THE CRYOGENIC HYDROGEN MASER: PROJECTED PERFORMANCE AND RECENT PROGRESS TOWARDS SPACEBORNE APPLICATIONS

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ABSTRACT

The possibility of significant improvement in the frequency stability of hydrogen masers by operation at cryogenic temperatures (< 1 K) is discussed. The results of the Harvard/SAO collaboration to build and operate a cryogenic hydrogen maser are summarized, and ongoing work to include space-qualified technology in the cryogenic system is described. Finally, a short list is given of scientific applications (on Earth and in space) of a cryogenic hydrogen maser of superior frequency stability.

1. INTRODUCTION

Currently, room temperature hydrogen masers can provide fractional frequency stability close to 10^{-16} for averaging intervals of about 10^4 seconds. Hydrogen maser operation at cryogenic temperatures (≈ 0.5 K) may bring this stability into the 10^{-18} region, as both thermal noise and the line-broadening effect of interatomic hydrogen collisions would be reduced by more than two orders of magnitude[1]. Phenomena exist, however, that may prevent a substantial improvement in frequency stability. In a cryogenic hydrogen maser (CHM) a liquid helium film replaces Teflon as the storage chamber wall coating; superior frequency stability will require proper control of the temperature dependent frequency shift associated with this helium wall. Also, recent quantum mechanically exact calculations[2] of hydrogen atom-atom collisions predict low temperature behavior that may mitigate any frequency stability improvement. The projected performance of cryogenic masers in general, and the Harvard/SAO (Smithsonian Astrophysical Observatory) CHM in particular, will be discussed in section 2, below.

Section 3 includes an overview of the design of the Harvard/SAO CHM, a summary of the results achieved to date with this system, and a discussion of ongoing work to incorporate space-qualified cryogenic technology with the CHM. The National Aeronautics and Space Administration has provided support for the construction of a compact ^{3}Helium refigerator for use with the Harvard/SAO CHM. Many of the cryogenic technical problems involved in this project have already been addressed by the recent NASA-sponsored development of a space-worthy recirculating ^{3}Helium refrigerator. If a CHM proves to be significantly more stable than a room temperature maser, then our system could easily be modified into a fully space-qualified CHM. Such a spaceborne clock would permit both improved and new tests of relativistic gravitation, and would be useful in space-based radio astronomy. Some of the possibilities for new science to be done with a CHM, in space as well as in the laboratory on Earth, will be presented in section 4.

2. PROJECTED PERFORMANCE OF A CHM

The two sources of noise that limit the performance of room temperature hydrogen masers, for averaging time intervals $< 10^4$ seconds, are the added white phase noise of the first stage of amplification of the maser signal (the "preamp"), and thermal noise within the atomic hydrogen's transition linewidth (causing a random walk in phase). The added white phase noise leads to a τ^{-1} dependence of the maser's Allan deviation[3] (or two-sample deviation) $\sigma_y(\tau)$, where τ is the averaging time interval; this effect typically is the dominant source of maser frequency instability for $\tau < 20$ to 100 seconds. The thermal noise within the atomic line gives a $\tau^{-1/2}$ dependence to $\sigma_y(\tau)$, and typically dominates observed maser performance for $\tau > 100$ seconds. For $\tau > 10^4$ seconds, systematic frequency variations usually dominate.

