Project of a Satellite Slow Beam Atomic Clock with CPT-Ramsey Registration

Zholnerov V.S
Russian Institute of Radionavigation and Time
St.-Petersburg, Russia
zholnerov@mail.ru

Vershovskiy A.K.
Ioffe Phys.-Tech. Institute of Russian Academy of Science
St.-Petersburg, Russia
antver@mail.ioffe.ru

Rozhdestvenskiy Yu.V.
ITMO University
St.-Petersburg, Russia
rozd-yu@mail.ru

***Abstract*—A scheme of a satellite slow-beam microwave atomic clock is presented. A modified Zeeman slower is used for longitudinal cooling of the atomic beam, and a combined CPT-Ramsey registration technique with space domain separation is used for the signal registration.**

I. Introduction

The current stage of development of the global positioning systems, such as GPS, GLONASS, Galileo, requires achieving satellite clock stability at the level of $10^{-13}\tau^{-1/2}$ (10^{-15} per day). At the same time, prototypes of cold-atoms and ions optical clock already exist which provide long-term stability at the level of 10^{-16} and even 10^{-17} [1]. These devices can be successfully used as ground-based time standards - as an alternative to microwave standards based both on thermal and cold (e.g. atomic fountain) atomic beams.

However, all the attempts to build a satellite optical clock face certain difficulties; among them – building (1) a compact and reliable source of resonance laser light with the super-narrow (~1 Hz) frequency distribution, based on a stabilized laser locked to high-Q Fabry-Perot cavity, and (2) a scheme for transferring frequency from optical to microwave band based on a femtosecond laser able to emit so-called "super-continuum" – i.e. light, spanning over one octave in the frequency domain. The common drawbacks of all these projects are high power consumption, large dimensions and weight.

Therefore it makes sense to consider thoroughly schemes of microwave clocks based on cold atoms, and investigate the new opportunities – both in laser cooling techniques and in detection techniques, – that can be used for improving their stability to the level of $10^{-13}\tau^{-1/2}$, and in prospect – to the level of $10^{-14}\tau^{-1/2}$.

II. Statement of the Problem

In this report we suggest a scheme of a satellite microwave atomic clock that uses a slow pulsed atomic beam (Fig.1). The scheme uses a modified compact Zeeman slower for longitudinal cooling of the atomic beam and the combined CPT-Ramsey registration technique with space domain separation of resonant beams – for the registration of atomic transition frequency.

The main factors impeding the use of Zeeman atomic beam slowers [2] in satellite clock schemes are their dimensions and power consumption. Let us consider a group of atoms that characterize by initial velocity v_0; the distance to the full stop for these atoms is $z_0 = v_0^2/2a$, where $a < 0$ is the atomic beam deceleration. The initial value of the magnetic field is usually chosen in order to provide interaction of the resonance light with atoms with $v_0 \le \bar{v}$, where $\bar{v}$ is the mean velocity of the atomic beam, and therefore effective slowing of the most atoms in the beam is being achieved. The maximal deceleration which atom can acquire by absorbing one photon, is

$$a = \hbar k\gamma / M\,, \tag{1}$$

where $k = 2\pi/\lambda$, 2γ is the natural linewidth of the atomic transition, M is the mass of the atom. Consequently, if $v_0 = \bar{v}$, then the minimal stopping distance L_{min} is

$$L_{\min} = \frac{v_0^{\,2}}{2a} = \frac{M\,\bar{v}^2}{2\hbar k\gamma}. \tag{2}$$

