

# Recent progress in optically-pumped cesium beam clock at Peking University

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**Abstract.** A compact, long-life, and low-drift cesium beam clock is investigated at Peking University, where the atoms are magnetic-state selected and optically detected. Stability close to that of the best commercial cesium clocks has been achieved from 10 to  $10^5$  s. As previously shown, the short-term stability is determined by atomic shot noise or laser frequency noise. The stabilizations of microwave power and C-field improve the long-term stability, with the help of a digital servo system based on field-programmable gate array.

## 1. Introduction

Magnetic state selection is a simple and stable method in a cesium beam clock, even though, compared with optical selection, it decreases the number of atoms that approaches the detection region. Therefore, cesium clocks with magnetic state selection have been studied and applied for more than fifty years [1]. On the other hand, optically pumped cesium clocks have shown better short-term frequency stability [2, 3], indicating that laser is an alternative method of state preparation and detection. To avoid the life limitation due to the electron multiplier, we try to use optical detection instead of the traditional detection method in our cesium beam clock [4], which is also aiming at a compact device for long-term time-keeping. Operating in the atomic shot noise region, with frequency stability of  $9 \times 10^{-12} \cdot \tau^{-1/2}$  that reaches  $3 \times 10^{-14}$  at  $10^5$  s, the clock is potentially suitable for terrestrial and space-borne application. Noise analysis shows that the short-term stability is limited at higher oven temperature, by noise induced by laser frequency deviation, which makes demands of the laser source. The laser frequency noise is coupled by the relatively narrow line shape of absorption of the atoms. Digital circuits based on field-programmable gate array (FPGA) help controlling the servo loops.

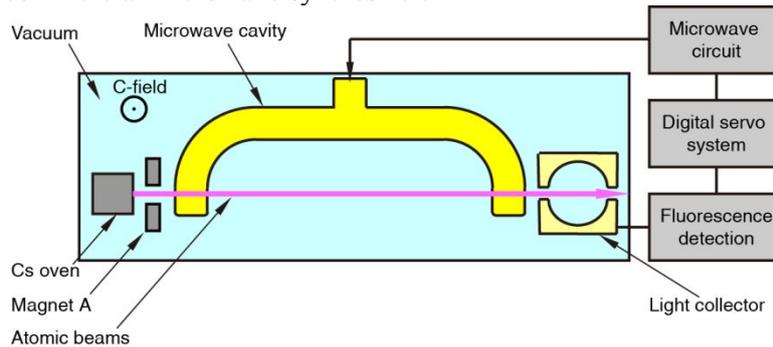
## 2. Experimental set-up

As shown in figure 1, in a sealed vacuum tube, two thermal Cs beams, collimated by collimators, emit from an oven which is temperature-controlled. They cross the inhomogeneous magnetic field generated by a set of magnets, partly deflected, depending on the state of atoms, towards the microwave interrogation region. The two beams separate in the direction parallel to the C-field, hence not distinguishable in the figure. An E-bend Ramsey cavity, whose field-free length is 17 cm, makes microwave interrogation possible. Coils surrounding the cavity generate a homogeneous magnetic field, the C-field, which is needed to separate the  $m_F = 0$  clock transition from then magnetic-field



sensitive transitions. Two apertures on the cavity wall, each with size of  $1.8 \times 6 \text{ mm}^2$ , determine the cross section of the beams. The beams passing the cavity reach the optical-detection region, which is surrounded by a pair of spherical mirrors. Laser beam (not shown), pointing parallel to the C-field, irradiates the atoms, whose fluorescence is reflected by the mirrors and detected by a photo diode. The microwave interrogation region and optical detection region are independently shielded.

Digital servo system based on FPGA, as shown in figure 2, which is an improved version of that described in [5], is implemented. It has three servo loops, local-oscillator loop, microwave-power loop, and C-field loop, working sequentially. Microwave frequency is modulated by a 78Hz square wave, with the help of a commercial microwave synthesizer.



**Figure 1.** Experimental set-up. (colour online)

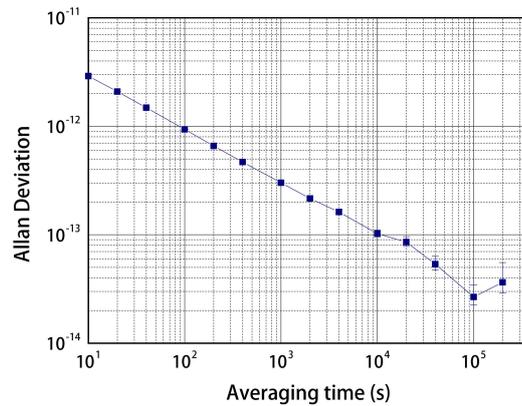


**Figure 2.** The printed circuit board of the servo system. (colour online)

The 852-nm laser beam is generated by either an external cavity diode laser (ECDL) or a distributed feedback (DFB) diode laser, whose nominal line widths are 100 kHz and 2 MHz respectively. The frequency of the laser is locked to the  $F=4-F'=5$  transition, which is a cyclic transition, of Cs D2 line with an independent saturated absorption spectroscopy. The modulation frequency of the laser, for the purpose of its frequency locking, is 5 kHz. Incident light power to the tube is 3 mW for ECDL and 10 mW for DFB.

