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# Fine-Structure Artifact of the Velocity Distribution of Cs Beam Tubes as Measured by the Pulsed Microwave Power Technique


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An artifact of the pulsed microwave power technique used to measure the velocity distributions of Cs beam tubes is a fine structure on the distribution. In previously reported measurements the signal-to-noise ratio was not high enough to show this structure clearly. This paper presents results that show this structure in detail. To predict these results, a simple theory has been used that considers the Ramsey response function (i.e., output tube current vs. microwave frequency) as being a simple electrical-filter transfer function for the input of the pulse-modulated microwave power. Calculations that assume the principle of superposition give predictions that are in close agreement with the measured results. This theory also predicts how to set the pulse width so that the fine-structure artifact is minimized.

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# Preface

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# I. Introduction

The knowledge of the velocity distribution of a cesium (Cs) beam tube provides considerable insight into the performance and alignment of the beam optics, which in turn affects the final performance of the frequency standard. To measure these velocity distributions, early investigators [1,2,3] developed a method that used the pulsed excitation of atomic beam devices that had Ramsey-type interaction regions; this allowed for the observation of signals that were due to very narrow velocity groups. A completely automatic system that employed this pulsed microwave technique was set up in our laboratories. Figure 1 is a block diagram of the equipment used; the set-up is described in detail in [4].

Figure 2 shows the operation of the Ramsey cavity with pulsed microwave power. For a pulse period of $T$ the velocity $v$ selected is $L/T$, as shown. The pulse width $\tau$ is chosen to be less than the Cs ions' time of flight through the interaction regions, i.e., less than $l/v$.

In the process of making some of our early velocity-distribution measurements, we noticed what appeared to be a periodic structure on the distribution. At first we thought this structure to be noise in the measurement system; however, as we improved our system further, we could see that the structure was clearly there. The amplitude of this structure was found to be a function of the pulse width. A typical example of the structure is shown in Figure 3, which is a plot of the Cs velocity distribution $\rho(v)$.

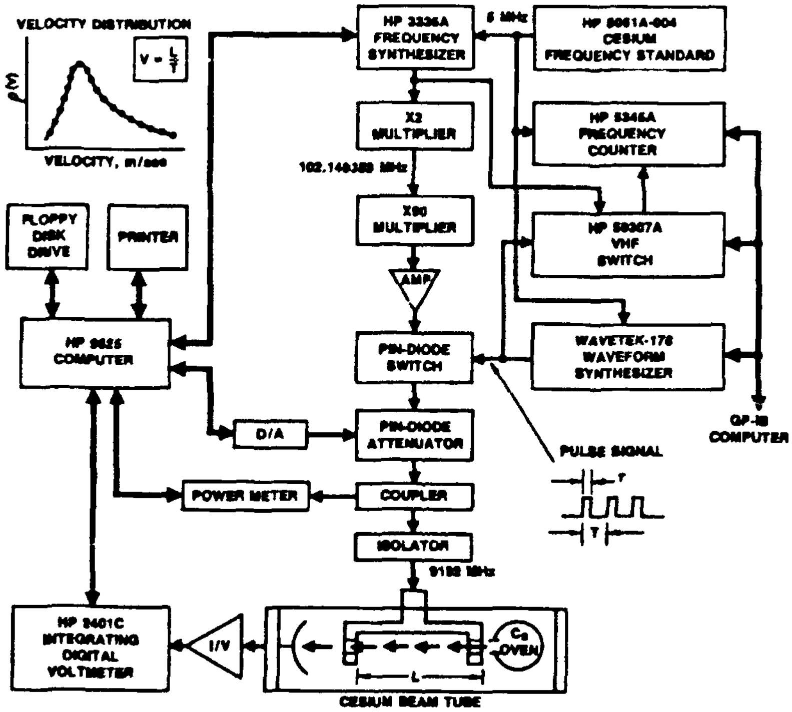


Figure 1. Block Diagram of the System for Measuring the Velocity Distribution of the Cs Beam Tube under Pulsed Microwave Conditions

