.

(iii) The microwave interrogation is provided by SRS DS345 generator stabilized to a passive hydrogen maser, which radiation will be delivered to the ion cloud via home-made horn antenna. To remove degeneracy of magnetic sublevels magnetic field with induction on the order of $B \approx 10 \text{ mG}$ along the trap axis should be applied.

(iv) The fluorescence signal at 280 nm is collected by high aperture lens assembly made from UV grade fused silica with antireflection coating and detected by a photomultiplier tube (PMT).

4. Expected performance

Since the ion cloud size is by two orders of magnitude less than clock transition wavelength, Lamb-Dicke regime is realized and the first order Doppler effect is suppressed. The main systematics are expected to be the second order Doppler and the quadratic Zeeman effect. Other systematics as the Stark effect, caused by mutual interaction between ions are negligible. The second order Doppler effect can be expressed as [18]:

$$\frac{\delta \nu_{\text{dop}}}{\nu} = \frac{3k_B T}{2mc^2} \left(1 + \frac{2}{3} N_d^k\right),$$

where $k_B$ – the Boltzman constant, $T$ – the temperature of the ion cloud, $m$ – the ion mass, $c$ – the speed of light in vacuum and $N_d^k$ characterizes the second-order Doppler shift caused by micromotion. For this type of traps and in presence of laser cooling $N_d^k \approx 3$. For estimated 1 K temperature uncertainty, relative uncertainty of the clock transition frequency becomes $\delta \nu_{\text{dop}}/\nu = 2 \times 10^{-14}$.

Uncertainty due to the quadratic Zeeman effect can be expressed as

$$\frac{\delta \nu_{\text{Zeeman}}}{\nu} = \frac{2\eta B \delta B}{v_{\text{HFS}}},$$

If $\delta B = 1 \mu\text{G}$, relative frequency uncertainty of the clock transition frequency is estimated to be $\Delta \nu_{\text{Zeeman}}/\nu = 3 \times 10^{-14}$.

The relative instability can be estimated as [19]

$$\sigma_\delta (\tau) = \frac{1}{2 \pi \nu_0 \Delta T_{\text{ramps}} \text{SNR}} \sqrt{\frac{T_c}{\tau}}, \tau \geq T_c \geq 2 \Delta T_{\text{ramps}},$$

where SNR – signal to noise ratio, $\tau$ – measurement cycle time, $T_c$ – averaging time. If the only noise presented is the quantum projection noise, then $\text{SNR} = \sqrt{N_{\text{ions}}}$, where $N_{\text{ions}}$ – number of ions in the trap. With $\nu_0=1.789 \text{ GHz}$, $\Delta T_{\text{ramps}} = 1 \text{ s}$, $T_c = 2 \Delta T_{\text{ramps}}$, $N_{\text{ions}} = 10^6$ the estimated relative instability is $1.3 \times 10^{-13} \tau^{-1/2}$.

5. Conclusion

Design and expected performance of the microwave frequency standard based on laser-cooled $^{25}\text{Mg}^+$ ions are presented. The estimated fractional inaccuracy of the standard is estimated to be on the level of $3 \times 10^{-14}$ and mostly limited by the quadratic Zeeman effect. The fractional instability at the short averaging time is estimated to be of $1.3 \times 10^{-14} \tau^{-1/2}$. Experiments aimed for study the microwave transition $^{25}\text{Mg}^+$ ions are important for new generation of frequency references as well as for elements of quantum logic, where ions can play as an interface between microwave and optical Q-bits.

Acknowledgments

The work is supported by the Russian Science Foundation (Grant 16-12-00096).

References

[1] Dow J M, Neilan R E et al. 2009 Journal of Geodesy 83 p 191.
[2] Gilbert S L, Swann W C et al. 2001 Proc. SPIE 4269 p 184.
[3] Rosenband T, Hume D B et al. 2008 Science 319 p 1808.
[4] Nicholson T L, Campbell S L et al. 2015 Nature Communications 6 p 6896.
[5] Chou C W, Hume D et al. 2010 *Phys. Rev. Lett.* **104** p 070802.
[6] Cao J, Zhang P et al. 2016 *arXiv preprint* arXiv:1607.03731.
[7] Falke S, Lemke N et al. 2014 *New J. Phys.* **16** p 073023.
[8] Häffner S, Falke S et al. 2015 *Optics Letters* **40** p 2112.
[9] Matei D G, Legero T et al. 2016 *J. Phys.: Conf. Series* **723** p 012031.
[10] Rochat P, Droz F et al. 2012 *Proc. of European Nav. Conf.* 25.
[11] Burt E A, Diener W A et al. 2008 *IEEE transactions on ultrasonics, ferroelectrics and frequency control* **55** p 2586.
[12] Knab H, Niebing K et al. 1985 *IEEE Transactions on Instrumentation and Measurement* **34**(2) 242.
[13] Bollinger J J, Heinzen D J et al. 1991 *IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT* **40** p 126.
[14] Schwindt P D D, Jau Y et al. 2016 *Rev. Sci. Instrum.* **87** p 053112.
[15] Miao K, Zhang J W et al. 2015 *Optics Letters* **40** p 4249.
[16] Tjoelker R L, Prestage J D et al. 2016 *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* **63** p 1034.
[17] Semerikov I A, Zalivako I V et al. 2016 *Quantum Electron* **46** p 935.
[18] Prestage J D, Tjoelker R L et al. 1999 *Joint Meeting EFTF - IEEE IFCS* **124** p 121.
[19] Fisk P T H 1997 *Rep. Prog. Phys.* **60** p 761.