

X-524-72-210

PREPRINT

NASA TM X- 65932

HYDROGEN AS AN ATOMIC BEAM STANDARD

(NASA-TM-X-65932) HYDROGEN AS AN ATOMIC
BEAM STANDARD H.E. Peters (NASA) Jun.
1972 14 p

N72-27763

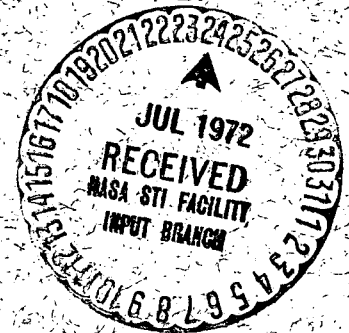
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H. E. PETERS

JUNE 1972



— GODDARD SPACE FLIGHT CENTER —
GREENBELT, MARYLAND

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Summary

Consideration is given to the use of atomic hydrogen's ($F = 1, m = 0 - F = 0, m = 0$) hyperfine transition in a free atom beam device. The atomic hydrogen maser, which is the traditional frequency standard instrument based upon this transition, has one significant limitation in standards work, the well known wall shift, which is inherent in any atom interrogation method which confines atoms in storage volumes. Experiments which measure the wall shift, while precise to the order of 10^{-12} or better, have met with vigorous objection, primarily on philosophical grounds. The cesium beam standard, which has several significant errors, and also involves intermittent correction techniques to fully relate to the transition frequency with comparable exactitude, has the advantage that the atom is not deflected in its passage through the interaction region.

After a preliminary discussion of feasibility, new experimental work with a hydrogen beam is described. A space focused magnetic resonance technique with separated oscillatory fields is used with a monochromatic beam of cold hydrogen atoms which are selected from a higher temperature source. The first resonance curves and other experimental results are presented. These results are interpreted from the point of view of accuracy potential and frequency stability, and are compared with hydrogen maser and cesium beam capabilities.

Introduction

The ubiquitous hydrogen atom, since it is the simplest of all the elements and has the closest analytical relationships with a myriad of physical phenomena, might be suspect of being the first to be considered by a majority of scientists when deciding which basic particle is the optimum one with which to relate definitions of fundamental physical constants. The naturally reproducible interaction of the proton and the electron in hydrogen has historically provided a most elementary and precise standard against which generations of physicists have compared their theories and established the agreement (or otherwise) of their hypotheses with regard to the realities of physical measurements. And the results have had the most profound impact in all areas of science, philosophy, and technology.

However, in the world of standards and their applications, there are other constraints than philosophical beauty to be satisfied. The most vital of these constraints is that we must be able to realize "accuracy" in a fundamental sense. For "accuracy," it is usually agreeable that we select some intrinsically invariant quantity to which we can relate with a minimum of instrumental uncertainty. Thus, for practical purposes, it is the instrumental method, and the inherent perturbations and errors thereby intervening upon the quantity to which we wish to relate, which determines our success (or our lack thereof) in achieving "accuracy."

The instrumental method heretofore used in relating to the atomic hydrogen hyperfine transition with "accuracy" has been the atomic hydrogen maser¹. The fantastically good stability, the exceptional resettability, and the outstanding "accuracy" capability realizable with H-masers has, however apparently hidden and obscured until now the desire or the possibility of

relating to this transition with a different, and in some ways possibly superior, instrumental technique — namely that of atomic beam resonance.

This is somewhat understandable, for the preponderant variable which limits H-maser "accuracy" is the "wall shift." The wall shift has a gross value of only 2×10^{-11} (NASA, GSFC NP H-masers), and the associated inaccuracy is over a factor of ten smaller than this. In addition, very promising work is in progress in several laboratories² which may reduce even this small uncertainty greatly in the future. Nevertheless, the "wall shift" has been the only publicized unrefuted contradiction to use of atomic hydrogen as THE standard at this time.

Therefore, the only apparent generally acceptable solution would seem to be to free the atom from the enveloping walls of the maser storage bulb. We must observe this atom in free fall. And, the only practical way that this might be done in an earth bound laboratory is with the traditional atomic beam magnetic resonance method.

Feasibility

To use hydrogen successfully in a free atom beam standard will require that we modify some traditional precepts relating to feasibility. First, consider that the room temperature atom, with a mass essentially that of the proton, has a velocity near 3 kilometers per second! This should be compared with the cesium atom, which with a mass essentially 133 times greater, has a nominal ambient velocity of about 230 meters per second. The requirement of small line width (large line Q) demands that we observe the atom for as long a time as possible, thus either our apparatus must be exceptionally long, or we must slow this atom down.

Slow hydrogen atoms are not inherently inconceivable, though. Unlike cesium or other likely metal atoms, which have negligible vapor pressure at low temperature, molecular hydrogen has a vapor pressure of 1.7 torr, even at 10°K. Additionally, in experiments relating to H-masers at GSFC³, wherein variable electromagnetic state selectors were used as velocity selectors, it has been shown possible to select great intensities of low velocity atoms from the usual room temperature sources. (On the order of 10^{13} well collimated state selected 30°K atoms per second at the source, at present.) This is adequately slow, but much slower atoms at adequate intensities may also be available, and work is in progress at GSFC and elsewhere⁴ to improve upon this. Figure 1 illustrates the theoretical temperature distribution, and shows one realized operating point.

The second most difficult precept is that ground state hydrogen cannot be detected in an efficient, noise free, way; the best previous detectors being Pirani gauges, or electron bombardment ionizer devices with about .001 efficiency. There are several reasons why this need not limit us in an optimized H-beam device. One is that relatively intense sources of hydrogen atoms are available, 10^{18} or 10^{19} atoms per second if desired, and so we do not require perfect detection. Another is that very precise space focused beam geometries are feasible, particularly for low velocity hydrogen atoms, so that large aperture detectors

which are inherently noisy need not be used. Also, several very promising new detector techniques based upon atomic hydrogen's unique chemical and thermodynamic properties are conceivable, and experiments are in progress at GSFC to prove them out.³ Present results with a simple Penning discharge vacuum gauge have resulted in detected beam signal to noise ratios on the order of 1000 to 1 or better, and this is already more than adequate to achieve "accuracy" with 30°K atoms. Cryogenic devices, as well as chemical techniques involving chemiluminescent interactions or triggered chemical chain reactions are some of the other promising techniques presently under investigation at GSFC. The question may now be not so much whether sufficient detection sensitivity is available to realize "accuracy," but whether the developed hydrogen beam may not even be a superior standard for short term stability, as well as for long term continuous operation in a basic time scale system.

