

## Single State Selection System for Hydrogen Masers

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### Abstract

We describe a single-state selection system for hydrogen masers based upon the adiabatic fast passage method of state inversion. The present design improves the vacuum performance over a previously reported system, and includes increased storage bulb collimation. The system provides line Q's up to  $7.2 \times 10^9$ , and removes from the hydrogen beam approximately 90% of atoms in the  $F = 1$ ,  $m_F = 1$  state.

### INTRODUCTION AND SYSTEM DESIGN

In the hydrogen maser, hydrogen atoms in the  $F = 1$ ,  $m_F = 0$  hyperfine state (called state "c") are confined in a storage bulb where they make transitions to the  $F = -1$ ,  $m_F = 0$  state (state "a"). In masers with traditional state selectors, the state selection magnet removes from the atomic beam entering the storage bulb essentially all atoms in states "a" and "b" ( $F = 1$ ,  $m_F = -1$ ), leaving equal numbers of atoms in states "c" and "d" ( $F = 1$ ,  $m_F = 1$ ). Atoms other than in state "c" do not contribute to maser oscillation, but cause undesired spin exchange relaxation of the radiating atoms, and can cause frequency shifts of the output signal<sup>[1]</sup>. By eliminating the state "d" atoms from the beam, it is possible to reduce these undesirable effects and achieve increased frequency stability. We have designed a single-state selection system that removes approximately 90% of the state "d" atoms from the beam<sup>[2]</sup>. We describe here a system with improved construction, and discuss results obtained using the system.

The single-state selection system consists of a traditional hexapole state selection magnet that removes atoms in states "a" and "b" from the atomic beam, followed by a state-changing apparatus that inverts atoms in state "d" into the "b" state but leaves "c" atoms undisturbed. A second state selection magnet then removes the "b" atoms from the beam, leaving only the desired "c" atoms to enter the storage bulb. In our design, the state changing mechanism, which operates on the adiabatic fast passage (AFP) principle,<sup>[3]</sup> consists of two electromagnets, shown in Fig. 1: a longitudinal variable-pitch solenoid that creates a DC magnetic field varying in intensity along the beam path between roughly 0.3 and 3 gauss, and a transverse four-wire coil, mounted within the solenoid, that produces an RF magnetic field with a frequency on the order of 2 MHz. In the present design the state-changing coils are wound on six aluminum oxide tubes secured to an aluminum framework by molybdenum snap rings. The low vapor pressure materials used minimize the evolution of background gases that can contribute to beam scattering, while the open construction allows increased pumping speed in the beam region. These characteristics permit the use of increased beam flux, thus improving the short-term frequency stability attainable.

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regression of  $P$  on  $D$ , and  $q$  and  $\gamma_t$  and calculated from the resulting values of  $a_1$  and  $a_0$ [2]. The beam optics of the present state-selector is suboptimal, restricting the range of beam flux that can be achieved and thus the curvature of the measured  $P$  vs.  $D$  function. For this reason we have determined the value of  $a_2$  with the single state selection system removed from the maser, and used the resulting  $a_2$ , along with  $P$  measured as a function of  $D$ , to determine  $a_1$  and  $a_0$  when the system is installed. Typical data for the determination of  $a_2$  are shown in Fig. 2, which includes the beam power  $P$  and the function  $P - a_2 D^2$ ; the excellent fit of the latter to a straight line indicates the close agreement between the data and theory.

Data obtained with the present system are shown in Table 1.

Case	Collimator Diameter (mm)	AFP ON		AFP OFF		$q_{\text{off}}/q_{\text{on}}$	
		$q$	$\gamma_t$	$q$	$\gamma_t$		
1	5.6	.0482	1.134	.0934	1.086	1.94	
2	5.6	.0523	1.116	.0936	1.074	1.79	
3	3.2	.0625	0.554	.1176	0.559	1.80	
4	5.6	---	---	.0761	1.194		Field uniform
5	5.6	---	---	.0835	1.347		Field skewed

