

HYDROGEN MASER FREQUENCY STANDARD

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INTRODUCTION

Since its invention in 1959 by Kleppner, Goldenberg, and Ramsey (1962) and Kleppner et al. (1965), the hydrogen maser has become an indispensable component of very long baseline interferometer systems. During the last decade, the development of the maser and its supporting control and signal procuring equipment has been strongly benefited by two phases of a project to measure the gravitational redshift, the first of which began in 1964 with NASA support and which has continued until the recent successful test of the equivalence principle using a space-borne maser (Vessot and Levine, 1979).

The intent of this paper is to describe the fundamental theoretical limitations of the maser and the systematic processes that cause instability and to describe some aspects of recently designed masers. A design for field use that has evolved from the development of the space-borne maser will be described. The performance of this type of maser is close to theoretical limits imposed by thermal noise. Further developments of smaller masers for space and terrestrial use and our recent work on masers operating at low temperatures will also be discussed.

The Maser Oscillator

The hydrogen maser is an oscillator whose power comes from the careful release of energy from the hyperfine interaction of the electron and proton of an aggregate of hydrogen atoms. This energy is, of course, familiar to radio astronomers as the 21-cm line of atomic hydrogen. Figure 1 shows a schematic diagram of the maser and the hyperfine levels of atomic hydrogen. In the maser, atoms are obtained by dissociating molecular hydrogen by placing molecular hydrogen in a radio frequency (rf) discharge tube at a pressure of a few tenths of a torr. The outlet of this rf dissociator is usually a set of collimator tubes which produces a fairly narrow, cylindrical beam of neutral atomic hydrogen directed along the axis of a 6-pole state selector magnet that provides a highly inhomogeneous magnetic field in the radial direction (4-pole magnets are used successfully also). The field strength along the axis of the magnet is zero and increases quadratically in magnitude with radius to a level of about 10 kilogauss at the circularly arrayed pole tips of the magnet. Atoms enter the magnet from the source collimator within a conical spread of a few degrees. Those in the $F = 1$, $m_F = 1$, and $m_F = 0$ states have induced magnetic dipole moments that interact with the magnetic gradient so as to experience a force directed radially inward and are focussed into a storage bulb. Atoms in

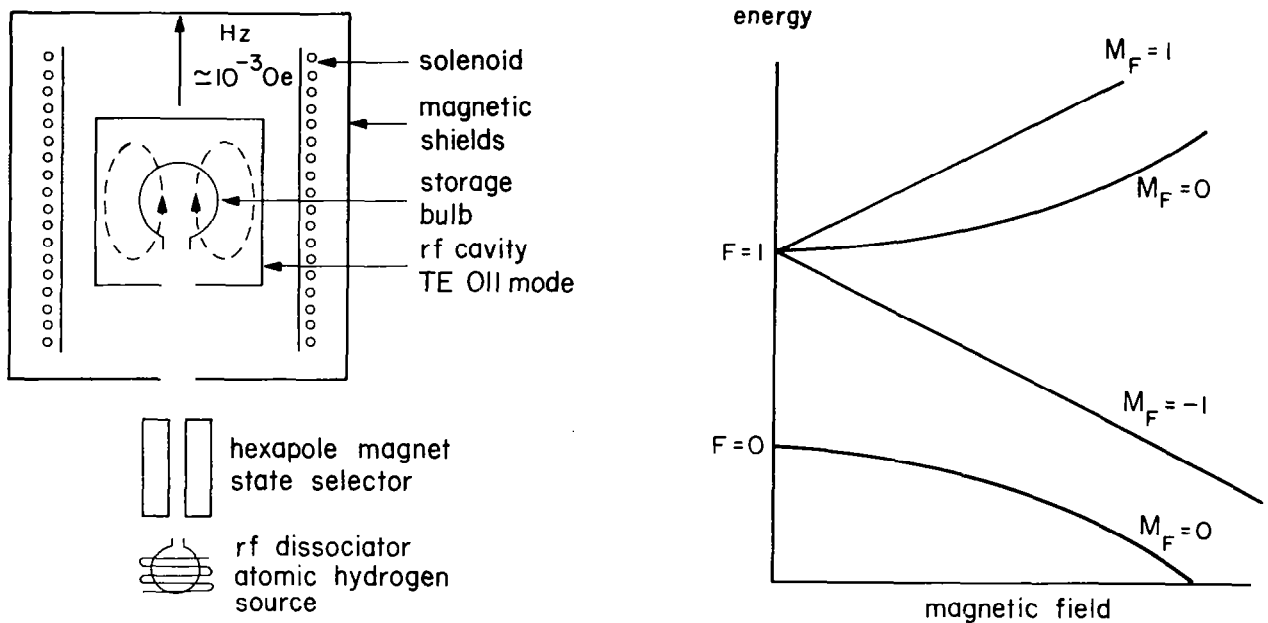


Figure 1. Schematic diagram of atomic hydrogen masers and energy levels of ground-state atomic hydrogen.

the $F = 1$, $m_F = 1$, and $F = 0$, $m_F = 0$ states have dipole moments of opposite sign and are directed outward. The field strength and length of the magnet are designed so as to focus the $F = 1$, $m_F = 0$, and $m_F = 1$ state atoms into the storage bulb through its collimator. (Note that the lateral dimensions of figure 1 are exaggerated. Typically, the beam diameter is about 3 mm and the magnet length about 7 cm.)

The storage volume is the heart of the maser. It serves to confine a constantly replenished set of atoms in an in-phase region of microwave rf magnetic field within a TE_{111} cavity resonator, so that phase coherent stimulated emission of microwave energy from the atoms will result. According to Heisenberg's uncertainty principle of quantum mechanics, the longer the unperturbed interaction time, the narrower the resonance linewidth that can be achieved. Our objective is to store the atoms as unperturbed as possible for as long as possible so as to have as narrow a resonance as possible to define the maser's output frequency. Using kinetic theory, we can design bulbs several centimeters in diameter which, at room temperature, will confine the average hydrogen atom for about 1 second. In principle, we can thus obtain a resonance width of 1 Hz provided all other perturbations to the hydrogen atom can be controlled. The successful operation of the maser hinges on our providing a coating which reflects the hydrogen atom hundreds of thousands of times without appreciably altering the phase of the precessing, magnetically coupled, electron and proton (let alone allowing the atoms to make unwanted transitions or even to chemically combine with other atoms or recombine with themselves). The currently used coatings are usually made of Teflon® (duPont).

