RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 34, NUMBER 3 SEPTEMBER 1986

Hydrogen maser at temperatures below 1 K

Ronald L. Walsworth, Jr., Isaac F. Silvera, H. P. Godfried,* and C. C. Agosta
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

Robert F. C. Vessot and Edward M. Mattison
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
(Received 30 May 1986)

We describe the design and operation of a cryogenic hydrogen maser for use at temperatures below 1 K. The maser incorporates a cooled atomic hydrogen beam and cylindrical dielectrically loaded resonant cavity with liquid-He-covered walls to prevent hydrogen recombination and dephasing of the atoms' oscillating dipole moment upon wall collisions. We have observed maser oscillation from approximately 350 to 575 mK at power levels up to 5×10^{-13} W, and have measured the maser's line Q and frequency as a function of temperature and helium-film thickness.

We have designed, built, and demonstrated operation of a cryogenic hydrogen maser (CHM) operating in the temperature range of 350–600 mK. Our maser design is similar to that of a conventional room-temperature maser,[1] except that the atomic hydrogen beam is cooled to low temperature, and the resonator consists of a dielectically loaded cylindrical cavity made of sapphire.[2] A novel feature is a continuously flowing superfluid helium film that covers the maser storage volume walls to prevent recombination of the hydrogen atoms and to preserve the phase of their oscillating dipole moment. This film is eventually adsorbed by a large sorption pump operating at 6 K. The CHM has been predicted by Hardy and co-workers,[3,4] to have frequency stabilities in the range 10^{-18} for averaging times of about 10^3 s; moreover, the reproducibility of the helium film should yield a reproducible wall shift so that this barrier to the use of the H maser as a primary time standard could be removed. Although room-temperature H masers have been operated[5] with stabilities of a few parts in 10^{16}, their accuracy is limited to several parts in 10^{13} by the irreproducible wall shift of Teflon surfaces. Preliminary performance results of our maser, which has been designed to yield the high predicted stability, are reported here.

A cryogenic H maser operating with H_2 or He surfaces was first proposed by Crampton, Phillips, and Kleppner[6] in 1978 before a low-temperature gas of hydrogen could be produced. A few years later Silvera and Walraven[7] succeeded in stabilizing atomic hydrogen at low temperatures with helium-covered walls in high and zero magnetic field. Morrow, Jochemsen, Berlinsky, and Hardy[8] observed very long lifetimes when they studied the zero-field wall and pressure shifts of the hydrogen hyperfine transition frequency on helium surfaces, using resonance techniques. The wall shift and pressure shift are both negative, reducing the transition frequency, in the sub-Kelvin range. They also found that the combined wall and pressure shift, which affects the maser frequency, has a minimum in its absolute value at around 0.5 K so that operation in this temperature region should produce great stability with regard to thermal fluctuations. Vessot, Levine, and Mattison[9] discussed the advantages of low-temperature operation of the H maser. Berlinsky and Hardy[3] showed that an increase in frequency stability by a factor of order 10^3 over room-temperature masers could be gained by operating below 1 K, due principally to the large reduction in the spin exchange cross section at low temperature. Masers with CF_4-coated storage surfaces[10] and Ne surfaces[11] have been operated below room temperature, but these do not appear to have the promise of the sub-Kelvin H maser. Recently, Hess *et al.*[12] and Hurlimann *et al.*[13] have demonstrated operation of H masers at sub-Kelvin temperatures using different approaches than the one described here.

In the H maser, maser oscillation results from radiative transitions between the c and a hyperfine states. [The states in order of increasing energy are designated a and b ($m_s=-\frac{1}{2}$, $m_i=\frac{1}{2}$, and $-\frac{1}{2}$, respectively) and c and d ($m_s=\frac{1}{2}$, $m_i=-\frac{1}{2}$, and $\frac{1}{2}$, respectively). The b, c, and d states are degenerate in zero magnetic field.] The basic requirement for maser oscillation is to continuously fill a region of a resonator, in our case the center region of a cylindrical TE_{011} mode microwave cavity, with an inverted population of the c hyperfine state. Our maser is shown in Fig. 1. Atomic hydrogen in all four hyperfine states flows out of a room-temperature microwave discharge into the cryostat through a Teflon-lined tube and is thermalized by a 3-mm-diam source aperture at 10 K, as described by Walraven and Silvera.[14] The cold beam then enters a 1.3-cm-long hexapole magnet that focuses atoms in the c and d hyperfine states into the aperture of the cylindrical dielectrically loaded microwave cavity. An axial beam stop at the exit of the hexapole magnet prevents undeflected atoms from entering the cavity. The cavity is mounted in good thermal contact within a large copper isothermal chamber that is suspended from the mixing chamber of a dilution refrigerator and can be cooled down to about 300 mK. In order to attenuate the earth's magnetic field and achieve high frequency stability the cavity is surrounded by four nested shields made of Cryoperm, a material with high magnetic susceptibility at low temperatures. These shields operate at 4.2 K and are thermally isolated from the cavity. A uniform axial magnetic field of a few milligauss is produced in the storage volume by a solenoid made up of three separately energized coils. The solenoid is located outside the copper cylinder and within the inner-

