

## VII. ATOMIC BEAMS\*

Prof. J. R. Zacharias	Dr. R. F. C. Vessot	D. S. Edmonds, Jr.
Prof. J. G. King	D. D. Babb	E. P. Hilar
Prof. C. L. Searle	V. J. Bates	G. W. Stroke
Dr. S. Ketudat	H. H. Brown, Jr.	R. Weiss
	B. DiBartolo	

### RESEARCH OBJECTIVES

In the Quarterly Progress Report of January 15, 1957, page 50, we wrote, "The distributions of electric charge and magnetism in an atomic nucleus are usually described in terms of multipole moments limited in number by the magnitude of the nuclear angular momentum. In this laboratory, atomic-beam techniques are used to determine such electric and magnetic moments. In addition, information about the radial distribution of nuclear magnetism can be obtained in cases in which more than one isotope is available. These techniques lend themselves to such precision that they were used in this laboratory for the development of the most accurate atomic clock. In turn, these clocks are being used to make studies on the nature of time itself. Precision apparatus is under construction to observe not only the dependence of atomic time on gravitational potential but also the epochal dependence of nuclear, gravitational, and atomic time. Similar studies are being made on the velocity of light." This is still a reasonable statement of our objectives. However, the past year has not been very fruitful for the group.

Some experiments proved more complicated to construct than was originally hoped. One major effort of observation proved intractable and was finally abandoned.

We pointed out earlier that we were going to try to eliminate one of the inherent weaknesses of atomic-beam frequency standards that use the Ramsey two-cavity method by using two antiparallel beams that pass simultaneously through the same Ramsey cavities. The notion was that if the two cavities are not exactly in phase, the average frequencies of the two beams would nonetheless average to the proper one. R. F. C. Vessot's apparatus for demonstrating this is on the point of working, but the need for making two beams work simultaneously at a high precision makes the experiment difficult. The apparatus includes a device for selecting velocities in such a way that the phases of the cavities can be set to equality with only one beam.

An experiment for trying to observe atomic cesium under free fall for time intervals of a second or more has been underway for several years. The major obstacles in this experiment were thought to be: (a) the general vacuum, and (b) scattering of atoms by other atoms of the beam, especially in the neighborhood of the oven. In the beam tube, which is 10 inches in diameter and 28 feet long, we can hold a pressure of  $10^{-9}$  mm Hg with the aid of a liquid-helium trap. We have tried two types of oven: one with canals, and the other an open boat of liquid cesium. In neither case do we see atoms focused onto a detector. R. Weiss has gone further, to try to find slow atoms at the top of the 28-foot tube. He finds slow atoms that live in the apparatus, in Maxwellian abundance, for almost one-fifth of a second. We seem to run out of signal-to-noise ratio for atoms that are slower than that. We have therefore given up this experiment as being too difficult, at least for us.

Since we seek an absolute measurement of frequency that will stand the test of time and be regarded as accurate within the limits of proposed error one hundred years from now, we still feel that it is necessary to try experiments of this sort. Such experiments are still in the thinking stage.

Results of the experiment for measuring the Stark effect on the hyperfine structure of cesium will appear as Technical Report 322, by R. D. Haun. An experiment for discovering any discrepancies in the application of the Breit-Rabi formula for atomic

---

\*This research was supported in part by Purchase Order DDL-B222 with Lincoln Laboratory, which is supported by the Department of the Army, the Department of the Navy, and the Department of the Air Force under Contract AF19(122)-458 with M. I. T.

## (VII. ATOMIC BEAMS)

cesium has been completed but the data have not been entirely evaluated. The results of this experiment will be reported later.

J. G. King, J. R. Zacharias

### A. HYPERFINE STRUCTURE OF BROMINE

In our new laboratory we are constructing and re-erecting apparatus for the precision measurement of the hyperfine structure of the stable bromine isotopes. We expect to obtain a precision that is a hundredfold greater than that attained by King and Jaccarino in their early work on bromine (1). This will enable us to determine the octopole interaction. We are also planning to measure  $\Delta\nu$  and  $g_J$  in the  $P_{1/2}$  state.

Klystrons that are phase-locked to harmonics of our standard frequency have been prepared. The vacuum envelope (No. 2) has been overhauled and fitted with new pump traps that should greatly reduce the amount of oil in the apparatus. As soon as a vacuum is obtained, development of the detector mass spectrometer and the source of atoms will begin.