The third area which demands review now is the most important from the point of view of "accuracy." This involves the electromagnetic interactions and field sensitivities of the ground state hydrogen atom. As a basis for discussion, hydrogen's hyperfine energy level diagram is given on the left in Figure 2. Cesium is given on the right for comparison. As usual energy (or frequency) is given as the ordinate, and magnetic field as the abscissa. For hydrogen, the single electron, with $J = 1/2$ and the single proton, with $I = 1/2$, result in this simple energy level scheme with only four quantum levels. There is only one circularly polarized microwave (sigma) transition, and two linearly polarized (Pi) transitions. These couple only to components of an RF transition field which are in quadrature, thus with properly aligned RF and DC magnetic fields, only one transition need be induced. The slope of the $m = \pm 1$ states is relatively large, 1.4×10^6 MHz per Gauss, with the advantage that when desired these states may be relatively well separated. The field dependence of the f_0 transition is only $\Delta f_H = 2750 \text{ Hz}$. These conditions, among others, allow the hydrogen f_0 resonance, to be observed at as low a magnetic field as can be uniformly produced. (Typical H-maser operation is at .001 Gauss or less^{5,2} and the field homogeneity is such that operation at less than 30 microgauss is easily achieved; operational magnetic corrections are typically 2×10^{-12} or less, with negligible inaccuracy in determination.) Further, it has been feasible with hydrogen^{2,3}, through controlled adiabatic and non-adiabatic transitions in a beam, to isolate and to orient the individual atomic magnetic moment sublevels in space and in time in a manner inconceivable with a complex atom such as cesium. Atomic beam systems are thereby conceptually possible which allow detailed analysis of field conditions in the beam path.

In contrast with hydrogen, Cs_{133} has 55 protons, 55 electrons, and 78 neutrons. The nuclear spin of $I = 7/2$ in association with the net electronic spin $J = 1/2$ produces a complex hyperfine multiplet with a total of 35 possible transitions. This complex structure results in some of the most difficult and intricate analysis and measurement problems in achieving "accuracy" with cesium. The seven sigma resonances in cesium are spaced at intervals of $7 \times 10^5 \text{ Hz}$ per gauss and couple to the same RF field polarities as the f_0 transition, with the result that operation is not feasible at less than about .04 gauss without inaccuracies arising because of encroaching neighbors. Additionally, the Pi transition resonances occur at $3.5 \times 10^5 \text{ Hz}$ per Gauss intervals, so that any misalignment of the RF and DC magnetic fields may introduce additional unacceptable inaccuracies at low fields. The dependence of the cesium f_0 transition on magnetic field is given by $\Delta f_{\text{Cs}} = 427 \text{ Hz}$; at .04 Gauss the net magnetic offset is found to be 7.5×10^{-11} fractionally, whereas in hydrogen, at an easily realizable

.000, 4 Gauss, the net offset is only 3×10^{-13} . Thus the larger field levels required for operation with cesium inevitably make this standard more susceptible to magnetic field errors or perturbations than is the case with hydrogen. Figure 3 shows a field calibration plot measured for a coil placed within a typical set of magnetic shields for use about a hydrogen beam cavity. The fields are uniform along the axis within approximately 20 microgauss or better, and the field magnitude is reproducibly controlled as indicated in the figure.

The fourth precept which demands review of this time relates to the fact that hydrogen's f_0 transition has a frequency of 1.4 - GHz in comparison with cesium's 9.2 - GHz. It is an ingrained misconception that a higher frequency is an untarnished blessing for either "accuracy" or for stability. True, a narrower fractional line width accompanies higher frequency, but the slopes of the resonance curve at the half power points in combination with the signal to noise ratio are joint primary criteria which determine the precision of centering the line. While the slope is a measure of the line Q, the signal to noise ratio is a function of beam intensity, so that a great beam intensity can completely overcome the effect of lesser line Q for stability purposes; and if the resonance is undistorted, the same holds for "accuracy."

Resonance distortions or biases caused by cavity and electronic problems at high frequency are, however, the predominant inaccuracy problem with cesium at present.^{7,8} At 9.2 GHz there are up to 200 or more half wavelength modes in typical laboratory standard cesium cavities, and neither the cavity nor the cesium beam has radial or reciprocal symmetry, so that cavity phase shifts, off axis fields, travelling waves, mechanical instabilities, etc. make inaccuracy factors very difficult to evaluate or to confirm.

At 1.4 GHz, however, simple, single mode, symmetrical cavities, with dimensions ideal for beam tube interaction lengths, are easily fabricated with great relative precision. The RF field conditions in such cavities are easily established and controlled. With single mode, high Q, cavities the phases at the ends are much more precisely identical, and the RF field center position and direction can be made to match the beam axis precisely. Extremely stable cavities with similar modes and dimensions have been successfully used for years in hydrogen masers.^{5,3}

Experimental Apparatus

With the foregoing considerations in mind, an experimental program was begun at GSFC in 1969 to test the ideas and to develop and optimize an atomic hydrogen beam resonance standard. The first experimental apparatus, which is called HBX - 1, was built especially for convenience in testing sources, velocity distributions, state selector systems, detectors, and other parts. This apparatus is shown in Figure 3. For historical purposes it may be noted that this is the first free atom atomic hydrogen beam resonance apparatus for standards applications. The A end, with source, is on the right, the B end, with detector is on the left. Two large 500 liter per second ion vacuum pumps are used which have large gate valves to allow rapid cycle times in changing parts. The large center cylinder encloses the cavity region, which is under precise thermal control. The cavity is enclosed in a four level set of electrically and thermally isolated magnetic shields identical to those used in GSFC hydrogen masers.

The detector installed here is a Penning discharge gauge. Provision has been made to test several other detector types also in the near future. Fixed hexapole state selecting magnets

are installed in the two chambers above the pumps in this particular assemblage, however, electromagnetic variable state selectors which cover a wide range of atomic velocities have been built and tested at this writing, and are presently being installed.