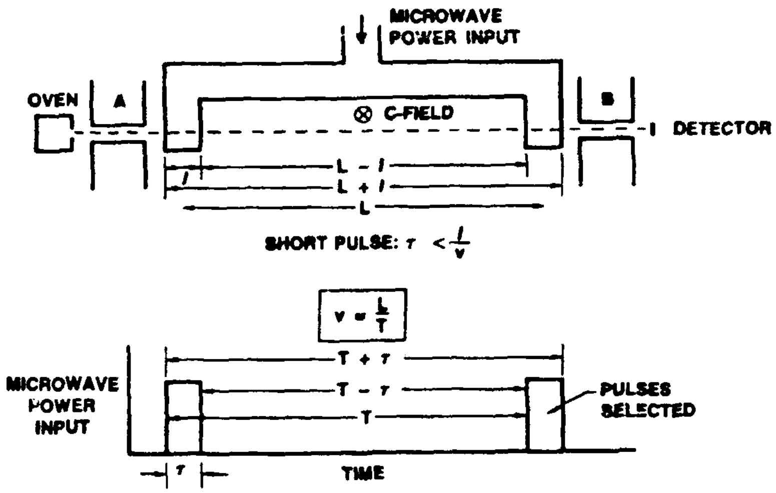


Figure 2. Operation of the Ramsey Cavity with Pulsed Microwave Power. The design of the Ramsey dual-interaction region allows one to select the velocity of the atomic beam by setting the period $T$ of the microwave pulses.

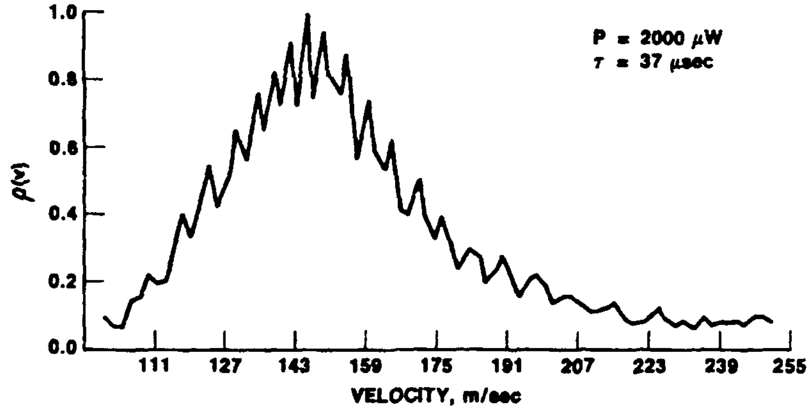


Figure 3. Measured Velocity Distribution for a Cs Beam Tube Using a Pulse Width of 37 $\mu$sec and a Peak Microwave Power of 2000 $\mu$W

## II. Discussion

The structure shown in Figure 3 can be understood by looking at the pulse-power spectrum and viewing the Ramsey response function as a filter for this spectrum. The Ramsey response for the tube measured in Figure 3 is shown in Figure 4. For a pulse modulation function as shown in Figure 5, the Fourier components are given by

$$F(t) = \sum_{n=0,1,2,3,\dots} A_n \cos 2\pi n \frac{t}{T} \tag{1}$$

where

$$A_0 = \frac{\tau}{T} \tag{2}$$

and

$$A_n = 2\frac{\tau}{T}\frac{\sin \pi n \frac{\tau}{T}}{\pi n \frac{\tau}{T}}, \quad n = 1, 2, 3, \dots \tag{3}$$

