Progress in Building NRC's Cesium Fountain Clock

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***Abstract*—We report recent progress made on the construction of a cesium fountain atomic clock at the Frequency and Time Group of the National Research Council (NRC) Canada. We also report future design plans and operation scheme of the fountain.**

I. Introduction

A cesium fountain atomic clock is being assembled at the Frequency and Time Laboratories of the National Research Council (NRC) Canada. Recent progress and future plans are reported here. Our new cesium fountain clock FCs1 is at the stage of building the physical package and testing its many components. After earlier work on a prototype system [1], we made most of the recent advances with the construction of the physical package. Only non-magnetic metals are used for the vacuum chamber and the supporting frame: titanium, copper, aluminum and brass. Indium wire seals are used everywhere except for the standard conflat flanges used on both ion pumps. Our goal is to realize a fountain with a short term stability of 7×10^{-14} at one second and a relative inaccuracy below 10^{-15}.

II. Description of the Physical Package

A schematic diagram of the physical package of the clock is shown in Fig. 1. The dimensions are shown to scale. The external frame is a 200 cm tall rectangular aluminum structure. The main support shelf, located 54 cm above the ground, supports the detection section and one ion pump. A smaller shelf, 175 cm above ground, supports the weight of the second ion pump. Except for the two ion pumps, the entire vacuum chamber is supported by the detection section. Small windows located at the top and bottom of the chamber allow to see through the structure and check the operation of the shutters. No laser beam is used along that vertical axis.

A. Atom Trapping, Cooling and Launching

Cesium atoms are captured and cooled in a 110 beam geometry. Six 25 mm diameter ports are available on the titanium chamber for the laser beams. Two additional 13 mm ports are available for the cesium vapor to enter the chamber at the bottom and for the cooled atoms to be launched from the top. A cesium cell is contained inside a small stainless steel cylindrical vacuum chamber and temperature stabilized with Peltier elements. The magneto-optical trap (MOT) is designed with small anti-Helmholtz coils located as near as possible from the center of the trap, with a radius of 41 mm and separated by 50 mm. The use of small radius coils reduces the parasitic magnetic field in the drift region located 76 cm above the MOT. Larger anti-Helmholtz coils with opposing currents are used to reduce the quadrupole component of the field far from the MOT. Two additional ports are available to monitor the fluorescence from the trapped atoms. The trapping and launching beams are fed with optical fibers, expanded to a 17 mm beam waist and clipped with a 20 mm circular aperture before sending them to the MOT. These beams are aligned with mirrors mounted on an orientable frame. Thus, the verticality of the launch direction can be adjusted without disturbing the trap alignment.

B. Preparation and Detection

The atoms are prepared in the $F = 3$, $m_F = 0$ state before the Ramsey interrogation. After the launch, the atoms are all in the $F = 4$ states. A rectangular TM_{210} microwave cavity located just below the detection section pumps the $F = 4$, $m_F = 0$ atoms to the $F = 3$, $m_F = 0$ state. The atoms remaining in the $F = 4$ are taken out with a 4–5' pusher beam.

The atomic populations are measured after the Ramsey interrogation in a four-beam scheme as in [2] using circularly polarized beams tuned to the 3–4' and the 4–5' transitions. The atoms first pass through the upper region labeled Detection #2 in Fig. 1. This region is split in two parts, the upper part for 4–5' counter-propagating beams that are used to detect the atoms in the $F = 4$ state, and the lower part for a single 4–5' beam used as a pusher (the same pusher beam used on the atoms on their way up). The lower region, Detection #1, contains two pairs of counter-propagating beams: at the top, a repumper tuned to 3–4' transfers the atoms to the $F = 4$ state. The lowest beams, tuned to the 4–5' transition, are used to detect the atoms in the $F = 4$ state

