Update on the Development of NRC-FCs1

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***Abstract*—The first observation of Ramsey fringes is reported for NRC-FCs1. Preliminary measurements of the atomic temperature, sensitivity on launch angle and stability of the error signal are also presented. Work is underway to increase the contrast of the Ramsey fringes and improve the signal to noise ratio by using the state selection cavity, completing the detection region, demagnetizing the shields, and decreasing the atomic temperature.**

I. INTRODUCTION

Preliminary measurements obtained with the fountain clock NRC-FCs1 developed at the National Research Council Canada are reported in this paper. Not all of the planned features described in [1] were implemented for the results presented in this paper. The fountain clock uses a magneto-optical trap (MOT) aligned for a launch in the 110 direction. Three optical fibers bring the laser radiation to the MOT assembly mounted on three adjustable points for alignment of the launch direction. The launch sequence starts with a downward acceleration before the final upward acceleration across almost the entire diameter of the laser beams. The detection region is split into two detection areas, each with counterpropagating beams tuned to the F=4 to F'=5 transition. A third beam is located just above the lower detection beam and is used to pump atoms in the F=3 state returning from the Ramsey interrogation to the F=4 state for detection by the lower beam. Only one of four available 1 cm^2 photodetectors is currently used in each detection area. The fountain clock uses a transversal C-field with a rectangular Ramsey cavity operating in the TM_{210} mode, located 76.8 cm above the MOT. Only one of the two coupling antennas was used for the measurements presented here.

Important improvements on the results will result from using all the designed features and optimizations for this clock. Some of these include using the proper turn-off time for MOT fields, integrating the fluorescence signal obtained with all the photodiodes, smoothly decreasing the intensity of the laser beams during the launch, implementing rotating shutters, using the state selection cavity, adjusting the polarizations of the detection beams, and normalizing the beam intensities.