The energy is released from the state-selected atoms stored in the bulb and delivered to the cavity resonator whose quality factor is sufficiently high that the rf magnetic field from its stored energy will continue to stimulate atoms that follow so as deliver power equal to the combination of cavity dissipation and power coupled to the external receiver system. Under these conditions, the level of oscillation is sustained.

As in all oscillators where two or more resonators are coupled electromagnetically, there is a frequency pulling effect which is proportional to the ratio of the quality factor Q_c of the pulling resonator (here the cavity) and the pulled resonator (here the atom, which has a quality factor Q_a). The relationship is:

$$\Delta f_{\text{pulling}} = \frac{Q_{\text{cavity}}}{Q_{\text{atoms}}} \cdot \Delta f_{\text{atoms}}$$

This is an approximation. The exact relationship also involves the spin exchange frequency shift [4]; however, the “pulling” effect that remains is still proportional to the cavity, offset.

When we look at typical values for masers, we find that $Q_{\text{cavity}} \sim 30,000$ and $Q_{\text{atoms}} = Q_a \sim 2 \times 10^9$, so that to keep the frequency within $\Delta f/f \sim 10^{-15}$ the cavity resonance frequency changes must be kept to ± 0.1 Hz.

A further condition for stable oscillation is that a low level (~ 1 milligauss) uniform magnetic field must be applied in the direction of the magnetic component of the rf field to provide an axis of direction so that the $\Delta M_F = \pm 0$ transitions, allowed from the selection rules of quantum mechanics, will be selectively stimulated. The transition $F = 1, m_F = 0 \rightarrow F = 0, m_F = 0$ in hydrogen at low field ($\ll 550$ Gauss) has second-order frequency dependence with magnetic field given by $\Delta f_{\text{magnetic}} = 2,750 \text{ H}^2 \text{ Gauss}$. For these so-called “clock” transitions, the frequency sensitivity to change in magnetic field is least at low fields. However, the fields must be maintained constant and uniform enough so that, throughout the storage volume, the moving atoms experience no motion-induced magnetic variations with spectral components that will excite transitions between the $\Delta M_F \pm 1$ hyperfine sublevels. At weak fields, these transitions follow the relationship $f_z = 1.4 \times 10^6 \text{ Gauss}^{-1}$. These transitions are used to measure the average magnetic field in the bulbs by applying from an external coil a transverse rf field whose frequency is scanned until a dip is observed in the maser’s oscillation level.

The confinement of the atoms during the storage process also leads to systematic frequency shifts and poses a limitation to the available signal power output. The quality factor associated with the aggregate of stored atoms is given by

$$Q_a = \frac{\omega}{2\gamma}$$

where $\omega = 2\pi$ (oscillation frequency) and γ is the total transverse relaxation rate of the average atom in the bulb, which has the following major components:

$$\gamma_{2T} = \underbrace{\gamma_{\text{storage}}}_{\text{bulb}} + \underbrace{\gamma_{\text{wall}}}_{\text{relaxation}} + \underbrace{\gamma_{\text{spin}}}_{\text{exchange}} + \underbrace{\gamma_{\text{magnetic}}}_{\text{homogeneity}} + \dots$$

For a storage bulb of volume V_b with a hole of area A_e and collimator factor K , we have:

$$\gamma_2 = \frac{\bar{v}A_e}{4KV_b} + \frac{\bar{v}p}{\lambda} + \bar{v}_r\sigma_{se} \dots \quad (1)$$

Here,

$$\bar{v} = \sqrt{8kT/\pi m}$$

$$v_r = v/\sqrt{2} = \text{average relative velocity}$$

$$V_b = 4/3 \pi R^3 \text{ bulb volume}$$

$$\lambda = 4R/3 \text{ mean free distance between wall collisions}$$

} for a spherical bulb
of radius R

$$p = \text{probability of loss per wall collision}$$

$$\sigma_{se} = \text{spin exchange cross section}$$

$$n = \text{density of atoms in bulb}$$

Equation 1 can also be written as follows:

$$\gamma_2 = \left(\frac{8kT}{m}\right)^{1/2} \left(\frac{3}{16} \cdot \frac{A_e}{KR^3} + \frac{3}{4} \cdot \frac{p}{R} + \frac{n\sigma_{se}}{\sqrt{2}} \right) \quad (2)$$

and we see that the kinetic behavior of the atoms affects three processes:

- (1) the rate of emergence from the bulbs,
- (2) the rate of wall collision relaxation, and
- (3) the rate of loss from spin exchange relaxation.

These effects limit the storage time and, hence, the Q of the oscillating system. However, the spin exchange relaxation and wall relaxation are also accompanied by a frequency shift and the shift per collision is also a function of temperature. The temperature dependence of the wall relaxation probability depends very much on the type of surface. To complete the picture, we note that the spin exchange frequency shift also depends on the proportion of atoms in the various hyperfine states that enter the bulb.

The key to obtaining stability, then, is to keep the temperature, magnetic fields, and cavity resonance variables under close control. The solution is a question of design, and a considerable amount of engineering has been involved in the development of masers, chiefly in the control of temperature and eliminating the cavity resonator's sensitivity to temperature changes, the control of magnetic fields, the shielding of the atoms from outside field variations, and the control of atomic hydrogen beam flux.