Figure 4 is a schematic diagram showing one of many possible design configurations and operating modes. The RF source dissociator on the left is a typical recent hydrogen maser design (NASA NP hydrogen masers). A separate thermalizing region is provided in this source, and a multitube collimator is attached which confines most of the emergent atoms close to the beam axis. The A state selector defocuses the two lower hyperfine states and focuses the other two states in a symmetrical coaxial beam through the shield and cavity region to the B state selector. Here atoms, if they are still in either of the two upper states at this position, are focused to a small point at the entrance to the detector.

As the atoms leave the A state selector they pass into a magnetically shielded region between inner and outer magnetic shields where a "polarizing" coil is located. There is another, symmetrically located "B polarizer" near the opposite end. These coils produce small magnetic fields along the beam axis which go to essentially zero without direction change as the atoms near the entrance or pass out the exit of the magnetically shielded region. Due to the relatively slow Larmor precession of the atomic magnetic moments at low field, the resultant spin axis does not change direction significantly as the atoms pass through the shield holes. Thus the direction of the magnetic field which appears in the inner shielded region where the cavity is located determines the quantization axes therein; and the atoms can be in different states here than outside this region. This phenomenon is called a non-adiabatic transition ("Majorana flop").

In many applications of atomic beams such transitions are undesirable, and avoided. But in the present case it is a useful technique for eliminating some undesired state at the detector, or for controlling the orientation of atoms in a desirable way within the cavity interaction region.

The cavity is an axially symmetrical cylindrical-coaxial structure which is resonant in the TE_{011} mode. It has breaks in the inner conductor near the ends so that the RF magnetic field couples to the beam at these points. This is a simple separated oscillatory field configuration wherein the applied cavity RF field causes transitions in atoms which have magnetic orientation components transverse to the beam axis. Under ideal field conditions these transitions will be the ($F = 1, m = 0 - F = 0, m = 0$) resonance entirely.

The scheme at the bottom of figure 4 illustrates the progression of state selection and transition events in one of the likely operating modes. In beam tube jargon this is a "Flop out" system. The resonance curve illustrated at the right is a classical "Ramsey resonance."

Polarizing coils which provide three axis orientation control are presently being installed in place of the single, axially oriented, coils used in the first experiments. These will provide means for obtaining space averaged and time averaged resonance conditions, as well as providing the boundary conditions for observing Larmor precession angles as a function of static field within the transition region.

Results

The first successful experiments with HBX-1 were begun in July 1971. Figure 5 is one of the first resonance curves

obtained under the present conditions with hydrogen. This curve is relatively noisy, the signal to noise ratio being approximately 50 or 100 to one; it represents a major milestone, however, since it is the first concrete evidence of successful results with this type of standard. Additionally, now that atoms were being detected, optimization could begin.

This curve tells a great deal to those familiar with beam tube resonances. The half width is exactly what was expected on the basis of length of the interaction region and atom velocity as calculated from beam optics parameters. The interaction length is 50 centimeters, the calculated velocity is closely 100,000 centimeters per second, and the calculated line width is approximately 1.2 kilohertz, which is exactly what is observed here. This gives a line Q of 1.2×10^6 . The horizontal jumps which occur in this curve and in the other resonances in this report are all due to use of a noisy digital servo to control the frequency, and are not inherent in the resonance.

The slight asymmetry seen here is not due to a resonance distortion, but to a secondary transient characteristic of the detector. This may be seen in figure 6. This figure shows two transition curves taken with a slow, continuous, sweep; first from right to left, then from left to right. There is a long time constant drift, apparently thermal, in the detector which follows the quicker, short time constant, initial response. This gives the apparent hysteresis effect. With the normal phase lock loop for a beam tube resonance, this produces no instabilities or biases, since the modulation is relatively fast, and additionally, the detector average amplitude is constant for either direction of frequency change when the servo modulation is about line center. It will be noted that the signal to noise has improved greatly in figure 6 over that seen in figure 5. This is due to "zeroth order" optimization. Right after the first resonance curves were obtained, a misdirected source collimator was replaced and the overall mechanical alignment was improved. The other resonance curves shown in this report were then obtained.

Figure 7 shows a basically very important result. Here three resonance curves were obtained at successively lower values of the main magnetic field, the upper curve at 8.8 milligauss, the center one at .88 milligauss, and the lower one at essentially zero field. The amplitudes and shapes of these curves will be observed to be essentially identical. This illustrates that there are no degenerate sigma transitions. For comparison, with cesium at the field value of the upper curve, other sigma resonances would appear at 6.1 kilohertz intervals, each with a complete resonance pattern similar to this one. At the field of the center curve, they would be only 610 Hz away and all seven cesium sigma resonance patterns would occur within a space of 5 cm on this scale. At the lower field value, all seven cesium resonances would superimpose within a space of .5 cm or less.

The above observations do not in themselves prove that it will be possible to achieve the best accuracy at very low fields with hydrogen, but they do illustrate that certain phenomena, such as transitions in undesired atom states which are focused initially with the beam, are not inherently so near as to prevent such operation.

Another important feature discussed previously is illustrated in figure 8. This shows two resonance curves. In the upper curve only the ($F = 1, m = 0$) state was present in the detected beam, while in the lower curve both the (1, 0) and the (1, 1) state were detected. The presence or absence of the (1, 1) state is determined by the relative polarity of the A and B polarizing coil fields. The fact that both curves appear

identical shows that, at least to the limits observable in these curves, no gross distortions due to π transitions appear even when the entire population of the (1,1) state is detected. If such undesirable transitions occurred appreciably, the amplitude of the lower curve would be proportionally greater.

A natural question which would arise at this point is, "does varying the polarizing coil fields cause appreciable disturbance to the main magnetic field in the transition region?" Figure 9 illustrates that this should be minimal. The field used at the polarizing coils in controlling the states is typically less than 50 milligauss, and a change of plus or minus this amount about zero is seen to produce no more than a few microgauss change in the nearby main field value.

Figure 10 is a plot of the HBX-1 main field calibration which illustrates the excellent smooth control of the magnetic field in the transition region which is attained in practice. The uniformity is also very good along the beam axis over the length of the interaction region. Measurements indicate RMS deviations on the order of 20 microgauss or less are attained at present.