B. DiBartolo, S. Ketudat, J. G. King, J. R. Zacharias

### References

1. J. G. King and V. Jaccarino, The hyperfine structure and nuclear moments of the stable bromine isotopes, *Phys. Rev.* 94, 1610 (1954).

### B. LINEAR DECELERATOR FOR MOLECULES

The linear decelerator is a device that is intended to slow down molecules in a given state so that when they enter a microwave cavity they will undergo transitions of reduced natural width. The apparatus that we have constructed during the past year and a half is designed to use the inversion line of  $\text{NH}_3$  in the  $J=K=1$  state, which occurs at 23,694.48 mc. This apparatus consists of a cold (100° K) directional  $\text{NH}_3$  source; the decelerator, which is an array (1 meter long) of parallel-plate capacitors and drift spaces of such lengths that the time of flight of the decelerated molecules through each capacitor and drift space is constant; and a cylindrical cavity operating in the  $\text{TE}_{0,3,12}$  mode with appropriate input and output waveguides. The whole apparatus is operated at a pressure of  $10^{-8}$  mm Hg.

The decelerator is intended to operate as follows: Molecules in the upper inversion state  $J=K=1$ ,  $|m_J|=1$  lose energy when they enter a region of large electric field in one of the capacitors in the decelerator. If the field is greatly reduced while the molecules are in the uniform field of the capacitor, they will not, when they leave, regain the energy that they lost on entering. While the molecules are in the drift space the voltage across the capacitor is raised and the molecules once again lose energy upon entering

the high field. For reasonable fields (e.g.,  $10^5$  volts/cm) the molecules lose kinetic energy at the rate of  $1^\circ$  K per stage. If the source temperature is  $100^\circ$  K, molecules of one-half of the most probable velocity will be brought to rest in the 25 stages of our apparatus. These molecules, or rather their neighbors in the velocity spectrum, spend a long time in the cavity, where they contribute to the inducing rf field by undergoing induced emission, and are thus detected.

It is difficult to estimate the effective solid angle of the decelerator for the desired molecules. Calculations indicate that there is a net focusing effect for molecules in the desired state. Molecules in the lower inversion state would also be decelerated on leaving the capacitor, but would be defocused. Phase stability is also of importance and probably it will be necessary to use a triangular or sinusoidal voltage rather than the square wave that was technically easier to achieve with a conventional thyatron switch arrangement that delivers a 15-kv square wave at 6 kc into the 0.001- $\mu$ f capacitance of the decelerator unit. Some shaping of the square wave can, of course, be done.

The microwave receiver uses type 2K50 as a local oscillator for a balanced detector. The 2K50 is phase-locked to a harmonic of an S-band klystron which, in turn, is phase-locked to a harmonic of a 1-mc crystal, with various balanced modulators and mixers introduced to allow continuous tuning. A 200-kc i-f amplifier with a gain of 120 db and a bandwidth of 20 cps is used to detect the signal from the cavity. All offset frequencies are derived from crystal oscillators. We are grateful to Professor C. L. Searle and Mr. R. E. Lyon for the initial development of the microwave receiver.

Tests of the completed system will soon be carried out, and further details will be given in a later report.

J. R. Zacharias, J. G. King

## C. MEASUREMENT OF THE VELOCITY OF LIGHT

### 1. Precision Cylindrical Cavity

What is probably the most precise cylindrical cavity in existence has now been completed to microinch tolerances by an optical process out of General Electric Company well-annealed fused quartz by the Boston University Physical Research Laboratory under the direction of George Random in consultation with our Research Laboratory of Electronics group. The silver coating of this cavity to optical uniformity and good electric conductivity will also be undertaken by the Boston University laboratory.

