

# Status of the atomic fountain clock at the National Research Council of Canada

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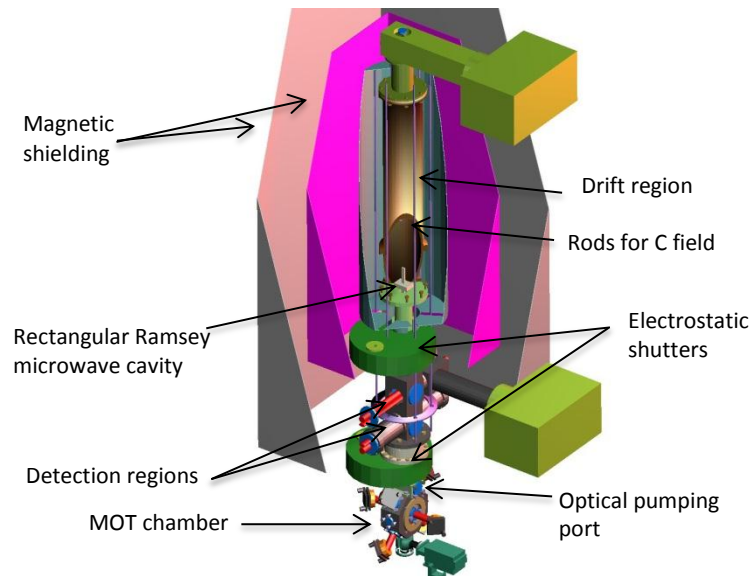
**Abstract.** Despite the rapid advances in optical frequency standards, caesium fountain clocks retain a critical role as the most accurate primary frequency standards available. At the National Research Council Canada, we are working to develop a second generation caesium fountain clock. Work is currently underway to improve several systems of FCs1, such as the laser system and microwave local oscillator, which will be incorporated into its refurbished version, FCs2. In addition, we have added an optical pumping stage which has increased the detected atom number by over a factor of six. In collaboration with the National Physical Laboratory (NPL), we are planning on replacing the physics package of FCs1. We will report on several recent improvements to FCs1, along with our progress in the development of FCs2.

## 1. Introduction

Current state of the art caesium fountain clocks can reach uncertainty levels of a few parts in  $10^{16}$  [1-3]. Though this uncertainty is one to two orders of magnitude higher than that of the top performing optical clocks, fountain clocks are extremely robust primary standards and represent the most accurate realization of the International System (SI) second. At the National Research Council of Canada (NRC), we are currently working to rebuild our current caesium fountain FCs1 with several design changes. With these design changes and several technical improvements, we hope to achieve state of the art accuracy in its refurbished form, FCs2.

Here, we report on several technical improvements made to NRC FCs1 that have allowed us to increase the signal to noise and stability of our fountain. These improvements include changes to the laser setup, as well as the implementation of an optical pumping stage. We also describe our proposed design changes for FCs2, and report on our progress.





**Figure 1.** Physics package for NRC FCs1.

## 2. Experimental methods

### 2.1. Physics package

Figure 1 shows a schematic of the physics package for NRC-FCs1. It uses a (1,1,0) magneto-optical trap (MOT) beam geometry with beam diameters of  $\sim 30$  mm. The C field is generated using 4 parallel, current-carrying rods which create a magnetic field transverse to the atoms' trajectory. The physics package also includes electrostatic shutters designed to allow the juggling of atoms to reduce the Dick effect. These shutters, however, have been problematic and have never been used in the operation of FCs1.

