

PROBLEMS IN HYDROGEN MASER DESIGN AND  
\*  
SUGGESTED IMPROVEMENTS

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ABSTRACT

Frequency shifts due to changing magnetic field inhomogeneities can limit the stability of atomic hydrogen maser standards. They can be minimized by careful design of the magnetic shields, by centering the storage bottle in the microwave cavity, and by operating at relatively high ambient magnetic fields, so as to make these frequency shifts less than one part in  $10^{-13}$  and the instabilities due to changes of field much smaller than  $10^{-13}$ . The inhomogeneity shift is also reduced by increasing the atom storage time, as are both the instabilities due to changes of cavity tuning and the amount of hydrogen atom flux required for self-sustained oscillation. Strategies for improved atom storage times include new surface materials and improved collimation techniques.

INTRODUCTION

Atomic hydrogen maser frequency standards are normally operated at very low average magnetic fields, in order to take advantage of the quadratic dependence of frequency on magnetic field so as to minimize errors due to changes of the average magnetic field.<sup>1</sup> Unfortunately, in low average magnetic fields the hydrogen maser oscillation frequency is subject to appreciable errors due to changes of gradients in the magnetic field. Motion through static and microwave magnetic field gradients by the radiating atoms induces hyperfine transitions which pull the oscillation frequency by amounts which can vary as the static magnetic field gradients change over time.<sup>2,3</sup> This report provides rough estimates of frequency shifts to be expected because of this mechanism and suggests strategies for minimizing the effects on long term frequency stability.

## MOTIONAL FREQUENCY SHIFTS

Changes  $\delta\nu_{\text{osc}}$  of the spin exchange tuned hydrogen maser oscillation frequency<sup>1</sup> due to changes of static magnetic field gradient are of the order of<sup>3</sup>

$$\delta\nu_{\text{osc}} \approx \pm(3 \text{ to } 6) \times 10^{-3} (\pi T_B)^{-1} (\rho_{11} - \rho_{33})_0 [1 + (1.5 \times 10^{-5} \omega_z)^4]^{-\frac{1}{2}} \delta(\pi T_M)^{-\frac{1}{2}}. \quad (1)$$

$(\pi T_B)^{-1}$  is the contribution to the atomic resonance linewidth from the rate at which atoms escape from the storage bottle. It can be reduced by using a small effective exit area, but it cannot be reduced much below the contribution  $(\pi T_W)^{-1}$  to resonance linewidth from wall collision relaxation plus the contribution  $(\pi T_M)^{-1}$  from motion through static magnetic field gradients, without limiting the oscillation power level and spin exchange timing range.  $(\rho_{11} - \rho_{33})_0$  is the net average electron polarization of the hydrogen atom beam as it enters the storage bottle. It can be reduced with some loss of oscillation power and tuning range by driving Zeeman transitions in the atomic beam before it enters the storage bottle, or it can be reduced without loss of power or tuning range using the double focusing technique to eliminate atoms in the uppermost hyperfine state from the atomic beam.<sup>4,5</sup>  $\omega_z$  is the angular frequency of the  $\Delta F=0$  Zeeman transitions and is directly proportional to the static magnetic field averaged over the storage bottle. The contribution  $(\pi T_M)^{-1}$  of magnetic field gradient relaxation to the atomic resonance linewidth is proportional to the mean square deviation of the static magnetic field from its average, so that  $\delta(\pi T_M)^{-\frac{1}{2}}$  is proportional to the change of amplitude of the static magnetic field gradient.  $(\pi T_M)^{-1}$  depends on  $\omega_z$  roughly as  $[1 + (1.5 \times 10^{-5} \omega_z)^4]^{-\frac{1}{2}}$ , so that  $\delta\nu_{\text{osc}}$  falls off with increasing static magnetic field roughly as  $\omega^{-4}$  and can be made arbitrarily small by operating the hydrogen maser at relatively high magnetic fields such that  $\omega_z$  is large compared to the rate at which atoms bounce back and forth across the storage bottle. In that case care must be taken to precisely measure and make relatively large corrections for the magnetic field dependence of the oscillation frequency in such high magnetic fields. The factor  $\pm(3 \text{ to } 6) \times 10^{-3}$  in eq.(1) depends in sign and magnitude on the correlation between static magnetic field inhomogeneities and the configuration of the microwave magnetic field in the hydrogen maser cavity. Carefully centering the storage bottle in the cavity eliminates oscillation frequency pulling from first and all odd order static magnetic field gradients.

