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# Recirculating cryogenic hydrogen maser

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We report on the design and initial testing of a new type of hydrogen maser, operated at dilution refrigerator temperatures, in which H atoms circulate back and forth between a microwave-pumped state selector and the maser cavity. Other novel design features include liquid-$^4$He-coated walls, He-cooled electronics, and the use of microscopic magnetic particles to relax the two lowest hyperfine levels in the state selector. Stabilities at least as good as that of a Rb clock and a high-stability quartz oscillator are observed for measuring times between 1 and 300 s.

In this paper we report on the construction and preliminary evaluation of a new type of hydrogen maser, in which H atoms circulate back and forth between a microwave-pumped state selector and a 1420-MHz maser cavity at a temperature of 0.5 K. The technology which was used to design this maser is derived from our earlier low-temperature studies of H atoms in zero magnetic field[1] and of spin-polarized H in high field.[2] We have predicted[3] that masers of this type should eventually lead to a 1000-fold improvement in the state of the art in frequency stability. The results reported here represent an important step toward the achievement of that goal.

The conventional atomic hydrogen maser[4] is still the most stable of all frequency standards for intermediate and long measuring times ($1\ \mathrm{s} \lesssim \tau \lesssim 10^6\ \mathrm{s}$),[5] and thus hydrogen masers are a natural choice for use in terrestial and interplanetary navigation, for very-long-baseline interferometry, and for tests of general relativity. Such applications make full use of the extremely high stability of present masers ($\Delta f/f \lesssim 10^{-15}$, $\tau \approx 1$ h) and provide an incentive for research to invent new, more stable oscillators. Eight years ago, Crampton, Phillips, and Kleppner[6] suggested that a cryogenic hydrogen maser (CHM) might show improved stability because of the much smaller spin-exchange broadening at low $T$. Cryogenic hydrogen masers were also discussed by Vessot, Levine, and Mattison,[5] and in 1982 two of the present authors[3] published a detailed theoretical analysis of the potential frequency stability of a CHM with liquid-$^4$He-coated walls operating at a temperature near 0.5 K. Experimental progress toward this goal has been slow. In 1984 Crampton, Jones, Nunes, and Souza[7] reported operation of a solid-Ne-coated maser at 10 K. The first observations of maser action with liquid-$^4$He-coated walls are presented here and in the accompanying paper by Hess *et al.*[8]

The most important reason for operating a maser at low $T$ is the greatly reduced spin-exchange cross section which allows the use of a higher flux of state-selected H atoms without broadening the maser line. In addition, all experiments with H atoms at low $T$ require the use of liquid-$^4$He-coated walls which may be more reproducible than conventional fluorocarbon wall coatings. The initial stimulus of our research was the discovery[9] of a temperature $T_{\mathrm{min}}$ at which the frequency shift due to the combined effect of the He-vapor pressure shift and He-coated wall shift goes through a minimum as a function of temperature. For the present apparatus, this temperature is about 0.6 K. Adapting conventional theories of maser stability, we analyzed the potential performance of a maser with liquid-$^4$He-coated walls, operating at $T_{\mathrm{min}}$ and employing He-cooled electronics for the first stage of amplification. For conventional maser-bulb and cavity sizes and for the optimal bulk holding time and flux, we predicted[3] a stability (Allan variance) of $\Delta f/f \approx 2\times10^{-18}$ for an averaging time $\tau = 10^3$ s.

The apparatus described in this paper is a prototype which incorporates a number of design features which are uniquely cryogenic in nature. In addition to liquid-$^4$He-coated walls and a cryogenic amplifier, we make use of "magnetic compression" to confine atoms in the state selector. The state selector is based on a small 14-kG superconducting magnet at the center of which is a microwave cavity, connected by a tube to the maser bulb (see Fig. 1). Atoms are initially injected into the cavity from a low-temperature source (not shown in Fig. 1) which is identical to that used by us in previous experiments.[2] The microwave cavity is tuned to the ESR frequency of the *b*-to-*c* transition (see Fig. 2). The *c*-state atoms are ejected from the state-selector magnet toward the maser bulb which is surrounded by a 1420-MHz split-ring resonator[10] with an unloaded $Q$ of 2850. Most of the *c* atoms radiate in the cavity and eventually emerge as *a* atoms at which point they are sucked back into the state selector.[11] An attractive feature of this scheme is that the state selector only pumps the *c* state in contrast to the situation in conventional masers, where the beam is formed from equal fractions of *c* and *d* atoms.

