Velocity Distribution Measurement of an Optically Pumped Cesium Frequency Standard at the NRLM

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ABSTRACT

The velocity distributions of the optically pumped Cs frequency standard are measured using the rf pulse excitation method. The results are shifted toward higher beam velocity than the Maxwellian distribution and suggest a dependence on vacuum pressure. The velocity distribution is not sensitive to the laser power for pumping and detection, if the power is more than a few mW. The second-order Doppler shift was estimated as $\Delta f = -3.1 \pm 0.1$ mHz.

1. INTRODUCTION

The National Research Laboratory of Metrology is developing an optically pumped cesium frequency standard[1] that is expected to improve remarkably the accuracy of the standard. For the accuracy evaluation of a primary laboratory type standard, it is very important to know the velocity distribution of the atomic beam. The second-order Doppler shift is estimated by measuring the velocity distribution using the pulse excitation method[2].

When we denote the length between the two microwave cavities L and the interval of pulse period T, only the atoms with velocity v=L/T contribute to the Ramsey resonance signal. We applied a long pulse method which is suitable for laboratory type long tubes. The long pulse means $t > l/v$, where l is the length of the single cavity section, and t is the microwave pulse duration. If the phase difference between the two microwave cavities is zero, the Ramsey resonance signal is given by

$$P \propto \sin^2 2b\tau \cdot \cos^2(\lambda T/2), \qquad (1)$$

where $\tau = l/v$, $\lambda = 2\pi(\nu - \nu_o)$ and b is proportional to the square root of the microwave power. When we maintain $2b\tau = \pi/2$ by controlling the microwave power, the amplitude of the Ramsey resonance signal S can be written as

$$S \propto (t/T) \cdot \Delta v \cdot \rho(v), \qquad (2)$$

where $\rho(v)$ is the velocity distribution function and Δv is the velocity window given by $\Delta v \approx (l/L + t/T) \cdot v$.

If we also keep $t/T=$ const., we can easily obtain

$$\rho(v) \propto S \cdot T. \qquad (3)$$

This paper presents the results of the velocity distribution measurements and the estimation of the second-order Doppler shift of the optically pumped standard.

2. MEASURING SYSTEM

Figure 1 shows a block diagram of the automated velocity distribution measurement system. The pumping laser is stabilized to the $F=4-F'=4$ component in the D_2 line while the detection laser is stabilized to the $F=4-F'=5$ component. Both laser lights are σ polarized. The cross sections of the laser beams are about 2 mm × 4 mm. Our apparatus has L of 0.96 m and l of 0.01 m. The C-field strength is 7.9 A/m and the effective cross section of the Cs atomic beam is 3.2 mm × 3.2 mm. The beam is reversible for the correction of cavity phase difference. The ovens were normally operated at 110 ℃. The room temperature was maintained at 23± 1 ℃.

In Fig. 1, the microwave power from the gunn diode oscillator is chopped into a pulse width t and a period T using a pulse generator and a PIN-diode modulator, and it is provided to the Ramsey cavity. We set at $t/T=1/10$. Although the velocity window is not so narrow, its influence on the estimation of the second-order Doppler shift is less than 1% [3].

The microwave power level is also adjusted using step attenuators. The signal from the tube's detector is amplified and measured with a digital voltmeter. This output is fed to a personal computer, thus the frequencies of the peak and valley of Ramsey resonance are automatically searched by the computer and the peak-to-valley amplitude is calculated.

3. EXPERIMENTAL RESULTS

Figure 2 shows the typical velocity distributions in both beam directions obtained by the experiments. The frequency stand-

ards in the NRLM are placed in an east(E)- west(W) direction for effective magnetic shielding from the earth. We then indicate the atomic beam directions as E→W or W→E.
The second-order Doppler shift was calculated using

$$\Delta f = -\frac{f_0}{2c^2} \cdot \frac{\int_0^\infty \rho(v)\sin^2(2bl/v)dv}{\int_0^\infty 1/v^2 \rho(v)\sin^2(2bl/v)dv}, \quad (4)$$

where f_0 is the resonance frequency.
At the optimum microwave power, b was found to be 20.8 krad/s experimentally. Then the second-order Doppler shift from the velocity distribution was calculated as

$$\Delta f = -3.1 \pm 0.1 \text{ mHz}. \quad (5)$$

The difference of the second-order Doppler shifts in both beam directions was within 0.1 mHz.