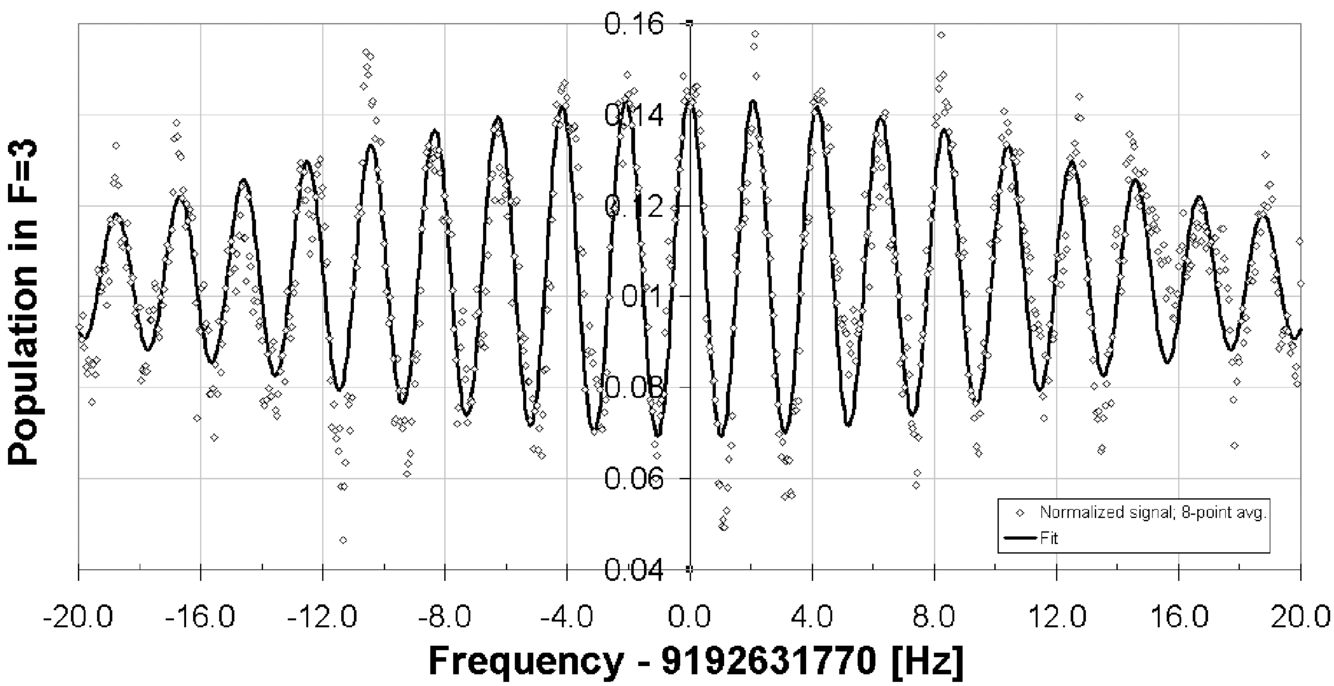

Fig. 1. First Ramsey fringes obtained with NRC-FCs1 from the average of eight scans taken sequentially. The reduced fringe contrast at 16 Hz may be caused by some residual field from the magnetic shields, which have not been demagnetized.

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II. Measurements

A. Ramsey Fringes

The first Ramsey fringes are shown on Fig. 1. Eight scans with a 0.05 Hz frequency step size were averaged to produce this plot. The fitted width of the fringes is 1.04 Hz with a contrast of 0.074. It is expected that by using the state selection cavity, the contrast will improve by a factor of 9 to 0.67. A lower atomic temperature should also increase the contrast. The fringes show some anomaly at 16 Hz which may be due to residual magnetic fields. A broader scan showed a Rabi pedestal having a width consistent with the duration of the Ramsey pulse. The transitions on the other Zeeman levels have not been measured.

B. Launch Sequence

The launch cycle is as follows: Atoms are collected in the MOT for 450 ms. They are accelerated down for 9 ms to 1 m/s, then accelerated up for 5 ms to 4.51 m/s. During the last step, the lasers are detuned to the red by 10Γ for a period of 13 ms, with their intensities decreased by a factor of four. For maximum cooling, this will be replaced by a smoothly decreasing intensity during the last step.

Atoms were initially launched at a height of 30 cm for an initial adjustment of the verticality of the laser beams. Successive adjustments were made as the launch height was increased. The highest launch resulted in a trajectory reaching a height of 27 cm above the Ramsey cavity.

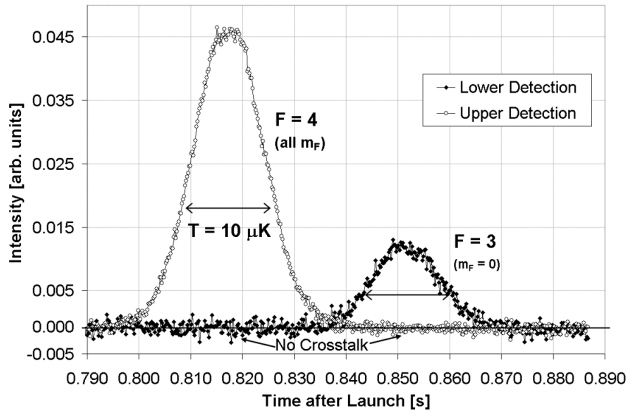

Fig. 2. Time of flight measurements. The traces show the signals recorded by the two fluorescence detectors. Five cycles were averaged. The two signals are well decoupled as is shown by the absence of crosstalk. For this measurement, part of the upper beam was blocked to push the atoms in the F=4 state away from the lower detection area.