Manual switching of the polarizing coils, or the RF resonance power, to change the detected state populations is illustrated in figure 11. The importance of this curve is that it shows essentially 100% efficiency in eliminating the (1,1) state from the detected beam, and that only the perturbations which affect the principal resonance will be of first order importance. The relatively fast initial time constant of the detector is also apparent, as well as the longer period transient (slow detector drift). As indicated previously, the phase lock loop for locking to the resonance will not be affected by the slow transient.

The most important experimental results which have been obtained to date are illustrated above. As far as this work has gone, there is excellent confirmation of the theoretical expectations. The next important steps are presently being implemented. These are: (1) to determine complete velocity distributions of atoms from both room temperature and cooled sources of various designs, (2) to develop improved detectors, (3) to complete external electronics such as synthesizers, multipliers, phase lock loops, etc., so that a "flywheel" oscillator may be locked to the resonance, (4) to make fundamental comparisons between hydrogen beam devices and hydrogen masers and establish independent measurements of the wall shift and second order doppler shift, (5) to confirm the accuracy expectations for the free atom beam device through systematic measurement and analysis and intercomparisons.

There is much other important and interesting work to be done to prove out this "new" technique, but the essential features are presently becoming apparent, and the prospects are extremely encouraging. This brings out the most important question, that is: What performance may be expected in terms of "accuracy," stability, etc. in future practical operational hydrogen beam resonance standards?

"Accuracy" Potential

The most important goal that must be satisfied is accuracy capability. It is not possible to provide a detailed analysis at this time, as so much depends upon the final design configuration, as well as experimental confirmation of the magnitude of possible perturbations or biases associated with the final design details. Additionally, the criterion of demonstrated reproducibility through comparisons of independent instruments must be met, as well as the criterion of long term invariance of the results with an individual standard. However, it can be established

qualitatively at this time that the "accuracy" expectations are extremely good.

a. Cavity effects.

With hydrogen the single node cavity is approximately 10 inches in diameter and the length may be varied as desired. The length of the HBX-1 cavity is 23 inches. There is complete electrical symmetry about the beam and magnetic field axis, and there are no other cavity resonances significantly near the desired mode frequency. The cavity is coupled at precisely half way between ends, and with the relatively high Q, high stability, cavities the possibility of phase shifts or travelling waves is minimized. The beam also has axial and radial symmetry. This must be compared with typical cesium cavities with up to 200 half wavelengths along the axis, with nearly degenerate cavity resonances inevitably nearby, and with typical beam cross sections not uniformly symmetrical. The cavity effects, though they are the largest effective error contribution in cesium, are nevertheless analyzable and determinate at the 10^{-12} level or less.⁷ With at least an order of magnitude improvement in H-beam cavities, the cavity related errors should be much less than 10^{-13} , probably on the order of 10^{-14} with eventual optimization.

As in cesium, the first order doppler effects are minimal, and in addition are of the same nature as cavity phase shift effects, so that they are effectively included above.

b. Second order doppler correction.

The almost monochromatic H-beam atom velocities by calculation and by experiment have a small spread of approximately 1%. In addition, the atom velocity may be varied continuously over wide ranges. These facts make it possible to determine the second order doppler correction experimentally with great precision. Particularly with the low temperature beam the error should be less than 10^{-14} .

c. RF power and spectra dependent shifts.

With the very symmetrical and undistorted resonance possible with monochromatic hydrogen, relatively small inherent change of frequency with power should occur. Additionally, with the relatively low frequency of hydrogen, the RF spectra related shifts should also be relatively small. Extrapolating from cesium data, errors of this type will not likely be much greater than a few parts in 10^{15} .

d. Spin exchange shifts.

Calculations based upon spin exchange frequency corrections experimentally measured in hydrogen masers, when related to the parameters of the H-beam, indicate that net spin exchange pulling in a high intensity beam will be of the order of 10^{-15} or so, and that the associated errors will be somewhat smaller than this, so the possibility of spin exchange errors may be neglected in relation to other errors, particularly with cooler, lower intensity beams.

e. Magnetic effects.

The natural pulling of the (0-0) resonance in hydrogen at low field values is a small effect. The absence of other

sigma transitions and minimal coupling to Pi transitions in properly oriented RF and DC magnetic fields is uniquely optimum with hydrogenic hyperfine spectra. There are additionally, unusual modes of operation we can produce with hydrogen where states enter the transition region with $m = +1$ or -1 orientations at right angles to the beam direction, and these can be rotated or changed so that transitions effectively measure the field values in off axis directions. It is also still feasible to use transverse Zeeman modulation to determine the fields precisely, particularly with long cavity designs or with very cold, slow, hydrogen. While the field determination inaccuracy may not be so small as with hydrogen masers, where it is negligible, it can be far better than is the case with cesium, where uncertainties less than 10^{-13} are attainable. Thus it may be expected that hydrogen field associated errors will be much less than 10^{-13} .

On the basis of the above observations, it is estimated that the net intrinsic accuracy capability at the hydrogen beam standard will be of the order of one part in 10^{13} or less.

Stability Potential

From present experimental evidence, it can be shown that there is also a potential for very good frequency stability in H-beam standards. The equation relating fractional frequency deviation σ , to line Q and signal to noise ratio when beam shot noise predominates is

$$\sigma = \frac{K}{Q \sqrt{n t}}$$

where n is the detected beam intensity (atoms per second), t is the associated measuring time, and $k = .2$ with sufficient approximation (for square wave frequency modulation). As a worst case estimate, the present experimentally observed signal to noise ratio of 1000 to one for a one second interval may be used. The line Q in the present case is 10^6 , and these values give

$$\sigma = \frac{2 \times 10^{-10}}{\sqrt{t}} \text{ (worst case)}$$

and so even with the first experimental configuration a measuring time of 10^6 seconds will provide a precision of 2×10^{-13} , which is far better than today's state of the art "accuracy."

If, instead, we assume perfect detection at a flux level of 10^{11} atoms per second, the result is 7×10^{-13} for one second intervals, and 7×10^{-16} for ten days!