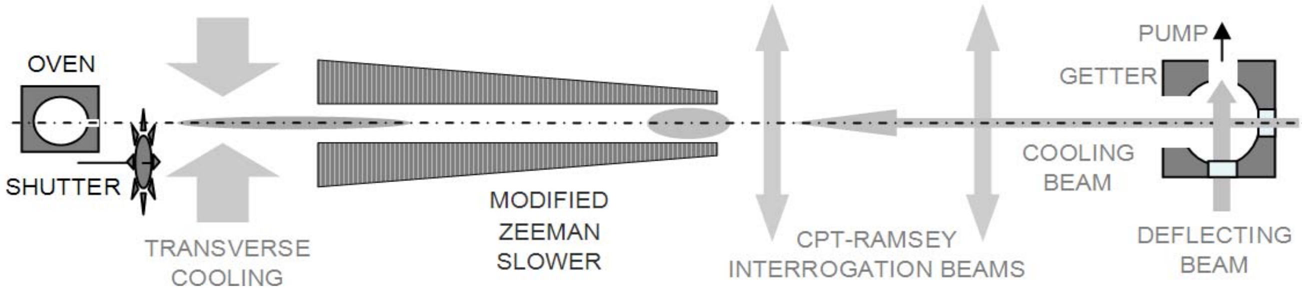

Figure 1. Sheme of the atomic beam preparation/registration unit of the satellite clock.

E.g. for thermal Rb beam with the resonant transition at $\lambda = 780$ nm and the lifetime of the excited state $t_e = 27$ ns, the minimal stopping distance is $L_{min} = 75$cm, and the minimal stopping time is $t_{min} = 3.7$ ms.

III. The Proposed Solution

Below we suggest an essential modification of Zeeman slower, implying that the initial values of the magnetic field and laser frequency are chosen in order to provide an effective slowing of the slowest group of atoms with $v_0 << \bar{v}$ (Fig.2). This change will inevitably lead to the decrease in the number of cooled atoms; thus, at $v_0 = \bar{v}/2$ the number of cooled atoms will consist 2.65% of the total number of the atoms in the thermal beam, and at $v_0 = \bar{v}/4$ – only 0.18%. However, the loss of the atoms will be compensated in metrological aspect by the possibility of their deep cooling to velocities $v < 10$ m/s, and by corresponding narrowing of the atomic resonance line.

This modification allows to decrease considerably dimensions of the Zeeman slower, as well as its power consumption; so, if initial velocity $v_0 = \bar{v}/2$ is chosen, the length of a solenoid of the Zeeman slower will be reduced four times, which is only 18.75 cm in the case of Rb. Moreover, if the value of the magnetic field B_{min} at one ending of the solenoid is close to zero, then (gradient given) the value of the magnetic field B_{max} at its other ending is proportional to the solenoid length: $B_{max} \sim l \sim v_0^2$, and therefore the power consumption is $P \sim l^2 \sim v_0^4$. Consequently, two-fold decrease of v_0 results in 16-fold decrease of the power consumption.

Let us consider the pulsed mode of the Zeeman slower and the registration scheme. This mode allows:

- to prevent heating of the slow ($v \leq v_0$) atoms by collisions with the fast ($v > v_0$) atoms;
- to separate the fast atoms, which were not decelerated in the slower, from the slow atoms decelerated down to < 10 m/s, and henceforth register only slow atoms;
- to additionally reduce the power consumption of the slower; we expect that the mean power dissipated on the solenoid, will not exceed 100 W;
- to completely eliminate the influence of the resonance light and the magnetic field on the atomic transition frequency during the registration process.

The working cycle of the proposed device consists of the following stages:

1) At the start of the cycle the shutter opens, letting the atoms out of the oven; the transverse cooling beams, the longitudinal cooling beam, and the magnetic field in the solenoid are switched on.
2) Before the first cold atoms reach the slower output, the shutter closes, and the fast ($v > v_0$) atoms leave the slower. Switching off one of transverse cooling beam would allow to accelerate cutting off the atomic beam.
3) At the moment when the last slow atoms leave the slower, all the cooling beams as well as the magnetic field in the solenoid are switched off.
4) The slow atoms reach the registration zone, where their resonant transition frequencies are being measured by CPT-Ramsey technique in the spatially separated optical fields.

In order to eliminate a possibility of covering the glass window (one which is used for feeding the longitudinal slowing beam into the vacuum chamber) by the atoms deposited from the atomic beam, the atoms after passing through the registration zone may be additionally deflected by the resonant transverse beam which may be switched on before the registration starts (in order to deflect the fast atoms) and after the registration ends (in order to deflect the slow atoms).