As we used cycling transition for detection, the velocity distribution function should be expressed by the Maxwellian distribution as $\propto v^2\exp(-mv^2/2k\Theta)$, where m is the mass of a Cs atom, k is the Boltzmann constant and Θ is oven temperature in K. The solid line in Fig. 2 shows the predicted distribution at the oven temperature of 110 ℃. We can see the results are shifted from the Maxwellian distribution. We supposed that it might come from the scattering of lower velocity atoms by the residual gas molecules in the vacuum chamber. We therefore took some measurements at the different vacuum pressures. Figure 3 is the velocity distribution measured for the vacuum pressures of 1×10^{-5} Pa and 6×10^{-5} Pa. The results show that the shifting depends on the degree of vacuum. At the higher vacuum pressure, the second-order Doppler shift at the optimum microwave power was estimated as $\Delta f = -3.4 \pm 0.1$ mHz. As the vacuum pressure does not change so much during the continuous operation, this influence is negligible.

Figure 4 shows the velocity distributions in two different oven temperatures; one is with a nominal temperature (110 ℃) and the other is with a low temperature (83 ℃). We can recognize that the difference between the experimental result and theoretical prediction becomes smaller at the temperature of 83 ℃.

We measured the velocity distributions in different laser power conditions, because it is considered that the laser power would play a very important roll in the forming of the velocity distributions in the optically pumped atomic beam. Figure 5 shows the dependence of the laser power for pumping and detection. When the pumping power is decreased to 40% (4 mW), there is no change in the velocity distribution and signal intensity. When the detection laser power is decreased to 40% (1.4 mW), the signal intensity decreases to 30%. However the velocity distribution does not depend on detection laser power. These are very important results for the measurement of the velocity-dependent frequency shifts.

As optically pumped Cs frequency standard have generally broad velocity distributions, we expected to encounter the second sub-harmonic signal. However the effect on the velocity distribution was smaller than we expected. We have not observed the effect of it yet.

4. CONCLUSIONS

We drew the following conclusions:

(1) Velocity distributions are shifted toward higher velocity than the Maxwellian distribution, the shifts depend on the vacuum pressure and become smaller at lower oven temperature.

(2) The velocity distribution is not sensitive to the laser power for pumping and detection, if the power is more than a few mW.

(3) The second-order Doppler shift at the optimum microwave power was estimated to be $\Delta f = -3.1 \pm 0.1$ mHz.