The VLB-10 and -11 series masers built by the Smithsonian Astrophysical Observatory (SAO) have evolved from spacecraft maser designs where ruggedness, light weight, small size, and low power consumption have been important considerations. All of these have cavity structures made of Cervit R (Owens-Illinois), a very stable, low thermal expansion, glass-ceramic material that is well isolated mechanically from stress variation induced by barometric changes. Of the 14 masers built, all have large 8-element ion pumps with about 5-year capacity.

Figure 2 shows the lightweight (185 gram) fused silica spherical bulb with its integral collimator tube mounted to the end plate of the all-Cervit cavity. The fact that the dielectric constant of fused silica has a small but significant temperature coefficient makes it important to load the cavity dielectrically as little as possible; hence, the emphasis on a lightweight bulb. The cavity-bulb assembly has a temperature coefficient of resonance frequency $\delta f_c/\delta T \approx -300 \text{ Hz/C}^\circ$. The cavity end plates and cylinder interior are coated with silver and, for mechanical stability, their joints are lapped. The assembly is clamped together with about 200 kg preload applied by cannister surrounding the cavity equipped with a constant force Belleville washer to minimize temperature induced stress changes from the cannister. As shown in figure 3, the assembly is mounted on a false bottom within a vacuum chamber (shown in the background) so as to avoid the effects of barometric pressure variations. The vacuum chamber is secured to the base plate with three thin-walled titanium studs and connected by a thin-walled titanium bellows neck tube to the ion pump shown, without its magnets, in figure 4. The neck is equipped with a temperature controlled guard station to which are connected the small diameter coaxial cables leading to the cavity.

Immediately surrounding the cavity vacuum chamber is a nested set of four layers of magnetic shields made of carefully annealed moly-permalloy ® (Allegheny Ludlum) which are separated at their ends by glass foam thermal insulation and insulated radially by layers of ethafoam ® (Dow Corning). Not shown is a closely fitted aluminum oven cannister that surrounds the second magnetic shield (counting from inside). This oven is divided into two separately controlled zones and operates at 43°C . The cavity vacuum chamber is temperature controlled in three separate zones at 50°C . As seen in figure 5, three of the four magnetic shields have torrispherical ends to minimize

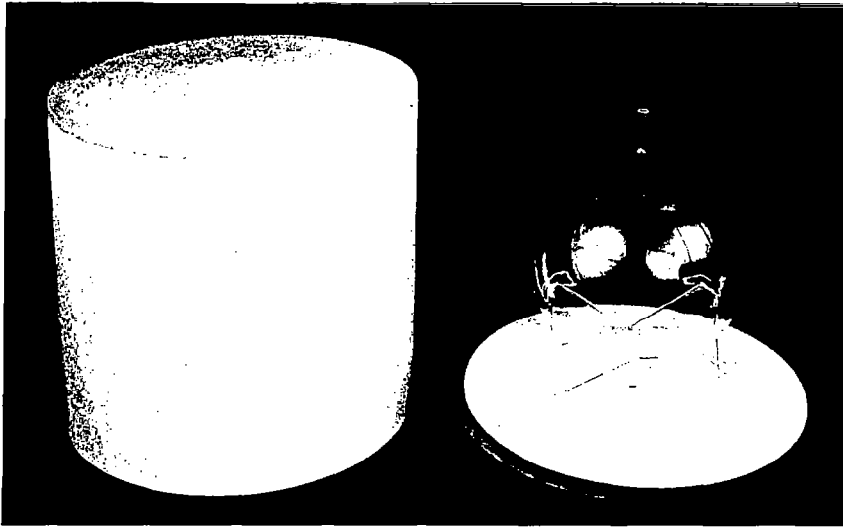


Figure 2. Cervit cavity and fused silica storage bulb used in SAO's VLG-11 series masers.



Figure 3. Assembly of Cervit cavity showing false bottom to isolate the cavity from barometric stress changes. Vacuum bell jar is shown in background.

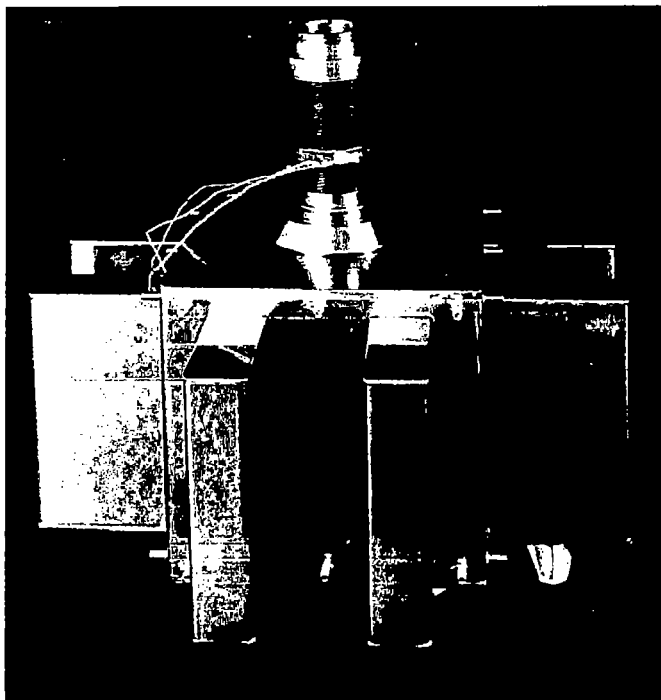


Figure 4. Eight-element Ultek ion pump shown without magnets. Titanium bellows vacuum connection to bell jar base is shown with heat station installed.



Figure 5. Four-layer magnetic shields showing torrispherical domes on outer shields and foam-glass separators for thermal isolation.

local mechanical stress and the consequent loss of magnetic permeability. The innermost shield has flat ends and encloses a three-section printed circuit solenoid shown in figure 6. This is symmetrically wound so that the windings proceed forward on the inside and return on the outside and the go-return wires are overlaid as strip lines to minimize stray fields that could spoil the homogeneity of the magnetic field in the bulb.

