

Proposal of a dual-ball atomic fountain clock

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A simple improved structure is designed to trap and launch two cold atomic balls vertically at the same time, which works like “two fountains”, but is more compact since most components of the “two fountains” are shared. It is expected to improve the stability of the fountain markedly.

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Atomic fountain clocks (AFCs) are the most accurate running clocks in the world. Researches on AFCs and space clocks based on AFC technique^[1,2] are still active for improving the devices such as obtaining better stability and uncertainty. Theoretic analysis demonstrates that the frequency stability of AFCs is at the magnitude of $10^{-14}\tau^{-1/2}$ (τ is the sampling time) and is limited by quantum projection noises. But limited by pulsed running mode, the frequency stability is degraded due to the frequency noise of the interrogation oscillator, named as Dick effect^[3,4]. The frequency stabilities of most AFCs are lower than the theoretic value by at least one order of magnitude^[5]. It not only affects the short-term and long-term stabilities, but also requires much more comparing time to reach the noise floor. Many improvements are used to increase the stability of AFCs, with the ideas mainly focused on decreasing the noise of interrogation oscillator, which require complex and expensive additional devices such as cryogenic-sapphire oscillator^[6] or optical comb^[7]. The continuous AFCs^[8] and juggling clocks^[9] are used to improve the instability; as limited by structures, the uncertainty of these clocks are worse than that of normal AFCs. A new idea on decreasing the noise of interrogation oscillator by shortening the cycle of fountain is proposed by analyzing the mechanics of Dick effect, details are described as following.

The schematic diagram of dual-ball atomic fountain (DBAF) is illustrated in Fig. 1, except for its atom cooling and launching part. It is the same as a normal AFC including four components: cooling and launching chamber (CLC), state-selection chamber (SSC), detection zone, and interaction zone. The process cycle of DBAF and normal fountains are also alike. At first, atoms are trapped, cooled, and launched by five laser beams in CLC. Then they are selected to $m_F=0$ pure state when passing through SSC and the detection zone. As moving upwards, they enter into the interaction zone, and reach their apogees and then fall down due to gravity, interact with microwave field twice when they pass by the cavity. Then they fall to the detection zone, and the numbers of the two hyperfine states are detected by a two-state detecting method. The detailed description of fountain cycle can be found in many papers, such as in Ref. [10].

The difference between DBAF and other fountains is

that the DBAF launches two balls of atoms at the same time due to a novel design of CLC shown in Fig. 2, which can be understood as two configurations of magneto-optical trap (MOT) and optical molasses (OM) in the same vertical axis. Both configurations are so-called “(1,1,0)”, three mutually orthogonal pairs of counter propagating laser beams are imagined to run along the six face normals of a cube balanced on one of its face diagonals, two pairs are 45° inclined to the vertical axis, and the other pair is horizontal. The number of required beams with the same polarization other than the horizontal beam is reduced to 5 by using mirrors: four 45° inclined beams with the same right-hand circular polarization pass each atomic ball once, and the horizontal beam with left-hand circular polarization passes each twice. This structure of CLC can not only capture and cool down two atomic balls by MOT and OM, but also make the two balls launch at the same time with the same initial velocity $\sqrt{2}\delta\lambda$ (λ is the laser wavelength) in the same vertical axis when the frequencies of upward beams and downward beams are detuned to $\omega + \delta$ and $\omega - \delta$ in

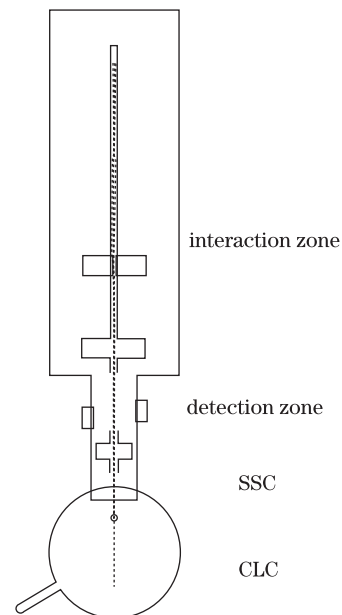


Fig. 1. Schematic diagram of the DBAF.