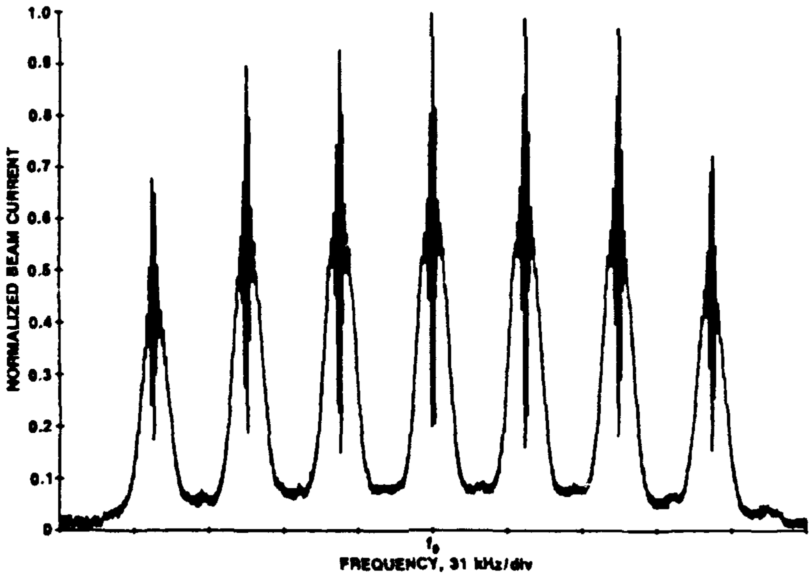


Figure 4. The CW Ramsey Patterns of All Seven Transitions in a Cs Beam Tube

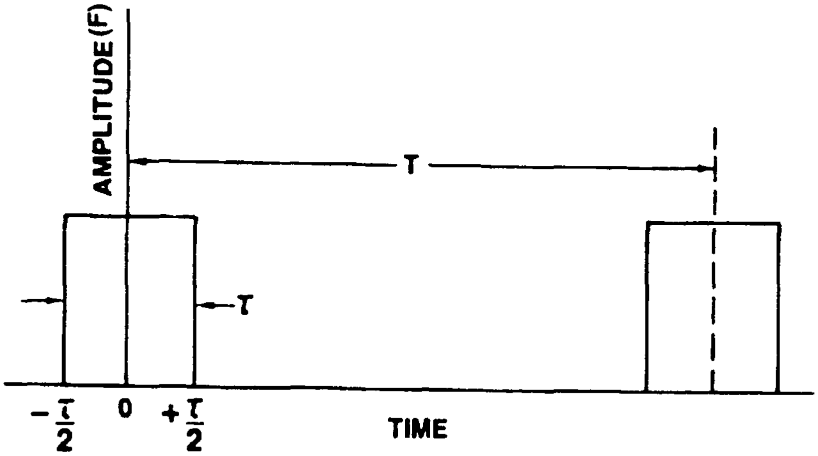


Figure 5. Pulse Modulation Waveform

Each of these components modulates the rf carrier to give a pair of equal components at $f_0 \pm n/T$, where $f_0$ is the rf carrier. Figure 6 shows this amplitude distribution (which we will refer to as the sin $x/x$ distribution) in relation to the Ramsey response function. For the particular C-field used for the tube, the separation in the Ramsey responses (i.e., the Zeeman frequency $f_z$) was 38.86 kHz. The tube length $L$ is $\approx$ 12.5 cm; therefore, for a velocity of 150 m/sec, the modulation frequency would be $\approx$ 1200 Hz. There are therefore 38.86/1.2 $\cong$ 33 components between the component at $f_0$ and the component at $f_0$ + 38.86 kHz. Figure 6 is drawn for a $\tau$ of about 10 $\mu$sec, which places the first null in the sin $x/x$ distribution at 100 kHz. For ease of illustration, the separations of the pulse components are depicted as much wider than is actually the case.

Figure 7 shows the location of the components for the central Ramsey transition as well as for the first upper transition. Each of the components gives a maximum current and therefore, to the extent that the principle of superposition applies, the output current will be a maximum. The rf frequency is then swept and the component in the output current at the modulation frequency $f_m$ (= $1/T$) is then the measure of the density of the atoms in the beam at the velocity $v_m$, where

$$v_m = Lf_m. \tag{4}$$

The carrier is then reset to $f_0$ and $f_m$ is changed slightly to $f_m + \Delta f$, to enable one to look at a slightly different velocity, $v_m + \Delta v$. Then

$$\Delta v = L\Delta f. \tag{5}$$

Note that the components close to $f_0$ change slowly; i.e., the first sideband pair moves by $\Delta f$, the second by $2\Delta f$, and so on. However, the components at the first upper transition move very rapidly; i.e., $n$ is very high. If $\Delta f$ is chosen such that each of the components at the first upper transition moves by $f_m$, we will again have a maximum-current situation. Then