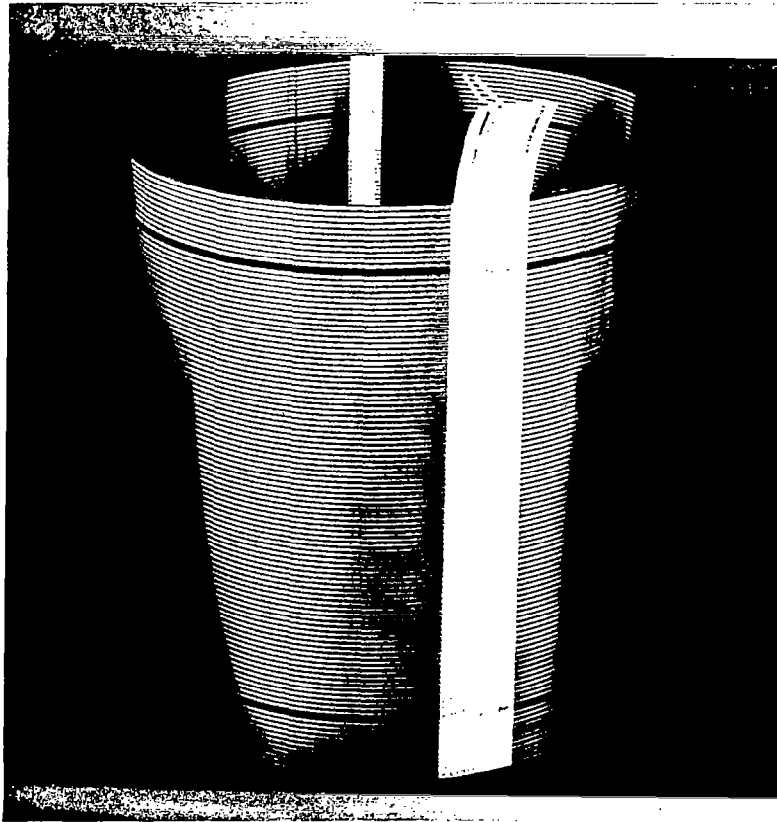


Figure 6. Two-sided printed circuit solenoid. Inner and outer windings in each of three sections form a complete solenoid with go-return wires connected by two-sided strip line to minimize stray magnetic fields.

The three separately-controlled solenoid sections are arranged so that axial second-order magnetic field variations can be compensated without adding spurious fourth order variations.

The completed maser assembly is shown in figure 7 with side panels and electronic box covers removed. The upper cylindrical structure is the magnetic shield surrounding the ion pump; beneath it can be seen the outermost magnetic shield for the cavity assembly. All panels swing out on hinges for servicing, and the electronic circuit boards for the maser control can be unplugged for testing and servicing. The aluminum frame is mounted on casters and the whole system weighs 300 kg and consumes 120 watts of dc power at 28 volts.

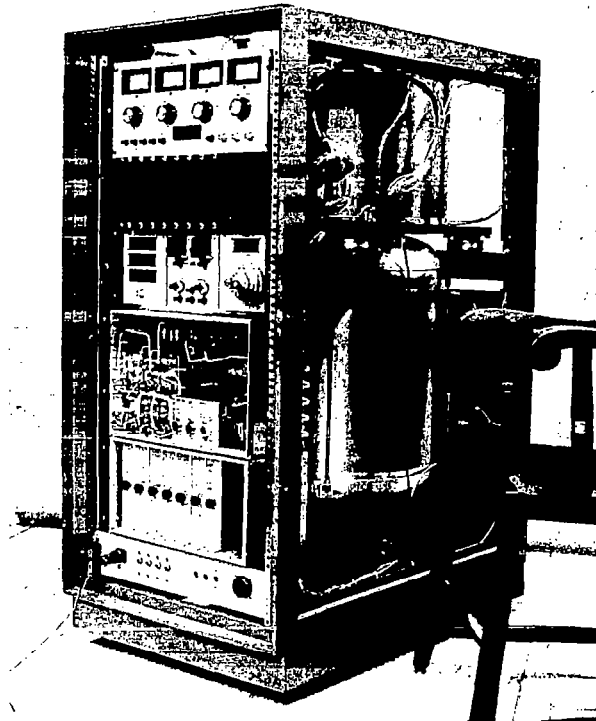


Figure 7. Assembled VLG-11 maser with access panels removed, control and monitor panels hinge out. The eight control modules can be unplugged for testing.

Fundamental Limitations to Maser Stability

The previous section discussed some aspects of engineering approaches to cope with the systematic frequency shifts in masers that are used in field applications. This section addresses the fundamental thermodynamic limitations of the maser's stability.

There are two reasonably separable sources of fundamental instability in the hydrogen maser. The first is the result of thermal noise, kT , with frequency components lying within the atomic transition linewidth. The effect of this noise is given by the expression

$$\frac{\Delta f}{f}(\tau) = \sigma_f(\tau) = \frac{1}{Q_q} \sqrt{\frac{kT}{P_b \tau}} \dots \quad (3)$$

where Q_q is the atomic line Q , P_b is the power delivered by the atoms, and T is the absolute temperature of the oscillator. The fractional instability $\Delta f/f = \sigma(\tau)$, which is the one-sigma probability of the difference between two adjacent measurements, each of duration τ , is a function of the averaging time interval, τ (Allen, 1966). For this type of instability, we see that the expectation value of the σ_f vs. τ plot will show a $\tau^{-1/2}$ behavior. This expression is fundamental to all oscillators.

