Proposal of a Novel Compact Cold Atomic Fountain Clock *

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(Received 21 June 2003)

We propose a novel atomic fountain clock which is compact and transportable. The clock is 60-cm in height. Its linewidth is expected to be 1.75 Hz, with accuracy 10^{-14}, stability 10^{-14} and signal–noise ratio 10^3. A hollow beam is applied as atomic wave-guide, which can increase the stability and the signal–noise ratio by one order. The hollow beam will not affect the accuracy of the clock, if the frequency shift due to the hollow beam is amended and the fluctuation of the hollow beam intensity is controlled to be smaller than 0.6%.

PACS: 32. 80. Pj, 06. 30. Ft, 42. 50. Vk

With the advance of laser cooling physics, the atomic frequency standard technique has been greatly developed in recent years, and the most remarkable progress comes from atomic fountain of ^{87}Rb and ^{133}Cs.[1–5] Many renowned institutes and laboratories for measuring and timing, such as BNM-LPTF, NIST, PTB, Yale, etc.,[6] have begun the research of atomic fountain (AF); some have obtained cold atomic fountain clocks, which are far superior to traditional atomic clocks. The AF clock of BNM-LPTF has reached a second-stability of 4×10^{-14}, a long stability of 6×10^{-16}, and a relative accuracy of 2.4×10^{-15}. These high-accuracy and high-stability atomic clocks, acting as keeping-time clock or primary clock, are bulky and untransportable. Thus they are not applicable in many high-tech fields, such as orientation, communication, navigation, and global positioning system (GPS). An atomic clock used in these fields should be compact, portable, of low-power supply, and insensitive to circumstances, but with lower requirements in accuracy than a primary clock.

Our AF satisfies these requirements. It is compact and portable, with predicted accuracy of 10^{-14}, and can substitute for miniature Cs beam atomic clocks. The device has two characteristics. One is its compact design, especially in that its toss tube is about 10 cm, which is far less than the present AF. It is based on analysis of the AF linewidth that has determinant effect on the accuracy. The spectrum of an AF is the Ramsey one whose linewidth is inversely proportional to atom-tossing time, and atoms spend more per-height time nearby climax. Therefore, even low projecting height can lead to very high accuracy. The second characteristic is the application of the hollow beam in order to increase the short term stability and signal–noise ratio (SNR) and to decrease collision shift.

The setup of our compact fountain is shown in Fig. 1. The cold atomic source is at the bottom of the device. The chamber is based on a normal six-way tube of CF35, with four windows on two diagonals, and its height is 125 mm. ^{87}Rb atoms are trapped in a magnetic-optical trap (MOT) in the $|F = 2, m_F\rangle$ state, then cooled and thrown upward along the $(0, 0, 1)$ direction by a moving optical molasses. At the beginning of molasses cooling, a hollow beam ascends from the bottom window, and atoms are confined in a hollow ring.

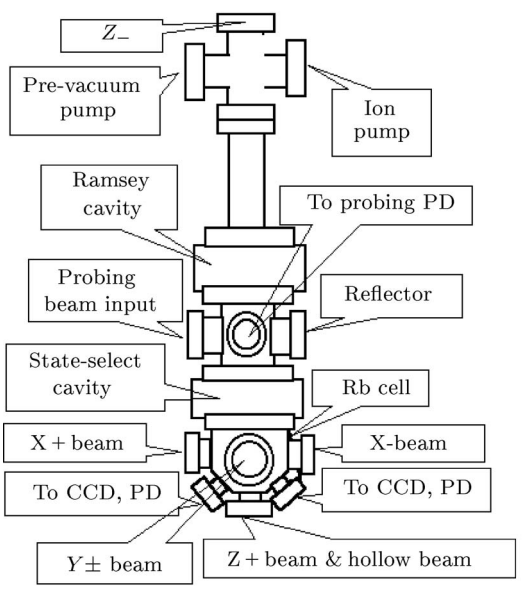


Fig. 1. Setup of a compact atomic fountain.

Above the tube is a cylindrical state-selection cavity operating in the TE_{011} mode. Atoms experience a π microwave pulse when they pass through the cavity. Most atoms in the $|F = 2, m_F = 0\rangle$ state transit to $|F = 1, m_F = 0\rangle$, while atoms in the $|F = 2, m_F \neq 0\rangle$ state keep in the former state and are pushed away by

* Supported by the National Natural Science Foundation of China under Grant No 60008002, the Key Oriental Project of Chinese Academy of Sciences (KGCX$_2$-SW-110), and the Shanghai Optical-Tech Special Project under Grant No 01DJGK015.

