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# PROGRESS TOWARD AN OPTICALLY PUMPED CESIUM BEAM FREQUENCY STANDARD*

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## Abstract

The National Bureau of Standards is planning to build a cesium-beam, primary frequency standard based on the application of optical pumping for state selection and atom detection. The goal is an accuracy of $10^{14}$.

Theoretical studies have been able to identify only Rabi pulling as a mechanism for Majorana-transition-induced frequency shifts. Together with considerations of magnetic field uniformity, this has led us to adopt a longitudinal C-field. In turn, this has required a hybrid magnetic shield design with an active component to cancel ambient fields. Elimination of state-selecting magnets together with polarization control of the optical pumping should eliminate effects of Majorana transitions.

Optical pumping should also permit simultaneous operation of counter-propagating beams with closer trajectory retrace than is possible with magnetic state selection. Real-time measurements of end-to-end cavity phase shift and even servo control are anticipated. Requirements on distributed cavity phase shift have led to consideration of a "race track" shaped cavity termination in place of the more conventional shorted waveguide.

Noise measurements have shown that simple monolithic diode lasers produce too much FM noise to allow one to reach the shot noise limit in atom detection. Techniques for control of diode noise and linewidth are being tried and compared.

## Introduction

The possibility for realizing cesium atomic beam frequency standards in which the state preparation and subsequent detection are accomplished by means of laser driven optical pumping and resonance fluorescence has been studied for several years both theoretically and in the laboratory.[1] This technology offers so much potential for improving the evaluation and/or control of several of the more serious accuracy-limiting systematic errors found in conventional beam standards that the National Bureau of Standards has begun a project to build a large prototype standard in which we can investigate the realizable limits of the technology. After the prototype is used to study some basic effects like frequency shifts due to fluorescent light and blackbody radiation, Majorana effects and distributed-cavity phase shift in new cavity geometries it is expected that this device can become the next NBS primary standard with only minor modifications. For this reason the design specifications are those of a standard in which the accuracy should be about $10^{14}$.

The major building blocks of such a standard are (aside from electronics and laser systems): microwave cavity, magnetic shields, fluorescence collection optics and the vacuum envelope. However, their designs are highly interdependent. The design logic has to be based on the interplay of the major systematic error causing effects found in atomic beam frequency standards.

## Magnetic Field and Rabi Pulling

The requirements on C-field homogeneity and stability needed to control the quadratic Zeeman shift are severe unless small field values can be used. On the other hand, shifts caused by the overlapping wings of other Zeeman transitions (Rabi pulling) are reduced by working at higher fields. The tradeoff can be facilitated by adopting a longitudinal C-field. This geometry will result in better field homogeneity. Also, in this geometry, most microwave cavities contain a field pattern which varies as a half-sine-wave along the atomic beam rather than the more common rectangular pulse. Theoretical studies have shown that the associated Rabi line shape is smoother and much smaller in the wings than in the case of the rectangular pulse[2], thereby reducing Rabi pulling. This will allow one to work at the lower C-field values required by stability considerations without excessive Rabi pulling.

However, the longitudinal C-field is not without drawbacks. Long cylindrical shields have a smaller shielding factor in the axial direction[3]; the direction in which the shielding now becomes most critical. This has forced us to consider a hybrid shield package in which an actively servoed coil outside the passive shields will be used to buck the ambient longitudinal field to near zero.

It may also be possible to actively servo the mean C-field value by monitoring the frequency of the first field sensitive transition. The microwave power can be modulated to put a small amount of power into sidebands at the separation of these transitions. With an additional audio modulation, different from that of the main clock servo and a separate phase sensitive detection channel in parallel with the main servo, one could monitor and control the effective C-field. Because this need not be a tight or fast servo loop, the time constant could be quite long and the amount of signal (noise) insignificant with respect to the signal from the main clock transition.

## Majorana Effects

The theoretical effort has focused on Majorana transitions and Rabi pulling. Rabi pulling, as

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pointed out above, can result when the wings of the Rabi pedestals of other Zeeman components in the hyperfine spectrum overlap the clock transition. But a net shift occurs only if the distribution of population among the magnetic sublevels is asymmetric, since the spectrum is otherwise symmetric at low magnetic fields. When magnetic state selection is used, the symmetry is broken in the high magnetic fields and atoms with different m values follow slightly different trajectories. Hence, asymmetric populations and the associated Rabi pulling are a common source of error in conventional cesium standards. Majorana transitions can compound the problem by transferring atoms from the more asymmetrically populated high m sublevels to the low m sublevels closest to the clock transition.

