GENERAL PHYSICS

I. MOLECULAR BEAMS*

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A. CESIUM BEAM ATOMIC CLOCK

A new beam tube, which was last mentioned in Quarterly Progress Report No. 80 (page 2), that differs in design from previous clocks, primarily in possessing a recirculating oven,[1] and in detail in magnet and cavity design, has been completed. The construction of the associated low-frequency electronics system is nearly complete.

The proposed system for the new clock is shown in Fig. I-1. The theoretical clock

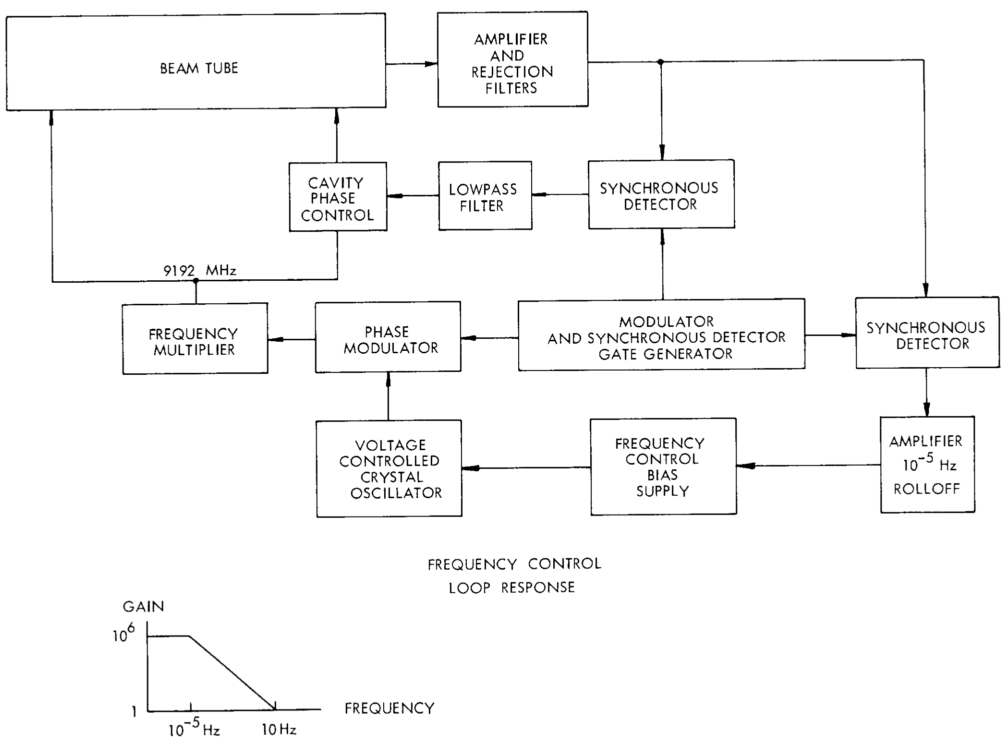

Fig. I-1. Atomic clock diagram and frequency-control loop response.

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stability for beam shot noise only is

$$\frac{\sigma[<\phi>_{t,\tau}]}{\omega_o} = \frac{5 \times 10^{-13}}{\tau^{1/2}}, \qquad \tau \leq 10^6 \text{ sec},$$

where $\sigma[<\phi>_{t,\tau}]$ is the variance of the average frequency departure from the undisturbed cesium resonance frequency ω_o for an averaging time τ. We hope that this shot-noise limitation can be reached by utilizing the high beam current provided by a recirculating oven and by making use of the cavity phase-error correction capabilities of frequency impulse modulation.[2] It has been found that the noise of a cesium beam detected by a niobium hot wire is approximately the theoretical shot noise attributable to pressure fluctuations in the region of the modulation frequency.