In cases 1, 2, and 3, the ratio  $q_{\text{off}}/q_{\text{on}}$  is between 1.79 and 1.94, for considerably different collimator diameters, indicating that more than 90% of the state "d" atoms have been removed from the beam when the AFP system is on. With the smaller collimator (lower  $\gamma_d$ ),  $q$  is larger than for the larger collimator. Decreasing  $\gamma_d$  enhances the relative contribution of  $\gamma_m$  to  $\gamma_t$ ; therefore if magnetic or other relaxation mechanisms are not negligible, decreasing the geometrical bulb relaxation rate (or the recombination rate) can increase the value of  $q$ . This effect is seen in cases 4 and 5, for which the AFP system was removed from the maser. In case 5, the internal magnetic field in the resonant cavity was deliberately made non-uniform to increase magnetic relaxation. The value of  $q$  increased by a factor of 1.10 over the value for case 4, in which the field was uniform. The  $\gamma_t$  increased by a factor of 1.13 from case 4 to case 5, which is within 3% of the increase of  $q$ .

## CONCLUSION

The work reported here demonstrates that a single-state selection system based on the adiabatic fast passage principle is capable of removing over 90 percent of unwanted atoms from the maser's hydrogen beam. Furthermore, high line Qs, in the range of  $7 \times 10^9$ , are achievable with currently available storage bulb wall coatings. The system described is designed to operate at high flux levels; combined with high line Qs, this ability has the potential of increasing both long- and short-term frequency stability.

## BULB COLLIMATION

Previous experiments<sup>[2,4]</sup> have shown that substantially increased storage times over those usually observed are possible with improved storage bulb coatings. Loss of atoms from the bulb results from both recombination of hydrogen atoms into molecules on the bulb wall and escape of atoms from the bulb's entrance aperture. Then in order to realize a lower total loss rate

$$\gamma_d = \gamma_r + \gamma_b$$

a decrease in the recombination rate  $\gamma_r$  must be accompanied by a decrease in the escape rate  $\gamma_b$ ; otherwise  $\gamma_b$  would come to dominate the loss rate and a further decrease in  $\gamma_r$  would become ineffective. To achieve higher line Qs, and thus increased long-term frequency stability, we have increased the collimation of the storage bulb aperture. In a preliminary approach, we inserted into the bulb's 5.6-mm diameter collimator a snugly fitting machined Teflon tube with a 3.2-mm inside diameter. With this collimator in place we measured line Qs as high as  $7.2 \times 10^9$ .

## MEASUREMENT OF PERFORMANCE

The effectiveness of the single-state selection system in eliminating state "d" atoms is determined by calculating the ratio of the quantity  $q$  measured with the AFP system off and on.  $q$ , a parameter related to the maser's operating characteristics,<sup>[5,2]</sup> is given by

$$q = K \left( \frac{\gamma_t}{\gamma_d} \right) \left( \frac{I_{tot}}{I} \right) \quad (1)$$

Here  $K$  is a proportionality factor that contains atomic constants and quantities characteristic of the maser, including the volume of the storage bulb and resonant cavity, the bulb's filling factor, and the loaded cavity Q.  $\gamma_t$  is the total density-independent atomic relaxation rate, and can be expressed as

$$\gamma_t = \gamma_d + \gamma_m + \gamma'$$

where  $\gamma_m$  is the relaxation rate due to inhomogeneous magnetic fields and  $\gamma'$  includes any other density-independent relaxation mechanisms. By definition,  $\gamma_t$  excludes spin-exchange relaxation.  $I$  is the flux of state "c" atoms entering the storage bulb, while  $I_{tot}$  is the total flux of hydrogen atoms entering the bulb; thus the ratio  $I_{tot}/I$  measures the purity of the beam. For a properly operating traditional state selector,  $I_{tot}/I = 2$ , since  $I_{tot}$  consists of equal numbers of "c" and "d" state atoms, while  $I$  includes only "c" atoms. In contrast, an ideal single-state selector is expected to have  $I_{tot}/I = 1$ . We measure the improvement in  $I_{tot}/I$  due to the single state selector from the corresponding change in  $q$  when the AFP system is turned off and on.  $q$  is found by measuring the RF power  $P$  delivered by the atomic beam, and the corresponding line Q, for several values of atomic flux.  $P$  is a quadratic function of inverse line Q:

$$P = a_2 D^2 + a_1 D + a_0 \quad (2)$$

where  $D=1/(\text{line Q})$ . The coefficients  $a_2$ ,  $a_1$ , and  $a_0$  are determined from a stepwise linear

We are currently working to improve the optics of the beam handling system, and to combine the system with a vacuum-enclosed dissociator, prior to testing its frequency stability.