As is shown in Figure 1, the performance of room temperature H masers is optimum for averaging time intervals $\sim 10^3 - 10^4$ seconds, with $\sigma_y(\tau)$ reaching a minimum $\approx 5 \times 10^{-16}$. A maser optimized for operation ≈ 0.5 K could reach $\sigma_y(\tau) \approx 10^{-18}$ for similar averaging times, assuming that the added white phase noise of the preamp and the thermal noise within the atomic line remain the dominant sources of frequency instability. For both these noise sources the great gain in frequency stability comes from the reduction of the system's temperature (including the preamp noise temperature for the added white phase noise) by a factor of about 500, and the reduction of the line broadening effect of hydrogen-hydrogen collisions by nearly three orders of magnitude[1]. These results follow from an application of the system parameters for a typical room temperature (SAO) H maser, and for the Harvard/SAO CHM, to the expressions given in Figure 1 for the $\sigma_y(\tau)$ of the two aforementioned noise sources; straightforward derivations of the $\sigma_y(\tau)$ expressions can be found in references 4 and 5, for the thermal noise within the atomic line and the added white phase noise, respectively. The qualitative reasons that a CHM may exhibit such a significant improvement in frequency stability are: it should be possible to operate a CHM at much higher output power levels than a room temperature maser, with the same linewidth (i.e. line Q), due to the greatly reduced interatomic collisional broadening; in addition thermal noise effects are greatly reduced. Thus both the *signal* and the *noise* of a CHM should be improved over a room temperature maser, yielding a more stable frequency source.

Systematic effects will inevitably limit the frequency stability of a CHM, but at what level and from what sources? Many of the causes of systematic frequency drift in room temperature masers are related to slow, long-term changes ("creep") in the maser cavity materials, or to sensitivity to external influences such as local temperature and magnetic field. These effects may be greatly reduced in a CHM, as materials are in general much more stable mechanically and thermally at low temperatures, and since significantly improved magnetic shielding is possible at low temperatures with the use of superconducting materials. Thus it is reasonable that the conventional sources of systematic frequency drift may be reduced sufficiently in a CHM to allow substantial improvements in frequency stability to be realized. Nevertheless, there are two sources of frequency instability in a CHM that may limit such achievements. The first is the temperature dependence of the frequency shift due to hydrogen atom collisions with the liquid helium film that serves as the storage chamber wall coating in a CHM, and with the helium vapor associated with the film[1]. As shown in Figure 2, the frequency shift due to collisions with the helium wall is negative, and increases in magnitude as the temperature of the system is lowered (the hydrogen atoms remain on the wall longer during collisions, since they are moving slower). The frequency shift due to collisions with the helium gas in the storage chamber is also negative, but it increases in magnitude as the temperature is <u>raised</u> (as the vapor pressure of the helium rises). Thus a minimum in the magnitude of the H-He frequency shift occurs for T ~ 0.5 - 0.6 K; the exact temperature of the minimum depends on the geometry of the CHM, for the Harvard/SAO CHM it is 0.53 K. This minimum provides a point of operation where the frequency is insensitive to temperature deviations and fluctuations to first order. Nonetheless, temperature control and homogeneity at the level of 10 μK will be required to keep fractional frequency deviations $< 10^{-18}$. This level of temperature control can be achieved in cryogenic systems, but remains challenging, especially for a device of the physical size of a maser.

The second source of frequency instability that may be important in a CHM is the nature of the hydrogen-hydrogen collisions at low temperatures. In Figure 3 the effects of these collisions (normalized with respect to H density) are plotted against temperature, as determined by a complete, quantum mechanical calculation[2] of the problem (results that have been verified experimentally[1] are given by solid lines). As discussed above, the linewidth broadening effect of H-H collisions decreases by almost three orders of magnitude as the temperature is reduced from ~ 300 K to ~ 0.5 K. The H-H collisional frequency shift is compensated at room temperature by an appropriate tuning of the maser cavity; the result being that the maser frequency is effectively insensitive to variations in the input H flux, and to any variations in the linewidth (thus the maser performance is limited by the added white phase noise and the thermal noise within the atomic line). The calculation of the H-H collisional interaction reveals, however, that there is an additional component to the collisional frequency shift that cannot be compensated for in the manner just described. At the frequency stability level of a room temperature maser (~ 10^{-15}) this additional frequency shift effect is not observed, but as one attempts to reach stabilities of 10^{-17} to 10^{-18} (with a CHM) the effect becomes important. A determination of the veracity of this H-H interaction calculation, at low temperatures, is one of the major short-term goals of the Harvard/SAO CHM research effort.