Optical state selection by circularly polarized light propagating in the direction of the magnetic field can produce a strong asymmetry in the populations of the Zeeman sublevels. However, either the use of linearly polarized light, or light propagating perpendicular to the magnetic field should produce symmetric populations. Doing both, we expect to achieve highly symmetric populations and a consequent vanishing of Rabi pulling. Thus, optical pumping permits the deliberate introduction of Rabi pulling or its suppression.

Majorana transitions are caused by directional changes in the magnetic field as seen by atoms passing through the apparatus. Elimination of the state-selecting magnets and extension of the C-field and magnetic shields over the optical pumping region should keep the field sufficiently uniform that Majorana transitions will not occur. Even if they do occur, they will not lead to Rabi pulling shifts since the optical pumping produces a symmetric population distribution. Majorana-transition probabilities have the same symmetry properties as rotation operators and can not generate asymmetric populations from initially symmetric ones.

## Phase Shifts and Cavity Design

Phase shifts in the microwave cavity can be divided into two classes. One is the variation in phase from one end of the cavity to the other caused by electrically asymmetric lengths of the two arms of the Ramsey cavity and is usually evaluated by beam reversal. The second is the variation in phase across the window in the cavity through which the atomic beam passes. This distributed-cavity phase-shift is relatively small, being caused by propagation losses in the waveguide.[4] Even though it is not explicitly evaluated in present standards, its existence places limits on one's ability to accurately evaluate the larger end-to-end phase shift.

The end-to-end phase error seen by an atom traversing an imperfect cavity can be evaluated by measuring the frequency difference when atoms are made to traverse the same cavity in exactly the opposite direction. The word same is underlined to emphasize that nothing must happen to the cavity during the reversal that may result in changes in its phase shifts; hence, the beam direction is usually reversed rather than the cavity itself. This evaluation process is further complicated and limited by mechanisms which spatially disperse the atomic beam, generating inhomogeneities in flux density and velocity across the beam which then vary along the beam. These inhomogeneities create an undesirable sensitivity to distributed-cavity phase shift in the beam reversal process by limiting the precision of the beam retrace. This causes a differential sensing of the distributed phase shifts for the two directions.

Magnetic state selection is a velocity dependent process resulting in a fan shaped beam (assuming dipole optics) with higher velocities being deflected less and slower velocities deflected more. State selection by optical pumping, on the other hand, does not result in significant spatial beam dispersion. This alone should result in a substantial improvement in our ability to evaluate end-to-end phase shift.

An optically pumped laboratory standard offers the additional possibility of monitoring end-to-end cavity phase shift in real time and perhaps servo controlling it.[5] Figure 1 shows a schematic of a beam tube in which counter propagating beams operate simultaneously through the same cavity. The beam flux is sufficiently low that the two beams do not collisionally interact. The optical state selection/detection process could work as follows.

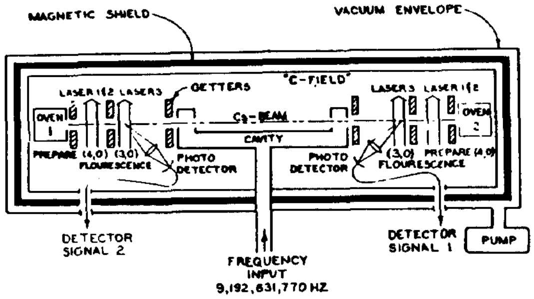

Figure 1. Schematic of a beam tube in which counter propagating beams operate simultaneously.

The beam from the oven on the left side of the figure first passes through a region of optical pumping in which one hyperfine state is essentially depleted of all population. On passing through the Ramsey cavity some population is excited back into that state and subsequently detected by resonance fluorescence in the detection zone on the right end of the cavity. A second oven and optical pumping region on the right with their corresponding detection zone on the left make the machine totally symmetric. The optical detection process is resonant only with atoms in the terminal state of the clock transition and therefore, to the extent that the optical pumping is complete, is virtually blind to atoms that have not yet undergone the clock transition. Furthermore, the subsequent signal processing electronics are sensitive only to the modulation imposed on the signal by the microwaves. The result is that, to a very high degree, each detector is sensitive only to the beam coming from its corresponding oven and not to the simultaneous presence of a counter propagating beam. In this way the frequency error caused by the net cavity phase shift can be monitored in real time. The simple expedient of differentially heating one arm of the Ramsey cavity can then be used to cause differential expansion and drive the error to zero.