For purposes of estimating the actually realizable stability in optimally designed future H-beam standards, it will be assumed that some success will be had with cooling our present sources, or that improved focusing efficiency is achieved, so that a factor of 50 improvement in present detected flux levels occurs. Also, it will be assumed that the line Q will be improved by a factor of at least two either by lengthening the cavity or by selecting lower velocity atoms. In the ideal detector case the one second stability is then found to be 5×10^{-14} . If we now assume that detectors will never be found which are more than .25% efficient, the stability is calculated as 1×10^{-12} (one second) and 3×10^{-15} (one day).

Figure 12 summarizes the performance results anticipated with H-beams, and compares these with typical performance of H-masers and of cesium beams. Here it should be emphasized that some improvement in stability with H-masers, cesium beams, or the other devices may be expected in the future, although more than an order of magnitude does not seem likely due to the relatively advanced state of present development with these devices. Additionally, it does not seem too likely that the hydrogen beam will ever find widespread use where portability, price, or size is the overriding criterion. However, for applications where accuracy, and resettability, as well as simultaneous long and short term stability, are the most important requirements, the H-beam certainly appears to have the potential to excel by a large factor.

Conclusion

From the outlook and results presented herein, it is clear that the most stringent demands of the scientist, metrologist, and technologist, as well as the tastes of the natural philosopher can be met with regard to frequency and time standards by choosing atomic hydrogen as the basic reference. There are now at least two good, "accurate," ways to look at the hydrogen atom. Both those who might continue to prefer the hydrogen maser as their instrument, as well as those who prefer the beam techniques, can satisfy their inclinations and desires.

The free atom hydrogen beam technique does combine, however, in a rather nice way the technologies of hydrogen masers and cesium beams. It is an additional boon, perhaps, that it is also a very rewarding experience for anyone to experiment with and to utilize the transitions and trajectories of the simplest atom in the purest of quantum states under conditions where it is primarily restrained in space only by its own linear and angular momentum.

At this point, it should be emphasized that all the comparisons to cesium herein are not intended to denigrate or to criticize the work of the many dedicated and talented people who have achieved such remarkable results with cesium beams. Indeed, it is to their great credit that the extreme accuracies which are achieved today with cesium were accomplished in spite of great obstacles and difficulties.

In conclusion I wish to express my thanks for the great debt this work owes to the many colleagues and cohorts, past as well as present, with whom I have had the great privilege and good fortune of being associated. I would also like to reaffirm the debt we all owe to the many pioneers in this field who have recorded their knowledge for our enlightenment and for our use, as well as for our pleasure.

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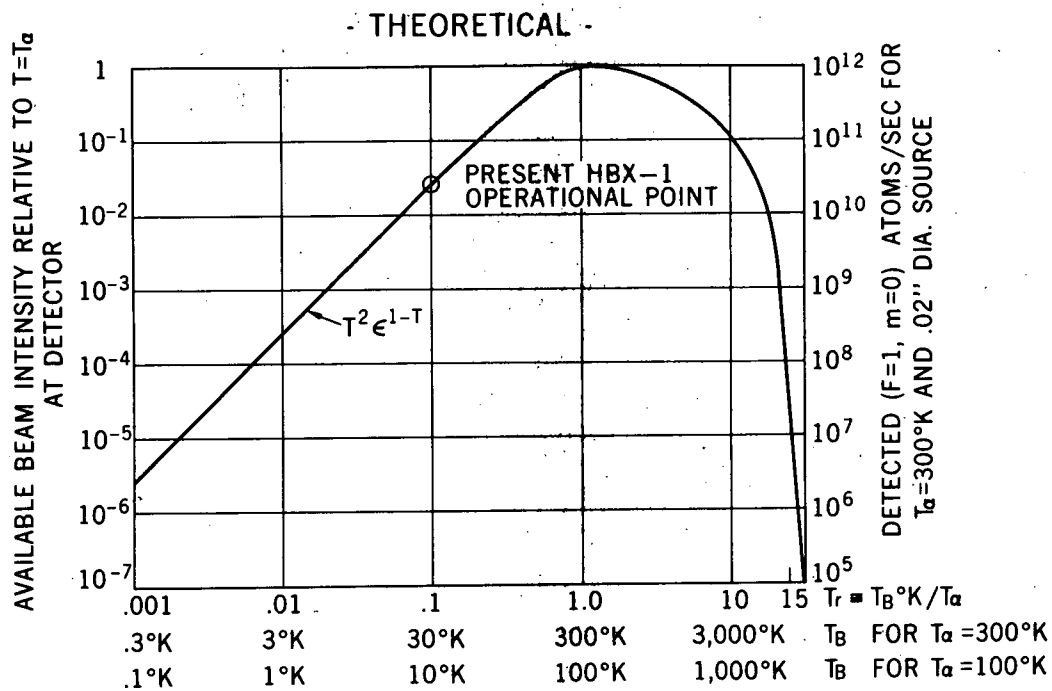


Figure 1. Hydrogen atom temperature distribution.

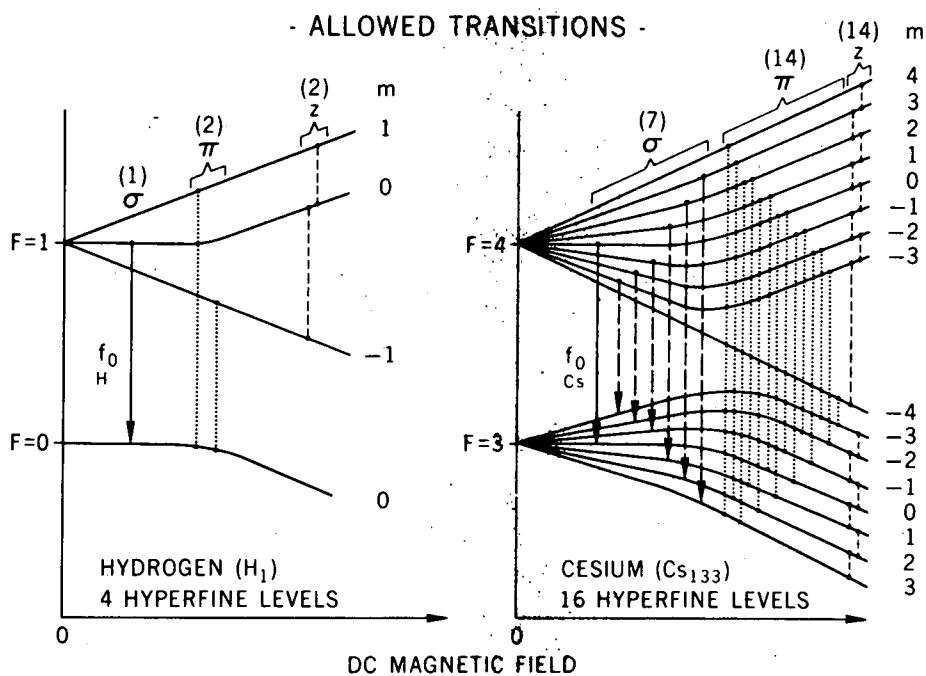


Figure 2. Hydrogen and cesium hyperfine energy levels.