3. THE HARVARD/SAO CHM

Figure 4 shows a cutaway, schematic view of the CHM built and operated by the Harvard/SAO collaboration[6]. The system was designed to be accomodated in a pre-existing dilution refrigerator facility (capable of reaching 0.005 K), in rough analogy with room temperature H maser designs. A room temperature microwave discharge outside of the refrigerator provides atomic hydrogen. The H beam is piped into the refrigerator and thermalized at ~ 10 K, where the desired atomic hydrogen states are focussed by a hexapole magnet into the H storage chamber, located inside a sapphire resonant cavity. A sapphire cavity is used in the CHM because of its smaller size for the same resonant frequency (due to the large dielectric constant of sapphire): the dilution refrigerator could not hold an object as large as a conventional room temperature maser cavity. Also, sapphire resonant cavities are mechanically stable and can have high Q's at low temperatures. The cavity frequency can be externally controlled over a range of ~ 1 MHz. A nested set of four magnetic shields, currently made out of a conventional high permeability alloy, surrounds the isothermal vacuum vessel housing the resonant cavity. There are longitudinal solenoids around the beam tube (between the hexapole magnet and the cavity) and the cavity to provide a static magnetic field (~ 1 mG in the H storage chamber). Also, transverse rf fields can be applied to the H storage chamber region and to the beam tube region, for determination of the static magnetic field strength and for the mixing of the Zeeman levels. Liquid helium flows continuously into the CHM; at temperatures < 1 K it forms a superfluid film that uniformly coats all surfaces, including the walls of the H storage chamber. The helium flows down towards the warmer regions of the CHM, evaporates, and is differentially pumped by a large sorption pump (this also pumps away the "spent" hydrogen leaving the resonant cavity). The lifetime of the sorption pump in the current design is about 3 weeks.

The Harvard/SAO CHM was first oscillated in 1986[6], one of three CHM's operated, independently, for the first time that year[7,8]. Measurements were made of the H-He frequency shift and the line Q, as a function of temperature, for thin liquid helium film wall coatings, and much was learned of the limitations of the cryogenic design. The system was operated again in 1988, after modifications. It was learned that it is important to have a relatively thick and benign wall coating (e.g. 20 μm of teflon) between the sapphire and the liquid helium film (thickness < 0.02 μm) to prevent sapphire paramagnetic sites from rapidly flipping the H atom spins (thereby severely broadening the atomic line and preventing oscillation).

Limited access to the dilution refrigerator for which the Harvard/SAO CHM was first built has led us to begin a program to design and construct a closed cycle ^{3}Helium refrigerator dedicated to housing the CHM. In addition, it was decided to use space-worthy cryogenic technology in the new refrigerator, when feasible, with an eye towards the long-term goal of operating a CHM of superior frequency stability in space. This effort has broadened our collaboration to include Alabama Cryogenic Engineering (ACE), Inc., experts in space-worthy cryogenic technology. Specifically, the new ^{3}Helium refrigerator may include the following elements (see Figure 5): a lightweight, compact, sealed ^{3}Helium pump that can operate in any orientation relative to the Earth's gravitational field; and a ^{3}Helium evaporation chamber containing a porous silver sinter plug to act as a "sponge" to hold the liquid ^{3}Helium in place in weightless conditions. In the recent past, ACE has developed functioning cryogenic systems employing these technologies. The new ^{3}Helium refrigerator is expected to be working by the end of next summer, at which point the CHM will be installed and operated. We hope to make frequency stability measurements of the CHM soon thereafter, using a "three-cornered hat" method to simultaneously intercompare the CHM with two room temperature SAO masers.