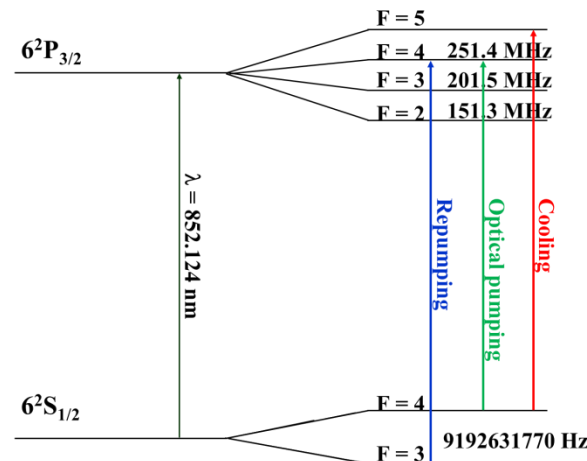
In FCs2, we will use a (0,0,1) MOT beam geometry. We will also use the more conventional technique of providing a C field along the vertical axis of the atom's trajectory, via a solenoid wound around the drift tube. The electrostatic shutters will be also eliminated in FCs2, simplifying the system and allowing a more compact design.

### 2.2. Laser setup

Until recently, the laser system has relied on master and repumper external cavity diode lasers, as well as four slave diode lasers to amplify the cooling and detection light. The slave diode lasers presented the weak point in the stability of the laser system, as they would regularly need to be adjusted. We have recently replaced the slave diode lasers with 2 tapered amplifier systems (Sacher TEC 400). These systems have proven to be extremely robust and have dramatically improved the stability of the system. They require only occasional adjustment to their seed beam alignment. In addition, they require less space on the optical table, and allow the total beam path lengths to be reduced, further increasing the stability of the system.

### 2.3. Optical Pumping

In a typical experimental launch sequence, the atoms are cooled and launched from a moving optical molasses in the  $F=4$  state (roughly equally populated  $m_F$  states) before they pass through a state selection microwave cavity which applies a  $\pi$  pulse of microwaves on the  $|F=4, m_F=0\rangle \rightarrow |F'=3, m_F'=0\rangle$  transition. Atoms left in the  $F=4$  ground state are eliminated by applying a “pusher” beam of light to cycle atoms on the  $|F=4\rangle \rightarrow |F'=5\rangle$  transition. This procedure gives a clean sample of atoms only in the  $|F=3, m_F=0\rangle$  clock state, but it reduces the atom number by roughly  $8/9=89\%$ .



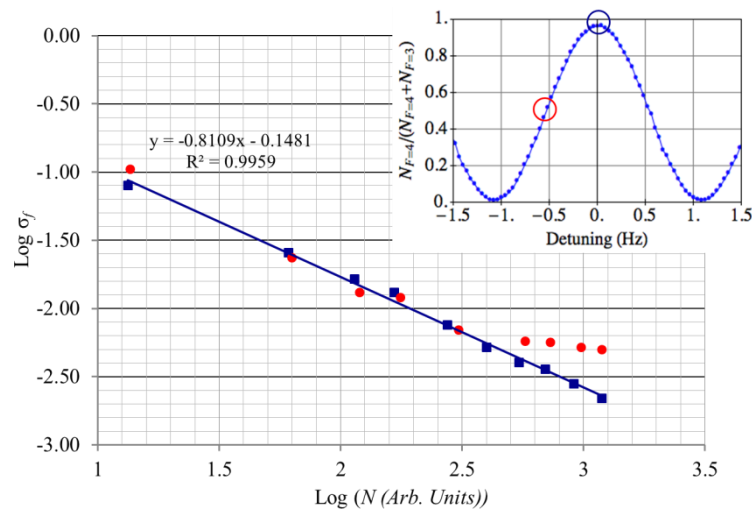
**Figure 2.** Partial energy level diagram of  $^{133}\text{Cs}$ .

We have recently implemented an optical pumping stage which allows us to cycle atoms into the  $|F=4, m_F=0\rangle$  state. In this case, after the atoms are launched but before they reach the state selection cavity, we apply optical pumping light which is tuned to the  $F=4 \rightarrow F=4'$  transition, as shown in Fig. 2. If the light is  $\pi$  polarized, transitions with  $\Delta m=0$  are forbidden. We also apply repump light, tuned to the  $F=3 \rightarrow F'=4$  transition. Whenever an atom is repumped into the  $|F=4, m_F=0\rangle$  state, it will become dark to the optical pumping light and therefore the atoms will be preferentially pumped into this state.