Beam reversal, however, treats only the as-perceived end-to-end phase shift without regard to potential sensitivity to residual distributed phase shift which may creep into the system through non-exact beam retrace. The distributed phase shift caused by propagation losses in conventional shorted waveguide cavities has been analyzed[4,6] and shows that for an error no larger than $3 \times 10^{-15}$ (the level we would need in a standard of $10^{-14}$ overall accuracy), the center of gravity of perfectly homogeneous beams must retrace to better than 100 µm. This is an uncomfortable limit and it has caused us to look for cavity designs in which the effect is smaller.

Ideally, the microwave field at the point of atomic beam passage should be a perfect standing wave. Most waveguide cavities used in the past generated the standing wave by reflecting a traveling wave back upon itself at a short. Since a short is not a perfect conductor, the reflected wave is not quite equal to the incident wave. It is this inequality in the counter-propagating traveling waves that gives rise to the distributed phase shift. We plan to use a racetrack shaped cavity (Fig. 2) whose field more closely approaches the ideal standing wave, and hence, produces the desired lower sensitivity to beam retrace errors. An analysis of the distributed-cavity phase shift to be expected in this cavity (including effects attributable to imperfect fabrication) is provided in an accompanying paper.[7] We have made several test pieces both by machining the cavity into a solid copper block and by assembling standard microwave pieces. Measurements of cavity Q, resonance frequencies and imperfection induced coupling to undesirable modes have confirmed the model.

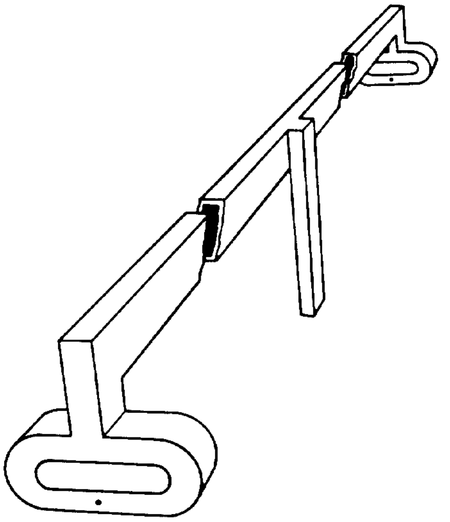

Figure 2. New cavity, proposed to reduce the effects of distributed-cavity phase shift.

## A Horizontal Beam Tube and Gravitationally Induced Beam Dispersion

In horizontal beam tubes, the effect of gravity is to disperse the atomic beam with slow atoms falling more than fast ones over the length of the machine. In long standards the resulting spread can be several millimeters. To retain the advantages of the homogeneous beam produced by optical pumping, our new standard must be either relatively short or vertical.

A large vertical machine potentially presents problems with variations in cavity phase shift and shielding produced by temperature changes and gravitational strain effects. It could also suffer from temperature gradients. Such a machine could not easily be made large enough to offer a significant advantage in line Q. Hence, we are designing a horizontal beam tube with a Ramsey cavity of about 1.5 m, significantly shorter than the 3.75 m of NBS-6.

The residual sensitivity to distributed-cavity phase shift caused by the gravitationally dispersed beam can be handled in several ways. Distributed-cavity phase shift by its very nature is oriented along the Poynting vector in the cavity. By orienting the cavity so this is orthogonal to the beam dispersion one gains some immunity from this effect. One might also deflect the atom beam with photon pressure in a way that partially cancels the gravitational dispersion. Using a cycling transition, all velocities can be caused to refocus at some designated point downstream. For a flight path of 2 m, average velocity atoms will require 15 photon scatterings. Certainly one would have no trouble scattering enough photons to accomplish the desired deflection. On the contrary, this number is so small that one must be concerned about the unintentional deflection and/or beam blow up possible in some of the state selection schemes that have been proposed.

## Optics, Lasers and Related Topics

The potential systematic error caused by fluorescent light produced in the optical pumping process has already been treated theoretically.[8] Within the constraints on atomic beam length presented above, the laser beams can be arranged far enough from the Ramsey cavity to keep light shifts acceptably small.