$$f_m = n\Delta f, \tag{6}$$

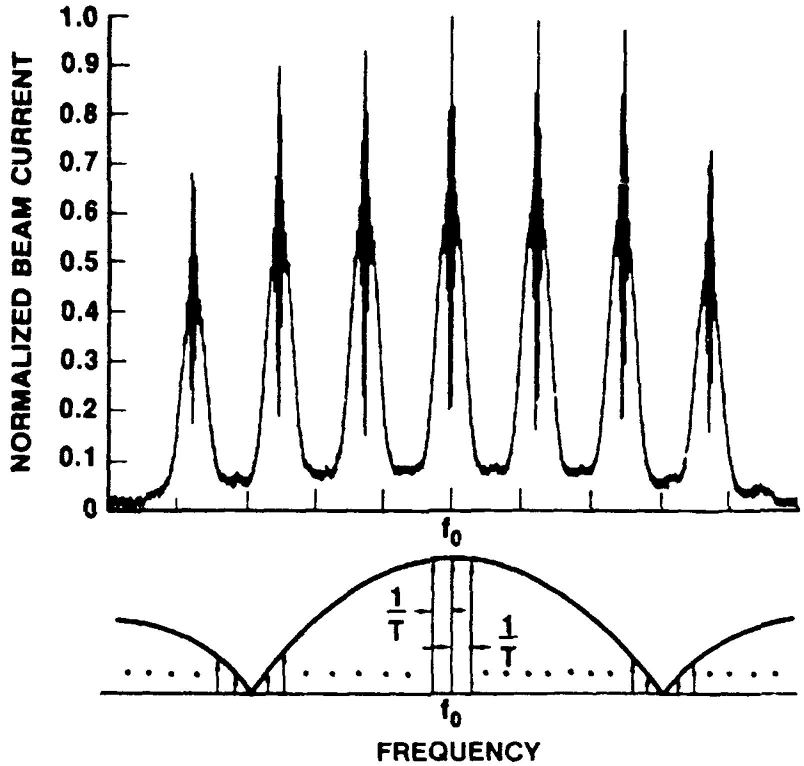


Figure 6. Ramsey Response in Relation to the Pulsed Microwave Spectrum for a Narrow Pulse Width

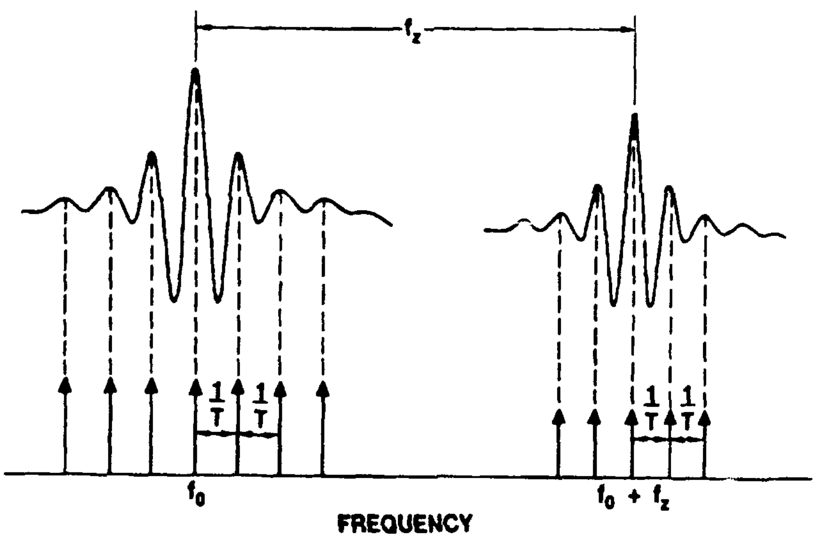


Figure 7. Main and First Upper Ramsey Response in Relation to the Pulsed Microwave Spectrum

but

$$n = \frac{f_z}{f_m}. \tag{7}$$

Hence

$$\Delta\nu = L\frac{f_m^2}{f_z}. \tag{8}$$

In other words, from these very heuristic arguments a fine-structure velocity period of $Lf_m^2/f_z$ has been predicted.