4. SCIENTIFIC USES OF A CHM

A spaceborne clock of superior frequency stability (such as may be provided by a CHM) could be employed in the improvement of several scientific tests of relativity, in the important effort to detect long wavelength gravitational radiation, and as a component in a space-based radio astronomy observatory. The verification of the gravitational redshift (a consequence of the Weak Equivalence Principle of relativity) could be improved by more than an order of magnitude with a clock in an eccentric Earth orbit, and by nearly five orders of magnitude with a clock sent over a pole of the Sun[9]. Also, a space-based clock would allow a test of the isotropy of the speed of light at a level approaching one part in a trillion[9]; the best Earth-based tests are at the level of 100 parts in a trillion[10]. The largest amplitude gravitational waves are believed to be generated by rare, large-scale cataclysmic events, and to have long wavelengths (> 10^8 km) and hence long periods (> 1000 seconds)[11]. Detection of this long wavelength gravitational radiation would require a network of clocks of superior frequency stability located in deep space (over a range > one wavelength ~ 10^8 km)[9]. A radio astronomy observatory in space would employ VLBI (Very Long Baseline Interferometry) techniques, and the associated synchronization of distant radio antennas. Improved, space-based clocks would allow greater measurement sensitivity by permitting an increased observation baseline to be used, and would eliminate the problem of tropospheric noise that would arise with the use of ground-based clocks[12].

Prior to any use in space, a great deal of atomic and low temperature physics may be done with the CHM on Earth. As discussed above, the various hydrogen-helium and hydrogen-hydrogen interactions need to be studied, both to understand the details of the low energy atomic physics involved (entering the "quantum mechanical regime" of slow moving atoms), and to determine the practical feasibility of the CHM as a clock. In addition, the CHM could be used to study interesting "collective phenomena" such as: spin (or magnetization) waves that can propogate in a low temperature (< 1 K) atomic hydrogen gas a quantum mechanical effect[13]; and "chaos" in the CHM's output signal amplitude for high maser cavity Q's (> 300,000), a result of the nonlinearity of the equations of motion (the "Maxwell-Bloch" equations) governing the maser's radiative transitions[14]. Finally, the CHM could be exploited as an effective two-level oscillator of great frequency stability to make an improved test of the linear superposition of quantum mechanics. A failure of the linear superposition principle would result in a dependence of the H maser output frequency on the relative population of the two masing states (energy levels)[15]. Recent measurements with room temperature H masers set "state-of-the-art" limits on this effect[16]. The measurements are limited by the maser frequency stability; thus a CHM of superior frequency stability would allow an improved test to be performed.

5. CONCLUSION

In this paper the possibility of significantly improving H maser frequency stability by operation at temperatures ≈ 0.5 K has been examined, and the Harvard/SAO cryogenic H maser (CHM) research program has been reviewed. It was found that the noise sources that limit room temperature H maser stability for $\tau < 10^4$ seconds are greatly reduced at low temperature, such that an Allan deviation approaching 10^{-18} can become feasible. Nevertheless, new sources of frequency deviation may emerge at low temperature (involving the hydrogen-helium and hydrogen-hydrogen collisional frequency shifts) to mitigate any stability improvement. The determination of the nature and importance of these effects is one of the main short-term goals of the Harvard/SAO effort, described above. In addition, a discussion was given of recent progress to include space-worthy cryogenic technology in the Harvard/SAO CHM, and the science that could be performed (in space and on Earth) with a CHM of superior frequency stability.