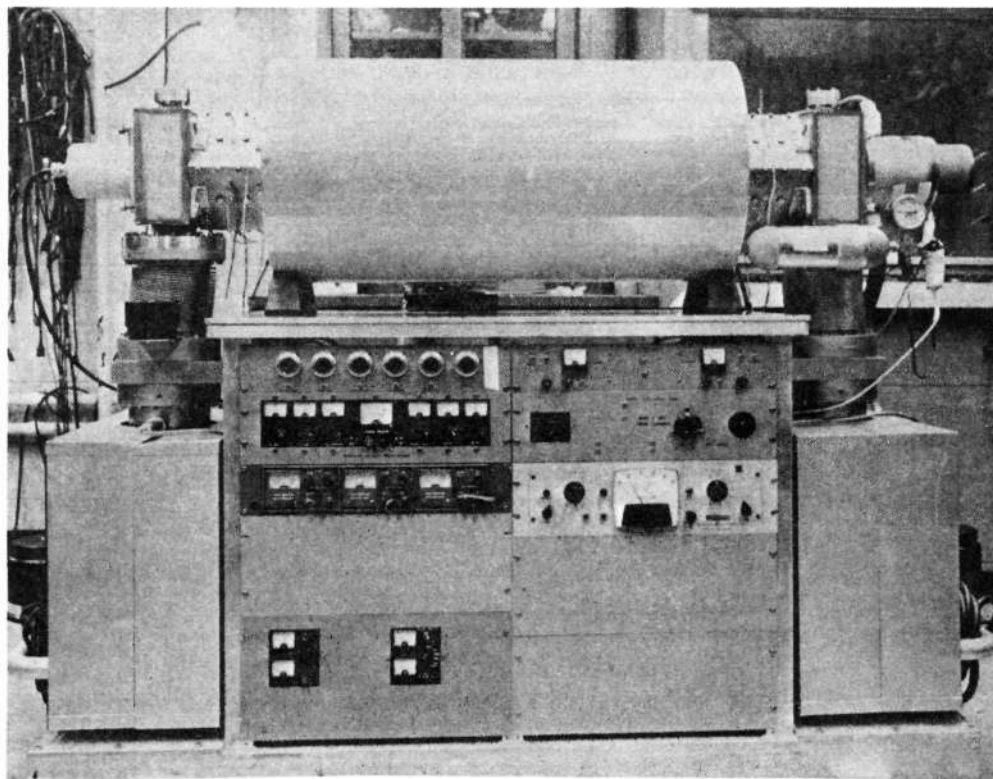


Figure 3. Picture of HBX-1 atomic hydrogen beam experimental apparatus.

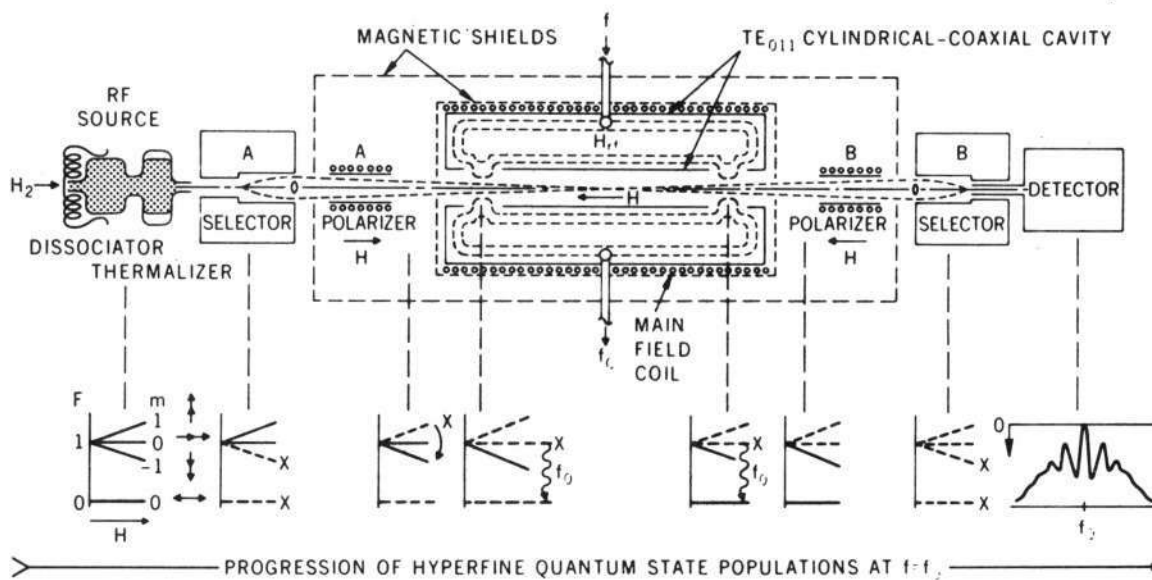


Figure 4. Hydrogen atomic beam standard schematic.