 © 1986 The American Physical Society

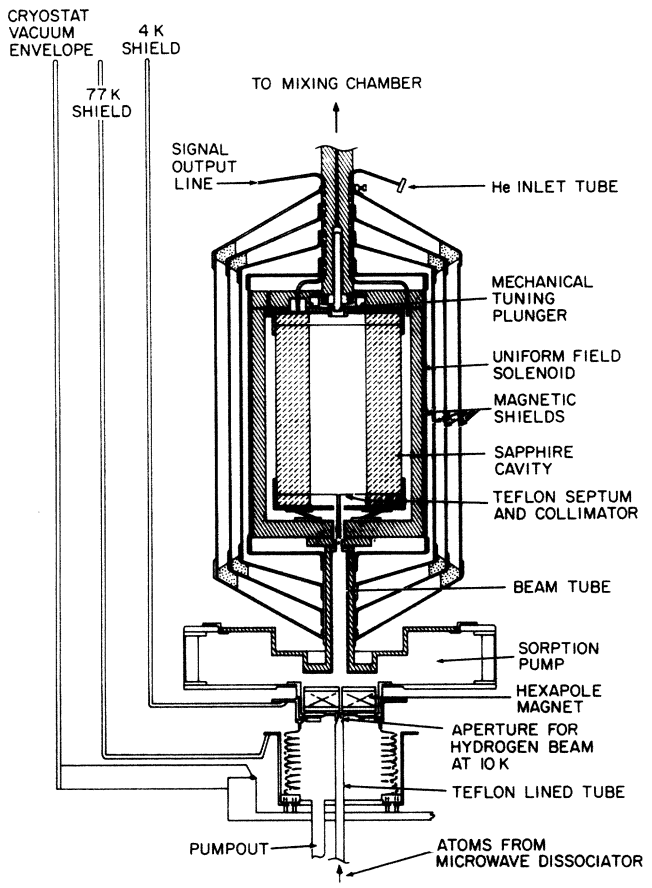

FIG. 1. Cross-sectional view of the cryogenic hydrogen mazer.

most magnetic shield. A two-loop transverse coil (not shown) is attached to the wall of the microwave cavity. It is used to measure the cavity field by inducing audio frequency c-d and c-b transitions that are detected by quenching of the maser oscillation. Another coil, mounted outside the beam tube between the hexapole and the cavity aperture, provides a small static "holding field" to prevent depolarization of the state-selected beam due to Majorana transitions.

The resonant cavity consists of three pieces of c-cut single crystal sapphire. The central cylindrical section has an axial hole through its length that forms the hydrogen storage volume. The cylinder is capped by two annular sapphire disks. The interior of the cylinder is coated with Teflon for tests at higher temperatures, and the disks are separated from the cylinder by Teflon septa. The cavity's electrically conducting surfaces are cup-shaped copper plates at the top and bottom, and thin copper shim stock tightly wrapped around the cylinder. A Teflon tube (4-mm i.d., and 27 mm long) passes through the lower septum to admit hydrogen atoms into the storage volume. By confining the atoms to a region where the microwave field is uniform, rather than allowing them to occupy the ends of the cavity, the septa improve the filling factor. The dimensions of the Teflon tube determine the storage time of the atoms in the cavity, which is calculated to be 7.5 s at 0.5 K. The cavity frequency can be mechanically tuned over a 600-kHz range with a cylindrical plunger that is externally operated. This allows us both to tune the cavity to resonance and to measure the atomic linewidth, or line Q, by detuning the cavity from resonance and measuring the ensuing maser frequency shift. The cavity is weakly coupled to a 50-Ω output coaxial cable by a pick-up loop near the end of the cavity. The cavity Q is about 20000 at room temperature, increasing to 65000 at low temperature. Due to the temperature dependence of the sapphire's dielectric coefficient, the cavity frequeny increases by about 12 MHz in cooling from room temperature to 0.5 K. Preliminary measurements enabled us to size the sapphire so that at about 0.5 K the cavity frequency can be tuned to the H-maser transition frequency of 1 420 405 751 Hz.