However, in the case of hydrogen masers where the signal output is rather weak, typically 10^{-12} watts or so, we must contend with another manifestation of thermal noise – that of the noise added to the signal at the input to the receiver system. Here, the instability is described by the expression

$$\frac{\Delta f}{f}(\tau) = \sigma_a(\tau) = \frac{1}{2\pi f \tau} \sqrt{\frac{FKTB}{P_0}} \dots \quad (4)$$

where F is the noise figure of the receiver system, B is effective noise bandwidth of the overall system, and P_0 is the power delivered to the receiver. We note that a σ vs. τ plot of this type of instability shows a τ^{-1} behavior. These two processes can be added as incoherent effects, and we obtain

$$\sigma(\tau) = (\sigma_a)^2 + (\sigma_f)^2 \text{ }^{1/2} = \left\{ \frac{kT}{2} \left[\frac{FB}{2\pi^2 f^2 P_0 \tau^2} + \frac{1}{(Q_q)^2 P_b \tau} \right] \right\}^{1/2} .$$

This behavior is illustrated in figure 8, which shows the performance data from the VLG-11 series masers described earlier. The maser operating parameters are listed in the figure and provide data for predicting the stability which is shown in the dotted line. The data follows the prediction reasonably well up to $\tau \sim 3,600$ seconds, where $\sigma(\tau) = 6 \times 10^{-16}$. For $\tau > 3,600$ seconds, very slow systematic drifts between the masers, which were likely to have resulted from an air conditioner failure 10 days earlier, made the statistical representation inappropriate.

A Cryogenically Cooled Hydrogen Maser

From the previous data, it is clear that we are close to the limits imposed by thermodynamics. Increasing the power level to offset the noise by increasing the atomic hydrogen flux intensity can improve the short term stability but does so at the expense of the longer term behavior. The result of increasing the flux is to reduce the atomic line Q which results from increasing the density n of the atoms in the bulb and thus, raising the level of spin exchange relaxation (see equations 1 and 2).

In late 1977, experiments by D. Kleppner and co-workers at the Massachusetts Institute of Technology (MIT) showed that atomic hydrogen could be stored in gaseous form at temperatures as low as 4 K (Crampton et al., 1979). This led to the speculation that the frozen molecular hydrogen that coated the walls of the storage vessel and prevented recombination could also serve as a wall coating to preserve the phase of the oscillating hydrogen atom during collisions. Crampton and his colleagues showed this was not a good wall coating for hydrogen masers (Crampton et al., 1978).

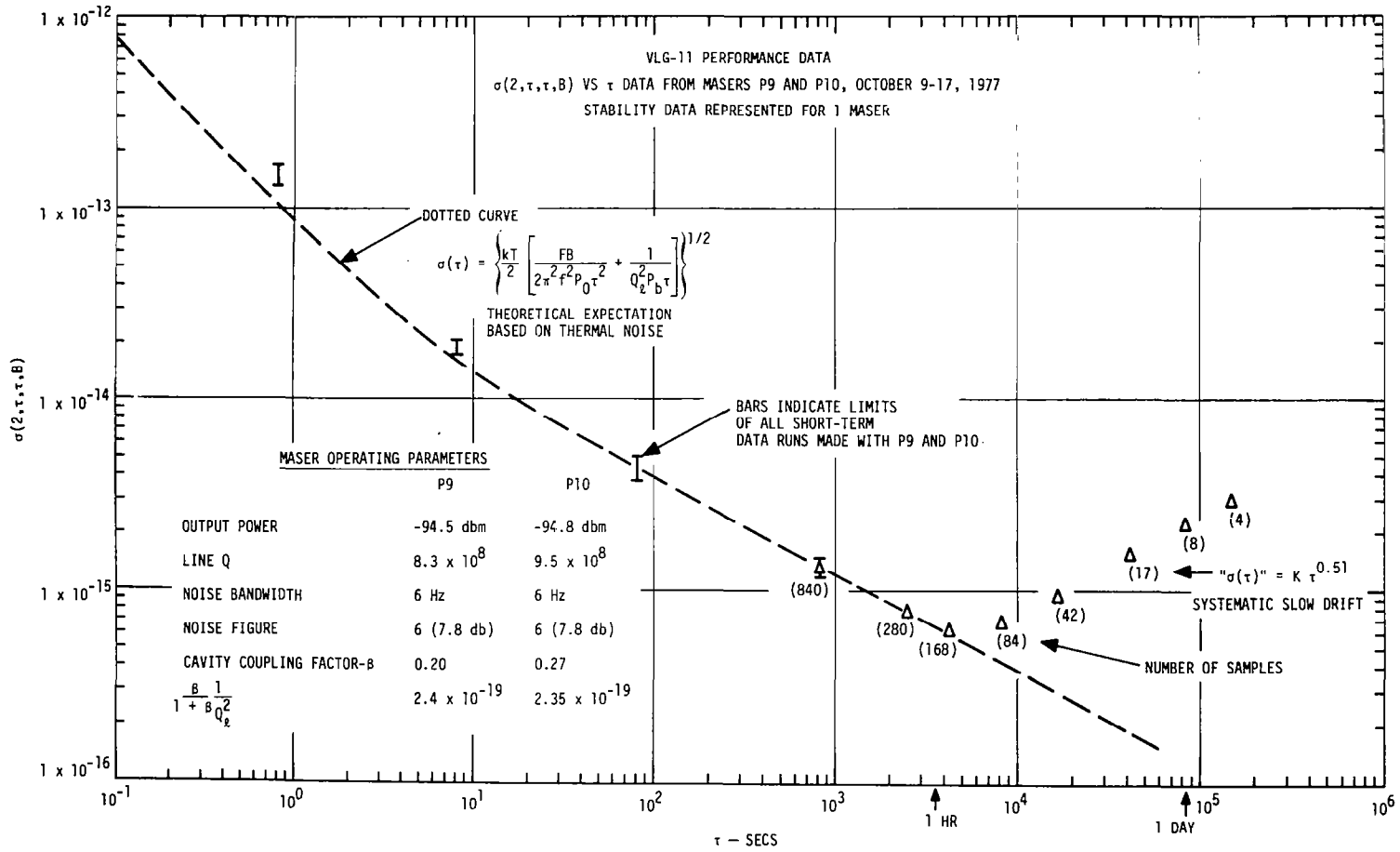


Figure 8. Allan variance plot of performance VLG-11 masers. Dotted lines shows theoretically expected performance.