1. Theoretical Work

Following the lines developed by Cutler,[3] work has been carried out on calculating the effects of various types of noise on clock stability. Explicit expressions for noise sensitivity have been obtained for a simplified (linearly additive noise) loop equation, and work on a more complete power spectral density (vectorially additive noise) theory is now in progress. The effects of distortion of the modulation signal and imperfect synchronous detection are also of extreme importance to clock stability; these problems are being investigated at the present time. A system analysis, which has resulted in clarification of how frequency and phase errors are generated and transmitted through the loop, has been carried out.

2. Recirculating Oven

It is a fundamental theorem of cesium beam resonance apparatus that larger beam currents lead to larger signal-to-noise ratios, and consequently to better stability. Unfortunately, in most devices the amount of cesium which forms a collimated beam is small compared with the total cesium lost from the oven, because of the $\cos^2\theta$ intensity distribution of atoms emerging from a slit. Thus impractically large amounts of cesium would be needed to provide an intense beam during a long running period. It was proposed that a recirculating oven be built on the plan sketched in Fig. I-2.

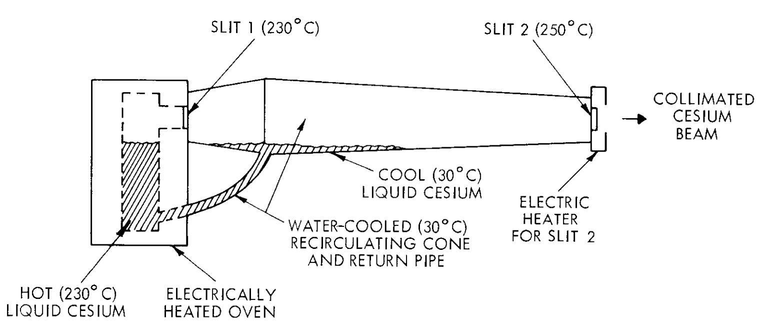

Fig. I-2. Recirculating oven.