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a descending beam of the $|5^2S_{1/2}F = 2\rangle \rightarrow |5^2P_{3/2}F = 3\rangle$ cycling transition.

Atoms ascend and enter into the Ramsey cavity and toss tube. The Ramsey cavity works in the TE_{011} mode, with an estimated high unload Q of 8000, made of oxygen-free copper, and directly connected to vacuum tube. The two cavities differ in microwave power: i.e. atoms experience a $\pi/2$ microwave pulse in the Ramsey cavity, unlike a π pulse in the state-selection cavity. After passing through the Ramsey cavity, atoms ascend 10 cm in the toss tube and then fall down, passing through the Ramsey cavity again and experiencing a $\pi/2$ microwave pulse again. The ballistic flight time above the Ramsey cavity is 0.29 s, and the estimated linewidth is 1.75 Hz.

Atoms cross the three beams in the detection zone posed under the Ramsey cavity. The first is the beam of the $|5^2S_{1/2}F = 2\rangle \rightarrow |5^2P_{3/2}F = 3\rangle$ cycling transition. The main part of the beam is reflected by a mirror, but part of it at the bottom is not. Atoms in the $|F = 2, m_F = 0\rangle$ state radiate fluorescence when they interact with the standing wave field, and are pushed away by the travelling wave field. The fluorescence is collected by a low-noise photodiode. All the remaining atoms in the $|F = 1, m_F = 0\rangle$ state, falling down and crossing a beam of $|5^2S_{1/2}F = 1\rangle$ to $|5^2P_{3/2}F = 2\rangle$ light, are prepared to the $|F = 2, m_F\rangle$ state. Then they cross another beam of the $|5^2S_{1/2}F = 2\rangle$ to $|5^2P_{3/2}F = 3\rangle$ transition and are detected. With the atom number in two hyperfine levels, the effect of fluctuation of atoms can be suppressed so as to obtain the normalized Ramsey spectrum.

A four-way cross is installed on the top of the device to connect ion pump, pre-vacuum pump and top window. An inner C-field bobbin and the first layer of magnetic shield surround the toss tube and Ramsey cavity. The second magnetic shield envelops the first magnet shield, detection zone, and state-selection cavity. The last layer surrounds the whole setup except for the ion pump which has its own magnetic shield.

The transition spectrum of AF is a Ramsey oscillation, with transition probability p_e given by [7]

$$p_e = \frac{1}{2}[1 + \cos(\delta T)] \sin^2(\Omega\tau/2), \tag{1}$$

where $\delta = \omega_l - \omega_a$ is the detuning, T is the flying time of atoms above cavity, Ω is the Rabi frequency, and τ is the time of atoms traversing cavity. The linewidth of the Ramsey spectrum $\Delta\nu$ relates to T or throwing height H from the top of cavity:

$$\Delta\nu = 1/2T = 1/(\sqrt{32H/g}). \tag{2}$$

Since $\Delta\nu$ is reciprocal to $H^{1/2}$, decrease of $\Delta\nu$ results in a large increase of H. Improvement of linewidth from 2 Hz to 1 Hz is less important to AF, but increasing device volume and projecting range from 8 cm to 30 cm brings much more difficulty. We choose $H = 10$ cm, and $\Delta\nu = 1.75$ Hz is a little less than bulk AF, but the volume is reduced remarkably.

The short term stability of an AF can be written as [8–11]

$$\sigma_y(t) = N_{at}^{-1/2}\sqrt{T_c/t}/\pi Q_{at}, \tag{3}$$

where t, T_c, Q_{at} and N_{at} are the transition frequency, measurement time in seconds, fountain duration, atomic quality factor and detected atom number, respectively. Substituting $Q_{at} = \nu/\Delta\nu = 5.2 \times 10^9$ and $T_c \approx 2$ s into Eq. (3), we obtain

$$\sigma_y(t) = 0.86 \times 10^{-10} \times N_{at}^{1/2} t^{-1/2}. \tag{4}$$

The SNR is another important parameter of AF, written as [4]

$$S/N = 2N_{at}^{1/2}. \tag{5}$$

Equations (4) and (5) show that more atoms result in better stability and higher SNR. Usually, 10^6 is the maximum atom number of an AF because the trapped atoms are about 10^8, while aperture of cavity, molasses cooling, and state-selection will lose atoms by two orders. Lower temperature or higher atomic density can increase the detected atom number, but both are difficult to be realized. In fact, the two ways will enhance collision shift which is a primary element limiting the AF accuracy. However to a 10^{-14}-accuracy AF, the effect can be safely ignored. Thus we confine atoms in a blue-shift hollow beam in the projecting process. This idea has been mentioned in Refs. [12,13].