C. Microwave Cavity

When the microwave cavity was fabricated, it's resonance frequency was measured at atmospheric pressure with helium flowing through the cut-off waveguides. It was tuned to be resonant with the cesium transition at 30 C once installed in a vacuum. The Ramsey cavity is indirectly heated by the surrounding vacuum chamber. Fine coaxial wires, wrapped around the exterior of the vacuum chamber, are used in order to produce the

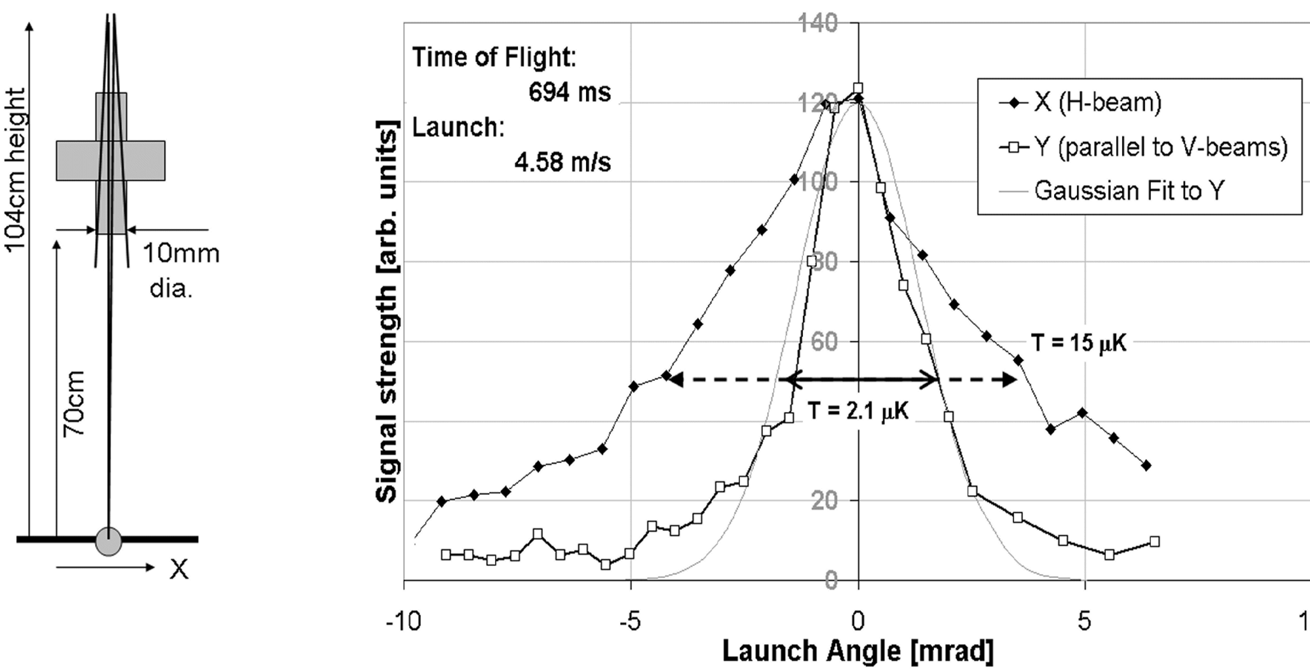

Fig. 3. Fluorescence intensity proportional to the number of atoms falling in front of the upper detector as a function of launch angle. The inset (left) shows the geometry of the system. Two transversal temperatures were determined. Due to the high asymmetry of the data for the X angle, the temperature was estimated from the width of the peak at half maximum. A Gaussian fit to the result for the Y angle was used to determine the other transversal temperature.

smallest possible magnetic field from the heating wire. With the cavity now inside the vacuum chamber, its resonance frequency was measured for temperatures ranging from 22 C to 26 C. Extrapolation of the data shows that the cavity will be tuned at 29 C.

The microwave power into the Ramsey cavity was varied to produce Rabi oscillations up to a $5\pi/2$ pulse. The power was then adjusted for a $\pi/2$ pulse for the remaining measurements.

D. Velocity Dispersion

The velocity dispersion of the launched atoms was measured along three orthogonal directions. Here, we quantify the velocity dispersion with an equivalent "temperature", even if thermal equilibrium is not achieved. The time of flight signal measured at the detection provides a measurement of the longitudinal temperature. It is shown on Fig. 2 for the two detection regions. A temperature of approximately 10 µK was determined for both curves. Note also that the two signals are completely independent, as there is no crosstalk signal visible on the curves.

