Toward the use of an additional degree of freedom of the Zeeman slower frequency tuning

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Abstract. In this paper the simplifying possibility of the scheme of the optical lattice clocks using a single source of the slowing laser radiation for the two installations of the $^{87}$Sr isotope optical clocks is considered. We designed the scheme where the correction of the constant component of the partial frequency-detuning magnetic field for the each Zeeman slower is achieved. Calculations of the resonance curve of the longitudinal magnetic field of the slower field are given with the introduction of the additional magnetic component into the calculation for the additional detuning and, at the same time, the frequency detuning of the magnetic field profile by an additional coil. The field of the additional coil, which is included into Zeeman slower, does not change the resonance profile of the magnetic field. The possibility of detuning within the width of the cooling transition is shown.

1. Introduction

Nowadays the development and the creation of the optical lattice clocks (OLC) can be attributed to the most priority areas of scientific and technical development. These devices have the ultra-high quality factor of the clock transition, which can be transferred from the optical to radio frequency range. The area of the applications for this type of the frequency reference source (FRS) has been a in radio communications, in tracking of the tectonic movements and changes in gravity, as well as the corresponding position in space. One of the main part of these devices is the source of the atoms, for example, the $^{87}$Sr isotope. The devices with the directed thermal beam of the atoms with a device for their deceleration, based on the Zeeman effect, is widely distributed in various experiments where Doppler-free spectroscopy is used. The uniqueness of the developed RFS is metrological characteristics, such as frequency uncertainty up to $10^{-17}$ with a potential uncertainty limit of up to $10^{-19}$ [1-3]. The comparison of such optical FRS with devices with higher uncertainty will not allow showing the superiority of the optical FRS; therefore, it is necessary to simultaneously compare the two optical FRS with each other.

In FRS the devices use the thermal beam of alkali and alkaline earth metals. In this case, the atoms have velocities at the level of 400-500 m/s, which is not allowed to carry out spectroscopy of narrow atomic transitions due to the Doppler effect and need to be decelerate down to 40-50 m/s. The step of deceleration of the atoms in FRS is made by using the combination of the magnetic field profile and
laser radiation. Obtaining the resonant shape of the magnetic field for atomic deceleration is possible by two ways: using a coil with a current [4-6] and using permanent magnets [7-9]. The coil has about 600-700 turns and is wound according to a specially designed shape. Permanent magnets are also placed along the axis and provide a resonant profile of the magnetic field along the axis of the thermal beam of the atoms. The Zeeman slower system with the coil with current will be considered.

2. The design of the Zeeman slower systems with common laser source
The operating principle of the Zeeman atomic beam slower is based on the deceleration of a thermal atomic beam passing along an axis with a counter-laser beam. The deceleration efficiency depends on the degree of monotonicity of the inhomogeneous magnetic field and the impact of the laser beam that is opposed to the atomic beam. This leads to compensation for the Doppler shift by compensating for changes in the Zeeman shift. The profile of the resonant magnetic field along the slower should correspond to the Doppler shift gradient. The magnetic field profile of the Zeeman slower is usually created using a coil of copper wire with a current and can have a heat emission of 25 to 300 watts. This leads to the heating of the pipe section to a temperature substantially higher than room temperature and increase the thermal impact on the clock transition of the atoms.

The two systems were implemented that consisted of two sources of $^{87}$Sr atoms, two Zeeman slower systems, two vacuum chambers with the common source of laser radiation and the system for stabilizing the parameters of the laser source. Since the line width of the $^1S_0-^1P_0$ cooling transition is 32 MHz, the frequency (wavelength) of the slowing down radiation was stabilized using the Angstrom WS-U8 wavemeter with the corresponding fixed detuning for the Doppler effect (see Figure 1). In the designed scheme to obtain the beam for the Zeeman slowers for the both installations, an IR laser with the wavelength of 921 nm with an amplifier and a butterfly resonator with a PPKTP crystal was used. The operation frequency of the laser is controlled by a wavemeter with an accuracy of ± 2 MHz. The optical amplifier provides ~ 800 mW at the output and is stabilized with an accuracy of 1 mW. With the help of a half-wave plate and a polarization cube, the output radiation is merged and directed into the vacuum systems of both installations.

![Figure 1. Sketch of the Zeeman slower systems of two $^{87}$Sr OLC with optical and magnetic fields. The addition coil is placed under the main part of the Zeeman slower.](image)

3. Theoretical basis of the introduction of an additional coil
As was mentioned earlier, the effect is caused by the action of the radiation on the atoms with appropriate detunings. The deceleration radiation force is described as Eq. 1 [4]:

$$F_{rf} = -\hbar k \frac{\Gamma_{se}}{2 \left(1 + s + 4 \frac{\Delta^2}{\Gamma_{se}^2}\right)}$$

(1)

where $\hbar$ - Planck constant, $k$ - wave vector, $\Gamma_{se}$ - width of the cooling transition, $s$ - ratio between the intensity of the laser and the saturation intensity (for the Sr transition $^1S_0-^1P_0$, $\text{min } I_{sat} =$
43 mW/cm²) so called saturation parameter and Δ is detuning of the laser from atomic resonance.