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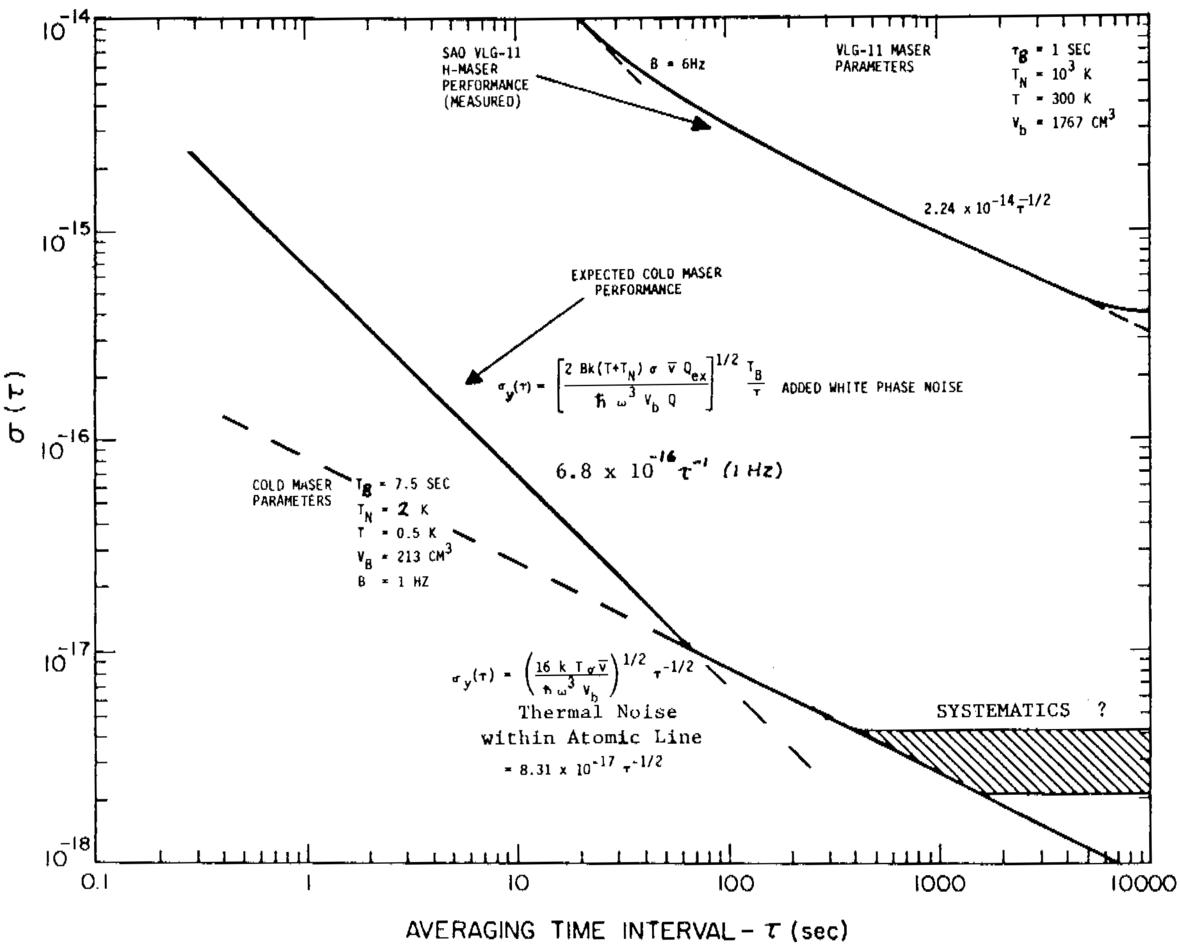
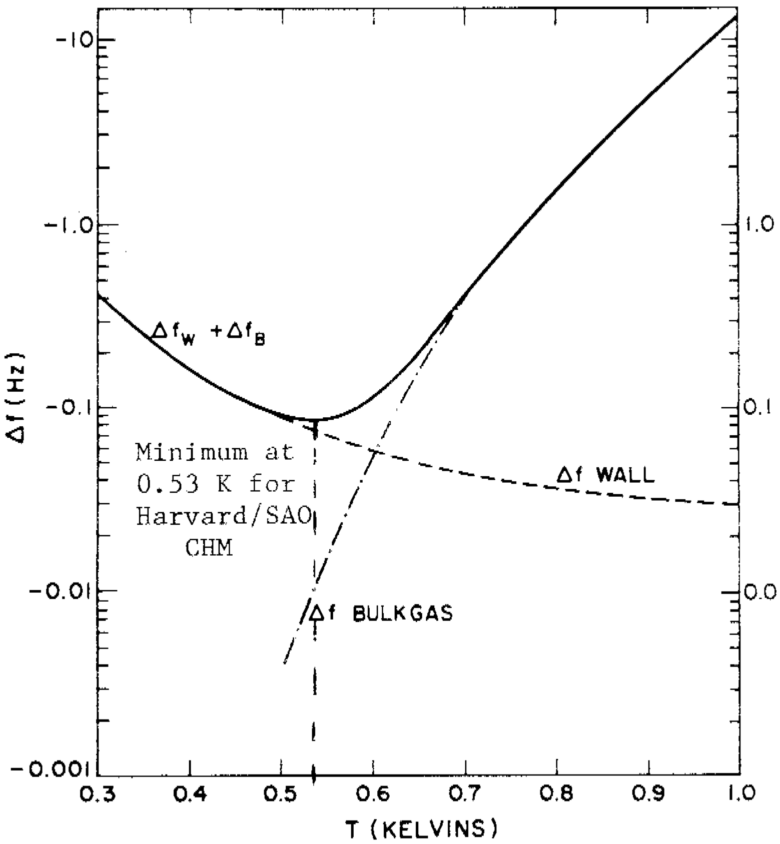