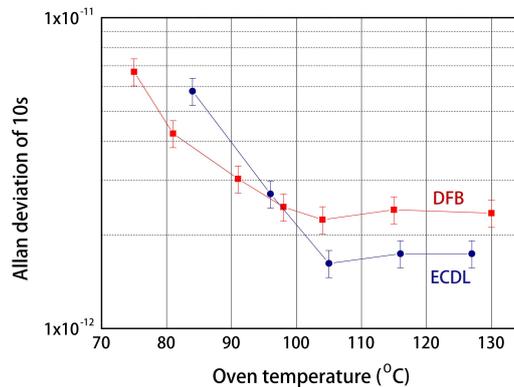
### 3. Results

Allan deviation calculated from a 15-day continuous measurement without C-field stabilization, during which the oven temperature is 95 °C and light source is ECDL, is illustrated in figure 3, where the fitted Allan deviation is  $9 \times 10^{-12} \cdot \tau^{-1/2}$  from 10 to  $10^5$  s. The short-term stability is at the same level as the best commercial magnetic-state-selection clocks, e.g. 5071A, high performance. For longer integration time than  $10^5$  s, the stability is degraded. A previous measurement without microwave power locking loop demonstrated a long-term stability limit of  $2 \times 10^{-13}$ , which motivated us to incorporate the microwave power stabilization in the current stage of development.



**Figure 3.** The Allan Deviation of a 15-day continuous measurement.

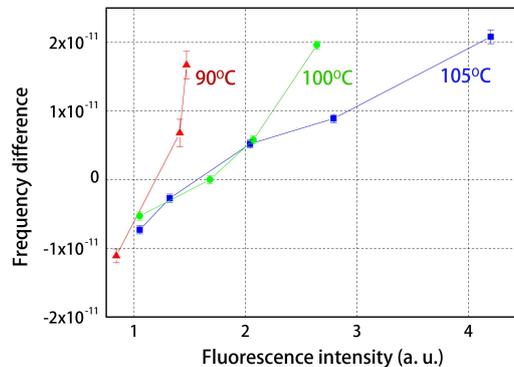
The 10-s stability is plotted in figure 4, with respect to Ramsey signal amplitude that is varied by controlling the oven temperature. It is seen that short-term stability with ECDL, which is locked to  $F=4-F^7=5$  cyclic transition, saturates when oven temperature is above 105 °C. This indicates that noise due to laser frequency deviation becomes dominant at high oven temperature, which is explained in detail in [4]. When the light source is replaced by the DFB laser locked to the same transition, the short-term stability is saturated to a larger value, at a temperature slightly lower than that of ECDL, because the DFB's laser frequency noise becomes dominant more easily.



**Figure 4.** The short-term stability depending on the oven temperature and laser choice, red for DFB and blue for ECDL. (colour online)

Long-term stability is limited by several possible causes, including light shift, C-field shift and shift related to the microwave cavity. The frequency difference with respect of the fluorescence power depending on the incident power, with ECDL, is plotted in figure 5. The output frequency is significantly influenced, with total variation of  $3 \times 10^{-11}$  from 0 to 20 mW, by change of incident power. It is seen that when the fluorescence intensity is small, the frequency shifts are close under different oven temperatures, indicating that the light shift caused by fluorescence is the main shift. On the other hand, when the fluorescence intensity is large, the shifts have differences, because the scattered light becomes intense. When oven temperature is lower, extra incident light power is needed, because of saturation, to assure the same fluorescence, leading to a larger frequency shift caused by scattered light. Near the operation conditions, the measured slope of frequency shift with respect to incident light power is  $1.3 \times 10^{-12}$  /mW. In order to achieve the clock's long-term stability in  $10^{-15}$  range, the laser's power perhaps needs to be stabilized. The C-field stabilization is considered to

be necessary for the frequency varies strongly with C-field due to second-order Zeeman frequency shift. The cavity is tuned to the clock frequency before the measurement to minimize the cavity-pulling frequency shift. The cavity loaded quality factor is approximately 1000 and the estimated frequency shift is  $3 \times 10^{-13}$  for cavity mistuning of 1 MHz. However, the performance of the cavity is still unknown during a long-term operation.



**Figure 5.** Light shift at different oven temperatures, red, green and blue for 90, 100 and 105 °C. (colour online)

#### 4. Conclusion

The application of optical detection in place of the traditional detection method in cesium clocks allows a long life of the clock in principle. However, the optical detection leads to some effects, e.g. light shift, that affect the performance of the clock. Moreover, the long-term operation of laser diode has to be taken care of. Besides, the digital circuits need further modification to complete the laser frequency stabilization and automatic control.

#### Acknowledgments

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