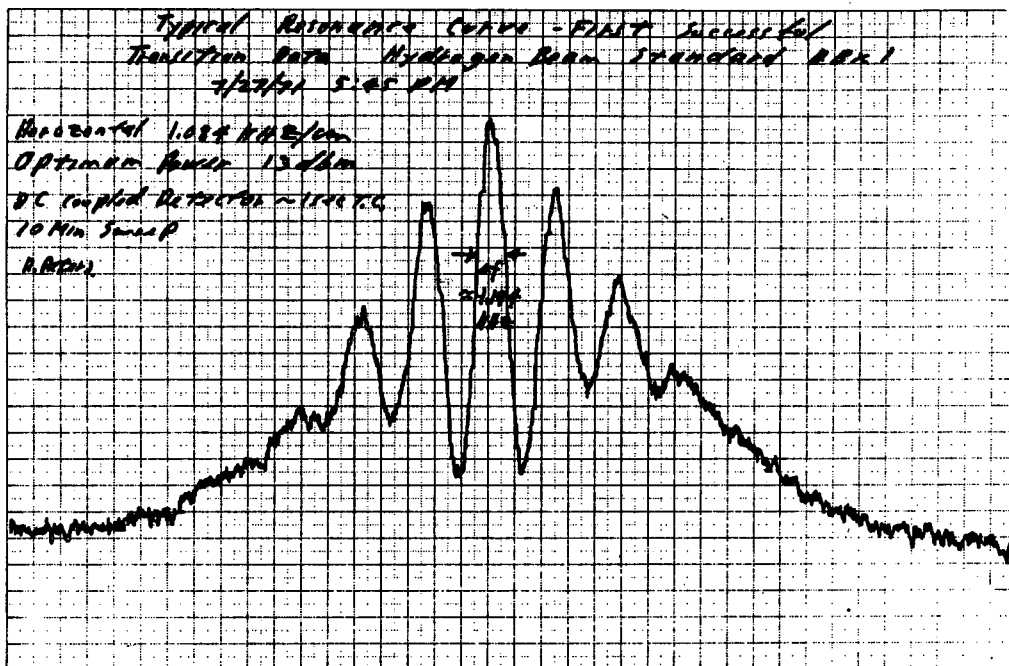


Figure 5. First transition curve.

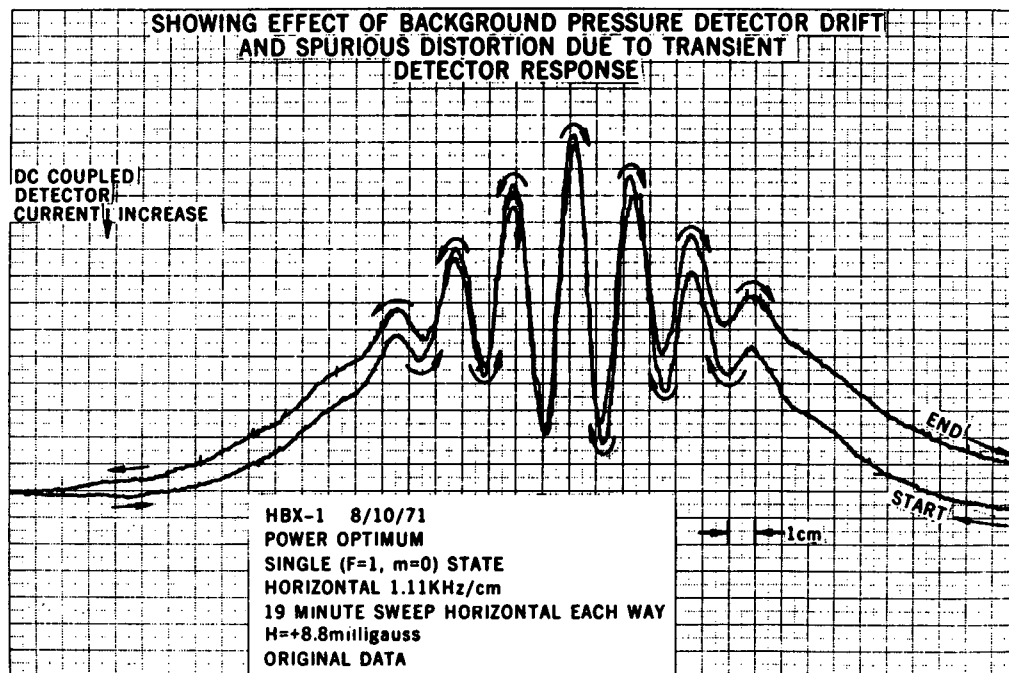


Figure 6. Transitions with reverse retrace.

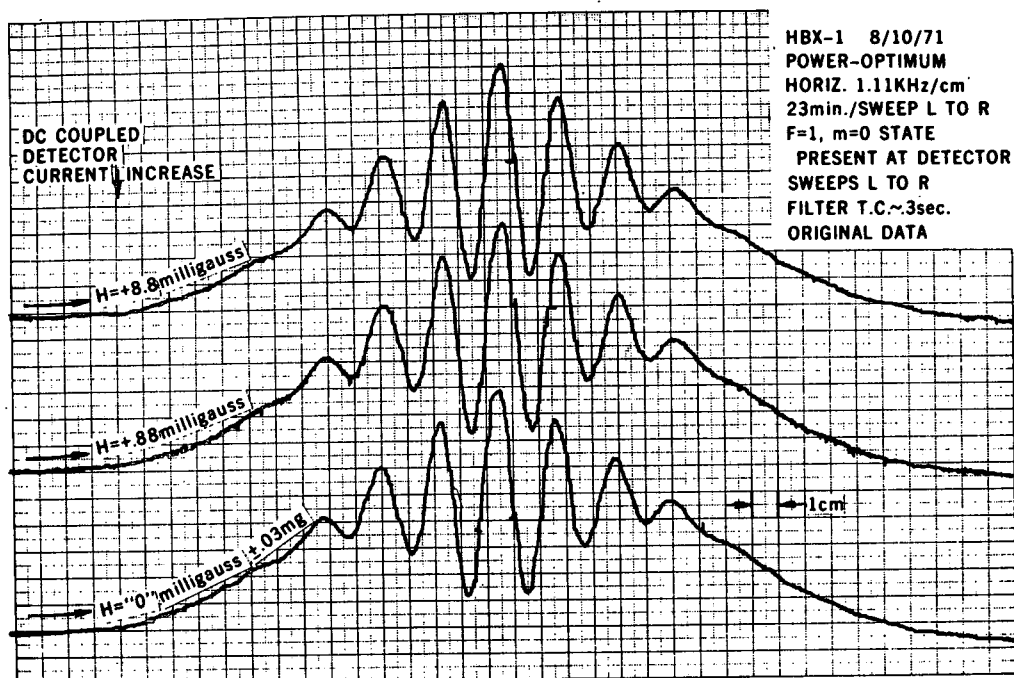


Figure 7. Transitions at various fields.