The temperatures in the other two transversal directions were obtained by monitoring the intensity of the return signal as a function of the launch angle. As the launch angle is varied away from vertical, more atoms will hit the lower cut-off waveguide below the Ramsey cavity. A larger temperature reduces the sensitivity of the intensity on the launch angle because the atomic cloud is larger. The inset on the left of Fig. 3 shows the geometry of the experiment. The horizontal beam of the MOT defines the X-axis of the system, the Y-axis is perpendicular to the page and the Z-axis is vertical. The atoms are launched to a height of 104 cm, then fall back through the lowest aperture of the cavity before being detected. The 10 mm diameter aperture of the Ramsey cavity is located 70 cm above the MOT.

The first measurement shows the signal as a function of the angle in the X direction (that is, the MOT beams pivot about the Y-axis). The low sensitivity of the signal intensity on the angle implies a fairly high temperature of 15 µK. When the MOT is rotated in the Y direction (about the X-axis), the signal drops more rapidly, indicating a colder temperature of the order of 2.1 µK. The difference between the two directions is most likely due to the asymmetric 110 beam configuration. In the X direction, the atoms are guided by the horizontal counterpropagating beams in an optical potential of spatial dimension $\lambda/2$. In the Y direction, the atoms are guided by four beams at 45° from the vertical, producing a wider potential of spatial dimension $\sqrt{2}\,\lambda/2$. The colder temperature may result from the larger dimension of the optical potential. More studies are required to understand these results. Since the atomic distributions (in position and velocity) affect the transverse phase shift occurring inside the Ramsey cavity, it will be interesting to study how this affects the sensitivity of the clock on the transverse temperature. In the present configuration, the direction corresponding to the low velocity dispersion is parallel to the C-field.

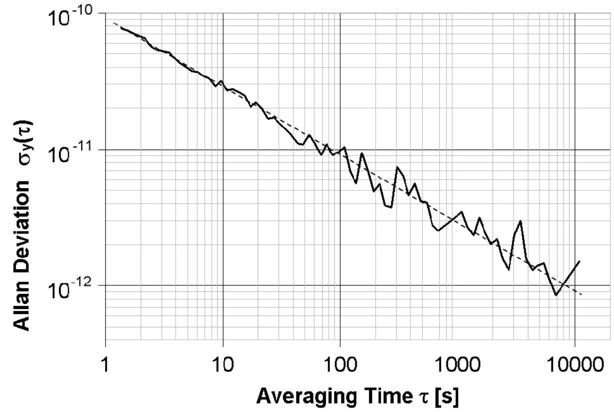

Fig. 4. Allan deviation of the first error signal. Improvements are needed, but this shows that the fountain clock can run for 8 hours without problem.

E. Stability of the Error Signal

The microwave synthesizer was locked to a signal from a hydrogen maser. The error signal generated by modulating the frequency ±0.5 Hz about the center frequency was analyzed with the Allan deviation (Fig. 4). The fountain was run continuously for almost eight hours to demonstrate the stability of all the components. An Allan deviation of 9×10^{-11} at 1 s is not surprising considering the preliminary nature of these tests. However, the expected $\tau^{-1/2}$ dependence of the Allan deviation is seen. Some adjustments of the laser intensities in the MOT were made manually during the run, but this was done without interrupting the measurements. It is hoped that only minor modifications will be required to extend the autonomous operation to several days.

III. Conclusion

These measurements constitute the beginning of the evaluation of the standard. The results are needed to quantify the advantages of operation with a transversal C-field, symmetrically fed microwave cavities, light shutters and a cooled drift region. Systematic errors and the dependence on operating parameters will be studied next for the evaluation of the uncertainties of the standard.

Acknowledgment

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References

[1] L. Marmet B. Hoger, P. Dubé, A.A. Madej, J.E. Bernard, "Detailed description of FCs1: NRC's cesium fountain primary standard," Proceedings of the 2008 IEEE International Frequency Control Symposium, 386 (May 2008).