During a recent program at SAO to study low temperature operation of a maser, we succeeded in making a maser oscillate at 25K by introducing a carbon tetrafluoride into the cavity and freezing it onto the surface (Vessot et al., 1979). This provides a wall coating that consists essentially of tightly bound fluorine atoms. This surface, to the impacting hydrogen atom (at least from the outside), appears quite similar to the Teflon surface normally used at room temperature. We believe that studies at low temperature will gain us a great deal of information about the hydrogen interaction process during collisions and that, from a better understanding of wall materials, we may be able to design a more suitable surface for use at room temperature.

The advantages to be realized from low temperature operation (Vessot et al., 1977), even at 25K, are obvious if we look at equation 2, where the effects of thermal noise are considered. In addition, we should remember that the spin exchange cross-section for hydrogen-hydrogen collisions, σ_{se} , diminishes very drastically for temperatures below 100K (Allison, 1972). At 25K, it is at about 40 percent of its room temperature value; at 10K, it is about 10 percent. This makes it possible to increase the power level substantially.

From our understanding of the behavior of room temperature masers, we can extrapolate the expected performance at lower temperatures only if we can control the wall relaxation probability, p , in equation 2. Figure 9 shows the relationship of the frequency stability of the SAO VLG-series masers and the expected performance of the maser that operates at 25K. The projected stability for operation at 4K is also shown; however, we still have to demonstrate its operation.

In the near future, we expect to make frequency comparisons between two cold masers, each in its own cryostat, using low noise electronics equipment housed in a separate cryostat to see how well we can realize the expected performance.

Developments Toward Small Size Active and Passive Masers

Until recently, the size of the hydrogen maser has been chiefly dictated by the cavity resonator, which for the TE_{110} mode tuned at 1.42 GHz typically has inside dimensions 28 cm diameter and 28 cm length. Other cavity structures and modes have been studied (Mattison et al., 1975 and 1976) and tested, including dielectrically loaded structures and "magnetron" structures (Peters, 1978). While the impetus for smaller hydrogen masers mostly results from space applications, their use as portable devices can be foreseen.

The small size of the TE_{111} mode cavity made it possible to use a 7" I.D. dewar for the cryogenic maser experiments mentioned earlier. The cavity is shown in figure 10. A comparison of the size, weight, and power of the maser designed for the 1976 redshift experiment and a projected space-borne maser using the TE_{111} mode cavity is shown in figure 11.

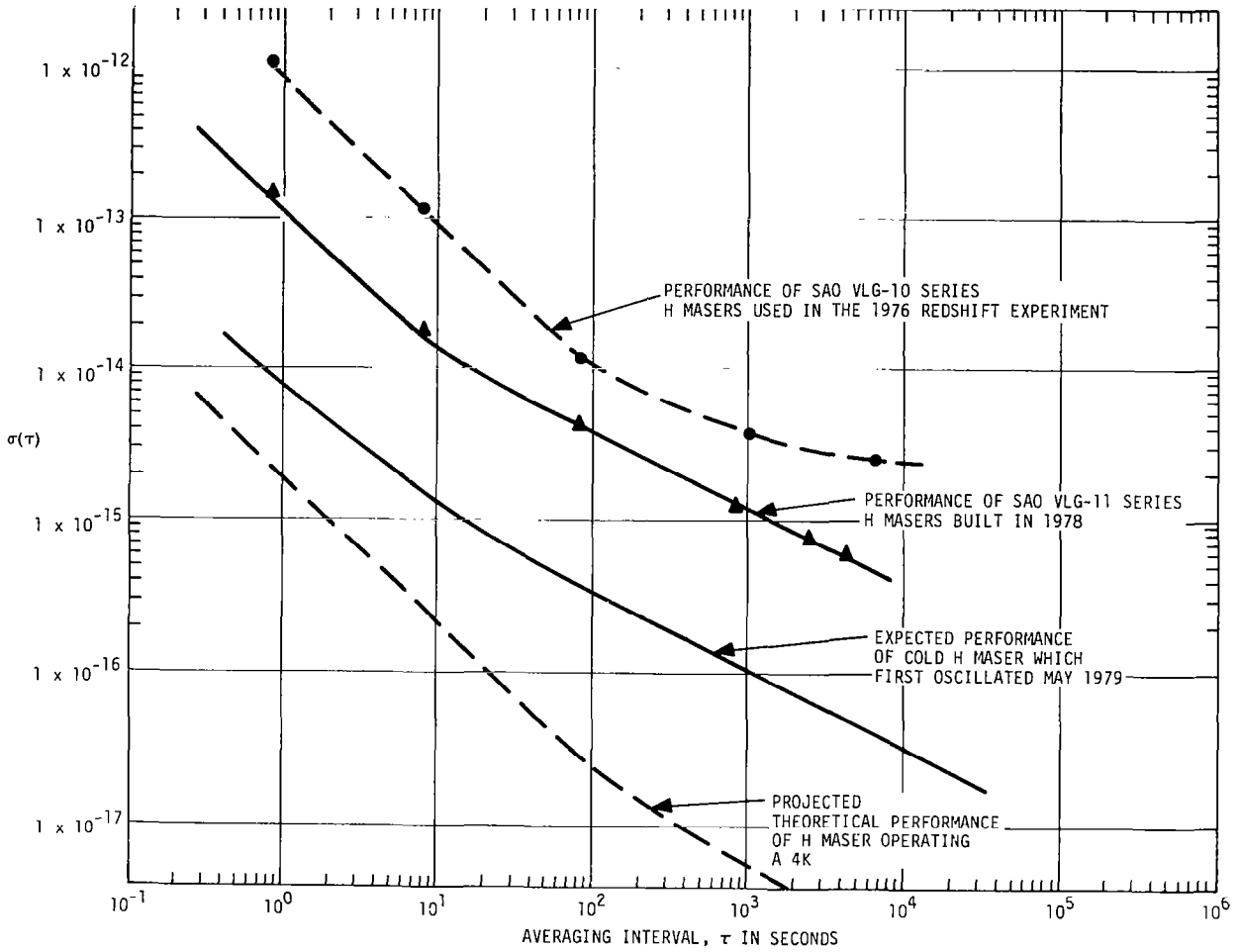


Figure 9. Projected performance of cold hydrogen masers. Lower solid line is predicted for operation at 30K. A maser was operated at 25K in May, 1979 [8].