The basic mechanical elements of the apparatus, which will be used, first, for experimenting with mechanical guidance schemes for moving the end plate parallel to itself at a reasonably uniform velocity with microinch precision, are being assembled in our Laboratory. The experimental results described in the Quarterly Progress

(VII. ATOMIC BEAMS)

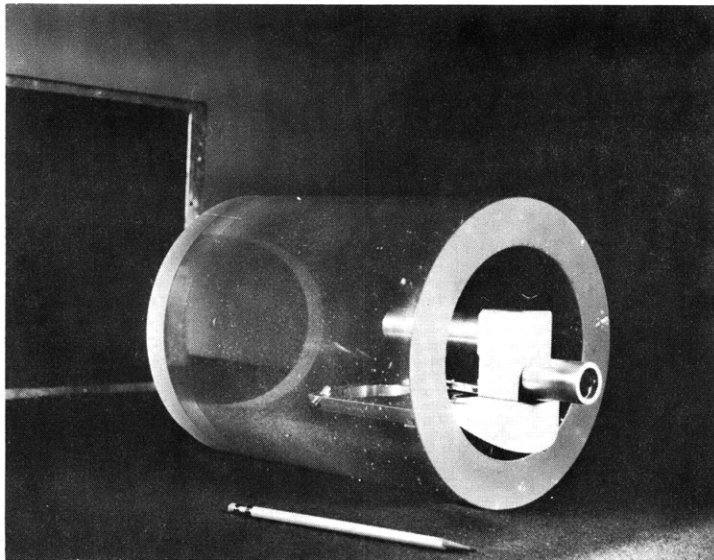


Fig. VII-1. Fused quartz cavity with diameter-measuring device.

Report of October 15, 1956, page 46, have determined the principle of having brass shoes guide a moving glass (or quartz) cylindrical (2-inch diameter) rod to avoid stick-slip effects. The shoes consist of two groups of three horizontal cylindrical (0.25-inch diameter) brass rods, two rods in each group forming a "vee" and the third pressing the vertical quartz rod against them by gentle spring action. The quartz rod and the moving end plate, which will be interferometrically servo-controlled in rotation with respect to the rod so that they are normal to the cylinder axis, have not yet been optically manufactured.

Figure VII-1 shows a photograph of the finished fused quartz cavity with the mechanical-interferometric curvature-measuring device that was especially designed for the testing of this cylinder. The cylinder is 11.5 inches long, with an inner diameter of 6.350 inches and an outer diameter of 9.25 inches. The uniformity of the inner diameter (with respect to both ellipticity and axial-diameter variations) was found from measurement to be within  $\pm 1.5 \times 10^{-6}$  inch, and the highly polished inner surface has considerably less than one part in  $10^6$  of its area covered by residual bubbles. The electromagnetic diameter of the silver-plated cavity will be determined to a good approximation by microwave and interferometric guide wavelength measurements at two frequencies in a simple, exactly known ratio. We are planning to determine the absolute diameter more accurately by comparing the mechanical diameter values with an adjustable Fabry-Pérot interferometer system by means of a null-reading device, such as a two-outlet (or possibly three-outlet) air gauge mounted on the moving end-plate system. When the air-gauge detectors read "zero" in both the cavity and the

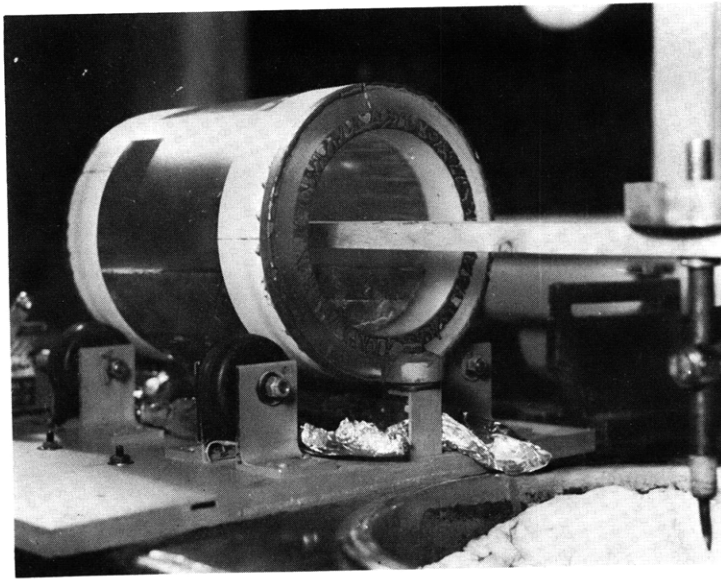


Fig. VII-2. Fused quartz cavity in process of being ground.

Fabry-Pérot interferometer, the diameter-measuring problem has been reduced to a determination of the spacing of the two Fabry-Pérot plates, which can easily be achieved by classical "inspection" methods in terms of known light wavelengths.