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#### REFERENCES

1. Crampton, S.B., and H. T. M. Wang,  
*Duration of spin-exchange collisions*, Phys. Rev. A12, 1305 (1975).
2. Mattison, E.M., R.F.C. Vessot, and W. Shen,  
*Single-state selection system for hydrogen masers*, IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. UFFC-34, p. 622 (1987)
3. Audoin, Claude, Michel Desaintfuscien, Pierre Petit, and Jean-Pierre Schermann,  
*Design of a double focalization in a hydrogen maser*, IEEE Trans. on Instr. and Mass. IM-17, 351 (1968).
4. Vessot, R.F.C., E.M. Mattison, E. A. Imbier, and Z. C. Zhai,  
*Atomic hydrogen maser measurements with wall surfaces of carbon tetrafluoride*, in Proc. 16th Ann. Precise Time and Time Interval Applications and Planning Meeting, 1984, p. 357.
5. Kleppner, D., H.C. Berg, S.B. Crampton, N.F. Ramsey, R.F.C. Vessot, H.E. Peters, and J. Vanier,  
*Hydrogen maser principles and techniques*, Phys. Rev. 138, A972 (1965).

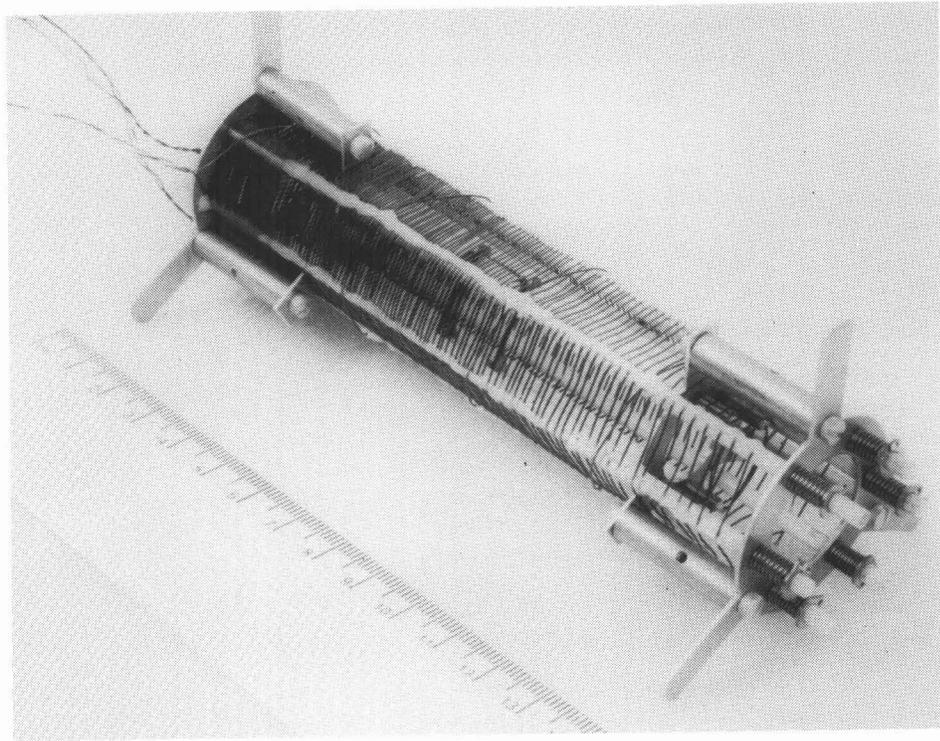


Figure 1.