In the absence of efficient relaxation mechanisms, this scheme would quickly pump most of the atoms into the *a* state at the center of the state-selector magnet, and hence, a key step in the cycle is the saturation of the *a*-*b* transition in the state selector. This is accomplished by bringing the atoms into contact with a "relaxing foil" in which cobalt is electroplated into micropores with characteristic linear dimensions of order $10^2$–$10^3$ Å (Ref. 12) underneath the ubiquitous liquid-$^4$He film. The populations of *a* and *b* atoms which move along the He-coated foil are equilibrated because the spectral density of magnetic field fluctuations which they experience is quite large at the *a*-*b* transition frequency of about 1 GHz.[2,13]

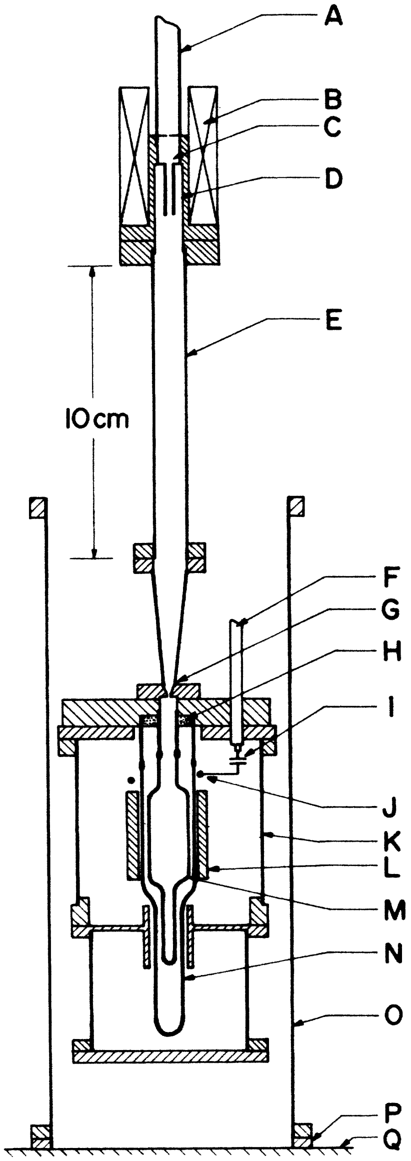

FIG. 1. Simplified and partly schematic diagram of the cryogenic hydrogen maser drawn approximately to scale. *A*: waveguide for 40-GHz pump microwaves, *B*: 14-kG superconducting magnet with persistent switch, *C*: 40-GHz microwave cavity; *D*: region where ~15 layers of "relaxing foil" are placed (not shown), *E*: atom tube; *F*: coaxial output from the 1.4-GHz cavity, *G*: region containing the orifice that sets the maser bulb holding time, *H*: silver sinter for thermal contact between copper flange and liquid $^4$He surrounding maser bulb, *I*: variable capacitor for adjustable tuning, *J*: coupling coil, *K*: outer wall of resonator chamber, *L*: split-ring resonator (the movable tuning plate is not shown), *M*: Pyrex maser bulb, *N*: outer Pyrex bulb to hold liquid-$^4$He cooling bath, *O*: lead plated brass cylinder for trapping in maser bias field, about 80 mG in the current experiment. Not shown is the bias coil which is situated outside the lead shield and just inside a $\mu$-metal shield, also not shown, which is used to produce a low, relatively homogeneous magnetic field; *P*: thermal impedance which allows lead shield to be heated above $T_c$ when the bottom vacuum flange *Q* is at 4.2 K. The atoms from the source travel down the waveguide *A* and enter the pump cavity through a small pinhole in a piece of Mylar covering the coupling aperture.

It is worth emphasizing the recirculating nature of the operation in which atoms cycle back and forth between the state selector and the maser cavity. It is not necessary to provide a continuous supply of atoms because the lifetime of atoms in the cell is very long. The actual value of the lifetime depends inversely on the density of atoms in the cell and on the effective rate constants for recombination in the presence of He gas and on the liquid-$^4$He surface. These rate constants depend in turn on the magnetic field and H-atom density profiles. For an estimated density of $10^{11}$ cm$^{-3}$, and $T \approx 0.5$ K, we have observed a recombination lifetime of about 50 h.