We should note that although $\Delta\nu$ is not a function of the pulse period $\tau$, the amplitude of the structure certainly will be. For example, a pulse that is much narrower than $1/f_z$ will result in a very broad power spectrum (such as that shown in Figure 6) and will consequently yield a large amplitude in the fine structure. Conversely, if the pulse width is chosen so as to put the nulls in the sin $x/x$ function at the upper Ramsey responses, the effect will be minimized, because a smaller share of the sideband energy is in the upper and lower Ramsey responses. This case is illustrated in Figure 8.

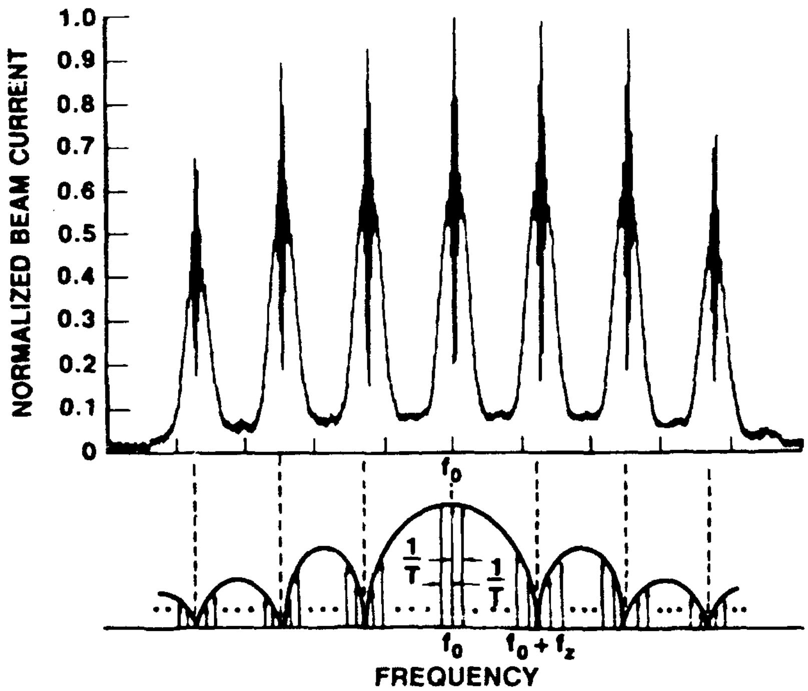


Figure 8. Ramsey Response in Relation to the Pulsed Microwave Spectrum for a Pulse Width that Places the Spectral Nulls at the Centers of the Upper and Lower Ramsey Responses

## III. Measurements

The velocity measurement shown in Figure 3 was for a pulse width of 37 μsec. The Zeeman frequency for this tube was 38.86 kHz and thus the second maximum in the sin $x/x$ distribution is very close to the first upper and lower Ramsey responses. This pulse width also places the third and fourth maxima in the sin $x/x$ distribution close to the second and third upper and lower Ramsey responses. Therefore, there should be a clear fine structure, and indeed, this structure is easily seen in Figure 3.

The same tube with the same C-field was measured for a very narrow (10 μsec) pulse. This should also result in a clear fine structure. Figure 9(a) shows the results of this measurement. It is a little surprising that the minima of the distribution are so close to zero. This might be because the polarity of the components in the first side lobe in the sin $x/x$ distribution is reversed from that in the main lobe. Choosing the pulse width such that the first null in the sin $x/x$ distribution is at the first upper and lower Ramsey responses should result in a minimum structure, and in fact Figure 9(b) shows this result. Similarly, placing the second null at the upper and lower Ramsey responses should also minimize this structure. Figure 9(c) confirms this.