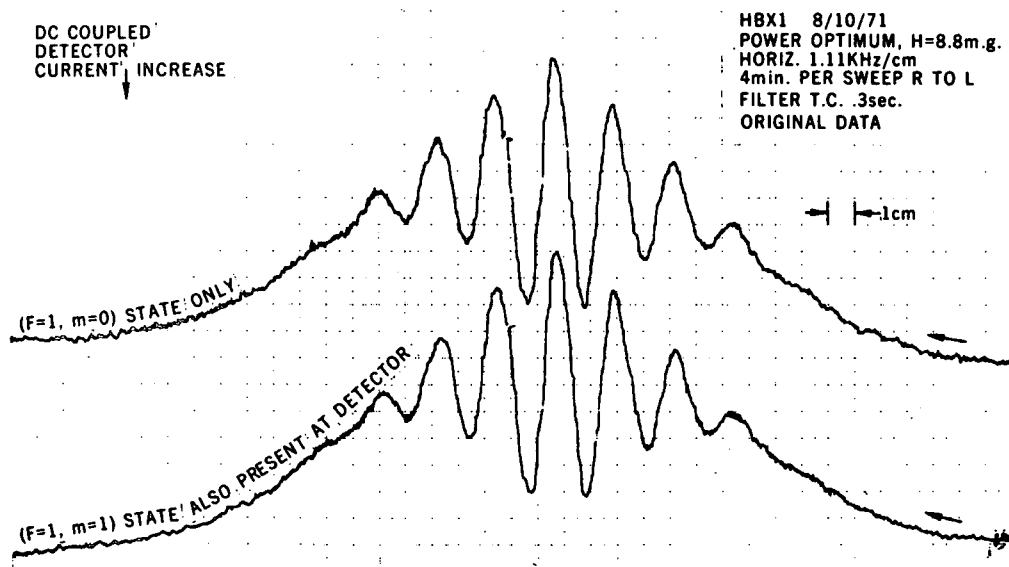
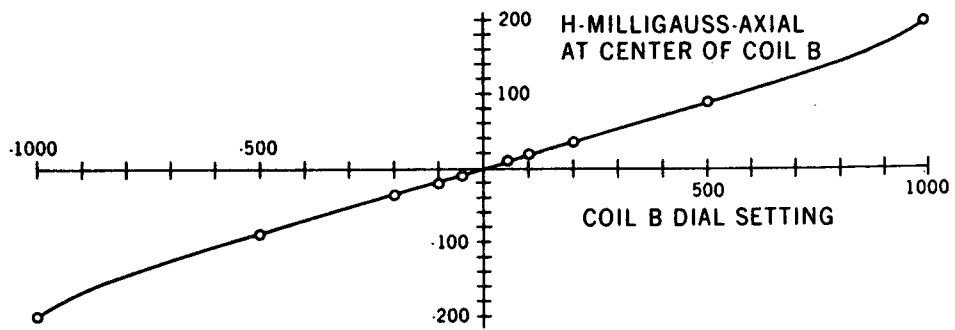


Figure 8. Transitions with and without $m = 1$ state present.



**VARIATION OF MAIN FIELD ADJACENT TO INNER SHIELD
CAP HOLE AS POLARIZING FIELD IS VARIED**

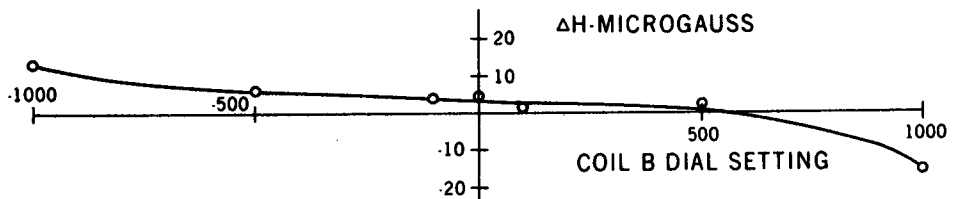


Figure 9. HBX-1 polarizing coil field calibration.

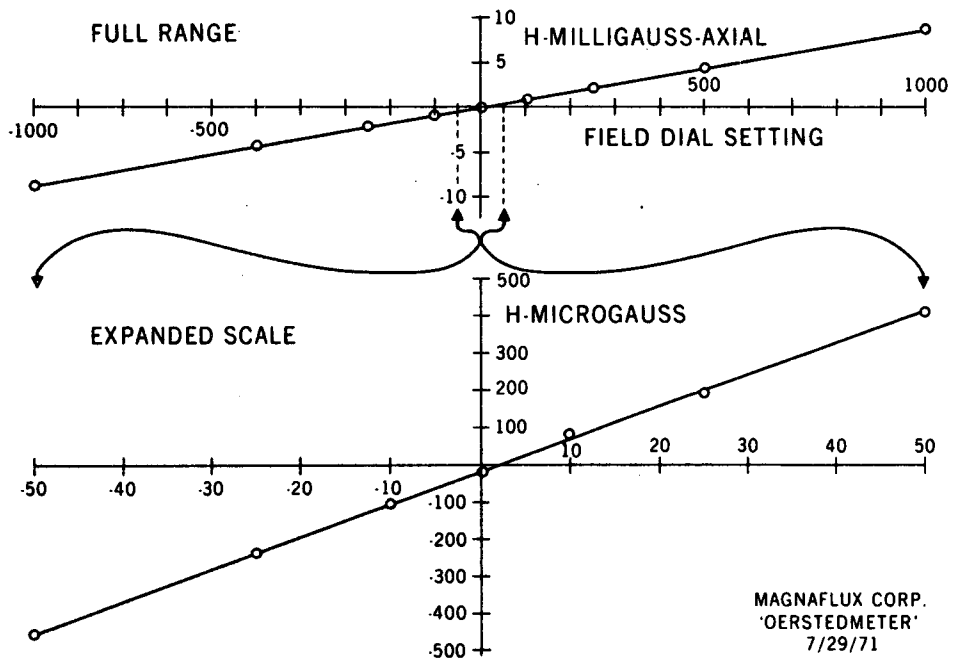


Figure 10. HBX-1 main field calibration.