In order to prevent recombination of hydrogen at sub-Kelvin temperatures, all surfaces must be covered by a film of liquid helium.[7] Since the ^{4}He is superfluid at the CHM operating temperatures, it flows to cover all surfaces, but in particular it is driven to warmer regions. Helium from a room-temperature source of variable pressure is introduced into the cavity via a capillary tube. Without proper measures the liquid helium would flow out of the cavity aperture and up the outer walls to warmer regions where it would vaporize, destroy the vacuum, and warm the dilution refrigerator to high temperatures. We have built a giant sorption pump between the beam tube and the hexapole magnet. The pump chamber is filled with activated charcoal that is thermally linked to the pump's bottom plate at 6 K. The top plate operates at the maser temperature and is thermally isolated from the bottom plate by a 25-μm-thick Kapton wall. The two plates are structurally strengthened by six tubes of G-10 fiberglass-reinforced epoxy. The helium film vaporizes at the Kapton walls and, due to baffles, the vapor is cryopumped before diffusing back to the central region, where it would attenuate the hydrogen beam.

At higher temperatures, of order 550 mK, the vapor pressure of a saturated film of He is high enough that it ordinarily would attenuate the beam in the beam tube region, reducing the population of c-state atoms below the threshold for oscillation. To prevent this we have built a novel "dynamic" He pump. Since the vapor pressure of very thin films of He is substantially lower than the saturated value, we have placed a large number of concentric sheets of copper foil in the beam tube area so that the helium film that flows out of the cavity aperture is subdivided into a large number of thin undersaturated films with a low vapor pressure that flows in parallel along the sheets. In addition, the cryopumping copper surfaces also adsorb helium that flows out of the aperture in the vapor phase. Our current tests of the performance of the dynamic pump are inconclusive.

We have observed maser oscillation of our CHM from approximately 350–575 mK at power levels up to 5×10^{-13} W. Due to technical cryogenic problems[15] we were unable to make measurements for periods longer than about three hours; more important, we were limited to helium flow rates that we estimate are lower than those required to achieve saturated films. (We assume the film thickness to be essentially proportional to flow rate until the film is saturated.) As a consequence, in this article we concentrate on the relationship between film thickness and

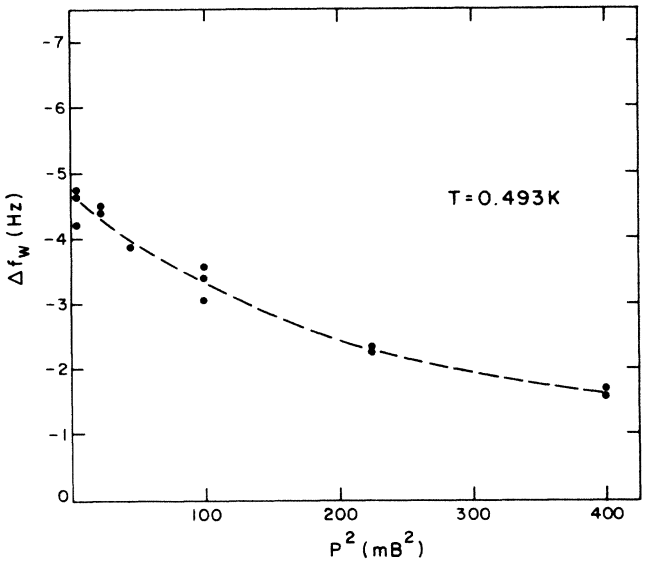

FIG. 2. Plot of the wall shift vs driving pressure of the He film.

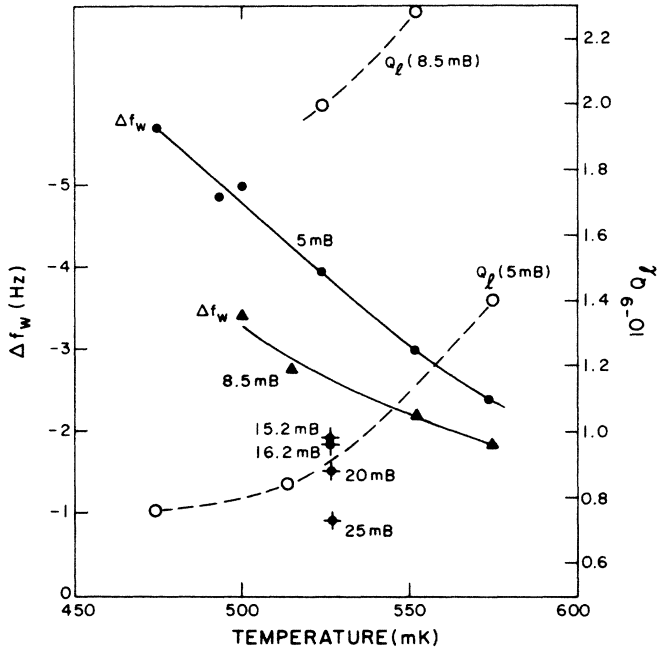

FIG. 3. The wall shift and line Q as a function of temperature for several values of driving pressure of the He film. Wall shift data as a function of pressure at 525 mK are also shown.

both the maser frequency (i.e., the wall shift) and the linewidth or line Q, which is important for the frequency stability of the maser.