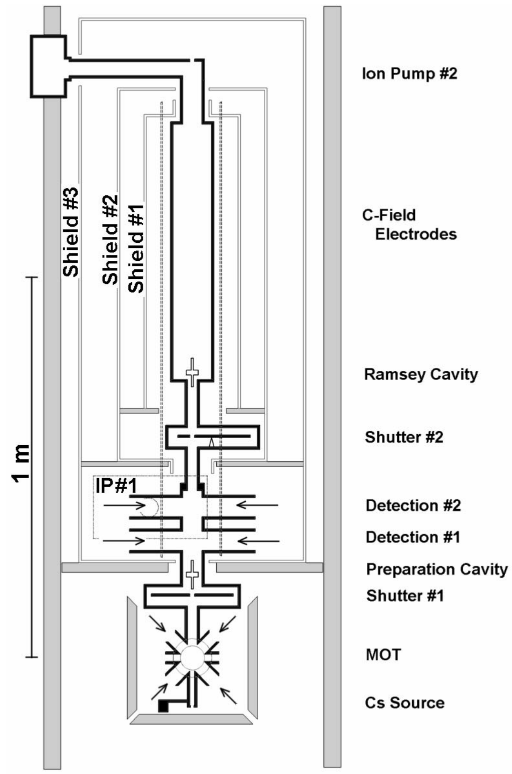

Figure 1. Schematic section of the fountain clock. Dimensions are to scale. IP#1: Ion Pump #1.

(which were in the F = 3 state). To obtain the maximum intensity stability, all 4–5' beams used for detection are obtained by four-way splitting an intensity-stabilized beam.

The detection regions are separated by 10 cm so that fluorescence and scattered 3–4' light from the detection region #1 does not reach atoms that have not yet been probed in the detection region #2. Fluorescence is collected with a Fresnel lens of focal length f = 51 mm and a numerical aperture NA = 1. The light is then focused on the detector with another Fresnel lens with f = 43 mm. The fluorescence region is imaged by the optics on a 23 mm × 5 mm region which overlaps with the detector made of a pair of $10 \times 10\ \text{mm}^2$ PIN photodiodes mounted side by side. This arrangement is used on both sides of the vacuum chamber and covers 24% of the solid angle to efficiently collect the fluorescence. The signal is amplified with a S/N ratio of 500 and a bandwidth of 15 kHz.

C. *Light Shutters*

Two electrostatic shutters [3] are used to attenuate the scattered and fluorescence light by at least 50 dB. One is located between the MOT and the detection region to prevent fluorescence from the MOT to change the state of the atoms before being detected, therefore increasing the contrast of the Ramsey fringes. The second shutter is located between the detection region and the drift region. This reduces the light shift by preventing fluorescence from the detected atoms to reach the upper part of the fountain. The estimated light shift contribution is estimated to be below 10^{-15}. The shutters allow the fountain to operate with a very small dead time and mitigate noise degradation by reducing the Dick effect [4].

The shutters are made with a thin titanium disk supported on a vertical needle-like pin for minimum friction. A thin titanium cylinder supports the disk at its center. It is inserted over the pin to prevent any wobbling motion of the disk and provides an electrical grounding path. The disk has eight tabs around its circumference which are in close proximity to a set of 24 electrodes surrounding the disk. An electric potential applied on these electrodes produces the high electric fields required to pull on the tabs and cause rotation of the disk. The electrodes are connected in three groups of eight electrodes each. By applying an electric potential on the appropriate group, the direction of the torque on the disk can be controlled. The voltage on these electrodes is pulsed with a variable duty cycle to control the magnitude of the torque. Two photodiodes and a LED are used to detect the position and direction of rotation of the disk. A programmable microcontroller synchronizes the rotating disk to the launch cycle of the fountain. The algorithm used to control the speed and phase of the disk will be described elsewhere [5].

The disk of the lowest shutter contains a single hole, 5 mm in diameter, which lines up with the vertical axis of the fountain at launch time to let the atoms through. The disk of the upper shutter contains two long slits, 10 mm wide and forming an arc of 80° and 67° and separated by 52°. These openings are for atoms going up and down respectively, with the possibility of having a fountain height of 31 cm to 50 cm above the cavity. The upper shutter is rotated at twice the rate of the fountain cycle to increase response time of the openings and closings. By changing the phase of the shutter rotation, it is possible to block a part of the atomic cloud. This will allow a control of which part of the cavity is used to interrogate the Cs atoms in the hope to measure transverse phase variations of the microwave field.

D. *Ramsey Interrogation and C-field*

The Ramsey pulses are applied with a rectangular TM_{210} microwave cavity. The cavity is made of oxygen-free copper and is split in two halves along the vertical plane for ease of construction and attenuation of some unwanted modes. The microwave modes are excited with two antennas symmetrically located on the bottom face of the cavity. A transversal C-field is produced with four vertical current-carrying rods [6]. A map of the field shows a spatial variation smaller than 2% peak-to-peak over the length of the drift region (Fig. 2). Fine adjustment of the direction of the C-field with the magnetic component of the cavity field is possible by adding a small current in an extra pair of rods.