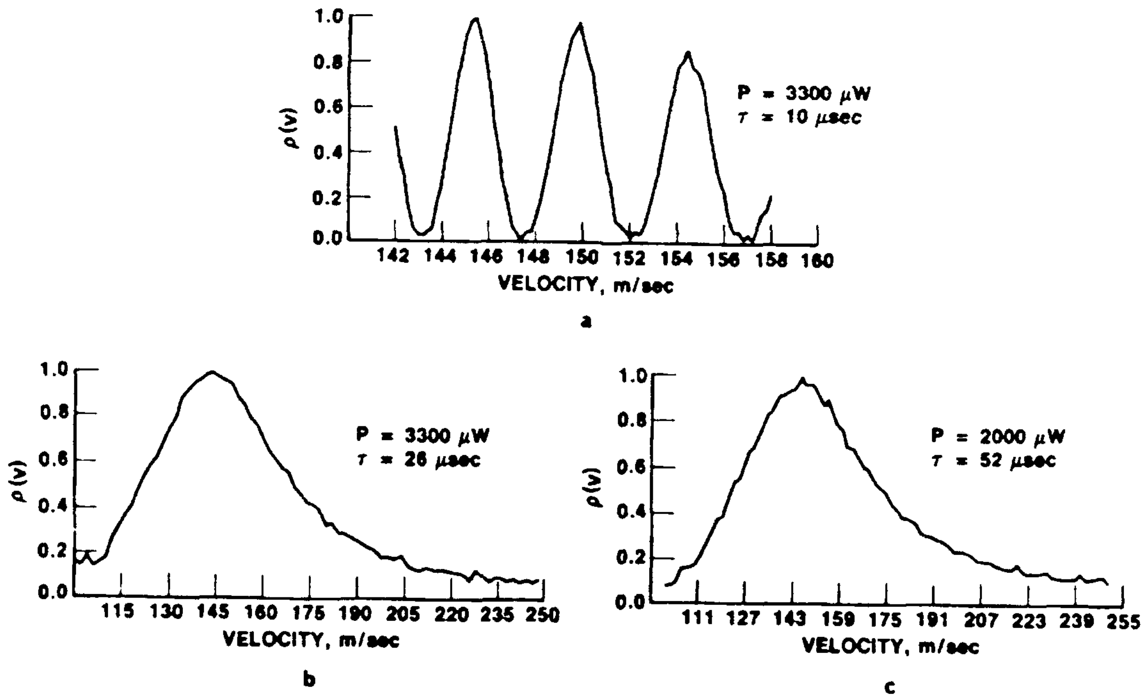


Figure 9. Measured Cs Velocity Distributions for Three Pulse Widths and Peak Microwave Powers, as Indicated. (a) 10 μsec and 3300 μW, (b) 26 μsec and 3300 μW, and (c) 52 μsec and 2000 μW.

Table 1: Fine-Structure Period $\Delta\nu$ for Three Cs Beam Tubes

| Tube | $\tau$, μsec | $f_z$, kHz | Measured, m/sec | Calculated, m/sec |
|---|---|---|---|---|
| A | 37 | 38.86 | 4.42 | 4.29 |
| A | 10 | 38.86 | 4.59 | 4.48 |
| B | 10 | 33.43 | 2.79 | 2.81 |
| C | 20 | 30.55 | 3.67 | 3.79 |

Table 1 presents a comparison of the measured and calculated [from Eq. (8)] fine-structure periods for the cases shown in Figures 3 and 9(a), as well as for measurements made on two other tubes from two other manufacturers. Each of the tubes is between 12 and 13 cm long. Note that the two calculated $\Delta\nu$ for the two different $\tau$'s for tube A were for two slightly different velocity ranges, and hence are slightly different. In general, the agreement between the calculated and measured $\Delta$'s is excellent.

# IV. Conclusions

A fine-structure feature on the velocity distribution of Cs beam tubes, as measured by the pulsed microwave power technique, has been identified and quantified. This feature was shown to result from the existence of large spectral components at the frequencies of the upper and lower Ramsey responses. It has been shown that this feature can be minimized by choosing the pulse width such that the nulls in the microwave power spectrum are at these upper and lower Ramsey responses. Specifically, this means that the pulse width should be chosen to be an integer multiple of the reciprocal of the Zeeman frequency. A simple theory was developed to enable one to predict the fine-structure period as a function of the beam velocity, the tube length, and the Zeeman frequency. This theory employed the concept of the Ramsey response pattern as an electrical filter. This concept may be useful in other tube studies, e.g. those of modulation effects. Also, measurements were presented that demonstrated close agreement between the measured fine-structure period and the calculated one. Finally, it was shown that the fine structure virtually disappears if the pulse period is chosen to be an integer multiple of the reciprocal of the Zeeman frequency.

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