Hollow beam confines atoms by optical trap. An optical trap is characterized by its depth or equivalently by the temperature of potential barrier. If the temperature of atoms is much lower than the equivalent temperature of potential barrier, atoms will be bounded for a long time,[14] otherwise they flee the trap. The potential of an optical trap can be approximately expressed as [15]

$$U(r) = \frac{\hbar\delta}{2} \ln\left(1 + \frac{I(r)/I_s}{1 + (2\delta/\Gamma)^2}\right) \approx \frac{\hbar\delta}{2} \frac{I(r)/I_s}{(2\delta/\Gamma)^2}, \tag{6}$$

with $\delta \gg \Gamma$ and $(2\delta/\Gamma)^2 \gg I(r)/I_s$. Here Γ is the natural linewidth, I is the optical intensity, and $I_s = \Gamma(\pi hc/3\lambda^3)$ is the saturation intensity. For transition of $5^2S_{1/2}$ to $5^2P_{3/2}$ of ^{87}Rb, $\Gamma = 2\pi \times 5.98$ MHz and $I_s = 1.65\,\mathrm{mW/cm^2}$. Large δ (order of GHz or more) is used to decrease the heating effect due to the atom–photon interaction.

A novel optical path constructing hollow beam is shown in Fig. 2, consisting of an axicon, a reflector, a hollow reflector, and some lenses. The distribution of optical intensity reads as [16–19]

$$I(r, z) = \frac{P_0}{\sqrt{2\pi^3} \cdot r_0(z) w(z)} \cdot \exp\Big[-\frac{2(r - r_0(z))^2}{w(z)^2}\Big], \tag{7}$$

where P_0 is laser power, r is the radial coordinate of the beam, z is the axial coordinate, w is the effective thickness of beam annulus and r_0 is the radius of beam annulus. In our case, $r_0 = 5\,\mathrm{mm}$, $w = 50\,\mu\mathrm{m}$, and $\Delta z \leq 200\,\mathrm{mm}$, thus $I(r,z)$ is approximately independent of z. Therefore, the potential of the hollow beam can be expressed by

$$U(r) = \frac{\hbar\Gamma^2}{8\delta \cdot I_s}\frac{P_0}{\sqrt{2\pi^3}r_0 w}\exp\Big[-\frac{2(r-r_0)^2}{w^2}\Big] \equiv U_{\max}\cdot\exp\Big[-\frac{2(r-r_0)^2}{w^2}\Big], \quad (8)$$

where $U_{\max}$ is the maximum potential of hollow beam. If $r_0 = 5\,\mathrm{mm}$, $w = 50\,\mu\mathrm{m}$, $\delta = 80\,\mathrm{GHz}$ and $P_0 = 500\,\mathrm{mW}$, then $U_{\max} \approx 100\,\mu\mathrm{K}$, which is much higher than the temperature of atoms after molasses-cooling. Thus the hollow beam effectively prevents atom loss in the projecting process. Thus, the total atom number N_{at} will be more than 10^6, the stability of AF will be increased to 10^{-14}, and the SNR will be better than 10^3.

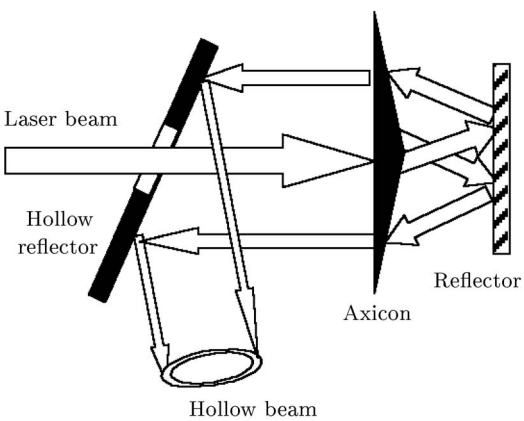


Fig. 2. Setting of varying a Gauss beam to a hollow beam.