Figure 1. Comparison of Frequency Stability of Room Temperature H Maser (Measured) and Cryogenic H Maser (Projected)

Figure 2
Frequency Shifts due to
Hydrogen-Helium Collisions



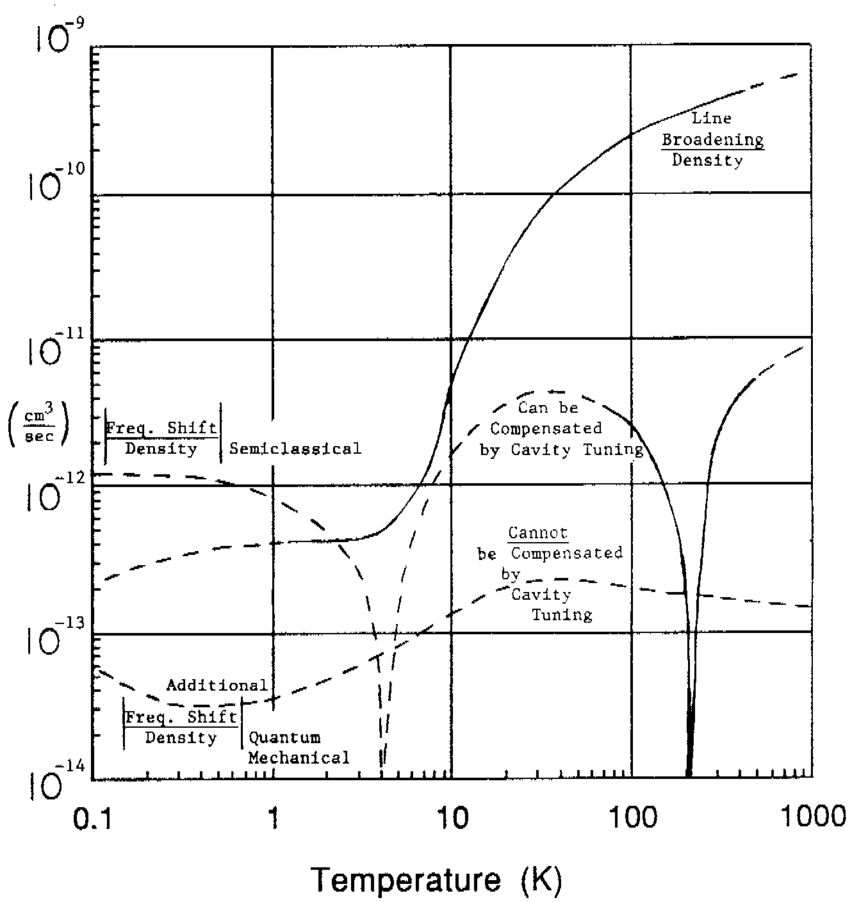


Figure 3
Linewidth Broadening and
Frequency Shifts due to
H-H Collisions

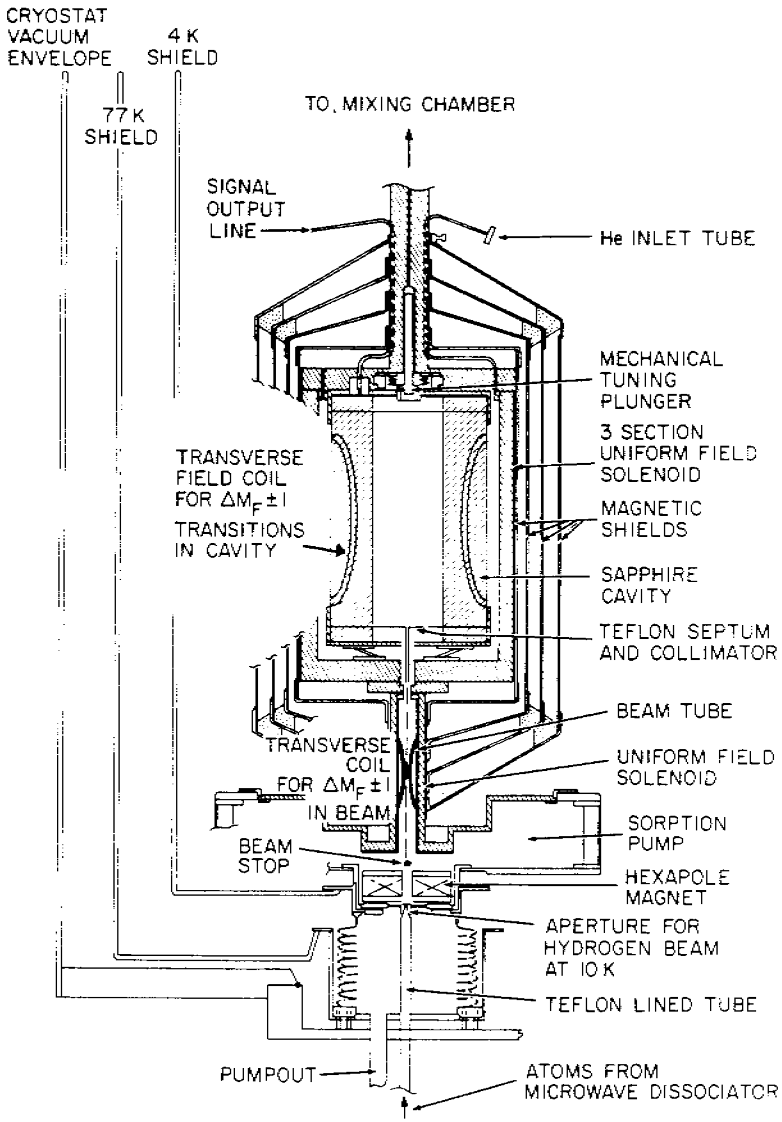


Figure 4.
Cutaway schematic view of Harvard/SAO CHM (as configured in dilution refrig.)