The rate equations which have been used to analyze the performance of conventional masers[3,4,14,15] can also be applied to the case of cryogenic masers. One significant difference, however, has to do with the relationship between the incident flux $I_{\rm tot}$ and the density $n_{\rm H}$ of H atoms in the bulb. In a conventional maser, the density of atoms outside the bulb is effectively zero, and there is a flux $I_{\rm tot}$ of *c* and *d* atoms into the bulb. Then in steady state, the density in the bulb is

$$n_{\rm H} = I_{\rm tot}\frac{T_B}{V_B} , \tag{1}$$

where $T_B$ is the holding time of the bulb and $V_B$ is its volume. By contrast, in the CHM, the average density just outside the entrance to the maser bulb is equal to that inside the bulb. However, the individual state populations $n_i^0$, $i = a,b,c,d$ outside the bulb are different from the pop-

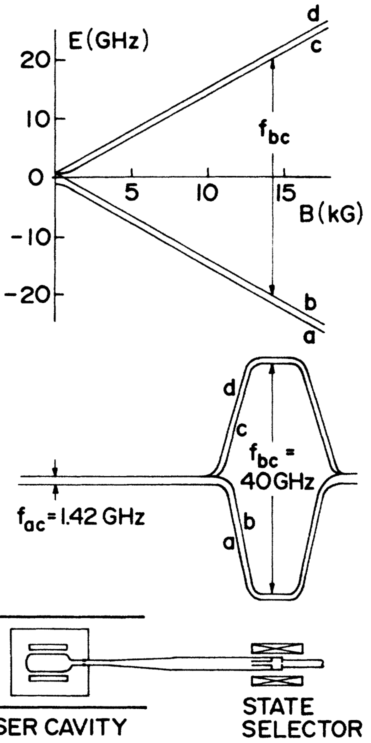

FIG. 2. Breit-Rabi diagram for H showing labeling of states, along with a schematic indication of the energy splittings as a function of position in the recirculating cryogenic hydrogen maser.

ulations $n_i$ inside. The small entrance hole acts as an impedance to flow which we again characterize by a bulb time $T_B$. The region outside the bulb may be thought of as a polarization reservoir with the $n_i^0$ being determined by the effect of the state-selector pump and by the operation of the maser. The difference in densities $\delta_{ac}^0 = n_c^0 - n_a^0$ outside the bulb can be used to define an effective flux

$$I = \delta_{ac}^0 V_B/T_B \ . \tag{2}$$

The power radiated by atoms in the maser is given by

$$P = \frac{\hbar\omega}{2}(I - I_0 T_B^2/T_1 T_2) \ , \tag{3}$$

where $1/T_1 = 1/T_B + \sigma_{ex} v n_H$ and $1/T_2 = 1/T_B + \sigma_{ex} v n_H/2$ ($\sigma_{ex}$ is the spin-exchange cross section and $v$ is the average relative velocity). At low atom densities where $T_{1,2} \approx T_B$,

$$I_0 = \hbar V_c/(4\pi\mu_B^2 \eta Q T_B^2) \tag{4}$$

is the threshold flux which is required to turn on the maser, $\eta$ is the filling factor ($\eta \approx 0.3$ for our apparatus), and $Q$ is the loaded $Q$ of the cavity which is about 1700 for this experiment. For our measured bulb time $T_B = 0.6$ s and cavity volume $V_c \approx 12$ cm$^3$, this means that the effective flux into the cavity must be at least $6 \times 10^{10}$ s$^{-1}$ for maser action to occur or equivalently that there must be a density difference $\delta_{ac}^0 = 7 \times 10^9$ cm$^{-3}$ for our bulb volume of 5.15 cm$^3$.