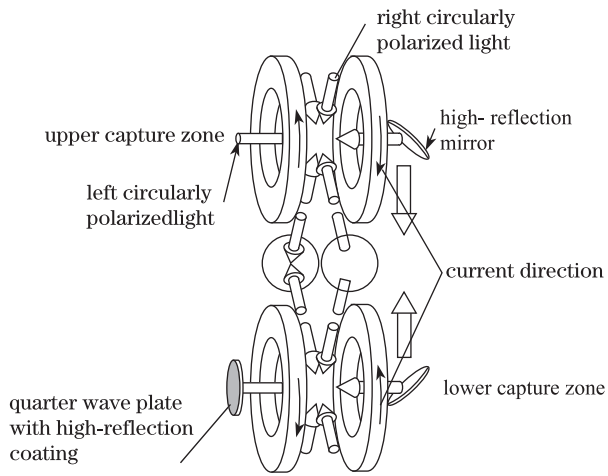


Fig. 2. Schematic diagram of CLC.

the OM stage, respectively, so the distance between the two balls will be a constant in the whole fountain cycle.

As the two MOT/OM structures are not independent, they affect each other at two parts, one is the superposition of the MOT's gradient magnetic fields created by two pairs of anti-Helmholtz coils, and the other is the unbalance of counter-propagating laser beams due to the loss of transition by windows, reflection by mirrors, and scattering by atoms. To discuss the first issue, some data of the structure are given as follows: the two anti-Helmholtz coil-pairs have some components with external diameter/internal diameter/distance of 100 mm/60 mm/50 mm, which are mirror symmetric to a horizontal plane with the center-center distance of 150 mm, and the total current of every coils is 150 A. The radial magnetic field gradient is about 5 Gs/cm near the center, and the axial magnetic field gradient is 10 Gs/cm. The curve and map of magnetic field are shown in Figs. 3 and 4, respectively. The deviation of the magnetic zero point to the geometrical center is about 0.35 mm, which can be compensated by offsetting the center of optical beams or be ignored since 0.35 mm is far less than the diameter of laser beam (about 20 mm) or the length of cold atoms (several millimeters). For the second issue, optical scattering makes it hard to obtain a perfect power balance in the MOT and OM stage. However, a similar experiment in our group has demonstrated that the effect of unbalance

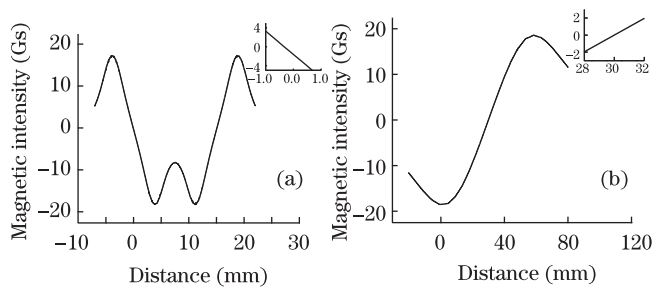


Fig. 3. (a) Radial and (b) axial magnetic fields following distance to their centers in the dual coils. Insets show the magnetic zero point drifting compared with a normal anti-Helmholtz coil pair. The deviations of the magnetic zero point to the geometric center at the radial and axial directions are about 0.35 and 0 mm, respectively.