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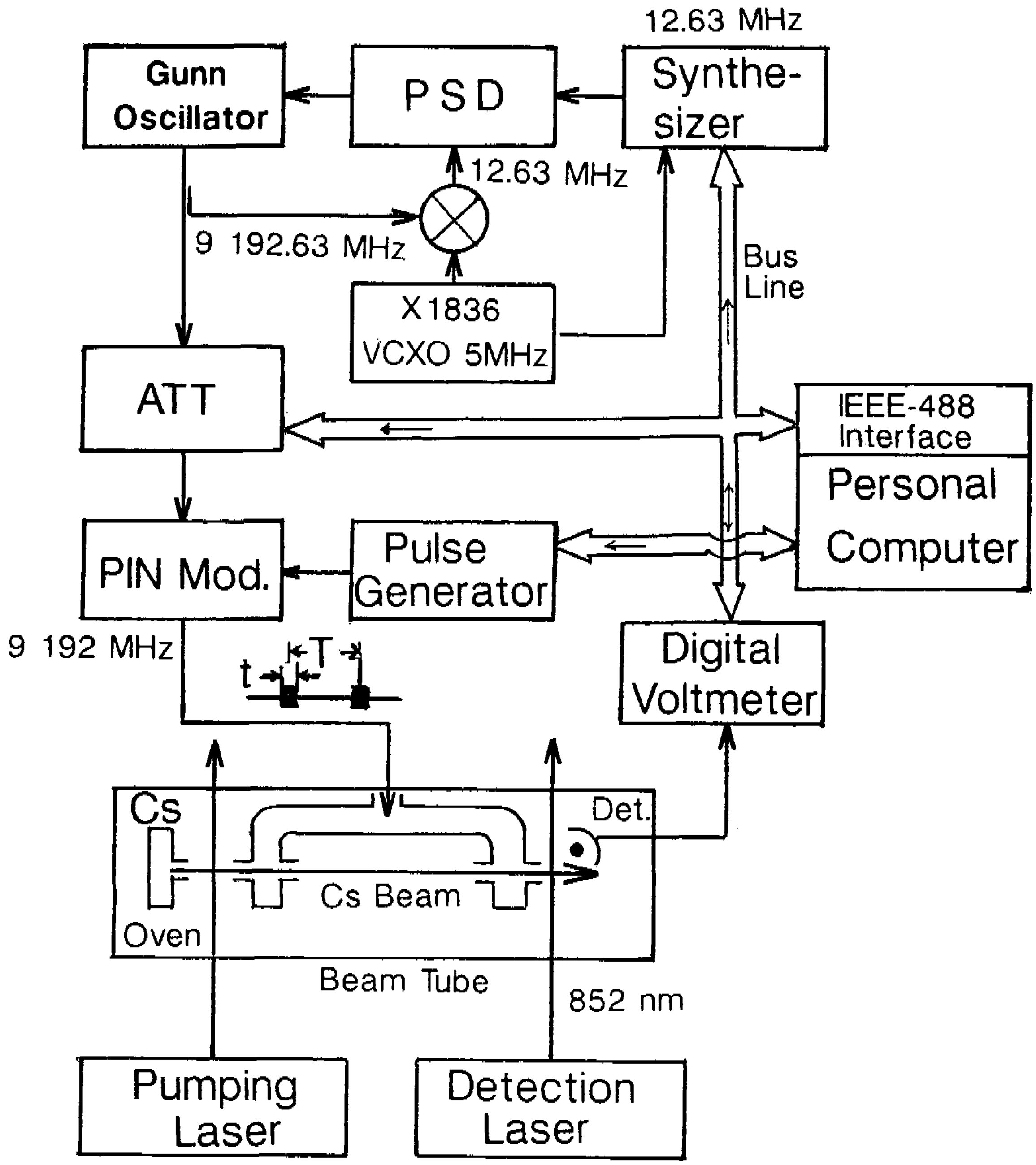

Fig. 1 Block diagram of the automated velocity distribution measurement system.
PSD: Phase Sensitive Detector, ATT: Attenuator,
VCXO: Voltage Controlled Crystal Oscillator.