We have found that this technique has resulted in an increase in detected atom number of over a factor of 6. One limitation to the technique is that the extra scattered photons will heat the atomic cloud, increasing losses at the apertures of microwave cavities.

### 3. Results

With our recent improvements to the stability and detected atom number, we have achieved a signal to noise ratio (SNR) of over 1000. This puts the fountain into a regime where it is limited by the short term stability of the local oscillator. The local oscillator is a NIST spaceclock microwave synthesizer locked to a 5 MHz maser reference signal. To test if the fountain was limited by the short term stability of our microwaves, we measured the standard deviation of our detected population fraction,  $F = N_{F=4} / (N_{F=3} + N_{F=4})$ . The log of the detected noise is plotted against the log of the total atom number (controlled by varying the loading time), as shown in Fig. 3.



**Figure 3.** Log of the standard deviation of the measured population fraction vs the log of total detected atom number (in arb. units). The blue squares show data taken on resonance, while the red circles show data taken with the microwaves detuned to achieve equal populations in  $F=3$  and  $F=4$ , as shown in the inset.

Here we took data at the peak of the central Ramsey fringe (blue), where noise in the local oscillator should have no effect due to the zero slope of the Ramsey fringe, as well as on the side of the Ramsey fringe where any noise in the frequency of the microwaves would impact the measured fraction. As shown in Fig. 3, we find that while the blue data points show a continuing decrease with increasing atom number, the red data points level off. This is evidence that the short term stability is currently limited by the local oscillator.

#### 4. Progress towards FCs2

In collaboration with the UK National Physical Laboratory (NPL), we are currently developing a new physics package for FCs2. This fountain will reuse many elements from FCs1 such as the laser system and microwave sources. Therefore we are making several improvements to those systems before a new physics package is ready to be installed.

##### 4.1. Microwave local oscillator

As shown above, the short term stability is limited by the local oscillator. This will certainly still be the case when we integrate our newly designed physics package, which has a significantly higher collection efficiency for the detection optics. To improve the stability of the local oscillator, we have purchased an ultra-high performance crystal oscillator from Microsemi (1000C model) to serve as the 5 MHz reference for our microwave synthesizer. The phase noise is  $-130$  dBc at 1 Hz and the instability is  $\sigma_y < 2 \times 10^{-13}$  from 0.1s to 100s. This performance could show a significant improvement over the maser which is currently used as a 5 MHz reference. In future, we hope to implement an optical local oscillator, derived from an ultra-stable laser [4] locked via a frequency comb.

##### 4.2. Laser system

As described briefly above, our laser system is based on two external cavity diode lasers to provide the radiation for repumping and cooling/optical pumping/detection. We have replaced the slave diodes with tapered amplifier systems which have dramatically reduced the maintenance and downtime for the system.

Currently, we have visible noise on our detection signals due to an oscillation on the frequency of our cooling laser (Vortex 7017). We hope to replace this laser with a newer model, not susceptible to the mechanical resonance which causes this  $\sim 2$  kHz oscillation. In addition, we plan to implement a fast feedback to the laser current, which will result in a higher-bandwidth lock and better compensate for this type of modulation on the laser.

#### 4.3. Physics Package

The physics package of NRC FCs1 will be replaced with one based on the design of NPL CsF3. The most significant differences will be;

- (0,0,1) geometry with light delivered via six optical fibers, attached to the vacuum chamber by cage systems. This will ease alignment of MOT beams and the verticality of the atom cloud launch.
- Solid angle of detection will increase to  $\sim 30\%$ , an increase of over a factor of two.
- The C-field will be parallel to the atoms' motion, in contrast to the transverse C-field of NRC-FCs1.
- The cavity will be made with cylindrical geometry, with four input ports to facilitate the characterisation of the distributed cavity phase shift [5].

#### 5. Conclusions

We have presented improvements of the signal to noise and stability of FCs1, with a SNR of over 1000 and stability limited by the our microwave local oscillator. We have successfully added an optical pumping stage which has increased our detected atom number by over a factor of six. With these improvements, along with the current work to further upgrade our local oscillator, laser system, and physics package, we hope to achieve state of the art performance with FCs2.

#### References

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