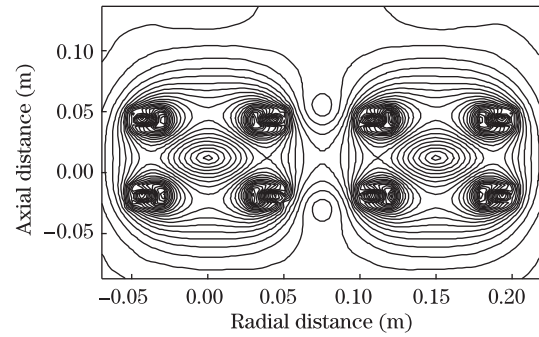


Fig. 4. Contour plot of the magnetic intensity around the center of the two cooling zones. The left part corresponds to the upper cooling zone. The distance between the two cooling zones is designed as 150 mm, and the position (0,0) corresponds to the center of the upper cooling zone.

is limited^[11,12], which means that either the number or the temperature of launching atoms is similar to that of a normal atomic fountain (AF).

The DBAF clock locks its error signal with the following process. In one cycle, two atomic balls are launched and interacted with microwave field in the same cavity. When the upper one passes through the cavity, the angular frequency is tuned to $\omega_u - \Delta\omega_u$, where ω_u and $\Delta\omega_u$ are the center angular frequency and half linewidth of the Ramsey center fringe in the upper ball, respectively; when the lower ball passes through the cavity, the angular frequency is turned to $\omega_l + \Delta\omega_l$, where ω_l and $\Delta\omega_l$ are the center angular frequency and half linewidth of the Ramsey center fringe of the lower ball, respectively. P_u and P_l , denoting the transition probabilities of two atomic balls, respectively, can be expressed as

$$P_u(\delta\omega) \approx \frac{A_u}{2} \left(-\frac{\pi\delta\omega}{2\Delta\omega_u} + 1 \right), \quad (1)$$

$$P_l(\delta\omega) \approx \frac{A_l}{2} \left(\frac{\pi\delta\omega}{2\Delta\omega_l} + 1 \right), \quad (2)$$

where A_u and A_l are the peak-peak values of Ramsey center fringes of the two atomic balls, respectively, $\delta\omega$ is angular frequency error. The error signal can be derived as

$$\delta\omega = \frac{4}{\pi} \left(\frac{P_l}{A_l} - \frac{P_u}{A_u} \right) / \left(\frac{1}{\Delta\omega_u} + \frac{1}{\Delta\omega_l} \right). \quad (3)$$

Considering the symmetry of the structure, in the next cycle, the error signal is obtained from the transition probabilities of the two atomic balls when the angular frequencies are tuned to $\omega_u + \Delta\omega_u$ and $\omega_l - \Delta\omega_l$, i.e., the right side of the Ramsey center fringe of the upper ball and the left side of the Ramsey center fringe of the lower ball. The unified expression is given as

$$\delta\omega_k = (-1)^{k-1} \frac{4}{\pi} \left(\frac{P_{lk}}{A_l} - \frac{P_{uk}}{A_u} \right) / \left(\frac{1}{\Delta\omega_u} + \frac{1}{\Delta\omega_l} \right), \quad (4)$$

where k means the k th lock-in cycle. Then all parameters shown in the aforementioned discussion are measurable: P_u and P_l can be obtained by two-state detection of AFC; when the device works as a normal AFC of upper/lower atomic ball, $\Delta\omega_u/\Delta\omega_l$ and A_u/A_l can be obtained by analyzing the Ramsey fringe, and ω_u/ω_l is deduced by the total uncertainty evaluation.

The frequency stability is evaluated by Allan standard deviation of the frequency drift feedback. The frequency stability of AFC in pulsed running mode is limited by the frequency noise of the interrogation oscillator. A down conversion process of local oscillation frequency noise components because of the non-continuous probing of the atomic transition frequency in a fountain (Dick effect)^[3,4,13,14] affects the short term stability. Thus, in the case of the Ramsey interrogation with $T \gg \tau_p$ and $0.4 < d < 0.7$, where T is the time interval between two Ramsey microwave pulses, τ_p is the interaction time between microwave and atoms, duty cycle $d = T/T_c$, T_c is the fountain period for a single atomic ball, the frequency stability can be described as^[14]