Three magnetic shields are used for static attenuation of the external field variations. Each shield is demagnetized with an ac current passing through four coils installed around the sections of the shields. To ensure that every part of the

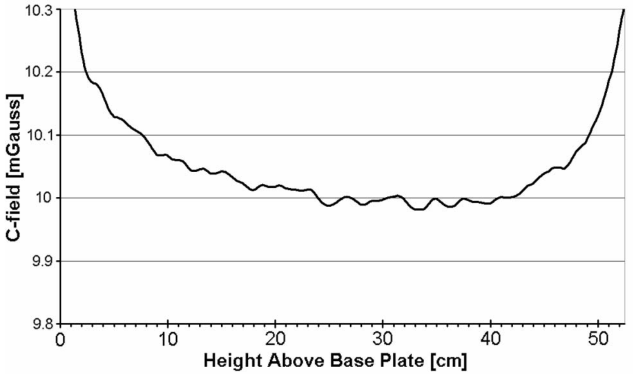

Figure 2. Map of the C-field. The cavity is 2.5 cm above the base plate.

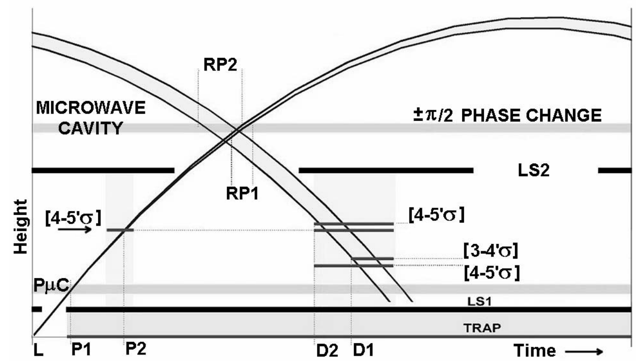

Figure 3. Timing sequence for one launch cycle. LS1 and LS2: light shutters, PμC: preparation microwave cavity, RP1 and RP2: Ramsey pulses which may overlap in time, L: launch, P1: microwave preparation, P2: push, D2: detection of F = 4, D1: detection of remaining atoms.

shield (sides and top) is demagnetized, the coils are connected two different ways which guide the flux lines along the sides in one case, or through the sides and top of the shield with the other combination. Measurements of the attenuation of the horizontal component give a factor 65 for the cylindrically shaped shield #1. Shields #2 and #3 have a rectangular shape. The attenuation of shield #2 has not been measured yet, but the external shield provides an attenuation of the horizontal component of the magnetic field by a factor 12. The attenuation of the vertical component is not as good, but this is not an issue because the magnitude of the C-field is only affected to second order by a vertical magnetic field. Additional attenuation is obtained from an active field-compensation system which controls a current in three pairs of coils located around the physical package. Properties data of mu-metal shows that its permeability with a field of 3000 Gauss increases by a factor five over the small field permeability before decreasing as saturation sets in. Assuming we can add a uniform magnetic field bias to magnetize uniformly one of the rectangular shields, an increase of the permeability of the mu-metal by a factor five should be obtained.

A copper vacuum chamber is used around the drift region for temperature uniformity. One ion pump is connected to the top of the drift region, the other to the upper detection region.

III. Operation of the Fountain Clock

A. *Launch and timing sequence*

The launch and timing sequence is represented graphically in Fig. 3. The vertical position of the launched atomic cloud is represented as a function of time by two lines giving the higher and lower limits of the cloud. Thick black horizontal lines represent a closed shutter.

The sequence begins on the left with the launch of the trapped atoms. The atoms go through the first shutter LS1 which closes before the MOT is turned on for trapping the next atomic cloud. The atoms pass through the first preparation cavity and the 4–5' pusher beam. Fluorescence from the pusher beam is blocked by the upper shutter, which opens later to let the atoms to the Ramsey interrogation. As the atoms enter the interrogation cavity, the cloud of atoms launched on the previous cycle exits the cavity on its way down. The precise timing of the launches can be adjusted to obtain an adjustable overlap of the ramsey pulses RP1 and RP2. The atom clouds can be made to intersect inside the cavity if collisional effects are to be studied. During the period of time the upward going cloud of atoms is in free fall, a phase shift of $\pm\pi/2$ is imposed on the cavity for a square-wave phase modulation interrogation [7]. The upper light shutter closes before the downward going cloud is optically interrogated at D2. This isolates the drifting atoms from the fluorescence light coming from the detection region. The beams of the detection part #2 are turned on to first detect the atoms in the F = 4 state and then to push them out of the cloud. At D1, the F = 3 atoms are pumped to the F = 4 state and detected.