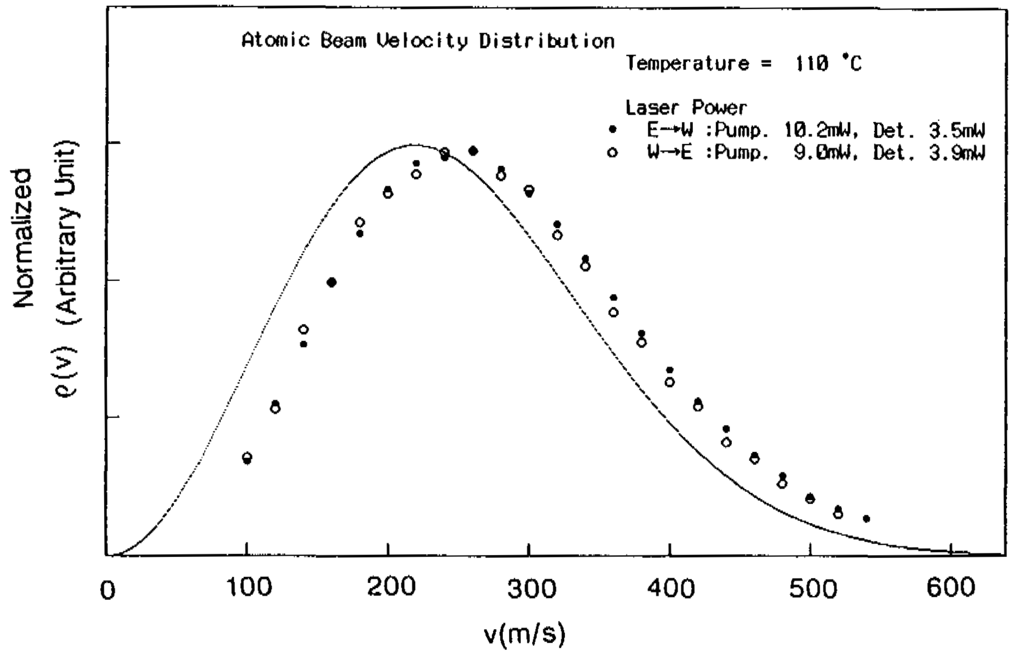

Fig. 2 Typical velocity distributions of the optically pumped Cs standard at the NRLM. The solid curve is the calculated Maxwellian distribution.

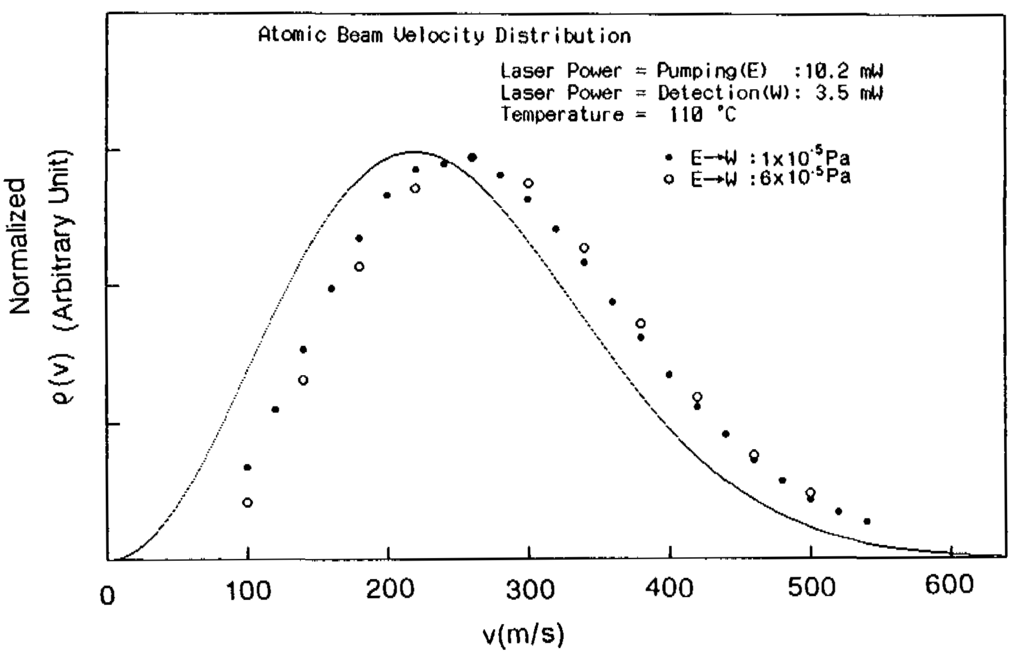

Fig. 3 Velocity distributions at the vacuum pressure 1×10^{-5} Pa and 6×10^{-5} Pa.