$$\sigma_{y \text{ lim}}(\tau) \cong \frac{\sigma_y^{\text{LO}}}{\sqrt{2 \ln 2}} \left| \frac{\sin(\pi d)}{\pi d} \right| \sqrt{\frac{T_e}{\tau}}, \quad (5)$$

where σ_y^{LO} is flicker floor of the interrogation oscillator, τ is sampling time, and T_e is the effective fountain period for DBAF. The duty cycle of the double atomic clouds is the same as that of the single atomic cloud, but the period of the former is reduced to about 50%, which improves the short term stability of the AF.

The frequency uncertainty contribution in DBAF is similar to those in normal fountains, including the second-order Zeeman effect^[15], cold collisions, distributed cavity phase, gravity, microwave leakage, black-body radiation and so on. Most of them are independent of the structure of DBAF, which can be evaluated by the same methods as that of normal fountains, and the result is close to that of the case of an up-ball or a down-ball single fountain^[16,17]. Several effects are relative to the structure of DBAF, including microwave leakage and light shift.

The microwave leakage shift depending on microwave power is paid attention to because the other atomic ball is interfered when one atomic ball interacts with microwave field in a single microwave cavity in DBAF. To repress the microwave leakage, it is suggested to extend the cut-off waveguide to the whole free-flight zone. For a TE₀₁ cylindrical cavity, the propagation constant in the cylindrical cut-off waveguide is expressed as^[18]

$$\beta = \sqrt{(2\pi/\lambda_0)^2 - (2\chi_{01}/D_{\text{WG}})^2}, \quad (6)$$

where $\chi_{01} \cong 3.8317$ is the first zero value of the 0th order Bessel function $J_0(\chi)$, $\lambda_0 = 4.4$ cm is the microwave cavity resonance wavelength for ⁸⁷Rb, and D_{WG} is the effective diameter of the cut-off waveguide and its typical value is about 14 mm. Thus, the attenuation velocity of the microwave power is calculated to be -46 dB/cm. When the length of the cut-off waveguide is longer than 15 cm, the attenuation is greater than -690 dB, and the shift will be attenuated to an acceptable level.

Light shift of DBAF affects the uncertainty in the following way. When one atomic ball is interacting with an

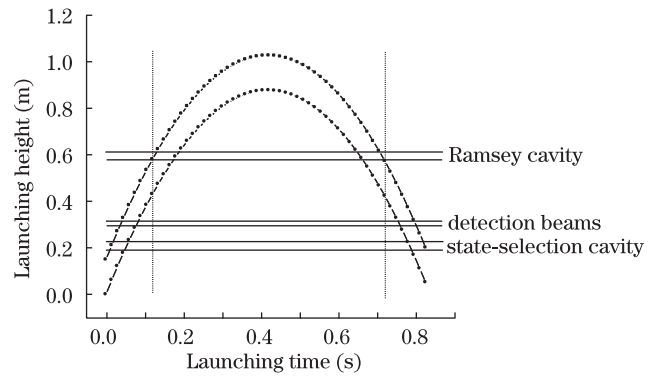


Fig. 5. Relationship between launching height and time. Squares stand for the upper atomic ball, dots stand for the lower atomic ball, and the launching velocities of the balls are both 4.188 m/s.

optical field and radiates photons, the other ball is flying in the interaction zone and is affected by the optical field resulting from these photons. This effect can be re-trained by proper configuration of clock structure. The relationship between the height and time when launching two atomic balls is illustrated in Fig. 5. The data are based on the operating clock in our group, and the effect of light shift is eliminated by switching off the probing lasers when the upper atomic ball is flying in the interacting zone.

In conclusion, DBAF, a proposal after a single improvement on normal fountains, can increase the short-term stability by $1/\sqrt{2}$. In other words, the time for reaching the noise floor can be shortened by half. And the expected uncertainty of DBAF is close to that of a normal fountain.

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