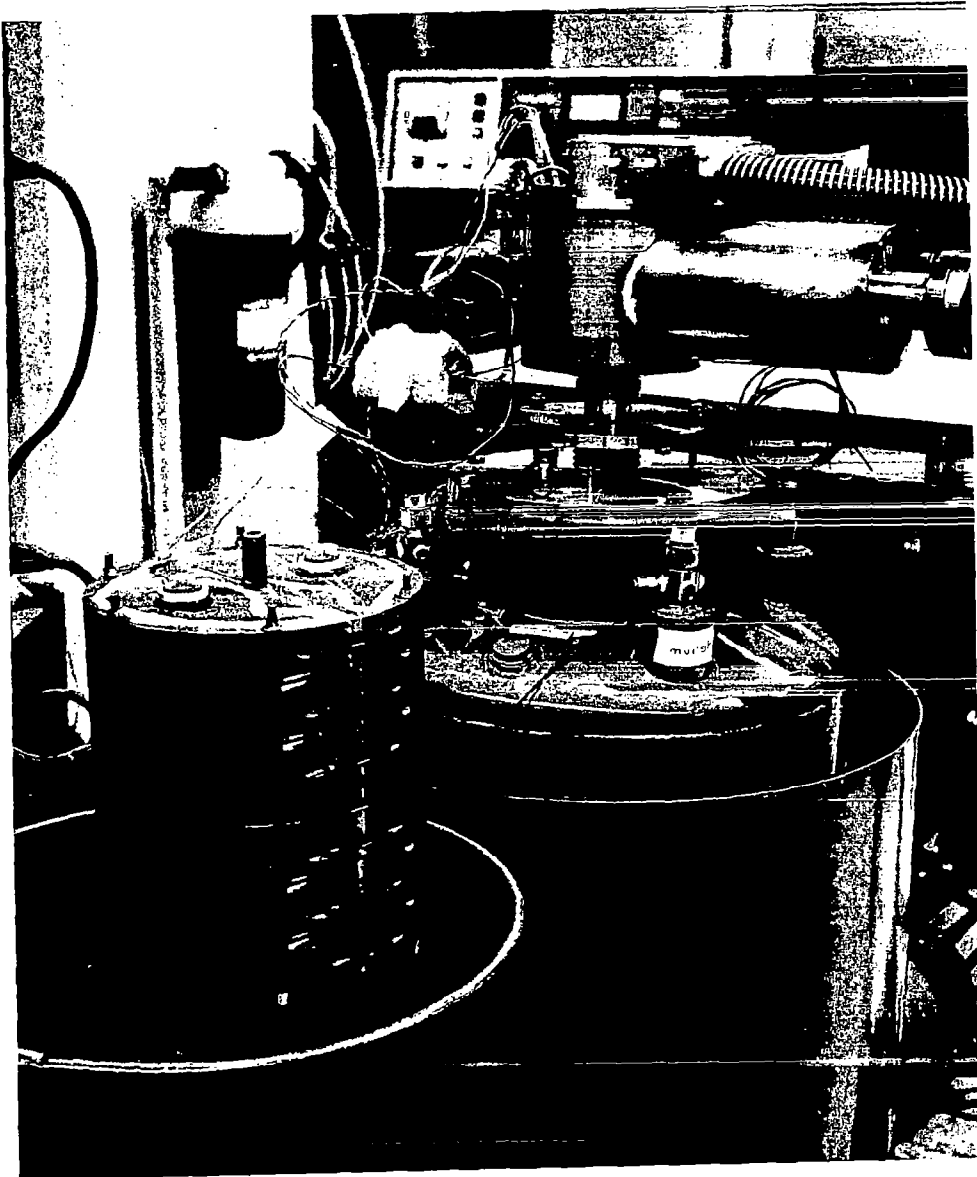


Figure 10. TE-111 mode cavity and cold hydrogen maser dewar system. Cavity is 7" diameter.