Thus, in proposed scheme, all the cooling beams as well as the magnetic field in the solenoid are switched off during the registration process; in this aspect this scheme differs from all existing at the moment cold-beam standards using Zeeman slowers. Reduced solenoid dimensions, and respectively low

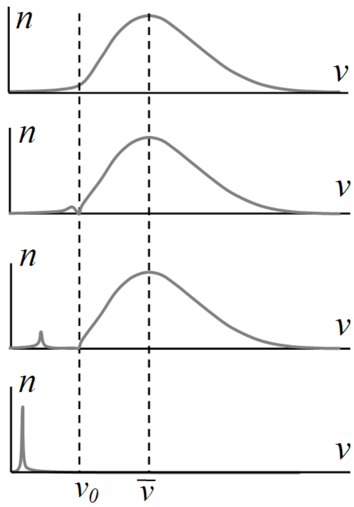

Figure 2. The evolution of the time velocity distribution during the cooling of the slow part of the atoms in the Zeeman slower. The lowest graph corresponds to the moment when the fast atoms have left the slower.

inductivity ensure zeroing of the magnetic field before the start of the registration process.

The proposed scheme does not use the bend of the slow atomic beam, typical for the devices of this type. This bend, or deflection of slow beam before entering the registration zone provides a considerable reduction of the resonant transition light shift, since the light scattered by the atoms can not enter the registration zone. The sharper the bend, the lower the possibility of scattering the light into the registration zone; therefore free of the light shift schemes require large bending angles which leads to the loss of atoms, and to the increase in size and power consumption of the device.

The method of the registration of the atomic resonance in the spatially separated laser light beams, exciting Raman (or CPT - Coherent Population Trapping) resonances, – when low-frequency coherence is being produced by the light fields resonant to the neighboring transitions of a three-level Λ-atom, – in the first time was applied to the thermal atomic beam in [3], but in most of the following works the spatial separation of the inquiring Ramsey beams was replaced with their separation in the time domain; this technique was applied to the cold atoms in MOT [4,5] as well as to the hot atoms in a cell [6].

Here we suggest to return to the scheme with the spatial separation of the registering Ramsey beams. Since the lifetime of low-frequency coherence is determined by various relaxation processes, which are very well suppressed in a cold atomic beam, the Ramsey resonance linewidth is fully determined by a time of flight through the interaction area. The time of flight can be increased up to the parts of a second (comparable to that in atomic fountain) and therefore the resonance linewidth can be reduced to the level of Hz.

The transition to the whole-optical registration and excluding of the microwave cavity from the device scheme will allow to eliminate or reduce considerably many stability deteriorating factors such as pulling the resonance frequency, instability of the phase along the cavity, microwave leaks from the cavity, etc. However, the factors specific for the CPT technique such as a frequency shift by side harmonics of the laser light, must be taken into account.

It is also important to have in mind a gravitational deflection of the atoms from the device axis, when testing device on the Earth surface (and if the axis is not vertical). Nevertheless, the influence of this effect will not be as destructive as in the schemes using the microwave cavity, since the laser registration area may be made as wide as necessary.

IV. Conclusion

According to the simple estimations, at the final beam velocity about 3 m/s and the distance between registering CPT beams about 30 cm (corresponding to the resonance linewidth of 5 Hz) the resonance quality $Q \sim 10^9$ may be achieved, and in order to provide $10^{-13}\tau^{-1/2}$ stability one needs to inquire 10^8 atoms per second. Taking into the consideration that the proposed technique of slowing only small part of the thermal velocity distribution results in reduction of the output beam intensity by $1.5 \div 2$ orders of magnitude, and the mean beam intensity will decrease by approximately one order of magnitude because of the pulsed beam mode – in the thermal beam produced by the oven we will need about $10^{11} \div 10^{12}$ atoms in the solid angle 1/100 of steradian, which seems to be quite realistic.

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