It should be mentioned that the hollow beam also brings negative effects: one is the frequency shift and the linewidth broadening due to atom–photon collisions, the other is the scattering loss of atoms. For a portable atomic clock, after the frequency shift is computed and corrected, the accuracy will not be affected. The fluctuation of light intensity will broaden the linewidth, but this effect can be ignored if the fluctuation is limited in a range and the frequency broadening due to it is far less than 1.75 Hz of the Ramsey linewidth. In radiation field, the frequency shift of the $5^2S_{1/2}$ ground state is [15]

$$\Delta(r) = \frac{\delta}{[1+(2\delta/\Gamma)^2]I_s}\cdot\frac{2}{3}I(r), \quad (9)$$

while that of excited state is far less, and can be ignored. By fitting the atom cloud to Boltzmann's distribution, and the average frequency shift of all atoms can be expressed by

$$\bar{\Delta} = \int \Delta dN/N = \frac{\Gamma^2}{6\cdot\delta\cdot I_s}\int I(r)\cdot\exp\Big(-\frac{U}{k_BT}\Big)rdr\Big/\int\exp\Big(-\frac{U}{k_BT}\Big)rdr \approx \frac{2U_{\max}}{3\hbar r_0^2}\int\exp\Big[-\frac{2(r-r_0)^2}{w^2} - \frac{U_{\max}}{k_BT}\exp\Big[-\frac{2(r-r_0)^2}{w^2}\Big]\Big]rdr. \quad (10)$$

If $U_{\max} \approx 100\,\mu\mathrm{K}$ and $T = 20\,\mu\mathrm{K}$, Eq. (10) yields $\bar{\Delta} = 2\pi \times 1.5\,\mathrm{kHz}$. The frequency broadening due to fluctuation of the hollow beam intensity can be given by

$$d\bar{\Delta} = (\partial\bar{\Delta}/\partial P_0)\cdot dP_0 = -2\pi\times 161\cdot(dP_0/P_0)\mathrm{Hz}. \quad (11)$$

If the fluctuation of intensity dP_0/P_0 is below 0.6%, the frequency broadening is less than 1 Hz, and will not affect the Ramsey spectrum.

Another negative effect of hollow beam is the photon-scattering, which changes the signal-atoms into the noise-atoms or pushes the atoms out of the trap, and thus decreases the SNR and the short-term stability. The primary scattering mechanism is spontaneous radiation. By supposing $\delta \gg \Gamma$, the rate of spontaneous radiation can be given by [15]

$$p_{sp}(I(r)) = \frac{[I(r)/I_s](\Gamma/2)}{[1+I(r)/I_s+(2\delta/\Gamma)^2]}. \quad (12)$$

Thus the average loss rate $\bar{p}_{sp}$ reads as

$$\bar{p}_{sp} = \int p_{sp}(I(r))\exp\Big(-\frac{U}{k_BT}\Big)rdr\cdot\Big[\int\exp\Big(-\frac{U}{k_BT}\Big)rdr\Big]^{-1} \cong 3\times10^{-3}/\mathrm{s}. \quad (13)$$

Thus, $\bar{p}_{sp}\cdot T \cong 10^{-3} \ll 1$, and the photon-scattering loss can be neglected. Other important scattering mechanisms are the Rayleigh scattering and the Raman scattering. The Rayleigh scattering is described by the Rayleigh formula:[20,21]

$$p_{Rayl}(I) = \frac{8\pi I(r)}{3\hbar}r_e^2\frac{(\omega_l)^3}{(\omega_a)^4} \cong 1.9\times10^{-7}\mathrm{s}^{-1} \ll \bar{p}_{sp}, \quad (14)$$

where r_e is the classical radius of the electron. The Raman scattering loss rate $\bar{p}_{\mathrm{Ram}}$ is far less than $\bar{p}_{Rayl}$.[20] Thus, the photon-scattering loss can be neglected.

In conclusion, we have proposed a novel scheme of a compact ^{87}Rb atomic fountain, which can be used to substitute a miniature Cs beam atomic clock. New ideas are shown in the device, such as short toss tube, microwave cavity connected to vacuum tube directly, and hollow beam that constrains atoms in the projecting process. The device is compact (only 60 cm high),

yet with accuracy 10^{-14}, stability 10^{-14}, and SNR 10^3. The hollow beam increases the stability and the SNR by about one order of magnitude, but it brings about two disadvantages, namely the frequency shift and broadening. The frequency shift is about several hundreds of Hz, but it will not affect the accuracy because it can be corrected. If the intensity fluctuation is controlled to be smaller than 0.6%, the broadening will be less than the Ramsey linewidth and will not affect the Ramsey spectrum.

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