Eq.(1) predicts frequency shifts which are small enough to be hard to detect yet large enough to contribute to long term frequency instability. For example, for  $(\pi T_M)^{-1} \approx 0.1$  Hz. a change of static magnetic field gradient of 10% may give a shift of order  $5 \times 10^{-14}$  of the oscillation frequency. The shift may be larger or smaller depending on the configuration of static magnetic field gradient,

but model calculations based on plausible field configurations suggest this order of magnitude at very low average magnetic field and  $(\rho_{11} + \rho_{33})_0 \approx 1/2$ . Of course, this source of oscillation frequency instability can be reduced by reducing changes of static magnetic field gradient by careful magnetic shield design, or by reducing any of the other factors in eq.(1).

#### INCREASED HYDROGEN ATOM STORAGE TIME

We have been doing experiments to maximize hydrogen atom storage time using multtube collimators to confine the atoms in the storage bottles longer, thereby reducing both the factor  $(\pi T_B)^{-1}$  in eq.(1) and the overall linewidths at which the hydrogen maser is tuned and operated. Lower overall linewidth means less oscillation frequency instability due to drifts of the microwave cavity tuning. The beam intensity required for oscillation is also less, so that requirements of pumping speed and pump element life are eased. The only disadvantage is that the oscillation power level is reduced, so that longer averaging times are required.

Table one shows a comparison between relaxation rates and relative beam intensities measured for two 5" diameter spheres coated with FEP Teflon, one of which had a conventional stem to limit egress by the atoms and the other a multtube collimator in place of the stem.

TABLE ONE

|                  | With Stem          | With Collimator  |
|------------------|--------------------|------------------|
| $(\pi T_B)^{-1}$ | .67 Hz             | .27 Hz           |
| $(\pi T_O)^{-1}$ | .87 Hz             | .49 Hz           |
| I                | 1                  | .27              |
| $V_C$            | 5.16 $\text{cm}^3$ | .1 $\text{cm}^3$ |

The stem was 7.54 mm I.D. by 115.6 mm long and was coated with FEP Teflon. The collimator was a bundle of tubes having .05 mm pore diameters by 1 mm long and said by the manufacturer<sup>6</sup> to have 50% transparency before being coated with fluorinated drifilm. The  $(\pi T_B)^{-1}$  contribution to the resonance linewidth due to atom escape from the storage bottle was substantially reduced for the bottle with the collimator. The overall density-independent linewidth  $(\pi T_O)^{-1}$ , including  $(\pi T_B)^{-1}$ ,  $(\pi T_M)^{-1}$  and wall collision relaxation, was also substantially reduced but by a smaller ratio because of a similar .2 Hz contribution by wall collision relaxation in both cases. Comparing the measured  $(\pi T_B)^{-1}$  for the bottle with the collimator to what would be predicted by geometry suggested that the transparency of the collimator after coating was only 38%. The relative input beam intensity I for similar source conditions

was even less than .38, probably due to alignment problems. Despite the alignment loss, the ratio of maximum available resonance linewidth to  $(\pi T_0)^{-1}$ , which determines the spin exchange tuning range, was 1.2 times greater for the bottle with the collimator because of the much longer storage time. The volume  $V_c$  of the collimator, which is an important factor in the motional averaging frequency shifts discussed by Brenner,<sup>7</sup> was only .02 as large as the volume of the stem.

These results are promising, and we plan to try some collimators having larger pore diameters for easier alignment and better transparency after coating but with some increase of volume. We also plan to try some new coating materials, in order to reduce the contribution to  $(\pi T_0)^{-1}$  from wall collision relaxation, but we have not yet found anything better than FEP Teflon.

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