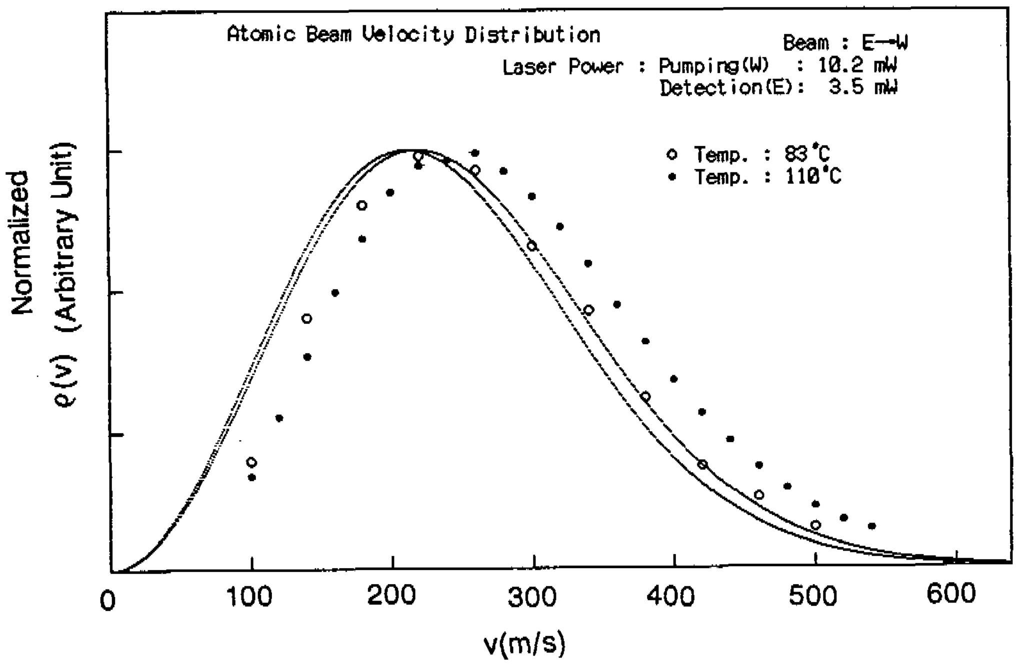

Fig. 4 Velocity distributions at the oven temperatures of 110 ℃ and 83 ℃.

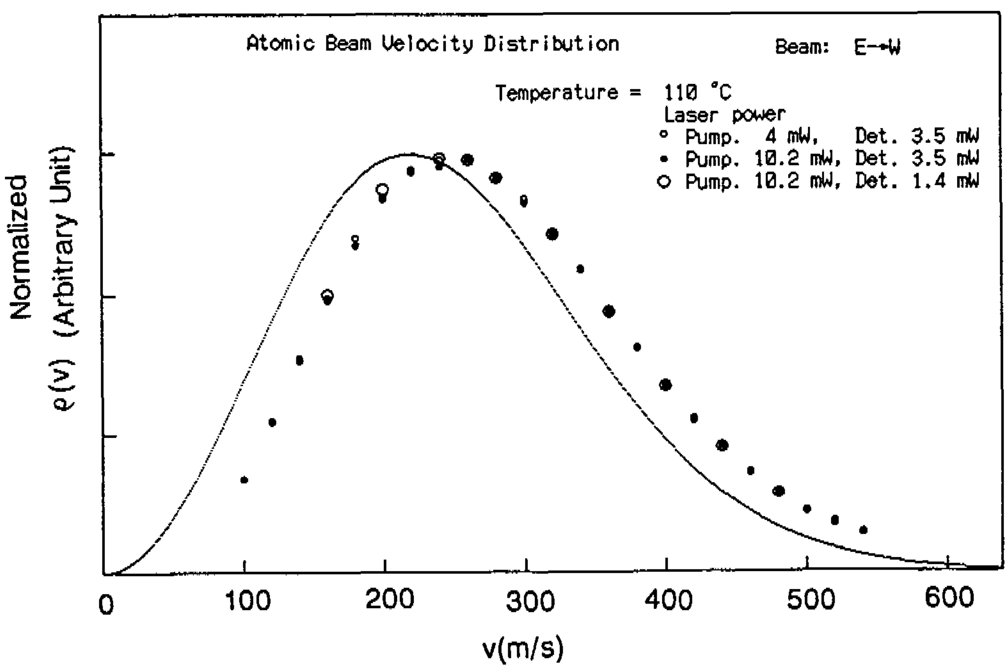

Fig. 5 Velocity distributions for the different laser power for pumping and detection.