The fluorescence collection optics are shown in figure 3. A pair of spherical mirrors will collect and image the fluorescence onto the end of a light pipe which will relay the light out through the magnetic shields to a silicon photodiode detector

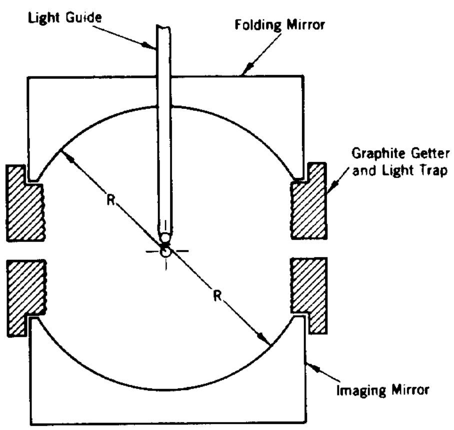

Figure 3. Fluorescence collection optics.

outside the vacuum chamber. Ray trace programs have been used to model the coupling of light into the end of the light pipe. They show that for small object to image distance ratios, the spherical abberations are tolerable. Also, light scattered from the end of the light pipe by the Gaussian wings of the laser beam has been considered and appears manageable within the constraint just given on object to image distance. Depending on the light pipe technology used (glass clad or mirrored tube), up to 60% of the fluorescence can be collected. The use of the graphite skirt will reduce both the scattered light and background cesium within the detection area.

Our present work on diode lasers involves trying to achieve the fundamental detection limits imposed on the resonance fluorescence method by the atomic beam shot noise. With simple commercially available diode lasers one finds excess noise. At least one component of this noise on the cesium fluorescence signal is the result of diode laser frequency fluctuations which sweep the laser frequency across the narrow (~ 5 MHz) atomic linewidth.

We see improved signal to noise in the detected fluorescence when the diode laser frequency is actively locked to the cesium atoms or to an external reference cavity. In locking the laser to the cesium atomic fluorescence two methods have been used; 1)the laser is locked directly to the cesium atomic beam fluorescence or 2) the laser is locked to the resonance via a Doppler free saturated absorption signal in a separate cesium cell. All three of these techniques significantly reduce the excess noise on the fluorescence signal, but as of yet the noise is not reduced to the level expected for shot noise limited detection.

The locking systems employed until now reduce the laser frequency jitter at low Fourier frequencies (below ~ 20 kHz) and show a reduction in the amplitude noise on the fluorescence signal. It should be noted that with this low unity gain frequency the fast laser linewidth is not reduced. The present diode laser systems with weak optical feedback have a laser phase stability which is limited to no more than 20 ns. The rapid laser phase fluctuation requires a very fast servo-control system to appreciably reduce the diode linewidth.

Other sources of noise are being studied as are improved implementation of the present frequency control systems.

## Design Summary

We are building a prototype optically pumped, cesium-beam standard in which we can study systematic effects not amenable to study in conventional standards. It is our expectation that, after these studies, the device can be made to operate as a new primary standard with an accuracy of $10^{-14}$ or almost an order of magnitude better than our existing standard. At this level of accuracy our time scale will not support the presently practiced policy of evaluating the standard once per year. Rather the new standard will have to be evaluated monthly. To avoid this position, we are planning to make the standard operate at least quasi-continuously as a clock and, to the extent possible, be self evaluating. The design has followed from an analysis of all identified systematic errors.

To a large extent the design need not be committed to any particular optical pumping scheme at this time. Our plan is for a horizontal beam tube with a Ramsey cavity of about 1.5 m. It follows from this value and the mean thermal velocity, that a line Q of about $10^8$ is to be expected. To realize the stated accuracy goal will, therefore, place a heavy burden on the line centering servo. Our preliminary investigation (not discussed here) indicates the feasibility of the task.

A new racetrack shaped microwave cavity has been designed and modeled which will reduce distributed-cavity phase shift and requirements on beam retrace precision. Plans call for simultaneous operation of counter-propagating atomic beams and servo control of the end-to-end phase shift. Regions of optical pumping and detecting will be placed symmetrically on each end of the Ramsey cavity separated by 40 and 20cm respectively from the cavity. With the expected beam flux and pumping schemes, these separations are adequate to control light shifts.

For reasons of magnetic field control as well as Rabi line pulling, a longitudinal C-field has been selected. This in turn has required the use of a hybrid magnetic shield design in which both active and passive shielding will be used.

Work continues on diode laser characterization and control. The goal is to find a simple way to use the diode lasers and still reach the fundamental limits on clock performance. Failing this, we can resort to the much more complicated but certain techniques of external cavity lasers.

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