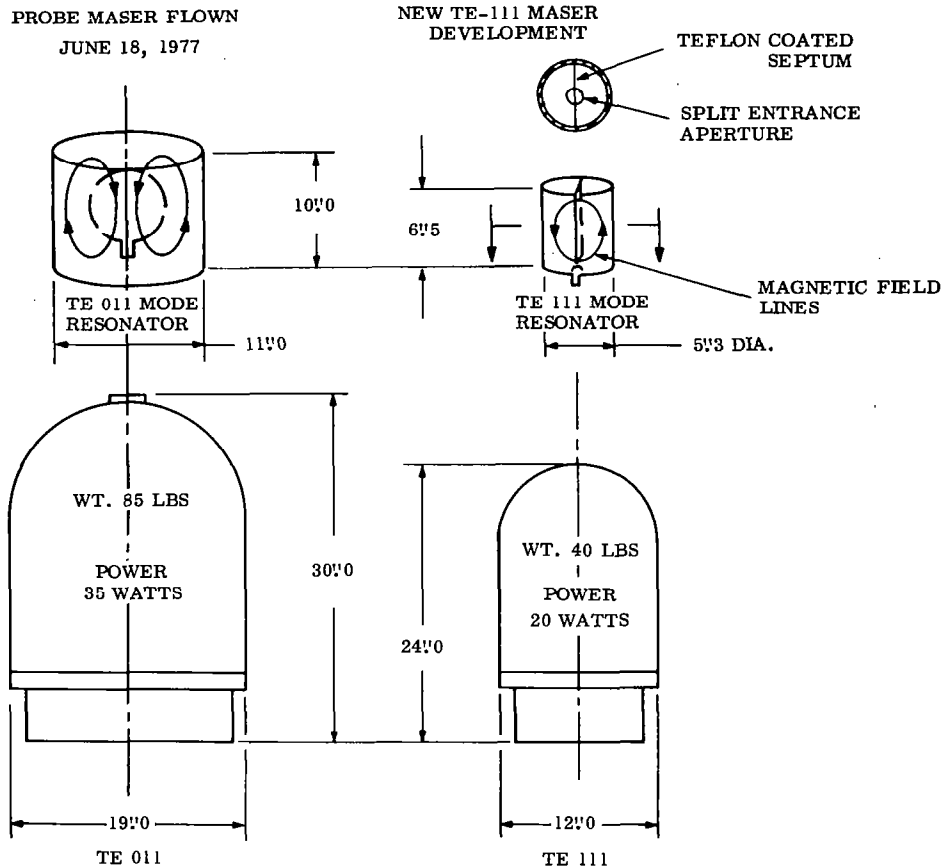


Figure 11. Comparison of size, weight and power of spaceborne masers using TE-111 cavity and masers used in 1976 spacecraft test of redshift [3].

Thus far, we have discussed the behavior of oscillating masers as ultra stable frequency sources. When operated below threshold, the hydrogen maser, operating as an amplifier, can be used to control the frequency of a flywheel oscillator. Since the cavity resonator no longer must have a Q high enough to maintain oscillation, one can use compact resonators with lower Q . One of these resonators is shown in figure 12. This is an experimental development model (Mattison et al., 1979) leading to a design for space-borne use in the Global Positioning System. The cavity resonator is made of a very thick walled cylinder of sapphire crystal silvered on the outside. The dielectric boundary between the inner region and the outer conductor is chosen to be at the position that optimizes the filling factor of the inner region, which is Teflon coated and serves as the storage volume. Storage times of 0.140 sec have been achieved.

Figure 13 shows the complete assembly, which comprises six zones of thermal control, five separate magnetic trimming coils, and a transverse "zeeman" coil (all-printed circuits), and four stages of magnetic shields.



Figure 12. Resonator assembly using thick-walled sapphire cavity-bulb combination for passive hydrogen maser. Vacuum chamber and inner oven are shown at right with four-layer magnetic shields and insulation.

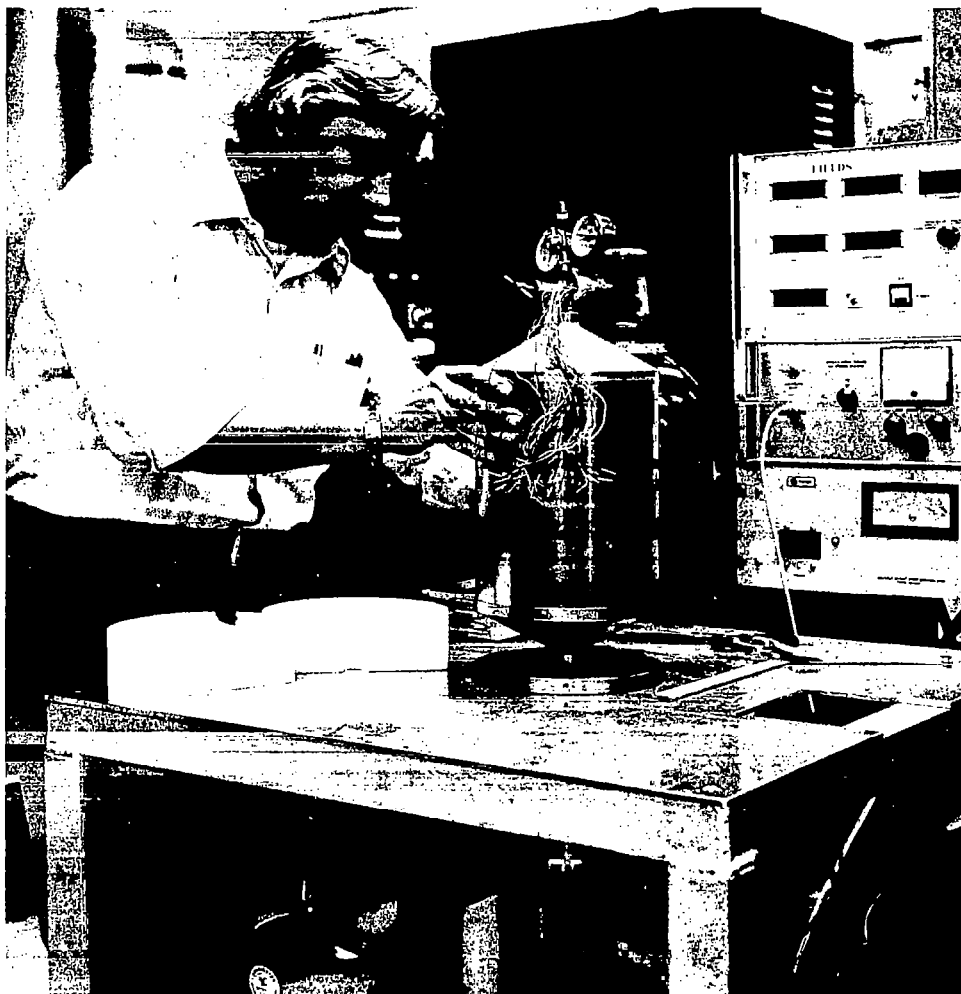


Figure 13. Passive maser cavity-bulb assembly on test stand showing magnetic shields with conical ends.

Even further reduction of size is possible with newly developed magnetron type of resonators which produce a large volume of in-phase rf field in which to store the atoms while occupying relatively little volume.

Conclusion

It has been 20 years since the maser was invented, and there has been fairly rapid growth in developments for making the maser a practical device. Stability data have steadily improved and now seem to be close to the limits imposed by the effects of thermal noise. Further work to understand the properties of the hydrogen atom as it collides with the storage surfaces is in progress and, in the

writer's opinion, there is still considerable improvement obtainable in the performance of atomic hydrogen masers as frequency standards.

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