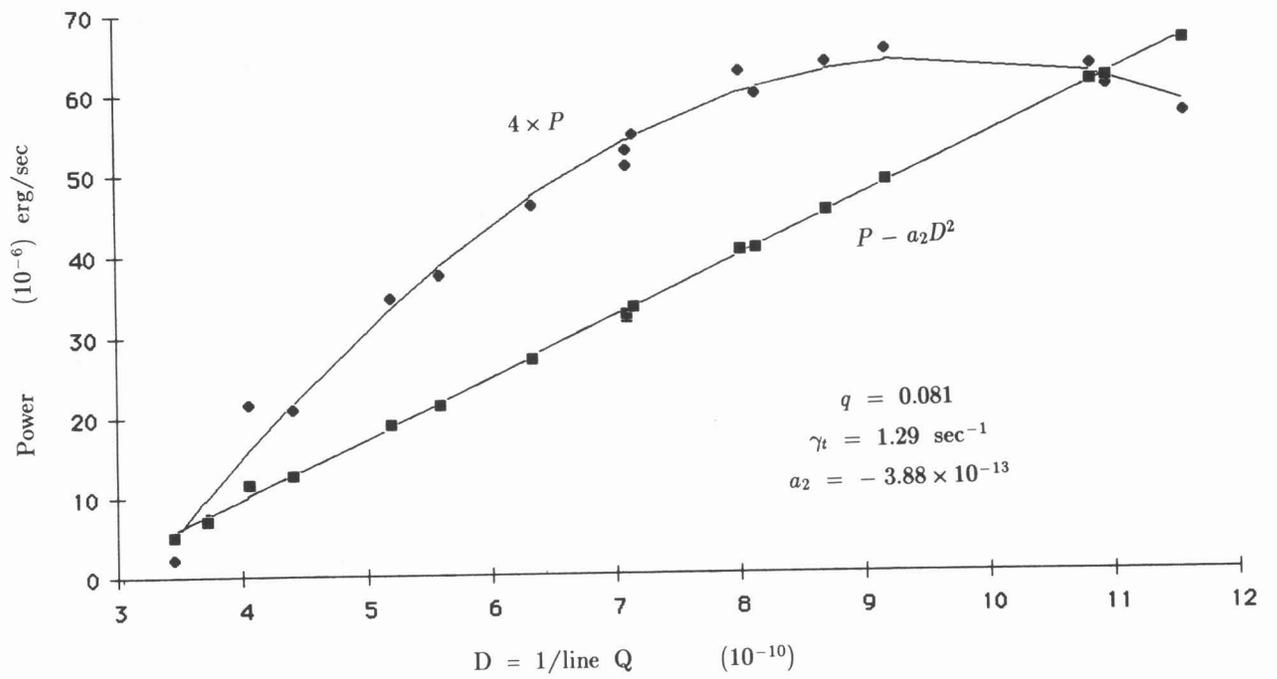


Figure 2.

## QUESTIONS AND ANSWERS

**Jacques Vanier, National Research Council:** Could you comment on the beam flux after you put the fast adiabatic passage technique into the system. There is the idea that you could reduce the flux quite a lot and you wouldn't need the source to supply the flux to operate at the high power level. Then your short term stability would be affected.

**Mr. Mattison:** So far we have not been able to get high flux with the adiabatic fast passage system and our present beam optics. Actually, our optics are not correct, our source is too far from the bulb. According to our calculations, we should get the same flux as we had without the system. In fact, we have not. Part of that is due to the fact that the source is at the wrong distance from the bulb. We are fixing that. Whether we can get as much flux as we like is a question that I can't answer at the moment.

**Brad Parkinson, Stanford University:** Can you tell us what the impact might be, if any, on long term reliability and lifetime?

**Mr. Mattison:** I don't see that it would impact it significantly. The only components that you are adding are a few electronic components, an oscillator and a DC power supply, and a few mechanical components. The only thing that I can think of is that you might have to run the source at a higher flux level than previously which might mean that you would have to replace the pump plates more often or reactivate the cartridges more often.

**Unidentified question from the audience:** What is the expected lifetime?

**Mr. Mattison:** That is hard to answer. You have to specify lifetime for what? We have had masers in the field for over twenty years and they are still going. For example, lifetime between reactivations might be four years instead of five or something of that order.

**Mr. Parkinson:** It seems to me that there is a wonderful history lately of your improving that lifetime and I would hope that this would be an extension of that wonderful history.

**Mr. Mattison:** I would hope so too. I don't think that it would effect it significantly.

**Ken Uglow, Uglow Electronics:** You spoke recently about teflon bombardment and its effect on life. It seems that this would help that.

**Mr. Mattison:** It would help only if you were running at reduced flux. Ideally what you would like to do would be to pump in twice as many state two atoms as before, but eliminate the state one and have the same flux. In that case, you would not change the effect of hydrogenation on the teflon wall.