Figure VII-2 shows the cavity in the process of being ground on an apparatus constructed for this purpose, in which the cylinder is rotated about its axis and the grinding tool moved back and forth axially. The noteworthy feature of this procedure is that, with the two movements originating at independently driven motors, the almost perfect circularity has been achieved with comparative ease, while the axial uniformity in diameter had to be carefully watched by varying the stroke length and the axial centering of the tool in both the grinding and polishing processes.

J. R. Zacharias, G. W. Stroke

#### D. STABILIZATION IN KLYSTRON PHASE-LOCKED OSCILLATOR LOOPS

Further theoretical and experimental work on the problem of phase-locking S-, X-, and K-band klystrons to 5-mc crystal oscillators (1, 2) has revealed several previously neglected sources of phase shift which prove to be of considerable importance in the design of stable feedback loops. A block diagram of a representative klystron stabilization loop is shown in Fig. VII-3. The klystron has a transfer function of the form  $K/s$ , with  $K$  varying from  $10^6$  radians/volt for an S-band klystron to  $10^7$  radians/volt for a K-band tube. The essential problem in stabilizing such a system is to limit all other phase shifts in the feedback loop to less than a total of  $90^\circ$  until  $|K/s|$  becomes

## (VII. ATOMIC BEAMS)

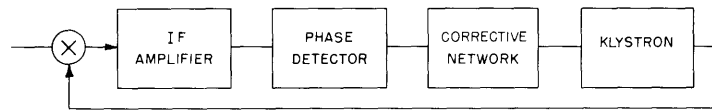


Fig. VII-3. Block diagram of klystron stabilization loop.

less than unity. The three principal sources of phase shift, other than the  $90^\circ$  shift implied by the  $1/s$  characteristic of the klystron, are tuned circuits in the phase detector, including any tuned element used to feed in the reference signal, the detection process in the phase detector, the repeller input capacitance of the klystron, and the shunt capacitance in the i-f amplifier.

### 1. Phase Detector

Any tuned circuit in the phase detector will cause phase shift in the device. A tuned circuit used to obtain a balanced reference signal to drive the detector would not, at first, appear to influence the input-signal phase, but the capacitance to ground of such a tuned circuit does introduce substantial phase shift unless the tuned circuit is of very low  $Q$ .

The "sampled-data" phase shift that is inherent in the detection process of the phase detector was a major source of phase shift in early designs. The time delay involved in any rectification-and-holding process, such as a peak detector, is inversely proportional to the carrier frequency. If "box-car" holding is assumed for the sake of simplicity, the phase shift corresponding to this time delay will be

$$\phi = \frac{\text{modulating frequency}}{2 \times \text{carrier frequency}} \times 360^\circ .$$

### 2. Klystron

The klystron introduces a fixed,  $90^\circ$  phase shift, and a variable phase shift because of repeller input capacitance. For an S-band klystron, this capacitance can be as large as  $100 \mu\mu\text{f}$ . There is also a possibility that some reactive component will be introduced because of the interaction of the repeller and the electron stream inside the tube. This effect has not been observed, probably because it occurs at a much higher frequency than the frequencies that have been considered here.

### 3. I-F Amplifier

The slope of the phase characteristic of the i-f amplifier is a direct measure of the amount of phase shift imparted to a phase-modulated wave passing through the amplifier. Since an RLC circuit has twice the phase-characteristic slope of an RC circuit, for a

given RC product, it is desirable, whenever it is possible, to use a video i-f amplifier rather than a tuned amplifier.

#### 4. Design Criteria

The following design criteria are suggested by the preceding discussion:

1. Use an untuned (video) i-f amplifier with either a broadband input transformer or a vacuum-tube inverter circuit to convert the balanced i-f input signals to a single-ended output.

2. Use a low-impedance phase detector to minimize klystron input capacitance effects.

3. Choose an i-f frequency that is as high as possible to minimize "sample-data" phase shift.

Obviously, these criteria are not necessarily compatible. Specifically, some compromise must be made in the selection of the i-f amplifier center frequency in accordance with items 1 and 3.