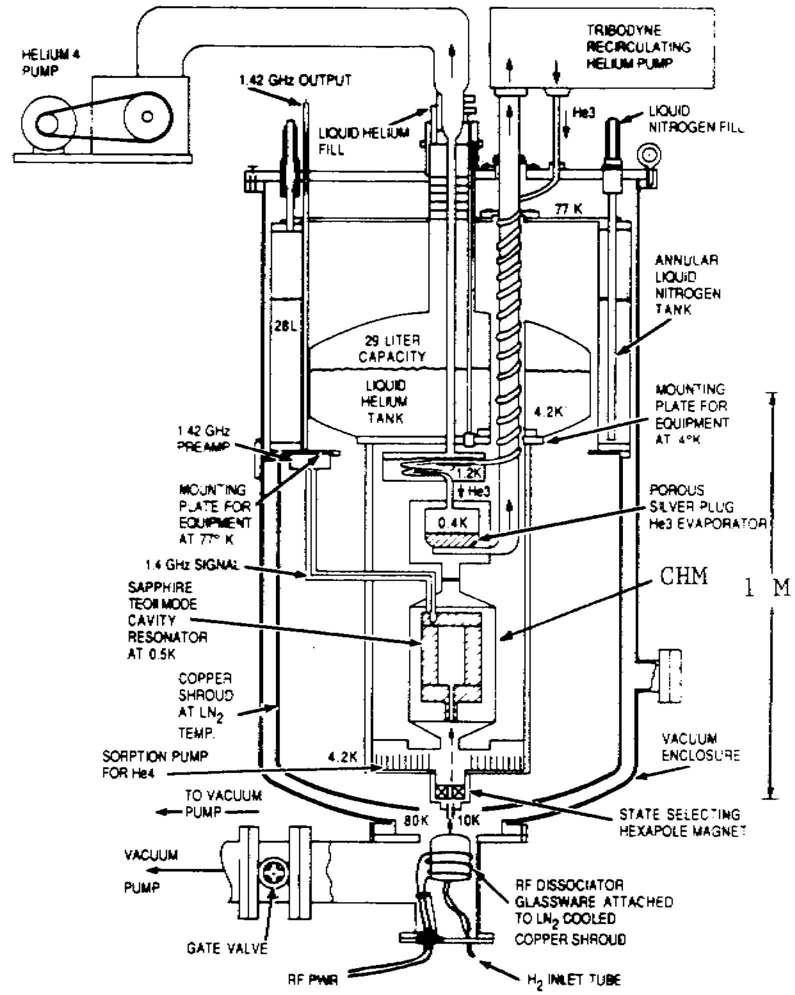


Figure 5.
Cutaway schematic view of CHM installed in new 3Helium refrigerator

QUESTIONS AND ANSWERS

CARROLL ALLEY, U OF MARYLAND: There are some here who are interested in quantum mechanics. Could you elaborate a little more on the planned studies.

MR. WALSWORTH: I have been performing experiments this fall with the room temperature masers, testing the linearity of quantum mechanics. This is a relatively new thing that was started y Steven Weinberg, about a year ago, doing some theoretical analysis, looking into whether or not one could develop a quantum mechanics that was not necessarily linear. One could generalize quantum mechanics and generalize the linearity that was involved in the superposition principle. He found in the detailed analysis, looking at the group algebra and other things, that he could, in a general way, for the internal degrees of freedom, the spin degrees of freedom, generalize the superposition principle by letting go of the distributive property in the superposition principle and holding on to the homogeneity properties. The result of this, experimentally, is that this predicts a output frequency of a spin system depends on their state distribution. This is opposed to an NMR or hydrogen maser or other spin system where the output frequency, the transition between two levels, does not depend on the distribution of the ensemble between these two levels, the tipping angle if you will, this theory predicts that the output frequency will depend on this distribution, much like a pendulum, a simple harmonic harmonic motion, the period of the pendulum is independent of the angle swung by the pendulum, non–linear terms in the equation of motion cause the period to depend on the angle. Quantum mechanics has been assumed since the 20's and 30's to be linear, but you might as well test it to see how well verify that, and maybe discover some new and interesting physics. Dave Weinland's group at NIST has made some very good measurements in nucleus spin systems and we are trying to do one in atomic spin systems with room temperature masers. Cryogenic masers would allow us to make a much better test because we are limited in the accuracy that we can measure frequency by the short term frequency stability right now.

JOHN DICK, JPL: I wonder if you could talk a little bit about the temperature coefficient, considering that this is a long term frequency standard. About 10^{-8} per $°C^2$ looks a little worrisome and I wonder if you could also say a little about the gradient due to the hydrogen flow.

MR. WALSWORTH: That is the temperature shift of the Helium? Some straightforward calculations that were done back in 1982 by Walter Hardy at the University of British Columbia, who is also working on cryogenic hydrogen masers, showed that for the typical curvature that you need something like 10 μK temperature control. I don't know if that corresponds to the number that you just quoted, but if it is true, it is not easy, but it is not impossible in this temperature regime. As far as the gradients of the hydrogen, the heating effect of the hydrogen as opposed to the helium, the helium is the major effect and I don't think there will be big gradients due to the hydrogen. The sapphire dielectric in our system is surrounded by copper shims outside the silver coating. This helps thermalize the sapphire.