The incident flux and, hence, the power radiated by the maser depend on the average density $n_H$ and on the microwave pumping power $P_\mu$. We were able to observe stable maser action for a range of densities $10^{11}$ cm$^{-3}$ $\leq n_H \leq 2 \times 10^{12}$ cm$^{-3}$ and temperatures $0.255 \leq T \leq 0.680$ K. For these densities and various $P_\mu$ the output of the maser varied from $5 \times 10^{-15}$ W to $5 \times 10^{-13}$ W. Since the spin-exchange rate constant $\sigma_{ex} v$ at these temperatures is about $10^{-12}$ cm$^3$s$^{-1}$, the highest density corresponds to $\sigma_{ex} v n_H \approx 1/T_B$, and we were, in fact, able to check this by measuring $T_1$ as a function of $n_H$.

The prototype apparatus shown in Fig. 1 was not intended to achieve the highest possible frequency stability but rather to test the basic design principles of the CHM. In particular, the use of a split-ring resonator rather than a larger conventional 1420-MHz cavity greatly simplified the construction at the cost of at least a factor of 10 in potential stability. We have also found the split-ring resonator to be somewhat microphonic, mainly due to mechanical instabilities of the variable tuning and coupling assemblies. We were unable to "spin-exchange tune" the maser cavity,[15] and thus amplitude fluctuations, which resulted from temperature fluctuations of the state selector, also degraded the frequency stability of the maser.

In spite of these difficulties, we were able to show that the stability of the CHM was at least as good as the stability of an Efratom model No. FRK-L Rb atomic clock which is presently the most stable oscillator in our lab. This comparison is shown in Fig. 3, where the two-sample Allan variance of the frequency difference of the two oscillators is plotted as a function of measuring time $\tau$. The Allan variances which we measure correspond quite closely to the expected performance of the Rb clock. In a subsequent low-temperature run we also compared the CHM to a high-quality quartz oscillator on short-term loan from the National Bureau of Standards (NBS). At $1 \text{ s} \leq \tau \leq 300$ s the Allan variance was $6 \times 10^{-13}$, equal to the measurements of Walls[16] on the oscillator. Thus the frequency fluctuations of the CHM could not be observed at this level.

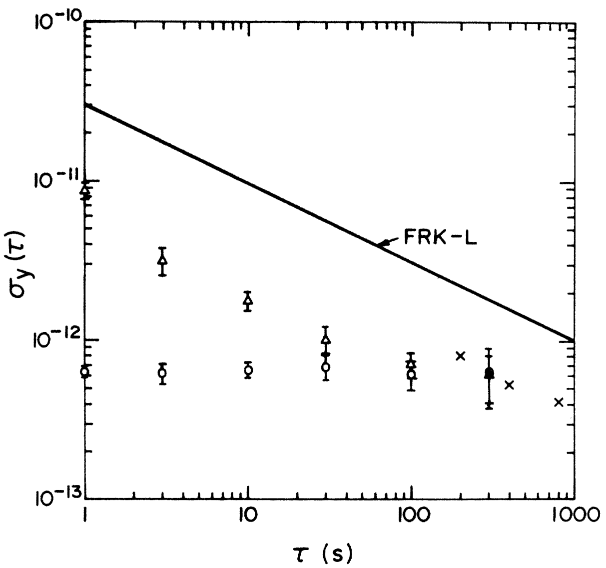

FIG. 3. Plot of measured relative frequency fluctuations $\Delta f/f$ [Allan variance $\sigma_y(\tau)$] vs averaging time $\tau$ taken at $T = 500$ mK. The triangles were obtained by comparing the CHM to an Efratom model FRK-L Rb frequency standard; the solid line represents the guaranteed specifications of the FRK-L standard, whereas the crosses represent actual measured values of its stability. The circles were obtained by comparison with an Oscilloquartz model B 5400 quartz oscillator; the values obtained are indistinguishable from the measured performance of the quartz oscillator alone (Ref. 16).

It is clear that in order to evaluate the performance of the CHM properly we will need better reference clocks. For the longer averaging times the best choice would seem to be a good conventional hydrogen maser. There are a number of obvious and relatively straightforward improvements that can be made in the CHM. We need more cooling and better temperature regulation of the state selector, electronic tuning of the maser cavity, and improved mechanical stability everywhere, but especially in the maser coupling and tuning assemblies. Given these improvements, we are hopeful that the CHM will surpass the performance of conventional masers, at which time it will be necessary to construct a second CHM or some other new kind of ultrastable oscillator in order to be able to evaluate further progress.

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