B. *Signal processing*

In our prototype of the fountain, it has been difficult to accurately measure the number of atoms because of a non-negligible background signal and of the noise present on this background. To improve these measurements, we acquired larger detectors and better optical components, improved the electronics and changed the geometry to reduce the background signal. A numerical method was also developped to reduce the sensitivity to background noise.

Two numbers need to be obtained at each launch cycle i of the fountain: the number of atoms N_{1i} in the F = 3 state and the number of atoms N_{2i} in the F = 4 state. The servo loop controls the microwave frequency to maintain the ratio N_{1i} / N_{2i} at a value of one. These numbers are obtained from the intensity measurements of the fluorescence in the two detection regions. At the basis of the method, we recognize two different types of quantities that influence the intensity measurements: those which change from cycle to cycle such as the number of atoms and noise, and those which are relatively constant from cycle to cycle such as the ratio N_{1i} / N_{2i}, the background, the pulse shape and the laser intensity. The method is based on fitting the measured signal from the detection region d (1 or 2) to a function representing the ideal averaged pulsed waveform $P_d(t)$ produced by the fluorescing atoms falling in front of the detector. The functions $P_1(t)$ and $P_2(t)$ are unknown a priori but can be obtained by averaging the fluorescence signals measured over several cycles.

We mathematically describe the measured signal by the sum of two terms, one proportional to the number of atoms N_{di} multiplied by the pulse shape function $P_d(t)$, the other as a background $b_d(t)$ independent of the number of atoms. While the number of atoms can vary by several percent from cycle to cycle, $P_d(t)$ and $b_d(t)$ change only by a small amount. The method described here extracts both functions from a number of measurements $V_{di}(t)$ measured at detector d. The number of atoms at cycle i is obtained from finding the parameters N_{di} that give the best least-squares fit between the measured signal $V_{di}(t)$ and the function $N_{di}\, P_d(t) + b_d(t)$. This is obtained by minimizing the integral

$$\int [\ V_{di}(t) - N_{di}\, P_d(t) - b_d(t)\ ]^2 \, dt. \tag{1}$$

The integral is done over a fixed time interval [0, T] which is long enough to contain the entire fluorescence pulse. An average value of $b_d(t)$ can be found from:

$$b_d(t) = < V_{di}(t) - (N_{1i} + N_{2i})P_d(t) / 2 > \tag{2}$$

where the angle brackets denote the average over several cycles. The new reference pulse shape is calculated similarly form the last cycles using

$$P_d(t) = < 2\ [\ V_{di}(t) - b_d(t)\ ] \,/\, (N_{1i} + N_{2i}) >. \tag{3}$$

The factor $(N_{1i} + N_{2i})/2$ present in (2) and (3) comes from the fact that we assume that the servo loop maintains the frequency such that on average $<N_{1i}> = <N_{2i}>$. In practice, the functions $P_d(t)$ and $b_d(t)$ can be obtained from a running average with an appropriately selected time constant. The number of atoms N_{di} can be used by the servo system to calculate the ratio of the atomic populations in the F = 3 and the F = 4 states.

A discussion of the conditions needed to obtain convergence of the algorithm is outside of the scope of this paper. However, convergence is obtained by a weak smoothing of the function $b_d(t)$ done at every cycle. Also, at least two points of the pulse shape must be given a value. It is natural to choose $P_d(0) = 0$ and $P_d(T) = 0$. One function must also be normalized to an arbitrary constant $\int P_1(t)dt = C$. The other function $P_2(t)$ adjusts itself to match the different pulse shape and the possible different gain of the second detector.

To show that the method reduces the sensitivity on the background noise, we note that (1) is minimized when

$$N = \left(\int V(t)P(t)\, dt - \int b(t)P(t)\, dt \right) \Big/ \int P^2(t)\, dt, \tag{4}$$

where the indices d and i have been dropped for clarity. Examination of the first term reveals that noise on the signal $V(t)$ located outside the peak does not affect the value of N because the function $P(t)$ becomes small. Only through many averages will that noise affect the value of N. This way, the method takes advantage of the stable quantities in the system to reduce the measurement noise.

ACKNOWLEDGMENT

We thank B. Hoger and R. Pelletier for their help in designing and building many electronic circuits and mechanical components of this experiment.

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