#### 5. Experimental Verification

An S-band klystron stabilization loop that was designed in accordance with two of the criteria has proved to be very successful. The specific departure from the design was the use of a 3.7-mc tuned i-f amplifier. In effect, increased phase shift in the i-f amplifier was traded for decreased sampled-data phase shift in the detector. The performance of the loop was outstanding in that the klystron tube could be struck with a screwdriver without loss of lock. Notwithstanding, we feel that system performance can be improved by striking a different balance between criteria 1 and 3, namely, by the use of a 1-mc untuned i-f amplifier. Such a system is now being constructed.

C. L. Searle

#### References

1. C. L. Searle and D. D. McRae, Stabilization of klystrons by phase locking to low-frequency quartz crystal oscillators, Quarterly Progress Report, Research Laboratory of Electronics, M.I.T., April 15, 1956, pp. 37-41.
2. R. E. Lyon, Frequency stabilization of K-band klystrons, Quarterly Progress Report, Research Laboratory of Electronics, M.I.T., Jan. 15, 1957, pp. 50-51.

#### E. RESONANCE DETECTOR: VELOCITY OF LIGHT EXPERIMENT

##### 1. System Design

A system has been constructed to detect cavity resonance. This system uses the amplitude variation of the cavity's output signal, but provisions have been made for

(VII. ATOMIC BEAMS)

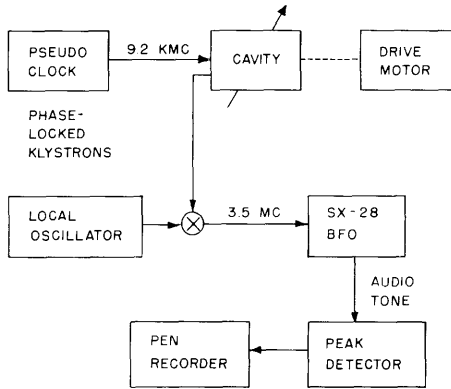


Fig. VII-4. Resonance detection system.

phase comparison of input and output if the accuracy requirements demand it. The cavity that is being used is the intermediate cavity that was constructed a year and a half ago. It is mounted on a lathe bed with one end plate on the tool carriage. The carriage is driven with a reciprocating motion by a small motor through a distance of 0.030 inch, which takes the cavity through one of its resonances. The microwaves are passed through two small holes in the fixed plate.

Two phase-locked klystrons are used in the system shown in Fig. VII-4, one to simulate the final frequency source, an atomic clock, and the other as a local oscillator. The output signal is mixed with the local-oscillator signal, and the difference signal of 3.5 mc is amplified by a communication receiver. Since the output signal is of low frequency, the beat frequency oscillator of the receiver is used, and the modulated tone is rectified by a peak detector. This provides a signal that is proportional to the output amplitude of the cavity even though it has a dc component. The peak detector voltage is recorded on a pen recorder.

2. Results

Preliminary results are shown in Fig. VII-5. A succession of cavity resonances is plotted, and the recorder sensitivity is increased by factors of 10 and 100. The

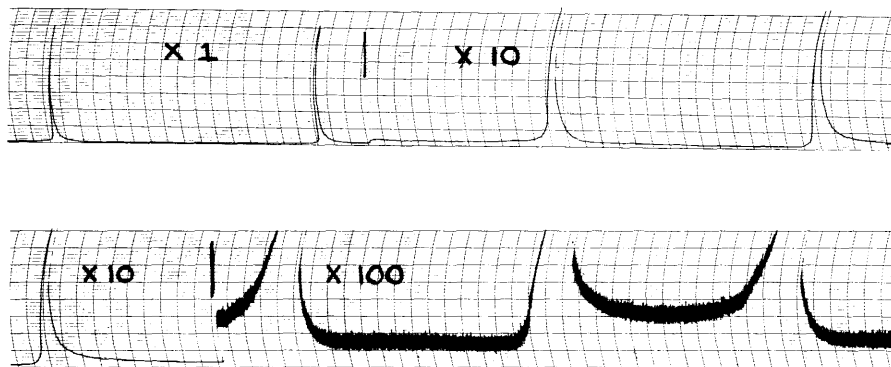


Fig. VII-5. Signal-to-noise measurement for resonance detector.

signal-to-noise ratio, as determined from these curves, is 300 to 1. This ratio can be improved by a factor of 2 or 3 by eliminating the obvious dissymmetry in the base



(VII. ATOMIC BEAMS)

line, which is caused by signal leakage around the cavity.

The pen recorder does not have the accuracy that is required for this measurement. It will be replaced by better detection equipment.

E. P. Hilar