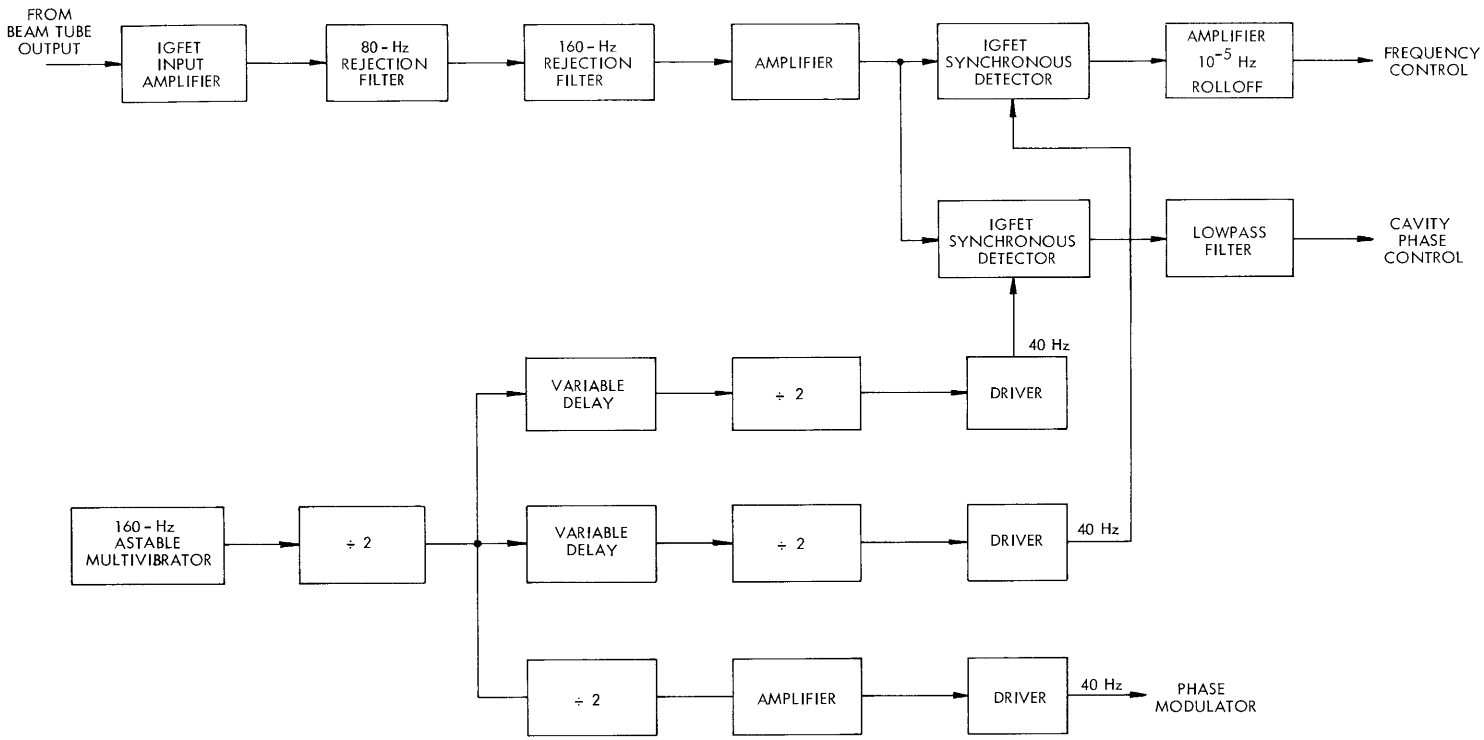

Fig. I-3. Low-frequency electronics system.

The oven was constructed, but it was found subsequently that large amounts of background gas emerging from the hot oven walls and failing to exit through the small slits 1 and 2 caused the recirculating cone to act as a long scattering chamber, thereby reducing beam intensity. A suitable pumpout device for the cone was made, and the beam intensity was restored to expected values. In a different earlier experiment[4] it was shown that vigorous outgassing of the oven, before filling with cesium, without the flow-restricting slits also cured the problem. Examination of the distribution of cesium in an oven frozen by application of dry ice indicated that recirculation may have been taking place. Not enough running time at high intensities has been accumulated yet to prove in the direct manner that recirculation must be taking place.

3. Low-Frequency Electronics

The proposed low-frequency electronics system is shown in Fig. I-3. Digital techniques have been used to produce a symmetrical (small even harmonic content) modulator signal, and to produce synchronous detector gate waveforms of variable delay that have a 90° phase difference when the variable delays are zero. Integrated circuits were found useful in both digital and linear circuitry, and were used to make active notch filters of high rejection and narrow stopband [the 80-Hz and 160-Hz notch filters are used to prevent saturation by even harmonics of the amplifier following them, since the even harmonics of the beam tube output are not zero when the phase and frequency errors of the loop are zero]. Use has also been made of recently available complementary insulated gate field-effect transistors to make extremely low-error synchronous detectors that are now undergoing testing.

D. Babitch, C. M. Bell

Footnotes and References

1. Proposed by C. O. Thornburg (1966).

2. The original paper on the subject of frequency impulse modulation is by R. S. Badessa, V. J. Bates, and C. L. Searle, "Frequency Impulse Modulation as a Means of Attaining Accuracy in Cesium Atomic Clocks," IEEE Trans., Vol. IM-13, No. 4, pp. 175-180, December 1964. In his Ph.D. thesis, C. O. Thornburg considerably expanded the theory, and recently S. G. Kukolich and K. W. Billman have carried out computer calculations and performed experiments (to be published in J. Appl. Phys.) proving the validity of the theory.

3. A fundamental work on noise in frequency sources is the paper by L. S. Cutler and C. L. Searle, "Some Aspects of the Theory and Measurement of Frequency Fluctuations in Frequency Standards," Proc. IEEE 54, 2 (1966).

4. T. R. Brown, Private communication, Research Laboratory of Electronics, M.I.T., 1966.