Laser detuning consists of the difference of the laser and atomic frequencies, first order Doppler term. For the compensation of the Doppler effect, the gradient of magnetic field was introduced. The full set of these terms is shown in the following equation (2):

\[ \Delta = \omega_L - \omega_0 - kv(z) - \frac{m_q \mu_B}{\hbar} B(z), \quad (2) \]

where \( \omega_L \) - angular laser frequency, \( \omega_0 \) - angular atomic frequency, \( v(z) \) – longitudinal velocity inside of the slower, \( m_q \) designated Zeeman sub-levels in state \( ^1P_1 \), \( \sigma, \sigma' \) polarizations and \( \mu_B \) is Bohr magneton.

In our case we had chosen the circular polarization to compensate the Doppler term. After some simple calculations, we can write the equation for magnetic field shape along the Zeeman slower system (Eq. 3) [10]:

\[ \frac{4}{\Gamma_{se}} \left[ \delta + kv_h(z) + \frac{\mu_B B(z)}{\hbar} \right]^2 = (1 + s) \left( \frac{1}{\eta} - 1 \right), \quad (3) \]

where \( \mu \) - deceleration efficiency that shows the value of the ratio between real and maximum decelerations.

The solution of this case is Eq. 4. The main idea is to introduce the additional constant magnetic field along of the Zeeman slower coil. It allows us to tune each slower system separately to optimize the deceleration process under the common detuning of the laser.

The plot of this magnetic field has the parabolic profile and the maximum really obtained edge-to-edge amplitude of the magnetic field in 100-110 mT on the axis (see Figure 2a and 2b).

\[ B(z) = B_0 + B_{add.coil} + B_i \sqrt{1 - \frac{z}{z_{max}}}, \quad (4) \]

where

\[ B_0 = -\frac{\hbar}{\mu_B} \left[ \delta + \frac{\Gamma}{2} \left( (1 + s) \frac{1}{\eta} - 1 \right) \right], \quad (5) \]

\[ B_i = -\frac{\hbar}{\mu_B} k \sqrt{2\eta |a_{max}| z_{max}^2}, \quad (6) \]

The component \( B_{add.coil} \) of Eq. 4 is the introduced component, which has a constant value of the magnetic field on the axis along the Zeeman coil. The way to obtain this configuration is shown in Figure 2. The additional coil is placed under the main coil or magnets array.

Figure 2. Cross-section of the Zeeman slower system: a – slower system with permanent magnets and an additional coil with current. The main array consists of five strings with (37 32 26 21 15) magnets in the appropriate string. The size of each neodymum magnet is 5x5x5 mm. The magnetic moment of the each magnet is 0.075 Am²; b – slower system with two coils has (145 123 105 87 70 60 52 47) turns in appropriate strings. The diameter of the wire is 1 mm. The additional coil for both slower systems consists of 42 turns with a 4mm copper tube.
Both coils of the slower system are placed on the vacuum tube with a diameter of 22cm as shown in Figure 2. During the experiment the current of the main coil of the Zeeman slower system has changed by ± 1A. Moreover, the profile of the magnetic field profile was stretched or squeezed as shown in Figure 3a as $B_{0}\text{calc}$ plots. As we mentioned above, the theoretical resonant magnetic field has a parabolic shape ($B_{0}\text{theory}$). The max deviation of the Zeeman magnetic field is calculated and the width of the effective possible transition shift is $\Delta = \pm \hbar \Gamma / \mu B = 2.1 \text{mT}$ (see Figure 3, $B_{0}\text{theory}$) [11].

Instead of tuning the efficiency by the main coil current changing, we suggest tuning the current of the additional coil. This tuning prevents the distortion of the resonant parabolic shape of the magnetic field, but it allows one to tune the position of the magnetic field shape, thereby the shift of the operation frequency of the slower system is without changing in the frequency of the laser beam detuning. In Figure 3b the shift of the main parabolic magnetic field ($B_{0}\text{theory}$) by the additional constant component ($B_{0}\text{calc}$) is shown.

![Figure 3](image)

**Figure 3.** Plots of the Zeeman slower magnetic fields for the case of the two electric coils: a – magnetic fields with different currents $I_{0} = 5^{+1}_{-1}$ A in the main coil; b – magnetic field of the slower system under the main coil current $I_{0} = 5$ A with an addition/correction component of the additional coil action and the detuning $\pm \Gamma$.

4. Conclusion

The paper represents the relatively new design of the Zeeman slower system for using in two FRS with a common laser source. The using of the additional coil to correct the frequency detuning of the atomic deceleration is suggested. The possibility to correct the constant component of the magnetic field profile, which appropriates the slower laser beams equivalent to frequency misalignment, is shown.

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