The flow rate is determined by the pressure p in a room-temperature helium reservoir. Since the flow should be proportional to p^2, so should the film thickness. In Fig. 2 we show the wall shift Δf_w (that is, the shift of the maser frequency from the value it would have for free atoms in the absence of walls) as a function of p^2 at a constant temperature of 0.493 K. At this temperature the wall shift for saturated surfaces is expected to be on the order of 0.1 Hz.[8] At very small values of flow the wall shift is substantial and decreases toward the saturated value as flow or film thickness increases. This is reasonable, as for thinner films the hydrogen atoms see a more polarizable substrate[16] and we would expect the hyperfine frequency to decrease. Figure 3 shows the wall shift as a function of temperature for fixed He flow rates. For a saturated film this curve is expected to be bowl shaped, the shift decreasing as temperature increases to about 0.6 K and then increasing at higher temperatures due to the pressure shift. Our data, which are for $T < 0.6$ K, are consistent with this behavior. In Fig. 3 we also show the line Q, $Q_l = \omega/2\gamma$, as a function of temperature for fixed He flow rates. Here ω is the frequency and γ is the total rate of phase loss due to atom escape from the cavity, wall collisions, spin exchange, magnetic field gradients, radiation damping, and other effects. If the line Q is limited only by the cavity escape time (7.5 s), then $Q_l = 3\times10^{10}$. We see that the measured values of Q_l are much smaller than the calculated value, but increase rapidly with temperature and, more important, with He-film thickness. In order to characterize the CHM as an oscillator of extreme frequency stability, it will be necessary to extend these measurements to saturated values of the helium film.

We would like to thank Pierre Crevoiserat for his expert craftsmanship in constructing the maser. This research was supported by a Scholarly Studies Program grant from the Smithsonian Institution, and a Department of Energy Grant No. DE-FG02-85ER45190. One of us (H.P.G.) acknowledges partial support from IBM.

*Present address: Ultra-Centrifuge Nederlands, Almelo, The Netherlands.

[1]D. H. Kleppner, M. Goldenberg, and N. F. Ramsey, Phys. Rev. **126**, 603 (1982).

[2]V. J. Folen, W. G. Maisch, J. D. White, C. A. Bartholomew, and A. H. Frank, U.S. Naval Research Laboratory Memorandum Report No. 4870, Washington, DC, 1982 (unpublished).

[3]A. J. Berlinsky and W. N. Hardy, in Proceedings of the Thirteenth Annual Precise Time and Time Interval Planning Meeting, 1982 (unpublished), p. 547.

[4]W. N. Hardy and M. Morrow, J. Phys. (Paris) Colloq. **42**, C8-171 (1981).

[5]R. F. C. Vessot, E. M. Mattison, E. A. Imbier, and Z. C. Zhai, in Proceedings of the Sixteenth Annual Precise Time and Time Interval Planning Meeting, 1984 (unpublished), p. 375.

[6]S. B. Crampton, W. D. Phillips, and D. Kleppner, Bull. Am. Phys. Soc. **23**, 86 (1978).

[7]I. F. Silvera and J. T. M. Walraven, Phys. Rev. Lett. **44**, 164 (1980).

[8]M. Morrow, R. Jochemsen, A. J. Berlinsky, and W. N. Hardy, Phys. Rev. Lett. **46**, 195 (1981); **47**, 455(E) (1981).

[9]R. F. C. Vessot, M. W. Levine, and E. M. Mattison, in Proceedings of the Ninth Annual Precise Time and Time Interval Planning Meeting, 1977 (unpublished), p. 549.

[10]R. F. C. Vessot, E. M. Mattison, and Z. C. Zhai, in Proceedings of the Sixteenth Annual Precise Time and Time Interval Planning Meeting, 1984 (unpublished), p. 357.

[11]S. B. Crampton, K. M. Jones, G. Nunes, and S. P. Souza, in Proceedings of the Sixteenth Annual Precise Time and Time Interval Planning Meeting, 1984 (unpublished), p. 339.

[12]H. F. Hess, G. P. Kochanski, J. M. Doyle, T. J. Greytak, and D. Kleppner (unpublished).

[13] M. D. Hurlimann, W. N. Hardy, A. J. Berlinsky, and R. W. Cline (unpublished).

[14]J. T. M. Walraven and I. F. Silvera, Rev. Sci. Instrum. **53**, 1167 (1982).

[15]A small He leak in the cryostat restricted the measurement period to about 150 min. During flow of the He film, heating increased because of another possible leak or more subtle complication, so that we were confined to low flow rates.

[16]H. Godfried, E. Eliel, J. Brisson, J. Gillaspy, C. Mallardeau, and I. F. Silvera, Phys. Rev. Lett. **55**, 1311 (1985).